



Experimental and numerical study on thermo-mechanical behaviour of carbon fibre reinforced polymer and structures reinforced with CFRP

Phi Long Nguyen

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EXPERIMENTAL AND NUMERICAL STUDY ON THERMO-MECHANICAL BEHAVIOUR OF CARBON FIBRE REINFORCED POLYMER AND STRUCTURES REINFORCED WITH CFRP

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Abstract

Carbon fibre reinforced polymer (CFRP) is one of common solutions in repairing / reinforcing/ strengthening/ retrofitting structures in civil engineering due to its advantages in mechanical properties, durability and workability. However, recent issues have raised concerns for fire performance of CFRP and CFRP reinforced structures. Throughout the literature, there are several investigations on the evolution of mechanical performance of CFRP and CFRP reinforced structures during or after exposing to different levels of temperature which are close to temperatures obtained during a fire. However, the results are scatter due to the diversity of materials used, the difference in test protocols, and limitation in test facility for elevated temperature use. Analytical and numerical studies are also conducted with parametric investigation to observe, improve, and propose recommendations for design guideline. Additionally, missing gap in experimental data has a significant influence on the applicability of the available results.

This research characterizes the behaviours of CFRPs and of concrete structure reinforced with CFRP material under three separated conditions concerning elevated temperature and mechanical loading that are close to different cases of fire application. The experimental and numerical methods used in this research are to further investigate the status of each material during the case studies. Particularly, residual test is used to study the mechanical performance of specimens cooled after exposing to elevated temperature respecting the evaluation of the remained behaviour of CFRP reinforced structures at post-fire situation for repairing/ retrofitting purpose. Two thermo-mechanical tests are used to study the mechanical performance of specimens at different elevated temperatures and their thermal performance at different mechanical statuses respecting the fire situation for predicting and designing purpose. The two final cases focus on the influence of loading order on the results to confirm the validity of experimental mechanical data obtained at different temperatures when applying for evaluating the fire performance of CFRP reinforced structure where mechanical effects and then temperature effects are combined.

In the first experimental part, 86 tests on two types of CFRP (one pre-fabricated in factory and one manually fabricated in laboratory) were studied in the temperature range from 20°C to 712°C. The performance of CFRP material is generally reduced as the temperature increases. The thermo-mechanical and residual ultimate strengths of P-CFRP gradually decrease from 20°C to 700°C, while its Young's modulus varies less than 10% from 20°C to 400°C and then significantly decreases at 600°C. The identified thermo-mechanical performance of CFRP was lower than its residual performance, especially at temperature beyond 400°C. Furthermore, the elevated temperature and mechanical load are experimentally shown to be relevant and thus the loading order has a small effect on the material performance under thermo-mechanical conditions. A new analytical model, proposed for the evolution of thermo-mechanical ultimate strength in function of temperature, has shown the ability to fit with two studied CFRPs and with those tested under similar thermo-mechanical condition in the literature.

In the second experimental part, 39 tests on CFRP reinforced concrete structures were conducted following three procedures via 8 series. The study concerns three adhesives and two common reinforcement methods. The experimental results show that the near surface mounted reinforcement method can improve the thermo-mechanical performance of the tested specimen comparing to externally bonding reinforcement method. It also confirms that the mechanical performance of CFRP reinforced concrete structure under elevated temperature condition is much lower than its performance under residual condition. The mechanical status of CFRP reinforced concrete structure also has an

influence on its ability to resist elevated temperature rise, which is close to fire, with the reduction rate depending on the used adhesive and reinforcement method. The modification of adhesive used also affects to the thermo-mechanical performance of CFRP reinforced concrete structure. Other experimental tests on insulated CFRP have shown ability to extend the thermal performance in terms of duration and failure temperature of this material. It is also shown that with the restriction from direct-contact with air, the studied CFRP material can resist to higher temperature level.

In the final numerical part, the finite element method has been used to predict the thermo-mechanical performance of CFRP reinforced structure and also thermal performance of insulated CFRP. The first model has successfully predicted the displacement response of CFRP reinforced concrete structure under mechanical load as elevated-temperature rise. Three cases under different mechanical loads have been verified with experimental results with the appropriateness. The extended results for standard fire temperature cases regarding the variation of mechanical load have been presented. A proposed thermal-based method is potential for predicting the service duration of CFRP reinforced concrete structure under constant mechanical loads subjecting to elevated-temperature rise. The second model on insulated CFRP also successfully predicts the thermal performance of an insulation material in protecting the CFRP material. The thermal based method again shows the potentiality in predicting the ability of the studied insulation to protect CFRP regarding the influence of mechanical load. The numerical result is potentially in both predicting fire performance and designing the CFRP reinforced structure in according to the fire safety requirement. The numerical model can be further developed to be better explaining the damage mechanism and more efficient in fire-safety design application for CFRP reinforced concrete structure.

Résumé

Le polymère renforcé de fibres de carbone (CFRP) est l'une des solutions courantes pour réparer/ renforcer/ fortifier/ rétrofiter les structures en génie civil en raison de ses avantages dans les propriétés mécaniques, la durabilité et la maniabilité. Cependant, des problèmes d'incendie récents ont soulevé des inquiétudes quant à la performance au feu du CFRP et des structures renforcées par CFRP. Dans la littérature, il existe plusieurs études sur l'évolution de la performance mécanique de CFRP et des structures renforcées par CFRP pendant ou après l'exposition à différents niveaux de température qui sont proches des températures obtenus durant un feu. Cependant, les résultats sont dispersés en raison de la diversité des matériaux utilisés, de la différence dans les protocoles d'essai et de la limitation de l'installation d'essai pour une utilisation à température élevée. Des études analytiques et numériques sont également menées avec une étude paramétrique pour observer, améliorer et proposer des recommandations pour les directives de conception. Cependant, le manque de données expérimentales a une influence significative sur l'applicabilité des résultats disponibles.

Cette recherche caractérise les comportements des CFRP et de la structure renforcée avec du matériau CFRP dans trois conditions distinctes concernant la température élevée et la charge mécanique qui sont proches des différents cas d'application au feu. Les méthodes expérimentales et numériques sont utilisées pour mener cette recherche afin d'étudier plus en détail l'état de chaque matériau au cours des études de cas. En particulier, l'essai résiduel est utilisé pour étudier la performance mécanique des spécimens refroidis après exposition à température élevée en respectant l'évaluation du comportement résiduel des structures renforcées en CFRP en situation post-incendie à des fins de réparation / renforcement. Deux essais thermomécaniques sont utilisés pour étudier la performance mécanique des échantillons à différentes températures élevées et leur performance thermique à différents états mécaniques en respectant la situation d'incendie pour la prédiction et la conception. Les deux derniers cas portent sur l'influence de l'ordre de chargement sur les résultats pour confirmer la validité des données mécaniques expérimentales obtenues à différentes températures lors de l'évaluation de la performance au feu de la structure renforcée par CFRP où les effets mécaniques et puis les effets thermiques sont combinés.

Dans la première partie expérimentale, 86 essais sur deux types de CFRP (un préfabriqué en usine et un fabriqué manuellement en laboratoire) ont été étudiés dans la plage de température de 20°C à 712°C. La performance du matériau CFRP est généralement réduite lorsque la température augmente. Les résistances thermomécaniques et résiduelles du P-CFRP diminuent graduellement de 20°C à 700°C, tandis que le module de Young varie de moins de 10% de 20°C à 400°C et ensuite diminue significativement à 600°C. La performance thermomécanique identifiée de CFRP a été inférieure que sa performance résiduelle, en particulier à une température supérieure à 400°C. En outre, la température élevée et la charge mécanique sont expérimentalement pertinentes et l'ordre de chargement a donc un faible effet sur les performances du matériau dans des conditions thermomécaniques. Un nouveau modèle analytique, proposé pour l'évolution de la résistance ultime thermomécanique en fonction de la température, a montré sa capacité à s'adapter à deux CFRP étudiés et à ceux testés dans des conditions thermomécaniques similaires dans la littérature.

Dans la seconde partie expérimentale, 39 essais sur les structures en béton renforcées par CFRP ont été réalisés selon trois procédures via 8 séries. L'étude concerne trois adhésifs et deux méthodes de renforcement courantes. Les résultats expérimentaux montrent que la méthode de renforcement monté en surface proche peut améliorer les performances thermomécaniques de l'échantillon testé par rapport à la méthode de renforcement par liaison externe. Il confirme également que la performance

mécanique du béton renforcée par CFRP à température élevée est beaucoup plus faible que sa performance dans des conditions résiduelles. L'état mécanique de la structure en béton renforcée par CFRP influe également sur sa capacité à résister à une élévation de température élevée, proche du feu, le taux de réduction dépend de la méthode de collage et du renforcement utilisée. La modification de l'adhésif utilisé affecte également la performance thermomécanique de la structure en béton renforcée par CFRP. D'autres essais supplémentaires sur les CFRP isolés ont montré une capacité à augmenter les performances thermiques en termes de durée et de température de rupture de ce matériau. Il est également montré qu'avec la restriction du contact direct avec l'air, le matériau CFRP étudié peut résister à un niveau de température plus élevé.

Dans la partie numérique finale, la méthode des éléments finis a été utilisée pour prédire la performance thermomécanique de la structure renforcée par CFRP et également la performance thermique du CFRP isolé. Le premier modèle a prédit avec succès la réponse de déplacement de la structure en béton renforcée par CFRP sous charge mécanique en tant qu'élévation à température élevée. Trois cas sous différentes charges mécaniques ont été vérifiés avec les résultats expérimentaux avec la pertinence. Les résultats étendus pour les cas de température de feu standard concernant la variation de la charge mécanique ont été présentés. Une méthode thermique proposée est un moyen de prédire la durée de service de la structure en béton renforcée par CFRP soumise aux charges mécaniques constantes et à une élévation de température élevée. Le deuxième modèle sur CFRP isolé prédit également avec succès la performance thermique d'un matériau isolant dans la protection du matériau CFRP. La méthode thermique montre à nouveau la possibilité de prédire la capacité de l'isolant étudié à protéger les CFRP en ce qui concerne l'influence de la charge mécanique. Le résultat numérique est potentiellement à la fois la prévision de la performance au feu et la conception de la structure renforcée par CFRP conformément aux exigences de sécurité d'incendie. Le modèle numérique peut encore être développé pour mieux expliquer le mécanisme d'endommagement et être plus efficace dans l'application de la conception de sécurité d'incendie pour la structure en béton renforcée par CFRP.

List of Publications

Publications until May 2018:

International journal articles:

1. Phi Long NGUYEN, Xuan Hong VU, and Emmanuel FERRIER, Characterization of pultruded carbon fibre reinforced polymer (P-CFRP) under two elevated temperature-mechanical load cases: Residual and thermo-mechanical regimes, *Construction and Building Materials*, vol. 165, pp. 395–412, Mar. 2018. (Impact factor 2016 of JCBM : 3.169)
2. Phi Long NGUYEN, Xuan Hong VU, and Emmanuel FERRIER (2018). Elevated temperature behaviour of carbon fibre-reinforced polymer applied by hand lay-up (M-CFRP) under simultaneous thermal and mechanical loadings: experimental and analytical investigation. *Fire Safety Journal* 100 (2018) 103-117, DOI: 10.1016/j.firesaf.2018.07.007 (Elsevier, Impact factor 2017: 1.888).
3. Phi Long NGUYEN, Xuan Hong VU, and Emmanuel FERRIER. Thermo-mechanical Performance of Carbon Fibre Reinforced Polymer (CFRP), with and without Fire Protection Material, under Combined Elevated Temperature and Mechanical Loading Condition. Submitted to *Composites Part B: Engineering* in 04th April 2018, under review 06th April 2018.
4. Phi Long NGUYEN, Xuan Hong VU, and Emmanuel FERRIER (2018). Effect of reinforcement methods: externally bonding reinforcement (EBR) and near surface mounted (NSM) on the thermo-mechanical performance of CFRP reinforced concrete structure under elevated temperatures. (In preparation).
5. Phi Long NGUYEN, Xuan Hong VU, and Emmanuel FERRIER (2018). Experimental study on the influence of adhesive on the thermo-mechanical performance of near surface mounted (NSM) CFRP reinforced concrete structure under elevated temperatures. (Submitted to *Engineering Structures* journal on September 13th 2018, under review from September 14th 2018).

Conference proceedings:

1. Phi Long NGUYEN, Xuan Hong VU, and Emmanuel FERRIER (2016). An Experimental Study On The Thermomechanical And Residual Behaviour Of The P-CFRP Subjected To High Temperature Loading. In *Proceedings of the Eighth International Conference on Fibre-Reinforced Polymer (FRP) Composites in Civil Engineering*, (Hong Kong, China: The Hong Kong Polytechnic University), pp. 797–803.
2. Phi Long NGUYEN, Xuan Hong VU, and Emmanuel FERRIER (2017). Behaviour of Carbon Fiber Reinforced Polymer (CFRP), with and without fire protection material, under combined elevated temperature and mechanical loading condition. In *Proceedings of SMAR 2017, Fourth Conference on Smart Monitoring, Assessment and Rehabilitation of Civil Structures*, (Zurich, Switzerland: ETH Zurich), p. ID109.
3. Phi Long NGUYEN, Xuan Hong VU, and Emmanuel FERRIER (2017). Experimental study on the thermo-mechanical behavior of Hand-made Carbon Fiber Reinforced Polymer (H-CFRP) simultaneously subjected to elevated temperature and mechanical loading. In *Proceedings of the 4th Congrès International de Géotechnique - Ouvrages -Structures*, (Ho Chi Minh City, Vietnam, Springer publisher, 2017), pp. 484–496.
4. Phi Long NGUYEN, Xuan Hong VU, and Emmanuel FERRIER (2017). Experimental study on the thermo-mechanical behavior of Hand-made Carbon Fiber Reinforced Polymer (H-CFRP)

simultaneously subjected to elevated temperature and mechanical loading. In Proceedings of Next Generation Design Guidelines for Composites in Construction, (Budapest, Hungary, 2017)

5. Phi Long NGUYEN, Xuan Hong VU, and Emmanuel FERRIER (May 2018). Experimental study on transient thermal performance of P-CFRP under tensile loading and close-to-fire condition. In Proceedings of 4th Conference of Science Technology, Ho Chi Minh University of Transport, Vietnam

6. Phi Long NGUYEN, Xuan Hong VU, and Emmanuel FERRIER (June 2018). Experimental and numerical study on thermomechanical behaviour of carbon fiber reinforced polymer (CFRP) and structures reinforced with CFRP. In Proceedings of « RUGC2018 - Les 36èmes Rencontres Universitaires de Génie Civil de l'AUGC », (Sainte Etienne, France)

7. Phi Long NGUYEN, Xuan Hong VU, and Emmanuel FERRIER (June 2018). Numerical Modeling of Thermal Behaviour of CFRP Reinforced Concrete Structure Exposed To Elevated Temperature. In Proceedings of the Tenth International Conference on Structure in Fire (Titanic Belfast, UK).

8. Phi Long NGUYEN, Xuan Hong VU, and Emmanuel FERRIER (July 2018). Experimental Study of Thermo-Mechanical Performance of CFRP Reinforced Concrete Structure. In Proceedings of the Ninth International Conference on Fibre-Reinforced Polymer Composites in Civil Engineering (Paris, France).

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List of symbols and notations

σ	: Normal stress, MPa
τ	: Shear stress, MPa
ε	: Strain
ρ	: Density, kG/m^3 , g/cm^3
$\rho(\theta)$	: Density at temperature θ , kG/m^3 , g/cm^3
f_c	: Compressive strength of concrete, MPa
θ, T	: Referenced temperature, $^{\circ}\text{C}$
λ	: Thermal conductivity, $\text{W/m.}^{\circ}\text{C}$
C_p	: Specific heat, J/kg.K
f_w	: Applied load ratio
F_c	: Control force, N
F_r	: Rupture force, N
F_w	: Applied force, N
E	: Young's modulus, GPa
NAS	: Nominal adhesive shear stress, MPa
S	: Contact region between concrete block and CFRP plates via adhesive
T_g	: Glass transition temperature, $^{\circ}\text{C}$
T_c	: Combustion temperature, $^{\circ}\text{C}$
T_d	: Decomposition temperature, $^{\circ}\text{C}$
T_m	: Melting temperature of polymer, $^{\circ}\text{C}$
T_a	: Ambient temperature, $^{\circ}\text{C}$
T_t	: Target temperature, $^{\circ}\text{C}$
t_w	: Exposure duration time (waiting time), minute
T_r	: Rupture temperature, $^{\circ}\text{C}$
DSC	: Differential scanning calorimetry
DMA	: Dynamic mechanical analysis
EBR	: Externally bonding reinforcement
FE	: Finite element
FRP	: Fibre reinforced polymer
CFRP	: Carbon fibre reinforced polymer
GFRP	: Glass fibre reinforced polymer

P-CFRP: Pultruded carbon fibre reinforced polymer

M-CFRP: Manually fabricated carbon fibre reinforced polymer

NSM : Near surface mounted reinforcement

RR : Residual regime

TM1 : Thermo-mechanical regime 1: thermo-mechanical test at constant temperature

TM2 : Thermo-mechanical regime 2: thermo-mechanical test at constant mechanical load

TGA : Thermal gravimetric analysis

WSP : With steel plate structure design

WOSP : Without steel plate structure design

Chapter 1:

Literature review

CHAPTER 1 : Literature review

This chapter aims to review the physical, chemical and thermal behaviours of materials including concrete, polymer composite and polymer under the effect of high temperature. Observations, logical explanations, the important findings and the strengths and limitations in experiment conducted in previous studies are analysed to prepare for later study on the mechanical behaviours on the above mentioned materials regarding elevated temperature conditions. In this section, fundamental knowledge about the fire and the evolution about the material behaviours in the fire-related conditions will be presented.

1.1. General of fire

A fire is a rapid oxidation of material in the exothermic chemical process of combustion, and releasing heat, light and variety of reaction products. For a fire to occur, it is essential for three following factors to concurrently exist:

- Presence of fuel: solid type of flammable material (wood, coal, paper...), liquid (petrol, alcohol ...), gas (butane, propane ...).
- Presence of an oxidant: a chemical substance which has the property allowing the combustion of a fuel (oxygen, air,...).
- Flame heat source: source of energy needed to start combustion (flame, spark, electric shock)

Basically, the ideal fire action can be divided into following phases: development (ignition + propagation), flashover, full intensity and decay. During the evolution of the fire, there may be a rapid transition stage between the first two phases, called flashover. This phenomenon generally occurs at a temperature of 500°C to 600°C if there is sufficient fuel oil, ventilation or the propensity of ignition.

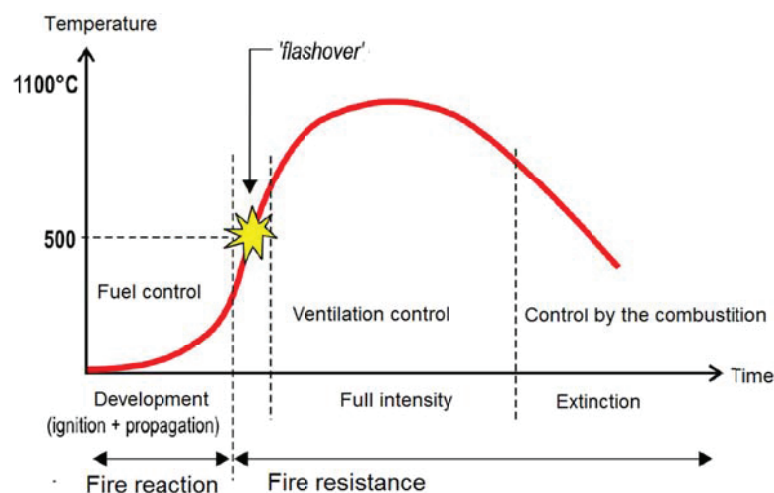


Figure 1: Development stages of a fire (Denoël, 2007)

First phase "Development of Fire":

- A period of smouldering fire, where the temperature is localized to the point of ignition; the first gas and smoke appraising; smouldering has a very low temperature and this duration is difficult to be estimated.

- A trigger time of the fire, where the focus is crisp but still localized, radiation or contact with flames reached nearby materials, hot gases emerge and fill the volume.

Generalized conflagration: Hot gases cause the fuel to ignite under the action of their temperature; fire is suddenly widespread in a very short time.

Second "full intensity" phase: The temperature rises to the peak (Figure 2a,b) and decreases until the temperature is equal to 80% of the maximum value (Figure 2b, (Harmathy, 1972a, 1972b)).

Third phase "decay": The fire of violence decreases with the gradual disappearance of the fuel.

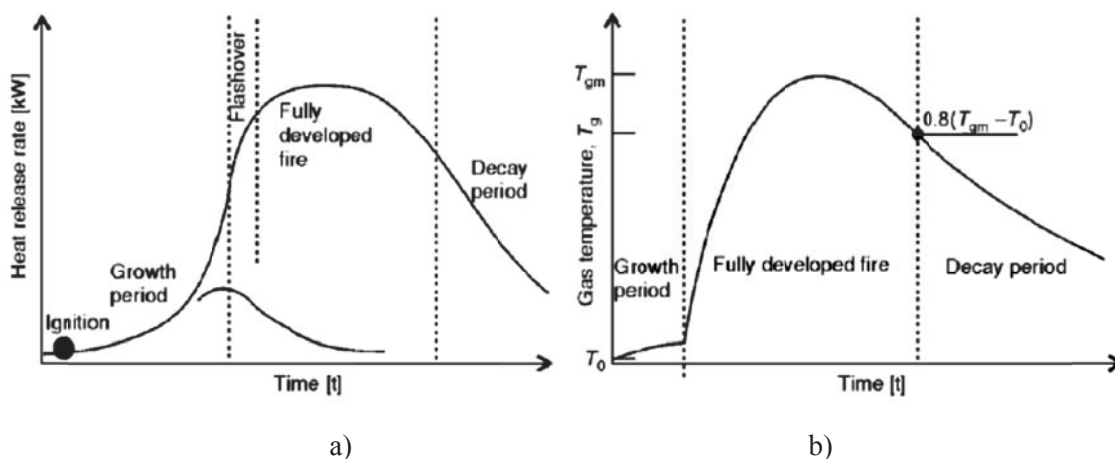


Figure 2: The time-temperature phases of a fire compartment ventilated: (a) ideal fire; (b) typical temperature history of the gasses contained in a fire compartment (Harmathy, 1972a, 1972b))

There are several parameters that can affect the severity and the duration of the fire:

- Quantity and distribution of combustible materials (fuel load)
- Burning rate of these materials
- Ventilation conditions.
- Geometry of the compartment
- Thermal properties of the walls of the compartment.
- Active struggle against fire measures.

Among these elements, fuel load and ventilation rate are two most essential factors for direct contribution to the fire controlling by providing enough the combustion (or fuel) and oxygen.

In general, a fire can be simulated by nominal curves, such as ISO 834 or ASTM E119 curves that display the relationship between the changes in the gas temperature as a function of time (Figure 3). These curves are developed to experimentally test the building elements in order to establish a relative ranking for both their resistance and reaction to fire (Denoël, 2007). They are essential for the elements tested in different furnace by ensuring that they will undergo the same thermal condition. These nominal curves also constitute a conventional reference for the modelling of a fire in a building. Figure 3 shows the nominal curves established from experience on the real fire occurring in building, petrochemical/offshore platform and tunnels.

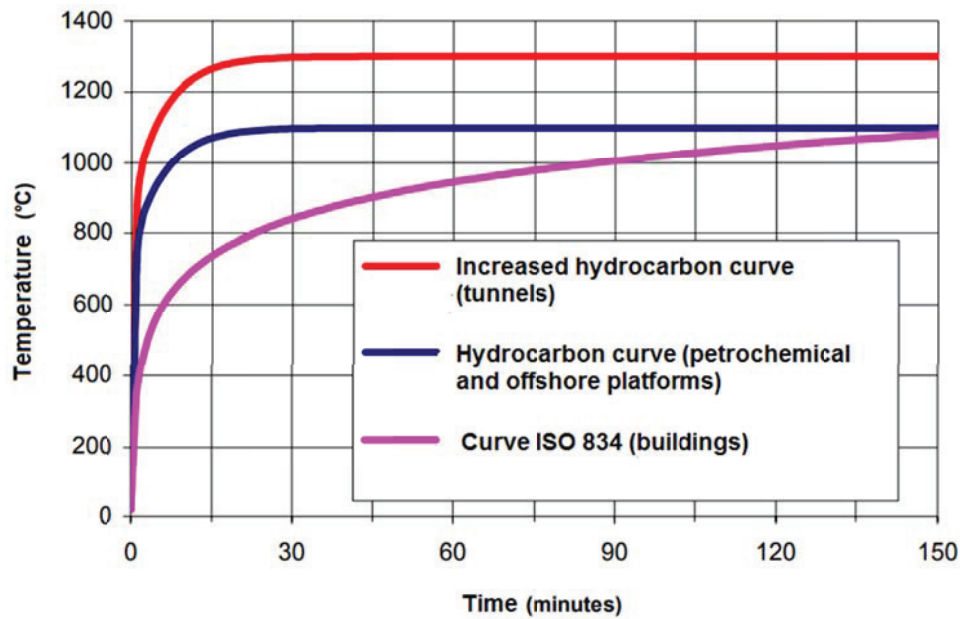


Figure 3: Different temperature curves (Denoël, 2007)

The ISO 834 standard, a logarithm curve in which the temperature increases continuously along the time but with a decreasing rate, will be used for laboratory testing. The value of fire resistance duration does not indicate the actual length of time during which a component resists to fire in a building, but it is a comparison indicating the severity of a fire which the component can resist. The ISO-834 curve can be presented as following equation in term of time and temperature:

$$\theta_g = 534 \log_{10}(8t + 1) + 20 \quad \text{Equation 1}$$

With: θ_g = gas temperature in the fire compartment (in °C)

t = time after the start of the test (in minutes).

Table 1: Main values of conventional temperature - time curve - ISO 834

Time, min	Temperature, °C	Time, min	Temperature, °C
0	20	90	1006
5	576	120	1049
10	687	180	1110
15	739	240	1153
30	842	300	1186
60	945	360	1214

The Equation 1 characterizing the standard curve ISO 834 shows two distinct phases during a fire (Figure 3): first, the flashover during which a very rapid increase in temperature occurs or a heat shock (about 800°C), followed by the other hand, the period in which the fire is fully developed, characterized by a less rapid increase in temperature up to 1200°C. This curve is intended to represent the products of cellulosic fires. The curve ISO 834 with the practical advantage is certain, shows deviations from a natural fire in buildings. Indeed, the following can be noted:

- ISO curve is a theoretical curve, which may be exceeded for a limited time in an actual fire; In addition, there is only one ISO curve for all types of buildings, regardless of the conditions of heat load and ventilation. However, a publication of the National Research and Safety Institute

(INRS) shows that only 6% of fires lasting more than an hour and the focus can reach 1130°C (Aussel et al., 2007).

- ISO curve must be taken into account for every compartment, even if it is very large. In fact, in a fire, the temperature varies by location;
- ISO curve does not take into account the phase of "pre-flashover" of a real fire;
- ISO curve involves an ever increasing temperature. In practice, it is proved that the temperature begins to decrease after the bulk of the fuel is burned;
- The temperature is uniform in the compartment; the only parameter on which they depend is time.

1.2. Material properties at elevated temperature

This subsection describes previous studies on concrete, FRP and CFRP, behaviour of polymer adhesives, concrete/adhesive/FRP Interface and FRP-concrete structure bonding.

1.2.1. Concrete

Concrete is used as a substrate that is reinforced/ repaired by the composite materials that are studied in this research. Therefore, this section presents an observation regarding the concrete's behaviour at high temperature, especially the ordinary concrete. The physical, thermal and mechanical properties according to the temperature as well as the cracking and damage mechanisms are briefly reviewed in the followings.

1.2.1.1. *Physical and chemical phenomena in the heated concrete*

Concrete is made up of three essential components: cement, aggregates and water. Over time, changes in properties (mechanical, physical and chemical, thermal properties) are primarily due to the hydration of cement (Missemer, 2012). Cement and water confer resistance to concrete. Their mixture initiates hydration reactions for passing anhydrous cement in a hardened cement paste. The two main hydrates formed are calcium silicate hydrates, denoted C-S-H and portlandite, denoted by Ca(OH)_2 or also CH. The role of this H-S-C is dominating in the cement paste resistance.

In concrete, water exists in various forms:

- Free water in the capillaries: it is easier to evaporate water at a temperature rise.
- The adsorbed water: this water is chemically or physically bonded to the surface hydrates. This water can be regarded as a structural element that is capable of transmitting stresses.
- The chemically bound water: it is the water consisting hydrates created during the hydration reaction.

Based on the evaporability (or ability to evaporate), there are two types of water (Missemer, 2012):

- Evaporable water refer mainly free water and adsorbed water freely, the evaporation of which is possible between 30°C and 120°C. Many authors observe that the evaporation depends on the speed of temperature rise. Indeed, the proportion of free evaporated water is greater at a given temperature when the heating rate is low. This results in a larger mass loss. But if the speed is too fast, the vapour may be trapped in the concrete.
- Non-evaporable water corresponds to the interlayer water and chemically bound water. Their evaporation requires a prolonged heating material that cannot be without consequences for the aggregates of the concrete and on the cementitious material.

Aggregates constitute the skeleton of concrete and occupy about 60-80% of its volume. Different types of aggregates can be used: limestone, silica, sand-lime, sandstone, basalt, expanded clay.... Calcareous

aggregates have strong bonds with the cement paste due to chemical reactions that occur over time. By against the siliceous aggregates are neutral with the cement paste and thus have weak bonds.

When concrete is subjected to temperatures increase, different physic-chemical transformations occur within concrete. These transformations can cover both the hardened cement paste and aggregates.

a. Changing of the cement paste:

Thermal gravimetric analysis (TGA) or differential thermal analysis (DTA) highlights the physicochemical changes that occur in the cement paste and result in the elevation of the temperature (Fares, 2010; Hager, 2004; Missemmer, 2012; Nguyen, 2013). The main transformations are summarized as follows:

- Between 30°C and 120°C, the free water and part of absorbed water evaporate. At 100°C, ettringite ($3\text{CaO}\cdot\text{A}_2\text{O}_3\cdot 3\text{CaSO}_4\cdot 32\text{H}_2\text{O}$) breaks down completely.
- Between 130°C and 170°C: the endothermic reaction of decomposition of gypsum ($\text{CaSO}_4\cdot 2\text{H}_2\text{O}$) is observed.
- Dehydration C-S-H gel observed before 100°C is continued until 450°C. The chemically bound water begins to escape from the concrete
- Between 450°C and 550°C decomposition of the portlandite according to the equation:



- Between 600°C and 700°C the C-S-H decomposition occurs. This is the second stage of dehydration of calcium hydrate within the concrete. It was therefore a new phase of the chemically bound water drain.
- From 650°C endothermic decomposition of limestone follows the equation:



- From 1300°C, the constituents (the paste and aggregate) start melting; this then causes the complete destruction of the material.

When physic-chemical transformations mentioned above occur in concrete, they are accompanied by variations in mass in fuction of temperature or following the exothermic or endotherm of the reaction, as illustrated in Figure 4.

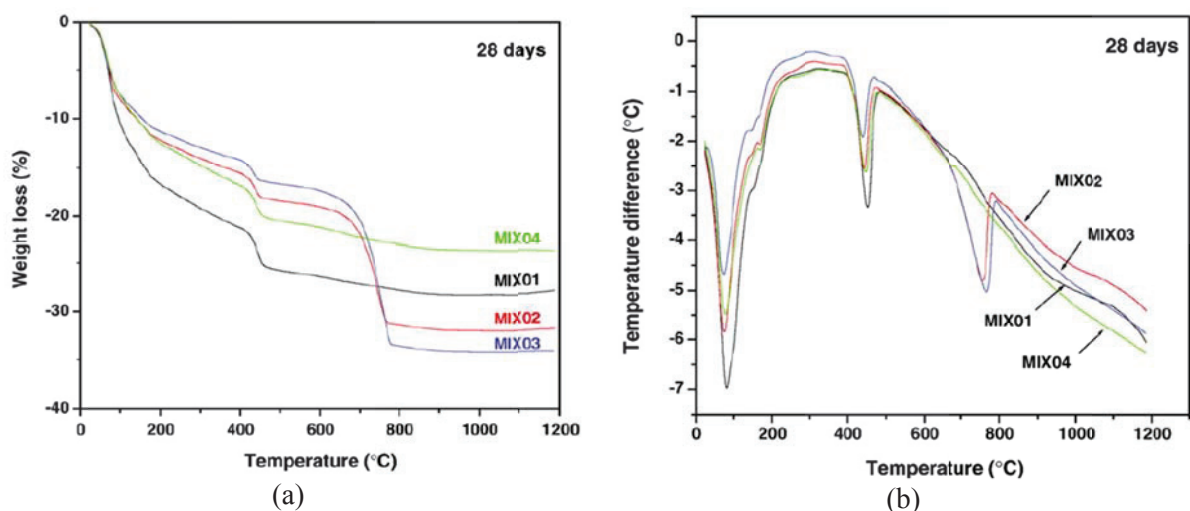


Figure 4: thermal gravimetric analysis (TGA) (a) and differential thermal analysis (DTA) (b) Four different cement pastes in a study of Ye et al, according (Missemmer, 2012)

During the cooling phase, there is silicates rehydration process which leads to the formation of new gels C-S-H. In addition, a new training portlandite is observed (Nguyen, 2013).

b. Evolution of aggregates

During a temperature rise, the aggregates undergo physicochemical changes. This is essentially the mineral structure which is changed with temperature. The limestone aggregates are quite stable up to the temperature of 650°C, 700°C. This temperature is the beginning of a mass loss of about 40% (Figure 7-a). This loss relates to the processing of calcite (CaCO_3) to CO_2 and CaO . Free lime (CaO) may react with the humidity of the air during the cooling phase and transform portlandite (Ca(OH)_2) by multiplying its volume by 2.5. Forming a new portlandite leads to an increase of cracks in the concrete which subsequently lead to a decrease in residual strength regarding the heat resistance of the limestone aggregate concretes heated beyond 700°C. For quartzite aggregate (siliceous), a relatively stable physical behaviour with the imposed temperature is found (Figure 5b). The structure of these minerals contain about 20% of combined water which is capable of partially reducing the release resistance of the material between 120°C-600°C. This removal of water can lead to cleavage of the aggregates. Around 570°C, the transformation of quartz aggregate from α -phase to β -phase is produced. This is accompanied by swelling (volume change of 1 to 5.7%) which may cause a damage in concrete (Nguyen, 2013).

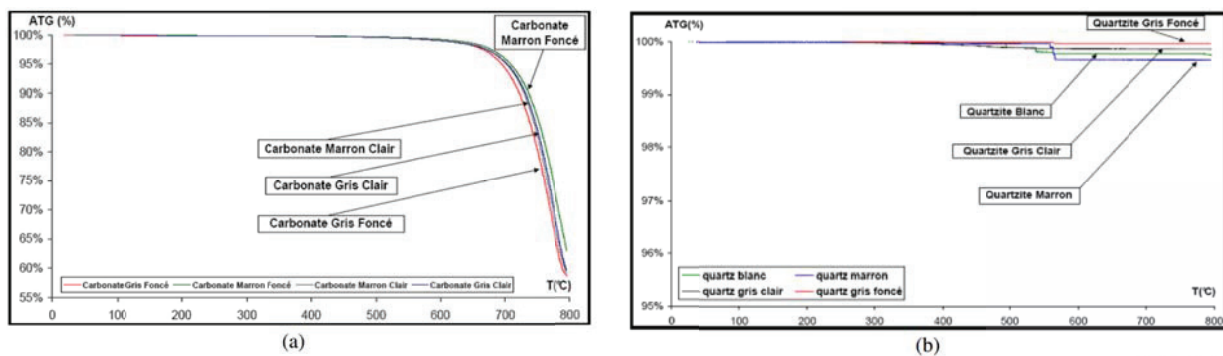


Figure 5: Thermo-gravimetric analysis of the aggregates: a) limestone; b) silica (Nguyen, 2013)

1.2.1.2. Evolution of the physical properties of the concrete during the heating

This subsection displays the evolution of the physical properties of the concrete during the heating. The mentioned physical properties include porosity, permeability, and mass loss.

a. Porosity

Measuring the water porosity or mercury heated concretes has been the subject of several studies. The results showed an increase in porosity with the temperature for ordinary concrete or the high-performance concrete (Nguyen, 2013). According Fares, there is an increase of 2.3% for ordinary concrete and 0.9% for high performance concrete between 105°C and 400°C (Fares, 2010). Figure 6 presents the evolution of total water porosity of concretes with temperature (Missemer, 2012). The increase in porosity can be the result of two processes: starting the water evaporating (free water and part of the bound water) increases the pore volume of the material and the occurrence of micro-cracks in the matrix. These micro-cracks may originate from the dehydration of the cementitious material, the incompatibilities between deformations and thermo-mechanical stresses (related to thermal gradients) of different components (aggregate, matrix, aggregate/matrix interface) of the cementitious material. Figure 7 shows the evolution of the pore distribution of an ordinary concrete after a mercury porosimeter test.

The proportion of increasingly large pores of larger diameters could be explained by the deterioration and merging of small pores which then create larger pores.

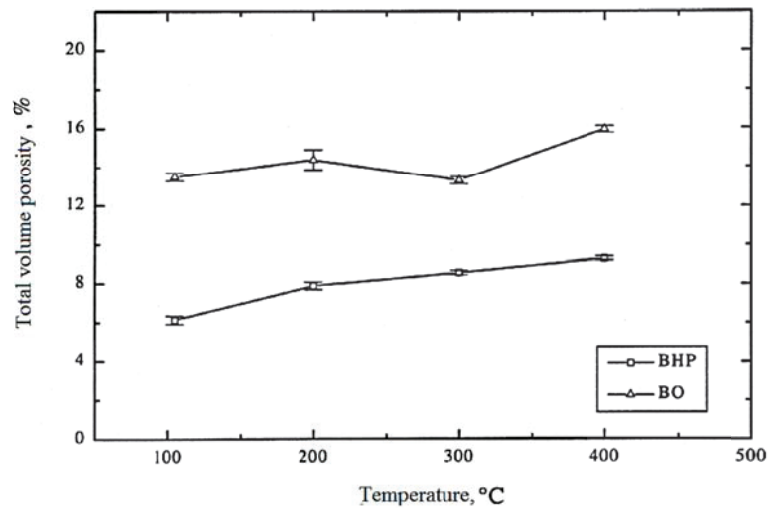


Figure 6: Evolution of the total porosity of a plain concrete (BO, $R_c = 36$ MPa) and a high-performance concrete (BHP, $R_c = 110$ MPa) (Missemer, 2012).

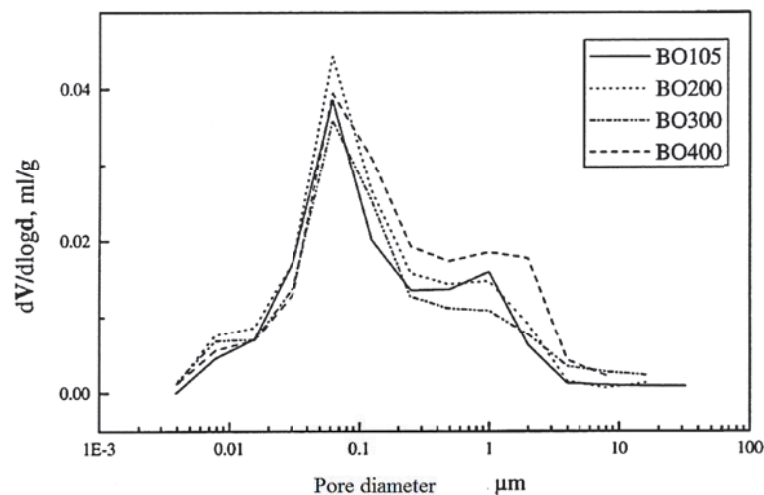


Figure 7: Pore distribution evolution for ordinary concrete ($R_c = 36$ MPa) (Missemer, 2012).

b. Permeability

Permeability is commonly used to assess the water-transport properties of concrete. The permeability of concrete depends fundamentally on the cement paste porosity which in turn is dependent on the water/cement ratio (W/C) and the concrete aging (Fares, 2010). Most studies on the change in concrete permeability with temperature showed an increase in the permeability of the material with increasing temperature (Figure 8 and Figure 9). This increase, which is small at temperatures around 100°C and significant at higher temperatures, can be attributed from the capillary water by drying, micro-cracking of the matrix due to the dehydration of C-S-H and incompatible deformation between the cement paste and aggregates.

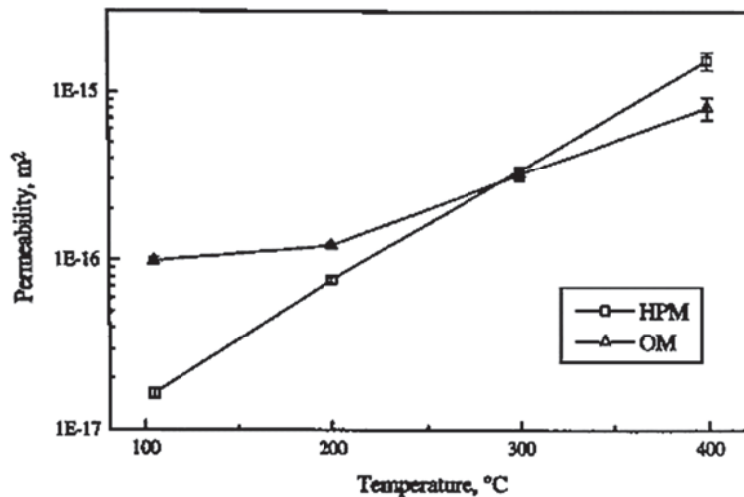


Figure 8: Permeability of mortars (HPM: high performance mortar; OM: ordinary mortar) as a function of the temperature (Fares, 2010)

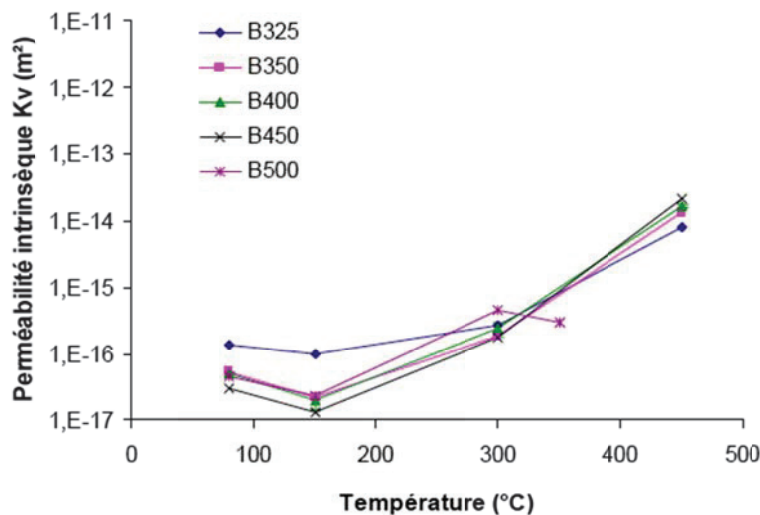


Figure 9: Change in the permeability of different concretes in function of the temperature (Tshimanga, 2007)

The material damage and permeability are deeply related, even at room temperature (Mindeguia, 2009). At high temperature and under the different combined effects, concrete undergoes damage such as:

- Matrix damage due to dehydration.
 - Micro-cracking of the matrix, the matrix/aggregate interface and the aggregates due to the deformation incompatibilities.
 - Thermo-mechanical damage due to thermal gradients (particularly important during a rapid heating such as fire).
 - Increase of permeability of the concrete (this facilitates the movement of fluids within concrete).
- c. Mass loss

During the heating, the concrete mass is subjected to a decrease due to the evaporation of water and the progressive dehydration of the cement paste hydrates. Figure 10 shows characteristic curves of the mass loss during the heating, as well as the curve of the velocity of the mass loss. The evolution of the mass loss is categorized into three areas: from 20°C to 150°C, a small loss of around 3% is observed; from 150°C to 300°C rapid mass loss happens, and then above 300°C the rate of mass loss decreases (Nguyen, 2013).

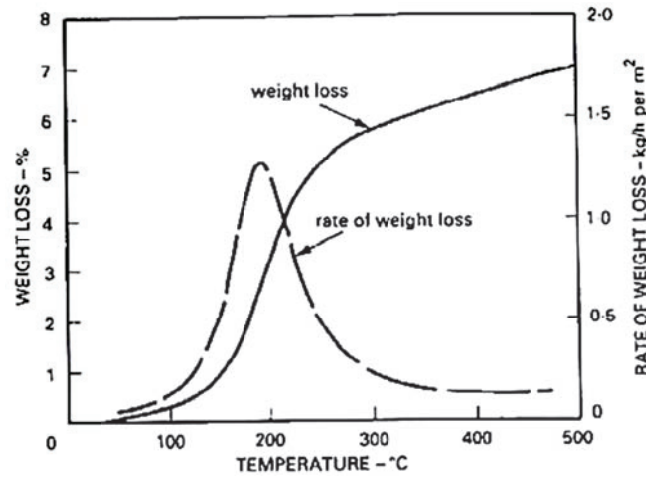


Figure 10: Mass loss during the heating and mass loss rate depending on the temperature (Hager, 2004).

d. Density

Figure 11 shows the measurements of bulk density for three high performance concretes (HPC) and an ordinary concrete (OC) in the National Project BHP 2000 (Fares, 2010; Hager, 2004). These results showed a small decrease in the density of the concrete in the temperature range between 100°C and 400°C due to the thermal expansion of the material and removal of water (Mindeguia, 2009). According to the Eurocodes EN 1992-1-2: 2004 (EN 1992-1-2), the variation of density with temperature is influenced by the loss of water and is defined as follows:

$$\begin{aligned} \rho(\theta) &= \rho(20^\circ \text{C}) = \text{referenced density} && \text{for } 20^\circ \text{C} \leq \theta \leq 115^\circ \text{C} \\ \rho(\theta) &= \rho(20^\circ \text{C}) \cdot \left(1 - \frac{0,02(\theta - 115)}{85}\right) && \text{for } 115^\circ \text{C} < \theta \leq 200^\circ \text{C} \\ \rho(\theta) &= \rho(20^\circ \text{C}) \cdot \left(0,98 - \frac{0,03(\theta - 200)}{200}\right) && \text{for } 200^\circ \text{C} < \theta \leq 400^\circ \text{C} \\ \rho(\theta) &= \rho(20^\circ \text{C}) \cdot \left(0,95 - \frac{0,07(\theta - 400)}{800}\right) && \text{for } 400^\circ \text{C} < \theta \leq 1200^\circ \text{C} \end{aligned}$$

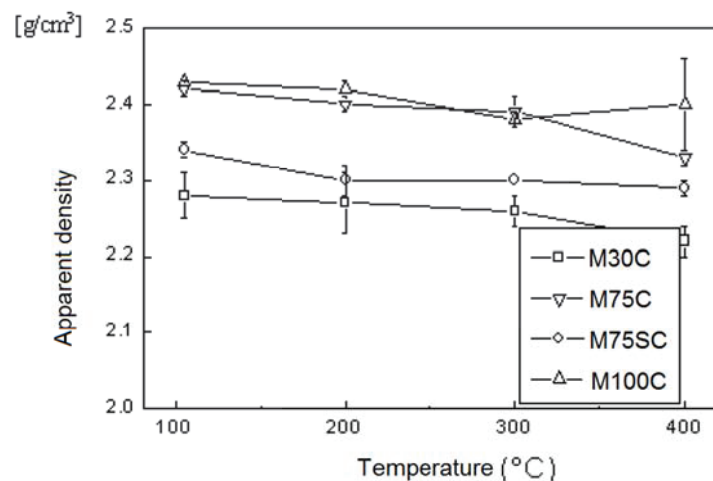


Figure 11: Apparent density of concretes (Hager, 2004);

M30C: ordinary calcareous aggregate concrete, medium compressive strength, $f_{c,avg.} = 30 \text{ MPa}$; M75C: high-performance concrete with limestone aggregates, $f_{c,avg.} = 75 \text{ MPa}$; M75SC: high performance concrete with silica-limestone aggregates, $f_{c,avg.} = 75 \text{ MPa}$; M100C: high-performance concrete with limestone aggregates, $f_{c,avg.} = 100 \text{ MPa}$

1.2.1.3. Thermal expansion

Subjected to a temperature change, concrete undergoes thermal deformation. This thermal deformation of the concrete is determined by the thermal expansion of the matrix and the aggregate. The thermal expansion coefficient is defined as the percentage of change in length of a specimen by a degree of the temperature rise. It strongly depends on the properties of these components including their nature and their quantity.

a. Thermal expansion of the hardened cement paste

The hardened cement paste expands in a first stage up to about 150°C (maximum expansion observed of 0.2%) then the material undergoes shrinkage (Figure 12). The initial expansion phase is generally attributed by the movements and volume expansion of water molecules (in all its forms) as well as to the reduction of the capillary forces of water on the solid due to the increase of the temperature (Bazant and Kaplan, 1996). The contraction phase is due to the departure of the water contained in the material. The transition from the expansion phase to the phase of contraction of the material depends on the heating rate (Figure 13). This shows the influence of the initial kinetic water of the material on its thermal expansion.

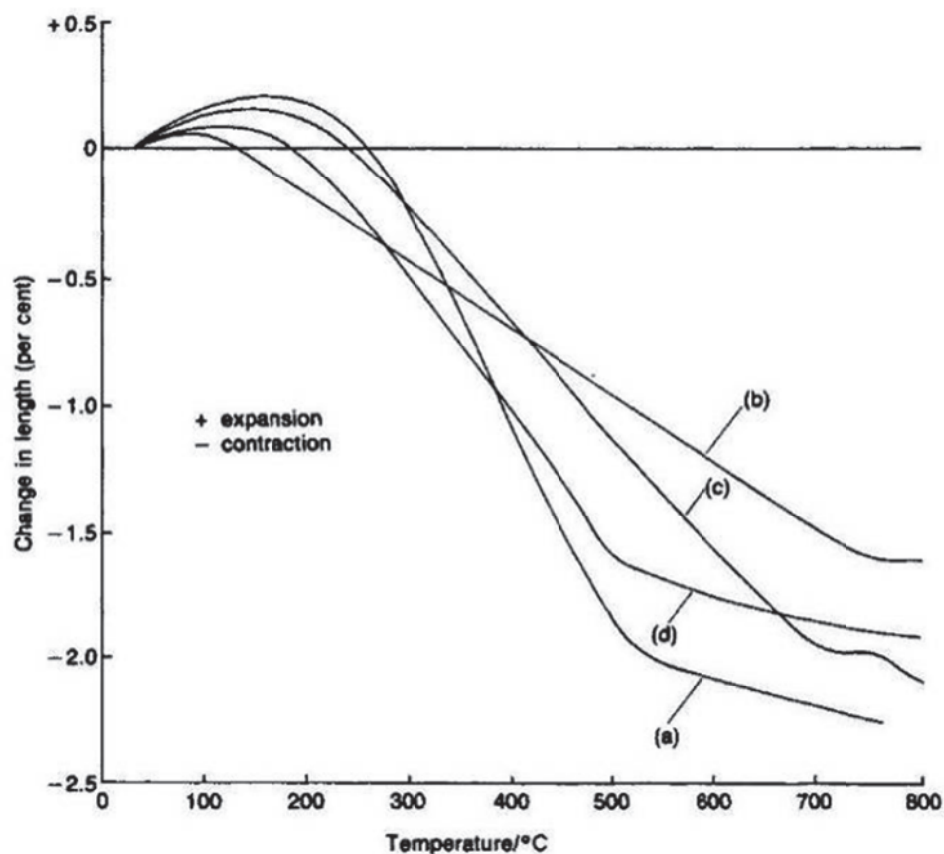


Figure 12: Thermal expansion of hardened cement paste in function of temperature in four different mechanical cases (Bazant and Kaplan, 1996).

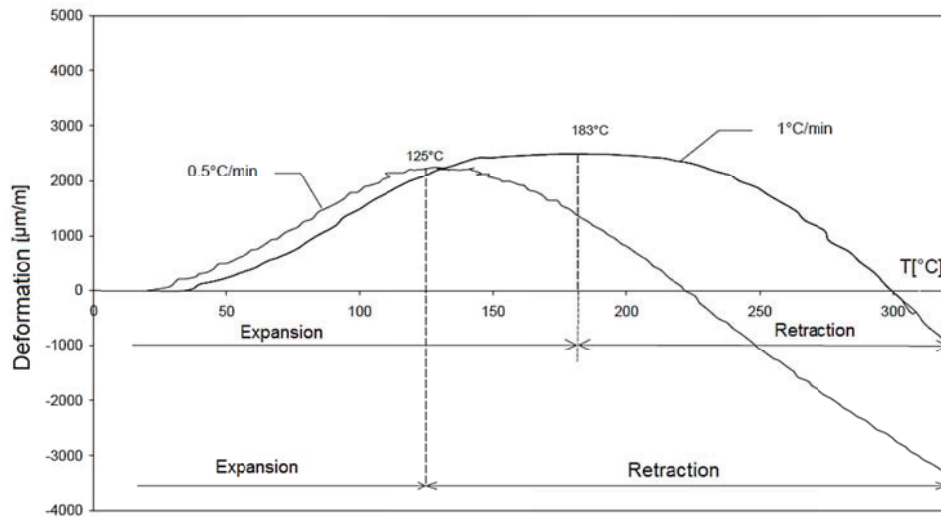


Figure 13: Influence of the heating rate on the thermal expansion of the cement paste (Hager, 2004)

b. Thermal expansion of aggregates

Aggregates have different thermal expansions in comparison to cement paste. In general, the aggregates used to make concrete expand the reached temperature range during a fire. The thermal expansion of aggregates depends on the mineralogical nature of the rocks, particularly their silica content. The limestone aggregate has a lower thermal expansion coefficient than that of the nature of the siliceous aggregate but higher than the basalt granulate (Nguyen, 2013). In addition, the transformation of α -quartz into β -quartz around 570°C is accompanied by a swelling of quartzite (siliceous) granulate. Figure 14 shows changes in the thermal expansion of different aggregates which all expand with temperature rise and are unable to reverse during the cooling phase (Hager, 2004).

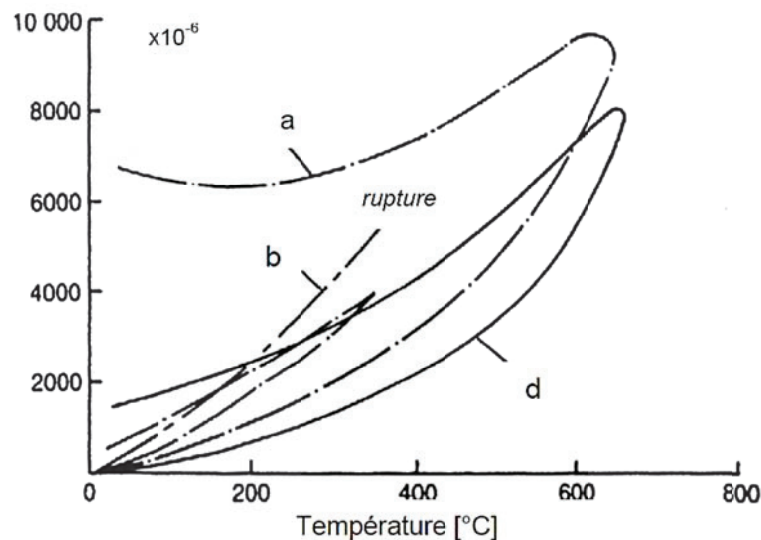


Figure 14: Evolution with temperature linear expansion different kinds of rocks: a) limestone; b) quartz; d) basalt (Hager, 2004)

c. Thermal expansion of concrete

Thermal expansion of concrete is mainly linked to aggregates which occupy about 70% of concrete volume. It strongly depends on nature of aggregates, initial water content thermal and chemical stability of concrete (Kodur, 2014; Menou, 2004). Figure 15 shows the thermal deformation of various types of lightweight concrete, limestone, basalt and quartzite. Based on these results, following findings were made:

- Thermal deformation of the concrete is not linearly dependent on the temperature.
- The main factor for thermal expansion is the nature of the aggregates.
- Beyond 600°C, most concretes have low expansion and sometimes a slight decline, due to chemical decomposition of various components

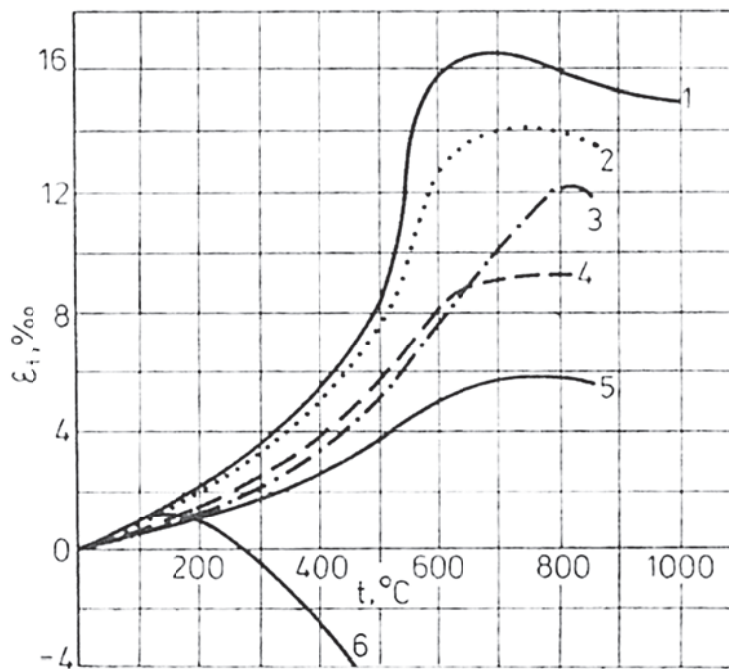


Figure 15: Thermal deformation of concretes with different types of aggregates (Hager, 2004);

1. Quartz, 2. Sandstone, 3. Limestone, 4. Basalt, 5. Expanded clays, 6. Cement paste

The opposite change of the thermal expansion of the aggregates and the cement paste generates deformation incompatibilities which cause tensile stresses in the cement paste, compressive stresses at the level of aggregates and tangential stresses at cement paste/aggregates interface. The opposite behaviour between aggregates and cement paste could therefore cause damage to the concrete material. One consequence of this damage is the appearance of cracks in matrix, trans-aggregates and especially the cement paste /aggregate interface where the materials have poor mechanical properties (Figure 16).

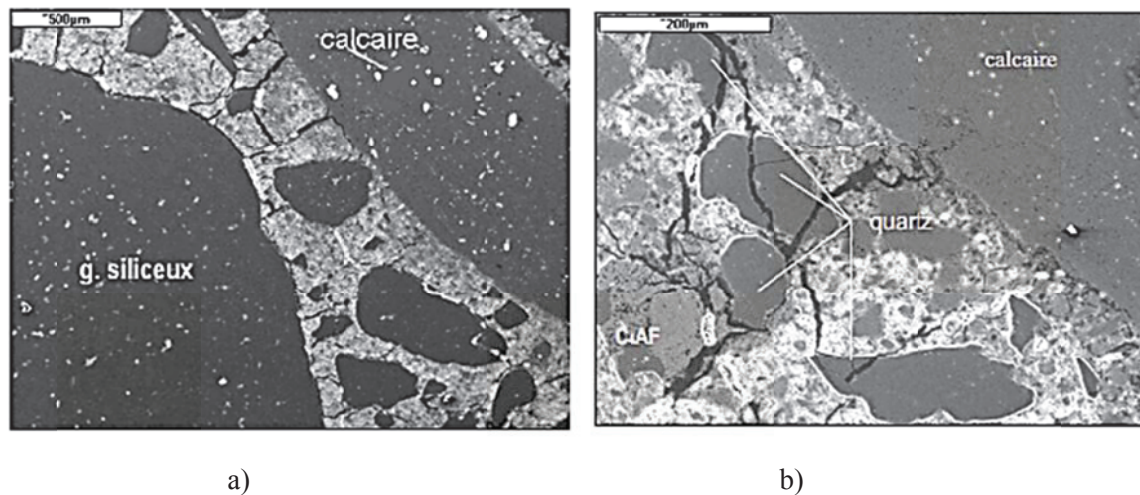


Figure 16: Observations of concrete samples heated to 600°C (Hager, 2004)

a) A crack in the cement paste and the paste/aggregate interface; b) trans-granular cracking crossing quartz

1.2.1.4. Evolution of thermal properties of concrete

This subsection summarizes evolution of thermal conductivity and specific heat as a function of temperature.

a. Thermal conductivity

Thermal conductivity is the ability of a material to conduct heat. It represents the energy (quantity of heat) transferred per unit area and time under a temperature gradient of 1 kelvin per meter. For concrete, that magnitude depends on several parameters: porosity, temperature, degree of hydration, water content, and type of aggregates (Menou, 2004). The thermal conductivity of ordinary concrete at ambient temperature is between 1.4 W/m.°C and 3.6 W/m.°C. The thermal conductivity of high-performance concrete is generally higher than that of ordinary concrete due to low water/cement ratio (W/C) and the use of different binders in high-performance concrete (Kodur, 2014). When temperature increases, the thermal conductivity of concrete generally reduces. Figure 17 illustrates the variation in thermal conductivity of ordinary concrete as function of temperature based on the published test data and empirical relationships (Kodur, 2014). The decrease in thermal conductivity is due to the drying of material and the dehydration in C-S-H that create voids (Missemer, 2012)). In addition, the appearance and development of cracks, caused by deformation incompatibilities of between thermal shrinkage of cement-paste and expansion of aggregates, limit the heat transfer in concrete (Nguyen, 2013). The variation of the measured data on the thermal conductivity is represented by the shaded area in Figure 17. This variation on a reported basis was mainly due to the water content, the type of aggregate, test conditions and measurement techniques used in the experiments (Kodur, 2014).

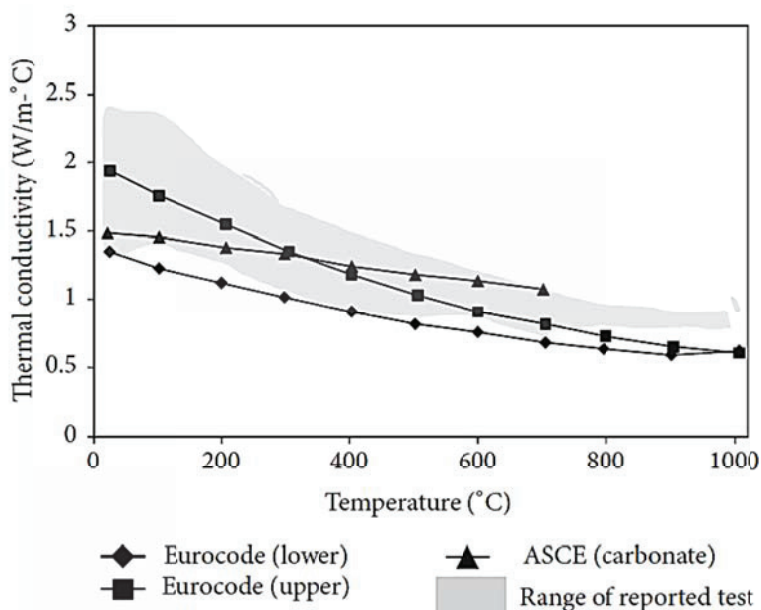


Figure 17: Variation in thermal conductivity of normal strength concrete in function of temperature (Kodur, 2014).

b. Specific heat

The specific heat or heat capacity (J/kg.K) is the amount of required heat per mass unit to raise the material temperature by one degree. This amount of energy is absorbed or restored by endothermic or exothermic reactions in the material. Consequently, the concrete specific-heat is sensitive to the different physic-chemical transformations at elevated temperatures, particularly from the free water (drying of the material to about 100°C), dehydration in C-S-H, de-hydroxylation portlandite (between 400°C and 500°C), and the transformation from α -quartz-to β -quartz around 570°C of siliceous aggregate (Kodur, 2014; Nguyen, 2013).

The concrete specific-heat at ambient temperature varies between 840J/kg.K and 1800J/kg.K depending on aggregate types (Kodur, 2014). The specific-heat of the hardened cement paste ranges from 700 J/kg.K to 1700J/kg.K at room temperature (Mindeguia, 2009). This quantity generally increases with the rise of temperature due to endothermic reactions. Figure 18 shows the variation of of specific heat at different temperature of two concretes with different aggregate type (Nguyen, 2013). With siliceous aggregate, the concrete specific-heat increased around 500°C due to the transformation of quartzite while with the limestone concrete (or carbonate aggregate concrete), specific-heat intensively increased between 600°C and 800°C because of the heat consumption in latent form for the de-carbonation of limestone. The drying effect was taken into account in the peak of specific heat between the temperatures ranging from 100°C to 200°C is depending on the water content of the concrete (Figure 19, (EN 1992-1-2)). Figure 19 also shows that the peak of specific heat of concrete depends on the water content of the concrete.

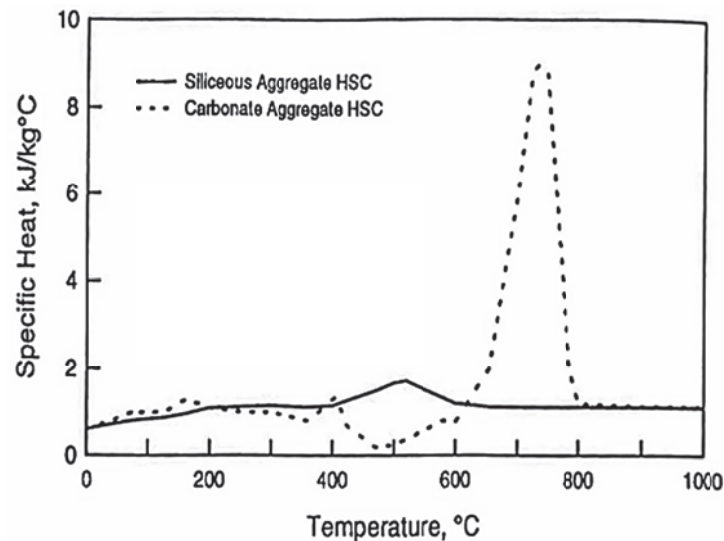


Figure 18: Specific heat at different temperatures of two concretes with different aggregates (Nguyen, 2013).

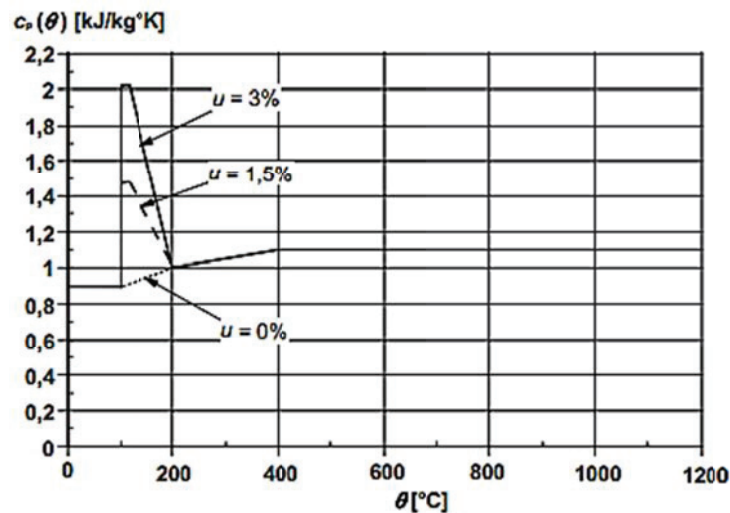


Figure 19: Specific heat as a function of temperature of concretes with three different water contents (0%; 1.5% and 3%) (EN 1992-1-2).

According to Kodur, the presence of fibres also has a minor influence on the specific heat of the concrete (Kodur, 2014). For example, for concrete added with polypropylene fibres, the combustion of these fibre products releases micro-channels from its evaporation; and thus the amount of heat absorbed to the dehydration of the chemically bound water decreases. For that reason, the specific heat of the concrete reduces in the temperature ranging from 600°C to 800°C. However, the concrete added with steel fibres shows a high specific heat in the temperature ranging from 400°C to 800°C, which can be attributed to the additional heat absorbed to the water of dehydration chemically bonded.

1.2.1.5. Evolution of mechanical properties of concrete

In general, the compressive strength, the tensile strength and elastic modulus in compression decrease with increasing temperature. Chemical transformations during heating can lead to the degradation of the microstructure of concrete (Nguyen, 2013).

a. Tensile strength

In the literature there are few results concerning the evolution of the tensile strength of the concrete as a function of temperature. This can be explained by the small contribution of tensile strength of concrete in the behaviour of structures. This property can be obtained, from a thermal point of view, by hot or residual test (after cooling) and from a technical point of view by tensile, splitting or flexural tests. Most researchers presented the results of changes in the tensile strength of concrete from residual test and those from splitting or bending test (Hager, 2004; Mindeguia, 2009). The lack of results of "hot" direct tension is mainly related to the difficulty of achieving the high temperature tests (difficulties in alignment of the specimen, flexural bending, influence of the testing devices, stiffness of the press, thermal gradients, etc...).

There are studies showing that the tensile strength of concrete decreases with increasing temperature. This decrease was attributed to thermal damage of the concrete in the form of micro-cracks (Kodur, 2014). In addition, changes in the tensile strength of the concrete with the temperature is affected by the same parameters as for the compressive strength: nature of the binder and aggregates; water content; experimental conditions such as the duration, the heating and cooling rates; the geometry of the test pieces; type of test (splitting, flexural or direct tension); test protocol (the direct high-temperature test or the test conducted at room temperature on a specimen which is previously subjected to a heating-cooling cycle); presence of fibres added to the concrete... Figure 20 shows the reported tensile strength results depending on the temperature (Fares, 2010). In this figure, tensile strength of concrete generally decreases when the temperature increases. Up to 300°C, its values are fairly dispersed with relative resistances ranging from 35% to 100%, smaller than the values provided by Eurocode. Beyond 300°C, these results are all higher than the values given by the Eurocode. There also exists in the literature a few results which show that the tensile strength of the concrete measured in "the direct high-temperature test" may increase with elevated temperature (Figure 21).

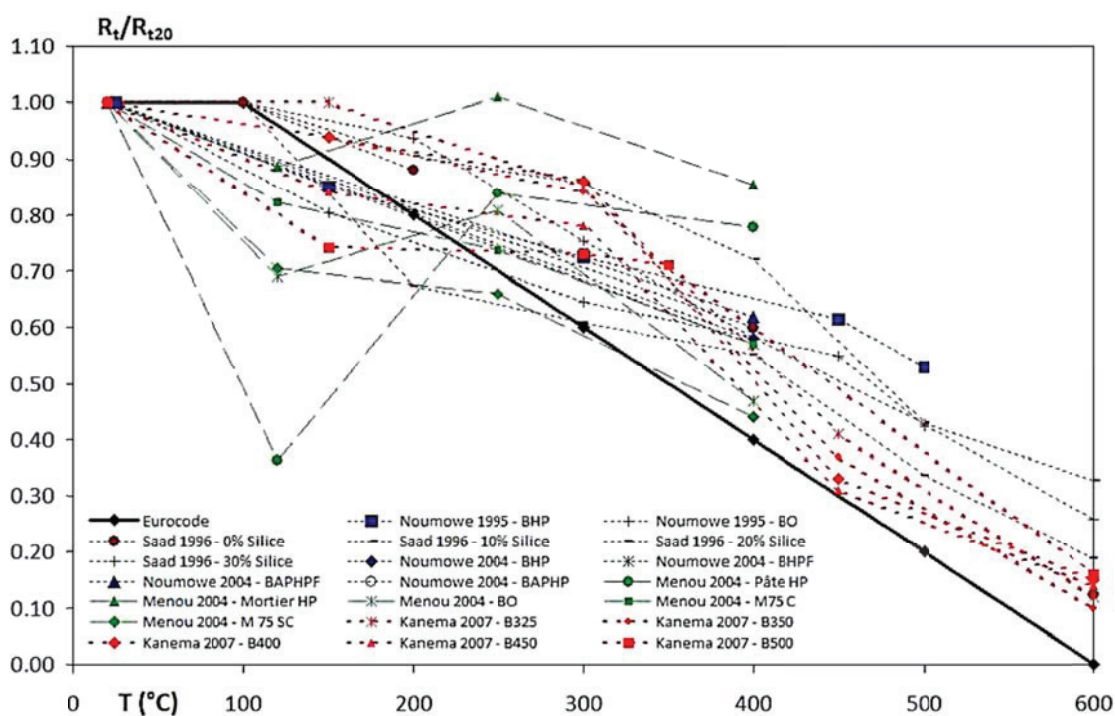


Figure 20: Different tensile strength results, reported by (Fares, 2010)

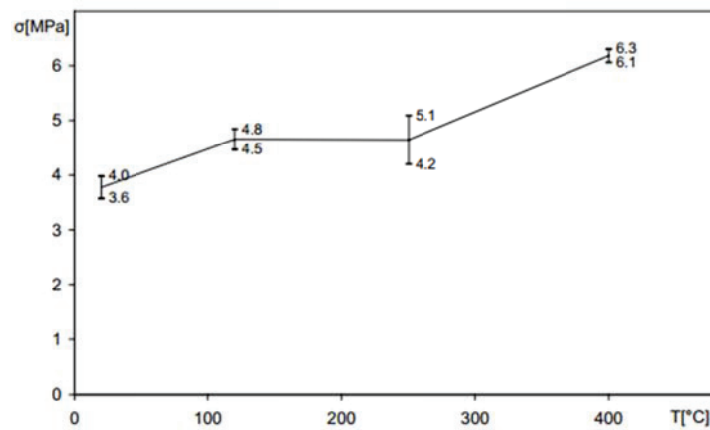


Figure 21: Evolution of the tensile strength in function of temperature of concrete by direct pulling (direct high-temperature test), (Hager, 2004).

b. Compressive strength

The compressive strength of concrete at high temperatures has been studied extensively in the literature. In general, the results from the literature showed that the compressive strength of concrete (in hot or residual condition) decreases with increase of temperature, especially beyond the temperature of 300°C (Nguyen, 2013). This is attributed to the combined effect of physical and chemical transformations and deformation incompatibilities between cement paste and aggregates (these incompatibilities cause matrix cracking, and the increase in concrete porosity) (Mindeguia, 2009). However, between 150°C and 250°C, the drying phase and the beginning of the dehydration cause a shrinkage of the matrix, thereby improve the compactness of the material and therefore its compressive strength (Mindeguia, 2009). For more information on the evolution of compressive strength of concrete at high/ elevated temperature, it is recommend to consult the works of (Bazant and Kaplan, 1996; Fares, 2010; Hager, 2004; Mindeguia, 2009; Missemer, 2012; Nguyen, 2013; Tshimanga, 2007).

1.2.1.6. Conclusion

This section synthesises the main observations and experimental results concerning the evolution of the behaviour of concrete at high temperatures. It is shown that under high temperature condition, concrete experiences several physical and chemical changes which strongly modify its thermo-mechanical properties. These physic-chemical transformations are water-into-steam processing, C-S-H gel dehydration, portlandite de-hydroxylation, quartzite-processing phase and limestone de-carbonisation. Among these parameters, water (in the form of free water, capillary water, adsorbed water and water chemically bound to the hydrated-cement) has a significant influence to concrete behaviour. During the temperature rise, water gradually escapes from the material, loses the bound free water and dehydrating hydrates. This represents the main cause of loss in mass of the concrete, causing the volume change of the material and the thermal stresses induced by the evaporated-water pressure in the pores. As temperature rise, the combination of physic-chemical transformations including water evaporation, the pored-pressure and the deformation-incompatibility between the hardened cement-paste and aggregates cause de-structuring of the hardened cement paste and aggregates. This breakdown directly affects thermal, mechanical properties and mechanical transfer of concrete material as followings:

- Increases in pore size, porosity and permeability of concrete.
- Occurrence and development of micro-cracks
- Variations in thermal properties such as thermal conductivity (decrease) and the specific heat.
- A modification (which is typically a decrease) in compressive strength, tensile strength, modulus with increasing temperature.

- Furthermore, the phenomenon of bursting can be attributed to two processes: the thermo-mechanical process (which causes thermal stresses) and the thermo-fluid process (a rise in internal pressure of the pores).

These above mentioned changes are irreversible behaviours due to the nature of irreversible chemical reactions (dehydration) and the occurrence of microstructural (cohesive failure). Finally, there is a wide scatter of the tensile strength of concrete subjected to high temperatures, because of different test protocols and various experimental parameters. To the best of author's knowledge, it lacks a synthetic study on the difference in behaviour of the concretes tested to two different protocols, "direct testing at elevated temperature" or "test at room temperature on heated-cooled specimens."

1.2.2. FRP and CFRP

The polymer reinforced with carbon fibre (Carbon Fibre Reinforced Polymer - CFRP) is a composite material that is popularly used in engineering application. In construction, CFRP is common in reinforcing concrete and steel structures due to its advantages in high tensile/ weight ratio, good properties in corrosion resistance and fatigue. The research about the mechanical performance of CFRP at room temperature working condition is various in types of CFRP and the type of structure reinforced by CFRP.

1.2.2.1. *Tensile performance of fibre reinforced polymer (FRP)*

In strengthening reinforced concrete structures (or other structures), the fibre reinforced polymer (FRP) is exploited for its tensile capacity. This section summarized the evolution of mechanical properties of FRP composites with thermosetting polymer matrix as temperature increase. When being subjected to the thermal load, most thermosetting resins and amorphous polymers show a major transition. This transition occurs in a narrow range of about several tens of degrees. The glass transition temperature of the commercial products used in civil infrastructure applications, varies between 50°C and 90°C (Dong and Hu, 2016; Foster and Bisby, 2008; Moussa et al., 2012a). When the temperature in the material reaches the transition temperature of the polymer matrix, the matrix becomes soften and the material's mechanical properties (Young's modulus, tensile strength) are reduced significantly. Therefore, the contribution of the matrix to the composite tensile strength gradually becomes negligible. This contribution reduces to zero after total decomposition of the matrix, characterized by a decomposition temperature T_d (from 250°C to 500°C (Mouritz and Gibson, 2006; Mouritz et al., 2006; Correia et al., 2010). Furthermore, the mechanical properties of fibres, in general, are not significantly affected at temperatures close to glass transition temperature T_g of the matrix. Several fibres themselves are intrinsically resistant to high temperatures. For example, carbon fibre modulus decreased only above 500°C and its tensile strength began only slightly to decrease from 400°C (Feih and Mouritz, 2012; Feih et al., 2009). Figure 22a also shows the evolutions of strength of some fibres at elevated temperatures. The carbon fibres are hardly affected by elevated temperature up to 1000°C, whereas the glass fibres retain most of their strength at 400°C. Thus, at low temperatures (between 20°C and temperatures around the glass transition temperature of the matrix), the stiffness reduction of a FRP composite can be mainly attributed to the degradation of the matrix. And the composite tensile strength at very high temperatures is generally controlled by the fibre, There are also several other factors affecting the change of these properties, for example the reinforcing rate, the fibre/matrix bonding ... Although the individual fibre can maintain their mechanical strength at high temperatures, however, when they are combined with the resin in a composite, the strength of the composite at high temperature can significantly decrease as shown in Figure 22b. At temperatures around 400°C, most composites lose a substantial part of its tensile strength. This is due to the softening and degradation of the polymer matrix at temperatures above its glass transition temperature. Thus, the mechanical load sharing function is

degraded and the individual fibre can be overloaded and broken gradually inducing ultimately rupture of the composite (Green et al., 2007).

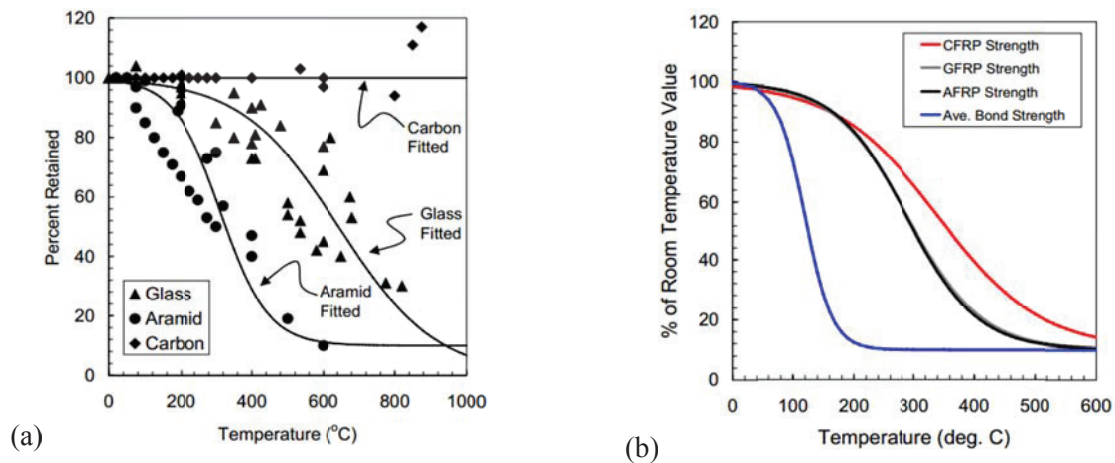


Figure 22: Evolution of ultimate strength of bare fibres (a) and composite FRP (b) depending on the temperature (Green et al., 2007)

1.2.2.2. Relation "stress-strain" depending on temperature

The reduction of mechanical behaviour of FRP composite exposed to high temperature (including the resistance and rigidity) is also observed through the variation of the stress-strain relation at different temperature. According to the available research data, few experimental studies provide data regarding the "stress-strain" relationship, mainly due to technical difficulty in measuring deformation at high temperature.

Wang et al. conducted experiments by pulling on cylindrical specimens of pultruded CFRP and GFRP in temperatures ranging from 20°C to 600°C (Wang et al., 2007). These specimens were used as internal reinforcement in concrete structures. They consist of carbon or glass fibres and a polyester resin matrix. All tests were carried out in the condition of thermally stable state. The sample is first heated to the desired temperature. After half an hour of waiting to get a uniform temperature within the material, the test is assessed monotonous mechanical loads under tension until failure. During the period of mechanical loading, the temperature of the specimen is kept constant (direct high-temperature test). A pair of displacement transducers was used to measure the deformation of the cylinder part within the furnace (heated part). These transducers started measuring the deformation at the same time that the mechanical load was applied. However, the displacement sensor system has failed to record deformation data for most of tests at elevated temperatures (beyond 350°C). It is because at these temperatures, the resin is burnt in the test tubes leading the fall of the transducers system. On test results, the authors found that the "stress-strain" relationship even at elevated temperatures (up to 600°C), almost linear until failure of the specimens. Figure 23 below shows an example of the stress-strain (" σ - ϵ ") curve of a CFRP specimen at 200°C.

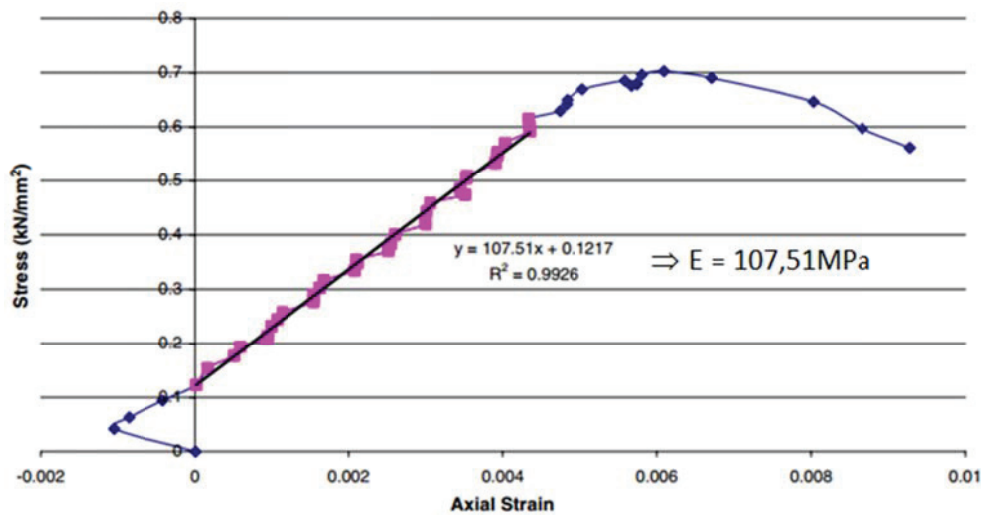


Figure 23: Stress-strain relationship of CFRP obtained by "direct test at elevated temperature" (200°C), (Wang et al., 2007)

The stress-strain relationship was also investigated on laminate CFRP (thermosetting epoxy resin matrix) in direct tensile tests under high temperature up to 520°C (Wang et al., 2011) (Figure 24). The limits of these results are that the obtained tensile modulus is based not on the displacement between two points of the test specimen but on the grips of the traction machine. However, the "stress-displacement" curves shown in Figure 24 reflect the trend of the "stress-strain" relationship. Particularly, the "stress-displacement" curves present nonlinearities in the temperatures ranging between 625°C and 706°C (the maximum temperature in this study). According to the authors, these nonlinearities are attributed to the loss of the mechanical performance of fibres from the oxidation of carbon fibres. This study learns that the duration of 5 minutes is sufficient to achieve thermal homogeneity referred in specimens of 1.4 mm in thickness and that an extension of this period does not affect the tensile resistance of laminates. In addition, exposure to high temperatures causes partial loss (from 97°C to 308) or total loss (from 395°C to 625°C) of the matrix in the tubes due to the decomposition of the epoxy, Figure 25. It was also demonstrated that the pure epoxy materials and epoxy matrix composites (CFRP, GFRP) significantly loses their weight at a temperature of 367°C (Foster and Bisby, 2005, 2008). However, carbon and glass fibres show almost no mass reduction in temperature up to 600°C (Figure 26).

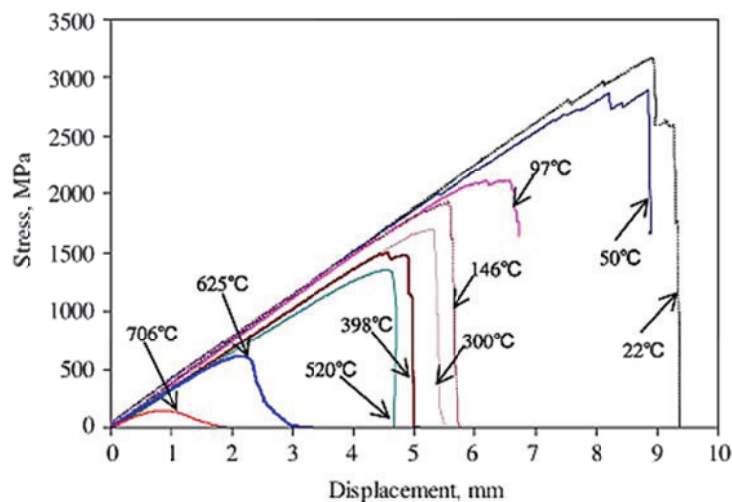


Figure 24: Relation "stress-displacement cross" in the high temperature direct tests on laminated CFRP, (Wang et al., 2011)



Figure 25: Partial decomposition (left) and total decomposition (right) of the epoxy matrix after exposure to elevated temperatures, (Wang et al., 2011)

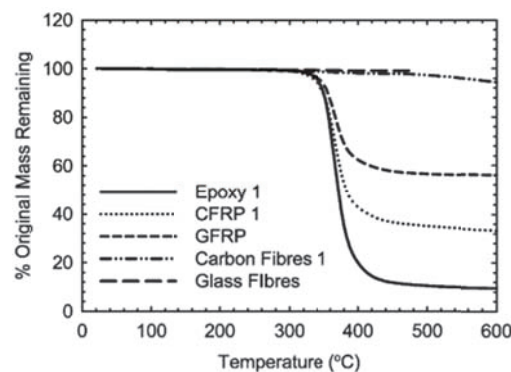


Figure 26: Mass loss in test specimens with temperature, (Foster and Bisby, 2005)

Residual linear "stress-strain" curves of laminate CFRP and GFRP have also been studied, Figure 27 (Foster and Bisby, 2005). The significant difference in this study in comparison with that mentioned above (direct test at high temperature) is that the test specimen were imposed with mechanical loads after being heated to the desired temperature and then cooled to room temperature. The regime of this test will now be called "residual" regime. In the previous study (Foster and Bisby, 2005), extensometer gauges were used to measure the deformation of the test specimens. However, the authors also reported that the strain gauges were detached before the rupture of most GFRP specimens. This again illustrates the difficulties in measuring of strain for FRP composites including at room temperature. In addition, it was observed that the epoxy polymer matrix of the tested specimens was almost completely burned after being exposed to 400°C (for 3 hours). Yu and Kodur (Yu and Kodur, 2014) used an LVDT to measure the movement of two clamping brackets on the tensile machine to estimate the elongation of the CFRP specimens. According to Cao et al. (Shenghu Cao et al., 2009), it was difficult to use strain gauges to measure deformation at elevated temperature up to 200°C.

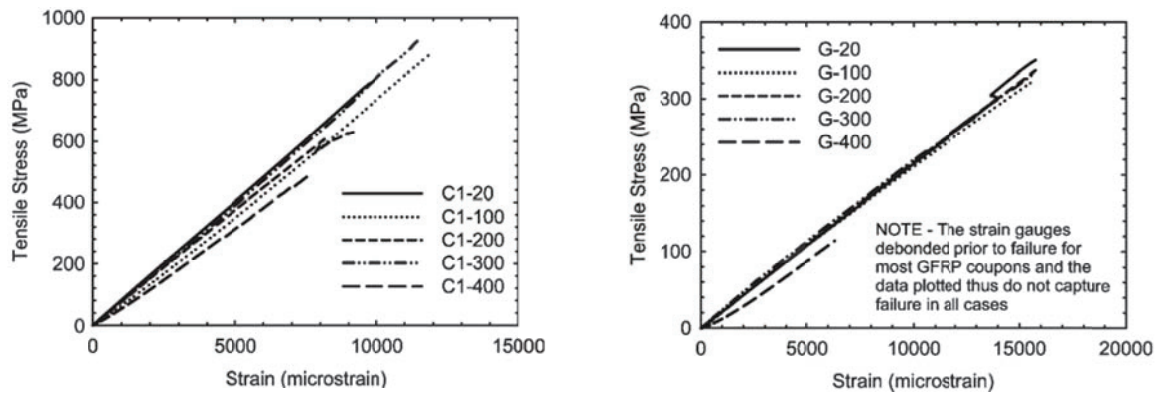


Figure 27: "Tensile stress - strain" Curves of CFRP composites (left) and GFRP (right) after exposure to high temperatures (tests carried out on heated-cooled cylinders), (Foster and Bisby, 2005)

Recently, the author of the present study (Nguyen et al., 2018) performed two series of tests on P-CFRP following both the thermo-mechanical procedure and residual procedure as the temperature increased from 20°C to 700°C. The details of research are further explained in the chapter 2. According to the results of the mentioned study, the residual performance of P-CFRP is higher than its thermo-mechanical performance. It is also shown that the P-CFRP decreased 50% of its strength at 300°C in the thermo-mechanical condition and 500°C in the residual condition, while its Young's modulus decreased by 50% at 540°C and 570°C in two conditions, respectively.

1.2.2.3. Tensile properties evolution

Because of difficulties in experiments (inability to measure the deformation of the composite), the results for the changes in mechanical properties of FRP composites mainly relate to their ultimate resistance. However, there are changes in Young's modulus as a function of the temperature of some materials (CFRP, GFRP polyester resin matrix) (Wang et al., 2007). The tests carried out in the latter study are high temperature direct tests (see sections mentioned above), Figure 28. It should be noted that the tensile modulus of GFRP remains constant up to a temperature of 400°C. In addition, the decrease of this modulus is very marked when the temperature increases progressively. At 500°C, this tensile modulus retains about 30% of its initial value. The results are not available for CFRP at higher temperatures due to the damage of strain measurement sensors. At temperatures up to 200°C, the evolution of the CFRP Young's modulus is similar to that of GFRP (a loss of about 14% of its initial value at 200°C). According to these authors, a degradation of CFRP and GFRP Young's modulus can also be found in the study of Saafi, but with a lower amplitude (Saafi, 2002), Figure 28.

The available results of residual tests carried out on "heated-cooled specimens" (Foster and Bisby, 2005, 2008) showed that the residual modulus of CFRP composite (resin epoxy matrix) slightly decreased up to 400°C and that of the GFRP composite presented a significant reduction above 300°C, Figure 30. However, it should be noted that the dispersion of test results increases with rising temperature of exposure. Finally, two analytical models proposed by Saafi and Bisby for the evolution of GFRP composite modulus as the increase of temperature were observed (Figure 29) (Adelzadeh et al., 2014). However, according to these models, it can be seen that the composite Young's modulus degrades significantly for temperatures above 200°C.

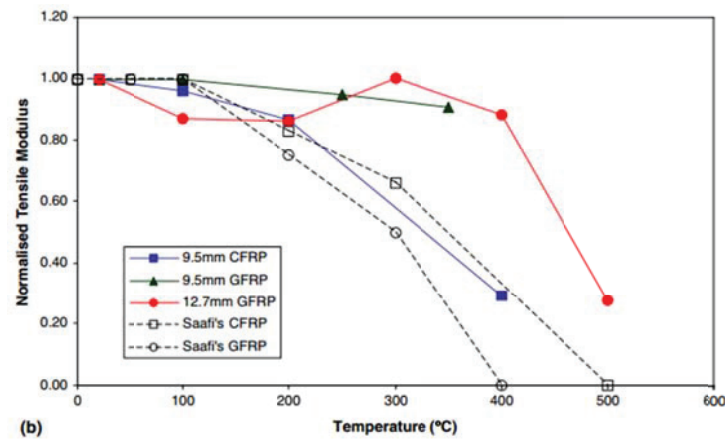


Figure 28: Young's modulus depending on the temperature of FRPs, (Wang et al., 2007)

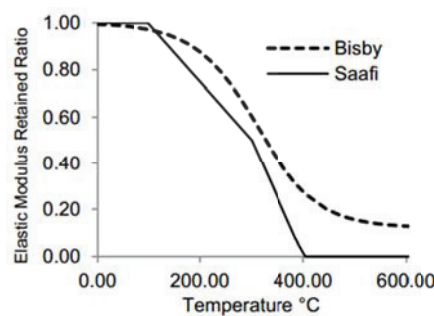


Figure 29: Models of Saafi and Bisby for the degradation of the Young's modulus of the GFRP at elevated temperatures, (Adelzadeh et al., 2014)

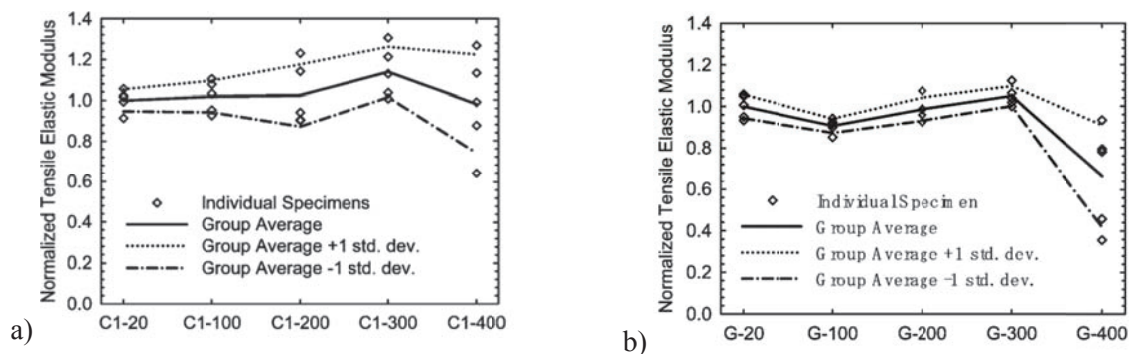


Figure 30: Variation in the residual tensile modulus with the rise of temperature of CFRP (a) and GFRP (b) (Foster and Bisby, 2005, 2008)

Yu and Kodur studied the influence of temperatures between 20°C and 600°C on the degradation of the tensile properties of pultruded CFRP strips and rods following the thermo-mechanical procedure (Yu and Kodur, 2014). The results showed that at 400°C, the tensile modulus decreased approximately 70% for both CFRP rods and strips (Figure 31a,b). At 500°C this tensile modulus decreased approximately 47% for CFRP (Figure 31a) rods and approximately 67% for CFRP strips (Figure 31b).

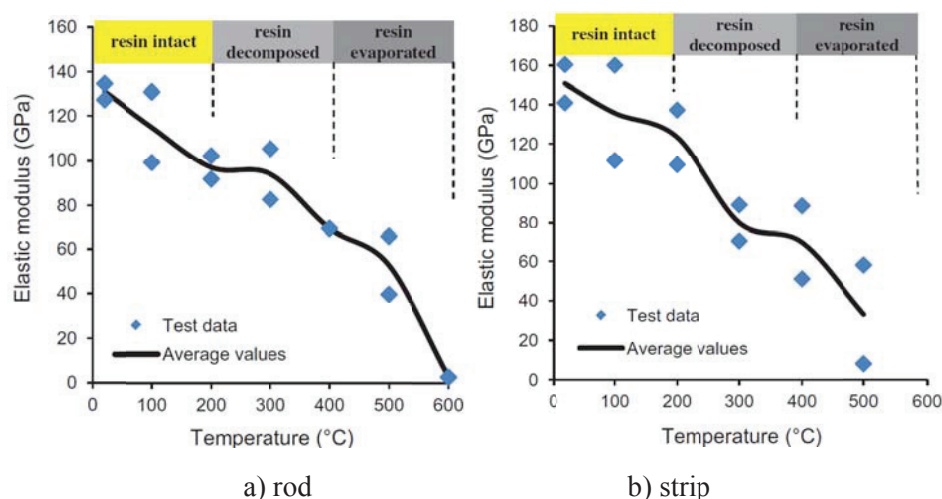


Figure 31: Variation of tensile modulus of pultruded CFRP rod (a) pultruded CFRP strip (b) with temperature (Yu and Kodur, 2014)

Hamad et al. investigated the residual mechanical properties of FRP bars (CFRP and GFRP) at elevated temperature condition ranging from 23°C to 450°C with deformation measured by local extensometer (Hamad et al., 2017). According to the results of the previous research, CFRP and GFRP bars (10 mm in diameter) reduced 50% of their modulus at about 375°C (Figure 32) in comparison with their Young's modulus obtained at 23°C.

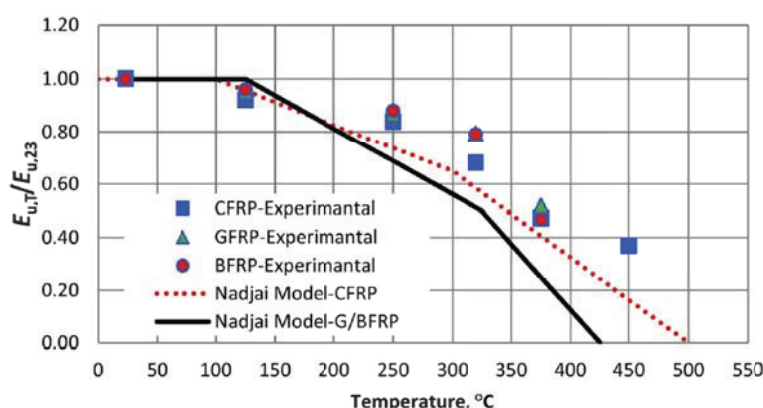


Figure 32: Residual elastic modulus for FRP bars under elevated temperatures (Hamad et al., 2017).

Although all the mentioned studies show a decrease of the Young's modulus of the CFRP and GFRP composite materials at elevated temperatures (over 200°C or 300°C or 400°C). It is clear that there is a relatively large difference in degradation level of properties of composite material as function of temperature in the various works. In the study of Wang et al. (Wang et al., 2007), the results of tests, conducted on two types of test specimens of GFRP (same material) but of different diameters (9.5 mm and 12.7 mm), showed a difference of Young's modulus reduction level with temperature (see Figure 28). This can be attributed to the difference in the composition of the materials tested, their reinforcing rate. This is also due to a lack of experimental data, as well as various experimental techniques used and to the effects of temperature on the accuracy of the strain measurements at elevated temperatures (deformation of instrumentation, instrumentation/substrate sliding). From the review from research data, there are currently no available standards specifying the test procedure related to the determination of the high-temperature behaviour for composite materials. In addition, it appears that the high temperature

effect increases the heterogeneity of the material resulting in the dispersion of the test data such as the Young's modulus or ultimate strength of FRP composite.

1.2.2.4. Tensile resistance

The study on rebar shape of test specimens under high temperature direct test showed that there was a gradual reduction in tensile strength of CFRP and GFRP composites at elevated temperatures (Wang et al., 2011), with a normalized tensile stress about zero at about 550°C for a GFRP and 600°C for a CFRP (Figure 33). According to these authors, this is a reasonable result comparing to that in the work of Blontrock (Blontrock et al., 1999).

Two models proposed by Saafi (Saafi, 2002) and Bisby (Bisby, 2003) for the evolution of the GFRP composite tensile strength as function of temperature were reported in the study of Adelzadeh et al. (Adelzadeh et al., 2014) (Figure 34). They also showed a nearly linear degradation of this magnitude in the temperature ranging between room temperature and 400°C.

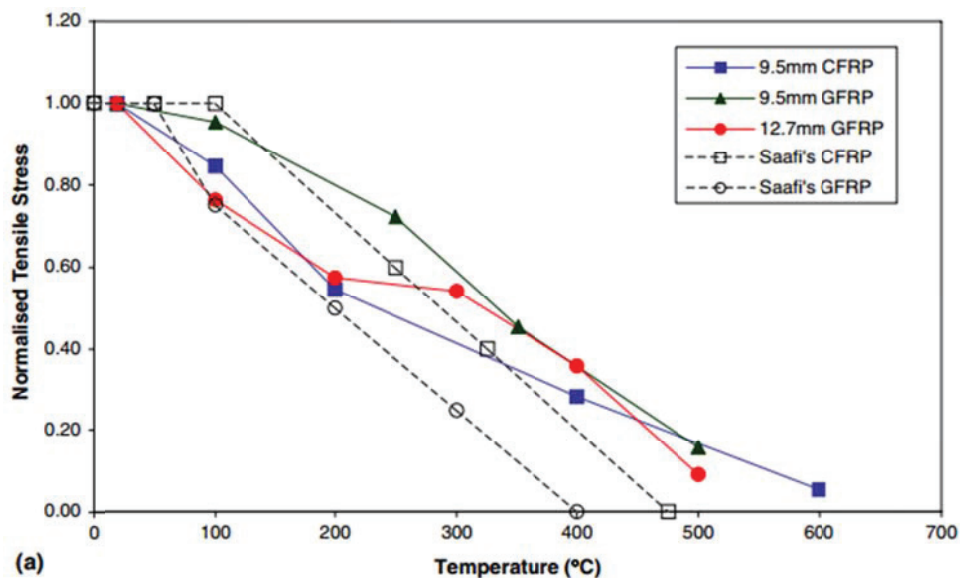


Figure 33: Evolution of the ultimate tensile strength of the composite depending on the temperature of FRP composite (Wang et al., 2007)

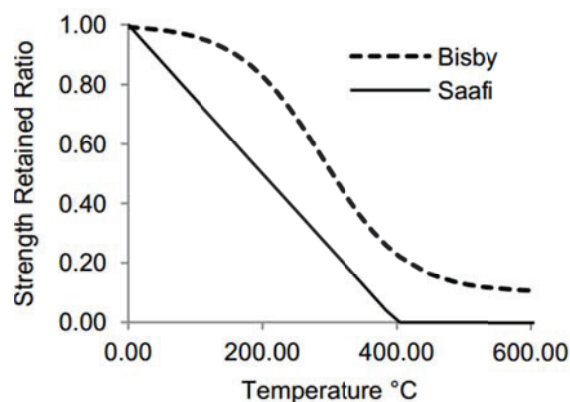


Figure 34: Models Saafi and Bisby for the degradation of the tensile strength of GFRP at elevated temperatures (Adelzadeh et al., 2014)

Furthermore, there was the "high temperature direct test" done on samples in the form of the laminated CFRP having the epoxy resin matrix (Wang et al., 2011). The results showed that there were two significant reductions in the tensile strength occurring in the temperature ranging between 20°C-150°C and 450°C-700°C (Figure 35). Between these two temperature ranges, there was a slight reduction in the ultimate strength of material. At 300°C the ultimate tensile strength of the CFRP was about 50% of that at room temperature. However, at 700°C, the latter retained about 5% of its initial value at room temperature.

Figure 36 shows a different evolution of the residual tensile strength of the CFRP and GFRP materials (epoxy resin matrix). These results were obtained by the tests carried out on "heated-cooled specimen" (residual regime) (Foster and Bisby, 2005, 2008). It was noted that the residual strength of the material decreased slightly with temperature up to 300°C, but severely beyond 400°C. At the latter temperature (400°C), the decrease in residual strength GFRP composite was greater than that of the CFRP composite. It was because that the resistance of the carbon fibres is better than that of glass fibres.

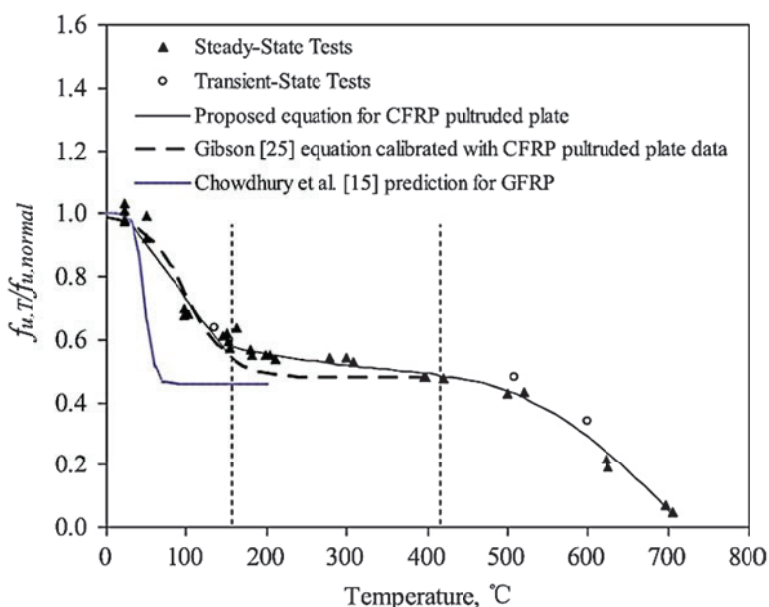


Figure 35: Evolution of the tensile strength of the CFRP composite as function of temperature, (Wang et al., 2011)

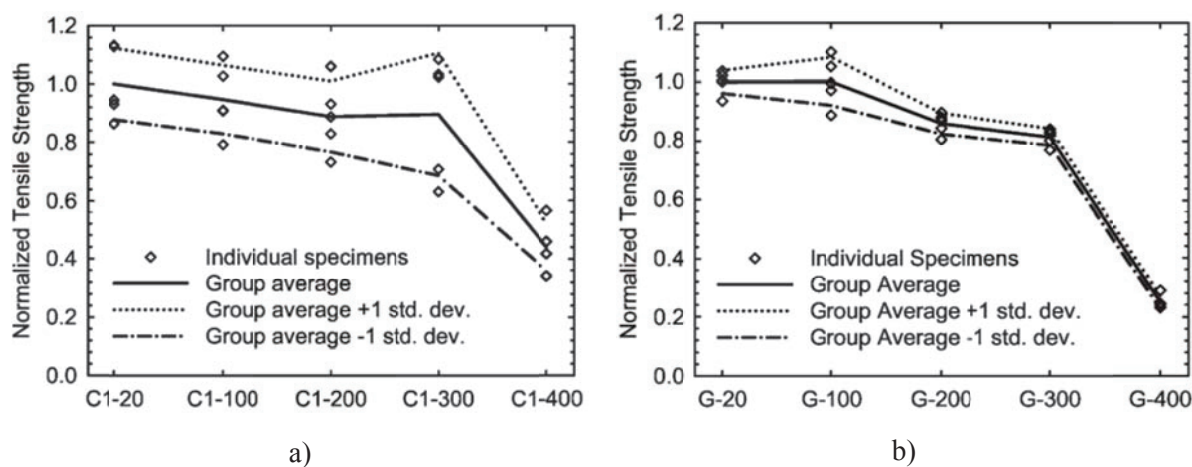


Figure 36: Evolution of residual tensile strength of CFRP (a) and GFRP (b) with the exposure temperature, (Foster and Bisby, 2005, 2008)

It is clear that the ultimate tensile strength of the CFRP and GFRP composite materials generally decreases with increasing temperature. Nevertheless, the level of evolution of this resistance with temperature depends not only on the composite composition, but also the test protocol ("high temperature direct test" or "residual test").

The results from Yu and Kodur showed that, at 300°C, the tensile strength decreased by approximately 40% for rods (Figure 37a) and 50% for strips (Figure 37b); and at 600°C, the tensile strength decreased by approximately 90% for both strips and rods (Figure 37a,b) (Yu and Kodur, 2014).

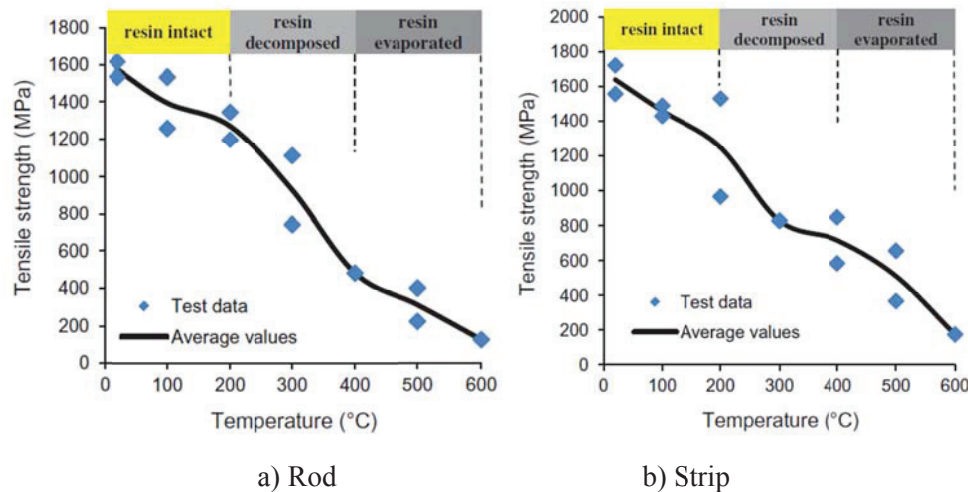


Figure 37: Variation of tensile strength of CFRP with temperature (Yu and Kodur, 2014)

Cao et al. investigated the thermo-mechanical tensile strength of CFRP sheets with two different methods of loading control at temperatures between 16°C and 200°C (Cao et al., 2011; Shenghu Cao et al., 2009). The results indicated that tensile strengths of CFRP sheets were significantly reduced as the temperature increased. From 16°C to 55°C, the tensile strength decreased by approximately 30% and then slightly varied around that value as the temperature increased to 200°C. According to Hamad et al., the CFRP bar reduced 50% of its strength at about 325°C (Figure 39) (Hamad et al., 2017).

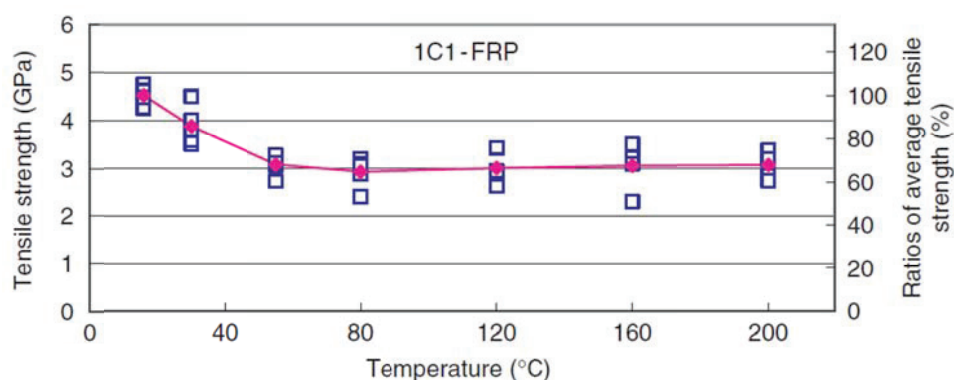


Figure 38: Tensile strengths and average strength ratios of CFRP sheets at different temperatures (Cao et al., 2011; Shenghu Cao et al., 2009).

Experiments conducted by Hamad et al. showed that under the tensile loading, which is performed by standard constant displacement rate of 3.0 mm/min, the residual tensile strengths of 10 mm CFRP and GFRP bars reduced by 50% at about 325°C (Figure 39) (Hamad et al., 2017).

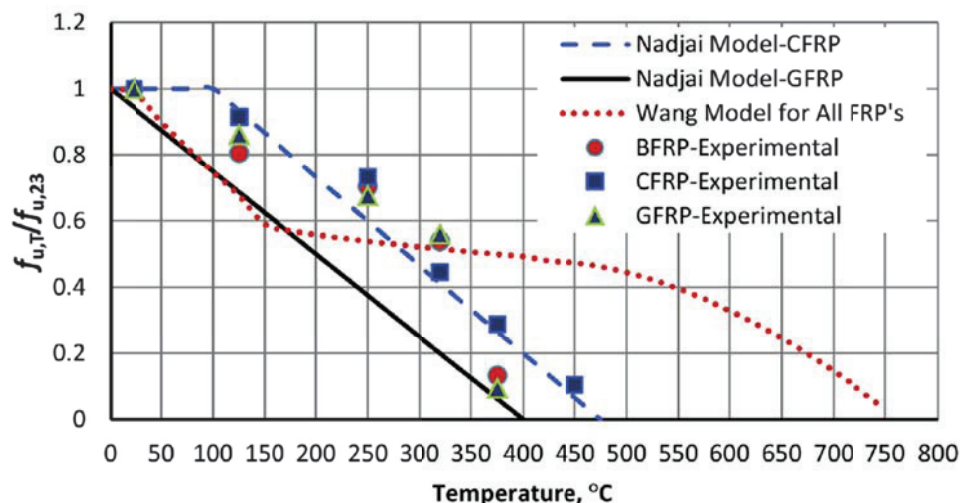


Figure 39: Residual tensile strength for FRP bars under elevated temperatures (Hamad et al., 2017).

1.2.2.5. Conclusion

In summary, the information on the thermo-mechanical behaviour of FRP composite at high temperatures is still rare, even as carbon/epoxy and glass/epoxy which are commonly used for civil engineering applications. Despite a small amount of study of FRP composites, the gathering of all the work covered in this part offers a general understanding of the thermo-mechanical behaviour of FRPs.

Generally, exposure to high temperature causes thermal, chemical, physical and mechanical complex phenomenon in a FRP composite such as: conduction, generation or absorption of heat, softening and decomposition of the polymer matrix (releasing of smoke and flammable gasses), the oxidation of carbon fibres.... In addition, these processes do not individually occur, but they overlap and/or interact with each other and are also influenced by the applied mechanical load. The thermal and mechanical behaviours of FRP composite obviously depend on several factors such as the type of resin, fibre type, the concentration of reinforcement (volume fraction or mass fraction) and its distribution in the volume of the composite nature of the reinforcement-matrix interface... Among these factors, the role of nature and the fraction of the polymer matrix are important. Its softening, degradation of mechanical performance and decomposition during a temperature increase generally cause reduction of the mechanical properties as well as the variation of the thermal properties of the FRP composite. At temperatures above T_g , the mechanical stress distribution of the matrix for the fibres is degraded and the individual fibre can be overloaded and gradually broken, especially with manually-fabricated FRP. The decomposition of the polymer matrix is also one of the main factors leading to the variation of the thermal conductivity and the specific heat via the gas flux, voids and endothermic/exothermic reactions. Therefore, although the fibres can retain their mechanical performance at high temperatures (over 400°C for glass and carbon fibres), the Young's modulus and ultimate tensile strength of composite may decrease significantly. Furthermore, the degradation of the mechanical properties of the fibres at very high temperatures also leads to the reduction of the mechanical performance and the possible change in the linearity of the composite behaviour. In addition, the pure epoxy and composite epoxy matrix materials (CFRP, GFRP) significantly lose their mass at a temperature above 300°C.

While most of the studies presented in this section show significant decreases in Young's modulus and ultimate tensile strength of CFRP and GFRP subjected to elevated temperatures (over 200°C, 300°C or 400°C). Nevertheless, it is very difficult to draw representative law of evolution of the mechanical properties due to the variety of composite type (nature and the fraction of its constituents), a scarcity of experimental data for each composite material and the difference in the type of thermo-mechanical

loading studied in different works ["direct testing at high temperature" (thermo-mechanical regime) or "testing on heated-cooled specimen" (residual regime)]. In addition, it is necessary to take account of the difficulty of measurement of the deformation of the composite material and the dispersion of the experimental data under elevated temperature. Therefore, it is obviously necessary to add as much as possible new experimental data to fill this gap. Several models for the evolution of the mechanical characteristics of the composites as a function of temperature have also been proposed, but their relevance still needs to continue to be evaluated and improved.

Finally, the previous experimental studies show that the measurements of the deformation or the displacement of composite, with instrumentation in direct contact with FRP specimen (e.g. gauges, LVDT) at elevated temperature condition, are very technically difficult and expensive. The elevated temperature can damage the measuring instrumentation. Furthermore, it is necessary to take into account the influence of temperature on the accuracy of measurement instrumentation. These are the main reasons why few experimental data on evolution of Young's modulus and ultimate deformation of FRP composites depending on temperature are available in the literature.

1.2.3. Behaviour of polymer adhesives

Adhesive is used to bond the composite sheets to substrate surfaces such as concrete or even steel structures. Common types of adhesive are known as epoxies, acrylics, ... Epoxies provide high bond strength with elevated temperature resistance, whereas acrylics provide moderate temperature resistance with good strength and rapid curing (Obaidat, 2011). Several considerations involved in improving the efficiency of adhesives. Careful surface preparation such as removing the cement paste, grinding the surface by using a disc sander, removing the dust generated by surface grinding using an air blower and careful curing are critical to bond performance (Obaidat, 2011; 2001). The most important part of FRP application is the procedure of laying adhesive between the composite material and substrate, Figure 40.

Typically, most of structural adhesives are thermosetting polymers although some thermoplastics are used (Canto, 2013). The physicochemical characteristics of thermosetting adhesives (mechanical and chemical resistance) are generally much higher than those of thermoplastics, especially regarding temperature resistance (Oudet, 1994). Table 2 shows properties of some common structural adhesives. Among them, epoxy adhesives are widely used in civil engineering field with a high chemical resistance or corrosion, good mechanical and thermal properties, excellent adhesion to various substrates, low shrinkage on curing and also good electrical insulation properties. This is generally a combination of an epoxy resin and a hardener. Epoxy resins are thermosetting polymers and their overall molecular structure after curing is amorphous (Odegard and Bandyopadhyay, 2011).

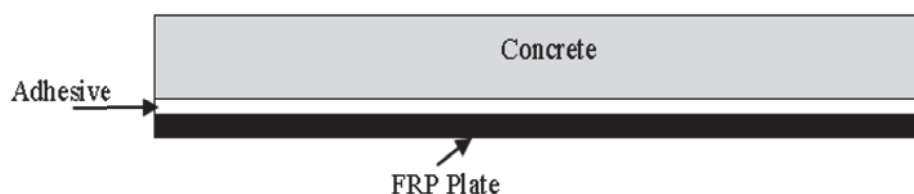


Figure 40: Concrete-FRP system (Obaidat, 2011)

Table 2: Comparative values of stiffness and strength of common structural adhesives (Canto, 2013)

Material	Relative density	Young's modulus, GPa	Shear modulus, GPa	Tensile strength, MPa
Epoxy adhesive	1.25	3	1.2	60
Polyethanes	1.2	0.02	0.008	40
Phenolic	1.3	3.5	1.4	50

The influence of temperature on the thermo-physical and mechanical properties (mass, thermal conductivity, specific heat, modulus, resistance) of the adhesive polymers (especially epoxy) was quite extensively studied. In general, the physic-mechanical properties of these adhesives change with the temperature especially when the temperature reaches the glass transition temperatures of adhesives. Some variations in the characteristics of epoxy adhesives are representatively shown on Figure 41, Figure 42, Figure 43, Figure 46, Figure 47 and Figure 48.

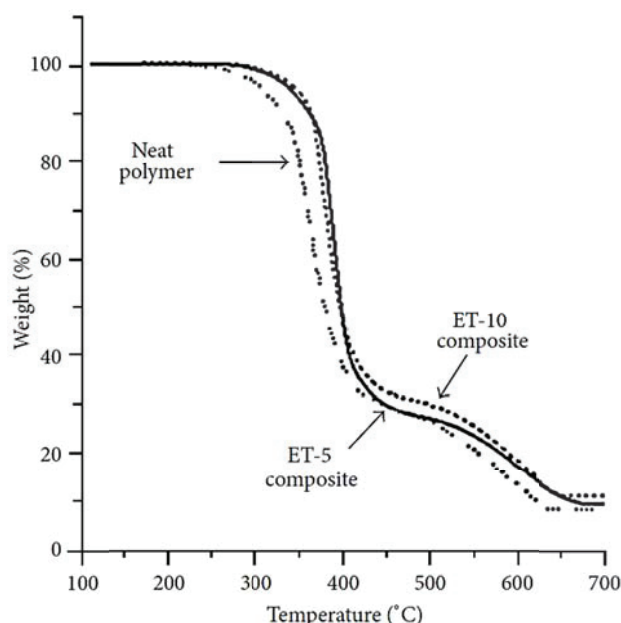


Figure 41: Typical thermogravimetric analysis (TGA) of an epoxy (neat polymer) and modified epoxies (ET-10 and ET-5 composites) (Rubab et al., 2014)

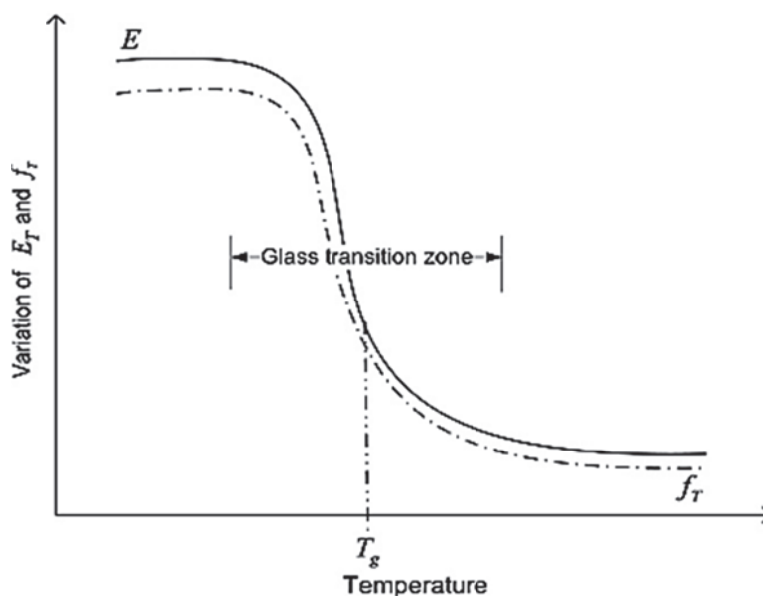


Figure 42: Diagram of the variation of Young's modulus and the tensile strength of the adhesive, (Ahmed and Kodur, 2011)

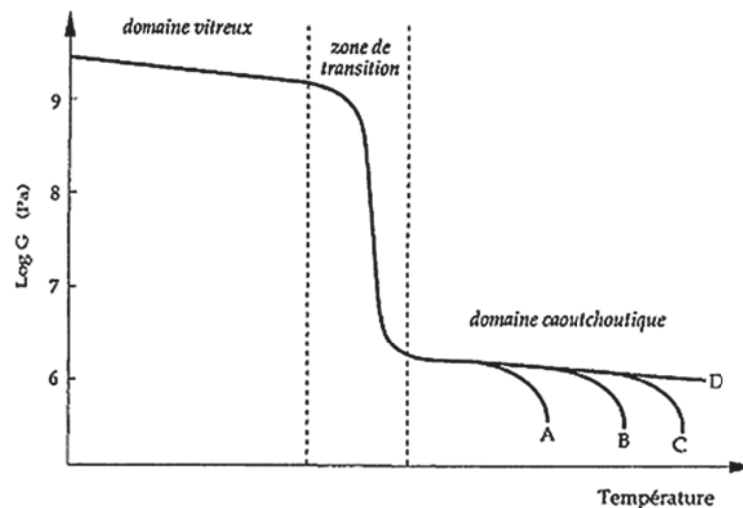


Figure 43: Variation of the shear modulus as a function of temperature for amorphous polymers (Oudet, 1994).

The change in mass of the adhesive is influenced by its decomposition (Souza and Reis, 2013). Moreover, changes in the physical or mechanical properties resulted from molecular movements and flexibility of the polymer chains (Perkins, 2011). Depending on the structure of the polymer chain, the material can undergo two significant transitions: the crystalline portions of the polymer will be a thermodynamic transition of the first order to the polymer melting temperature (T_m). The amorphous portions will be subjected to a second order thermodynamic transition at the glass transition temperature of the polymer (T_g). T_g is in fact a temperature range, rather than a specific temperature. When the temperature increases between the glass transition region, the polymer chains in the amorphous portions move and the polymer undergoes a transition from a "glassy" state to a "rubbery" state. In this region, the physical properties (specific heat, coefficient of thermal expansion) and mechanical properties (modulus, strength) of the polymer may drastically change. For most thermosetting polymers, such as epoxies, T_g can depend on the hardener, curing condition, composition and crosslink density of the polymer since these factors affect the mobility and flexibility of the polymer chains. Figure 44 shows the influence of curing time on the T_g of an epoxy. Generally, the T_g is measured by technique such as Differential Scanning Calorimetry (DSC) or dynamic mechanical analysis (DMA). After T_g , if the temperature continues to increase, material and polymers decompose, releasing of products such as smoke, gas, coal happen. Decomposition is totally beyond a temperature designated by T_d .

The effect of temperature also changes shape and characteristic parameters of "stress-strain" curve of a polymer adhesive. According to Revathi et al., at low temperatures, the epoxy resin exhibits a quasi-linear and fragile behaviour while at high temperatures, it has a ductile behaviour without flow (Revathi et al., 2014). In addition, as the temperature increases up to the T_g (viscoelastic region, 100°C), the epoxy becomes plastic, with a significant drop in modulus and tensile strength (Figure 45). This is attributed to the significant reduction of the intermolecular bonds and the possible distortion of the cross-link network above T_g . These results were also confirmed by Perkins (Perkins, 2011), without deformations which are immeasurable in experiments.

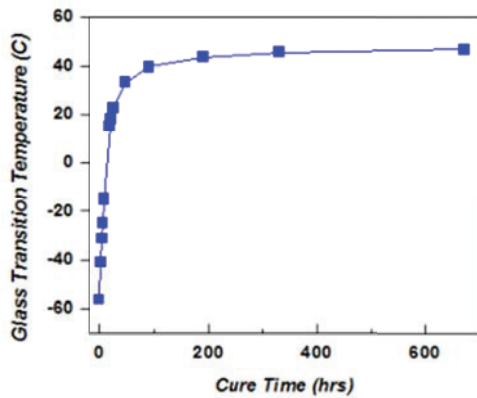


Figure 44: T_g as a function of time curing at ambient temperature for epoxy, (Perkins, 2011)

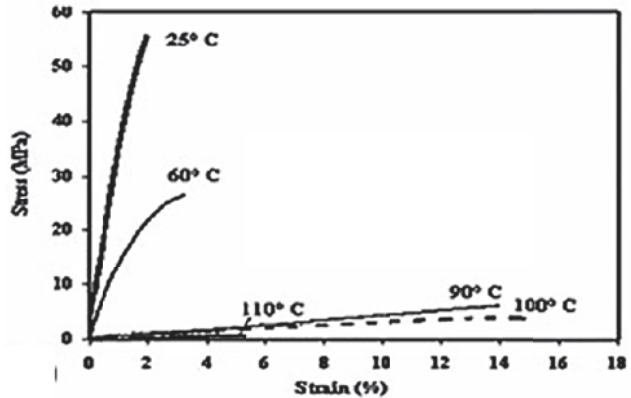


Figure 45: "Stress-strain" curves of an epoxy depending on the temperature, (Revathi et al., 2014)

Many authors have also studied the influence of temperature on the thermal properties of polymer adhesives such as thermal conductivity and specific heat but in a relatively narrow range of temperature (Evseeva and Tanaeva, 1995; Hussan, 2012; Pascault et al., 2002; Tsekmes et al., 2013). In general, the thermal conductivity of amorphous polymer at room temperature is in the range of 0.1 W/m.°C to 0.2 W/m.°C (Tant et al., 1995). It was shown that with this epoxy, the magnitude of thermal conductivity slightly varies in the range from room temperature up to one hundred degrees (Figure 46) (Evseeva and Tanaeva, 1995). The specific heat of the epoxy resin at room temperature is typically between 0.8 kJ/kg.°C and 1.2 kJ/kg.°C and increases as temperature rises. This increase is the most important in the glass transition region due to the absorption of heat to the transition state and physical decomposition (Figure 47). Several studies observed the influence of temperature on the density variation of polymer adhesive in general and in particular epoxy adhesives (Rubab et al., 2014; Souza and Reis, 2013)... Most of them showed that, for the epoxy resin, mass significantly decreased from about 300°C as the result of resin decomposition (Figure 48).

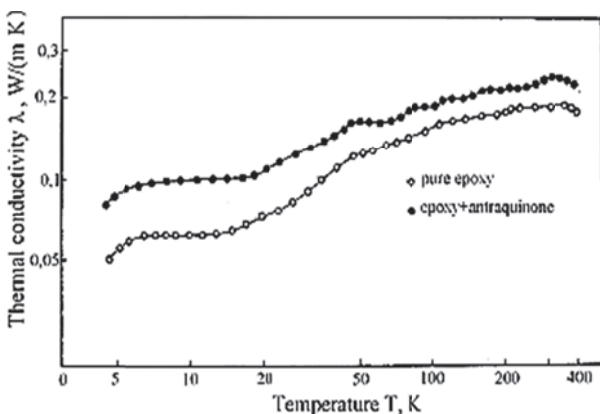


Figure 46: Thermal conductivity at different temperatures of a pure epoxy resin (Evseeva and Tanaeva, 1995)

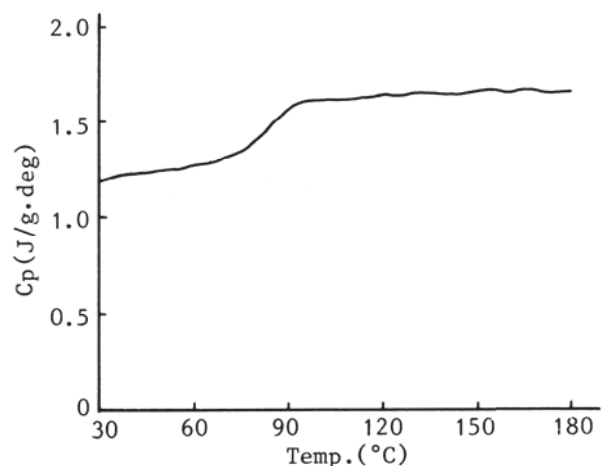


Figure 47: Specific heat of an epoxy adhesive according to the temperature (HITACHI, 1981)

Regarding the evolution of mechanical properties as the increase of temperature, some epoxy adhesives have been considered (Bascom and Cottingham, 1976; Moussa et al., 2012b). Bascom et al. investigated the temperature effects on mechanical properties of an epoxy adhesive from -40°C to 50°C (Bascom and Cottingham, 1976). Their reports indicated that the tensile strength reduction of the studied adhesive is about 35% at 50°C (the maximum observed temperature condition); whereas the glass transition temperature T_g was introduced as 68°C (without reporting on test method). Moussa et al. studied the residual properties of a commercial epoxy adhesives, which are commonly used in CFRP strengthening systems, from -35°C to 100°C (Moussa et al., 2012b). The results indicated that at moderate temperature of 60°C the strength and stiffness of the adhesive were below 20% of their values obtained at ambient temperature and thus can be negligible (Figure 49).

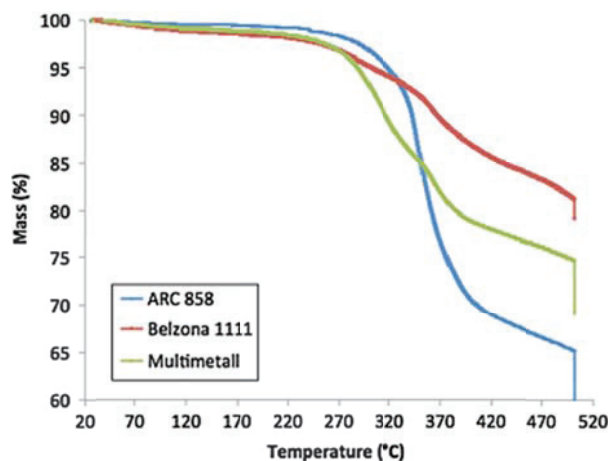


Figure 48: Thermo gravimetric analysis (TGA) of adhesives (Belzona 1111 and Multimetall) and ARC 858 (pure epoxy) (Souza and Reis, 2013)

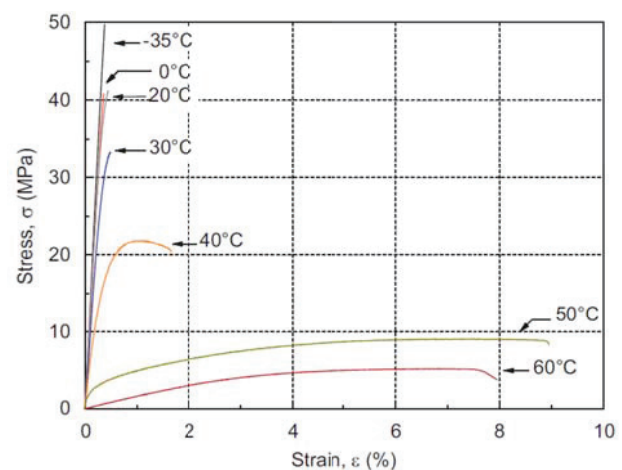


Figure 49: Influence of temperature on stress-strain relation of commercial epoxy adhesives (Moussa et al., 2012b)

1.2.4. Concrete/ adhesive/ FRP interface

In practice, the structural adhesive joints comply with the intended applications. It consists of two "composite-adhesive" interface and "adhesive-substrate" interface. Nevertheless, due to the location closing to the heat source, the "composite-adhesive" interface is the first one that should influence the behaviour of the joint. In the following, the research concerning the use of different joints relating the application of FRP are summarized and compared.

Tadeu et al. made several double overlap shear tests on concrete samples of $150 \times 100 \times 100$ mm (Tadeu and Branco, 2000). These samples are bonded with steel plates on the outside, at different temperatures (20°C , 30°C , 60°C , 90°C and 120°C). The authors noted a significant reduction of tensile strength with increasing temperature (32% reduction at 30°C , of $45 \div 51\%$ at 60°C and more than 90% at 120°C , Figure 50) and cohesive failures in the adhesive at temperatures above 30°C . This is because that the adhesive used has a low glass transition temperature T_g (Camata et al., 2007). Moreover, the thermal expansion coefficient of steel is very similar to concrete, so thermal stresses, generated in "concrete-steel strip" interface are very limited. Blontrock conducted shear tests at double recovery on separate concrete prisms ($150 \times 150 \times 800$ mm) (Blontrock, 2003). These prisms are externally reinforced composite CFRP laminates dishes. The samples were subjected to tensile loads at four temperature levels of 20°C , 40°C , 55°C and 70°C . Comparing with the maximum failure loads of the material obtained at 20°C , the tests carried out at 40°C and 55°C showed an increase of the failure load of 41% and 24% respectively. However, the tensile strength of the material has decreased by about 19% at 70°C .

(close to T_g), Figure 51. It was noted that the failure mode of concrete/adhesive/CFRP specimen at ambient temperature is failure within concrete but at elevated temperature, the failure was obtained at the concrete adhesive interface. Di Tommaso et al. have tested several concrete samples externally bonded with CFRP, at four temperatures: -100°C , -30°C , 20°C and 40°C (Di Tommaso et al., 2001). The test results indicated that the tensile strength at 40°C is lower than that obtained at room temperature. Camata et al. also revealed a similar trend in the evolution of the failure load of the double-shear specimens "CFRP reinforced concrete" (Camata et al., 2007). An increase in tensile strength at temperatures near T_g of the adhesive relates to that at room temperature. It then degrades at higher temperatures.

Klamer et al. have made double shear test and three-point bending tests on concrete specimens bonded with CFRP plates at different temperatures (-10°C , 20°C , 40°C , 50°C , 65°C and 75°C) (Klamer et al., 2005). The glass transition temperature T_g of the adhesive used is 62°C . The results of these tests show that the tensile strength is affected not only by temperature, but also depends on the test pattern used. Double overlap shear tests show an initial increase in tensile strength followed by a significant decrease in the load, during the temperature increase (beyond the glass transition temperature). However, in the bending tests, the tensile strength was little changed with temperature. Two types of failure were also observed in this study. At low temperatures (-10°C to $+40^{\circ}\text{C}$), shear failure occurred in the concrete, leaving a thin layer of 1 mm to 3 mm of concrete attached to the adhesive. At elevated temperatures (50°C to 75°C), the failure of the adhesive to the adhesive-concrete interface took place, leaving the adhesive attached to the concrete. However, in another experimental program on the effect of temperature on the separation/ delamination of CFRP, (Klamer et al., 2006) it demonstrated that the specimen configuration had a small influence on the failure mode. Moreover, in this study, the numerical simulations of the stress distribution and the interface shear strain showed that the difference in the coefficient of thermal expansion (CTE) between the concrete and the CFRP has a positive influence on the failure load (Figure 52); the decrease in the rigidity of the high-temperature adhesive redistributed the deformation over the anchorage length of CFRP (see Figure 53) and reduced the stress concentration. Thus, this decrease has a positive influence on the failure load.

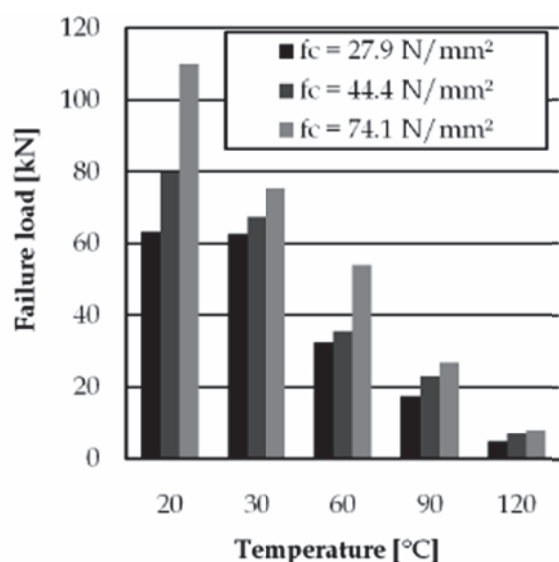


Figure 50: "Failure load-temperature" relationship obtained by shear tests carried out on double overlap specimens, (Tadeu and Branco, 2000) (Klamer et al., 2008)

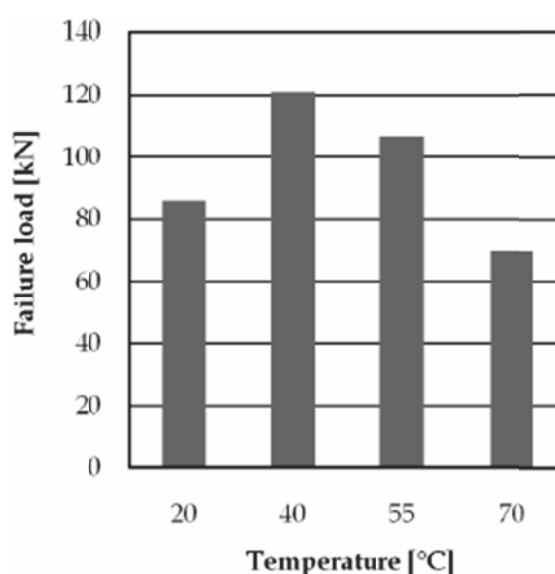


Figure 51: "Failure load-temperature" relationship obtained by shear tests carried out on double overlap specimens, (Blontrock, 2003) - (Klamer et al., 2008)

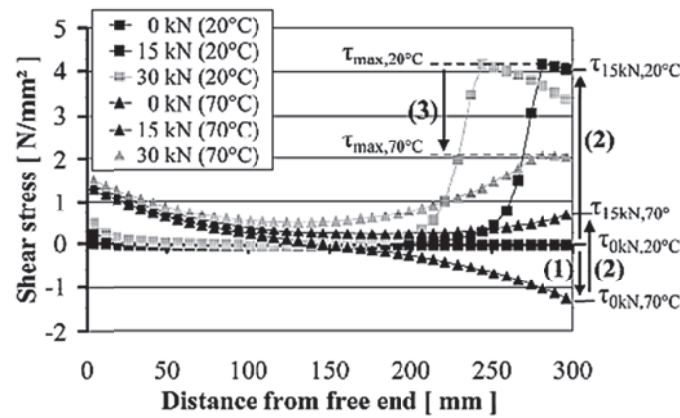


Figure 52: Shear stress at the concrete-adhesive interface, (Klamer et al., 2006)

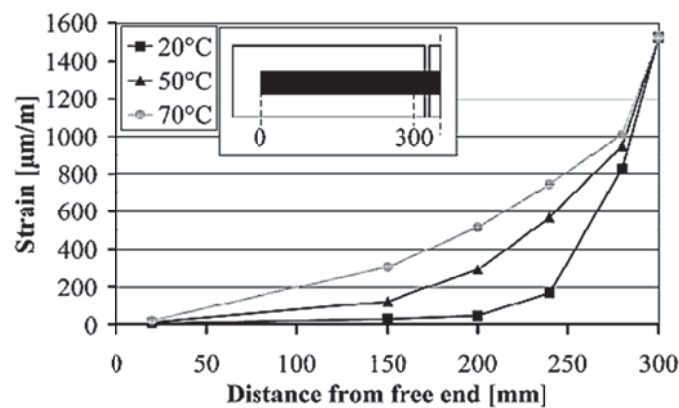


Figure 53: Deformation measured in CFRP at force of 30 kN, (Klamer et al., 2006)

The effect of temperature (20°C, 50°C, 65°C and 80°C) on the FRP-concrete bond behaviour was studied by Leone et al. (Leone et al., 2009) on double overlap shear concrete specimens (150x150x800 mm), reinforced with CFRP and GFRP. The results showed a decrease in the maximum shear stress at the FRP-concrete interface at temperatures above the transition temperature T_g of the adhesive (55°C). At 80°C, there was a reduction from 25% to 72% of the shear strength that depends on the type of FRP composite used. They showed a movement of peak stress from the loaded end to the free end of FRP with the increase of the mechanical load.

Ferrier et al. conducted an experimental study on the mechanical behaviour of double overlap CFRP/concrete specimens subjected to different temperatures (-40°C, -20°C, -10°C, 0°C, 20°C, 40°C, 60°C and 80°C) (Ferrier et al., 2012). The results showed that low temperatures (below 20°C) have little effect on the ultimate shear strength of CFRP/concrete specimens. However, with increasing temperature (20°C to 80°C, for example), a decrease in the shear resistance of CFRP/concrete specimens has been observed for temperatures above 40°C. Otherwise, failure modes of the studied specimens (cohesive fracture at concrete/CFRP interface) have been shown.

Gamage et al. numerically and experimentally studied the characteristics of the bonding of concrete blocks (130x130x300 mm), bonded with CFRP at elevated temperatures (Gamage et al., 2006). There are two series of shear tests. The first set consists of eleven samples without thermal insulation, and the second series includes two samples thermally protected by 50 mm of insulation thickness. The samples of the first series were initially subjected to a load of 50% of its bearing capacity at room temperature. They are then exposed to a temperature increase of 10°C/minute from room temperature. The purpose of these tests is to determine the ultimate temperature corresponding to the rupture. The second series have

only been exposed to high temperatures (presented by the standard AS 1530.4 curve without mechanical load). It is intended to measure the temperature at the interfaces. The results of these studies show that the strength of such joints, at elevated temperatures, is independent of the anchoring length of CFRP. Joint rupture always occurs in the epoxy adhesive when the temperature is approximately $70^{\circ}\text{C} \div 80^{\circ}\text{C}$, Figure 54. The un-insulated specimens lost the CFRP-concrete bond after $5 \div 6$ minutes of fire exposure presented by the standard AS 1530.4 curve. This indicated the need for thermal protection to maintain the effectiveness of the bond at elevated temperatures.

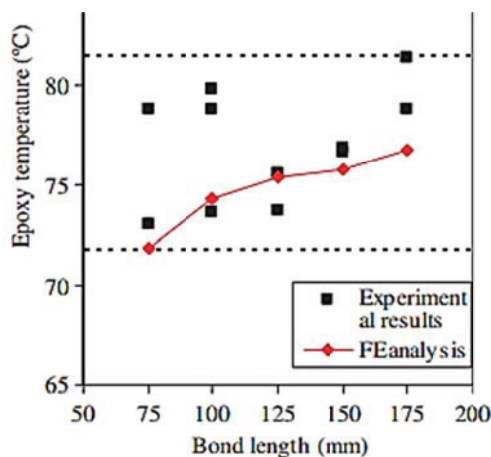


Figure 54: Temperature at the joint interface at the time of rupture in function of the anchor length of CFRP in CFRP/ concrete specimens (Gamage et al., 2006).

In summary, the studies as presented above are uncommon and they concentrate on the influence of temperature on the behaviour of "concrete/composite" interface. Most of these studies focus on the residual strength of the "FRP/adhesive/concrete" joints (or a decoupling between the thermal and mechanical stresses). These results demonstrated that the resin has an important role and therefore it will influence the bond performance and failure mode at different temperature levels beyond the glass transition temperature (T_g). Before the T_g , the substrate, particularly the concrete which is mentioned in the case studies, tends to damage adhesive joint between composite and concrete. Therefore, as the temperature increases, the failure mode of the "FRP/adhesive/concrete" joint can change from a shear failure in concrete to interfacial failure between composite and concrete. Furthermore, the failure temperature of the concrete/adhesive/FRP joint, under a constant mechanical load during heating, is independent from the anchorage length of FRP composite.

1.2.5. FRP-concrete structure bond

To apply the CFRP on to concrete structures, the CFRP can be directly bonded to concrete surface (externally bonding reinforcement method - EBR) or via dipping CFRP in to grooves on concrete surface with adhesive paste (near surface mounted method - NSM). The selection of reinforcement method depends on the structure and particular condition. For EBR reinforcement method, Bisby et al. investigated the residual performance of CFRP EBR reinforced concrete beams and columns subjected to fire using a normal epoxy adhesive (Bisby et al., 2005). The behaviour of steel-reinforced concrete beams, externally reinforced with carbon fibre-reinforced polymer (CFRP), under high-temperature loading (up to 500°C) has also been studied (Bisby, 2016; Bisby et al., 2013).

The residual confined performance of externally wrapped specimen exposed to fire using normal temperature epoxy paste has also been studied (Reddy et al., 2006). Firmino et al. experimentally studied the thermo-mechanical bond-performance of the EBR reinforced concrete structures between 20°C and

120°C (Firmo et al., 2015a). There is also investigation on the fire performance of EBR CFRP reinforced concrete beams under various load levels (Turkowski et al., 2017). For NSM reinforcement method, Al-Abdwais et al. observed the behaviour of the NSM CFRP reinforced concrete structures using cement-based adhesive at elevated temperature condition (Al-Abdwais et al., 2017). Jadooe et al. investigated the residual performance of NSM CFRP reinforced concrete via single lap test using a cement-based adhesive and an epoxy adhesive after 1 hour exposing to temperature from 200°C, 400°C and 600°C (Jadooe et al., 2017a, 2017b; Jadooe Awad et al., 2017).

In comparison between two reinforcement methods, Firmo et al. experimentally studied the performance of CFRP reinforced concrete beam in both cases of reinforcement (EBR and NSM) and used these results to explain the fire performance of CFRP reinforced concrete structure (Firmo et al., 2014). The results also showed that at room temperature, the NSM reinforced beam has 21%-35% better performance compare to EBR reinforced one depending on the bond configuration. Kotynia et al. also experimentally studied the performance of CFRP reinforced concrete structure using NSM and EBR reinforcement methods at non-temperature condition and also verified with numerical solution (Kotynia, 2012; Kotynia et al., 2008). The results showed that the NSM method allowed concrete beam higher failure strain, compared to EBR method. There are also other available studies for shear strengthening, compression strengthening of concrete structures or even CFRP pre-tensioned slabs at various temperature-mechanic testing conditions. For instant, Tan et al. investigated the residual performance of shear strengthening of glass FRP wrapped beams after being exposed to temperature-time history (Yuqian, 2010) following ASTM E-119 curve. These authors also reported on the performance of fibre-reinforced cement composite, basalt FRP laminates and basalt FRP-strengthened beams subjected to elevated temperature (Tan and Zhou, 2007, 2008, 2009). Kim et al. studied the residual shear performance of CFRP shear strengthened short beams after being exposed to temperature up to 200°C (Kim et al., 2012; Namrou and Kim, 2016; Yail J. Kim, 2012). Considering combined temperature-mechanic load, Cree et al. observed the shear performance of hand layup lap-splice test in two load cases with elevated temperature up to 200 °C (Cree et al., 2015; Duncan Cree et al., 2017; Gales et al., 2016). Terrasi et al. and Maluk et al. reported the fire behaviour of CFRP pre-stressed high-performance self-consolidating concrete slabs in an experimental study on thin slabs exposed to a standard fire (Maluk et al., 2010; Terrasi et al., 2012).

There are also several studies which focus on the fire behaviour of steel-reinforced concrete structures strengthened by CFRP (with or without fire protection systems) (Ahmed and Kodur, 2011; Chowdhury et al., 2012, 2007; Cree et al., 2012; Firmo and Correia, 2015; Firmo et al., 2012; Ji et al., 2013; Kodur et al., 2006; López et al., 2013; Maluk et al., 2015; Naser et al., 2012; Palmieri et al., 2013; Turkowski et al., 2017)

1.3. Analytical material models

Although several analytical models have been proposed for elevated temperature performance of material such as concrete, steel and FRP, but few models that perfectly address CFRP.

Gibson et al. (Gibson, 2005) used a hyperbolic tangential function (Equation 2) based on composite theory to predict the evolution of a laminate polyester/ glass system as the temperature rose up to 200°C:

$$P(T) = R^n \left[\frac{P_U + P_R}{2} - \frac{P_U - P_R}{2} \tanh \{k (T - T')\} \right] \quad \text{Equation 2}$$

Where P(T) is a particular property at temperature T, P_U and P_R are the un-relaxed and relaxed value of that property at low temperature and high temperature, respectively. K is a constant describing the breadth of distribution and T' is the mechanically determined glass transition temperature. These two parameters were identified by fitting with the experimental results. R is the residual resin content

coefficient (between 1 and 0) and its value, depending on the stress state, was proposed as 1 for resin-dominated properties and 0 for fibre-dominated properties (Gibson, 2005). The proposed model showed good agreement with the experimental compressive strength of the glass fibre system.

Bisby suggested a sigmoid function (Equation 3) to simulate the reduction in strength, stiffness and bond for CFRP and GFRP materials (Bisby, 2003):

$$\frac{f}{f_o} = \left(\frac{1-a}{2} \right) \tanh[-b(T-c)] + \left(\frac{1+a}{2} \right) \quad \text{Equation 3}$$

In this expression, f is a mechanical property at temperature T (strength, stiffness or bond strength), and f_o is the room temperature value of that mechanical property. The coefficient a was assumed as the residual value for the mechanical property, and coefficients b and c were identified through calibration based on the experimental results collected from literature published before 2004. The values of a , b , and c are shown in Table 3.

Table 3: Coefficients for tensile strength and Young's modulus of CFRP and GFRP proposed by Bisby, Equation 3, (Bisby, 2003)

Material	Property	Coefficients		
		a	b (x10e-3)	c
CFRP	Tensile strength	0.10	5.83	339.54
	Young's modulus	0.05	8.68	367.41
GFRP	Tensile strength	0.10	8.1	289.14
	Young's modulus	0.05	7.91	320.35

K. Wang et al. (Wang et al., 2011) calibrated the models of Bisby et al. (for FRP) (Bisby, 2003), Gibson et al. (for GFRP) (Gibson, 2005), and J. Chen et al. (for steel) (Chen and Young, 2006) to fit with his experimental results from 22°C to 706°C. The author confirmed that with Bisby's model (Equation 3), there is a discrepancy due to the scattered data from various FRP. According to K. Wang et al. (Wang et al., 2011), Gibson's model (Equation 2) better fitted with the experimental results for temperatures up to 400°C. On the other hand, after being calibrated, the model of J. Chen et al. (Equation 4) agreed well with the experimental results for all ranges of temperature (Wang et al., 2011). K. Wang calibrated the coefficients A , B , C and n in Equation 4 to fit with his experimental results. These are shown in Table 4 (Wang et al., 2011).

$$\frac{F_{u,T}}{F_{u,normal}} = A - \frac{(T-B)^n}{C} \quad \text{Equation 4}$$

Table 4: Prediction model by Wang et al. (Wang et al., 2011), Equation 4: Coefficients for the strength of pultruded CFRP at elevated temperature

Temperature range (°C)	Coefficients			
	A	B	C	n
22≤T<150	1.00	22	200	0.9
150≤T<420	0.59	150	490	0.7
420≤T<706	0.48	420	76000	1.8

Yu and Kodur (Yu and Kodur, 2014) calibrated Equation 3 proposed by Bisby (Bisby, 2003) using their experimental results with CFRP rods and strips, resulting in the following retention factors:

CFRP strips

$$\text{Strength: } f(T) = 0.56 - 0.44 \tanh[0.0052(T - 305)] \quad \text{Equation 5}$$

$$\text{Young's modulus: } E(T) = 0.51 - 0.49 \tanh[0.0035(T - 340)] \quad \text{Equation 6}$$

CFRP rods

$$\text{Strength: } f(T) = 0.54 - 0.46 \tanh[0.0064(T - 330)] \quad \text{Equation 7}$$

$$\text{Young's modulus: } E(T) = 0.51 - 0.49 \tanh[0.0033(T - 320)] \quad \text{Equation 8}$$

Where $f(T)$ and $E(T)$ are the reduction factors in the tensile strength and Young's modulus of the studied material, respectively. The prediction model exhibited a close match with the obtained results. The model is recommended for evaluating the fire response of structures strengthened with near-surface mounted FRP reinforcement.

Concerning the performance of FRP at severe temperature conditions, B. Ghadimi et al. had proposed a polynomial function to predict the residual compressive strength of pultruded glass fibre reinforced polymer regarding the temperature ranged from 20°C to 250°C (Ghadimi et al., 2017). The developed model can successfully predict the softening brittle response of the tested material that is subjected to cycles of thermal loading and compression.

1.4. Conclusion

The literature review has highlighted the interest of the scientific community to the mechanical performance of concrete, polymer composites (FRP), structural adhesives, concrete/adhesive/FRP interface as well as FRP-concrete bond as they are exposed to elevated temperatures which are always the most important defining characteristic of a fire. This is because these materials are commonly used for reinforcing, rehabilitating and repairing of civil engineering works and the fire is still existing risk and can occur in these structures.

In general, a fire in buildings is represented in the simplest way by nominal curves, ISO 834 or ASTM E119. However, the re-creation of these "temperature-time" curves is not always easy in experimental studies because of a very high speed of temperature increase during the first minutes. Therefore, in the civil engineering field, to study the effect of temperature on the mechanical behaviour of a material, steady state tests (where the temperature is constant with time) are commonly carried out instead of those in variable regime (where the temperature in the specimen body is a function of both time and the position).

The synthesis study clearly shows that the effect of temperature on the thermo-mechanical behaviour of concrete is widely studied. However, information about the FRP composites (especially the carbon/epoxy composite) subjected to elevated temperatures is still rare. Numerous physical, chemical, thermal and mechanical complex processes occur in concrete material, FRP composite and polymer adhesive during when they are exposed to elevated temperatures. These processes are the evaporation of water, conduction or convection, the generation or absorption of heat, softening or the transition from a "glassy" state to a "rubbery" state, the thermal expansion/contraction, the increasing of internal pressure, the chemical processing steps, the dehydration, the de-carbonation of limestone or the decomposition of

the polymer matrix and organic fibres, the oxidation of carbon fibres, the thermal deformation and cracking of the matrix, the delamination of fibre/matrix interface ... Moreover, these changes do not occur separately, but they overlap and/or interact with each other. These processes strongly affect the mechanical properties and thermo-mechanical tensile behaviour of materials. In summary, the evolution of main properties in function of temperature can be noted as followings:

a. For concrete:

- Reduction of the thermal conductivity attributes to the drying of the material, the occurrence and development of cracks caused by the incompatibility of deformation of the components and by the pressure in the pores, voids.
- The change in specific heat results from the drying effect of the material and endothermic reactions.
- The reduction of density results from the thermal expansion and the weight loss.
- The reductions in general of the compressive strength, the tensile strength, the Young's modulus of the concrete are caused by the increase in micro-cracking and porosity and internal stress result from thermal damage. Nevertheless, there is also an increase in the tensile strength of the concrete and of the cement paste at certain temperatures.
- Additionally, developments of phenomenon mentioned above are irreversible. Finally, it is also necessary to mark thermal expansion (up to about 150°C) followed by a large thermal shrinkage of the cement paste.

b. For FRP in general and CFRP in particular:

- There are reductions of the Young's modulus, tensile strength and change from linear behaviour to non-linear behaviour beyond the glass transition temperature. They relate to the softening, degradation of the mechanical performance of the components as well as the decomposition of the polymer matrix, to the oxidation of carbon fibres, to the micro-matrix cracking and to the delamination interfacial fibre/matrix.
- The variations of the thermal conductivity and the specific heat are caused by micro-cracking, voids and endothermic/exothermic reactions.
- The progressive mass loss (especially at temperatures above 300°C) of CFRP, GFRP closely relates to matrix decomposition.

c. For polymer adhesives in general and epoxy adhesive in particular:

- The weight loss (especially in the more than 300°C for the elevated temperature epoxy) attributes to thermal decomposition of the material.
- The change in physical state (from a "glassy" state to a "rubbery" state) and physical properties (specific heat, coefficient of thermal expansion) and mechanical properties (Young's modulus , resistance) happens in the region around the glass transition temperature
- There are evolutions of shape and characteristic parameters of the "stress-strain" curves (from a quasi linear and fragile behaviour to plasticized behaviour for the epoxy).

Nevertheless, the literature review also shows a significant dispersion of the experimental results concerning the tensile and thermal behaviour of the above mentioned materials. This is attributed to the diversity of the materials used (the nature, the volume fraction and the distribution of its constituents ...), to different test protocols [types of thermo-mechanical loadings: splitting, bending or direct traction, "direct high-temperature test" (thermo-mechanical test) or "ambient temperature test on hot-cooled specimens" (residual test)]. In addition, it is also necessary to mark the difficulties of measuring the specimen deformation using direct contact instruments under elevated temperatures condition (thermal influence on accuracy of instrumentation, sliding or detachment of the measurement sensors used on the substrate). Furthermore, the equipment used in most previous studies does not allow performing experiments with simultaneous effects from mechanical and elevated temperature loads. For this reason, residual tests carried on heated-cooled specimens are more common than thermo-mechanical tests

carried out on hot specimen for studying the influence of temperature the mechanical behaviour of materials. Finally, some models showing the evolution of mechanical properties of FRP have also been proposed but their appropriateness still needs to be assessed.

1.5. Objectives of this Ph.D. thesis

The application of FRP composites in the civil engineering sector is promising. However, the risks of fire accident in civil engineering structure raise several concerns around its application. For the application of FRP in civil engineering, fire concerns are complicated due to the existences of several chemical, physical and structural phenomena. Until now, understandings on the thermo-mechanical behaviour of FRP composites, which are close to fire case, are still very limited; mainly because of a small quantity of studies. Thus, it is obvious to continuously advance on this research theme. Particularly, the knowledge of the tensile behaviour of FRP materials under the simultaneous effects of mechanical loading and elevated temperature need to be supplemented based on "high temperature direct testing". Also, the evolution of the thermo-mechanical characteristics of the materials, especially the CFRP depending on the temperature, should also be considered. This will enrich the literature database and provide necessary information for the analysis models of the thermo-mechanical response of these materials in the event of fire. From all above reviews, following questions arise:

- What are the evolutions of the main characteristic parameters (ultimate stress and Young's modulus) of the CFRP material as a function of temperature and mechanical loading paths?
- Is there any difference between the thermo-mechanical behaviour (under "direct hot test") and the residual behaviour (under ambient-temperature tensile-test after hot-cooled procedure) of CFRP material when it is simultaneously subjected to elevated temperatures and mechanical load?
- Will the duration that CFRP material exposed to elevated temperature influence its properties (strength, modulus)?
- Is there any correlation between elevated temperature and mechanical effects to CFRP material performance (including mechanical resistance and thermal resistance)?
- Is there any difference between the performance of different types of CFRP, especially factory-prefabricated CFRP (or pultruded CFRP) and manually fabricated CFRP (in-situ/ hand lay-up/ wet lay-up CFRP)?
- In civil engineering applications, what implementation method can improve the performance of CFRP reinforced concrete structure under severe temperature and mechanical load especially regarding to condition close to standard fire cases?
- How to numerically model the performance of CFRP reinforced concrete structures under elevated temperature and mechanical load condition? And how to apply the model to predict their performance under different thermo-mechanical conditions (including fire-temperature condition)?

For the reasons stated above, the objectives of this Ph.D. thesis are to:

- Experimentally study performance of CFRPs and extend the properties data of the CFRPs when they are simultaneously subjected to thermal and mechanical loadings. The study expects to observe the evolution of thermo-mechanical properties of two types of CFRP (one was provided by laboratory's partner and one was manually fabricated at laboratory condition) with the thermo-mechanical stress-strain relationship of CFRP provided by non-contact measurement (laser extensometer). The behaviours of CFRP at three different combined conditions of elevated temperature and mechanical load are also expected to be clarified, especially at expected temperature range beyond 300°C and up to 1000°C. The relevance between experimental results and proposed models in the literature is expected to be identified.

- Experimentally study the thermo-mechanical performance of interface regarding the concrete/adhesive/CFRP bond under simultaneous elevated temperature and mechanical load. It is expected to identify an optimal solution to improve the concrete/adhesive/CFRP bond under severe temperature-mechanical condition that is close to standard fire condition.
- Numerically investigate the performance of CFRP in reinforcing the concrete structures by using finite element analysis based software (ANSYS) to apply the experimental test results of each component in assembly model. The successful model is then able to be applied in observing the behaviour of CFRP reinforced concrete structures under different combined elevated temperature and mechanical loading condition as well as optimizing, developing their performance in complicated temperature-mechanical condition.

Chapter 2:

Experimental approach:

Material scale

CHAPTER 2 **Experimental approach: Material scale**

This chapter presents the general ideas for fire application and then the details of experimental approach in which the apparatus, testing programs, and two types of CFRP are explained. The experimental results are then summarized, discussed and calibrated with analytical models proposed in the literature as well as another proposed model.

2.1. General

This subsection firstly displays general ideas for fire situation and then experimental test for fire application.

2.1.1. General ideas for fire situation

When a fire happens to a civil engineering structure, it can be partly or totally submerge in high temperature. It is difficult to identify the exact temperature evolution during each fire case. But it is true that during the fire, both mechanical loading and temperature loading can exist on the structure at the same time. According to ISO-834 or ASTM E119 curves about temperature evolution in a fire, the maximum temperature can reach up to approximately 1200°C. According to this, two practical cases raise:

- Case 1: after fire, it is necessary to estimate / evaluate the remained performance of structure. This is for the reparation / strengthening or even demolition depending on the purpose and budget. This task needs the residual properties of materials / elements at different level of temperature.
- Case 2: in fact, for the fire protection purposes, it is necessary to predict /evaluate the fire behaviour of a structure which are being designed or even operated. This is to control / determine the fire safety condition according to fire protection regulation. This task needs the thermo-mechanical data of properties of each material/ element at different level of temperature.

Actually in literature, due to difficulty in testing condition to manage both temperature and mechanical impacts (not many facility can perform both), in literature, the post-fire behaviour (or residual behaviour) is more popularly studied and this result is also already applied in numerical research and engineering designs.

The questions arise: Can we use residual experimental data to identify the structure performance during fire (case 2)? If not? Is there any correlation between residual result and thermo-mechanical result so that we can exploit the residual experimental data for thermo-mechanical purpose? For this reason, the investigation is undertaken and thus also provides thermo-mechanical experimental data of pultruded CFRP which can be used in numerical modelling for the purpose mentioned in case 2.

2.1.2. Experimental test for fire application

As CFRP (or FRP in general) is functional material, the role of fibre is exploited to resist the tensile action due to its advantages in tensile capacity but not compressive action. In the tested pultruded CFRP, the carbon fibres are unidirectional and the polymer matrix roles the skeleton to fibres. For that

reason, it is suitable to investigate the pultruded CFRP via tensile test. This section describes the equipment used, the specimens and test procedures, and presents a test summary.

2.2. Test apparatuses

In this research, a thermo-mechanical testing system (Figure 55) is used to study the thermo-mechanical and residual behaviour of pultruded CFRP material. The system includes two main components: a thermo-mechanical machine (the TM20kN-1200C) and a laser extensometer. During the test, the TM20kN-1200C controls the force and temperature applied to the sample following a predetermined procedure while the laser extensometer measures the tensile axial strain of the CFRP sample. The different experimental devices used in this research, such as the thermo-mechanical machine (Figure 55), the laser extensometer (Figure 55c, Figure 56a,b), the thermocouples (Figure 55), and the ball-joint loading heads (Figure 55, Figure 57) are described as follows.

2.2.1. Thermo-mechanical machine

This machine has a mechanical loading capacity up to 20kN (Figure 55a) and a furnace (Figure 55b) that can apply temperature up to 1200°C. The mechanical part of this machine can apply an axial tensile force to the testing specimen while the furnace heating chamber can increase the temperature surrounding the specimen at different rates (the maximum heating rate of the furnace is 30°C/minute). This system is automatic and servo-controllable and can simultaneously generate the mechanical and thermal loading. A force sensor (Figure 55) is placed outside the furnace to measure and control the applied force, and three thermocouples are placed inside the furnace to measure and control the temperature in the heating chamber. The furnace (Figure 55b) is a cylindrical programmable oven with external dimensions of 40 cm high by 30 cm in diameter, and the heating chamber is 28 cm high and 10 cm in diameter. The temperature and the heating rate are programmable so the testing systems can auto-control the test with different target temperature levels and ramp rates. The furnace is thermally insulated by glass fibres (Figure 57b) to ensure the temperature of the closed system inside the furnace is correct as established by the testing programme. There is a rectangular opening on the side of the furnace (Figure 56a) that allows two laser beams from the laser extensometer to measure the axial elongation of the specimen. This opening can be closed if the laser extensometer is not used.

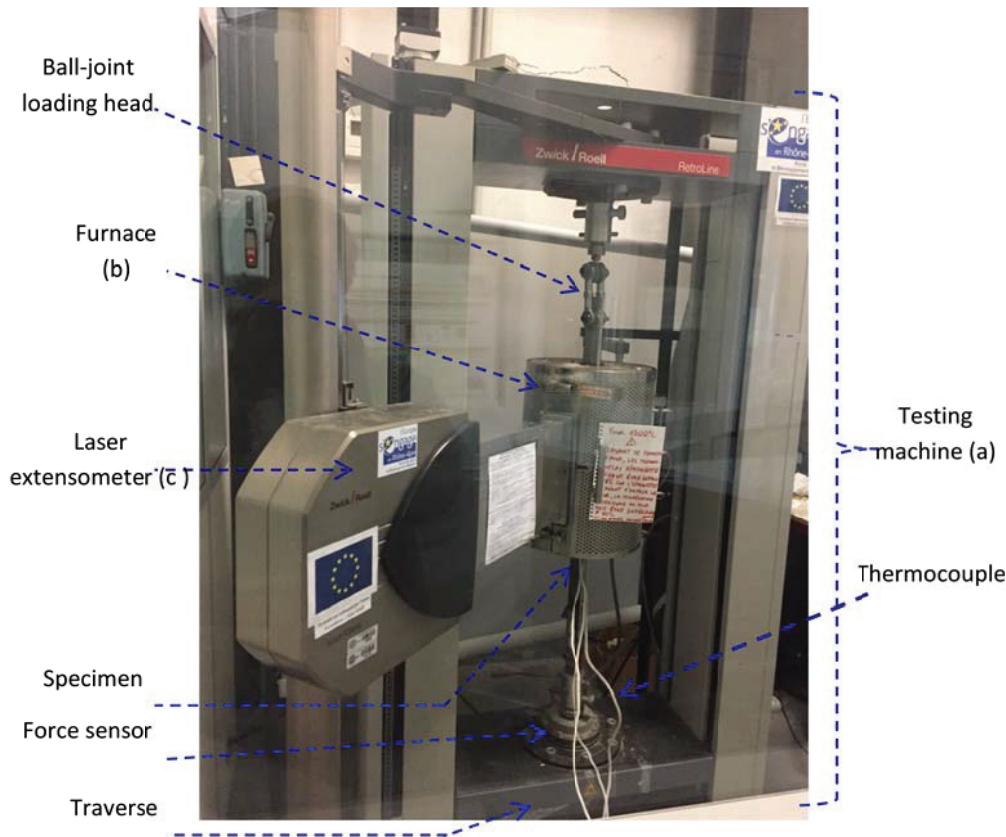


Figure 55: The thermo-mechanical testing system: a) tensile testing machine; b) furnace; c) laser extensometer

2.2.2. Laser extensometer

To measure the material deformation in this study, a laser extensometer (Figure 55c, Figure 56a,b) is used. The laser extensometer consists of two measuring heads with digital cameras and laser light sources mounted on motorized slides. It is used to measure the longitudinal strain of the specimen at elevated temperatures, potentially up to 700°C. This method is non-contact, which reduces errors caused by the temperature of the testing device, which is problematic in contact measurement methods. During use, the two laser bobbins form two laser diodes, passing through a rectangular guide tube and projecting on the surface of the specimen to evaluate the strain. The guide tube helps minimize environmental influences, such as air current on the measurement algorithm. A transparent glass wall (Figure 56b) separates the heating chamber and the space inside the guide tube to reduce the mutual thermal influences between the furnace and the laser extensometer. When the tested material is homogeneous, such as the pultruded CFRP material, the laser sensor measurement can provide the axial strain of the part of the specimen placed in the middle of the furnace during the test (Figure 56a). During the test, via laser sensor, the strain of the material will be observed, evaluated and recorded. The laser sensor for this machine, placed outside the furnace, is regularly maintained and calibrated to ensure its reliability. The process of laser sensor measurement has been developed and validated in previous works (Nguyen et al., 2016).

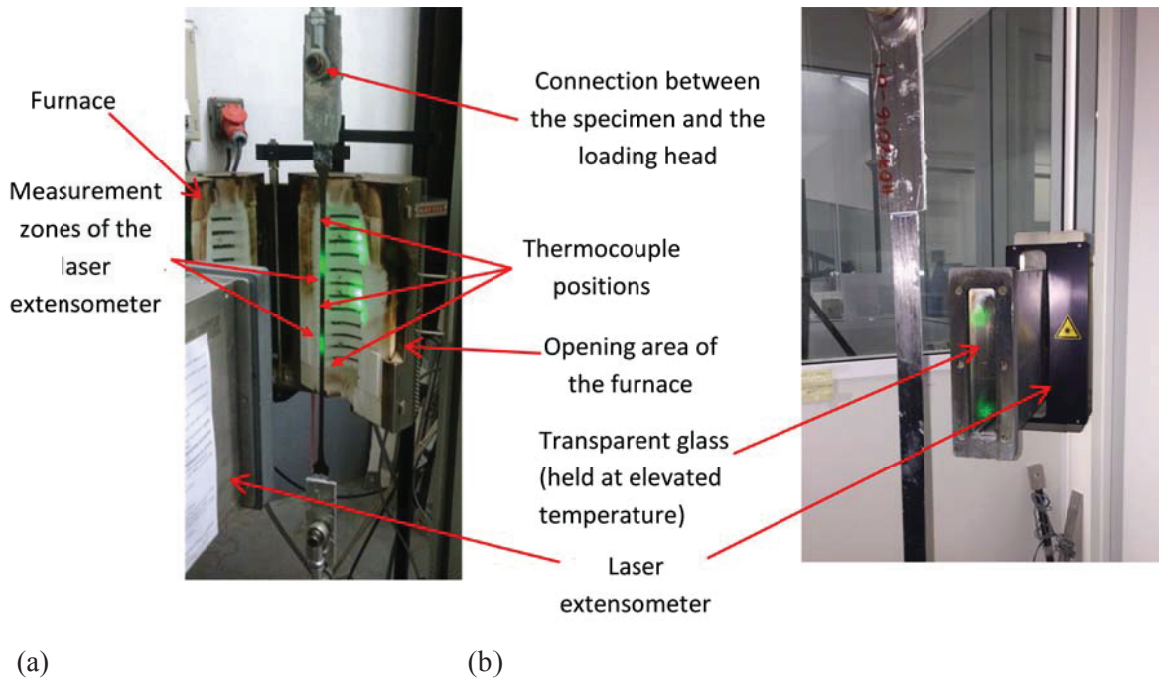


Figure 56: Measurement of the longitudinal strain of a P-CFRP specimen (by the laser extensometer); (a) Test at elevated temperature; (b) Side face view of the laser extensometer

2.2.3. Thermocouples

In this experiment, six thermocouples are used to measure and control the temperature during the test. Three thermocouples located on the inside wall of the heating chamber are used by the testing programme to control the furnace temperature, and three others are attached to the surface of the test sample (Figure 55, Figure 56a), equidistant from the middle of the furnace, to measure the real-time surface temperature of the sample.

2.2.4. Ball-joint loading heads

Figure 55 shows the configuration of a specimen placed in the middle of the furnace and tied with two ball-joint loading heads (Figure 57). The ball-joint loading head, suggested in previous studies (Contamine et al., 2011; Nguyen et al., 2016), allows for good characterization of the tensile behaviour of carbon fibre reinforced polymer (CFRP). This loading system allows hinging, which will minimize the bending effects caused by imperfect installation. This system will equally distribute the tensile loading to carbon fibres by guaranteeing that the CFRP specimen be axially loaded during the experimental test.



Figure 57: Ball-joint loading head and thermally insulated furnace

2.3. Test programs

In this research, the CFRP will be tested following three test processes, a residual test (RR) and two thermo-mechanical test which are thermo-mechanical test 1: static thermal test and thermo-mechanical test 2: static mechanic test . These three processes are described as follows.

2.3.1. Residual test (RR)

The purpose of this test is to identify the mechanical behaviour at the ambient temperature of the material after being exposed to a high temperature condition and then naturally cooled. Figure 58 shows the residual loading path used to test P-CFRP, consisting of four phases: a thermal loading phase, a thermal exposure at target loading phase, a thermal release phase and a residual loading phase. These four phases are described as follows.

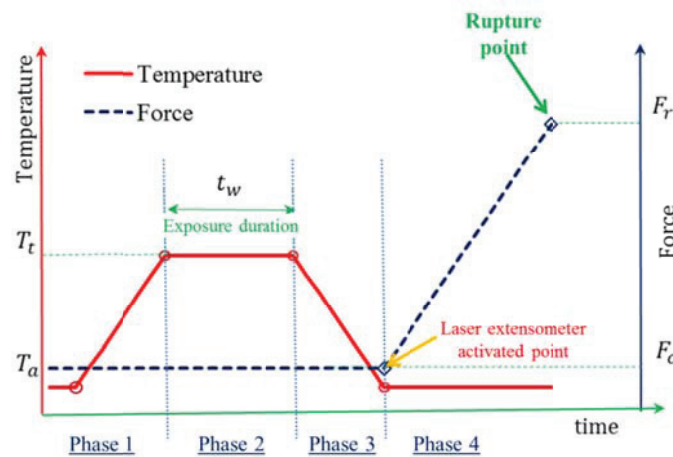


Figure 58: Residual test (RR)

Where: T_a : ambient temperature; T_t : target temperature; F_r : rupture force; t_w : exposure duration time (waiting time); F_c : control force; F_r : Rupture force

2.3.1.1. *Phase 1 - Thermal loading*

In this phase (Figure 58), the temperature surrounding the sample is steadily increased up to the target temperature, T_t (Figure 58) which is then maintained during the testing time. In this study, T_t ranges from 200°C to 700°C. The sample is first set up in the furnace. Then, a small initial control force ($F_c \sim 100\text{N}$, Figure 58) is applied to the specimen to generate the tensile status. The tensile force is programmed to increase and decrease between an upper value of 300N and a lower value of 100N. This cycle repeats 5 times to assure the sample is stable and axial. Next, the furnace begins heating the environment until the temperature reaches the target temperature. To maintain good operation and a homogeneous temperature during the test, the ramp rate is set between 7°C /min and 22°C /min, depending on the target temperature (Table 5). Based on these rates, the furnace takes approximately 30 minutes to reach its target temperature. The glass transition temperature (T_g) of the polymer matrix is between 100-125°C, and its combustion temperature (T_c) is approximately 350-400°C. Therefore, when the sample portion inside is heated to T_c , the polymer oxidation process starts and releases smoke while the carbon fibre remains intact. Therefore, in tests with $T_t > T_c$, when the temperature reaches T_c , smoke is emitted which may affect the laser extensometer. For that reason, an insulation barrier is used to block the side opening of the furnace. This helps reduce heat loss and diminishes thermal threats to the laser extensometer.

Table 5: Heating rates and corresponding ramp rates

Target temperature (°C)	100	200	300	400	500	600	700	800	900-1200
Ramp rate (°C/minute)	3	6	10	13	16	20	23	26	30

2.3.1.2. *Phase 2 - Thermal exposure at target loading*

In this second phase, the temperature surrounding the sample will be maintained at the target temperature for a predetermined period of time. During this stage, the furnace will keep providing energy to compensate for natural heat loss in order to maintain a stable temperature. When the CFRP material experiences thermal expansion, the mechanical part is programmed to compensate for the tension release and maintain the applied force at the established level. During this phase, due to the polymer oxidation, the released smoke continues to diffuse and prevents the laser extensometer from effectively tracking the sample surface. To obtain reliable laser extensometer measurements, it is necessary to wait until the polymer matrix inside the heating chamber has completely burned. For the pultruded CFRP sample, the polymer oxidation process normally occurs within 30 minutes after the target temperature is reached. In this study, to ensure both a homogenous environment around the specimen and clear visibility for the strain measurement, the duration of the thermal exposure is set at 60 minutes.

2.3.1.3. *Phase 3 - Thermal release*

In this phase (Figure 58), after being exposed to the target temperature for a predetermined period of time, the temperature surrounding the sample then naturally decreases until it reaches room temperature. The furnace is turned off to stop providing energy to the heating chamber while the heat continues to dissipate. As a result, the temperature surrounding the specimen naturally decreases until it reaches room temperature. Meanwhile, the applied tensile load is maintained until the cooling process has completely finished.

2.3.1.4. Phase 4 - Residual loading

In this phase (Figure 58), after the temperature surrounding the sample returns to room temperature, the applied uni-axial tensile load monotonically increases until the specimen ruptures. At the beginning of this phase, the insulation barrier on the sidewall of the furnace is removed and the laser extensometer is attached to the sidewall opening of the furnace. It is then activated and ready for recording strain data. During the mechanical loading process, the tensile strain is measured by the laser extensometer. It is identified as the residual axial tensile strain since it is the result of a mechanical effect (tensile load increase) obtained from the specimen after being heated and naturally cooled. The maximum strain value is identified as the ultimate residual strain ($\epsilon_{U,RR}$) corresponding to the rupture point at the target temperature. This residual axial tensile strain is also used to calculate Young's modulus for each preheated temperature level (E_{RR}).

2.3.2. Thermo-mechanical test 1: static thermal test (TM1)

This test is to identify the materials mechanical behaviour while the material is exposed to a high temperature. Figure 59 shows the thermo-mechanical loading path used to test pultruded CFRP in this research, including three phases: the thermal loading phase, the thermal exposure at target loading phase and the thermo-mechanical loading phase. These three phases are detailed as follows.

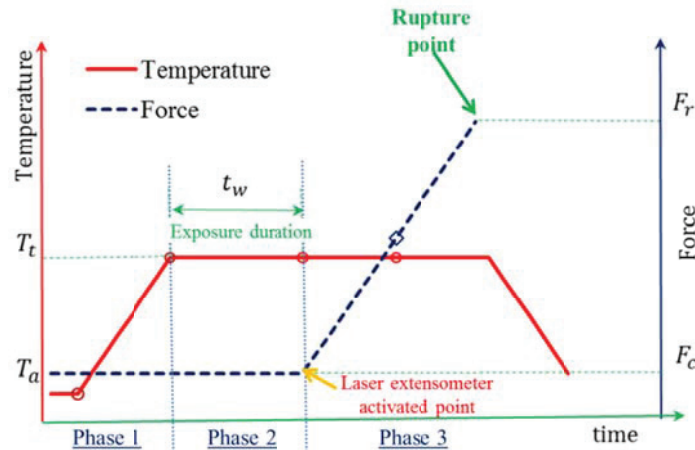


Figure 59: Thermo-mechanical test 1: the constant thermal load (TM1)

Where: T_a : ambient temperature; T_t : target temperature; F_r : failure force; t_w : exposure duration time; F_c : control force; F_r : rupture force.

2.3.2.1. Phase 1- Thermal loading

In this phase (Figure 59), the temperature surrounding the sample is steadily increased up to the target temperature, T_t (Figure 59) which is then maintained during the testing time. In this study, T_t ranges from 200°C to 700°C. At the beginning of this phase, after the sample is set up in the furnace, a small initial control force ($F_c \sim 100\text{N}$, Figure 59) is applied to the specimen to generate the tensile status. The tensile force is programmed to increase and decrease between an upper value of 300N and a lower value of 100N. This cycle repeats 5 times to assure the sample is stable and axial. Next, the furnace begins heating the environment until the temperature reaches the target temperature. To maintain good operation and a homogeneous temperature during the test, the ramp rate is set between 7°C /min and 22°C /min, depending on the target temperature (Table 5). Based on these rates, the furnace takes

approximately 30 minutes to reach its target temperature. The glass transition temperature (T_g) of the polymer matrix is between 100-125°C, and its combustion temperature (T_c) is approximately 350-400°C. Therefore, when the sample portion inside is heated to T_c , the polymer oxidation process starts and releases smoke while the carbon fibre remains intact. Therefore, in tests with $T_t > T_c$, when the temperature reaches T_c , smoke is emitted which may affect the laser extensometer. For that reason, an insulation barrier is used to block the side opening of the furnace. This helps reduce heat loss and diminishes thermal threats to the laser extensometer.

2.3.2.2. Phase 2 - Thermal exposure at target loading

In this second phase, the temperature surrounding the sample will be maintained at the target temperature for a predetermined period of time. During this stage, the furnace will keep providing energy to compensate for natural heat loss in order to maintain a stable temperature. When the CFRP material experiences thermal expansion, the mechanical part is programmed to compensate for the tension release and maintain the applied force at the established level. During this phase, due to the polymer oxidation, the released smoke continues to diffuse and prevents the laser extensometer from effectively tracking the sample surface. To obtain reliable laser extensometer measurements, it is necessary to wait until the polymer matrix inside the heating chamber has completely burned. For the pultruded CFRP sample, the polymer oxidation process normally occurs within 30 minutes after the target temperature is reached. In this study, to ensure both a homogenous environment around the specimen and clear visibility for the strain measurement, the duration of the thermal exposure is set at 60 minutes.

2.3.2.3. Phase 3 - Thermo-mechanical loading

During this phase, the applied uniaxial tensile load acting on the specimen monotonically increases until the rupture of the sample, while the temperature is maintained at the target level. After the duration of thermal exposure, the insulation barrier on the sidewall of the furnace is removed and the laser extensometer is attached to the sidewall opening of the furnace. It is then activated and ready for recording strain data. During this phase, the temperature in the heating chamber is maintained at a constant level, and the visibility inside the heating chamber is clear to allow the laser extensometer to measure the correct strain data. At the beginning of this phase, a force is applied cyclically 5 times to assure the stability and axial position of the sample. Next, a quasi-static, monotonous force is applied and increases until the specimen ruptures. This increase is controlled by the transverse of the testing machine (Figure 55a) with a movement speed of 300 $\mu\text{m}/\text{min}$ to prevent distortion effects to the laser extensometer image of the sample surface during the loading process at elevated temperature (this loading speed is selected based on the “ISO 527: Plastics — Determination of tensile properties”). When the applied force suddenly drops more than 50%, the loading process stops and the peak value is recorded as the rupture force. This rupture force is identified as the ultimate force that acts on the sample at the target temperature, which is then used to calculate the ultimate thermo-mechanical stress of the CFRP ($\sigma_{U, TM}$). During the mechanical loading process, the tensile strain is measured by the laser extensometer. This strain is identified as the thermo-mechanical axial tensile strain, which is the result of both a mechanical effect (tensile loading increase) and a thermal effect (steady target temperature). The maximum value of this strain is identified as the ultimate thermo-mechanical strain ($\varepsilon_{U, TM}$) corresponding to the rupture point at the target temperature. This strain is also used to calculate Young's modulus for each temperature level (E_{TM}).

2.3.3. Thermo-mechanical test 2: static mechanic test (TM2)

This test identifies the material's heat-resistant limit, while the material is subjected to a predetermined mechanical load. The objective of this test is to investigate the evolution of the thermal performance of M-CFRP at different mechanical load states. In this test, the mechanical test is first applied, and then the temperature is adjusted. Figure 60 shows the second thermo-mechanical loading path used to test M-CFRP in this research, including two phases: mechanical loading and thermal loading, which are detailed as follows.

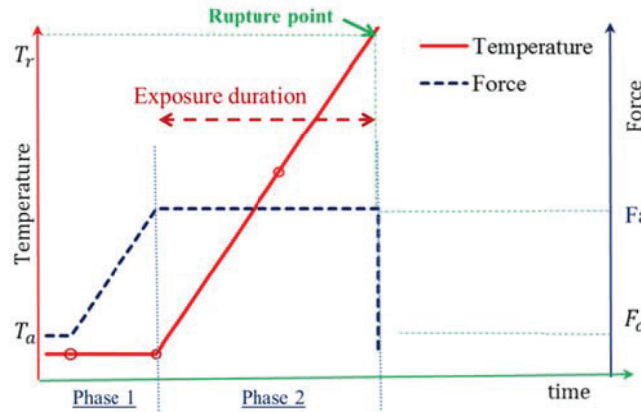


Figure 60: Thermo-mechanical test 2: the constant mechanical load (TM2),

Where T_a is the ambient temperature; T_r is the failure temperature; F_c is the control force; and F_w is the applied force.

2.3.3.1. Phase 1: mechanical loading

At the beginning of this phase, after the sample is set up in the furnace, a small initial control force ($F_c \sim 100\text{N}$, Figure 60) is applied to the specimen to generate the tensile status. The tensile force is programmed to increase and decrease between an upper value of 300N and a lower value of 100N. This cycle repeats 5 times to ensure that the sample is stable and axial. Then, the applied uniaxial tensile load acting on the specimen monotonically increases until reaching a applied force (F_w , Figure 60) with a movement speed of $300 \mu\text{m/min}$ to maintain the stability of the sample. The ratio between the applied stress and the average ultimate strength of M-CFRP at 20°C , obtained from the TM2 test, is identified as the stress ratio. In this test, the stress ratio varies between 0.1, 0.25, 0.5, 0.6, and 0.75.

2.3.3.2. Phase 2: thermal loading

As in ISO 834 (ISO-834, 1999), the standard evolution of the temperature with the function of time during a fire is described by Equation 1 (where t is time in minutes and T is temperature in Celsius degrees). Initially, the temperature increases rapidly, with the heat rate up to 111°C/minute in the first 5 minutes. The heat rate is reduced to 20°C/minute and 12°C/minute in the following 10 minutes and 15 minutes, and the temperature reaches 842°C after 30 minutes (Figure 61). For the above reason, to simulate the temperature conditions of a fire, it is better to have the average temperature in the furnace follow the relationship, as in Figure 61. Although the maximum heating rate of the used furnace is 30°C/minute , which is lower than the heat rate in the first 5 minutes of the ISO-834 curve (Figure 61), at this heat rate, the furnace can monitor and control the temperature reaching 900°C in 30 minutes.

Therefore, in this second phase, while F_w is maintained, the average temperature of the furnace surrounding the specimen increases from ambient temperature until failure of the specimen at a programmed heat rate of $30^\circ\text{C}/\text{minute}$. The temperature at which the specimen is broken is identified as the failure temperature (T_r), corresponding to the load level F_w and the duration from the beginning of the increasing temperature until the failure of the specimen is identified as the exposure duration corresponding to load level F_w .

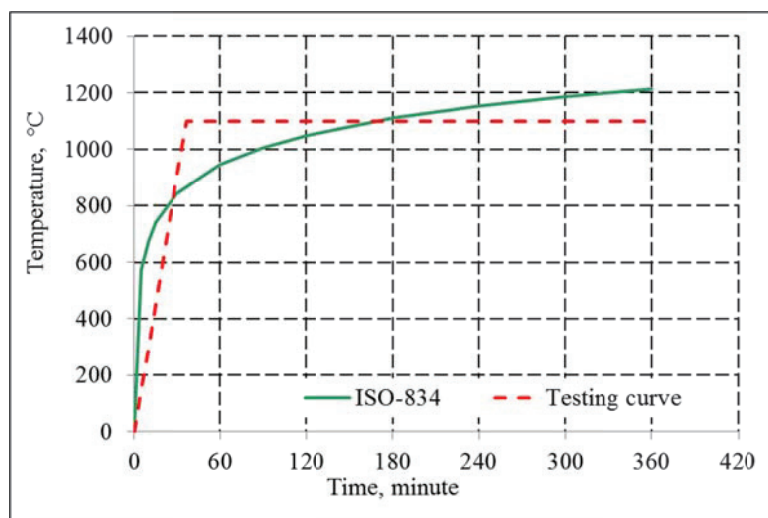


Figure 61: Standard fire curve and programmed temperature-time curve.

2.4. Presentation of the used materials

This subsection firstly describes pultruded CFRP and then manually- fabricated CFRP.

2.4.1. Pultruded CFRP

This section describes the studied P-CFRP material, including a description of the samples used and their preparation.

2.4.1.1. Material descriptions

In this research, the studied CFRP samples are commercial pultruded carbon fibre reinforced plates containing 68% carbon fibre (supplier's data). According to the product specification, the tensile strength is 2800 MPa and Young's modulus at ambient temperature is 165 GPa (supplier's data). The glass transition temperature of this CFRP, T_g , is above 100°C (supplier's data). The standard dimensions of this commercial product are 1.2 mm thick, 50 mm wide and 25 m long.

2.4.1.2. Sample description

Figure 62 shows the configuration of the test samples used in this research. Due to the dimensions of the heating chamber, the loading capacity of the mechanical testing system and its test sample limitations, the test sample dimensions were chosen to be 800 mm long, 6-8 mm wide and 1.2 mm thick. In a tensile test, the sample is normally placed in middle with the two ends gripped by the two clamps of the machine. The tensile axial force is transmitted to the sample by the friction of the contacted regions between the clamps and the sample. However, the tensile strength of pultruded

CFRP is much greater than the friction force. Thus, in order to better effectively transmit the tensile force from the mechanical parts to the CFRP material, two aluminium plates are attached to each end using an epoxy adhesive (Eponal 380) with shear resistance, tensile resistance and compression resistance of 15 MPa, 29.5 MPa and 83 MPa, respectively. The smooth surface of pultruded CFRP used in this research leads to low adhesive bond strength and consequently, the sample is prone to anchorage failure. For a tensile test of tendon CFRP, Wang Y.C. et al. (Tranchard et al., 2015) used expansive confined cement in a circular steel tube to reduce the occurrence of anchorage failure. Testing with a thin plate of textile concrete, R. Contamine et al. (Contamine et al., 2011) used bolts to support the aluminium plates and ensure that the failure will occur in the centre of the specimen, not in the anchorage region. For the previously mentioned reasons, in this research, aluminium plates are used to reinforce the two ends of the sample for the test at elevated temperature (Figure 62b). With the test at low testing temperatures, because the remaining tensile strength is high, reinforced bolts are used to improve the holding capacity of the plates (Figure 62a).

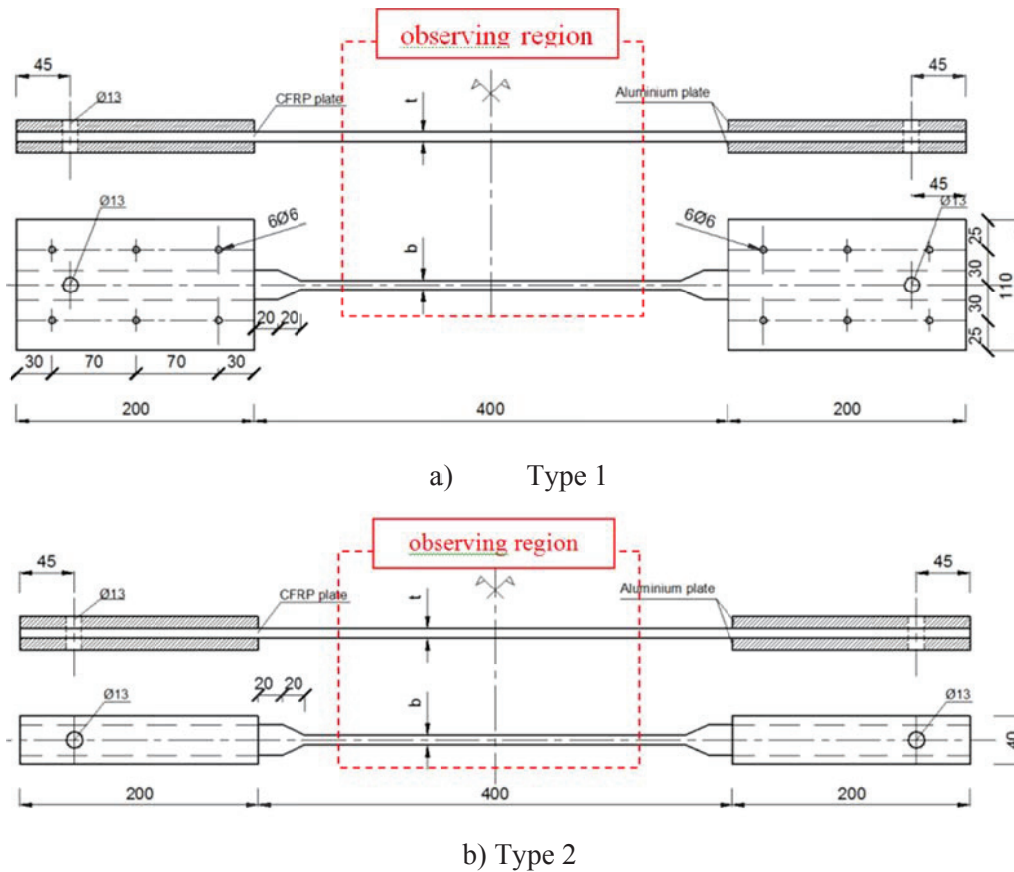


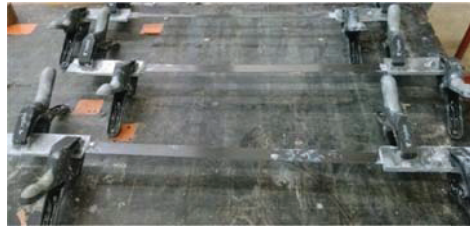
Figure 62: Configuration of the pultruded CFRP specimen (thickness: $t=1.2$ mm; width: $b=6-8$ mm)

a) Type 1: used for the test at low temperature; b) Type 2: used for the test at elevated temperature

2.4.1.1. Sample preparation

Figure 63 shows the preparation of the testing samples. The roll of commercial pultruded CFRP is first cut to 800 mm, 25 mm in length and width. The aluminium plates are then attached to the CFRP material using adhesive (Figure 63a, b). The CFRP specimen is then trimmed down to the design

dimensions (800 mm long and 6-8 mm wide) to fit in the TM20kN-1200C machine (Figure 55). Figure 63c,d show the completed samples ready for testing, both with and without supporting bolts.



a) Attaching the aluminium plates;



b) Samples after the waiting period



c) Samples ready for testing with supporting bolts;



d) Samples without supporting bolts

Figure 63: Sample preparation process

2.4.2. Manually-fabricated CFRP

Manually-fabricated FRP (or in-situ FRP, Hand lay-up or wet lay-up FRP) is FRP made following Wet/Hand lay-up process in which resins are impregnated by hand into fibres which are in the form of woven, knitted, stitched or bonded fabrics. This can be accomplished by rollers or brushes, with an increasing use of nip-roller type impregnators for forcing resin into the fabrics by means of rotating rollers and a bath of resin. In civil engineering, laminates are left to cure under standard atmospheric conditions. Generally, the used resins can be vary as epoxy, polyester, vinyl-ester, phenolic and fibres can be glass, carbon, aramid or flax fibre depending on the used purpose. The main advantages of this type FRP are: widely used for many years; simple principles to train; low cost tooling (under room-temperature curing condition) used; and variety in choice of suppliers and material types. In this study, the studied material (Manually-fabricated CFRP or M-CFRP) is made from carbon textile impregnated with two components epoxy. The material is popular used in civil engineering in strengthening/ repairing/ retrofitting structure such as concrete beams, columns or walls.

2.4.2.1. M-CFRP composition

The M-CFRP in this research was manually produced in the laboratory by applying the polymer matrix to one layer of one-direction carbon textile (Figure 22). The M-CFRP contains 25.3% of fibre (in volume) and is produced in the laboratory (based on average weight and dimension of produced

specimens measured in laboratory condition). The detailed properties of the carbon textile and polymer matrix are described in the following section.

2.4.2.2. *Carbon textile*

The carbon textile used includes non-twisted filaments. It is commonly used in high tensile applications such as pressure vessels, recreation, industry and engineering. According to datasheet from supplier, the tensile strength and modulus of this carbon fibre are 4900 MPa and 230 GPa, respectively, and its critical strain is 2.1%. The diameter of each filament is 7 μ m, and its density is 1.8 g/cm³. The standard dimension of the carbon textile is 1 m in width and 0.32 mm in thickness (310 g/m²), including approximately 3.7 carbon fibre yarns with a 1 cm long cross-section. Each yarn includes 12000 carbon filaments and its surface is pre-treated with resin compatibility epoxy. In civil engineering, this type of carbon fibre is used to repair/strengthen/retrofit structures with complicated shapes, such as confined-strengthening round columns, walls, shear strengthening in beams, or even bending-reinforcing for beams/slabs. To apply the M-CFRP on a structure, the carbon textile is wrapped or stretched along the structure surface, and the polymer is swept between the carbon textile and substrate surface or between the carbon layers.

2.4.2.3. *Polymer matrix*

The used polymer is a two-component epoxy with a mixed product density at 20°C and is 1.11 g/cm³. According to supplier's data, the material properties are as in the Table 6 (according to ASTM method).

Table 6: Epoxy material properties at 21 °C (datasheet)

Material property	ASTM method	Test value
T _g	D4065	82°C
Tensile Strength	D638	72.4 MPa
Tensile Modulus	D638	3.18 GPa
Elongation Percent	D638	5.0%
Compressive Strength	D695	86.2 MPa
Compressive Modulus	D695	3.2 GPa
Flexural Strength	D790	123.4 MPa
Flexural Modulus	D790	3.116 GPa

2.4.2.4. *Sample preparation*

In the laboratory, the carbon textile was prepared in a single layer and was 1 m in length and 0.5 m in width (according to the fibre direction, Figure 64). The textile was then stretched, fixed in the flat plate formwork and applied with a polymer matrix afterwards. A minimum curing duration at 72 hours for polymer at 60°C is required. However, due to the application situation, which is unable to attain this temperature condition with real scale structures. Moreover, according to Cree et al., the tensile strength and Young's modulus of M-CFRP at elevated temperature are little influenced by the curing temperature (Cree et al., 2015). For these reasons, the M-CFRP is produced and cured with room temperature condition in 7 days in a laboratory (Figure 65). The preparation of M-CFRP in this study was also made according to the preparation procedure established by the supplier of materials (carbon textile and polymer matrix). Based on the material consumption, the fibre volume ratio of this

manually fabricated CFRP (M-CFRP) is identified as approximately 25.33% (from measured weight and dimension).

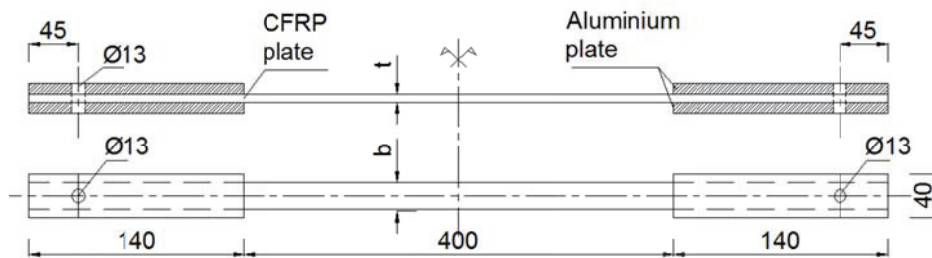


Figure 64: Unidirectional carbon textile.



Figure 65: Manually fabricated CFRP (M-CFRP).

Figure 66 displays the details of M-CFRP specimens that are used in this research. Due to the dimensions of the heating chamber (furnace, Figure 56) and the loading capacity of the mechanical testing system, the test sample dimensions were chosen as follows: 4 yarns in width (approximately 7 mm) and 740 mm in length (Figure 66a). To more effectively transmit the tensile force from the mechanical parts to the M-CFRP material, two aluminium plates are attached to each end using a two-component epoxy adhesive (Eponal 380) with shear resistance, tensile resistance and compression resistance of 15 MPa, 29.5 MPa and 83 MPa, respectively (datasheet).



a) Dimension of sample



b) Sample ready for testing

Figure 66: Detailed M-CFRP specimen.

In a tensile test, the sample is normally placed in the middle with the two ends gripped by the two friction clamps of the machine. The tensile axial force is transmitted to the sample by the friction from the contacted regions between the clamps and the sample. However, the limit dimension of the contact region and the smooth surface of M-CFRP can lead to anchorage failure due to insufficient friction

force (compared to the tensile strength of the testing material). To reduce the anchorage failure in the CFRP circular tendon, Wang Y.C. et al. (Wang et al., 2007) proposed using expansive confined cement in a circular steel tube. In tests with thin P-CFRP specimen (Phi Long et al., 2016), bolts to support the aluminium plates were used to ensure that failure will occur in the middle of the specimen, not in the anchorage region. In this research, based on the material properties, two aluminium ends are used to increase the bond effect between the M-CFRP specimen and loading head. A hole is drilled in each aluminium end to connect the specimen to two traverses via two ball-joint loading heads (Figure 57).

2.5. Test summary

This subsection presents test summary on pultruded CFRP and manually-fabricated CFRP.

2.5.1. Pultruded CFRP

There are 53 tests categorized into four groups: 8 tests at 20°C to verify the mechanical properties of pultruded CFRP at room temperature; 12 tests following the residual procedure and 22 tests following the thermo-mechanical test 1 to identify the evolution of the mechanical properties of P-CFRP under the two studied conditions; And finally, 11 tests following the thermo-mechanical test 2 to identify the evolution of thermal resistance at different mechanical loading conditions. The sample naming convention is in the form of “P.x.y.n” in which “P” indicates P-CFRP, “x” represents the test procedure, “y” indicates the temperature level (for RR and TM1) test and the mechanical load ratio in percentage (for TM2 test), and “n” gives the test number. The sample type is as described in Figure 62. During heating, the selected ramp rate is as shown in Table 5. The data (strain, loading and temperature) are recorded as explained in the equipment section. Table 7 lists the tests conducted in this study.

Table 7: Summary of the residual test (RR), thermo-mechanical test 1 (TM1) and thermo-mechanical test 2 (TM2) of P-CFRP

a) Summary of the the residual test (RR), thermo-mechanical test 1 (TM1)

Sample	Sample type	Test procedure	Temperature	Exposure duration time	Number of test
	1/2	RR/TM1/TM2	(°C)	minute	
P.O.20.1-8	1	-	20	-	8
P.RR.200.1-4	1	RR	200	60	4
P.RR.400.1-4	2	RR	400	60	4
P.RR.500.1	2	RR	500	60	1
P.RR.550.1	2	RR	550	60	1
P.RR.600.1-2	2	RR	600	60	2
P.TM1.200.1-5	1	TM1	200	60	5
P.TM1.400.1-9	2	TM1	400	10-90	9
P.TM1.500.1-3	2	TM1	500	60	3
P.TM1.550.1	2	TM1	550	60	1
P.TM1.600.1-3	2	TM1	600	60	3
P.TM1.700	2	TM1	700	60	1

b) Summary of the the thermo-mechanical test 2 (TM2)

Sample	Sample type	Test procedure	Stress ratio	Heating rate	Number of test
	1/2			°C /minute	
P.TM2.10.1-2	2	TM2	0.1	30	2
P.TM2.25.1-6	2	TM2	0.25	2-30	6
P.TM2.50.1-2	2	TM2	0.5	30	2
P.TM2.68.1	2	TM2	0.68	30	1

2.5.2. Manually-fabricated CFRP

In the following, the summaries of conducted tests with M-CFRP in this study are presented (Table 8). There are 33 tests divided into four groups: 3 test at 20°C to verify the mechanical properties of M-CFRP at room temperature; 6 tests following the residual procedure and 9 tests following the thermo-mechanical test 1 to identify the evolution of the mechanical properties of M-CFRP under the two studied conditions; and 15 tests following the thermo-mechanical test 2 to identify the evolution of thermal resistance at different mechanical loading conditions. The “M.x.y.n” format of sample’s name starts with M to indicate M-CFRP material and the x, y, n are as description in the tests with P-CFRP above.

Table 8: Summary of the residual test (RR), thermo-mechanical test 1 (TM1) and thermo-mechanical test 2 (TM2) of M-CFRP

a) Summary of the the residual test (RR), thermo-mechanical test 1 (TM1)

Sample	Sample type	Test procedure	Temperature	Exposure duration time	Number of test
	1/2			(°C) minute	
M.O.20.01-03	2	-	20	-	3
M.RR.200.01-03	2	RR	200	60	2
M.RR.400.01-03	2	RR	400	60	2
M.RR.600.01-03	2	RR	600	60	2
M.TM1.200.01-03	2	TM1	200	60	3
M.TM1.400.01-03	2	TM1	400	60	3
M.TM1.600.01-03	2	TM1	600	60	3

b) Summary of the the thermo-mechanical test 2 (TM2)

Sample	Sample type	Test procedure	Stress ratio	Heating rate	Number of test
	1/2			°C /minute	
M.TM2.10.01-03	2	TM2	0.10	30	3
M.TM2.25.01-03	2	TM2	0.25	30	3
M.TM2.50.01-03	2	TM2	0.50	30	3
M.TM2.60.01-03	2	TM2	0.60	30	3
M.TM2.75.01-03	2	TM2	0.75	30	3

2.6. Test results

This subsection describes obtained results on pultruded CFRP and manually-fabricated CFRP.

2.6.1. Pultruded CFRP

The test ends when the specimen fails. In almost all tests, failure occurs in the observation region (Figure 62) where the laser is directed (defined as MB in Table 9, 10 and 11), not in the anchorage region with the aluminium plates (defined as AB in Table 9, Table 11 and Table 10). In tests with MB failure, the maximum value of the force that occurs around the time of failure is identified as the ultimate force and used to calculate the ultimate stress. The stress-strain correlation is then used to identify Young's modulus for the material. In the tests with AB failure, because the P-CFRP material is not damaged, the stress corresponding to the rupture point does not represent the ultimate strength. However, Young's modulus of the material can be estimated using the stress-strain correlation before the rupture.

The experimental results are described in the following sections: tensile tests at 20°C, thermo-mechanical tests, residual tests, stress-strain relationship, evolution of the ultimate strength and the Young's modulus of P-CFRP according to temperature, effect of thermal exposure duration on thermo-mechanical properties of P-CFRP at 400°C and failure modes. A discussion of the experimental results is also presented.

2.6.1.1. Tensile tests at 20°C

Table 9 displays the detailed results of direct tensile tests at 20°C. The purpose of this test series is to identify the mechanical properties of P-CFRP at ambient temperature as well as validate the specification of the experimental procedure. In this test series, the material fails at stresses between 2051 MPa and 2618 MPa. Due to their high tensile strength, 6 of the 9 specimens failed at the aluminium position. The stress-strain curves at 20°C show a linear trend (see typical curve in Figure 67). Young's modulus varied between 144 GPa and 172 GPa for both the centre sample failure position (MB) and the aluminium failure position (AB) as shown in Table 9.

Table 9: Detailed result of tests at 20°C; MB: failure at the centre position; AB: failure at the aluminium position; NA: not available

Test No	Sample	Temperature	Rupture type	Ultimate stress	Young's modulus
		(°C)	MB/AB	(MPa)	(GPa)
1	C.20.01	20	AB	NA	143.7
2	C.20.02	20	MB	2051.1	147.1
3	C.20.03	20	AB	NA	155.5
4	C.20.04	20	AB	NA	151.9
5	C.20.05	20	AB	NA	156.1
6	C.20.06	20	MB	2618.2	161.3
7	C.20.07	20	AB	NA	168.0
8	C.20.08	20	MB	2498.9	172.3

2.6.1.2. *Residual tests*

Table 10 summaries the residual properties in the temperature range between 200°C and 600°C. The residual ultimate stress ranges from approximately 1865-1912 MPa at 200°C to 1400-1492 MPa at 400°C. At 500-550°C and 600°C, these values are approximately 1080-1140 MPa and 394-398 MPa, respectively. Among the 8 specimens heated between 200°C and 400°C, 3 samples failed at the aluminium position (AB), and thus the corresponding rupture stresses do not represent their residual ultimate stresses at these temperature levels. The results also show that the residual Young's modulus at 200°C, 400°C and 500°C do not vary much, approximately 160-180 GPa, 159-165 GPa and 155 GPa, respectively. At 600°C, the Young's modulus value is much lower, 46 GPa. The axial strain of the samples heated at high temperature (from 400°C to 600°C) is difficult to obtain due to the instability of the retained near-surface fibres during the tensile loading step.

Table 10: Details of residual tests (RR) from 200°C to 600°C; MB: failure at the centre position; AB: failure at the aluminium position; NA: not available

Test No	Sample Name	Temperature	Rupture type	Ultimate stress	Elastic modulus	Waiting time
		(°C)	(MB/AB)	(MPa)	(GPa)	(minute)
1	C.RR.200.01	200	AB	NA	179.9	60
2	C.RR.200.02	200	AB	NA	164.6	60
3	C.RR.200.03	200	MB	1865.1	172.9	60
4	C.RR.200.04	200	MB	1913.1	160.2	60
5	C.RR.400.01	400	MB	1378.7	NA	60
6	C.RR.400.02	400	AB	NA	165.1	60
7	C.RR.400.03	400	MB	1491.9	NA	60
8	C.RR.400.04	400	MB	1399.9	158.8	60
9	C.RR.500.01	500	MB	1139.0	154.6	60
10	C.RR.550.01	550	MB	1080.3	NA	60
11	C.RR.600.01	600	MB	393.8	NA	60
12	C.RR.600.02	600	MB	397.9	46.1	60

2.6.1.3. *Thermo-mechanical test 1 (TM1)*

Table 11 summaries the thermo-mechanical properties of P-CFRP for the temperature range between 200°C to 700°C. According to Figure 59, the thermo-mechanical ultimate strength at 200°C is higher than 1630-1640 MPa, reducing to approximately 1000-1100 MPa at 400°C, at 60 minutes of waiting time. At 500°C, 550°C and 600°C, these values are approximately 610-840 MPa, 390 MPa and 80-100 MPa, respectively. At 700°C, the material fails due to the oxidation of CFRP after the temperature in the heating room reaches 700°C for 8 minutes. At 200°C, 3 of 5 test samples failed at the aluminium position (AB). The collected stress-strain curves show linear behaviour (a typical curve is shown in Figure 67). Table 11 shows that Young's modulus for P-CFRP at 200°C varies between 137 GPa and 176 GPa. These values at 400°C vary between 152-165 GPa, 126-146 GPa, 144-156 GPa and 143 GPa in tests with waiting times of 10, 30, 60 and 90 minutes, respectively. At a temperature level of 500°C, Young's modulus for P-CFRP is reduced to approximately 117 GPa, and steadily falls to approximately 16 GPa at 600°C. After the polymer matrix has completely degraded

(normally above 400°C), the instability of the retained carbon fibres resulted in a failure of the laser extensometer to record the deformation in some tests.

Table 11: Details of thermo-mechanical tests I (TM1) from 200°C to 700°C; MB: failure at the centre position; AB: failure at the aluminium position; NA: not available

Test No	Sample	Temperature	Rupture type	Ultimate stress	Young's modulus	Exposure duration
		(°C)	(MB/AB)	(MPa)	(GPa)	(minute)
1	C.TM1.200.01	200	AB	NA	137.2	60
2	C.TM1.200.02	200	AB	NA	148.5	60
3	C.TM1.200.03	200	MB	1642.2	152.3	60
4	C.TM1.200.04	200	AB	NA	155.3	60
5	C.TM1.200.05	200	MB	1629.6	176.1	60
6	C.TM1.400.01	400	MB	1031.3	151.5	10
7	C.TM1.400.02	400	MB	902.8	164.6	10
8	C.TM1.400.03	400	MB	883.5	145.6	30
9	C.TM1.400.04	400	MB	1068.7	126.4	30
10	C.TM1.400.05	400	MB	1098.6	143.8	60
11	C.TM1.400.06	400	MB	1113.3	157.5	60
12	C.TM1.400.07	400	MB	1042.0	NA	60
13	C.TM1.400.08	400	MB	938.8	142.6	90
14	C.TM1.400.09	400	MB	1010.0	NA	90
15	C.TM1.500.01	500	MB	839.9	116.7	60
16	C.TM1.500.02	500	MB	609.9	NA	60
17	C.TM1.500.03	500	MB	643.8	NA	60
18	C.TM1.550.01	550	MB	392.7	NA	60
19	C.TM1.600.01	600	MB	73.5	16.7	60
20	C.TM1.600.02	600	MB	99.9	15.9	60
21	C.TM1.600.03	600	MB	79.5	NA	60
22	C.TM1.700.01	700	MB	0.0	NA	8

2.6.1.4. Thermo-mechanical test 2 (TM2)

Table 12 summaries details of P-CFRP specimens and the thermal performance including the failure temperature, exposure duration and actual heating rate of each conducted test in TM2 condition. In each test, the failure temperature is determined when the mechanical load that is applied drops by approximately 50% (in all tests, this drop quickly occurs with a magnitude of more than 50%). The exposure duration in this test is determined as the duration between the point at which the temperature starts to increase and the failure temperature. For the TM2 regime, the test starts from the room conditions, where the temperature can vary between 15°C and 25°C in the daytime. Furthermore, the temperature inside the furnace rises slowly at the beginning of each test at a low heating rate. In experimental test, the rise then becomes stable after the temperature reaches 30°C and maintains its rate until failure. Therefore, in this study, the start point for tests in the TM2 regime is chosen at 35°C to guarantee that the furnace is stably and effectively operating, and the end point is when the

specimen fails. Based on this, the average heating rate in this table is then determined and presented in Table 12. Because the high heating rate in the TM2 leads to smoke leakage, which can influence the precision of the laser extensometer, this device is deactivated, and there is no local deformation data except the global deformation obtained from two traverses.

As can be seen in Table 12, both the failure temperature and the exposure duration reduce as the stress ratio increases. Particularly, at a low stress ratio of 0.1, the average failure temperature is approximately 699°C, and the average exposure duration is 44 minutes. This corresponds to actual heating rate from 13.3 to 16.6°C/minute. As this ratio increases to 0.25, the exposure duration is 649°C, and exposure duration is approximately 34.7 minutes (at heating rate 16.7°C/minute). At a stress ratio of 0.5, these values are 436°C with a failure temperature at 32.3 minutes with the exposure duration. These values drop to 51.7°C and 1 minute at a stress ratio of 0.75 on average, respectively.

Table 12: Details of thermo-mechanical tests² (TM2) at different stress ratios;

No	Sample	Thickness	width	Stress ratio	Failure temperature	Exposure duration	Actual HR
		mm	mm		°C	min	°C/minute
1	C.TM2.10.1	1.22	8.26	0.10	712	39.7	16.6
2	C.TM2.10.2	1.22	6.96	0.10	686	47.6	13.3
3	C.TM2.25.1	1.22	6.64	0.25	669	27.3	26.4
4	C.TM2.25.2	1.22	6.12	0.25	609	28.3	19.9
5	C.TM2.25.3	1.22	6.07	0.25	601	47.1	12.3
6	C.TM2.25.4	1.22	5.76	0.25	649	34.7	16.7
7	C.TM2.25.5	1.22	8.45	0.25	664	25.2	25.6
8	C.TM2.25.6	1.22	6.46	0.25	584	258.8	2.1
9	C.TM2.50.1	1.22	9.3	0.50	489	50.3	10.5
10	C.TM2.50.2	1.22	7.52	0.50	384	14.3	23.0
11	C.TM2.68.1	1.22	6.83	0.68	41	1.0	15.0

2.6.1.5. Failure modes

The failure mode of the P-CFRP material depends on the temperature level between 20°C and 700°C. Table 13 presents the typical failure of the P-CFRP samples that were tested at different conditions: at 20°C (Table 13a), with the RR procedure (Table 13b), the TM1 (Table 13c), and TM2 (Table 13d). According to Table 13a, at 20°C, P-CFRP exhibits a brittle failure tendency for both the matrix and the carbon fibre (failure mode A). The failure position of the carbon fibre is random along the length of specimen. At 200°C (Table 13b,c), in RR condition, P-CFRP specimens display a brittle-like failure that is similar to their failure mode at 20°C while in TM1 regime the P-CFRP display more soften failure. It is because at this point of temperature, the polymer matrix has not started to degrade but melting. Therefore, in TM1 regime, matrix is soften and its role is maintaining the cross-fibre direction skeleton for carbon fibres as well as minor tensile capacity. But in RR regime, the temperature in polymer matrix has returned room temperature and hardened, thus the failure of P-CFRP is more likely to failure mode at 20°C comparing to TM1 regime. However, the failure mode at 400°C (Table 13b,c) demonstrates that during the testing process, the polymer matrix has melted and partly degraded, maintaining only the fibre skeleton. At this temperature level, both regimes fail due to the fibre rupture with small amount of polymer left inside thread group (failure mode B). For tests

at 500°C, 550°C and 600°C (Table 13b, c), due to resin degradation, there is no resin left in the testing region or the observing region in both regimes (Figure 62). Consequently, the remaining carbon fibres are not held together and the P-CFRP is unable to maintain its typical shape and thus P-CFRP fails due to the rupture of carbon fibres under mechanical effect (failure mode C). At 700°C (Table 13c), both the polymer matrix and the carbon fibres have completely oxidized after 20 minutes of exposure to temperature under the initial applied load. Therefore, the P-CFRP fails due to the rupture of remained fibres under thermal effect (failure mode D).

According to Table 13d, when the stress ratio increases from 0.1 to 0.68, the failure mode of P-CFRP conforms to the mode D as described in the TM1 regime. This conforms well to the failure temperature at ranges from 384°C to 712°C (Table 12). At a stress ratio of 0.68, the failure mode follows the mode A in the TM1 regime (failure temperature is 41°C). This is reasonable because in the TM2 regime, the heating rate is approximately 20°C/minute-30°C/minute (Table 11d); the temperature quickly reaches the glass transition temperature and then the degradation temperature of the polymer matrix. This leads to the failure of the matrix in the performance of P-CFRP. Although the specimen temperature during the test is not homogeneous, it is thin and slender; therefore, the temperature of carbon fibres quickly reaches 200°C, at which its retained resistance is approximately 60% - 70% (Table 12) and thus leads to failure.

Table 13: Typical failure at different conditions:

Table 13a: failure at room temperature

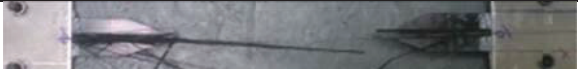
T (°C)	Sample	Failure image	Failure mode
20	P.20.6		A
	P.20.8		A

Table 13b: Typical failure of the samples tested with the RR procedure

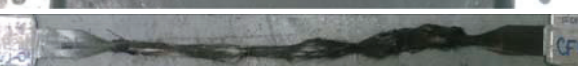
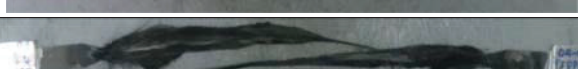
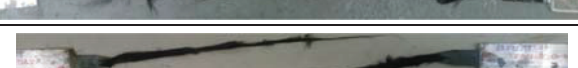
T (°C)	Sample	Failure image	Failure mode
200	P.RR.200.3		A
	P.RR.200.4		A
400	P.RR.400.1		B
	P.RR.400.4		B
500	P.RR.500.1		C
550	P.RR.550.1		C
600	P.RR.600.1		C
	P.RR.600.2		C

Table 13c : Typical failure of the samples tested with the TM1 procedure

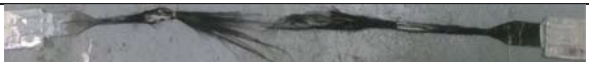
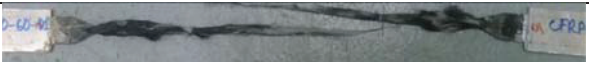
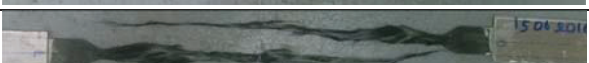
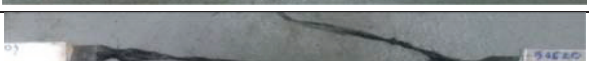
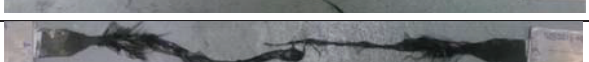
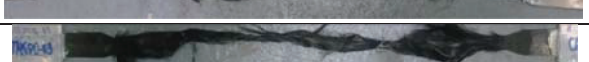
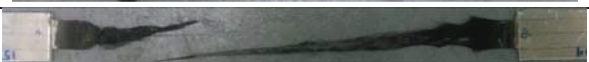
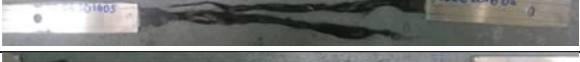
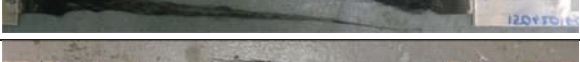
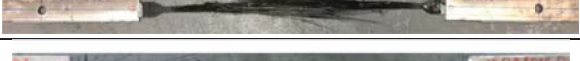
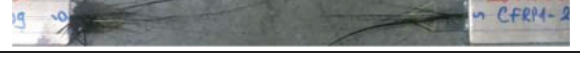
T (°C)	Sample	Failure image	Failure mode
200	P.TM1.200.3		B
	P.TM1.200.5		B
400	P.TM1.400.5		B
	P.TM1.400.6		B
500	P.TM1.500.1		C
	P.TM1.500.2		C
550	P.TM1.550.1		C
600	P.TM1.600.1		C
	P.TM1.600.3		C
700	P.TM1.700.1		D

Table 13d: Typical failure of the samples tested with the TM2 procedure

Stress ratio	Samples	Failure image	Failure mode
0.10	P.TM2.10.01		D
	P.TM2.10.02		D
0.25	P.TM2.25.01		D
	P.TM2.25.02		D
0.50	P.TM2.50.01		D
	P.TM2.50.02		D
0.68	P.TM2.68.02		A

2.6.2. Manually-fabricated CFRP

The results of the test in this series are determined as with P-CFRP. The results are divided into four groups: tests at 20°C, tests at RR, TM1 and TM2 programs. The following sections will present mentioned tests and also summary the failure modes in each tested group.

2.6.2.1. Tensile tests at 20°C

Table 14 displays the detailed results of direct tensile tests at 20°C. In this test series, the material fails at stresses between 816 MPa and 1001.3 MPa and the Young's modulus varied between 58.2 GPa and 67.9 GPa. All the specimens are broken in the middle position.

Table 14: Detailed result of M-CFRP at 20°C

No	Temp.	Sample	Thickness	Width	Failure force	Ultimate strength	Young's modulus	Retained stress ratio
-	°C	-	mm	mm	N	MPa	GPa	
1	20	M.20.01	0.72	10.87	7222	922.8	58.2	1.01
2	20	M.20.02	0.79	10.73	6921	816.5	60.6	0.89
3	20	M.20.03	0.72	10.78	7772	1001.3	67.9	1.10

2.6.2.2. Residual tests

Table 15 summaries the residual properties in the temperature range between 200°C and 600°C. The residual ultimate strength ranges from approximately 732-1044 MPa at 200°C to 535-662 MPa at 400°C and 75-119 MPa at 600°C. Whereas, the Young's modulus at 200°C is from 67.2 GPa to 74.7 GPa, at 400°C is from 37.2 GPa to 54.7 GPa at 600°C is 17.5 GPa. Similar to tests on P-CFRP, the failure strain of M.CFRP is unable to be obtained.

Table 15: Detailed result of the RR regime at different temperatures

No	Temp.	Sample	Thickness	Width	Failure force	Ultimate strength	Young's modulus	Retained stress ratio
-	°C	-	mm	mm	N	MPa	GPa	
1	200	M.RR.200.01	0.69	10.9	7849.8	1043.7	67.2	1.14
2	200	M.RR.200.02	0.73	11.67	6237.	732.1	74.7	0.80
3	400	M.RR.400.01	0.69	10.9	4021.6	534.7	37.2	0.59
4	400	M.RR.400.02	0.51	10.96	3700.6	662.1	54.7	0.72
5	600	M.RR.600.01	0.59	10.89	767.6	119.5	17.5	0.13
6	600	M.RR.600.02	0.49	10.49	385.7	75.0	-	0.08

2.6.2.3. Thermo-mechanical testing regime 1

In the following, Table 16 summarizes the results obtained from the TM1 regimes. In Table 16, the dimension of sample and the failure force obtained from each TM1 test are presented. They are then used to identify the ultimate strength corresponding to the exposed temperature based on the initial section. During the TM1 test, from the deformation data (obtained by the laser extensometer mentioned in 2.1.2) and loading data (from force sensor), the stress-strain curve at each temperature level is identified (Figure 78). Young's modulus at each temperature level is then identified from the curve slope and presented in Table 16 (based on "ISO 527").

As in Table 16, the retained stress ratio is identified as the ratio between the ultimate strength obtained at the tested temperature and the average ultimate strength obtained at 20°C (as estimated: 914 MPa, from Table 14). In test 9 of the TM1 regime, due to the technical incident, the laser

extensometer failed to record deformation of M-CFRP at 600°C; thus, Young's modulus is unavailable. According to Table 6, the ultimate strength of M-CFRP at 20°C varies between 816.5 MPa and 1001.3 MPa, and its Young's modulus varies between 58.2 GPa and 67.9 GPa. At 200°C, the variation of ultimate strength is smaller from 525.1 MPa to 660.9 MPa while with Young's modulus, the variation is greater, from 52.5 GPa to 77.3 GPa. At 400°C, the ultimate strength varies from 448.8 MPa to 479.3 MPa, and Young's modulus varies from 53.2 GPa to 68.3 GPa. At 600°C, these variations are from 107.8 MPa to 176.9 MPa with ultimate strength and from 34.2 GPa to 51.1 GPa with Young's modulus.

Table 16: Detailed result of the TM1 regime at different temperatures

No	Temp.	Sample	Thickness	Width	Failure force	Ultimate strength	Young's modulus	Retained stress ratio
-	°C	-	mm	mm	N	MPa	GPa	
1	200	M.TM1.200.01	0.79	10.83	5185	606.0	77.3	0.66
2	200	M.TM1.200.02	0.73	10.99	4213	525.1	67.4	0.57
3	200	M.TM1.200.03	0.66	11.13	4855	660.9	52.5	0.72
4	400	M.TM1.400.01	0.65	10.85	3165	448.8	66.9	0.49
5	400	M.TM1.400.02	0.73	10.95	3831	479.3	53.2	0.52
6	400	M.TM1.400.03	0.67	10.6	3361	473.3	68.3	0.52
7	600	M.TM1.600.01	0.7	10.43	984	134.8	34.2	0.15
8	600	M.TM1.600.02	0.66	10.85	1267	176.9	51.1	0.19
9	600	M.TM1.600.03	0.63	11.74	797	107.8	NA	0.12

2.6.2.4. Thermo-mechanical testing regime 2

In the following, Table 17 summarizes the results obtained from the TM1 regime. In Table 17, the dimension of each sample, the failure temperature and exposure duration obtained from each TM2 test are presented. In this series, the failure point, the failure temperature, exposure temperature and actual heating rate are identified in the same method in P-CFRP series.

According to Table 17, the failure temperature and exposure duration are reduced as the stress ratio increases. Particularly, at a low stress ratio of 0.1, the average failure temperature is approximately 634°C, and the average exposure duration is 33.5 minutes. As this ratio increases to 0.25, the exposure duration is 596°C, and exposure duration is approximately 23 minutes on average. At a stress ratio of 0.5, these values are 492°C with a failure temperature and 17.7 minutes with the exposure duration. These values decrease to 350°C and 11.7 minutes at a stress ratio of 0.6, dropping to 51.7°C and 1 minute at a stress ratio of 0.75 on average, respectively.

Table 17: Detailed result of TM2 regime at different stress ratios

No	Stress ratio	Sample	Thickness	Width	Failure temperature	Exposure duration	Actual heating rate
			mm	mm	°C	minutes	°C/minute
1	0.1	M.TM2.10.01	0.63	11.05	630.0	31.2	19.1
2	0.1	M.TM2.10.02	0.63	11	629.3	32.7	18.2
3	0.1	M.TM2.10.03	0.63	11.18	650.0	36.8	16.7
4	0.25	M.TM2.25.01	0.67	10.8	578.0	23.7	22.9
5	0.25	M.TM2.25.02	0.6	10.94	598.4	25.7	21.9
6	0.25	M.TM2.25.03	0.67	10.84	612.5	20.1	28.7
7	0.5	M.TM2.50.01	0.64	11.2	543.0	52.1	9.75
8	0.5	M.TM2.50.02	0.6	10.91	539.5	22.5	22.4
9	0.5	M.TM2.50.03	0.67	11.3	393.0	12.8	28.0
10	0.6	M.TM2.60.01	0.62	10.82	372.0	12.4	27.3
11	0.6	M.TM2.60.02	0.56	11.01	364.0	12.1	27.3
12	0.6	M.TM2.60.03	0.62	11.29	313.0	10.5	26.4
13	0.75	M.TM2.75.01	0.71	10.94	46.0	0.4	26.4
14	0.75	M.TM2.75.02	0.68	11.03	45.0	0.4	28.6
15	0.75	M.TM2.75.03	0.6	10.88	64.0	2.2	13.3

2.6.2.5. Failure modes

Table 18 through Table 21 display the type of failure found in all test conditions. Similar to the failure mode of P-CFRP, at 20°C, the specimen fails in middle position between two aluminium ends in which both the carbon fibres and polymer matrix are broken (mode A, Table 18). At 200°C, the specimen also fails in the middle. However, at a temperature that is much higher than the glass transition temperature of polymer, the matrix melts and plays a minor role in the tensile resistance of M-CFRP except for the horizontally bonding effect to fibres. Therefore, the shape of the specimen after testing at room temperature is random and varies depending on its position after failure (mode B). At 400°C, the matrix totally melts and starts decomposing and reduces its viscosity. Thus, only carbon fibres contribute to the tensile performance of M-CFRP, and each carbon fibre works individually. For that reason, at the failure region of M-CFRP (normally in the middle), each carbon fibre is broken at different section (mode C). At the failure point of M-CFRP, the broken carbon fibres remain together due to the friction effect of the remaining epoxy on the neighbouring fibres. At a room temperature after the test, the specimen can easily be split off by hand. In these temperature levels, the failure mode in RR condition tends to be closer to brittle mode because of the recovery-to-ambient-temperature condition after cooling phase while TM1 has softer mode due to the active of temperature maintains the viscosity of polymer matrix (Table 19 and Table 20). At 600°C, the polymer matrix is completely burnt, and the carbon fibres are partly oxidized. The M-CFRP is broken as the loading stress exceeds the resistance of the remaining carbon fibres because there is no resin left in the broken specimen (mode D). These failure modes show the similarity to the failure modes observed over pultruded CFRP (Feih and Mouritz, 2012; Gibson, 2005).

About failure mode of TM2 testing condition, according to Table 21, when the stress ratio increases from 0.1 to 0.6, the failure mode of M-CFRP conforms to the mode D as described in the TM1

regime. This well consists to the failure temperature at approximately 350°C - 650°C (Table 17). At a stress ratio of 0.75, the failure mode follows the mode A in the TM1 regime (failure temperature is approximately 45°C - 64°C). This is reasonable because in the TM2 regime, the heating rate is approximately 20°C/minute-30°C/minute (Table 17); the temperature quickly reaches the glass transition temperature and then the degradation temperature of the polymer matrix. This leads to the failure of the matrix in the performance of M-CFRP. Although the specimen temperature during the test is not homogeneous, it is thin and slender; therefore, the temperature of carbon fibres quickly reaches 200°C, at which its retained resistance is approximately 60% - 70% (Table 16) and thus leads to failure.

Table 18: Typical failures at different temperatures (Room temperature)

Temp. (°C)	Samples	Failure image	Failure mode
20	M.TM1.20.02		A
	M.TM1.20.03		A

Table 19: Typical failures at different temperatures (RR regime)

Temp. (°C)	Samples	Failure image	Failure mode
200	M.RR.200.01		A
	M.RR.200.02		A
400	M.RR.400.01		B
	M.RR.400.02		B
600	M.RR.600.01		C
	M.RR.600.02		C

Table 20: Typical failures at different temperatures (TM1 regime)

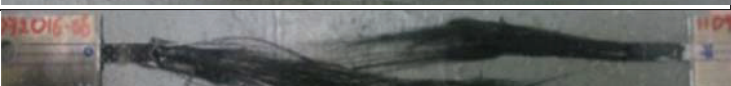
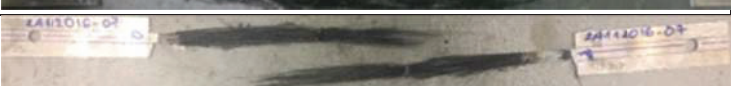
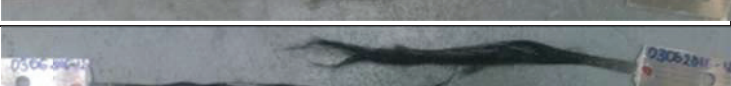
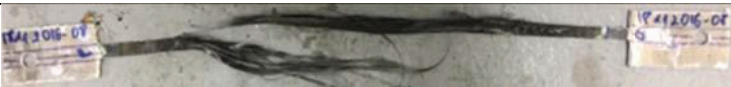
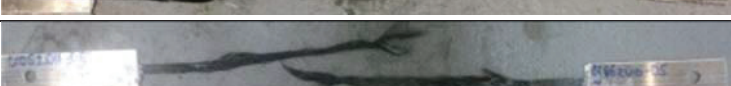
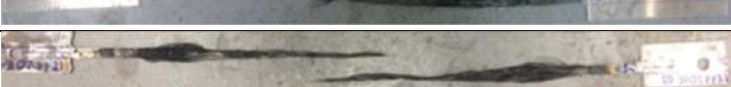
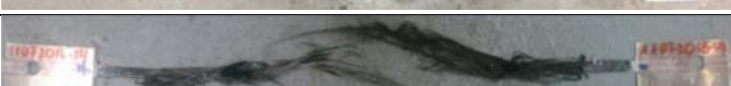
Temp. (°C)	Samples	Failure image	Failure mode
200	M.TM1.200.01		B
	M.TM1.200.02		B
400	M.TM1.400.02		C
	M.TM1.400.03		C
600	M.TM1.600.01		C
	M.TM1.600.02		C

Table 21: Typical failure at the different mechanical stress ratios of TM2

Stress ratio	Samples	Failure image	Failure mode
0.10	M.TM2.10.02		D
	M.TM2.10.03		D
0.25	M.TM2.25.01		D
	M.TM2.25.03		D
0.50	M.TM2.50.01		D
0.60	M.TM2.60.01		D
0.60	M.TM2.60.02		D
0.75	M.TM2.75.01		A
	M.TM2.75.03		A

2.7. Discussion

This section discusses the stress-strain correlation, the evolution of mechanical performance at different temperature, thermal performance at different mechanical state and mutual influence between temperature and mechanic load on overall performance of two type of CFRP are discussed and synthesized.

2.7.1. P-CFRP series

This subsection displays results of tests concerning the following points: stress-strain relationship, evolution of the ultimate strength and the Young's modulus of P-CFRP according to temperature, evolution of thermal resistance according to the ratio of applied mechanical load, dependent correlation between temperature and mechanical statuses on performance of P-CFRP, effect of thermal exposure duration on the thermo-mechanical properties of P-CFRP at 400°C, effect of heating rate on thermal resistance at 25% of applied load.

2.7.1.1. Stress-strain relationship

Figure 67 and Figure 68 show the stress-strain curves of the tested specimens. In the Figure 67 and Figure 68, for each temperature level, one average stress-strain curve is presented. The stress-strain curves obtained at 20°C generally exhibit linear properties. During the loading path, there are some minor peaks caused by the sudden fissure of fibres in close proximity to the surface. At 200°C, the residual curve (Figure 68) also displays linear behaviour with minor peaks while the thermo-mechanical curve is smoother. At 400°C, 500°C and 600°C, the curves in both procedures display a quasi-linear shape in the beginning, becoming nonlinear later in the test.

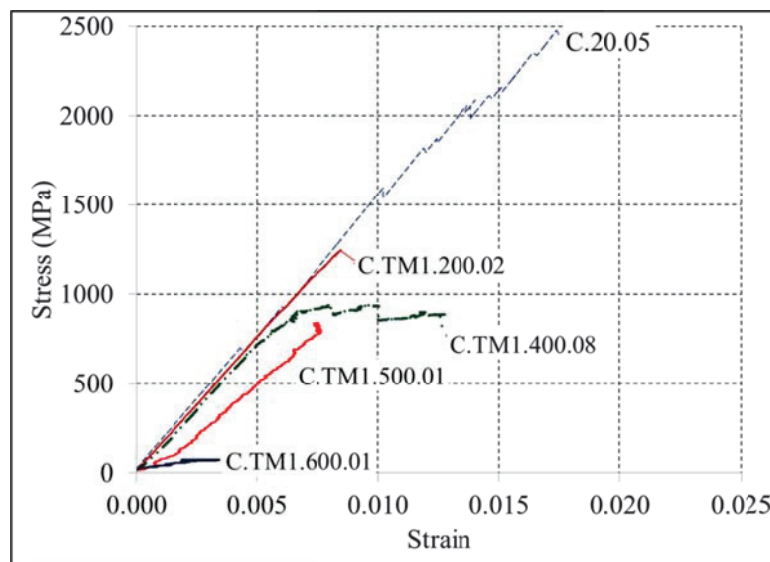


Figure 67: Typical thermo-mechanical stress-strain relationship at different temperature levels

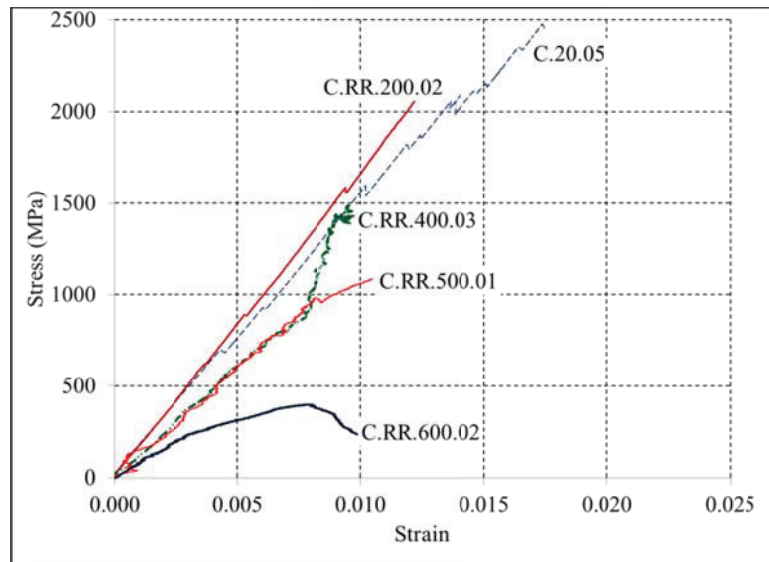


Figure 68: Typical residual stress-strain relationship at different temperature levels

2.7.1.2. Evolution of the ultimate strength and the Young's modulus of P-CFRP according to temperature

Table 22 and Table 23 summarize the analysed properties (the ultimate strength and the Young's modulus) of the thermo-mechanical and residual tests in the temperature range from 20°C to 700°C.

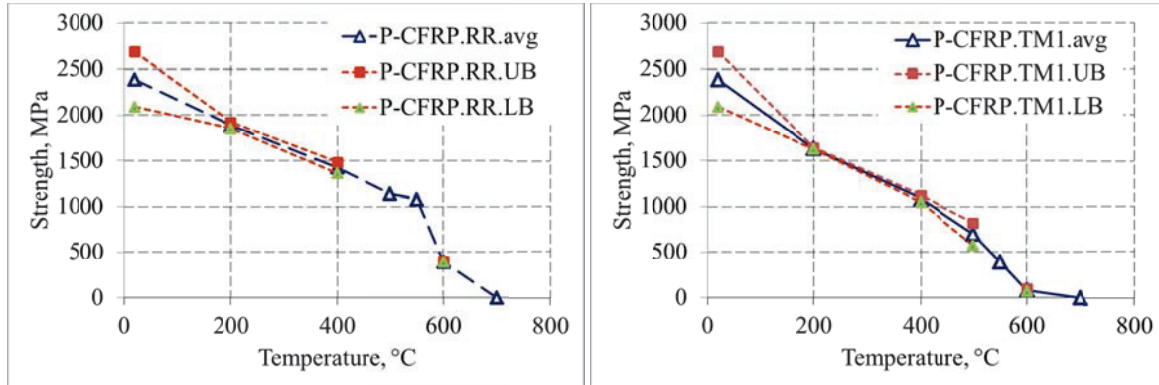
Table 22: Thermo-mechanical properties of P-CFRP at different temperatures

Temperature	Ultimate stress		Young's modulus	
	Average	Standard deviation	Average	Standard deviation
°C	(MPa)	(MPa)	(GPa)	(GPa)
20	2389.42	±298.98	156.992	±9.817
200	1635.89	±8.91	153.865	±14.2
400	1084.65	±37.62	150.641	±9.658
500	697.896	±124.18	116.695	-
550	392.662	-	-	-
600	84.282	±13.84	16.334	±0.5558
700	0	-	-	-

Table 23: Residual properties of P-CFRP at different temperatures

Temperature (°C)	Ultimate stress		Young's modulus	
	Average (MPa)	Standard deviation (MPa)	Average (GPa)	Standard deviation (GPa)
20	2389.42	±298.98	156.992	±9.817
200	1889.08	±33.92	169.404	±8.738
400	1423.52	±60.18	161.972	±4.443
500	1138.97	-	154.62	-
550	1080.28	-	-	-
600	395.877	±0.7312	46.061	-
700	0	-	-	-

Figure 69 and Figure 70 display the evolution of the ultimate strength and the Young's modulus for P-CFRP as the temperature increases in the two test procedures. The illustrations reveal that as temperature rises, the ultimate strength of P-CFRP decreases (Figure 69), while Young's modulus varies slightly (less than 10%) from 20°C to 400°C and then steadily drops as the temperature is raised to 500-600°C. The evolution of the obtained residual Young's modulus mirrors the results of Foster et al. (Foster and Bisby, 2005), which show that between 20°C and 400°C, the residual Young's modulus fluctuates with a slight increasing tendency.

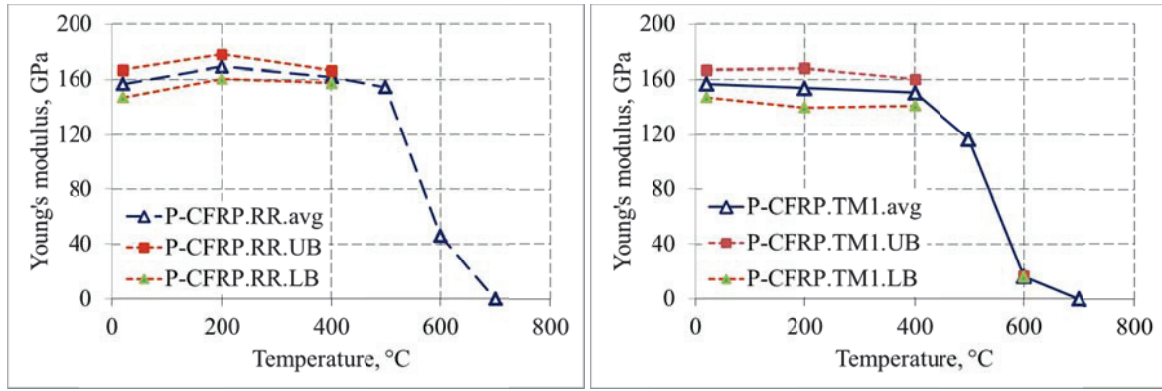


a) Residual tests

b) Thermo-mechanical tests

Figure 69: Evolution of the ultimate strength of P-CFRP as a function of temperature.

(a) Thermo-mechanical tests; (b) Residual tests



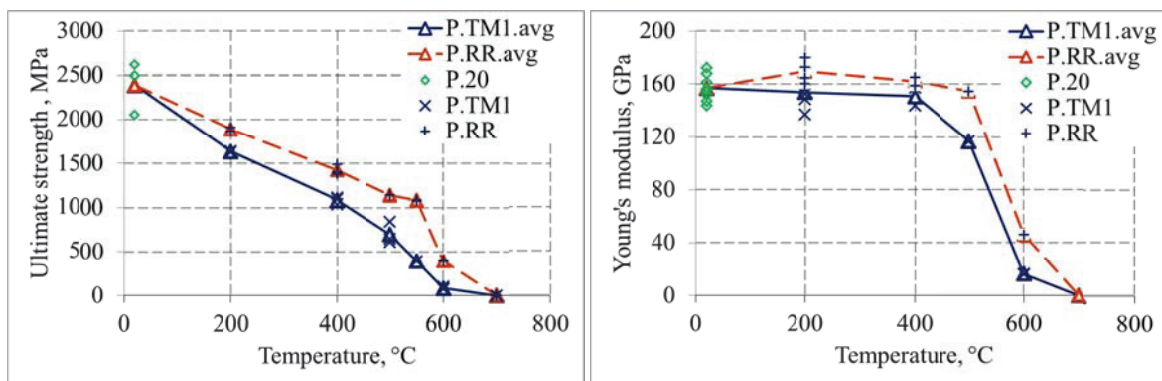
a) Residual tests

b) Thermo-mechanical tests

Figure 70: The evolution of Young's modulus for P-CFRP as a function of temperature.

(a) Thermo-mechanical tests; (b) Residual tests

The experimental findings confirm that the ultimate strength and Young's modulus of P-CFRP generally decrease as the temperature increases from 20°C to 700°C (Figure 71). Overall, the decrease in the thermo-mechanical ultimate stress is greater than the residual stress (Figure 71a). Specifically, at 200°C, the average ultimate strength is reduced by 32% for the thermo-mechanical test compared with 19% in the residual test. At 400°C, these rates are 55% and 41%, respectively. At 600°C, P-CFRP loses 96% of its tensile strength in the thermo-mechanical test and 83% in the residual test. Showing a similar trend, the thermo-mechanical Young's modulus is lower than the residual Young's modulus (Figure 71b). From 20°C to 400°C, the thermo-mechanical Young's modulus experienced little change (less than 10%) while the residual Young's modulus increased 8% at 200°C and 3% at 400°C compared with its value at 20°C. At 500°C, the thermo-mechanical Young's modulus of P-CFRP is reduced by 26% while the residual Young's modulus is only reduced by 2%. Significantly, the P-CFRP loses almost 90% of its thermo-mechanical Young's modulus and 70% of its residual Young's modulus at 600°C.



a) Ultimate strength

b) Young's modulus

Figure 71: The evolution of the thermo-mechanical and residual properties of P-CFRP as a function of temperature: (a) ultimate strength; (b) Young's modulus

2.7.1.3. Evolution of thermal resistance according to the ratio of applied mechanical load

In this section, Table 24 shows the analysed results obtained in Table 12 (regarding cases with actual heating rate about 15°C/minute to 20°C/minute); Figure 72 and Figure 73 show the evolution of failure temperature and exposure duration of P-CFRP at different mechanical status (stress ratio, Table 24). From the table and figures, when the stress ratio increases from 0.1 to 0.25, the failure temperature gradually decreases from 600°C to 649°C while the exposure duration decreases from 44 minutes to 35 minutes. At stress ratio 0.5, the failure temperature deeply reduces to 436.2°C while exposure duration slightly reduces to 32.3 minutes. At stress ratio 0.68, both the failure temperature and exposure duration quickly reduce to 41°C and 1 minute respectively.

Table 24: Analysed TM2 results.

Stress ratio	Failure temperature	Exposure duration
	°C	minute
0.1	699	44
0.25	649	35
0.5	436.2	32.3
0.68	41	1

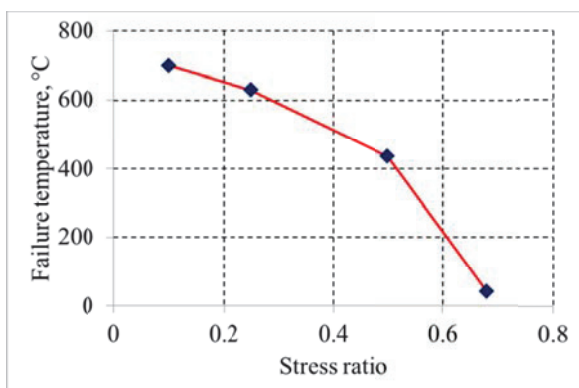


Figure 72: Evolution of the failure temperature of P-CFRP as a function of the stress ratio (TM2 regime).

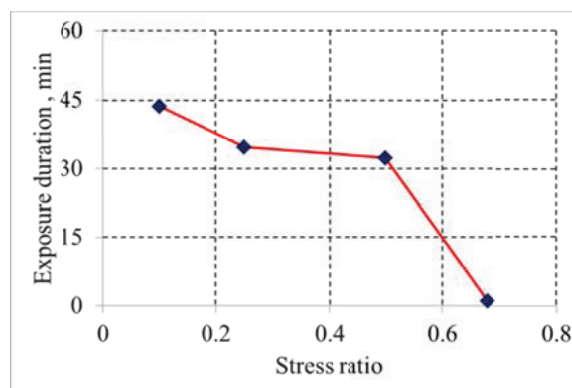


Figure 73: Evolution of the exposure duration of P-CFRP as a function of the stress ratio (TM2 regime).

2.7.1.4. Dependent correlation between temperature and mechanical statuses on performance of P-CFRP

From the results from TM1 and TM2 result of P-CFRP material, it shows that the higher the temperature that P-CFRP exposes to, the more its mechanical properties reduce and vice versa, the higher mechanical status that P-CFRP is applied, the more its thermal resistance reduce. The correlation between two factors is synthesized on Figure 74.

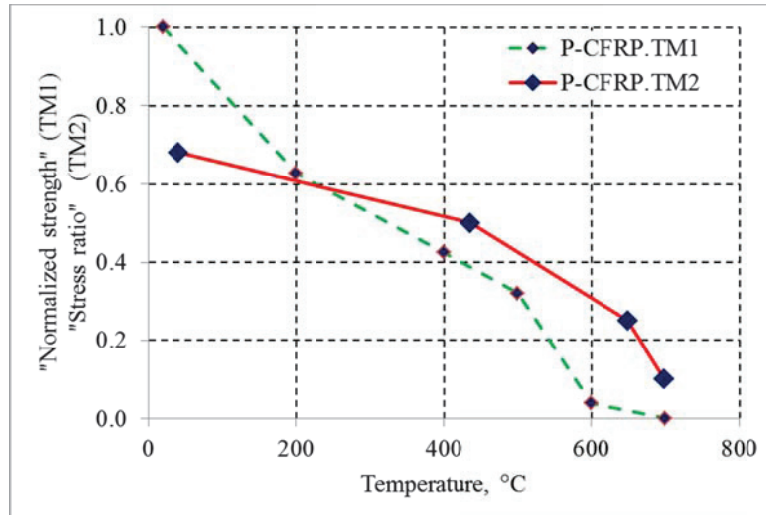


Figure 74: Correlation between the ultimate stress ratio and failure temperature of P-CFRP obtained from the TM1 and TM2 regimes.

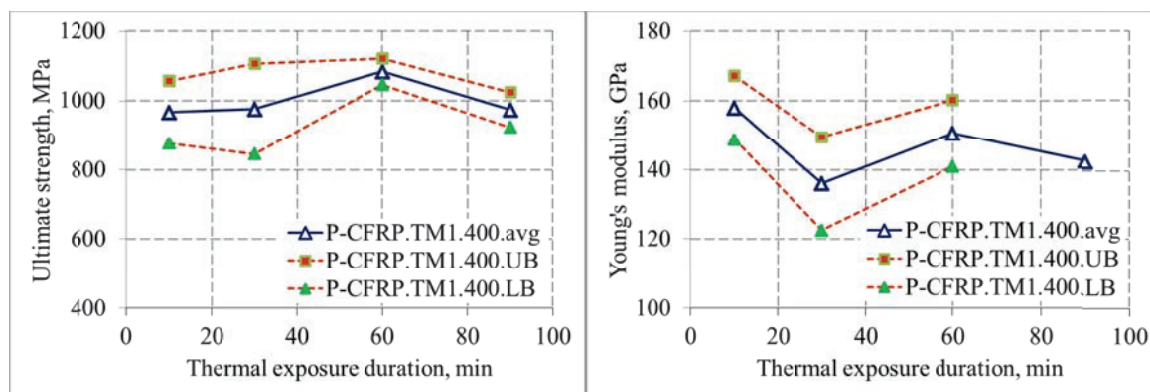
2.7.1.5. Effect of thermal exposure duration on the thermo-mechanical properties of P-CFRP at 400°C

Table 25 shows the values of thermo-mechanical ultimate strength and Young's modulus for P-CFRP as the thermal exposure duration (Figure 59) varies from 10 minutes to 90 minutes for a temperature of 400°C.

Table 25: The thermo-mechanical properties of P-CFRP at 400°C depend on thermal exposure duration

Thermal exposure duration (minute)	Ultimate strength			Young's modulus		
	Average	Difference		Average	Difference	
	(MPa)	(MPa)	(%)	(GPa)	(GPa)	(%)
10	967.1	33.45	3.34	158.0	11.2	7.64
30	976.1	24.45	2.45	136.0	10.8	7.36
60	1084.6	84.05	8.40	150.6	3.8	2.61
90	974.4	26.15	2.61	142.6	4.2	2.68
Average	1000.6			146.8		

This temperature (400°C) was chosen to study this effect because the thermo-mechanical and residual ultimate strengths of P-CFRP gradually reduce from 20°C to 700°C (Figure 69a, b) while its Young's modulus varies less than 10% from 20°C-400°C (Figure 70a, b). Figure 75 illustrates the evolution of the ultimate strength and Young's modulus of P-CFRP when the thermal exposure duration increases from 10 minutes to 90 minutes. This demonstrates that at 400°C, the thermal exposure duration has a minor influence on the ultimate strength and Young's modulus (less than 10%). Additionally, as seen in Figure 75, both ultimate strength and Young's modulus exhibit the same variation tendency between 30 and 90 minutes of thermal exposure duration.



a) Ultimate strength

b) Young's modulus

Figure 75: The effect of thermal exposure duration on thermo-mechanical properties at 400°C: (a) ultimate strength; (b) Young's modulus

2.7.1.6. Effect of heating rate on thermal resistance at 25% of applied load

Table 26 summaries the results obtained in TM2 test at different heating rates (in case stress ratio 0.25) and Figure 76 shows the variation of failure temperature at different actual heating rate. The variation of failure temperature is less than 5% compared to the average failure temperature at the actual heating rate from 10°C/min to 20°C/min. At higher or lower range of heating rate (within capacity of used machine and tested cases), the variation is less than 8%.

Table 26: Details of thermo-mechanical tests2 (TM2) at different heating rates (stress ratio: 0.25).

Heat rate, °C/min		Failure temperature, (T _r , °C)	Difference (%)
programed	actual		
2	2.1	584	7.21
10	12.3	601	4.51
15	16.7	649	3.15
20	19.9	609	3.20
25	25.6	664	5.54
30	26.4	669	6.23
Average		629	

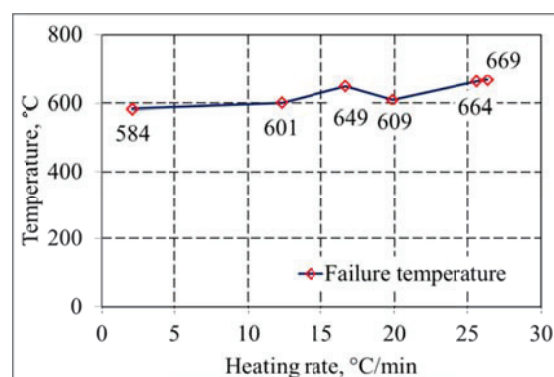


Figure 76: Variation of failure temperature of P-CFRP at different heating rates (TM2)

2.7.2.M- CFRP series

This section discusses the following results: the stress-strain relationship of M-CFRP at a constant temperature condition, the evolution of mechanical resistance at a different temperature condition, the evolution of thermal resistance at different mechanical statuses as well as and the dependent correlation between mechanical and temperature effects.

2.7.2.1. Stress-strain relationship of M-CFRP at constant temperature condition

Figure 77 and Figure 78 show that the M-CFRP displays a linear trend at most temperature levels. At 20°C and 200°C, these stress-strain curves display linear behaviour in both RR and TM1 conditions. At 400°C, the linear trend repeats in both RR and TM1 cases but in RR case, there is brittle rupture (Figure 77) while with TM1 there is ductile-like rupture (Figure 78). This could be resulted from the testing procedure with 1 hour of exposure to 400°C, at which all of the matrix is burnt and the loaded fibres start experiencing minor mass loss and diameter reduction (normally at 500°C with PAN fibre (Feih et al., 2009)). This leads to the sequential and gradual failure of a single fibre, which allows the M-CFRP to redistribute the stress over the remaining fibres over time. Therefore, in RR condition, the temperature has cooled back to ambient temperature when the carbon fibre is partly recovered and displays fragile rupture while at TM1 condition, the carbon fibres are under elevated temperature condition and tends to show nonlinear behaviour. At 600°C, the M-CFRP shows a linear trend, and the post-peak behaviour is short in TM1 condition and ignorable with the deformation extension compared to the overall deformation (Figure 78) due to the acceleration of mass loss and reduction in strength at the applied temperature (Feih et al., 2009); whereas, the RR result at this temperature shows longer post-peak performance (Figure 77).

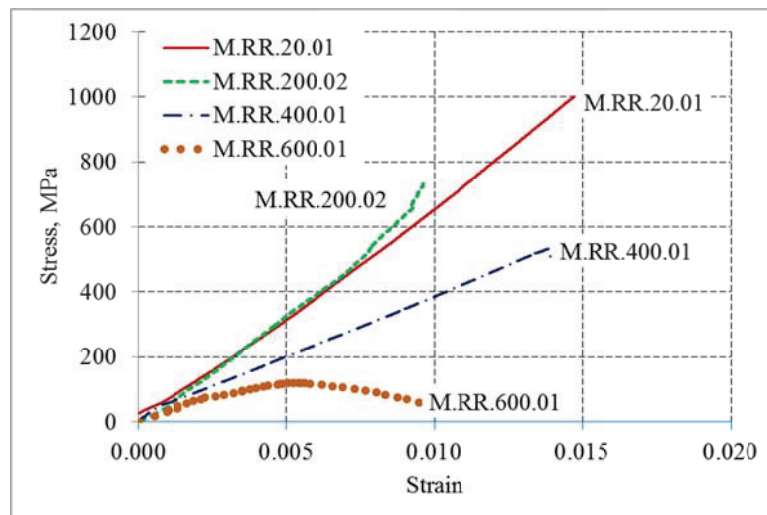


Figure 77: Typical thermo-mechanical stress-strain relations of M-CFRP at different temperature levels (RR regime)

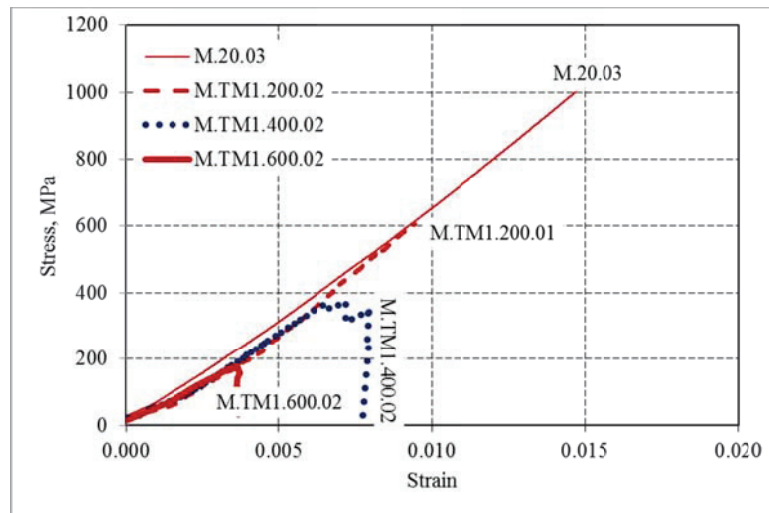


Figure 78: Typical thermo-mechanical stress-strain relations of M-CFRP at different temperatures (TM1 regime)

2.7.2.2. Evolution of mechanical resistance at different temperature conditions

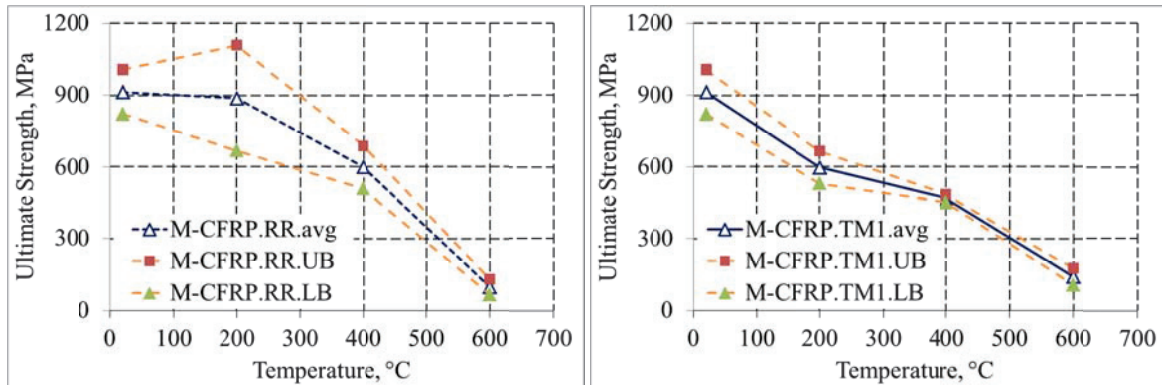
In the following section, Table 27 and Table 28 analyses the experimental results obtained from Table 15 and Table 16. Figure 79 and Figure 80 display the evolution of ultimate strength and Young's modulus as the temperature level increases from 20°C to 600°C. As seen from Figure 79, as the temperature increases, the ultimate strength of M-CFRP generally decreases. When the temperature level increases from 20°C to 200°C, the ultimate strength decreases from 913 MPa to 597 MPa (or reduces 35%). From 200°C to 400°C, this value decreases to 467 MPa (decreases another 14%) and remains at 139.8 MPa (15.3%) at 600°C. As shown in Figure 86, this evolution fits well with the previous results with pultruded laminate CFRP (or P-CFRP) obtained at the same testing condition (Phi Long et al., 2016) and shows similarity to other results of CFRP obtained in the literature (Wang et al., 2011, 2007; Yu and Kodur, 2014). Concerning this evolution, a major reduction occurs at temperatures between 400°C – 600°C because this temperature range facilitates the mass loss (Yin et al., 1994) and diameter reduction of carbon fibre (Feih et al., 2009).

Table 27: Analysed RR results.

Temperature	Ultimate strength			Young's modulus		
	Average	Deviation	Normalized	Average	Deviation	Normalized
°C	MPa	MPa	ratio	GPa	GPa	ratio
20	913.5	92.8	1.000	62.23	5.05	1.000
200	888	220	0.97	71	5	1.14
400	598	90	0.66	46	12	0.74
600	97	31	0.11	18	12	0.28

Table 28: Analysed TM1 results.

Temperature	Ultimate strength			Young's modulus		
	Average	Deviation	Normalized ratio	Average	Deviation	Normalized ratio
°C	MPa	MPa		GPa	GPa	
20	913.5	92.8	1.000	62.23	5.05	1.000
200	597.3	68.3	0.654	65.73	12.45	1.056
400	467.1	16.2	0.511	62.77	8.35	1.009
600	139.8	34.8	0.153	42.65	12.01	0.685

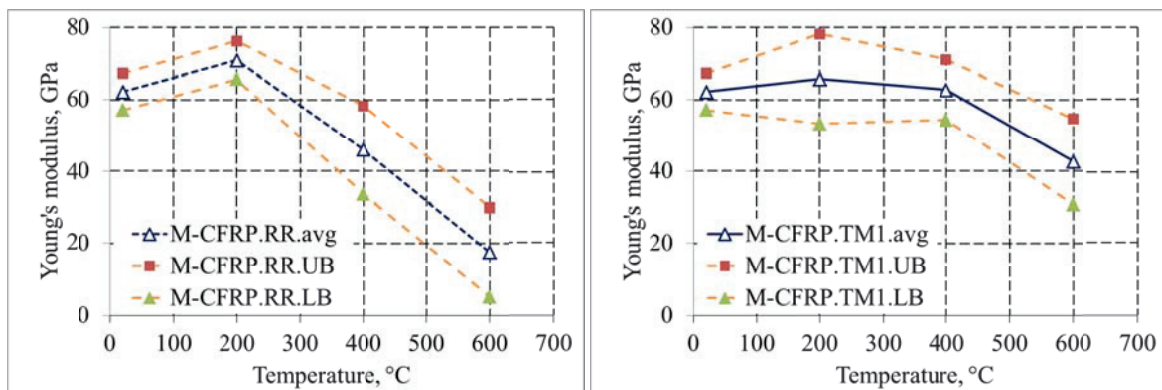


a) Residual tests

b) Thermo-mechanical tests

Figure 79: Evolution of the ultimate strength of M-CFRP as a function of temperature.

According to Table 28 and Figure 80, when the temperature increases from 20°C to 200°C, Young's modulus increases 6% from 62.2 GPa to 65.7 GPa. At 400°C, this modulus slightly reduces to 62.77 GPa (less than 1% of variation compared to that at 20°C), while at 600°C, this reduces to 42.65 GPa (equivalent to 31.5% of reduction).



a) Residual tests

b) Thermo-mechanical tests

Figure 80: Evolution of the Young's modulus of M-CFRP as a function of temperature.

2.7.2.3. Evolution of thermal resistance at difference mechanical statuses

In this section, Table 29 shows the analysed results obtained in Table 17, while Figure 81 and Figure 83 display the evolution of thermal resistance of M-CFRP as the stress ratio increases from 0.1 to 0.75 in terms of failure temperature and exposure duration. As seen from Table 29 and Figure 81, when the stress ratio increases from 0.1 to 0.5, the failure temperature gradually reduces from 636°C to 491°C (or for each percentage of stress increases, the failure temperature decreases by approximately 3.6°C). This failure temperature decreases to approximately 350°C at a stress ratio of 0.6 (14.2°C/percentage of stress) and quickly decreases to 52°C at a stress ratio of 0.75 (19.9°C/percentage of stress). The reduction rate of the failure temperature for each percentage increment of stress is illustrated in Figure 82. This reduction rate, obtained as the slope of failure-temperature reduction curve in Figure 81, reflects that the influence of the mechanical status to the thermal performance (in term of failure temperature) is different depending on the range of stress ratio. As this figure shows, with a stress ratio range of less than 0.5, for each percentage increase of stress ratio, the failure temperature reduces less than 4°C. Beyond this stress ratio range, the failure temperature can reduce up to 14°C-20°C for each percentage increase of stress ratio depending on the imposed load range.

Table 29: Analysed TM2 results.

Stress ratio	Failure temperature		Exposure duration		Actual heating rate	
	Average	Deviation	Average	Deviation	Average	Deviation
	°C	°C	minutes	minutes	°C/minute	°C/minute
0.1	636.4	11.8	33.5	2.9	18.0	1.2
0.25	596.3	17.3	23.2	2.8	24.5	3.7
0.5	491.8	85.6	17.7	6.9	25.2	4.0
0.6	349.7	32.0	11.7	1.0	27.0	0.5
0.75	51.7	10.7	1.0	1.0	22.8	8.3

Figure 83 displays the evolution of the exposure duration of M-CFRP as the stress ratio increases from 0.1 to 0.75, obtained under the TM2 testing condition. At a stress ratio of 0.1, the exposure duration is approximately 33.5 minutes. This duration quickly decreases to 23.2 minutes at a stress ratio of 0.25 and then gradually reduces to 17.7 minutes at a stress ratio of 0.5. With the stress ratio increase from 0.5 to 0.6 and then to 0.75, the exposure duration quickly reduces to 11.7 minutes and 1 minute, respectively. The evolution of exposure duration at different stress ratio presented in Figure 83 exhibits a reduction trend that is similar to that of evolution of failure temperature at different stress ratio presented in Figure 82 for the stress ratio between 0.25 and 0.75. It is because tests conducted at these stress ratio cases are obtained under similar heating rate. Figure 84 shows the average actual heating rate obtained from tests at different stress ratios. According to the Figure 84, the average actual heating rates in tests at stress ratio between 0.25 and 0.75 are about 25°C/minute; while in the tests at stress ratio of 0.1, the average actual heating rate is much lower at about 18°C/minute. This explains the reason for higher the exposure duration at stress ratio of 0.1 shown in Figure 83. As also displayed in Figure 84, although the actual heating rate is lower than the programmed heating rate at 30°C/minute, this rate is stable in almost all tests of the TM2 regime and thus guarantees the consolidated results. It should be noted that the actual heating rate is identified based on the whole test time, while the programmed heating rate at 30°C/minute is the maximum heating rate provided by the furnace.

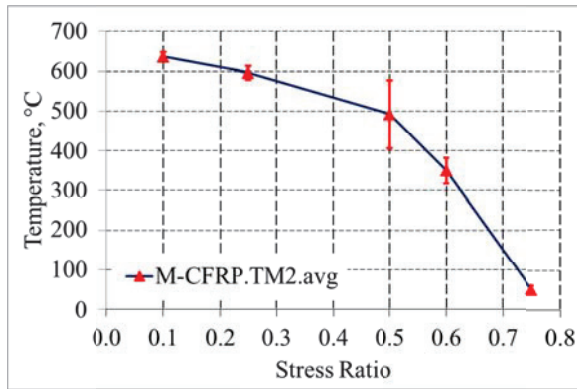


Figure 81: Evolution of the failure temperature of M-CFRP as a function of the stress ratio (TM2 regime).

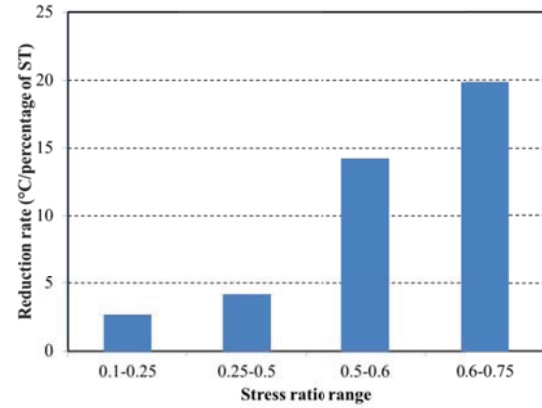


Figure 82: Reduction rate of the failure temperature over different stress ratio ranges.

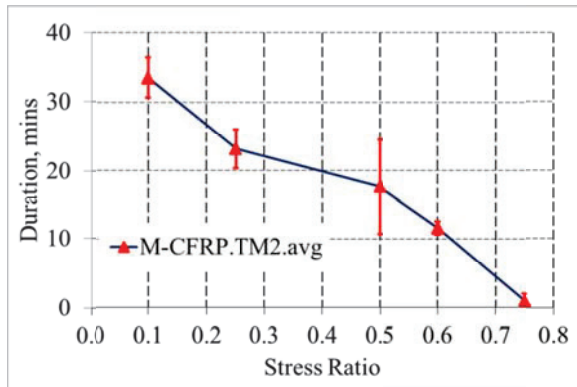


Figure 83: Evolution of the exposure duration of M-CFRP as a function of the stress ratio.

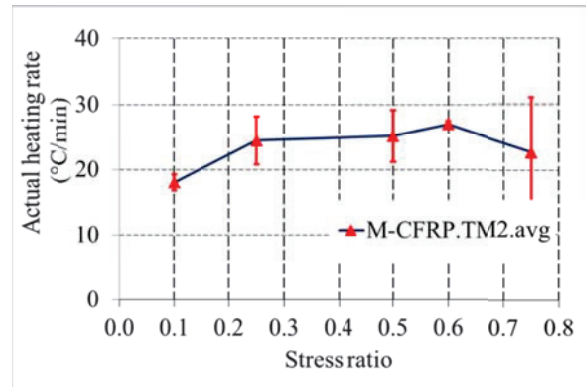


Figure 84: Actual heating rate at different stress ratios (TM2 regime).

2.7.2.4. Dependent correlation between mechanical and temperature effects

As can be seen from two precedent sections, when the applied temperature increases, the ultimate strength of M-CFRP decreases (TM1 regime); and vice versa, when the applied mechanical load increases, the failure temperature reduces (TM2 regime). Figure 85 displays the synchronization of two testing series, which clearly reflect the correlation between temperature and mechanical loadings.

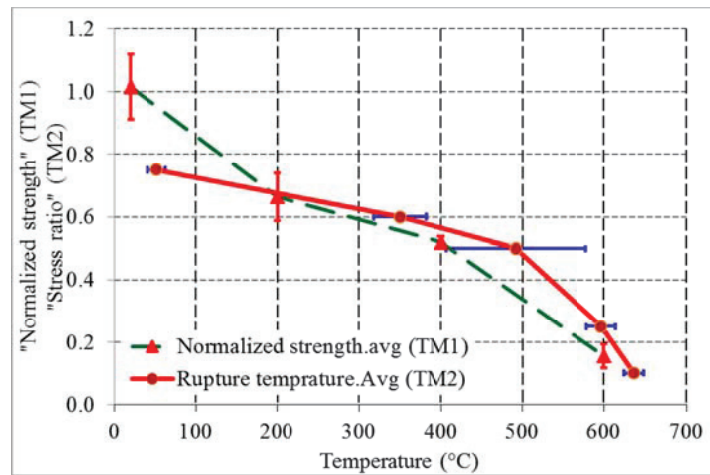


Figure 85: Correlation between the ultimate stress ratio and failure temperature of M-CFRP obtained from the TM1 and TM2 regimes.

2.7.3.Synthesis of experimental results

The obtained results obtained in two materials tested under RR and TM1 condition well consist together in each tested case. The normalized ultimate strengths obtained from P-CFRP and M-CFRP fit each other and closely follow the general reduction trend shown by the experimental results in the literature (Wang et al., 2011, 2007; Yu and Kodur, 2014). As can be seen in Figure 86, in two tested materials, the ultimate strength obtained in RR condition is higher than that of TM1 condition. The normalized residual ultimate strength of M-CFRP is greater than that of P-CFRP between 20°C and 400°C but then become smaller at the temperature between 400°C and 600°C. Whereas, the normalized values of thermo-mechanical ultimate strength of both P-CFRP and M-CFRP consist together.

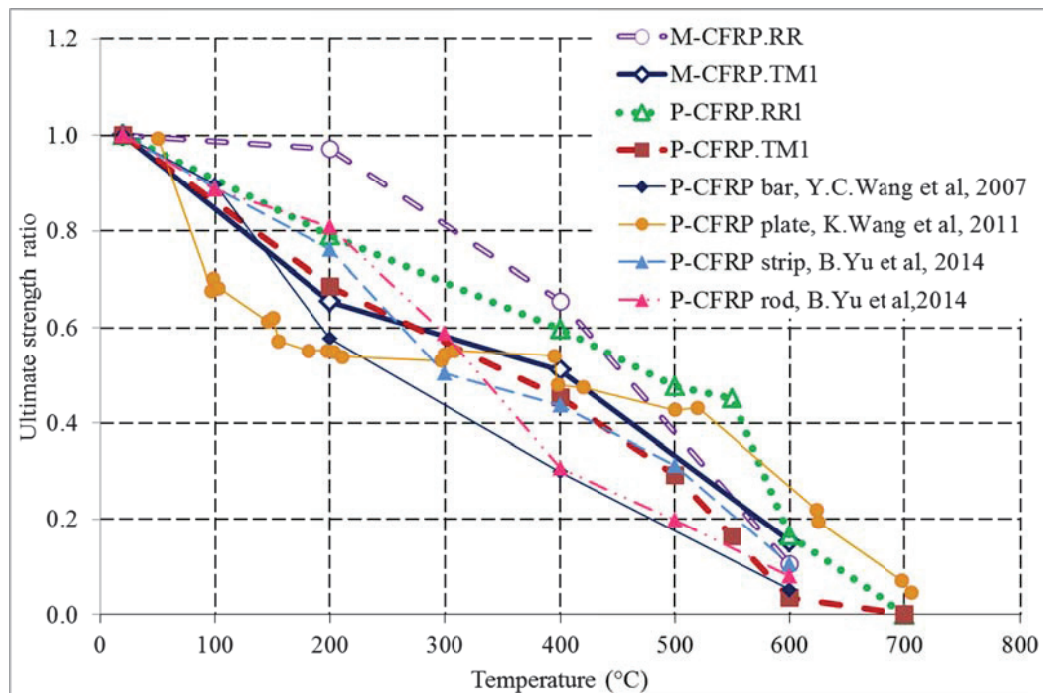


Figure 86: Comparison of the ultimate strength results of CFRP with the previous studies.

However, the Young's modulus obtained in this research show a different evolution trend compared to the result of Y.C. Wang et al. (Wang et al., 2007) and Yu, Kodur (Yu and Kodur, 2014) (Figure 87). From 20°C to 400°C, Young modulus of P-CFRP and M-CFRP are slightly varies or even increase (except residual Young's modulus of M-CFRP reduce about 25% at 400°C). The Young's modulus starts to reduce with steeping rate beyond 400°C. There are differences in the displacement measurement method between the conducted research and previous result. In this research, the used laser extensometer is non-contacted method, which is less likely to be influenced by temperature compared to the global deformation ((Wang et al., 2007)); exterior LVDT (Yu and Kodur, 2014). The results of Young's modulus obtained in this thesis is well confirmed by the individually experiment on carbon fibre by Feih (Feih et al., 2009), Young's modulus of the carbon fibre-type PAN slightly increases as the temperature increases from room temperature to 450°C because of the minor rate of mass loss and diameter reduction at this temperature but significant beyond 500°C. The obtained modulus of PAN carbon fibre, described as in Table 30, consolidates with the results obtained in this study and in previous results with P-CFRP (Phi Long et al., 2016).

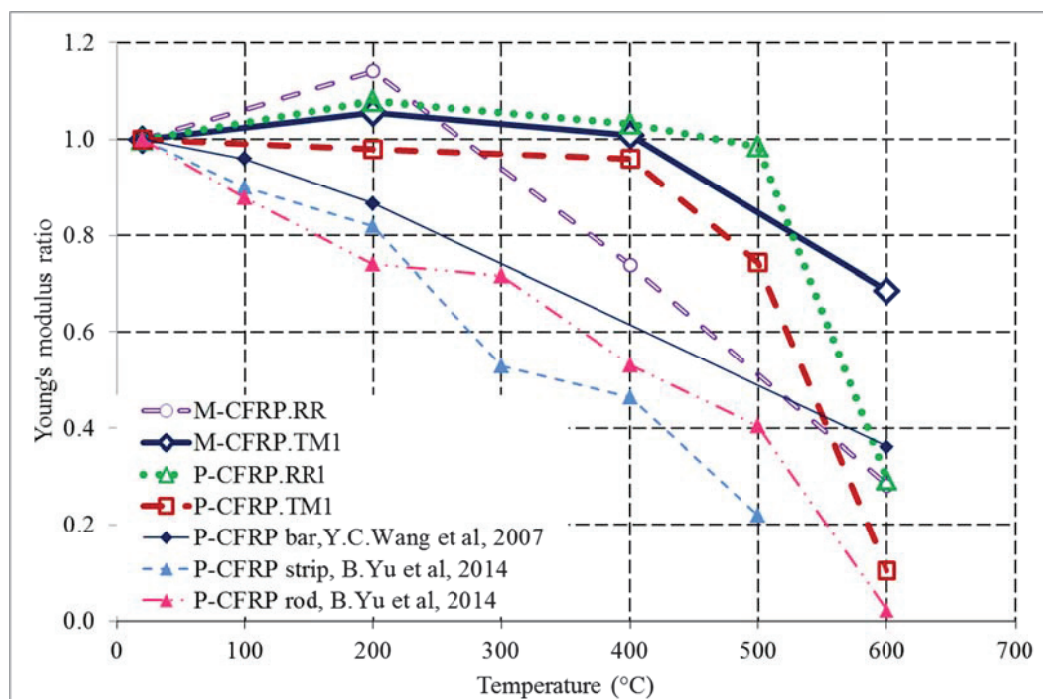


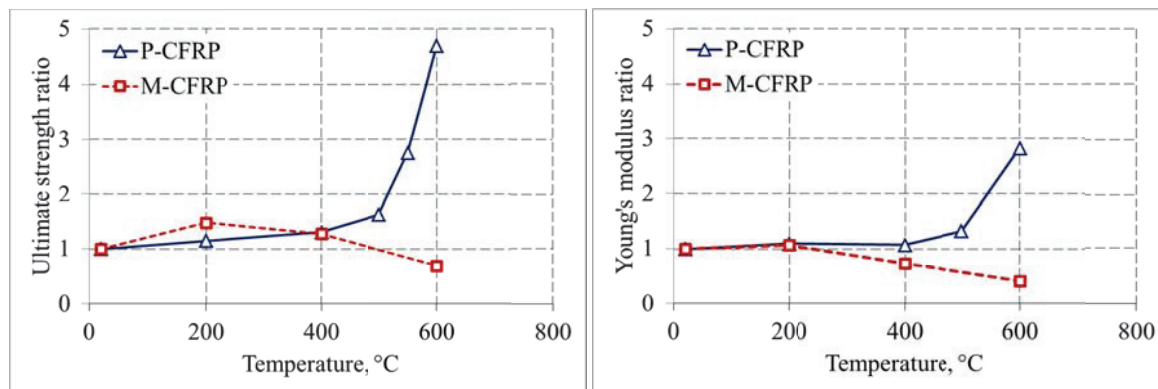
Figure 87: Comparison of the Young's modulus results of M-CFRP with previous studies.

Table 30: Evolution of Young's modulus of carbon fibres as temperature increases (Feih et al., 2009)

Value	Room temperature	350°C	450 °C
Young's modulus [GPa]	203±11	210±14	213±14

The ratios between the residual to thermo-mechanical properties of P-CFRP and M-CFRP, including ultimate strength and Young's modulus, are presented in Figure 88. From 20°C to 400°C, these differences between residual and thermo-mechanical properties are small in both P-CFRP and M-CFRP, and then they significantly become greater between 400°C to 600°C. The ultimate strength ratios of both P-CFRP and M-CFRP vary between 1 and 1.31 (with P-CFRP) and 1.49 (with M-

CFRP) in temperature range 20°C-400°C. From 400°C to 600°C, this ratio of P-CFRP increases rapidly to 4.7 while with that of M-CFRP, the ratio reduces to 0.7. With Young's modulus, the difference between residual and thermo-mechanical values of both materials is small between 20°C and 400°C: the ratio increases from 1 to 1.08 with P-CFRP while reduces from 1 to 0.73 with M-CFRP. From 400°C to 600°C, the residual-to-thermo-mechanical modulus ratio quickly increases to 2.83 with P-CFRP while with M-CFRP, the value significantly reduces to 0.41.



a) Ultimate strength;

b) Young's modulus

Figure 88: Ratio between residual and thermo-mechanical properties of CFRP at different temperatures

2.8. Analytical model

In this section, the experimental results of P-CFRP are used to evaluate and calibrate previous analytical models for the evolution of mechanical properties at different temperature condition. In the second part, an analytical model with the application for the mechanical performance at elevated temperature condition has been proposed.

2.8.1. Comparison with analytical models

As presented in the introduction, several prediction models have been proposed to estimate the evolution of mechanical properties as a function of temperature. This section will compare and then calibrate these models with the experimental results of P-CFRP material.

Figure 89 and Figure 90 display these models compared to the experimental results of P-CFRP obtained from this thesis. As seen from Figure 89, the prediction models by Bisby (Bisby, 2003) (Figure 89, curve a), Gibson (calibrated by Yu and Kodur (Yu and Kodur, 2014)) (Figure 89, curve c) and J. Chen (Chen and Young, 2006) (Figure 89, curve f) (adjusted by K. Wang (Wang et al., 2011)) show a close relationship to the experimental ultimate-strength evolution. The others, including the original from Bisby and Gibson (calibrated by K. Wang (Wang et al., 2011)) display a different general trend. The prediction model proposed by Bisby aligns more closely with the experimental Young's modulus evolution, while the other models do not (Figure 90).

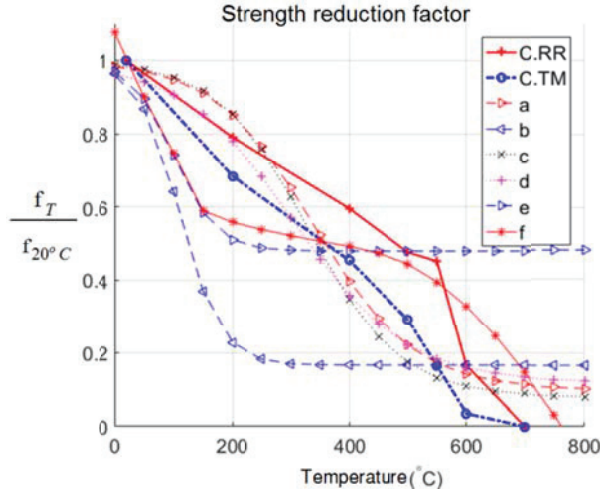


Figure 89: Prediction model for ultimate strength

a: Bisby's model (Bisby, 2003); b: Gibson's model (Gibson, 2005); c: Gibson's model for CFRP rods calibrated by Yu and Kodur (Yu and Kodur, 2014); d: Gibson's model for CFRP strips calibrated by Yu and Kodur (Yu and Kodur, 2014); e: Gibson's model for laminated CFRP calibrated by K. Wang (Wang et al., 2011); f: J. Chen's model (Chen and Young, 2006) for laminated CFRP calibrated by K. Wang (Wang et al., 2011)

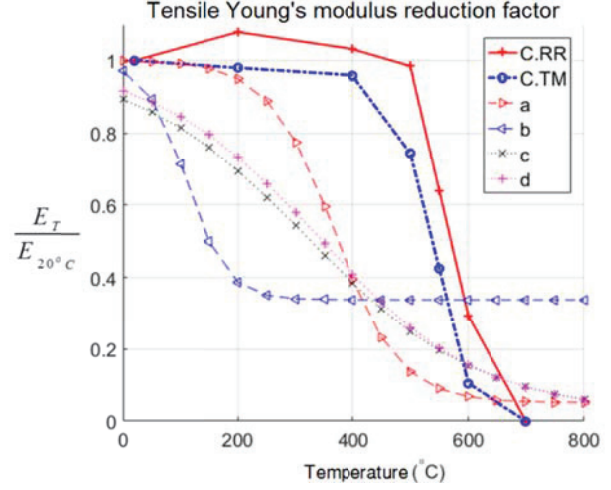


Figure 90: Prediction model for Young's modulus

a: Bisby's model (Bisby, 2003); b: Gibson's model (Gibson, 2005); c: Gibson's model for CFRP rods calibrated by Yu and Kodur (Yu and Kodur, 2014); d: Gibson's model for CFRP strips calibrated by Yu and Kodur (Yu and Kodur, 2014)

$$\frac{P(T)}{P_U} = R^n \left[\frac{1 + \frac{P_R}{P_U}}{2} - \frac{1 - \frac{P_R}{P_U}}{2} \tanh \{ k (T - T') \} \right] \quad \text{Equation 9}$$

In this study, author has calibrated the models proposed by Gibson (Gibson, 2005) (Equation 9, simplified from Equation 2), Bisby (Bisby, 2003) (Equation 3) and J. Chen (Chen and Young, 2006) (Equation 4) with the obtained experimental results using the least square approach combined with a random optimization method in MATLAB. The calibration results obtained from the models by Gibson and Bisby display better agreement with the current experimental results than the model by J. Chen. Table 31 and Table 32 present the calibrated coefficients of both the models by Gibson and Bisby.

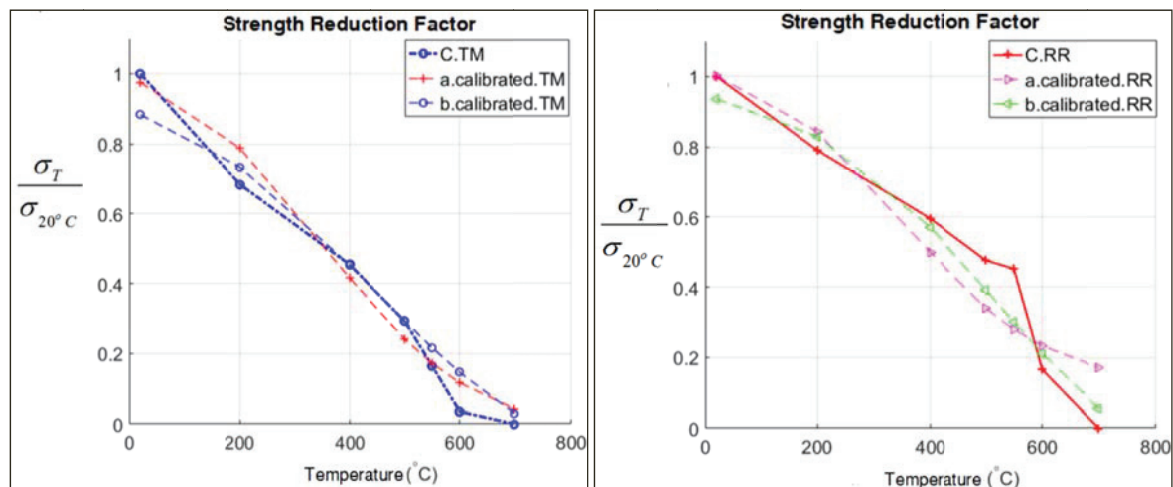
Table 31: Calibrated coefficients for Gibson's prediction model (Gibson, 2005) ($R=1$, $n=1$)

Calibration data	Pr/Pu	k	T'
Thermo-mechanical ultimate strength	-0.2	0.027	432.7
Residual ultimate strength	-0.2368	0.03	505.9
Thermo-mechanical Young's modulus	0.0175	0.0108	529.0
Residual Young's modulus	0.07	0.0166	576.9

Table 32: Calibrated coefficients for Bisby's prediction model (Bisby, 2003)

Calibration data	a	b	c
Thermo-mechanical ultimate strength	-0.0409	0.0036	350.0
Residual ultimate strength	0.1133	0.0039	350.0
Thermo-mechanical Young's modulus	0.0146	0.0157	574.6
Residual Young's modulus	-0.0154	0.0129	536.9

Figure 91 shows the correlation between the calibrated models and the experimental ultimate strength, and Figure 92 shows the correlation between the calibrated models and the experimental Young's modulus.

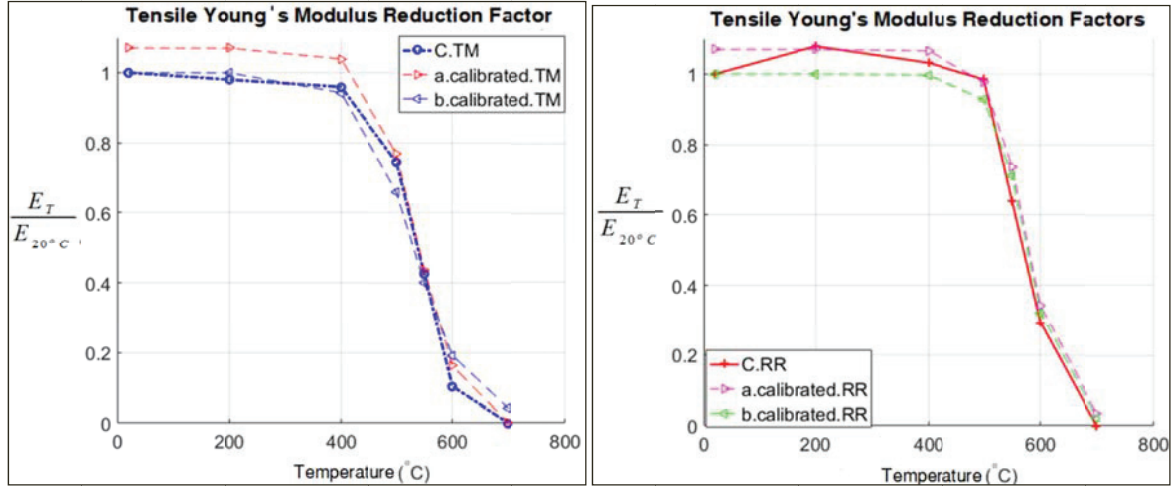


a) Thermo-mechanical ultimate strength; b) Residual test ultimate strength

Figure 91: Calibrated models compared with experimental ultimate strength.

a) Bisby's model (Bisby, 2003); b) Gibson's model (Gibson, 2005)

As seen in Figure 91, the calibrated models have small differences from the experimental ultimate strength between 20°C to 700°C. There are unique differences in the thermo-mechanical ultimate strength at 20°C for Gibson's model as well as residual ultimate strength at 600°C for Bisby's model. However, these differences are negligible compared with the experimental variation (Figure 69). On the other hand, from Figure 92, both calibrated models diverge at temperatures between 20°C and 400°C, where the Young's modulus remains at almost 90% of its value and then converges in the range of 400°C to 700°C, where Young's modulus drops sharply. From 20°C to 400°C, Gibson's calibrated model better fits the thermo-mechanical Young's modulus while Bisby's calibrated model better fits the residual Young's modulus.



(a) Thermo-mechanical Young's modulus;

(b) Residual Young's modulus

Figure 92: Calibrated models compared with experimental Young's modulus.

a) Bisby's model (Bisby, 2003); b) Gibson's model (Gibson, 2005)

2.8.2. Proposed analytical model for CFRP at thermo-mechanical condition

From the experimental results of second material series, it can be summarised that at temperatures ranging between 20°C and 200°C, the thermo-mechanical tensile strength of M-CFRP is significantly reduced up to 35% because that the glass transition of the used polymer is approximately 50°C – 90°C (Dong and Hu, 2016; Foster and Bisby, 2008; Moussa et al., 2012a). Above this temperature, the polymer melts and quickly loses its contribution to the composite performance. From 200°C to 500°C, its strength reduces slightly, approximately 15% because in this range, only carbon fibres contribute to the tensile performance of M-CFRP, and they experience small mass losses until 500°C (Yin et al., 1994). Above this temperature, this strength decreases quickly up to 40% due to the oxidation of carbon fibre, which is accelerated by the mechanical load and the strength reduction of the carbon fibre itself (Wang et al., 2011). The thermo-mechanical properties of M-CFRP well consist with those of P-CFRP. In this thesis, the authors propose using a three-degree polynomial function to illustrate the strength reduction of CFRP in a thermo-mechanical condition (condition with thermal and mechanical loads simultaneously) as seen in Equation 10:

$$\frac{\sigma_{u,T}}{\sigma_{u,20^\circ\text{C}}} = K_0 - K_1 \left(\frac{T - T_m}{T_{\text{max},10\%}} \right)^3 - K_2 \left(\frac{T - T_m}{T_{\text{max},10\%}} \right) \quad \text{Equation 10}$$

In which: T_m : The mechanical glass transition temperature; $T_{\text{max},10\%}$: Failure temperature at 10% of the stress ratio; K_0 : Coefficient (ranging between 0.4-0.6); K_1 and K_2 : Calibrated coefficients. In Equation 10, $T_{\text{max},10\%}$ is identified as the failure temperature at a stress ratio of 10% and T_m is the parameter relating to the temperature at which the curve is nearly symmetrical. K_0 , K_1 and K_2 are calibrated coefficients obtained by fitting with the experimental data. With the M-CFRP in this study, the values of factors are as follows: $T_m = 295^\circ\text{C}$, $T_{\text{max},10\%} = 636^\circ\text{C}$, $K_0 = 0.6$, $K_1 = 3.4$ and $K_2 = 0.3$. The calibrated result shows good agreement with the experimental data obtained from M-CFRP (Figure 93). Based on this result, the analytical model can be calibrated for evolution of thermo-mechanical ultimate strength at elevated temperature condition. The model was also used to calibrate the experimental data with the CFRP tested in similar thermo-mechanical conditions reported by (Phi

Long et al., 2016; Wang et al., 2011; Yu and Kodur, 2014) (Table 33). The calibrated models fit well with the reported data, as shown in Figure 94.

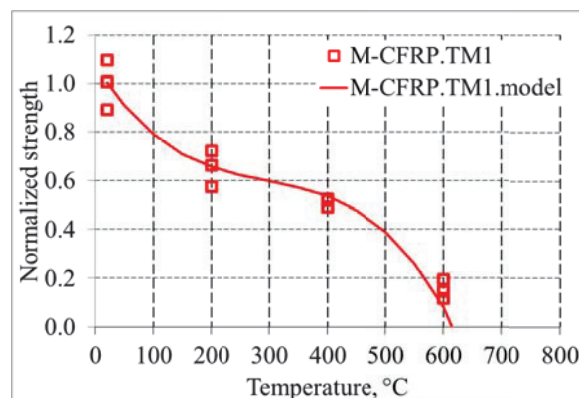


Figure 93: Analytical model with experimental result from M-CFRP.

Table 33: Calibrated results with different types of CFRP

N o	Experimental data			Calibrated results				
		Type of CFRP		T _m (°C)	T _{max} (°C)	K ₀	K	K ₂
1	(Nguyen et al., 2018)	P-CFRP	Laminate	315	650	0.50	3	0.50
2	(Wang et al., 2011)	P-CFRP	Laminate	350	700	0.50	2	0.35
3	(Yu and Kodur, 2014)	P-CFRP	Rod	315	650	0.50	2	0.80
4	(Yu and Kodur, 2014)	P-CFRP	Strip	315	636	0.55	1	0.80

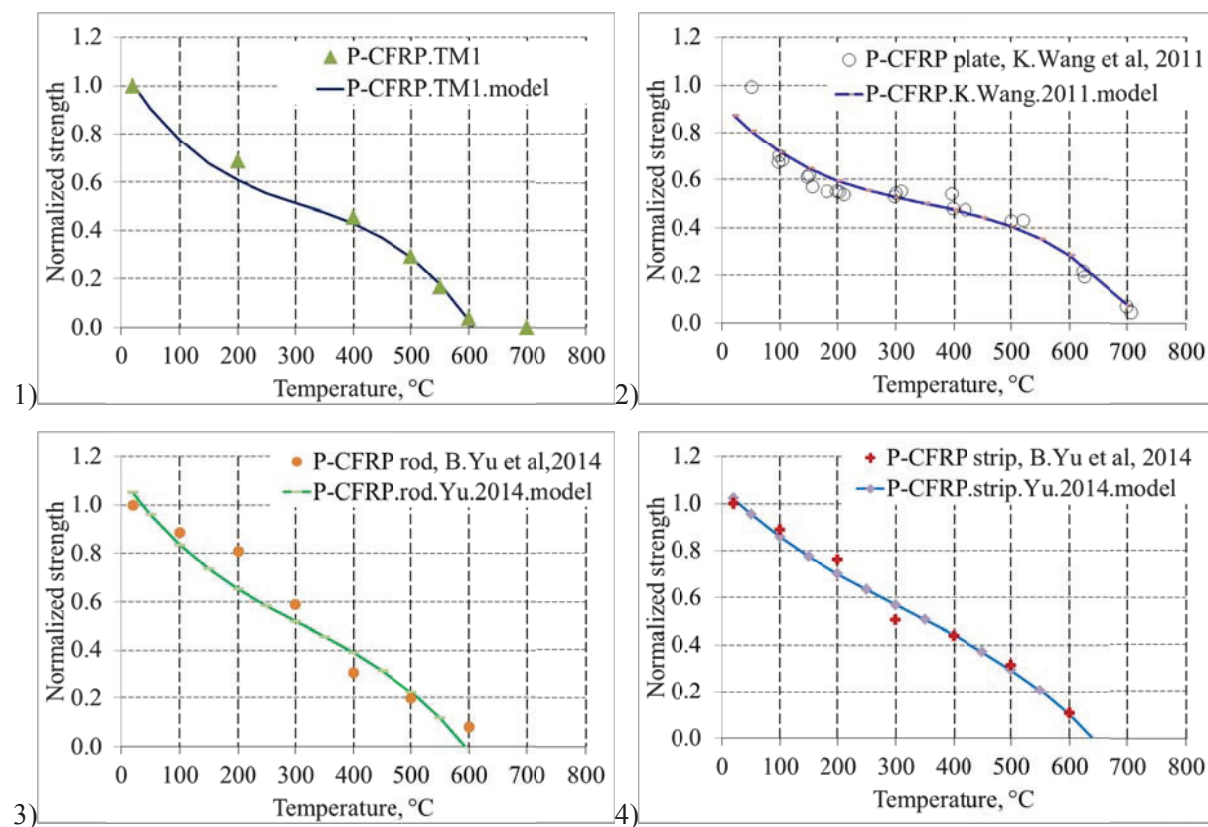


Figure 94: Comparison of the calibrated results with different types of CFRP.

2.9. Conclusion

The evolutions of the ultimate tensile stress and the Young's modulus of two types of CFRP (P-CFRP and M-CFRP) material as a function of the temperature between 20°C to 700°C have been experimentally identified. Some findings of this study are mentioned below:

The performance of the CFRP material is generally reduced as the temperature increases. The thermo-mechanical and residual ultimate strengths of P-CFRP gradually decrease from 20°C to 700°C, while its Young's modulus varies less than 10% from 20°C-400°C and then significantly decreases at 600°C. The thermo-mechanical and residual ultimate strengths of P-CFRP decrease by 50% at approximately 300°C and 500°C. The thermo-mechanical and residual Young's modulus of P-CFRP decreases by 50% at approximately 540°C in the thermo-mechanical procedure and at 570°C in the residual procedure. The evolution curves of the thermo-mechanical properties (both ultimate strength and Young's modulus) of P-CFRP are lower than the curves of residual properties for temperatures varying from 20°C to 600°C. The differences are minor from 20°C to 400°C but become remarkable from 500°C to 600°C. Similarly, the performances of M-CFRP material generally decrease when the material is exposed to increasing temperatures. The thermo-mechanical and residual strength gradually decreases when the temperature increases from 20°C to 700°C. The M-CFRP loses 50% of its strength at 400°C in thermo-mechanical condition and 45% in residual condition. Meanwhile, Young's modulus varies little in temperature, ranging from 20°C to 400°C and only decreases 30% at 600°C in thermo-mechanical condition but up to 72% with residual condition.

The correlation between thermal and mechanical loads has been experimentally confirmed. The evolution of the failure temperature and exposure duration of a CFRP in the function of mechanical loading (in terms of the stress ratio from 0.1 to 0.75) has been investigated. For both P-CFRP and M-CFRP, when the stress ratio increase from 0.1 to 0.5 (P-CFRP) and 0.6 (M-CFRP), the failure temperature and exposure duration gradually reduces and then significantly scales down when the stress ratio exceeds these values. This result contributes to the confirmation of the combined effect of thermal and mechanical impacts on the performance of CFRP at the same time.

The experimental result of P-CFRP at 400°C in two thermo-mechanical conditions confirm that thermo-mechanical ultimate strength and Young's modulus of P-CFRP experience little change with thermal exposure durations between 10 minutes and 90 minutes; In addition, the heating rate of exterior condition has small influence on the thermal resistance of P-CFRP at the stress ratio 0.25. It is because that the PAN carbon fibres are little affected by temperature which is under its degradation temperature.

The failure mode of CFRP depends on both the exposure temperature and applied mechanical load. As the temperature increases or the mechanical load decreases, the failure of CFRP changes from brittle to a more softened shape. This proves the mutual correlation between thermal and mechanical loads to the performance of CFRP material under thermo-mechanical condition. In a practical application of CFRP, the evolution of the failure temperature as a variation of mechanical load can be inferred from the evolution of strength as an increasing temperature and vice versa. In other words, the order of loading among the thermal and mechanical effects on CFRP has little influence on the obtained result.

At temperatures higher than the degradation temperature of the CFRP polymer matrix, the CFRP material starts releasing smoke, which can disturb the measurement of the material axial strain by the laser sensor.

The adjusted prediction models (by Gibson and Bisby) with the calibrated coefficients can predict the properties of P-CFRP under thermo-mechanical and residual conditions. From the authors' point of view, these results can be used for numerical modelling of behaviour of P-CFRP at the two studied elevated-temperature and mechanical conditions.

A three-degree polynomial analytical model has been proposed to apply with ultimate strength of CFRP in thermo-mechanical working conditions. The proposed model better fits with two studied CFRPs and other types of CFRP that have been reported with thermo-mechanical testing condition. This model can be used in numerically modelling of behaviour of CFRP, in which an elevated temperature and mechanical load are simultaneously applied.

From an application standpoint, there is little guideline for evaluating the fire performance of general structures (beams, slabs, columns) due to the missing gaps of available material data and calculation method. Even in research, the status of structure in a real fire is too complex and thus difficult to thoroughly understand. Among the factor that influence to the structure during fire, mechanical and thermal factors are mainly and simultaneously accounted for the structure failure, so they are the objects of our research. The used materials in this research are laminate pultruded CFRP (which is commonly used to externally reinforce structures) and M-CFRP (which is mainly used to strengthening structure in shear, flexural and confined performance). Therefore, the experimental data can be exploited in structure profiles such as concrete structures (beams, slabs,...), steel (beam,...) reinforced with CFRP. With data from three testing conditions, the case study could be evaluating the performance of structure during-fire with combined impacts of mechanical and thermal effects or post-fire condition.

In design application, regarding the working condition of CFRP in real fire, there may be more effects that can influence to the performance of CFRP for example: the direct contacting to fire or not, duration of exposing to temperature and the history of thermal interaction (such as peak temperature) or cyclic thermal action (Ghadimi et al., 2017; Russo et al., 2015)... So far in this research, the thermo-mechanical result is lower than residual one about 15% to 20% depending on the temperature level and the type of material. However, using the experimental data from thermo-mechanical test will provide closer condition to what can be happen during a real fire: that is the co-existence of both thermal and mechanical loads at the same time. The residual result, in another way, can be exploited in the evaluating the post-fire behaviour of structure reinforced with CFRP.

Moreover, in experimental study, the used of experimental performance of CFRP material under on the steady state temperature test can be used to imply its performance under transient temperature condition.

Chapter 3:

Experimental approach:

Structure scale

CHAPTER 3 **Experimental approach: Structure scales**

This chapter includes two main parts: the first part focuses on small scale CFRP reinforced concrete structure and the second part focuses on insulated CFRP specimen. In the first part, the performances of small-scale CFRP reinforced concrete structure with two reinforcement methods and three types of adhesive are investigated at three different combinations of temperature and mechanical effects. In the second part, an insulation material has been used to protect CFRP to determine its efficiency to protect CFRP material under the mutual influence of elevated temperature and mechanical loading.

3.1. Small scale CFRP reinforced concrete structures

This section is to experimentally study the performance of CFRP reinforced concrete structure under conditions with different combinations of temperature and mechanical effects. The objective this section is to focus on the performance of CFRP reinforced structure under different close-to-fire conditions (regarding the mechanical and temperature loads). Two methods of reinforcement and three bonding materials also are investigated in this section.

3.1.1. Presentation of the materials used - test design and preparation

This subsection respectively demonstrates the following points: design of sample, concrete, CFRP, adhesive, preparation procedure of sample.

3.1.1.1. *Design of sample*

The purpose of this study is to investigate the performance of CFRP-concrete bond at different thermo-temperature conditions. There are several methods that can be found in the literature to determine shear capacity of the joint such as single lap, double lap (Camli and Binici, 2007; Mazzotti et al., 2008) or even beam test (Chen and Teng, 2005). In this study, the standard double shear method (Ferrier et al., 2010) has been developed with adaptation to the testing device and testing conditions. The double lap testing specimen includes two concrete blocks connected by two CFRP strips using two reinforcement methods: externally bonding reinforcement (EBR) and near surface mounted (NSM) (Figure 95). The size of double shear sample has been reduced to meet the limit heating space of the furnace. There is a steel bar in the middle of sample that is welded to a steel plate at bottom of concrete block in order to connect the specimen with two loading heads. The steel plates on the bottom of concrete blocks are designed with the idea to exploit the compressive strength of concrete which is much higher than the material tensile strength (even at elevated temperature condition) and also to reduce the effect of tensile stress on bonded corner of concrete (Mazzotti et al., 2008). To bond CFRP to concrete, several proposed methods to determine the bond length and width at normal temperature condition have been summarized in previous research (Hosseini and Mostofinejad, 2014). In this study, with available testing apparatus, the CFRP is bonded to two concrete blocks with two different lengths: tie length of 90 mm on top part (anchorage bonding) and observed length of 70 mm on the bottom part (observed bonding, Figure 95) with the failure is expected to happen on the bottom block of concrete. In order to maintain the comparability and feasibility of the different configurations, the geometry of the observed bonded region between CFRP and concrete has been defined to be equal and are 2800 mm² totally for both sides and the anchorage bonded regions are 3600 mm² totally for both sides.

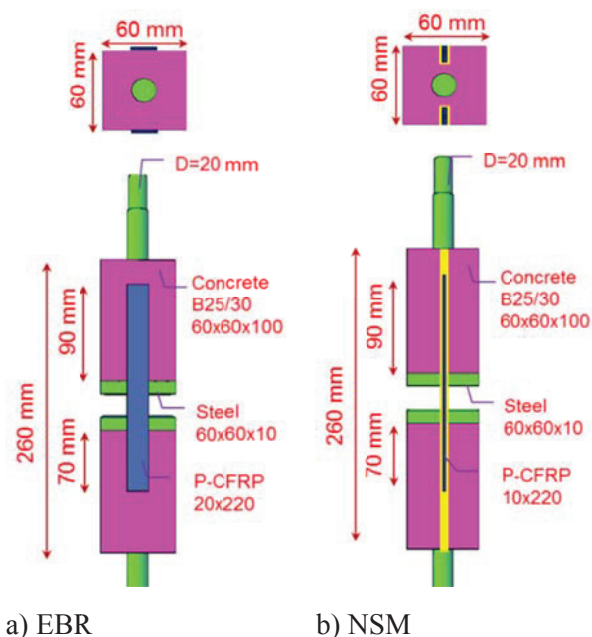


Figure 95: Details of two specimen configurations.

(a) externally bonding reinforcement (EBR) and (b) near surface mounted (NSM)

3.1.1.2. Concrete

Due to the small size of concrete block, the natural gravel (rounded in shape) for concrete has been sieved with maximum dimension at 6 mm to meet the sample requirements. The normalized standardized sand includes siliceous particles (generally isometric and rounded in shape) with maximum grain size of 2mm, accordance with the standard EN 196-1. The cement used is the Portland cement with commercial class of 32.5. The gravel, the sand and the cement, mentioned above, have been mixed to obtain the concrete of C25/30 after 28 days with the concrete is as described in Table 34.

Table 34: Concrete composition (for 1m³)

Portland cement, commercial class of 32.5	Water	Gravel, (d<6mm)	Normalized standard sand, (d<2mm)
kg	kg	kg	kg
336	180	1262	622

3.1.1.3. CFRP

The CFRP used is unidirectional prefabricated laminate with the standard cross-section of 1.2mmx50mm and 25m in length. This CFRP is P-CFRP which is already presented in the chapter 2. The CFRP is prepared in to plates with the dimensions of 10mmx220mm (width x length in mm) with NSM specimen and 20mm x 220mm (width x length in mm) with EBR specimens (Figure 95).

3.1.1.4. *Adhesive*

In this thesis, three adhesives have been used to bond CFRP on to concrete blocks including: two epoxies and one cement-based adhesive. The details of these three adhesives are shown below:

- The first type of epoxy (labelled Epoxy 1, commercial name: Duralco 4703) is a two-component adhesive with Al_2O_3 and metal particles. Its service temperature is introduced up to 350°C for short term applications and 320°C for long term applications. According to supplier's datasheet, the tensile strength and lap shear strength of this epoxy are respectively 81.4 MPa and 76.5 MPa (at 20°C). The resin's hardness is classified as shore D95 as ASTM D2240. Using this adhesive, it is expected to extend the service duration and also the performance of CFRP reinforced concrete under thermo-mechanical condition concerning fire case.
- The second type of epoxy (labelled epoxy 2, commercial name: Eponal 380) is a two-component product which is common use with concrete bonding. The service temperature range of this epoxy has not been mention in technical data as well as in the literature. The shear strength, tensile strength and compression strength of this epoxy at 20°C are respectively 15 MPa, 29.5 MPa and 83 MPa. As commonly used material in civil engineering, in this research, this adhesive is used as a referenced data for the service duration and the performance of CFRP reinforced concrete under thermo-mechanical condition concerning fire case.
- The cement-based adhesive (labelled cement-based adhesive) involves calcium aluminate cement (SECAR51, 81.37% by weight), polycarboxylate based superplasticizer (Peramin® CONPAC 700, 0.53% by weight), viscosity modifier agent (Master Matrix UW 400, 0.06% by weight) and water (18.04% by weight). This adhesive is used to study the efficiency of a cement-based adhesive in improving the service duration and the performance of CFRP reinforced concrete under thermo-mechanical condition concerning fire case.

3.1.1.5. *Preparation procedure of CFRP reinforced concrete specimens*

The concrete blocks were casted in mould with dimensions: 60x60x100 (dimension in mm, Figure 96 and Figure 97) and then prepared according to two configurations: the first type is prepared for EBR method and the second is prepared for NSM method (Figure 98, Figure 100). In the first type, the CFRP will be bonded directly on the grinded surface of concrete blocks using adhesive (only the two bonded surfaces need to be slight grinded, Figure 98-EBR). The CFRP plate is then bonded to concrete surface and held in position by two grips until the adhesive harden. In the second type, there are two cuts on two opposite sides of the concrete blocks with the depth at about 11 mm and the width at about 4 mm (Figure 97 and Figure 98-NSM). The adhesive is then prepared and mixed according to technical instruction before being used to bond CFRP on to two opposite slots in two blocks of concrete (Figure 99). After curing duration in laboratory temperature condition, the specimens are ready for tests (Figure 100).



Figure 96: Casting of concrete blocks.

a) Preparation of mould; b) Set up of thermocouples; c) Mix concrete; d) Casting of concrete and then concrete curing.

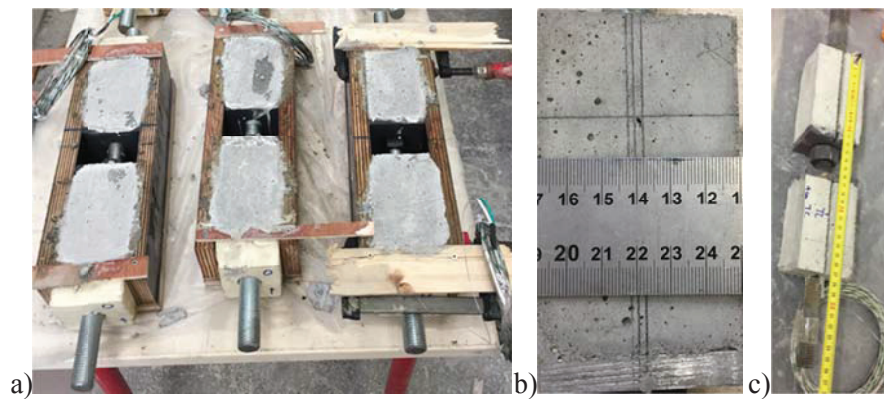


Figure 97: Preparation of concrete for bonding (NSM specimen).

a) Remove mould; b) Identify cut width; c) Locate thermocouples in the contact surface of concrete and CFRP

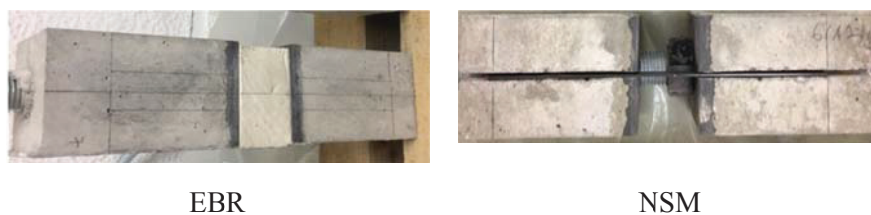


Figure 98: Prepared concrete blocks before bonding



Figure 99: Bonding of P-CFRP to concrete using adhesive.

a) Preparation of CFRP plate; b) Mix adhesive; c) Cure at ambient temperature condition



Figure 100: Samples ready for tests

3.1.2. Test apparatuses - setting of specimen

In this chapter, the thermo-mechanical system is also used to study the performance of CFRP reinforced concrete specimen at different temperature-mechanical conditions. In order to better explain the thermal status of specimen during the thermal loading phase, in some test cases, 10 thermo-couples have been set up to follow the increase of temperature at different position inside and outside of the specimen (from TC1 to TC10, Figure 101 and Figure 102). A thermal acquisition system has been used to read and record thermal data from thermo-couples at the same time when the thermo-mechanical system read mechanical and temperature data. As can be seen in Figure 101, there are 5 thermocouples from TC1 to TC5 placed inside the concrete block (observed part) to follow the heat transfer during the heating phase of furnace. Outside of specimen, there are 8 other thermocouples (Figure 102): 3 thermocouples from the thermo-mechanical system from TC-I, TC-II to TC-III to follow the temperature increase on the side of specimen at three different levels; 5 thermocouples from exterior system to measure the temperature increase at different positions: outside of the furnace (TC6 and TC10) and inside of the furnace (TC7 on top of specimen, TC8 on the middle of specimen but between two concrete blocks, and TC9 on the bottom of specimen)

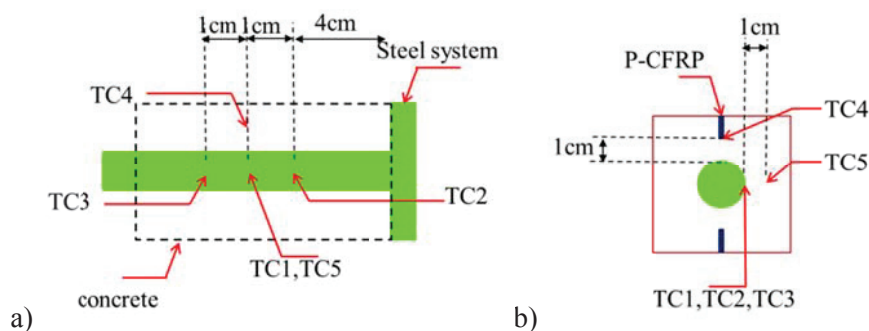


Figure 101: Configuration of thermocouples (TC) in specimen

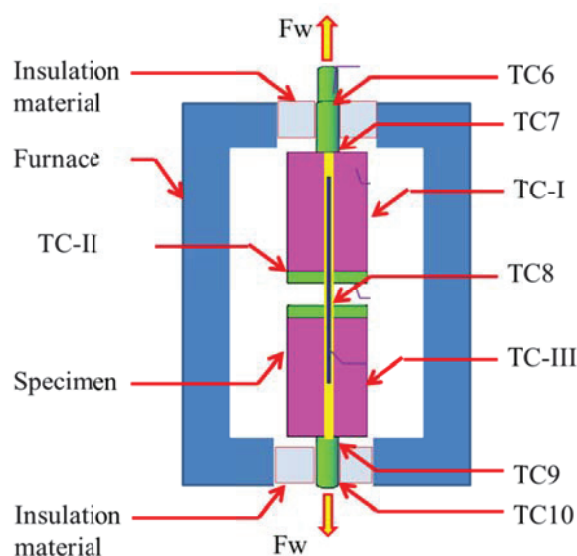


Figure 102: Configuration of thermocouples (TC) in furnace

3.1.3. Test summary

The experimental test in this chapter is to investigate the performance of CFRP bonded structure under thermo-mechanical conditions with consideration in reinforcement method, adhesive type and also testing method. There are three conditions that are used to investigate the performance of specimens: residual test (RR test), thermo-mechanical test with constant temperature (TM1 test) and thermo-mechanical test with constant mechanical load (TM2) which are mentioned with details in the chapter 2 (test programs). In this chapter, these three programs have been modified to adapt with the material performance as well as to better replicate the different conditions concerning fire case. In residual test, when the temperature surrounding the specimen increases from ambient temperature to reach a pre-defined level (T_i), the furnace stops heating. When specimen temperature gradually cools down and reaches ambient temperature and maintains stable at this level, the specimen is tested following direct tensile test. In another word, the waiting time (or exposure duration) in the phase 2 of RR test is set at 0 minute (Figure 58). Similarly, in TM1 testing condition, the waiting time (or exposure duration) in the phase 2 of TM1 test is also set at 0 minute (Figure 59). When the temperature around the specimen increases reaching the pre-defined level (T_i), the mechanical load will be applied on specimen following direct tensile procedure. The TM2 testing condition in this chapter is conducted as the same procedure as mentioned in the chapter 2. Table 35 summarizes 8

tested series of small scale CFRP reinforced concrete structure conducted in this research with the details in configuration, method of reinforcement, adhesive and tested program.

Table 35: Summary of tested series

Abbreviations used: EBR: external bonding reinforcement; NSM: near surface mounted reinforcement; WSP: specimen with steel plate; WOSP: specimen without steel plate; RR: residual regime test; TM1: thermomechanical test at constant temperature; TM2: thermomechanical test at constant load.

Series	Reinforcement method		Configuration		Adhesive			Test program			
	EBR	NSM	WSP	WOSP	Epoxy 1	Epoxy 2	Cement-based adhesive	20°C	RR	TM1	TM2
1		X	X	X	X			X			
2		X	X		X				X		
3		X	X		X					X	
4		X		X	X						X
5	X		X		X						X
6		X	X		X						X
7		X	X			X					X
8		X	X				X				X

The explanations for each series are as following details:

- Series 1: referenced series at 20°C. In this series, four specimens reinforced by NSM method have been tested following direct tensile procedure including two configurations: with steel plate (WSP) and without steel plate (WOSP) at the bottom of concrete blocks. The purpose is to experimentally evaluate the efficiency of steel plate in improving structure performance by better exploiting compressive capacity of concrete material.
- Series 2: RR test of CFRP reinforced concrete using NSM method. In this series, the specimens are tested at three levels of temperature: 75°C, 150°C and 300°C.
- Series 3: TM1 test of CFRP reinforced concrete using NSM method. The specimens are tested at three levels of temperature: 75°C, 150°C and 300°C.
- Series 4: TM2 test of CFRP reinforced concrete using NSM method. The specimens, prepared without steel plate at the bottom, are tested at two mechanical levels: 400N, 2800N.
- Series 5: TM2 test of CFRP reinforced concrete using EBR method. Specimens are tested at two levels of mechanical load: 400N and 1400N.
- Series 6, 7, 8: TM2 test of CFRP reinforced concrete using NSM method. The specimens, bonded by three different adhesives: epoxy 1, epoxy 2, cement-based, are test at different mechanical levels: 400N, 840N, 1400N and 2800N (series 6 only)

It should be noted that in this chapter, the temperature on RR and TM1 program is not homogeneous within the structure as test descriptions in the chapter 2. The conducted series are summarized in Table 35 and each result is presented in the following section.

3.1.4. Test results

This section displays the various results obtained from 8 above-mentioned series. The results of the series 1 through 3 show the mechanical performance of CFRP reinforced concrete specimens using epoxy 1 adhesive in three different cases: ambient temperature, residual and thermo-mechanical TM1 conditions. Other results of the series from 4 through 8 show the thermal performance of CFRP reinforced concrete specimens in thermo-mechanical TM2 condition with modifications in reinforcement method, adhesive used and also specimen configurations.

3.1.4.1. Series 1: mechanical performance at 20 °C of two specimen configurations

Table 36 summarizes the ultimate forces of specimens at 20°C with two configurations: with steel plate (WSP) and without steel plate (WOSP) at the bottom of concrete blocks. As the result, the failure load of WOSP specimen is about 12.941 kN on average while with WSP specimen, the average failure load is 17.829 kN (about 38% higher than WOSP specimen). Figure 103 displays the force-total displacement curves obtained in series 1. According to this, the curves show that both configurations have the same linear tendency with similar stiffness but their ultimate resistances are different.

Table 36: Summary of referenced test at 20 °C; WSP: specimen with steel plate; WOSP: specimen without steel plate.

Test No.	Specimen		Failure load, N	
	Configuration	No		Average
1	WSP	1	17814	17829
2		2	17844	
3	WOSP	1	12203	12941
4		2	13679	

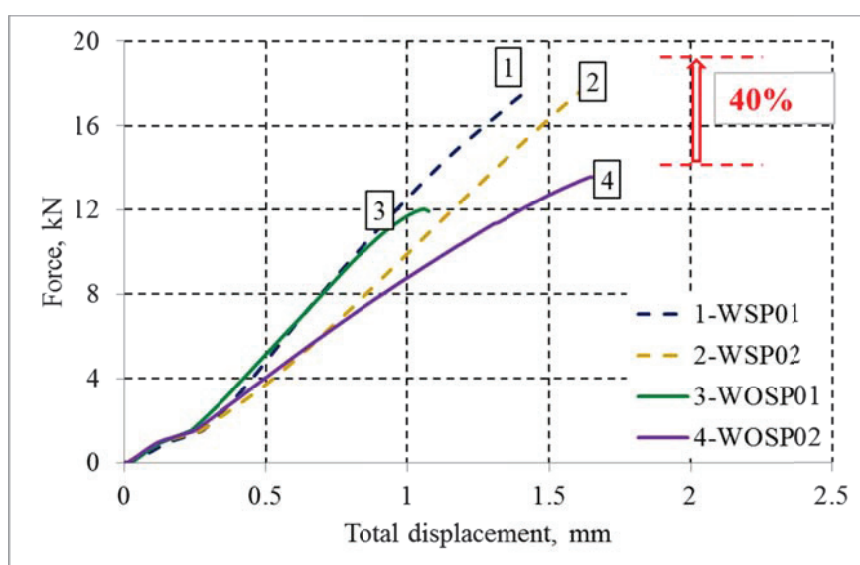


Figure 103: Force- total displacement curves at 20 °C; WSP: specimen with steel plate; WOSP: specimen without steel plate.

Figure 104 and Figure 105 respectively describe the failure of two specimen configurations. Figure 104 shows that without steel plate at the bottom of concrete block, the structure collapses due to the tensile or shear failure of concrete with failure surface is about 45° to the axis of tensile force. However, Figure 105 shows that with the reinforcement of steel plate at the bottom of concrete block, the structure collapses due to the compressive failure of concrete at the bonded corner in one side and shear failure at CFRP-adhesive interface on the other side.



Figure 104: Failure of WOSP specimen at 20 °C – series 1; WOSP: specimen without steel plate.



Figure 105: Failure of WSP specimen at 20 °C – series 1; WSP: specimen with steel plate.

3.1.4.2. Series 2: residual performance of CFRP reinforced concrete using NSM method

Table 37 summarizes the residual performance of specimens after being exposed to different temperature levels from 75°C to 300°C. The result indicates that as the temperature increases from 75°C to 300°C, the mechanical performance of CFRP reinforced concrete specimen varies a wide range: at 75°C, the failure load of specimen is 13161N, at 150°C the failure load can reach up to 28877N and even at 300°C, this failure load is 18997N. Table 37 shows that in the tests with target

temperature increases up to 300°C, although the actual heating rate increases from 2.06°C/minute to 4.41°C/minute, the duration to reach the target temperature of tests increases from 26.7 minute to 63.5 minutes.

Table 37: Summary of series 2: residual performance of specimens after being exposed to different temperature levels from 75°C to 300°C

Test No	Target temperature	Specimen No	Duration to reach target temperature	Actual heating rate	Failure load
	°C		minute	°C/minute	N
1	75	1	26.7	2.06	13161
2	150	1	41.7	3.12	28877
3	300	1	63.5	4.41	18997

Figure 106 displays the force - total displacement curves at different target temperatures from 75°C to 300°C in series 2. The residual curves show linear trend before reaching the peak load with a quick load reduction afterwards. There is post-peak performance in the tests 1 and 3 before the totally collapse of specimen.

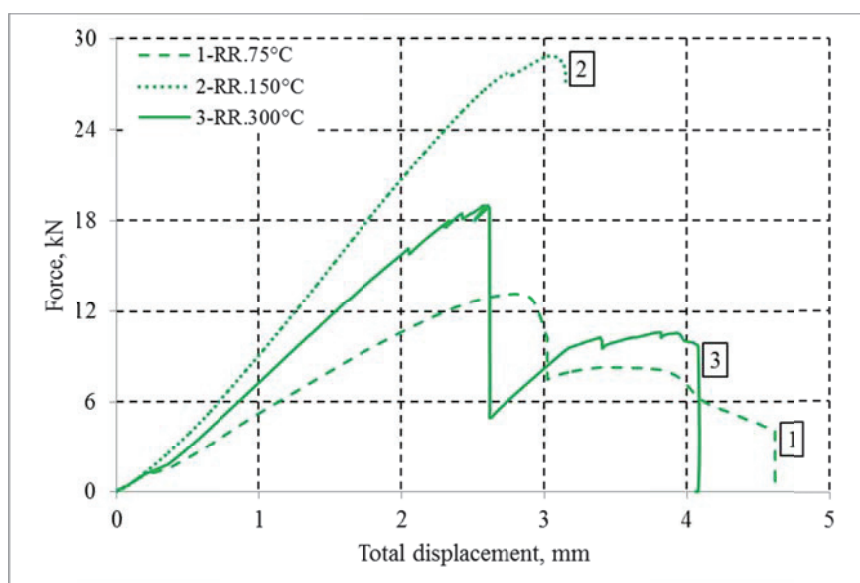


Figure 106: Force- total displacement curves at different temperature levels from 75°C to 300°C in series 2 (RR program)

Figure 107 shows the failure of residual specimens obtained in series 2. This shows that after failure, the concrete at the bond corner between steel plate and CFRP plate fails due to compression in one side and in the other side the bond between CFRP and the epoxy 1 fail, leading to the slippage.

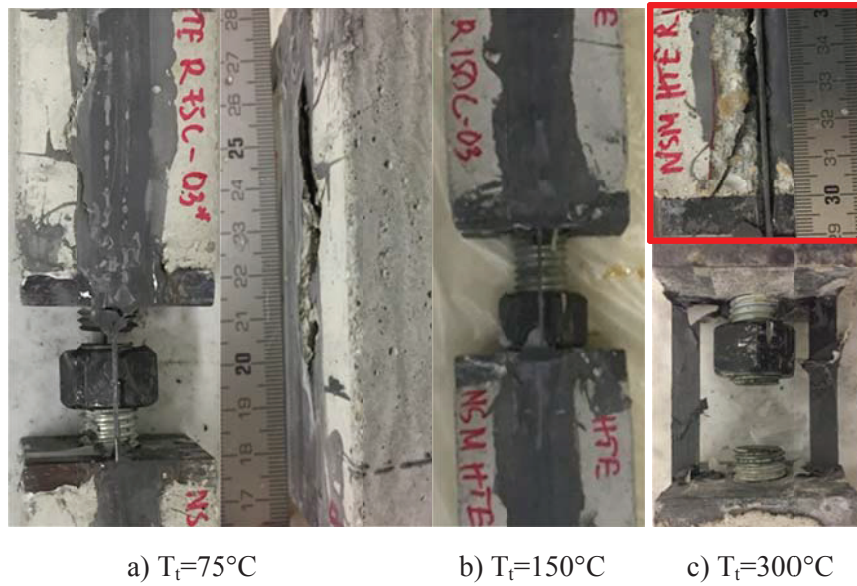
a) $T_i=75^{\circ}\text{C}$ b) $T_i=150^{\circ}\text{C}$ c) $T_i=300^{\circ}\text{C}$

Figure 107: Failure of specimens in series 2 under tensile loading and after being exposed to different temperatures: from 75°C , 150°C and to 300°C .

3.1.4.3. Series 3: Thermo-mechanical performance of CFRP reinforced concrete using NSM method (TM1 program)

Table 38 summarizes the results of thermo-mechanical performance of specimens at different temperature levels in series 3. It is indicated that as the target temperature increases, the mechanical failure load reduces on average. As indicated in Table 38, at low level of temperature (75°C , compared to maximum furnace capacity) it is more difficult to maintain condition at the programmed temperature level than higher temperature levels (150°C and 300°C). Particularly, at three tests 1, 2 and 3, the programmed target temperature was set at 75°C and it takes the furnace from 20 minutes to 25 minutes to increase from ambient temperature to 75°C . However, in tests 1 and 2, the temperature keeps rising gradually after reaching 75°C and so the target temperature has been modified to a higher level. As the result, the actual target temperatures in tests 1 and 2 are higher than the programmed value. For the tests from 4 to 7, the actual temperature conditions well follow the programmed value.

Table 38: Summary of series 3

Test No	Target temperature, $^{\circ}\text{C}$		Specimen No	Duration to reach target temperature minute	Actual heating rate $^{\circ}\text{C}/\text{minute}$	Failure load	
	Programmed	Actual				N	Average (N)
1	75	85	1	25.4 (75°C) 38.4 (85°C)	2.16 1.69	3769	3870.1
2	75	90	2	20.0 (75°C) 24.2 (90°C)	2.75 2.89	2120	
3	75	75	3	22.5 (75°C)	2.44	5722	
4	150	150	1	41.7 (150°C)	3.12	2713	2242.3
5	150	150	2	~ 58.2 (150°C)	2.23	1154	
6	150	150	3	47.7 (150°C)	2.73	2860	
7	300	300	1	91.0 (300°C)	3.08	1519	1519

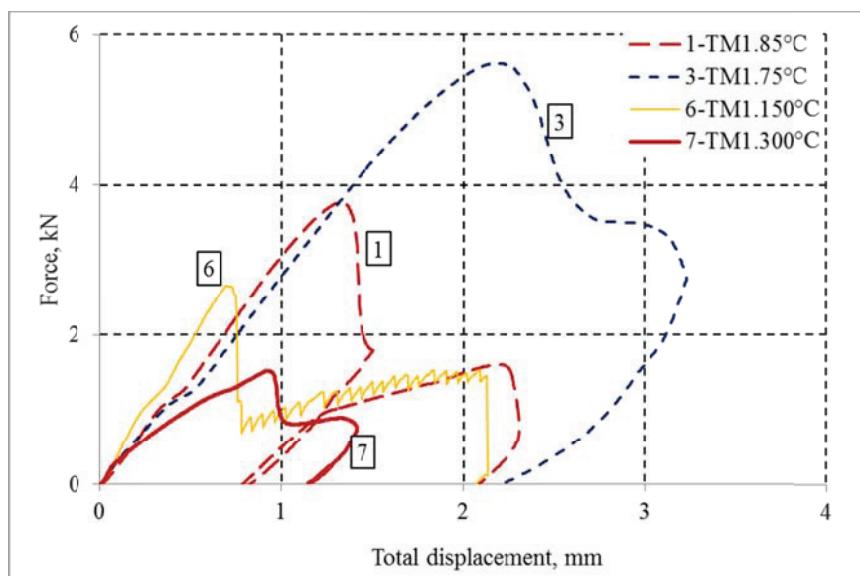


Figure 108: Force- total displacement curves at different temperature levels (75°C; 85°C; 150°C; 300°C) (TM1 program)

Figure 108 displays the force-total displacement curves of specimens tested with thermomechanical regime (TM1) at different target temperatures varying from 75°C to 300°C. In this series, the curves show the linear trend before reaching the peak load, and reduce at post-peak performance. According to Figure 108, the peak, post-peak value and total displacements of specimens reduce as the target temperature increases. Figure 109 displays the failures of specimens at different temperature levels in series 3. As can be seen from the figure, the specimens collapse due to the shear failure of CFRP-adhesive interface which then leads to slippage of CFRP plate in between adhesive layers.

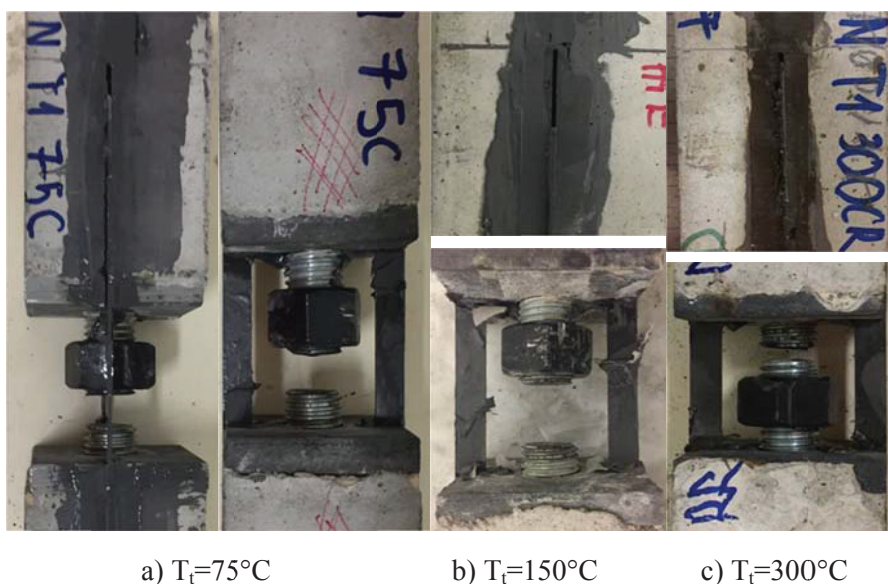


Figure 109: Failure mode of TM1 test - series 3 at three temperature levels

3.1.4.4. *Series 4: Thermo-mechanical performance of CFRP reinforced concrete using NSM method, without steel plate configuration (TM2 program)*

Table 39 summarizes the thermal performance of specimens of WOSP configuration at two different mechanical load cases: 400N and 2800N (series 4). The result shows that as the mechanical load increases from 400N to 2800N, the failure temperature reduces from 673°C to 252°C and the exposure duration reduces from 24.28 minutes to 8.84 minutes (at similar heating rate about 25.41°C/minute on average). Figure 110 and Figure 111 display force-time, temperature-time and total displacement-time curves meanwhile Figure 112 displays force-total displacement curves obtained from series 4. According to these figures, as the temperature increases during the test, the total displacement of specimen increases (Figure 111) while the mechanical load is maintained until failure (Figure 110).

Table 39: Summary of series 4: thermal performance of specimens of without steel plate (WOSP) configuration at different mechanical load cases (TM2 program)

Test No	Mechanical load (N)		Specimen No	Failure temperature	Exposure duration	Average heating rate
	Programmed	Actual		°C	minute	°C/minute
1	400	403	1	673	24.28	26.26
2	2800	2804	1	252	8.84	24.55

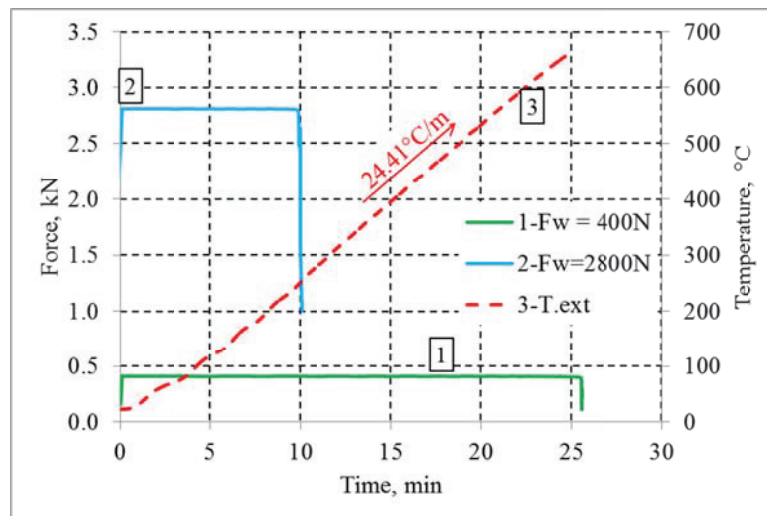


Figure 110: Force-time and temperature-time curves - series 4; WOSP specimens tested at 400N and 2800 N (TM2 program)

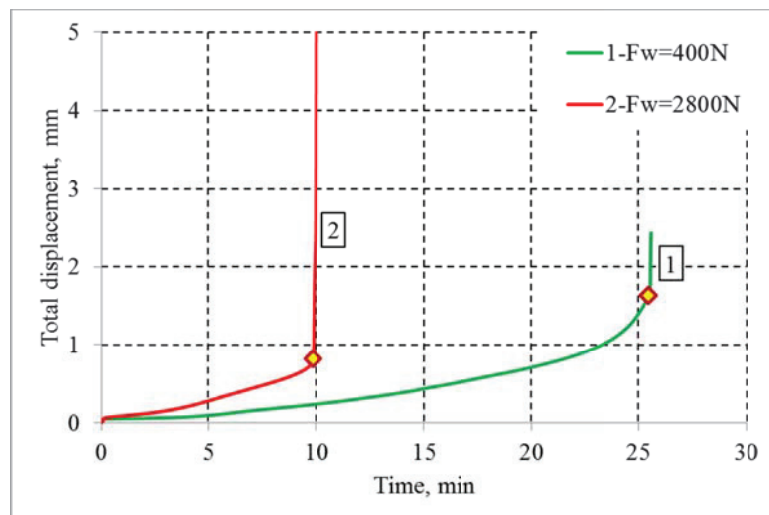


Figure 111: Total displacement- time curve – series 4; WOSP specimens tested at 400N and 2800 N (TM2 program)

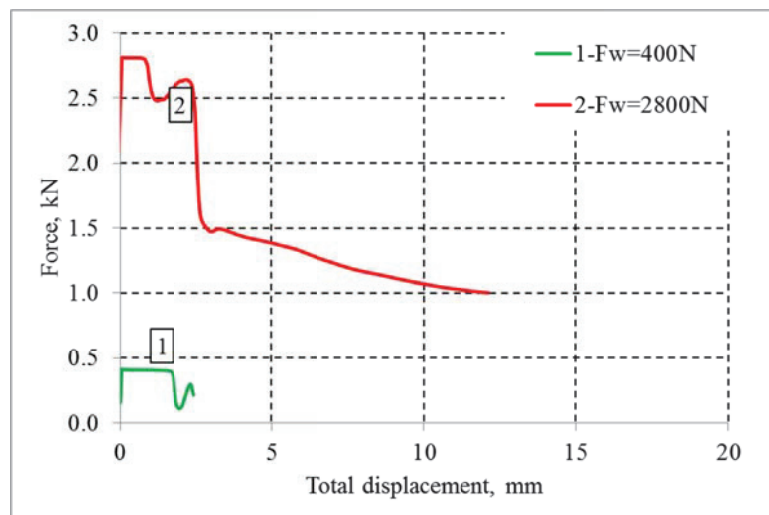


Figure 112: Force-total displacement curves at different mechanical load - series 4; WOSP specimens tested at 400N and 2800 N (TM2 program)

As can be seen from Figure 113 with specimen failures, the specimen collapse due to the shear failure of CFRP-adhesive interface which is resulted from the exceed of shear stress to the shear resistance. In the test 1 ($F_w = 400\text{N}$) the adhesive material has been partly burnt and the cracks appear and develop to inner direction of concrete blocks while in the test 2 ($F_w = 2800\text{N}$), the concrete blocks stay undamaged.

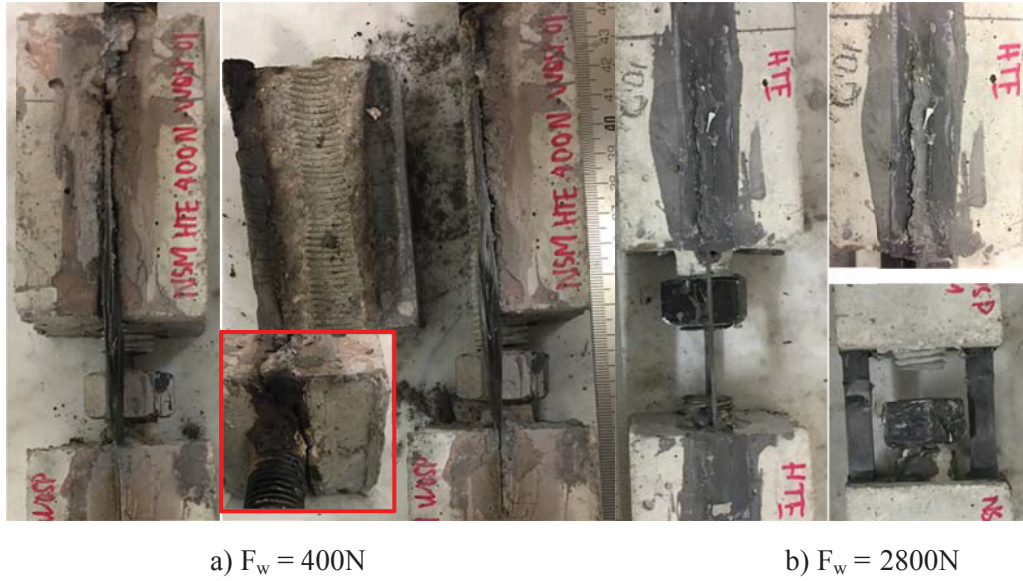


Figure 113: Failure of specimen without steel plate (TM2 test) – series 4

3.1.4.5. Series 5: Thermo-mechanical performance of CFRP reinforced concrete using EBR method (TM2 program).

Table 40 summarizes the thermal performance of CFRP reinforced concrete using EBR method (series 5). According to this table, the actual mechanical load applied on specimen is well controlled; the difference between programmed load and actual load is small (less than 2%). The failure temperature at the mechanical load of 400N is about 230°C corresponding to 8.3 minutes of exposure duration on average. At the mechanical load of 1400N, these values are 135°C and 4.6 minutes respectively. The average actual heating rate on the series is about 22.5°C/minute.

Table 40: Summary of series 5: thermal performance of CFRP reinforced concrete using EBR method

Test No	Mechanical load F_w , N		Specimen No	Failure temperature (°C)		Exposure duration (minute)		Actual heating rate, (°C/minute)	
	Programmed F_w	Actual F_w			Average		Average		Average
1	400	408	1	193	230.1	6.94	8.3	22.78	23.5
2	400	409	2	267		9.62		24.12	
3	1400	1406	1	138	134.6	4.73	4.6	21.78	21.6
4	1400	1404	2	131		4.51		21.34	

Figure 114 and Figure 115 display the temperature-time, force-time and total displacement-time curves while Figure 116 displays force-total displacement curves in each test mentioned in Table 40. During the test, the increases of exterior temperature are similar among the tests as shown in Figure 114 (curve number 5, Text) with the actual heating rate of 22.5°C/minute on average. As can be seen from these figures, when structure collapses, the force quickly drops (Figure 114), total displacement rapidly extends (Figure 115). After failure point, the structural performance is still partly maintained (Figure 116); it is because that the structure collapses due to the debonding of CFRP plate in one side while the other plate still stays (Figure 117).

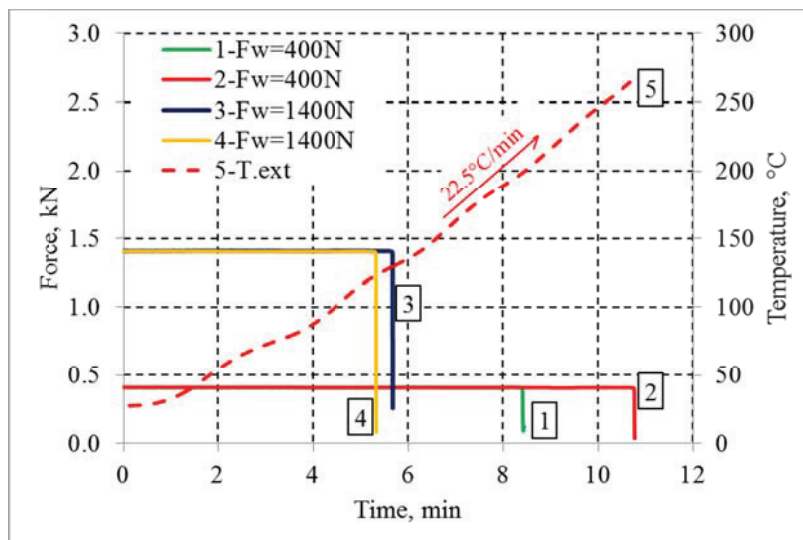


Figure 114: Force-time and temperature-time curves – series 5; thermal performance of CFRP reinforced concrete using EBR method

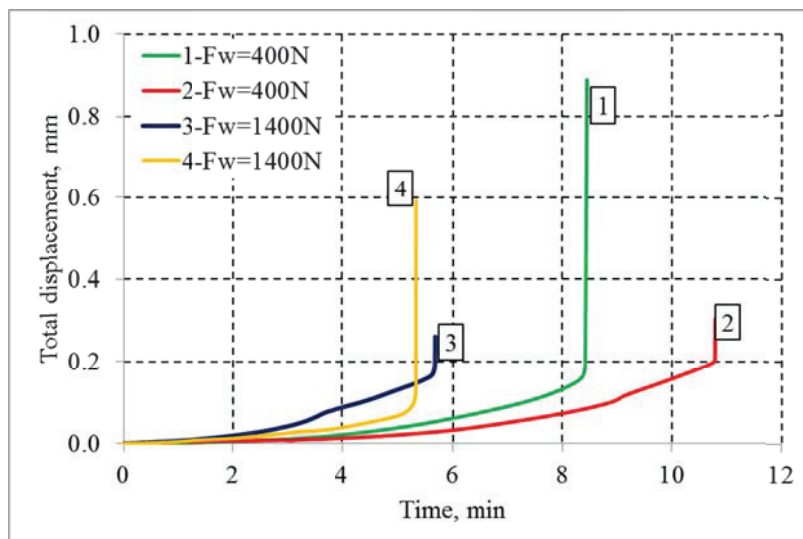


Figure 115: Total displacement- time curve – series 5; thermal performance of CFRP reinforced concrete using EBR method

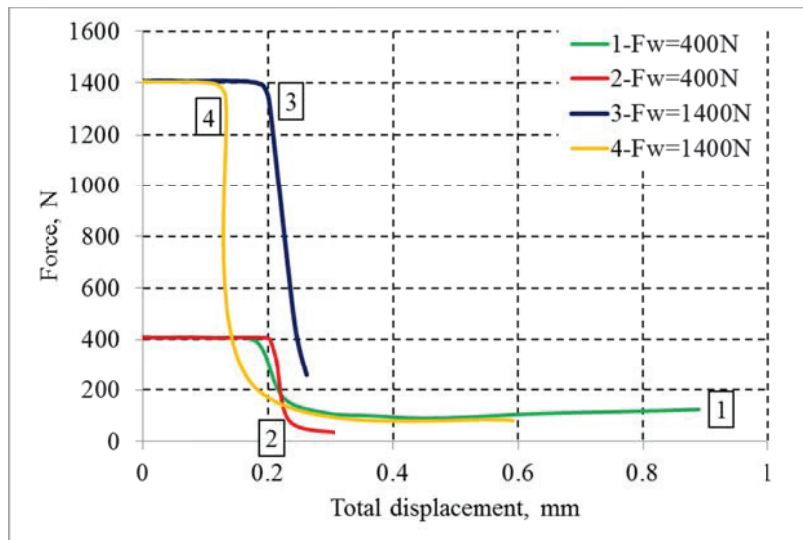


Figure 116: Force-total displacement curves at different mechanical loads – series 5; thermal performance of CFRP reinforced concrete using EBR method

As can be seen from Figure 117 with specimen failure, the structure collapses due to the failure at CFRP-adhesive interface in all the tested cases. The concrete and CFRP material has not been much damaged.

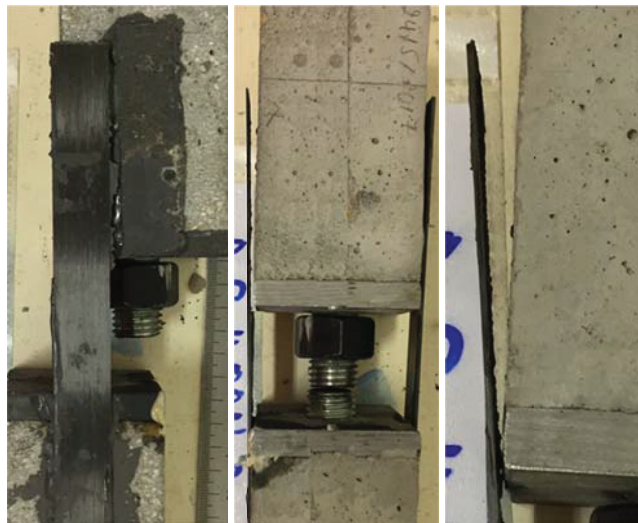


Figure 117: Failure of EBR specimen (TM2 test) – series 5

3.1.4.6. Series 6: Thermo-mechanical performance of CFRP reinforced concrete using NSM method- epoxy 1 (TM2 program)

Table 41 summarizes the thermal performance of CFRP reinforced concrete specimens at different mechanical load cases in series 6. The actual mechanical loads are close to the programmed values; the actual heating rate in the tests 3 to 9 are about 24.66°C/minute on average while in tests 1 and 2 the actual heating rate is 15°C/minute on average. As programmed, the heating rate is set at 30°C/minute and the maximum temperature level is set at 1100°C. Depending on the actual test condition, the furnace is controlled to maintain the temperature on specimen side homogenous with maximum temperature differences between TC-I, TC-II and TC-III that are less than 10°C. Because of

this condition, the actual heating rate estimated from average heating rate in heating phase is normally smaller than the programmed value.

Table 41: Summary of series 6: thermo-mechanical performance of CFRP reinforced concrete using NSM method- epoxy 1 (TM2 program)

Test No	Mechanical load F_w , N		Failure temperature, (°C)		Exposure duration, (minute)		Actual heating rate, °C/minute	
	Programmed F_w	Actual F_w		Average		Average		Average
1	400	407	799	837.8	53.10	53.4	14.39	15.0
2	400	407	877		53.61		15.70	
3	840	841	655	543.7	24.51	20.3	25.27	25.0
4	840	847	441		15.97		25.44	
5	840	842	535		20.55		24.34	
6	1400	1404	210	295.8	7.43	10.5	23.59	24.6
7	1400	1405	309		11.47		23.91	
8	1400	1400	368		12.71		26.18	
9	2800	2802	224	224	7.94	7.94	23.80	23.8

Figure 118, Figure 119 display temperature-time, force-time, total displacement-time curves and Figure 120 displays force-total displacement curves at different mechanical load cases of series 6. The temperature-time curve (curve number 10, Figure 118), obtained from the test 2, represent the typical temperature increase during the test period. According to this curve, the temperature in heating chamber increases with the actual heating rate of 24.4°C/minute which is close to the heating rate in the tests from 3 to 9 until reaching about 700°C. The heating rate then reduces to 4.3°C/minute due to homogenous temperature condition. Therefore, the overall heating rates of the tests 1 and 2 on Table 41 are lower than other test cases.

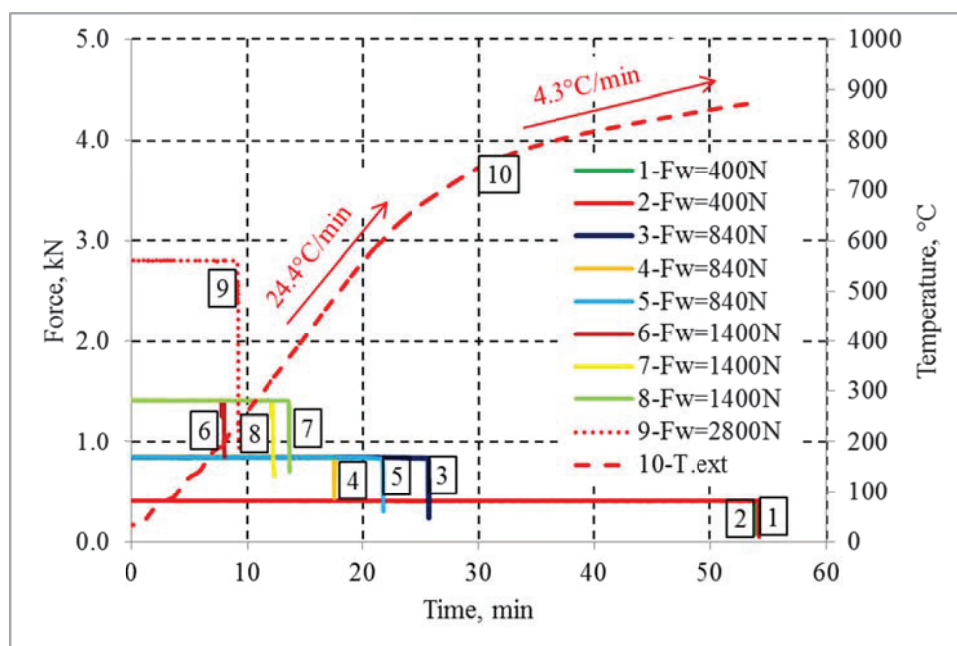


Figure 118: Force-time and temperature-time curves at different mechanical loads (TM2)– series6

Similar to series 5, Figure 118 and Figure 119 show that at failure points, applied force (Fw) quickly drops and total displacement rapidly extends. However, the force-total displacement curves (Figure 120) demonstrates that there is residual mechanical capacity. This phenomenon is identifiable in tests at mechanical load cases from 840N to 2800N.

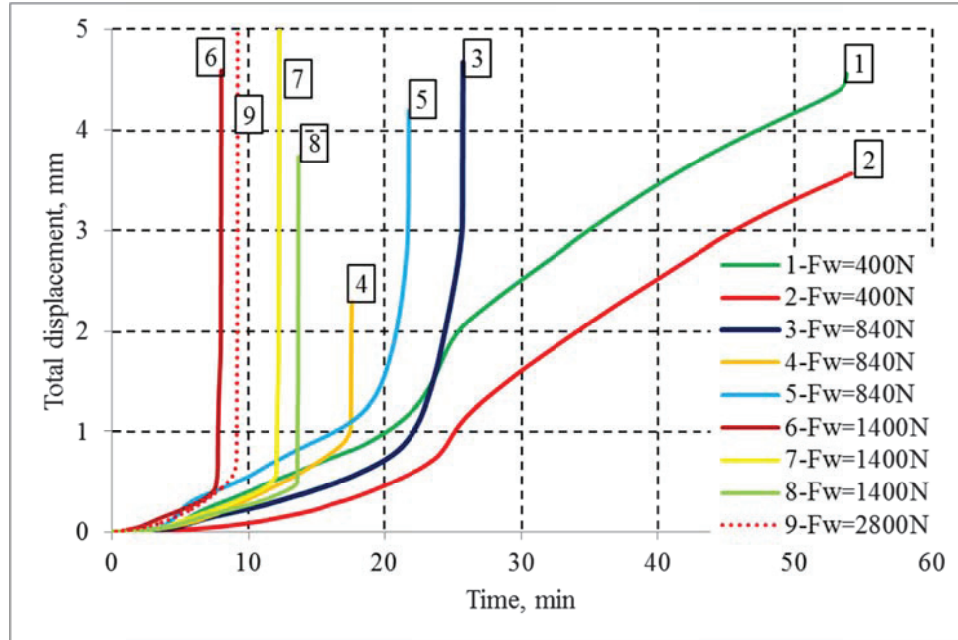


Figure 119: Total displacement- time curves at different mechanical loads (TM2) – series 6

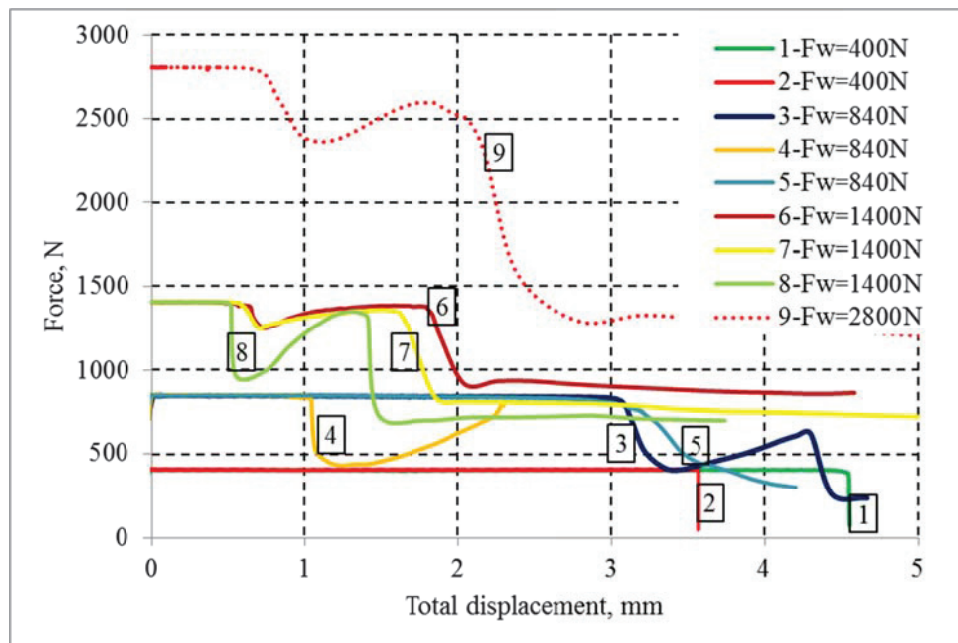


Figure 120: Force-total displacement curves at different mechanical loads (TM2) – series 6

Figure 121 and Figure 122 show the failures of specimens tested with TM2 regime at mechanical load cases from 400N to 2800N. According to these figures, there are significant differences between

failure modes corresponding to different mechanical loads. At 400N, the specimen collapses due to the oxidization of CFRP between two concrete blocks while in the concrete slots, polymer matrix of CFRP has been almost burnt. After specimen collapse, the temperature inside heating chamber gradually reduces and this allows the heat to continue to affect to the specimen. At the mechanical load of 840N, the surface adhesive has been little affected; matrix of CFRP has been partly oxidized while concrete block is undamaged. Specimen collapses due to shear failure at CFRP-adhesive interface which leads to the slippage of CFRP plate. At both mechanical load cases of 1400N and 2800N, specimen collapse due to shear failure at CFRP-adhesive interface, the physics of adhesive, CFRP and concrete are undamaged.

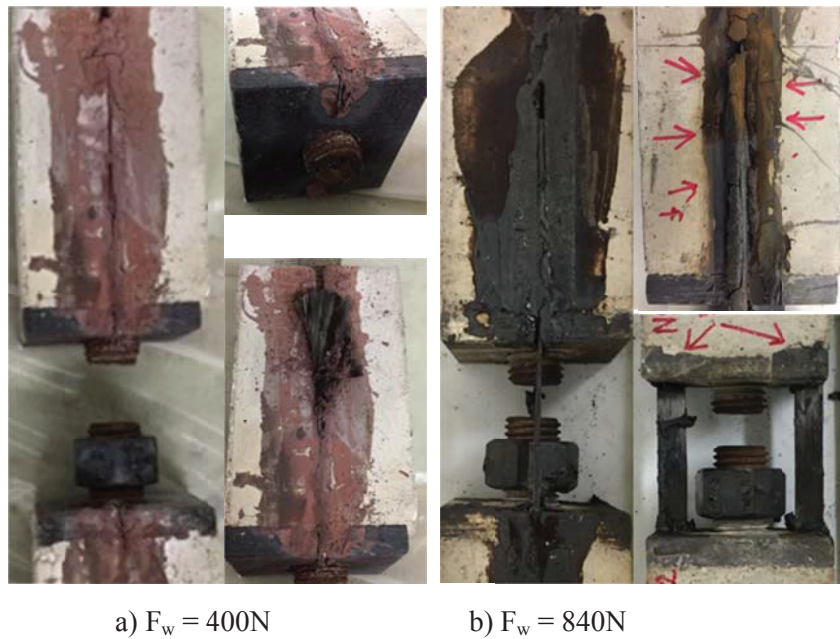


Figure 121: Failures of specimens tested with TM2 test – series 6

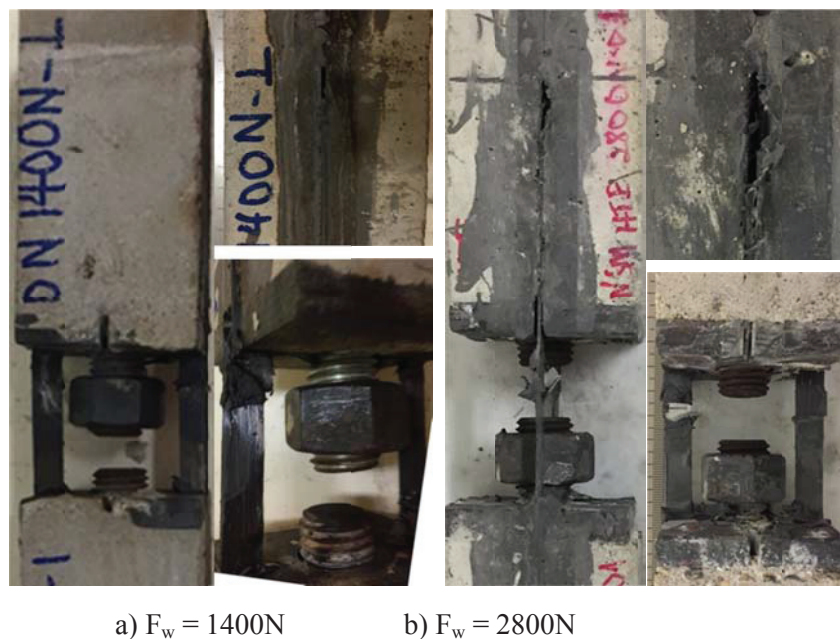


Figure 122: Failures of specimens tested with TM2 test – series 6

3.1.4.7. *Series 7: Thermo-mechanical performance of CFRP reinforced concrete using NSM method- epoxy 2 (TM2 program)*

Table 42 summarizes the thermal performance of CFRP reinforced concrete specimens at different mechanical load cases in series 7. In this series, the actual mechanical load and heating rate are well controlled. Therefore, the variations of mechanical loads and actual heating rates in this series are small. Both failure temperature and exposure duration reduce as mechanical load increases from 400N to 1400N: failure temperature slightly reduces from 550°C to 470°C and exposure duration reduces from 20.3 minutes to 16.6 minutes respectively.

Table 42: Summary of series 7: thermal performance of CFRP reinforced concrete specimens at different mechanical load cases

Test No	Mechanical load F_w , N		Specimen No	Failure temperature (°C)		Exposure duration, (minute)		Actual heating rate, (°C/minute)	
	Programmed F_w	Actual F_w			Average		Average		Average
1	400	411	1	530	549.9	20.20	20.3	24.51	25.4
2	400	412	2	570		20.33		26.31	
3	840	848	1	554	494.5	19.99	18.0	25.96	25.5
4	840	848	2	435		15.95		25.09	
5	1400	1405	1	528	469.8	18.78	16.6	26.24	26.2
6	1400	1403	2	412		14.39		26.19	

Figure 123 and Figure 124 display temperature-time, force-time, total displacement-time curves and Figure 125 displays force-total displacement curves at different mechanical load cases of series 7. As can be seen from the temperature-time curves (Figure 123) and also from Table 42, the temperature monotonically increases from ambient temperature until specimen failure. Heating rate and mechanical load slightly vary between tested cases due to well programmed testing system. Similar to result of series 6 (adhesive used: epoxy 1), the results of series 7 (adhesive used: epoxy 2) show that the failure temperature and exposure duration reduce as mechanical load increases. According to Figure 123, at the low mechanical load cases (from the test 1 to the test 4), the applied force has dropped several times before specimens completely collapse. This can be verified as in Figure 124, where the curves 1, 2 and 3 show small slips (<1mm) corresponding to each drop of mechanical load. The mechanical load is then recovered although the total displacement keeps expanding before totally collapsing (Figure 125).

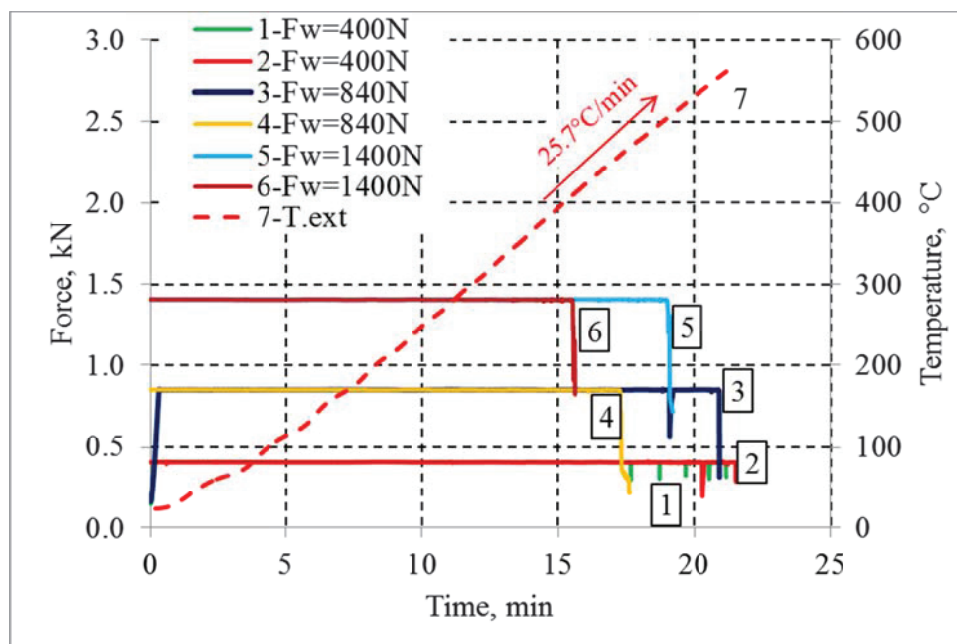


Figure 123: Force-time and temperature-time curves – series 7: thermal performance of CFRP reinforced concrete specimens at different mechanical load cases

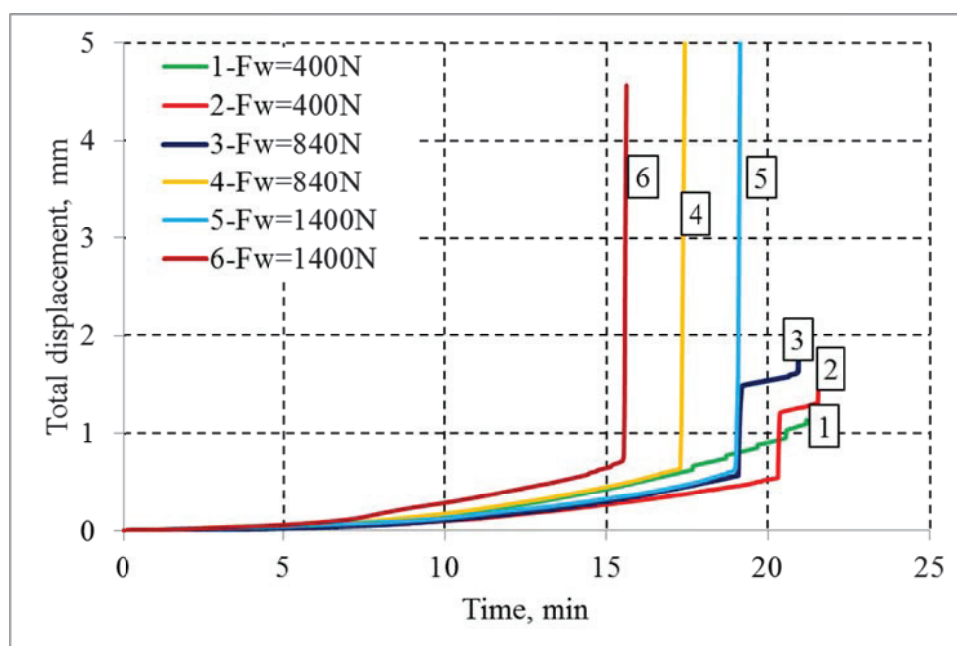


Figure 124: Total displacement- time curve – series: thermal performance of CFRP reinforced concrete specimens at different mechanical load cases

Figure 126 presents the failure of specimen tested in series 7. The failure image reveals that at the failure, the epoxy 2 has been oxidized and polymer matrix of CFRP has burnt with the portion depending on the mechanical load. The oxidation of adhesive and polymer matrix of CFRP lead to a reduction in shear resistance of adhesive and consequently make specimens to collapse. At the mechanical load of 1400N, the portion of oxidized adhesive and polymer matrix of CFRP is modest but at the mechanical load of 840N, this portion is greater and especially at 400N, adhesive has burnt

in to ash. In the meantime, the polymer matrix of CFRP has been partly oxidized (while carbon fibres are undamaged) and concrete is little affected at the mechanical load of 1400N and at 400N, there are cracks on concrete surface.

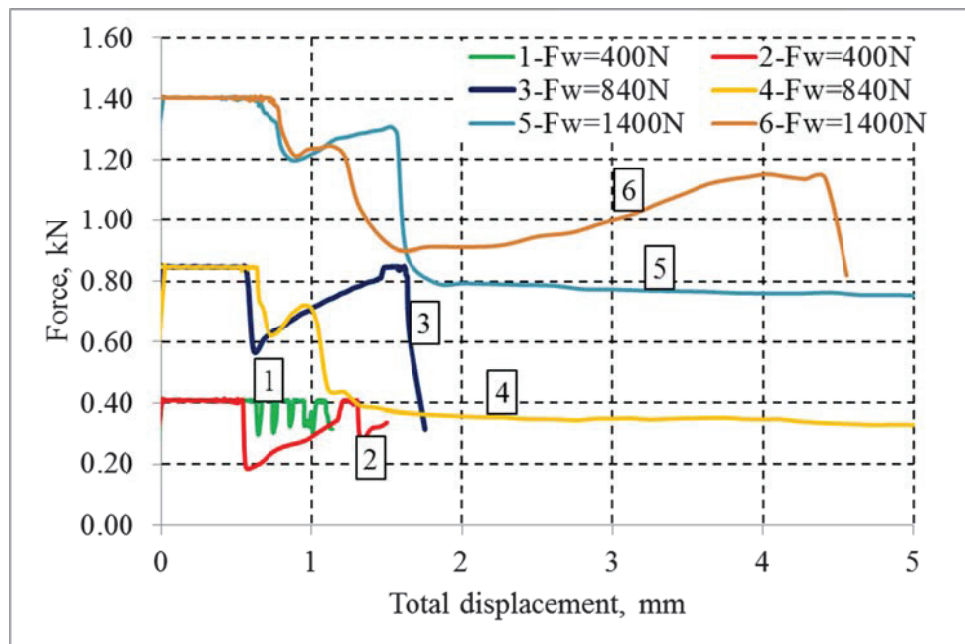


Figure 125: Force-total displacement curves– series 7: thermal performance of CFRP reinforced concrete specimens at different mechanical load cases

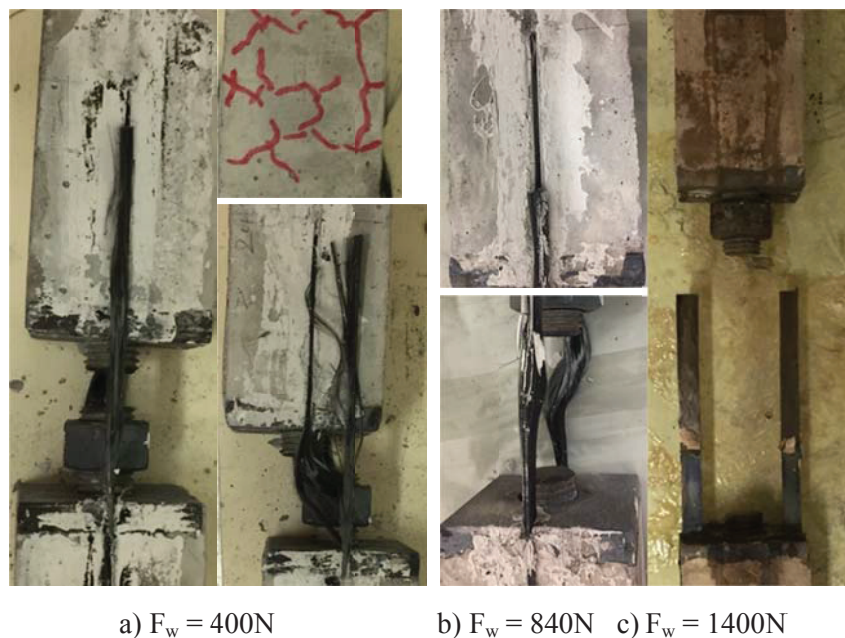


Figure 126: Failure of specimens tested with TM2 test – series 7

3.1.4.8. *Series 8: Thermo-mechanical performance of CFRP reinforced concrete using NSM method- cement-based adhesive (TM2 program)*

Table 43 summarizes the results obtained from series 8. According to the test, the result at 1400N is unavailable because that the resistance of specimen with cement-based adhesive has low mechanical capacity. Several methods to improve the contact surface such as sanded CFRP surface, replace CFRP with same material type of CFRP plate prepared with rough surface, but none can reach up to 1400N. According to these results, the differences in two mechanical cases (in failure temperature and exposure duration) are not significant. The failure temperature from the test 1 to the test 4 is slightly different between 617°C to 639°C (except that of test 2 which is much lower failure temperature at 443°C). The exposure-durations at two test cases are not much different despite of the variation in mechanical load (except that of the test 2).

Table 43: Summary of series 8: thermo-mechanical performance of CFRP reinforced concrete using NSM method- cement-based adhesive (TM2 program)

Test No	Mechanical load F_w , N		Specimen No	Failure temperature, (°C)		Exposure duration, (minute)		Actual heating rate, (°C/minute)	
	Programmed F_w	Actual F_w			Average		Average		Average
1	400	406	1	617	530	25.17	20.22	23.14	24.93
2	400	402	2	443		15.27		26.72	
3	840	845	1	627	632.6	22.82	23.3	25.92	25.6
4	840	841	2	639		23.84		25.31	

Figure 127 and Figure 128 present the development of temperature, force as time and Figure 129 presents the expanding of total displacement as time obtained in series 8. As can be seen from Figure 128, the total displacement-time curves at each mechanical load cases are close together; and curves between cases are separate from the other. As shown in Figure 128 and Figure 129, there is a small slip before the final collapse of specimen in the test 2. This may derive from defects during bonding process of cement-based adhesive, which has high viscosity which then is problematic to be filled in concrete slots.

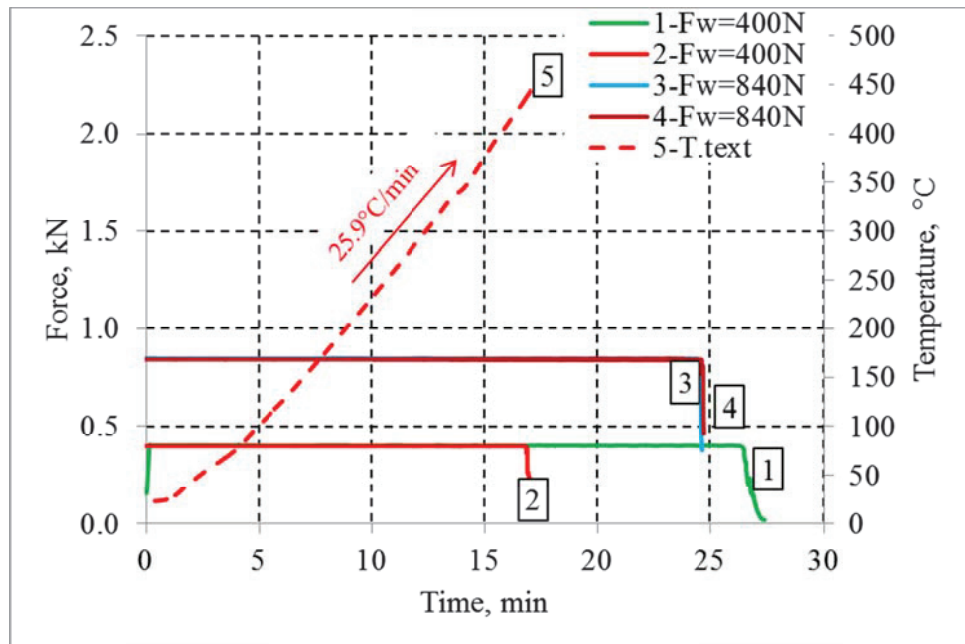


Figure 127: Force-time and temperature-time curves – series 8: thermo-mechanical performance of CFRP reinforced concrete using NSM method- cement-based adhesive (TM2 program)

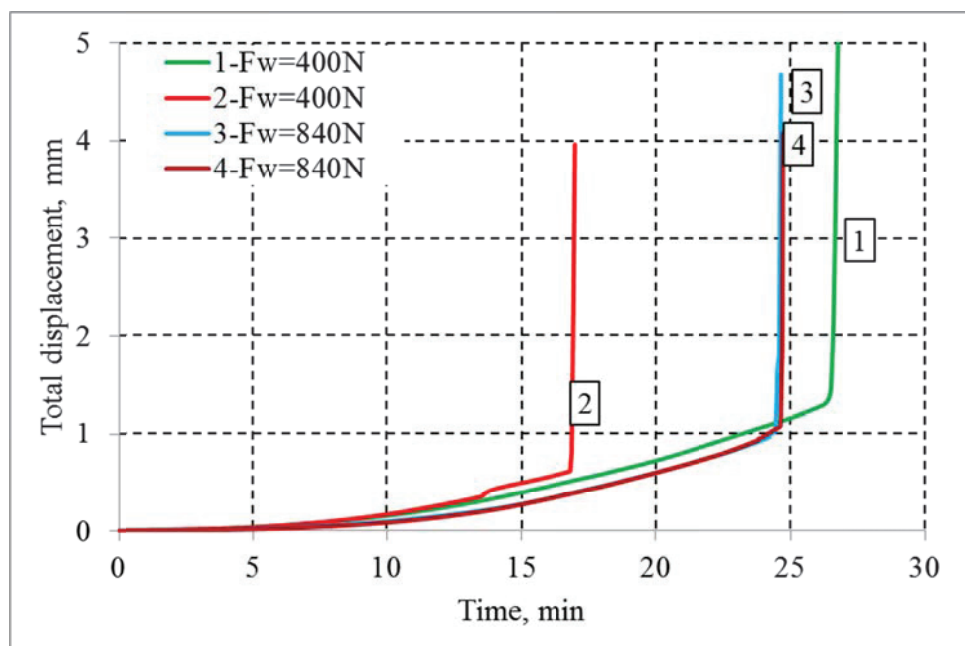


Figure 128: Total displacement- time curves – series 8: thermo-mechanical performance of CFRP reinforced concrete using NSM method- cement-based adhesive (TM2 program)

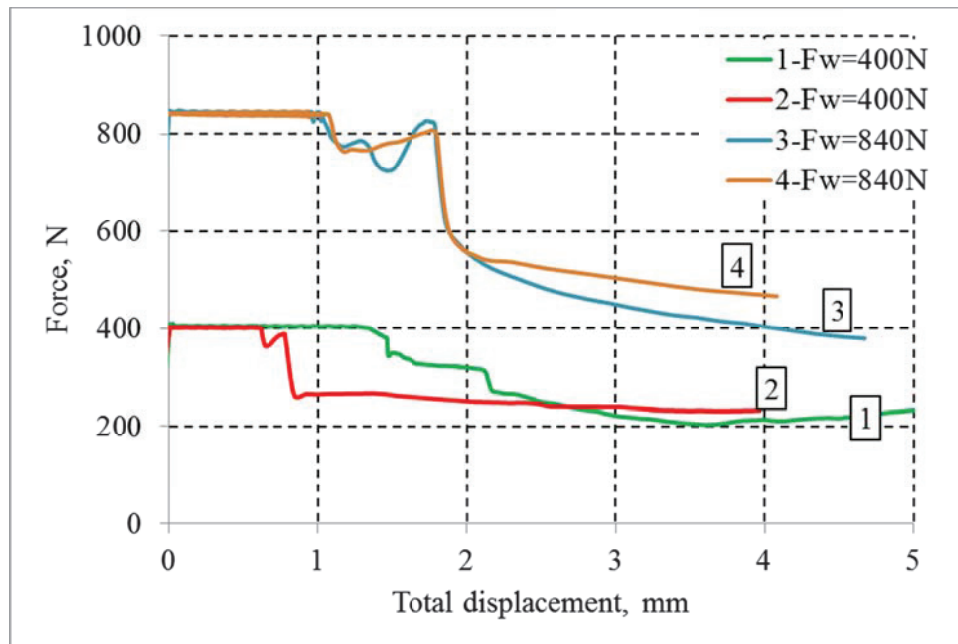


Figure 129: Force-total displacement curves at different mechanical loads – series 8: thermo-mechanical performance of CFRP reinforced concrete using NSM method- cement-based adhesive (TM2 program)

Figure 130 presents the failure of specimens bonded with cement based adhesive at different mechanical load (series 8). The failure image demonstrates that with cement-based adhesive, the specimens collapse due to shear failure at CFRP-adhesive interface. In both mechanical load cases, the used adhesive and concrete materials are not damaged. The polymer matrix of CFRP plate has been mostly oxidized.



Figure 130: Failure of specimens tested with TM2 test – series 8 a) $F_w = 400N$ b) $F_w = 840N$

3.1.4.9. *Actual temperature evolution during the test*

During the heating time of tests following RR, TM1 and TM2 program, the increase of temperature at different points inside and surround of specimens are recorded. Figure 131 through Figure 136 display the temperature increase at 13 points of specimens tested in TM1 program (Figure 131 through Figure 134) and TM2 program (Figure 135 and Figure 136) (see Figure 101 and Figure 102 for details of each TCi in a typical test).

Figure 131 displays the increase of temperature inside specimen and Figure 132 displays the increase of temperature around the sample of test No. 3 of test series 3 (TM1 program, 75°C). Figure 133 displays the increase of temperature inside specimen and Figure 134 displays the increase of temperature around the sample of test No. 6 (test series 3: TM1 program, 150°C). These figures show that at TM1 test program, the temperature surrounding specimen takes approximate 30 minutes to reach the target level (curve 6- T_{ext} , Figure 131 through Figure 134). This temperature maintains at the set level during the test until the failure of specimen. The temperatures at measured points inside specimen (from TC1 to TC5, Figure 131 and Figure 133) gradually increase and keep increasing until the failure. It is reasonable because the heat conduction inside specimen volume majorly depends on the thermal properties of concrete and steel and partly depends on thermal properties of adhesive and CFRP (due to its thin thickness). However, the temperature at top and bottom of concrete blocks (curve 2 to curve 4, Figure 132 and Figure 134) increases with more gradual rate compare to side position (curve 1, Figure 132 and Figure 134). It is because that the furnace controls temperature base on maximum three positions (TCI, TCII, TCIII) on the exterior side; moreover, the specimen volume is accounted for more than 30% of heating chamber volume while the heating capacity of the furnace is limited. These two reasons may result to the lower temperature at top and bottom of concrete blocks in comparison to side temperature.

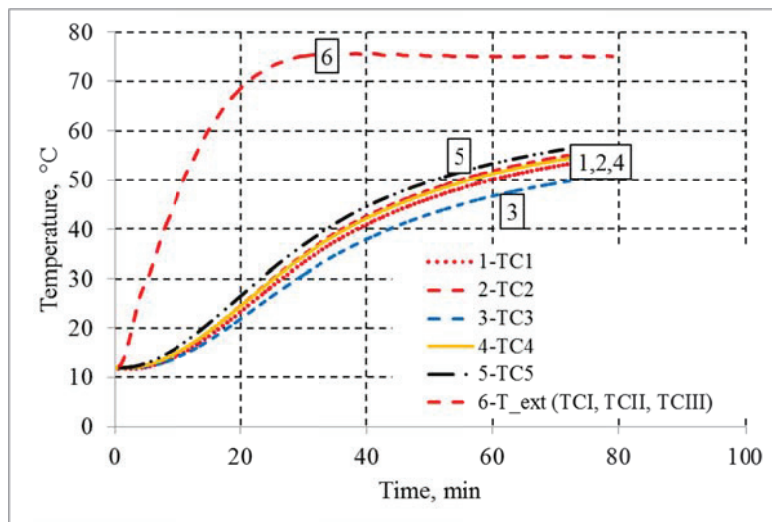


Figure 131: Temperature evolutions inside specimen (Test 3- series 3-TM1 program)

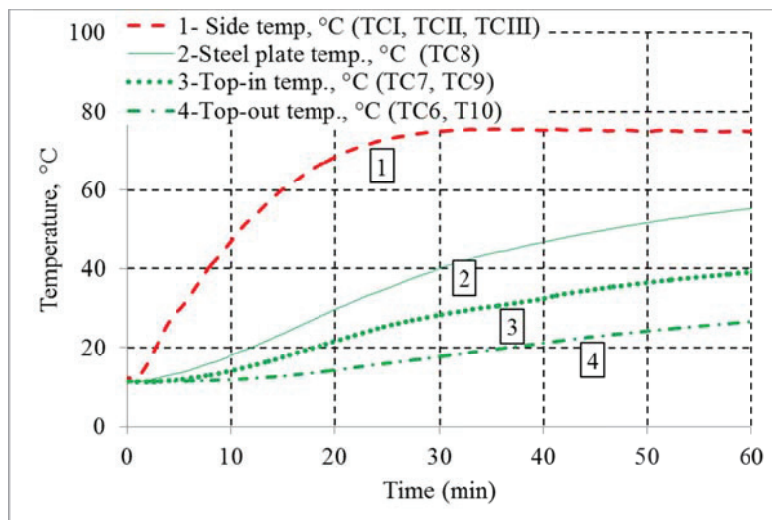


Figure 132: Temperature evolution at different positions surrounding specimen (Test 3- series 3-TM1 Program)

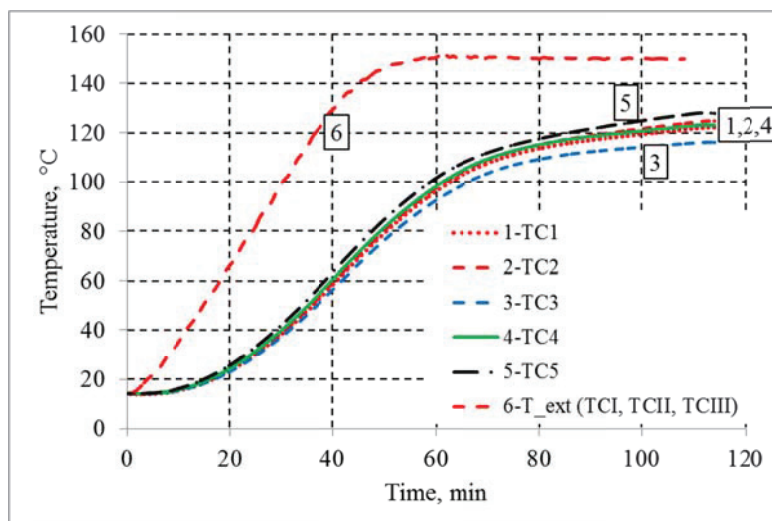


Figure 133: Temperature evolutions inside specimen (Test 6- series 3-TM1 program)

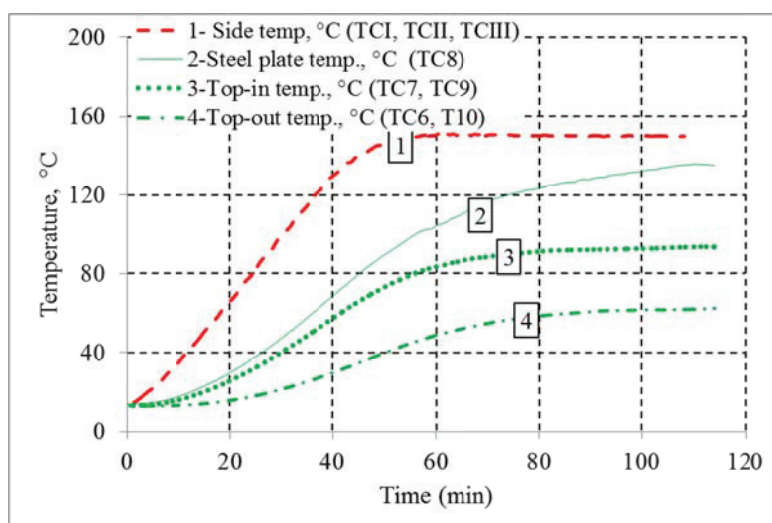


Figure 134: Temperature evolution at different positions surrounding specimen (Test 6- series 3-TM1 program)

During the TM2 test (from series 4 to series 8), because the increase of side temperature are programed with the heating rate of 30°C/minute in all the tests, therefore typical tests of some series are measured with 13 thermocouples at 13 points in some experiments and with the others, the number of measure points is less. Figure 135 displays the temperature curves on side of specimen (curve 6-T_ext, obtained from TC-I, TC-II and TC-III, Figure 102) and temperature curves inside observed concrete block (curve 1 to 5, obtained from TC1 to TC5, Figure 101). Figure 136 shows the temperature on top both positions inside (curve 3) and outside (curve 4) of furnace as well as between concrete block (curve 2) are smaller than the temperature on side (curve 1). The correlation between measurement points in TM2 program is similar to that obtained from TM1 programs. The side temperature is well controlled by the furnace (TC-I, TC-II, TC-III); the temperatures at top and bottom of concrete block are lower due to the high volume portion of specimen to the furnace; the increases of temperature inside the specimen are delayed due to the dependence of heat conduction on thermal properties of materials.

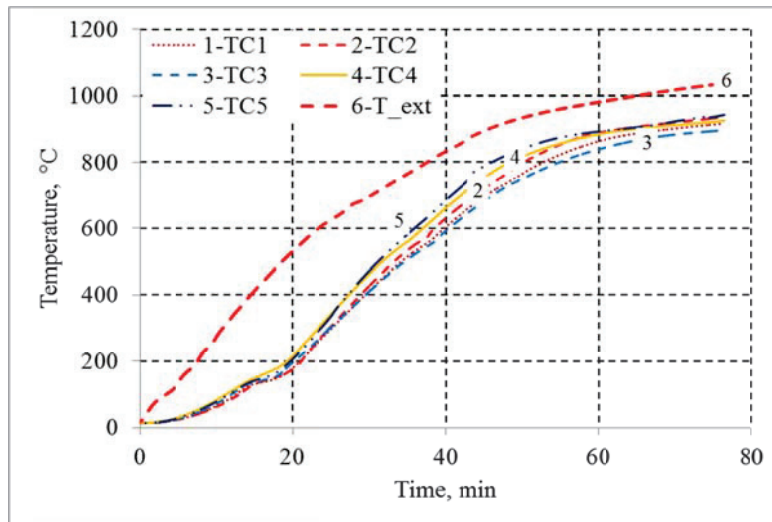


Figure 135: Temperature evolutions inside specimen (until reaching 1050 °C)

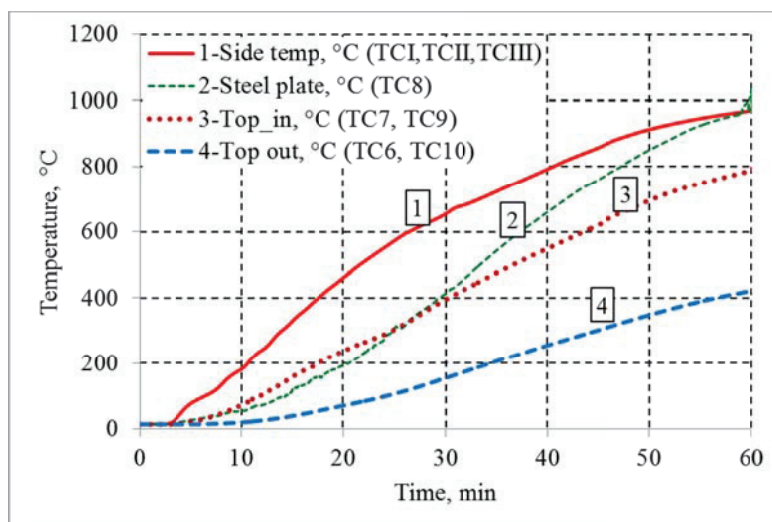


Figure 136: Temperature evolutions at different positions surrounding specimen (until reaching 1050 °C)

3.1.5. Discussion

This section discusses the mechanical performances at different temperature conditions and thermal performance at different mechanical states are analysed and discussed. The influences of reinforcement methods and the adhesives used are also compared afterwards. At the end of section, the detailed failures of each series are then synthesized for the efficiency of each configuration.

3.1.5.1. Mechanical performance at different temperature conditions

Table 44 presents the average mechanical performance of CFRP reinforced concrete specimens at different temperature levels from 20°C to 300°C according to three testing conditions. In these groups of specimen, the CFRP material reinforces concrete structure via NSM method using epoxy 1. The mechanical performance at each case is compared with the referenced mechanical performance at 20°C and is represented by normalized ratio value.

Table 44: Summary of mechanical performance at different tested temperature conditions; WSP: specimens with steel plate; WOSP: specimens without steel plate.

Temperature	Failure load						Note
	20°C - series 1		TM1- series 3		RR - series 2		
°C	N	Normalized ratio	N	Normalized ratio	N	Normalized ratio	
20	17829	1.00	-				WSP
20	12941	0.73	-				WOSP
75	-		5722	0.32	13161	0.74	WSP
85	-		3769	0.21	-	-	WSP
90	-		2120	0.12	-	-	WSP
150	-		2787	0.16	28878	1.62	WSP
300	-		1519	0.085	18997	1.07	WSP

Figure 137 plots the evolution of normalized mechanical performance of CFRP reinforced concrete specimens as temperature increases from 20°C to 300°C obtained in Table 44. It can be seen from this figure that at 20°C, the configuration with steel plate on the bottom of two concrete blocks has improved the performance of CFRP reinforced concrete specimen up to 37%. The difference in failure mode of series 1 has confirmed that with the reinforcement of steel plate, the compressive resistance of concrete has been better exploited thus enhances the performance of composite structure.

According to Figure 137, as the temperature increases, the thermo-mechanical performance of specimens (TM1 curve, series 3) reduces. It should be noted that in series 3, the mechanical load is applied immediately after temperature reaches the target temperature, thus the distribution of temperature inside specimen is not homogenous. It is because that the specimen volume accounts for about 30% of heating chamber volume and the heat conduction throughout concrete is influenced by the thermal properties of materials. According to Figure 137, the thermo-mechanical performance of specimen reduces when the temperature increases from 20°C to 300°C (TM1 curve, series 3). When the applied temperature increases from 20°C to 90°C, the mechanical performance of specimens rapidly reduces up to 88%. It is because that when the exterior temperature reaches 75°C, the temperature at inside interface between CFRP-adhesive-concrete (C-A-C) has reached about 40°C (TC4, Figure 131 and Figure 133) at which most epoxy adhesive starts its softening phase (Foster and

Bisby, 2008) and thus starts reducing its bonding capacity. When the exterior temperature reaches 90°C to 100°C, the C-A-C interface temperature reaches about 50°C -55°C (TC4, Figure 131, Figure 133) at which most of commercial thermo-setting epoxy resin starts its transition procedure from glassy state to viscous state and significantly reduces its performance (Foster and Bisby, 2008). Therefore, the normalized mechanical failure of specimen dramatically drops to 12% when applied temperature level is 90°C (TM1 curve, Figure 137). At target temperature from 90°C to 300°C, the mechanical performance of CFRP reinforced specimen slightly varies: at the target temperature of 150°C, the normalized mechanical failure slightly increases to 16% and then reduces to 8.5% at target temperature of 300°C (TM1 curve, Figure 137).

Accordingly, the residual performance of CFRP reinforced concrete specimens that were exposed to elevated temperature significantly fluctuates at temperature levels from 75°C to 300°C (Figure 137). At 75°C, the normalized mechanical performance reduces to 74%, but is still double than results of TM1 program. It is because during the heating, there is a small controlling mechanical load; therefore the bond effects at CFRP-adhesive interface as well as adhesive-concrete interface are well-maintained. Moreover, the expansion of concrete in this range of temperature (Hager, 2004) reduces the bonding effects and also the reduction in strength of epoxy adhesive thus the specimen performance reduces. From temperature level from 150°C to 300°C, the mechanical failure of RR program is higher than that at 20°C: at 150°C the normalized mechanical performance significantly increases up to 162% (10 times higher than corresponding TM1 result) and then reduces to 107% at 300°C (6.7 times higher than corresponding TM1 result). It is because that at the temperature about 150°C to 250°C, the cement paste in concrete starts its shrinkage with increasing magnitudes (depending on the mechanical and material cases, (Bazant and Kaplan, 1996)). This shrinkage also attributes by the dehydration of hydrates in concrete material (Hager, 2004). This shrinkage contributes to the confined effect to the adhesive and subsidiary to CFRP (Kotynia, 2012). In RR procedure, when the exterior temperature reaches 150°C, the minimum temperature in adhesive reaches about 90°C (TC4, Figure 133) which is slightly beyond the glass transition of common high-temperature performance epoxy. Therefore, the residual properties of the adhesive used may slightly improve when cooled from the temperature range between 60°C and 95°C (thermal curing on common epoxies, (Moussa et al., 2012b; Sinclair, 1992)). The combination of confined effect from concrete material and slight reduction in residual strength of epoxy enhances the residual mechanical performance of the concrete specimen. However, as the applied temperature reaches 300°C, the minimum temperature in adhesive may reach up to more than 100°C, whereas the reduction in residual strength becomes significant (Moussa et al., 2012b), the confined effects from concrete shrinkage may be greater than this reduction. As the result, although the mechanical performance at 300°C of the specimen reduces in comparison to that at 150°C, this performance is still greater than that at ambient temperature condition. These experimental results show that the RR procedure results in higher mechanical performance of CFRP reinforced structure in comparison to TM1 procedure. This result can potentially be implemented in several applications of temperature treatment to improve the mechanical performance of CFRP reinforced structures.

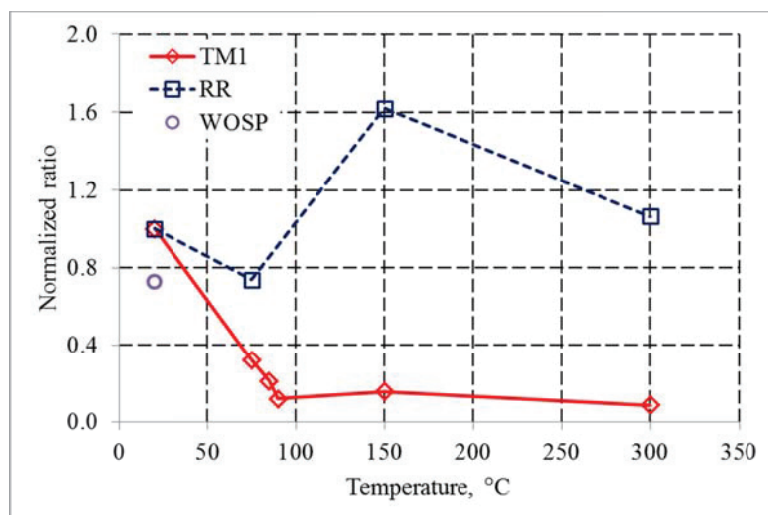


Figure 137: Evolution of failure load at different temperature conditions

3.1.5.2. Thermal performance at different mechanical load status

Table 45 summarizes results of series from 4 to 8 obtained in TM2 program; and Figure 138 shows the evolution of failure temperature of each series at different nominal adhesive shear stress. The nominal adhesive shear stress (NAS) in the following sections is identified as following:

$$\tau = \frac{F_w}{S} \quad \text{Equation 11}$$

In which: F_w is applied tensile force and S is the contact region between observed concrete block and bonded CFRP plates via adhesive.

Table 45: Summary of failure temperature at different mechanical loads of series 4 to 8

Mechanical load		Series	Failure temperature, °C				
			Series 4	Series 5	Series 6	Series 7	Series 8
Load	Nominal adhesive shear stress (NAS)	Reinforcement method	NSM	EBR	NSM	NSM	NSM
N	MPa	Adhesive type*	E1	E1	E1	E2	C
		Specimen design	WOSP	WSP	WSP	WSP	WSP
400	0.143	-	673	230.1	837.8	549.9	617
840	0.3	-	-	-	543.7	494.5	632.6
1400	0.5	-	-	134.6	295.8	469.8	-
2800	1.0	-	252	-	224	-	-

(*) E1: Epoxy 1; E2: Epoxy 2; and C: cement-based adhesive.

As can be seen from Figure 138, as the nominal adhesive shear stress (NAS) increases, the thermal resistance of CFRP reinforced concrete specimen generally reduces. It is shown that at NAS of 0.143 MPa, the thermal resistance of series 6 is at 838°C while those of series 4, 7, 8 are respectively 673°C, 550°C, 617°C and that of series 5 is 230°C. As NAS increases from 0.143 MPa to 0.3 MPa and then

0.5 MPa, the thermal resistance of series 6 experiences a significant reduction while with series 4, series 5 and series 7, these reductions are more gradual and with series 8 the thermal resistance is slightly increases between NAS of 0.143 MPa and of 0.3 MPa. As NAS increases from 0.5 MPa to 1.0 MPa, the thermal resistance of series 6 gradually reduces to 224°C which is approximately that of series 4 at 252°C. From above mentioned result, as NAS increases from 0.143 MPa to 0.5 MPa the configuration of series 6 experiences a significant reduction while with series 5 and series 6, the reduction is more gradual and series 8 experiences a slight increase. However, in this range of NAS, the series 4, 6, 7, and 8 (NSM reinforcement method) result in higher thermal performance than that of series 5 (EBR reinforcement method).

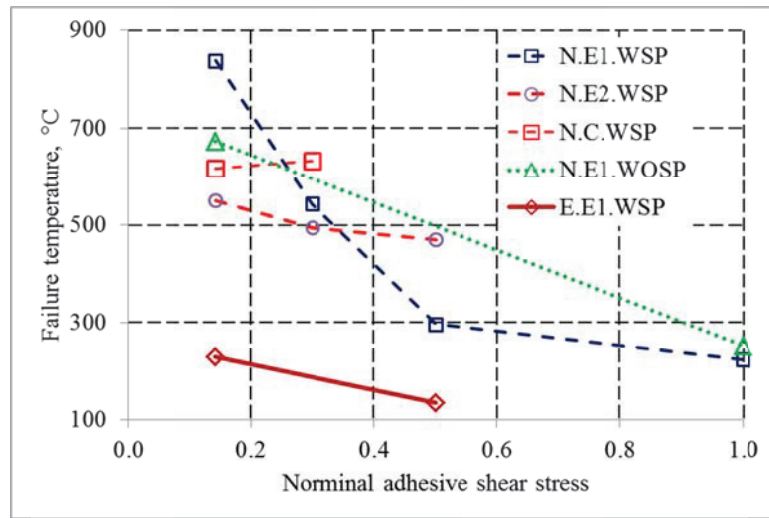


Figure 138: Evolution of thermal resistance at different nominal adhesive shear stress, (TM2)

N: NSM method; E: EBR method; E1: Epoxy 1; E2: Epoxy 2; C: cement-based; WSP: with steel plate configuration; WOSP: without steel plate configuration.

3.1.5.3. Efficiency of reinforcement method

Figure 139 shows the comparison between two reinforcement methods: EBR and NSM at two different tested mechanical loads. According to this figure, at low NAS of 0.143 MPa, the EBR-specimens can resist up to 230°C while NSM-specimen can resist up to temperature 838°C (about 3.65 times higher than EBR-specimen). At NAS of 0.5 MPa, the failure temperature of EBR-specimen reduces to 135°C and NSM-specimen reduces to 296°C but this is still 2.2 times higher than that EBR-specimen. This means that at both tested NAS cases, the NSM reinforcement method can improve the thermal-performance of CFRP reinforced concrete specimen following TM2 program.

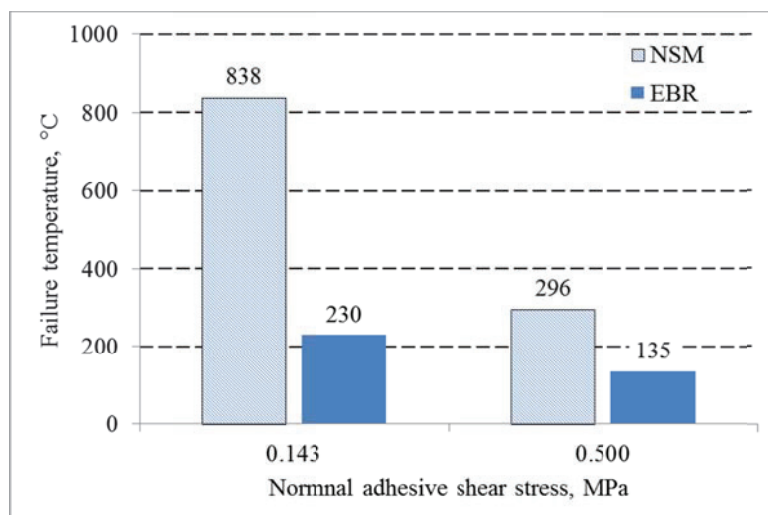


Figure 139: Comparison of efficiency between two method of reinforcement (EBR and NSM), TM2 program

3.1.5.4. Efficiency of adhesives used in thermo-mechanical performance.

Figure 140 presents the average failure temperature of three adhesives used at three different NAS cases following TM2 program. As can be seen from this figure, at NAS of 0.143 MPa, epoxy1-used-specimen (E1-specimen) can resist up to 838°C, which is higher than cement-based-used-specimen (C-specimen) at 617°C and then epoxy 2-used-specimen (E2-specimen) at 550°C. At NAS of 0.3 MPa, the thermal performance of two epoxy-specimens reduces, E1-specimen performance significant reduces to 544°C and E2-specimen performance reduces to 495°C, while C-specimen performance slightly increases to 633°C. At NAS of 0.5 MPa, the thermal-performance of E1-specimen reduces to 296°C which is lower than that of E2-specimen at about 470°C. The test of C-specimen at this mechanical level is unavailable because the C-specimen fails at NAS of 0.38 MPa in average during the mechanical loading phase of TM2 program.

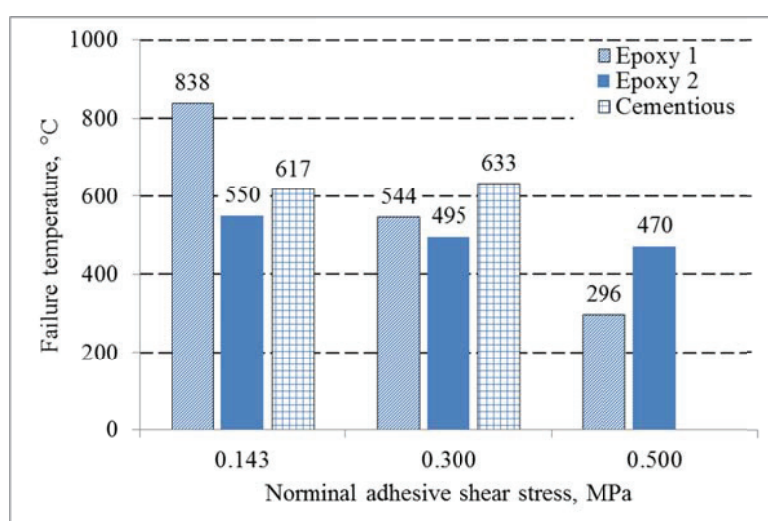


Figure 140: Comparison of efficiency between three adhesive types, TM2 program.

From the obtained results, regarding the bonding efficiency in CFRP reinforced concrete specimen, the epoxy 1 has higher thermal performance at low mechanical load level and this performance significantly reduces as the NAS increases. In contradiction, the epoxy 2 has lower thermal performance at low mechanical load, when the NAS increases, its thermal performance slightly reduces and maintains its higher thermal performance at NAS of 0.5 MPa, compared to epoxy 1. The cement-based has a middle low range of thermal performance at NAS of 0.143 MPa; however, the NAS has a small influence to its thermal performance in ranges between 0.143 MPa and 0.3 MPa.

3.1.5.5. *Comparison of failure mode*

Table 46 summarizes the status of structural element after tests of series 1, 2 and 3. According to this table, WOSP-specimen collapses due to the shear failure of concrete material while WSP-specimen collapses due to the failure of concrete material at compressive zone at the corner on one side and then subsequent shear failure at adhesive-CFRP interface on the other side. This demonstrates the effectiveness of the system used that has exploited the advantage of concrete material in compression. The result of series 2 (RR case) shows that with residual programme, the specimen firstly collapses due to the compressive failure of concrete on one side and then subsequent shear failure at CFRP-adhesive interface on the other side (Figure 106 and Figure 107). For the thermo-mechanical condition (TM1, series 3), the specimens gradually collapse (Figure 108) due to the shear failure at CFRP-adhesive interface (Figure 109). The failure of residual test on specimens that have collapsed after TM1 regime (RR* case) shows that the specimen continues to maintained certain mechanical capacity. They experience a quick collapsing (Figure 106) due to the shear failure of CFRP-adhesive interface (Figure 109).

Table 47 summarizes the status of structural element after test from series 4 to 8 following TM2 testing program. The result from series 4 shows that at low mechanical level NAS of 0.143 MPa, the WOSP-specimen collapses due to the CFRP-adhesive interface resulted from partly burnt of adhesive and separation crack of the concrete. At failure temperature, both CFRP adhesive and concrete material have been thermally affected. Beside the main rupture crack, there are several small cracks on concrete block surface (Figure 113a). At NAS of 1.0 MPa, the WOSP specimen collapses due to the shear failure of CFRP-adhesive interface while all others are undamaged (Figure 113b). Result from series 5 shows that with the EBR method and WSP configuration, the specimen collapses due to the shear failure at CFRP-adhesive interface at all other tested NAS levels (Figure 117). Result at NAS of 0.143 MPa of series 6 shows that the specimen collapses due to the tensile failure of CFRP at elevated temperature (Figure 121a). As can be seen from the summary shown on Table 47, at the failure temperature, all other structural elements have been partly thermally-affected. Different from series 4, the efficiency of steel-plate-design has been experimentally demonstrated that the shear failure of concrete has not contributed to the specimen failure (Figure 121a). As NAS increases from 0.3 MPa to 1.0 MPa, the shear failure of CFRP-adhesive interface dominates the cause of specimen collapse, with the tendency to be affected by temperature declines (Figure 121b and Figure 122). The series 7, in comparison with series 6, has the similar configuration but different adhesive. The result of series 7 shows that at NAS from 0.143 MPa to 0.3 MPa, the specimens collapse due to the shear failure of CFRP-adhesive interface and CFRP and adhesive have partly burnt and concrete has displayed micro cracks (Figure 126a, Figure 126b). At NAS of 0.5 MPa, the specimen also collapses because of shear failure of CFRP-adhesive interface, while the influence of elevated temperature to CFRP, adhesive and concrete is minor (Figure 126c). With the modification of adhesive to cement-based in series 8, the specimen collapses mainly because of shear failure at CFRP-adhesive interface. The adhesive, concrete material and adhesive-concrete interface are undamaged at the failure

temperature while with CFRP the polymer matrix has completely burnt at NAS of 0.143 MPa and partly burnt at NAS of 0.3 MPa.

Table 46: Summary status of structure components after tests in RR and TM1 programs

Series	Note	Temperature at failure, °C	Structure components					Cause of specimen collapses **
			CFRP (CF)	Adhesive /CFRP interface (CFA-I)	Adhesive (A)	Adhesive /concrete interface (ACO-I)	Concrete (CO)	
1	WOSP, NSM, E1	20	U	U	U	U	1.SF)	Shear failure of concrete
	WSP, NSM, E1	20	U	2.F	U	U	1.CF)	Compressive failure of concrete and then shear failure at CFRP-adhesive interface
2	RR WSP, NSM, E1	75-300	U	2.F	U	U	1.CF	Compressive failure of concrete and then shear failure at CFRP-adhesive interface
	RR*, WSP, NSM, E1	75-300	U	1.F	U	U	U	Shear failure at CFRP-adhesive interface
3	TM1 WSP, NSM, E1	75-300	U	1.F	U	U	U	Shear failure at CFRP-adhesive interface

Note: U: undamaged; F: failure; SF: shear failure; CF: compressive failure; X.*: X is order of failure

Table 47: Summary status of structure components after tests in TM2 program

Series	Note	NAS, MPa	Structure components					Cause of specimen collapses **
			CFRP (CF)	Adhesive / CFRP interface (CFA-I)	Adhesive (A)	Adhesive /concrete interface (ACO-I)	Concrete (CO)	
4	TM2, WOSP, NSM, E1	0.143	PBM	1.F	PB	PB	2.Cr	Shear failure at CFRP-adhesive interface then crack at concrete block

	TM2, WOSP, NSM, E1	1.0	U	1.F	U	U	U	Shear failure at CFRP-adhesive interface
5	TM2, WSP, EBR, E1	0.143 - 0.5	U	1.F	U	U	U	Shear failure at CFRP-adhesive interface
6	TM2, WSP, NSM, E1	0.143	B	PB	PB	PB	mCr	Tensile rupture of CFRP, adhesive, concrete and interfaces have been affected,
	TM2, WSP, NSM, E1	0.3	PBM	F	PB	PB	U	Shear failure of CFRP- adhesive interface; CFRP, adhesive and ACO interface are partly affected
	TM2, WSP, NSM, E1	0.5 - 1.0	U	F	U	U	U	Shear failure of CFRP-adhesive interface
7	TM2, WSP, NSM, E2	0.143 -0.3	PBM	F	B	F	mCr	Shear failure of CFRP-adhesive and adhesive -concrete interfaces, CFRP and concrete are partly affected
	TM2, WSP, NSM, E2	0.5	U	F	PB	U	U	Shear failure of CFRP-adhesive interface, adhesive is partly burnt
8	TM2, WSP, NSM, C	0.143	BM	F	U	U	U	Shear failure of CFRP-adhesive interface, matrix of CFRP is burnt
	TM2, WSP, NSM, C	0.3	PBM	F	U	U	U	Shear failure of CFRP-adhesive interface, matrix of CFRP is partly burnt

Note: U: undamaged; F: failure; PBM: Partly burnt matrix (for CFRP); B: burnt; PB: partly burnt; Cr: Crack (for concrete); mCr: micro-cracks (for concrete); X.: X is order of failure*

3.1.6. Conclusions

With the results from CFRP reinforced concrete specimen, following conclusions have been inferred:

- The residual performance of CFRP reinforced concrete specimen is much higher than its thermo-mechanical performance: 2 times higher at 75°C and 10-12.6 times higher at 150°C to 300°C.
- The thermal performance of CFRP reinforced concrete reduces as the imposed mechanical level increases, respecting the thermo-mechanical condition. The reduction rate depends on the specimen configuration, the reinforcement method, and also the use adhesive.
- The compressive state of concrete enhances the performance of CFRP reinforced structure in comparison with its shear state and the design of specimen has better exploited the advantage of concrete material. The mechanical performance at ambient temperature of specimen has been increased 37% with steel plate configuration and the failure mode of concrete changes from shear failure to compressive failure.
- The NSM reinforcement method has better improved the thermal performance of CFRP reinforced concrete than EBR method by extending the duration of thermal penetration from environment to the bonded interfaces. At low mechanical load state ($NAS = 0.143$ MPa), the failure temperature of NSM specimen is 3.6 times higher than EBR specimen while at higher mechanical state ($NAS=0.5$ MPa) the failure temperature of NSM specimen is 2.2 times higher than EBR specimen.
- The use of bonding adhesive takes an important role in the performance of CFRP reinforced concrete. The use of epoxy with Al_2O_3 + metal particle can significantly extend the failure temperature at low mechanical level, at medium mechanical level, the cement-based adhesive introduces better performance while at substantial mechanical level, the normal epoxy seem to be better choice.
- The test condition of TM2 program is close to fire condition regarding the simultaneousness of elevated temperature and imposed mechanical load. Therefore, the fire performance of civil engineering structure can be contributed from this result. In actual civil engineering application, the suitable design of load status, reinforcement method, and bonding adhesive can improve the fire performance of CFRP reinforced structure.

Discussion on the application of test design:

- With the steel plate design at the bottom of two concrete blocks, the steel plate shows better mechanical performance at different temperatures because that the advantage of concrete in compression is better exploited. In concrete structure, there are several positions in structures where the concrete performs its compressive strength such as anchorage zone for reinforcement, strut-and-tie designed model.

3.2. Insulation material

This section investigates the use of insulation material to protect the material and structure under thermal effect and thus can contribute to the extending of their thermal performance regarding to TM2 testing condition. An insulate material has been experimentally tested for its thermal performance and has then been applied for the thermal protection of the M-CFRP material in TM2 condition. The efficiency of the insulation material is then analysed and numerically extended for fire-temperature condition

3.2.1. Presentation of the used insulation material

The insulation that is used to protect the M-CFRP is a non-combustible material. As the supplier's data, its density is 0.458 g/cm^3 ; its compressive strength and bond strength are respectively $0.893 \times 10^{-3} \text{ MPa}$ and $8.012 \times 10^{-5} \text{ MPa}$. According to this data, its combustibility passes ASTM E136

3.2.2. Design of specimens

In this subsection, the insulation specimen and the insulated CFRP are respectively described.

3.2.2.1. *Insulation specimen*

The thermal resistance capacity of the used insulation is first studied through a heat transfer test via a cylinder sample (as described in Figure 141). There are 5 thermo-couples (TC1 to TC5, Figure 141) arranged inside and outside of the sample to follow the heat transfer inside the material during the test.

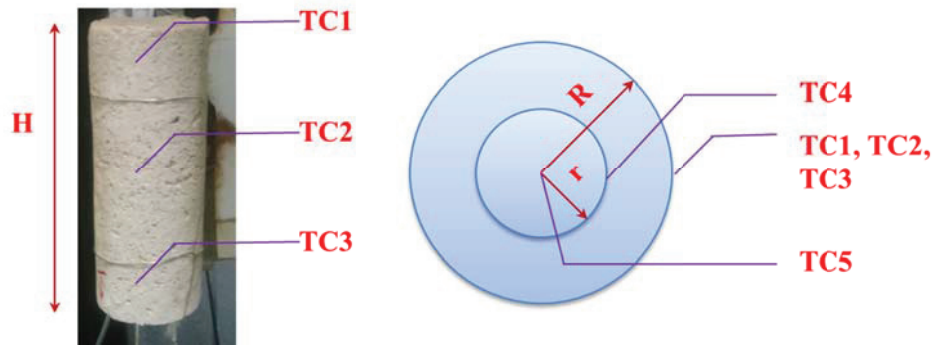


Figure 141: Cylinder sample to test thermal resistance of insulation material, $R=38\text{mm}$, $r=20\text{mm}$, $H=200\text{mm}$ with 5 positions (TC1, TC2, TC3, TC4, and TC5) of thermo-couple.

3.2.2.2. *Insulated CFRP*

Figure 142 shows the detailed dimension of the insulated M-CFRP specimen. The insulation material, after being tested for thermal resistance in heat transfer test, is then applied to protect the M-CFRP. During the test, the temperature evolution at the interface between CFRP and insulation material is followed by two thermo-couples (TC1, TC2; Figure 142).

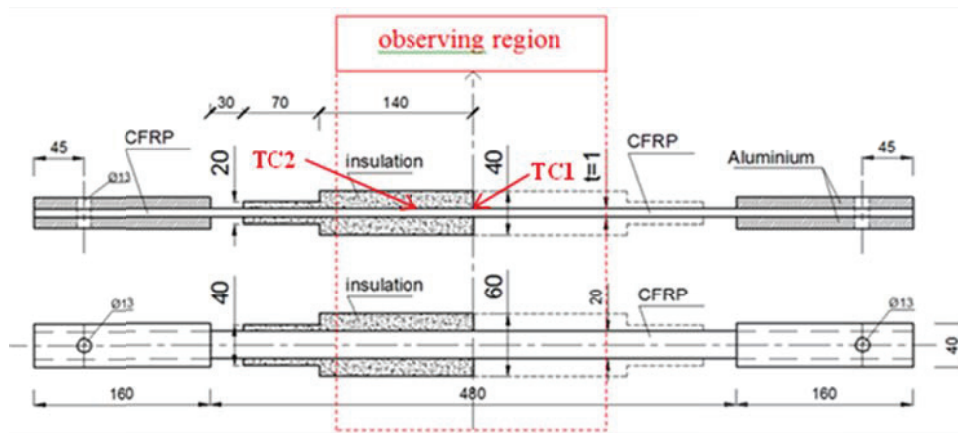


Figure 142: Detail of Ins-M-CFRP sample with two positions (TC1, TC2) of thermo-couple

3.2.3. Test program

The capacity to resist the elevated temperature of the used insulation is first studied through a heat transfer test (an additional test program as illustrated in Figure 143). In this test, the temperature surrounding the sample will be increased with the heat rate $30^{\circ}\text{C}/\text{minute}$ until reaching 1100°C . The measurement of temperature inside cylinder insulation (throughout 2 thermocouples: TC4 and TC5, Figure 141) will then be analysed to preliminarily determine its efficiency in protecting M-CFRP material under elevated temperature effect.

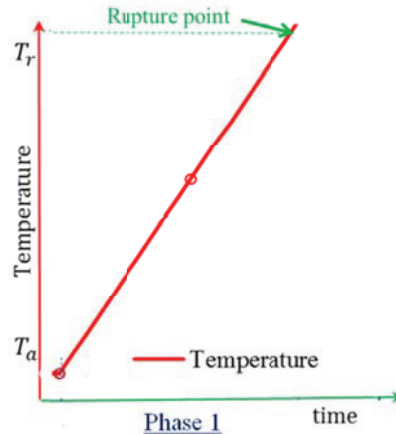


Figure 143: Thermal test with insulation material

In the second step, the insulated-M-CFRP specimens are tested following the TM2 testing program (Figure 60) to investigate the thermo-mechanical performance of insulated M-CFRP. The performance of insulation material and insulated M-CFRP are presented and discussed in the following sections.

3.2.4. Test results and discussion

This section presents the results of experimental tests and the discussion about the obtained results with insulation material and insulated CFRP.

3.2.4.1. Heat transfer test

Figure 144 shows the evolution of temperature at three different positions from the exterior to the interior of the cylinder insulation material (Figure 141). At the beginning of the test, the exterior temperature increases from initial condition with the ramp rate of $30^{\circ}\text{C}/\text{minute}$ in about 30 minutes and reaches 900°C . Afterwards, this temperature keeps increasing with ramp rate $4^{\circ}\text{C}/\text{minute}$ to reach about 1100°C in 50 minutes. The interior temperatures at thermo-couple 4 (TC4 in Figure 141, T_{in_1} in Figure 144) and thermo-couple 5 (TC5 in Figure 141, T_{in_2} in Figure 144) start to increase about 7 minutes to 14 minutes later than the exterior with ramp rate of $6.3^{\circ}\text{C}/\text{minute}$ and of $8.9^{\circ}\text{C}/\text{minute}$ respectively in the first phase. When the temperatures at TC4 and TC5 reach about 100°C , there are plateau phase in which the temperature slightly increases $1.3^{\circ}\text{C}/\text{minute}$ and $0.4^{\circ}\text{C}/\text{minute}$ in about 13 minutes and 30 minutes correspondingly. In the final phase, the temperature at TC4 steeply increases with ramp rate of $23^{\circ}\text{C}/\text{minute}$ while this rate at TC5 is $38^{\circ}\text{C}/\text{minute}$. Subsequently, these two temperatures reach 800°C in about 30 minutes and 20 minutes and the test is terminated due to safety condition when these temperatures reach 1029°C and 1007°C . This test shows that along the radius direction, the evolution of temperature is delayed and this impediment depends on the thickness of insulation layer (Figure 144). The evolution of the interior temperature of the insulation material clearly separates into three identified phases.

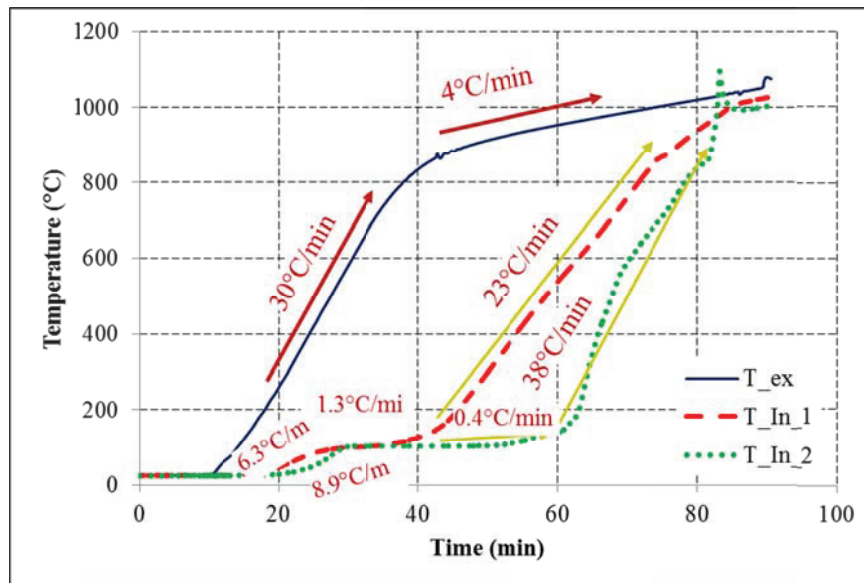


Figure 144: Evolution of exterior (T_{ex}) and interior (T_{in_1} ; T_{in_2}) temperatures of the insulation material during heat transfer test; temperatures obtained with thermocouples TC1, TC2, and TC3 (T_{ex}); TC4 (T_{in_1}); TC5 (T_{in_2}) (the thermocouple positions are shown in Figure 141)

3.2.4.2. Insulated M-CFRP under thermo-mechanical condition (TM2)

The obtained results with the M-CFRP samples protected with insulation material under the thermo-mechanical testing regime are presented in Table 48. The table shows the exterior and interior temperature of the insulation layer at the rupture point of M-CFRP and the exposure time that the material can maintain its performance. The obtained results include two cases of imposed load (0.2 and 0.3). The rupture temperatures in two loading cases are 780°C and 880°C and the exposure durations are 48 minutes and 37 minutes respectively.

Table 48: Thermal-mechanical performance of M-CFRP with insulation results

Sample ID	Applied load ratio, f_w	T_rup		Exposure duration minute
		T_ex	T_in	
		°C	°C	
C.T.020.Ins	0.2	780	867	47.93
C.T.030.Ins	0.3	880	688	36.58

Figure 145 and Figure 146 show the evolutions of temperature that are exterior and interior the insulation material layer during the thermo-mechanical test in two loading cases. When the applied load ratio is 0.2 (the corresponding imposed load is 2317N), the actual exterior temperature increases from room temperature (about 20°C) with the ramp rate is 28°C/minute and reaches 600°C in about 20 minutes (Figure 145). Afterwards, the ramp rate decreases until the rupture of the M-CFRP. The evolution of the interior temperature also separates into three phases: in the first phase, the temperature gradually increases from initial temperature to 95°C with the ramp rate is 11°C/minute. This phase takes about 5 minutes to complete. The interior temperature then slightly increases with the ramp rate of 0.65°C/minute in more than 10 minutes in the second phase before rapidly increasing with the ramp rate is about 40°C/minute in the third phase. In the test with applied load ratio of 0.3 (correspond to imposed load at 3476N), the exterior temperature increases with the ramp rate of 24.5°C/minute reaching 600°C in approximately 20 minutes (Figure 146). The increase of the interior temperature also identified as three separate phases. In the first phase, the temperature takes about 5 minutes to gradually increase from initial temperature to about 94°C. The temperature then slightly increases with the ramp rate of 0.95°C/minute in about 15 minutes in the second phase before steeply rises at the ramp rate of 58°C/minute until ruptures.

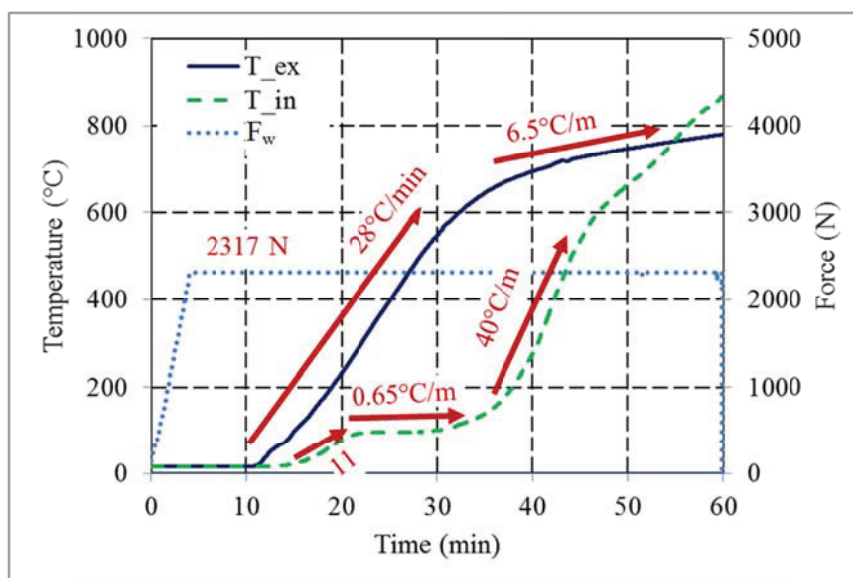


Figure 145: Evolution of external and internal temperatures of M-CFRP with the insulation material at 20% of applied load ratio (f_w)

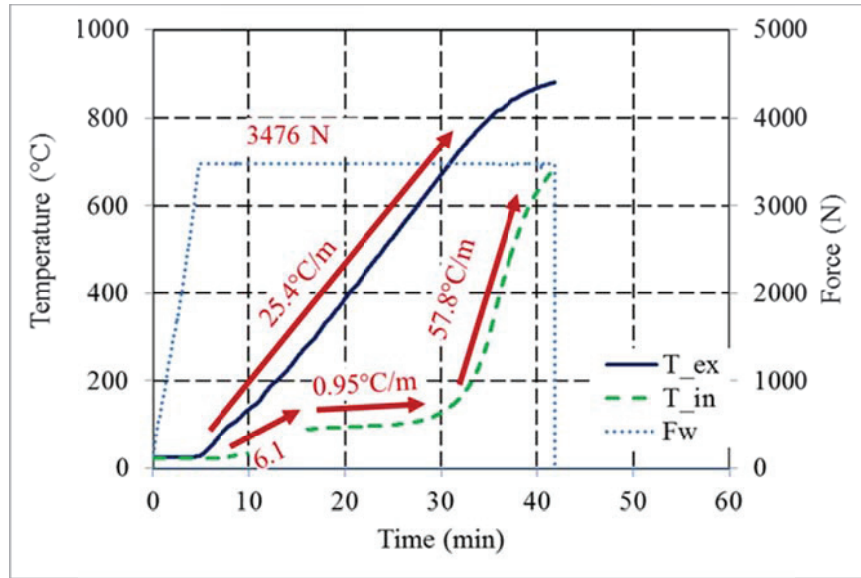


Figure 146: Evolution of external and internal temperatures of M-CFRP with the insulation material at 30% of applied load ratio (f_w)

The result also shows that the thermo-mechanical performance of M-CFRP protected with the insulation material varies according to different mechanical loading conditions (C.T2-Ins, Figure 147 and Figure 148). Particularly, the exposed temperature of the M-CFRP can increase about 150°C (at $f_w = 0.2$) and about 300°C (at $f_w = 0.3$) (Figure 147). Similarly, the exposure duration increases more than 20 minutes ($f_w=0.2$) and 15 minutes ($f_w=0.3$). The results within two insulated CFRP cases (Figure 145 and Figure 146) show that the exterior temperatures at failure are higher than the failure temperatures of the non-insulated results (Figure 147). The interior temperatures at failure, also the temperature at the surface of M-CFRP material, are higher than those of non-insulated cases. At 20% of applied load ratio, the exterior temperature at failure of the insulated specimen is about 750°C (Figure 145) compare to about 610°C of non-insulated specimen (interpolated from Figure 147). At 30% of applied load ratio, the interior temperatures at failure is about 687°C (Figure 146) which is higher than about 570°C of non-insulated specimen (interpolated from Figure 147). In both tests of insulated material, the ramp rates of temperature on the surface of CFRP material are about 40°C/minute and 57.8°C/minute (Figure 145 and Figure 146) which are higher the ramp rates of exterior temperature which are respectively about 28°C/minute and 25.4°C/minute. These results consist to the lower mass loss rate of epoxy resin at higher heating rate from 10°C/minute to 40°C/minute (Qingfeng and Wenfang, 2006; Urso Miano, 2011). It should be also noted that, in the case with insulation, the direct contact between oxygen, epoxy matrix and carbon fibre at high temperature is very limited; while in the case without insulation material, there is the existence of oxygen in the heating chamber which can accelerate the ignition of carbon fibre (Feih and Mouritz, 2012).

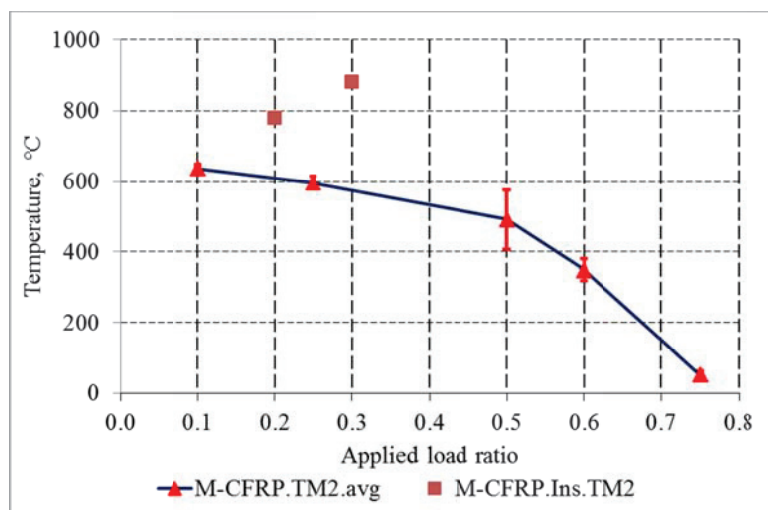


Figure 147: Failure temperature of M-CFRP at different applied load ratio (f_w)

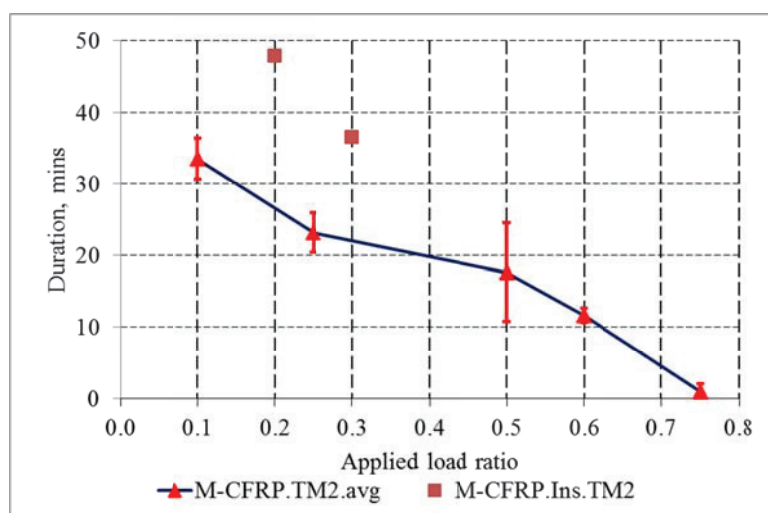


Figure 148: Exposure temperature of M-CFRP at different applied load ratio (f_w)

3.2.5. Conclusions

The aim of this section is to investigate the ability to delay heat conduction of insulation material and also the performance of insulated M-CFRP in TM2 condition. It is clear that the use of insulation material can improve the thermo-mechanical performance of M-CFRP in the testing regime. The used insulation is a commercial product with the material properties which is introduced by the manufacturer. The production procedure confers to the instruction of the manufacturer. According to the manufacturer, the thermal-resistance capacity depends on the thickness of the insulation layer. With of 2 cm thickness of the insulation, the heat penetration is impeded and the temperature on M-CFRP surface retards about 10 minutes (within the tested condition). In the testing condition, the M-CFRP protected with insulation material can expose to higher temperature and in longer duration due to both its insulation capacity and ability in limiting the direct-contact of CFRP and with oxygen.

Chapter 4:

Numerical modelling

CHAPTER 4 Numerical modelling

This chapter shows development of numerical modelling in order to numerically predict the thermo-mechanical performance of CFRP reinforced concrete specimens and insulated CFRP. It is presented in four following subsections: introduction, model 1-CFRP reinforced concrete specimens, model 2-insulated CFRP and conclusion.

4.1. Introduction

This chapter presents and discusses numerical simulations firstly focusing on the thermo-mechanical performance of CFRP reinforced concrete specimens and secondly on the thermal performance of an insulation material in protecting CFRP material under elevated temperature conditions. Based on the experimental result obtained in the chapters 2 and 3, and also reliable information in the literature, thermo-mechanical analyses, using finite element (FE) code, the licensed ANSYS APDL V15 software, are performed on the simulation to:

- Numerically model the mechanical performance of CFRP-reinforced concrete structure at room temperature.
- Study the thermal performance of CFRP reinforced concrete structure and insulation material at elevated temperature condition throughout 3D heat analysis.
- Investigate the thermo-mechanical performance of CFRP-reinforced concrete structure under different combined elevated-temperature and mechanical load conditions regarding the simultaneousness of the effect using sequential-couple fields.

Due to complexity and also expensive cost as well as time consuming of experiments, it is necessary to develop numerical model to better understand the effects of several temperature and mechanical conditions including fire case. In the latter of each part, the simulation is then used to predict the performance of the specimen under standard fire-temperature condition.

4.2. Model 1-CFRP reinforced concrete specimens

In this subsection, the numerical model, heat transfer model, structural analysis model, material properties at elevated temperature, boundary conditions are displayed. The numerical results are then discussed. This ends by conclusions.

4.2.1. Numerical model

In this numerical study, the NSM configuration of CFRP reinforced concrete specimens is modelled with the mechanical and thermal conditions that are in accordance to the TM2 condition. The purpose is to replicate the condition that is close to fire regarding the simultaneousness of loads: thermal load and mechanical load. Therefore, a coupled-field analysis, which is an analysis that takes into account the interaction (coupling) between two or more disciplines (fields) of engineering, is used in this study. Particularly, the sequential coupled thermal and mechanical analysis, or sequential thermal-stress analysis, is used to study the thermo-mechanical performance of NSM CFRP-reinforced concrete specimens (Figure 149). In this analysis method, the nodal temperatures from any load step or time-point in the thermal analysis are considered as nodal loads for the stress analysis. The result of the stress analysis is the combined result of both thermal and mechanical analysis. This method is more time efficient and flexible because two analyses can be performed independently of each other.

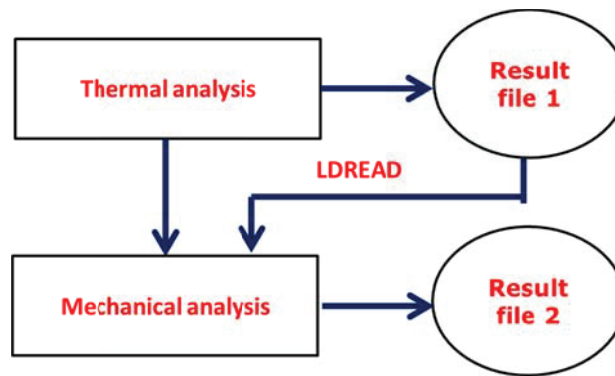


Figure 149 Sequential coupled thermal and mechanical analysis

Based on the sequential coupled field analysis mentioned above, a developed analysis procedure has been used to study the transient thermal-stress analysis corresponding to TM2 condition (Figure 150). In this transient thermal-stress analysis, firstly, a 3 dimensions-finite-element (3D FE) model is generated with the geometry and material information according to the experimental model. The thermal boundary condition is then applied on FE model corresponding to the exterior temperature evolutions obtained in the experiments. After that, the nonlinear transient thermal analysis is then performed on FE model with several time step increments. The numerical modelling result is then compared with the experiment based on the interior temperature at several predefined points. Once the thermal analysis is validated, the model is then converted into structural model to be ready for static stress analysis in the next step. In this step, the thermal result from thermal analysis at time step i , temperature distribution, is considered as temperature load in the second analysis. The mechanical boundary conditions are then applied on the FE structural model for stress analysis. The analysis result in this step is considered as the result of combined thermal load at time step i and mechanical load. The procedures from 5 to 7 are then repeated for several times until the thermal result of final time step is completed with stress analysis. The structural result at each time step is then collected and reported as the structural performance during the increase of temperature from the beginning to the end time point of the transient thermal process.

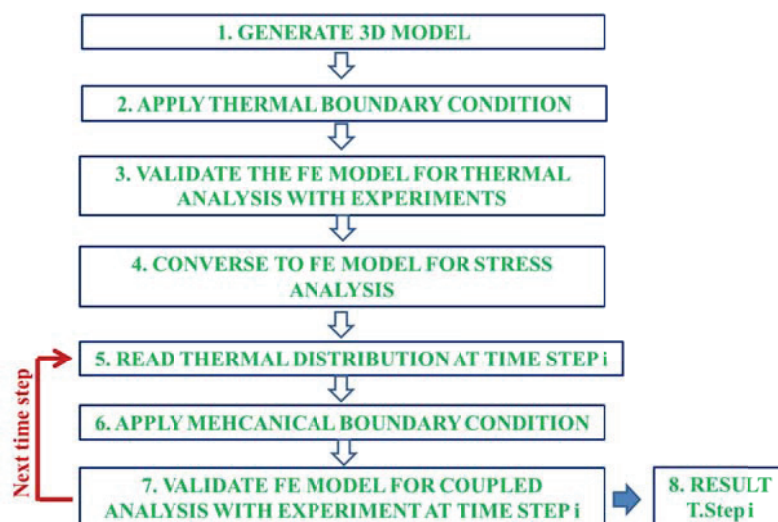


Figure 150: Analysis procedure developed for TM2 condition.

During the analysis, the element type chosen is thermal element SOLID70 (3D 8-nodes thermal solid, Figure 151) for the transient thermal analysis. For stress analysis SOLID45 (3D 8-nodes structural solid, Figure 152) is chosen for steel, CFRP, adhesive and concrete material.

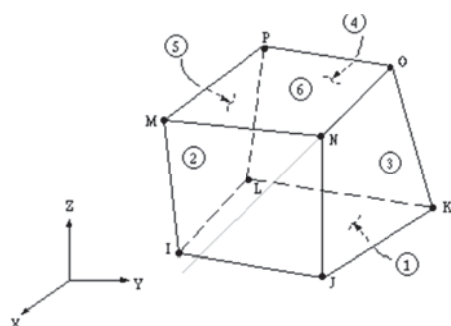


Figure 151: SOLID70 3-D thermal solid element

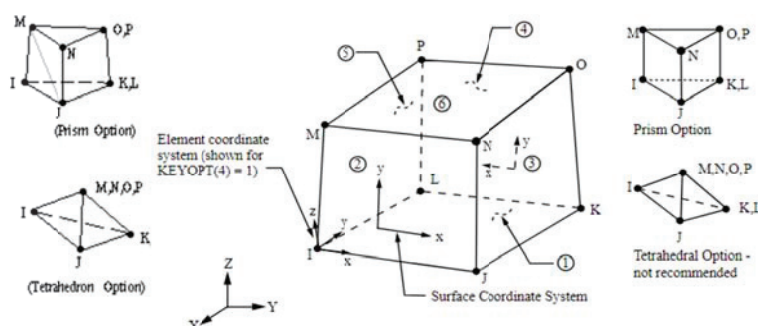


Figure 152: SOLID45 3-D structural solid element

Due to the symmetry of loading, boundary condition, material and temperature loading, an one fourth model was generated (Figure 153). Building one fourth model can simplify the computation process by reducing elements while maintain the reliability of analysis with time efficiency. During the analysis, numerical results at different positions inside the model are exploited for validation as well as parametric study (Figure 154). To obtain converged solution in this thesis, volumes are meshed as following:

- The CFRP is meshed with hexahedral shape with dimension of 1 mm in each dimension.
- The steel core is meshed with hexahedral shape with dimension of 3 mm in each dimension.
- The steel plate is meshed with tetrahedral shape with dimension of 3 mm in each dimension.
- The cohesive zone is meshed with quadrilateral shape with dimension of 3 mm in each dimension.
- The concrete block is meshed with tetrahedral shape with dimension of 5 mm in each dimension.

At the interface between different materials, the mesh is refined to adapt to the smaller mesh size (Figure 155). According to this mesh option, there are total 76455 elements in both thermal analysis and stress analysis.

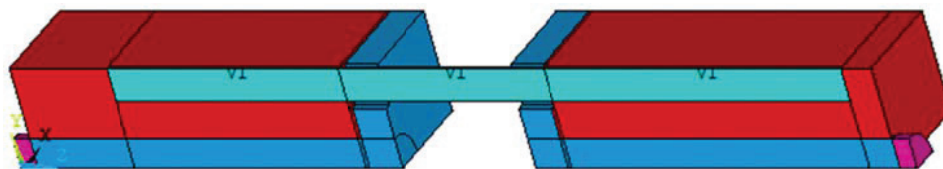


Figure 153: 3D FE model

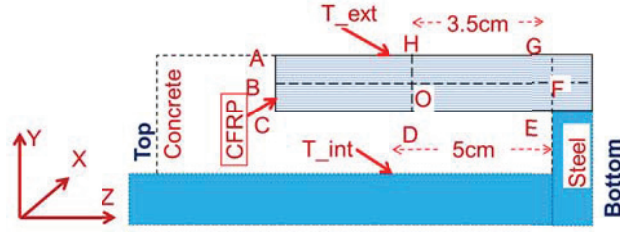


Figure 154: Bonded region between concrete and CFRP

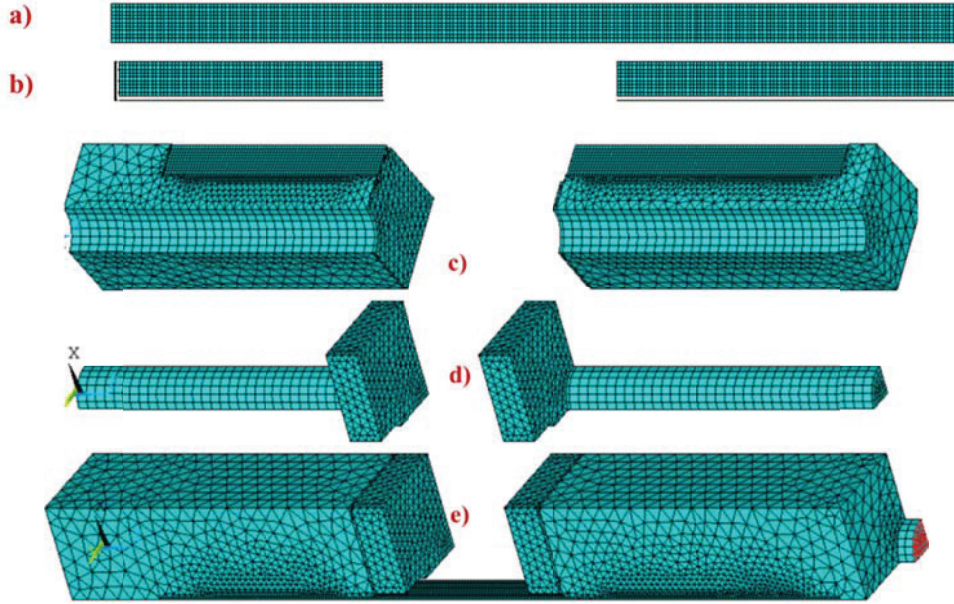


Figure 155: 3D FE model with meshed elements: a) CFRP; b) cohesive zone interface; c) concrete; d) steel system; e) 3D meshed model

4.2.2. Heat transfer model

The finite element model has been generated to study the heat transfer problem within the CFRP reinforced concrete specimen presented in the experiment at different temperature conditions. The studied FE model of the specimen has the same geometry configuration and dimension as in the experiment (Figure 153). The developed heat transfer model, which is able to predict temperature evolution in the 3D specimen, is based on the partial differential equation of heat:

$$\rho c \frac{\partial T}{\partial t} = \nabla \cdot (k \nabla T) = \frac{\partial}{\partial x} \left(k_x \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left(k_y \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left(k_z \frac{\partial T}{\partial z} \right) \quad \text{Equation 12}$$

In which: T is temperature, t is time, k_i is thermal conductivity, ρ is density and c is heat capacity

4.2.3. Structural analysis model

In this thesis, the static analysis is done using an implicit solver in which solution of each step requires a series of trial solutions (iterations) to establish equilibrium within a certain tolerance. To solve equations numerically, the automatic solution control can use the full Newton-Raphson option for the existence of non-linearity. Large-deflection effects are also considered in this simulation.

4.2.4. Material properties at elevated temperature

In the literature as well as design standards, there is available data for thermal and mechanical properties of concrete, steel and laminate CFRP at elevated temperature. In this numerical study, the main material properties of concrete and steel at ambient and elevated temperatures are adopted from Eurocodes. The other parameters for CFRP, adhesive, as well as those of concrete and steel which are not mentioned in Eurocodes, are referred to previous studies in the literature.

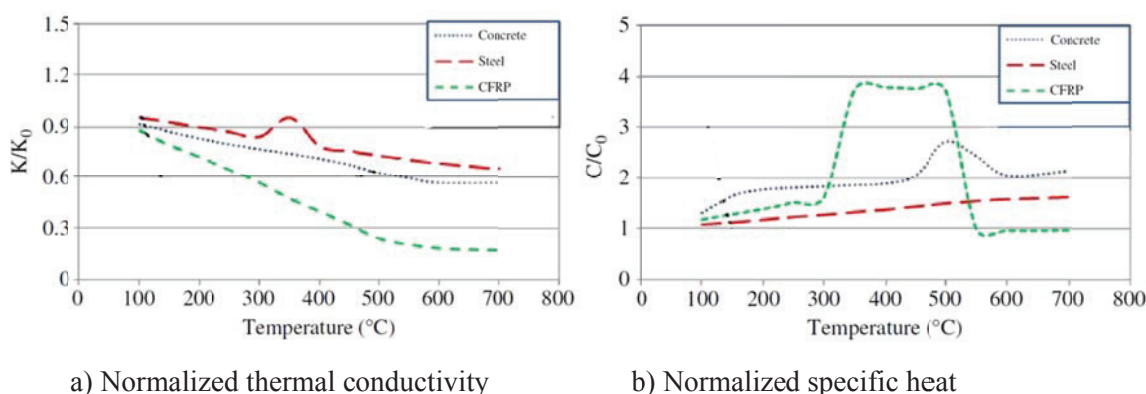
4.2.4.1. Thermal properties

To obtain numerical prediction for thermal analysis, the evolutions of thermal properties of CFRP, concrete, adhesive and also steel material have been adopted from Eurocode 2 and literature (Arruda et al., 2016; Bisby, 2003; Firmo J. P. et al., 2015; Hawileh et al., 2009) (Table 49 and Figure 156).

Table 49 Thermal properties of material at room temperature (Hawileh et al., 2009) and Eurocode 2

Material	K_{20} , W/mm.K	C_{20} , J/kg.K	ρ_{20} , kg/mm ³
Concrete	2.70E-03	722.8	2.40E-06
Steel	5.20E-03	452.2	7.86E-06
P-CFRP	1.30E-03	1210	1.60E-06

(K_{20} : thermal conductivity (W/mm.K); C_{20} : specific heat (J/kg.K); ρ_{20} : density (kg/mm³) at 20 °C)



a) Normalized thermal conductivity

b) Normalized specific heat

Figure 156 Normalized thermal properties with temperature (Hawileh et al., 2009).

4.2.4.2. Mechanical properties at elevated temperatures

In stress analysis, the mechanical properties at elevated temperature of concrete are adopted from Eurocodes and in literature as followings:

4.2.4.2.1. Concrete and steel materials

The evolution of mechanical properties of concrete and steel in this stress analysis are determined according to Eurocode 2 (for concrete, Figure 157) and Eurocode 3 (for steel, Figure 158).

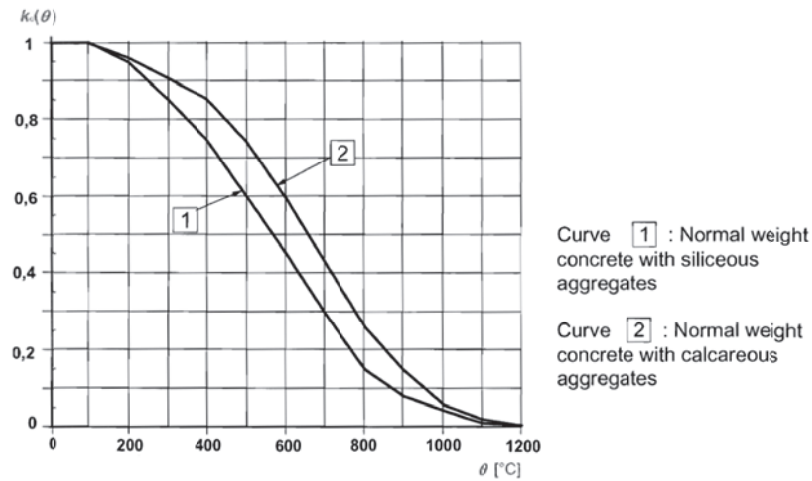


Figure 157: Strength reduction of concrete at elevated temperatures (EN 1992-1-2).

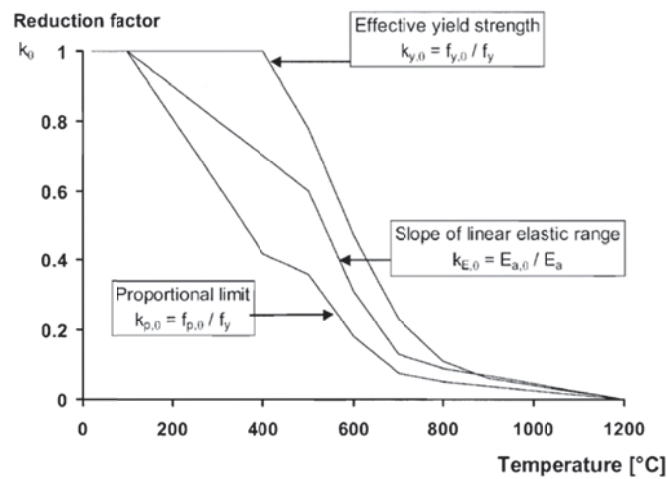


Figure 158: Strength reduction of steel at elevated temperatures (EN 1993-1-2)

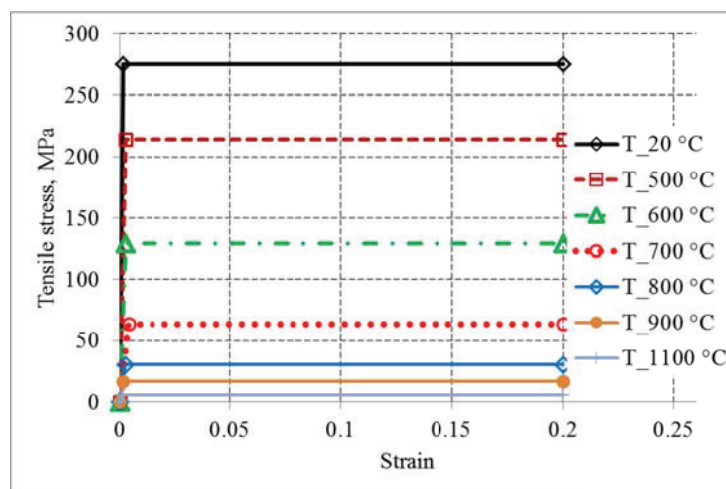


Figure 159: Stress-strain curves of reinforcing steel bars at elevated temperatures (EN 1993-1-2)

4.2.4.2.2. CFRP

Based on the experimental result obtained in the chapter 2, the mechanical properties of P-CFRP at elevated temperatures, which is used in this research, are as followings (Figure 160).

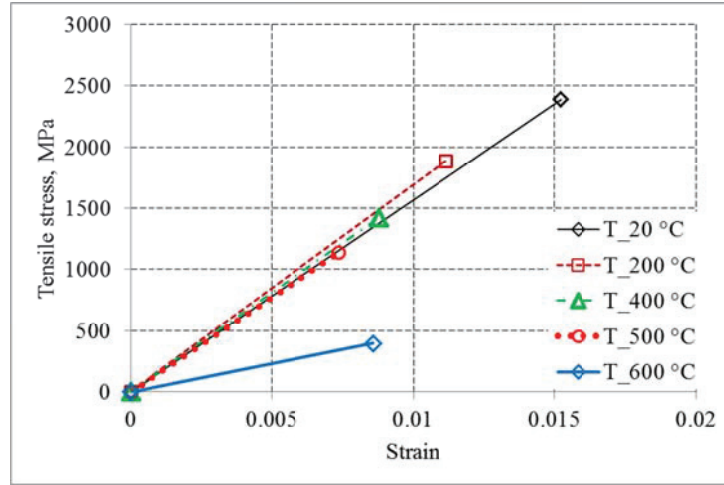


Figure 160: Linear stress-strain curves of P-CFRP at elevated temperatures obtained from experiments

4.2.4.2.3. Adhesive

Regarding to the element of the interface between P-CFRP and concrete substrate, the cohesive bilinear zone material model (CZM, (Alfano and Crisfield, 2001)) was used in this numerical study. This material model was developed in the ANSYS software for fracture or delamination along an interface between two materials. The interface element provides bilinear behaviour, and this model assumes that the separation of the material interfaces is dominated by the displacement jump tangent to the interface as shown in the Figure 161. The relation between tangential cohesive traction T_t and tangential displacement jump δ_t can be expressed as

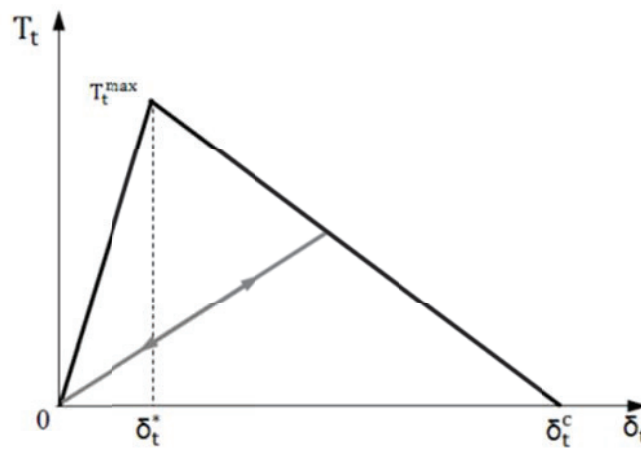


Figure 161: Cohesive bilinear zone material model for the interface (Alfano and Crisfield, 2001)

$$T_t = K_t \delta_t (1 - D_t) \quad \text{Equation 13}$$

Where : K_t is the tangential cohesive stiffness ; $\tau_t^{\max}$ is the maximum tangential cohesive traction; δ_t^* is the tangential displacement jump at maximum tangential cohesive traction; δ_t^c is the tangential displacement jump at the completion of debonding; D_t is the damage parameter associated with mode of dominated bilinear cohesive law, defined as Equation 14:

$$D_t = \begin{cases} 0 & \delta_t^{\max} \leq \delta_t^* \\ \left(\frac{\delta_t^{\max} - \delta_t^*}{\delta_t^{\max}} \right) \left(\frac{\delta_t^c}{\delta_t^c - \delta_t^*} \right) & \delta_t^* \leq \delta_t^{\max} \leq \delta_t^c \\ 1 & \delta_t^{\max} > \delta_t^c \end{cases} \quad \text{Equation 14}$$

The bond strength of single lap of Duralco 4703 (Epoxy 1) at three levels of temperature is reported by Victrex Europa GmbH ((Horst, 2000), Table 50). According to Firmo et al., the parameters of bond-slip model for EBR and NSM reinforcement methods can vary among wide range depending on the material ((Firmo et al., 2015a; Firmo J. P. et al., 2015), Table 51). Figure 162 displays the calibrated parameters for numerical modelling of the bond at different temperatures reported by Arruda et al. (Arruda et al., 2016). The calibrated parameters demonstrate that the mechanical performance of NSM method is almost double than that of EBR method. The calibrated properties were compared with analytical model for bond strength performance at elevated temperature with good consistence (Figure 163). Based on these results, the bond-slip parameters are calibrated for the P-CFRP-concrete bond in this numerical simulation for NSM reinforcement method (Figure 164).

Table 50: Duralco 4703 adhesives and test temperatures for single overlap shear experiments (Horst, 2000)

Properties	23°C	150°C	200°C
Lap strength τ [MPa]	3	3.4	1
W(95,n)	0.7	0.4	0.1
Number of samples, n	4	5	5
fracture mode	interfacial + cohesion failure	cohesion failure	cohesion failure

Table 51: Range of values for interface parameters for EBR and NSM (Firmo et al., 2015a; Firmo J. P. et al., 2015) .

Parameter	EBR		NSM	
	Minimum	Maximum	Minimum	Maximum
K (MPa/mm)	1	1500	2	1000
τ_{LM} (MPa)	0.5	25	1.5	20
S_{Lo} (mm)	0.2	1.0	0.4	1.5

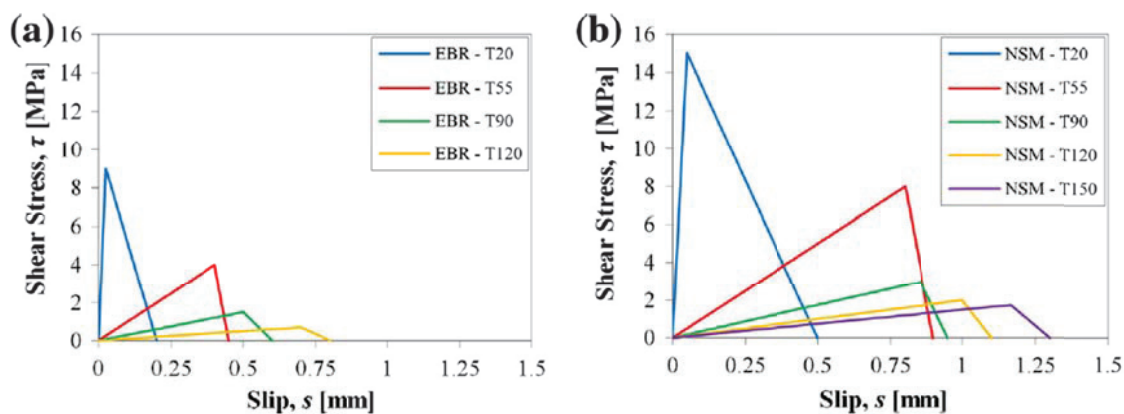


Figure 162: Bond-slip constitutive curves for all tested temperatures (Arruda et al., 2016).

(a) EBR and (b) NSM specimens

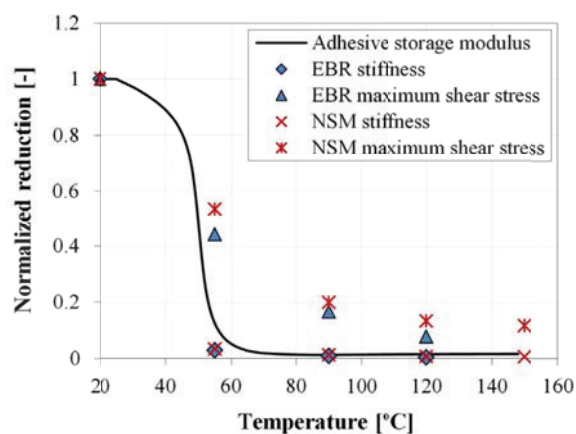


Figure 163: Normalized reduction with temperature of the adhesive storage modulus, stiffness and maximum shear stress of the proposed bond-slip relationships (Arruda et al., 2016).

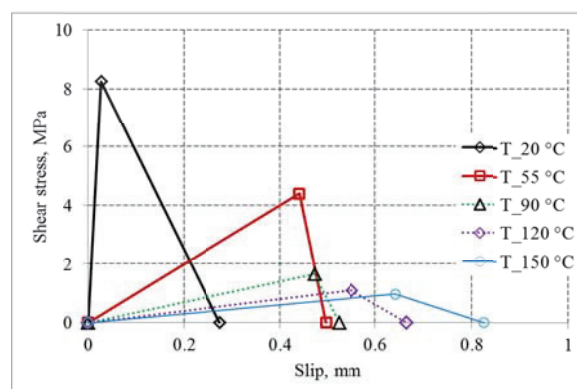


Figure 164: Bond-slip curves at different temperatures for NSM specimens in this research

4.2.5. Boundary conditions

This subsection respectively shows thermal analysis boundary conditions, stress analysis boundary conditions.

4.2.5.1. Thermal analysis boundary conditions

During thermal analysis, the temperature increase surrounding specimen is modelled as the temperature evolution in the experimental test. The thermal boundary condition of FE model is based on the exterior temperature evolution followed by three thermocouples along the side of specimens during the experiment. Figure 165 displays three thermal boundary conditions (of three mechanical cases) which replicate the typical measured side-temperatures of three typical tested cases obtained in experiments (series 6). The correlations between temperatures at different positions surrounding model (Figure 166) are based on the correlations between measured points in experiments (Figure 132).

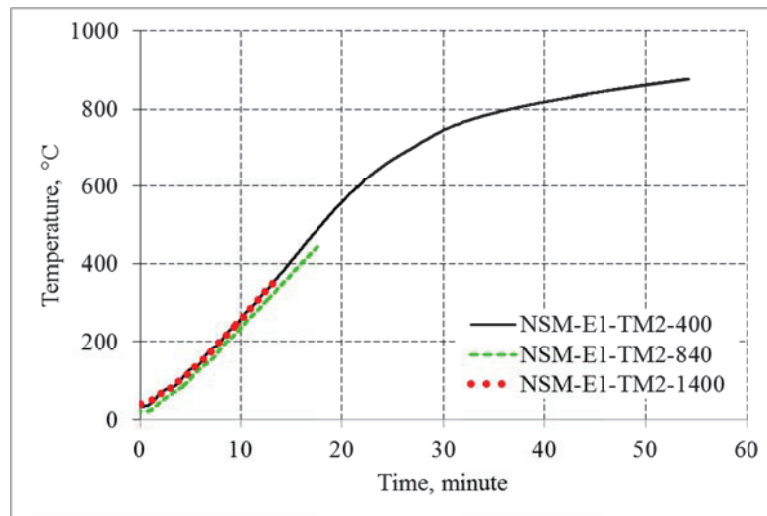


Figure 165: Exterior temperature evolution in three typical experiments (series 6)

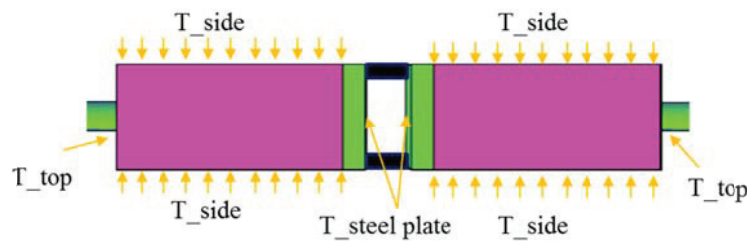


Figure 166: Thermal load on FE model

4.2.5.2. Stress analysis boundary conditions

During the TM2 testing condition, the specimen is applied with mechanical load and then maintained during the heating phase. The mechanical system is programed to quickly compensate the mechanical load loss caused by the thermal effects during heating phase. Therefore in the stress analysis, to better simulate the TM2 experiments, the FE model is fixed at one end, and mechanical tensile load is applied on the other end by surface load control method according to the load case (Figure 167). The temperature distribution, which is resulted from the thermal analysis, is loaded onto the FE model before analysing.



Figure 167: Mechanical load by surface load control method

4.2.6. Numerical results and discussions

This section presents and discusses the results from the numerical simulation with the experimental results regarding to three behaviours of NSM reinforced concrete specimen: mechanical response at room temperature, thermal analysis result at elevated temperature condition and thermo-mechanical response at temperature-mechanical condition. The comparative parameters are selected at the same points in P-CFRP reinforced specimen in experiments of series 1 and 6.

4.2.6.1. Mechanical performance at 20 °C

In this section, the mechanical analysis of CFRP reinforced concrete model at room temperature is presented. Figure 168 presents the force-total displacement curves at room temperature condition obtained from the numerical model (FE result curve) and experiments (WSP01 and WSP02, structure experiment series 1). The figure shows a good agreement between numerical prediction model and experimental result in the force-displacement relationship. According to this, the numerical model results in mechanical failure load (19.5 kN) which is about 9.4% higher than average experimental result (17.829 kN).

Figure 169, Figure 170 and Figure 171 display the distributions of normal stresses according x-axis (σ_{xx}), z-axis (σ_{zz}) and shear stress (τ_{yz}) at the end of mechanical analysis. According to Figure 169b, the concrete region contacting with ACDH area (Figure 154) undergoing a normal stress along x-axis which can contribute to the friction on CFRP surface and subsequently increase the mechanical performance of the bond. Figure 170a, the tensile stress between two steel plates is maximum and reduces along the direction into the bond. As in Figure 170b, there are two regions on concrete that experience the compressive stress and tensile stress along z-axis, respectively correspond to area ACDH (tensile) and area DEGH (compressive). The compressive effect at the corner CFRP and steel-plate (corresponds to area DEGH, Figure 154) reasonably explains for the experimental failure obtained in structure series 1 (WSP case, Figure 105). As displayed in Figure 171, at the CFRP-concrete interface, the region close to ABC line and DEFO area undergo higher shear stress τ_{yz} . Figure 172 shows the distribution of Von-Mises stress at the CFRP and the investigated concrete block. According to this figure, the regions which are next to lines BC and CD are under higher level of Von-Mises stress.

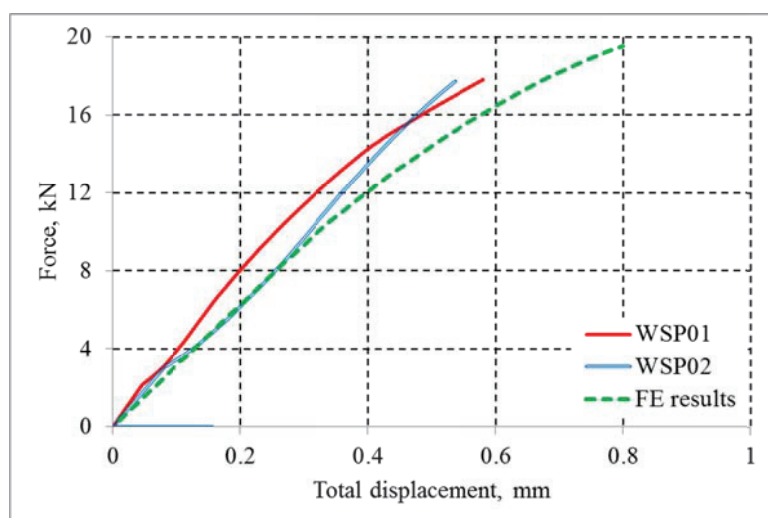
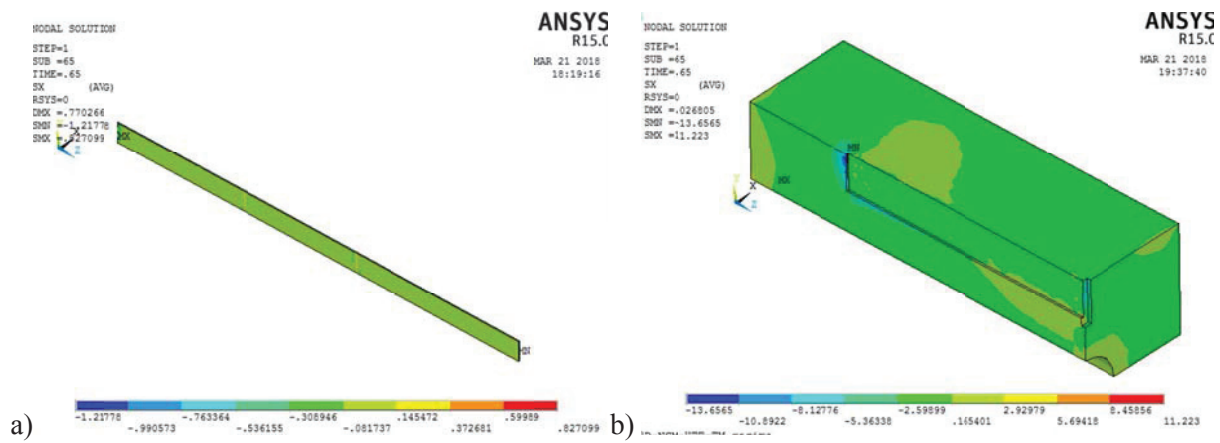
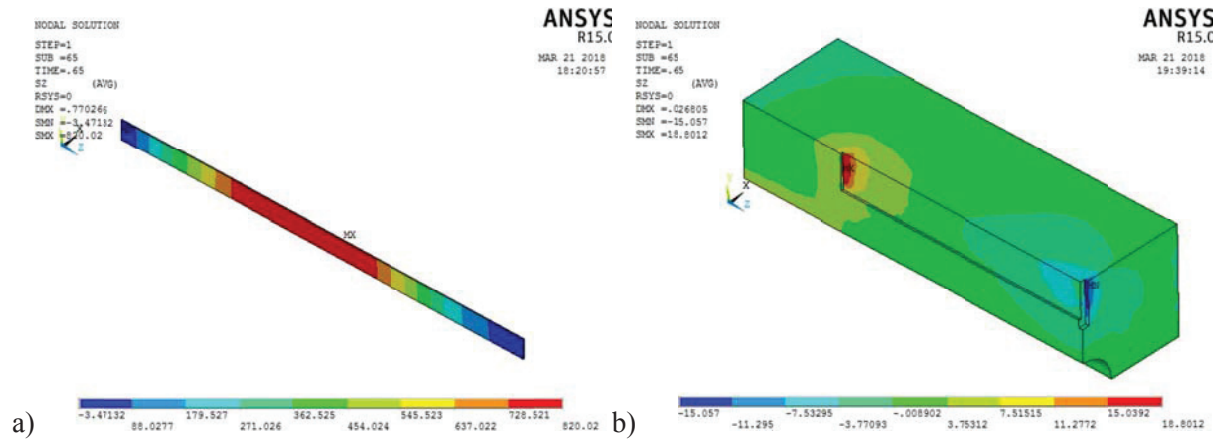


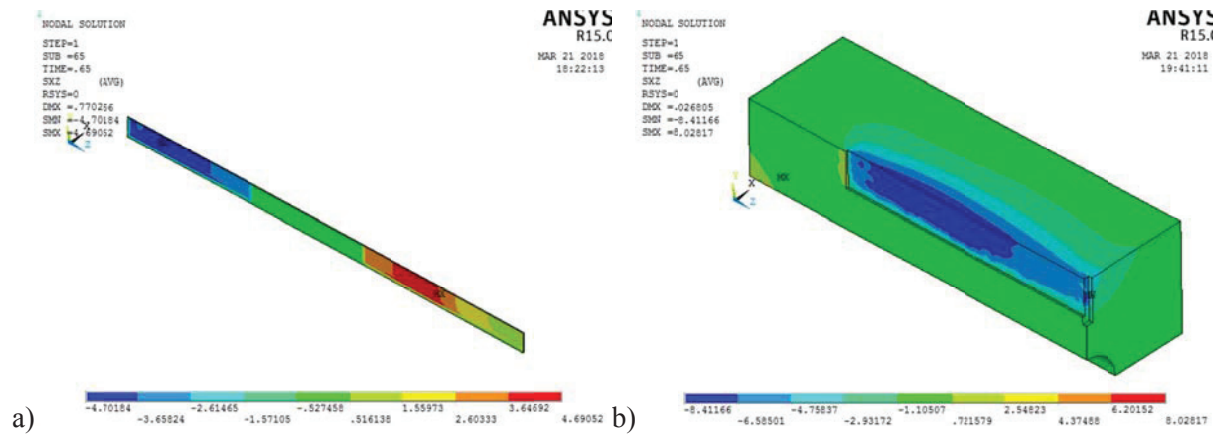
Figure 168: Force- total displacement relation at 20 °C of CFRP

Figure 169: Normal stress σ_{xx} .

a) CFRP; b) concrete

Figure 170: Normal stress σ_{zz} .

a) CFRP; b) concrete

Figure 171: Shear stress τ_{xz} .

a) CFRP; b) concrete

Figure 173 and Figure 174 display the distributions of normal stress σ_{xx} , and shear stress τ_{xz} , along path HD and BF at the end of analysis. According to Figure 173a, the normal stress σ_{xx} is small in the middle of HD path (from 2mm to 8mm of distance (from H-end)), but significantly increases at both

end H and end D. As described in Figure 173b, the absolute value of shear stress τ_{xz} is uniform at about 4 MPa between 0mm and 7mm of distance, then slightly increases to 4.3MPa at 8mm and then quickly reduces until 10mm of distance (from H-end). Figure 174a shows that the normal stress σ_{xx} along path BF is small and ignorable, excepts at two ends. As shear stress distribution (τ_{xz}) in Figure 174b, it generally reduces from 3.8 MPa at B to 2.7 MPa at E with a maximum value of 4.3MPa at 20mm from B-end.

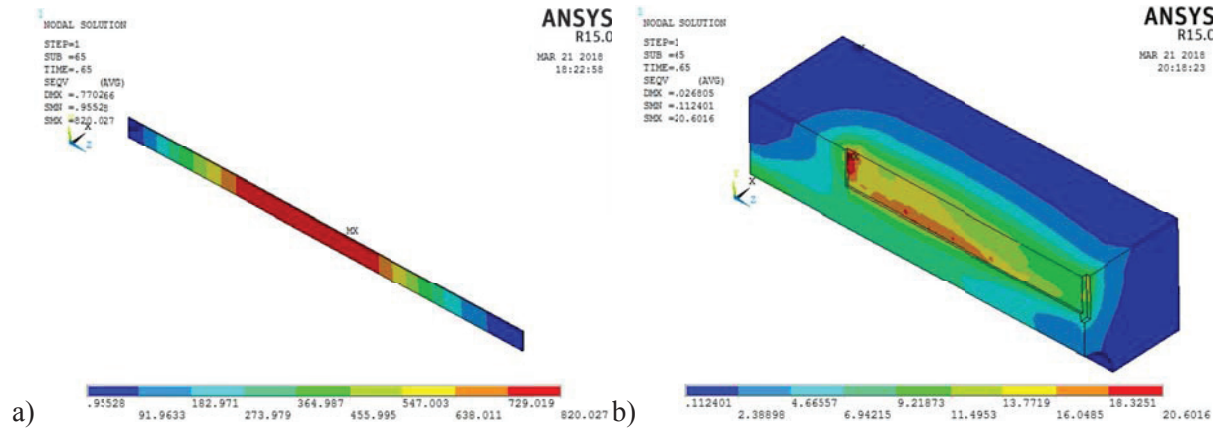


Figure 172: Von-Mises stress.

a) CFRP; b) concrete

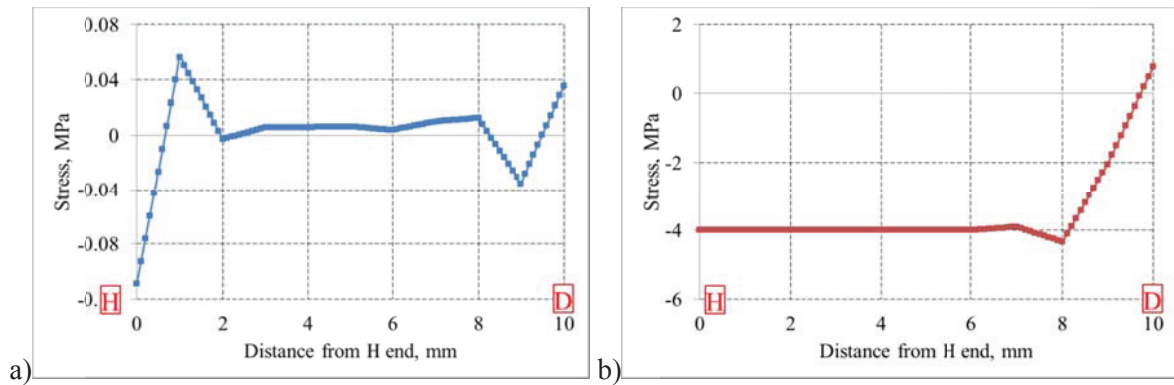


Figure 173: Stress distribution along HD path at 20 °C.

a) Normal stress σ_{xx} ; b) Shear stress τ_{xz}

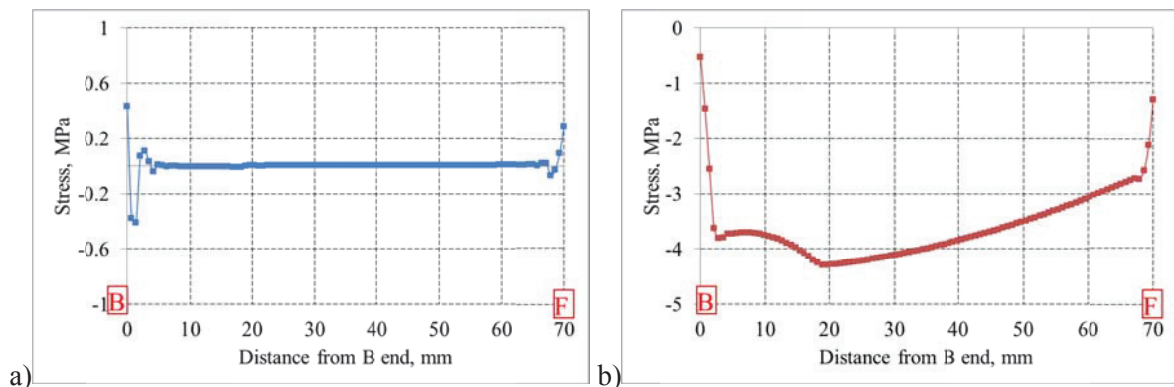


Figure 174: Stress distribution along BF path at 20 °C.

a) Normal stress σ_{xx} ; b) Shear stress τ_{xz}

4.2.6.2. Thermal analysis result of TM2 condition under $F_w = 840N$

This section presents the thermal analysis based on the experiments on structure series 6 (Chapter 3, section 3.1). The following results focus on analysing the mechanical load case $F_w = 840N$ and similar numerical results are presented in the annex. Figure 175 displays the temperature evolution at two observed points outside and inside specimen ($T_{ext.*}$ and $T_{int.*}$, Figure 154) obtained in experiments (test 3 through 5 of structure-series 6) and numerical solutions. The numerical exterior-temperature evolution ($T_{ext.N}$, Figure 175) confirms that the temperature condition applied on numerical model well replicates the experimental condition. The exterior temperature increases from 25°C and reaches 500°C after about 17.9 minutes with the heating rate about 26.5°C/minute as in experiment. The numerical interior temperature result ($T_{int.N}$, Figure 178) displays the good response to that obtained from the experiment 2 and similar trend with those obtained from the experiments 1 and 3. Figure 176 presents the experimental temperature evolutions at different thermo-couple positions (curve 1 to curve 6) and the predicted temperature results obtained from the numerical model (curve 7 to curve 10). According to the figure, the predicted temperature at 1 cm from concrete surface (TC5) is close to the experimental result (curve 10 vs. curve 6). However, the predicted temperatures at the concrete-steel interface (TC1) and at CFRP-concrete interface (TC4) are sooner than the experimental measurement (curve 8 vs. curve 2 and curve 9 vs. curve 5).

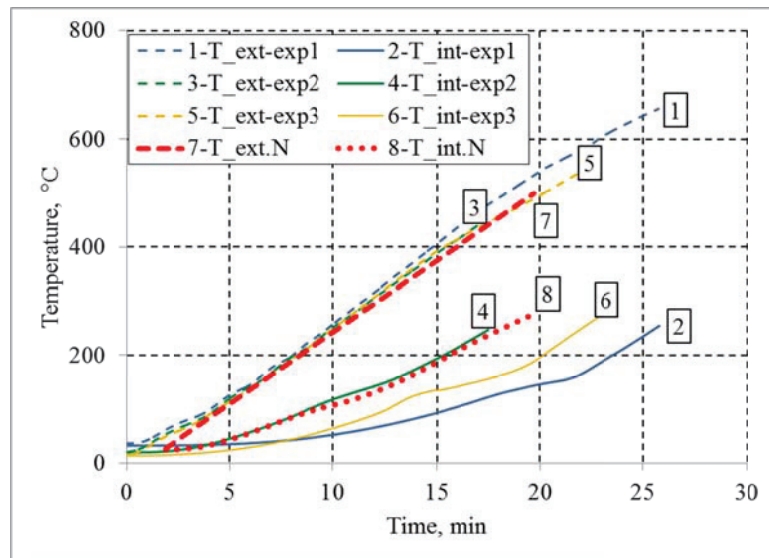


Figure 175 : Evolution of exterior temperature ($T_{ext.N}$ or $T_{ext.Ei}$) and interior temperature ($T_{int.N}$ or $T_{int.Ei}$) in sample obtained by numerical modelling (*.N) and experiment (*.exp); i: experiment number. (exp1: test 3-series 6; exp2: test 4-series 6; exp3: test5-series 6)

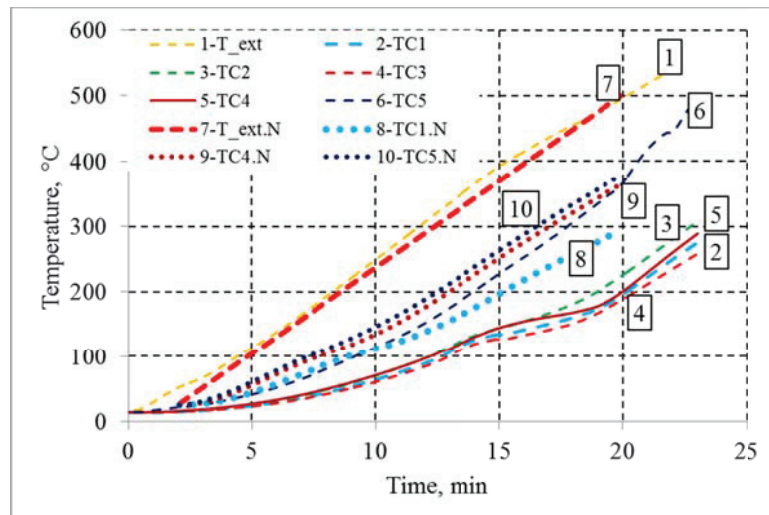


Figure 176: Temperature evolution at different points inside specimen obtained from experiment (test5-series 6) and numerical modelling (*.N) (see Figure 101 for thermo-couple positions)

Figure 177 shows the 3D temperature distribution in the CFRP and the concrete after being applied with the temperature evolution reaching up to 500°C. According to this figure, the temperature varies from 225°C to 500°C within the concrete and from 300°C to 500°C within the CFRP.

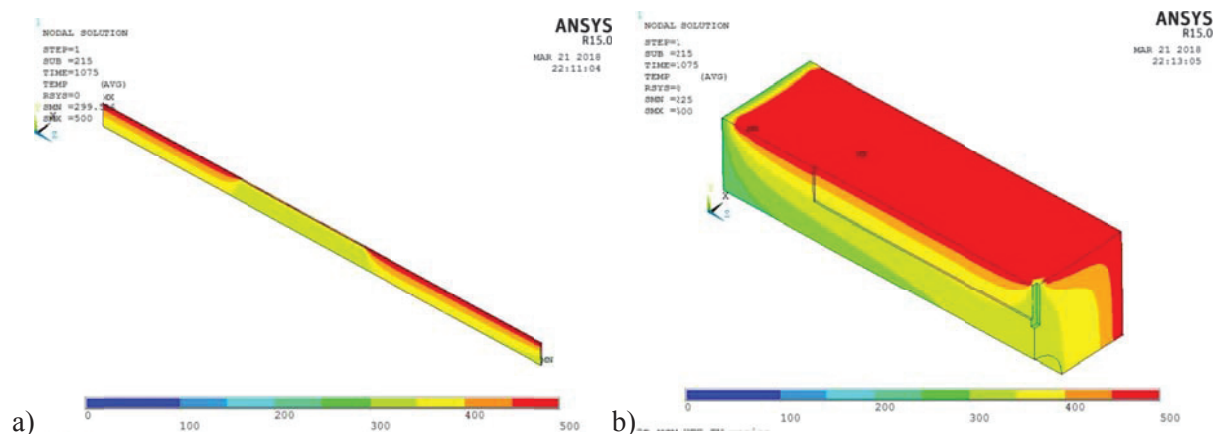


Figure 177: Numerical result of temperature distribution in sample (T2-840N).

a) CFRP; b) concrete

Based on the experimental results, the specimen collapses when the temperature at concrete-steel interface (T-int) reaches 243°C on average regardless the difference between interior-temperature evolutions (Figure 175). At this point of time, the numerical temperature distribution along four paths on the CFRP-concrete interface are plotted: two along the specimen axis (BF, CE) and two across specimen axis (AC, HD) (Figure 178) (see Figure 154 for positions of four paths)..

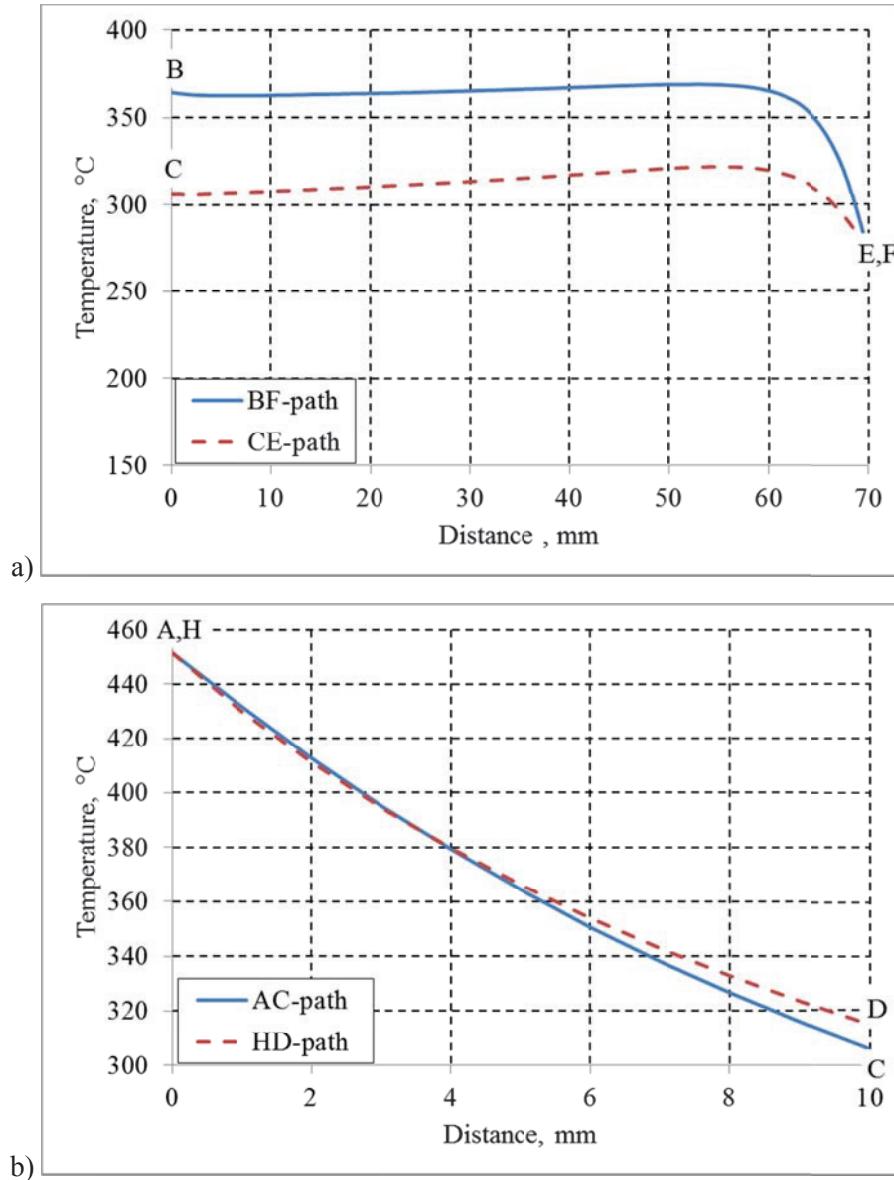


Figure 178: Temperature distribution along four paths on the CFRP-concrete interface at the failure.

The temperature distributions along BF and CE display the small difference between beginning points B and C to distance about 55mm (Figure 178a). The main temperature ranges of two paths are about 363°C and 310°C respectively. At the ends of two paths, the temperature turns smaller and is about 280°C at the points F and E. It is because the temperature applied to the steel plate is lower than side temperature of specimens simulated according to experimental situation (Figure 132, Figure 134 and Figure 136). The temperature distribution along the paths AC and HD widely varies from 451°C at exterior (points A and H) to about 310°C at interior (points C and D). This variation well consists with the temperature distribution at the end of analysis (Figure 177).

4.2.6.3. Thermal-mechanical result under $F_w=840N$

This section displays the numerical result of mechanical analysis after obtaining the thermal distribution from previous section. The mechanical load case $F_w=840N$ is applied to model and the behaviours of model are analysed at several time steps of thermal solution. Figure 179 displays the

total-displacement vs. time relation obtained in the numerical solution and experimental result. According to this figure, the development of total displacement is well predicted by the model.

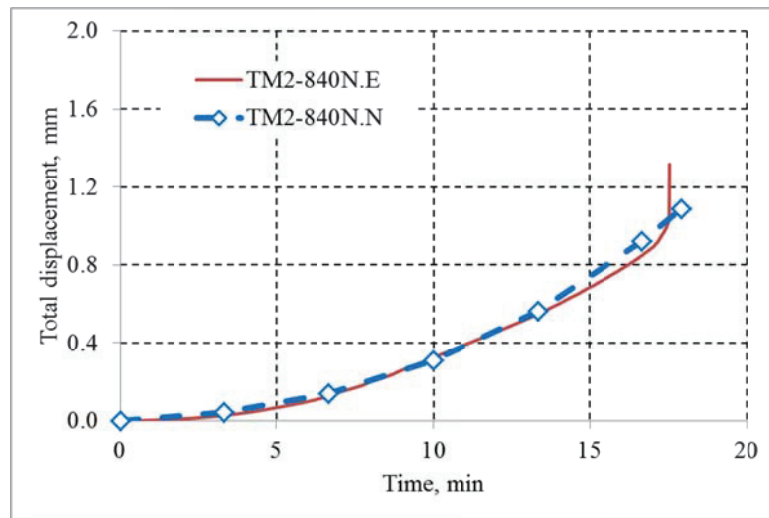


Figure 179: Total displacement vs. time curves at mechanical load $F_w=840\text{N}$ (obtained by numerical modelling (*.N) and experiment (*.E))

Figure 180, Figure 181 and Figure 182 display the normal stresses in x-axis and z-axis (σ_{xx} and σ_{zz}) and shear stress at CFRP-concrete interface (τ_{xz}) at the time when exterior temperature reaches 500°C . At this end time of analysis, the result shows that there is a concrete region close to CFRP-surface which is undergone in compressive stress σ_{zz} (Figure 181b). The compressive stress increases along the radius direction to the surface. The tensile stress on CFRP also varies with the magnitude increases along the radius direction (Figure 181a). Along the radius direction, the Von-Mises stress along the perimeter of the CFRP-concrete interface (path CDE, Figure 154) is greater than the side interface (Figure 183).

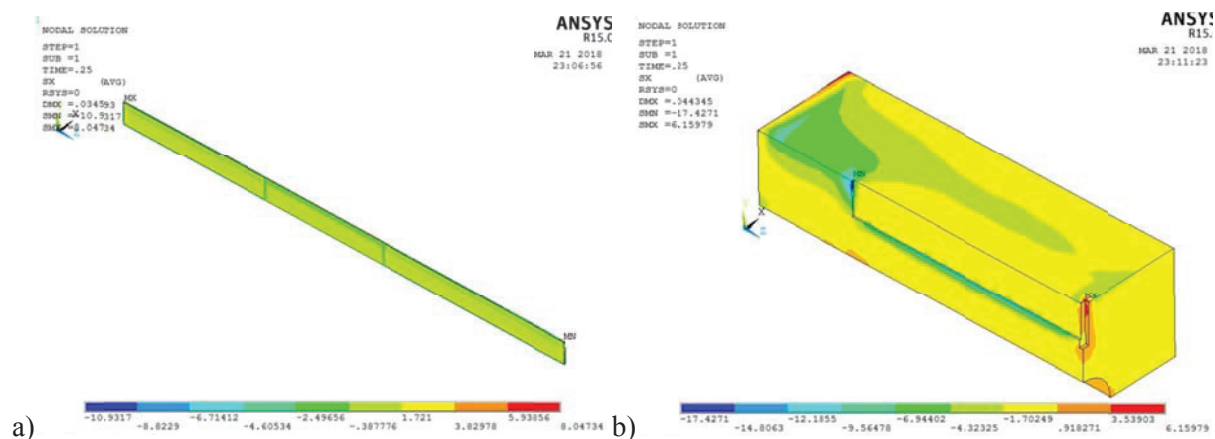
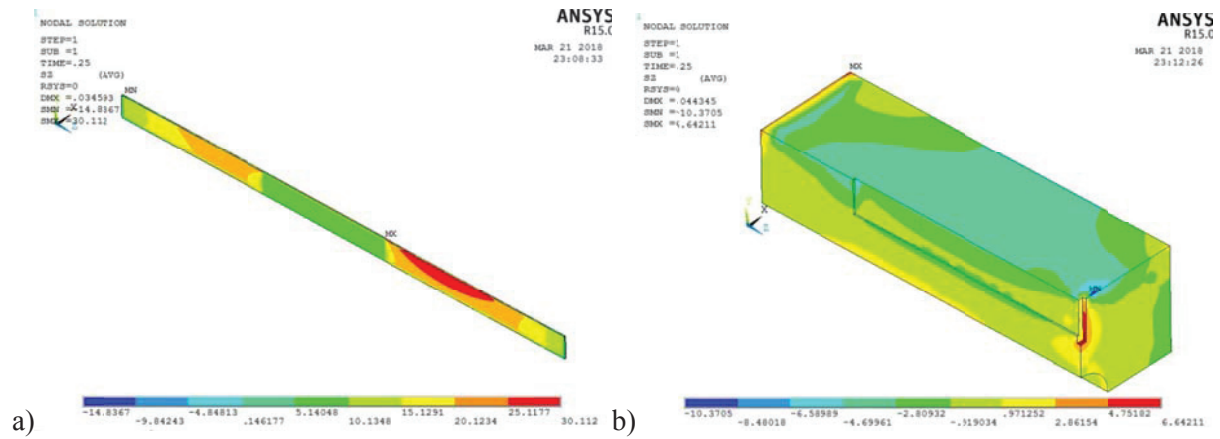
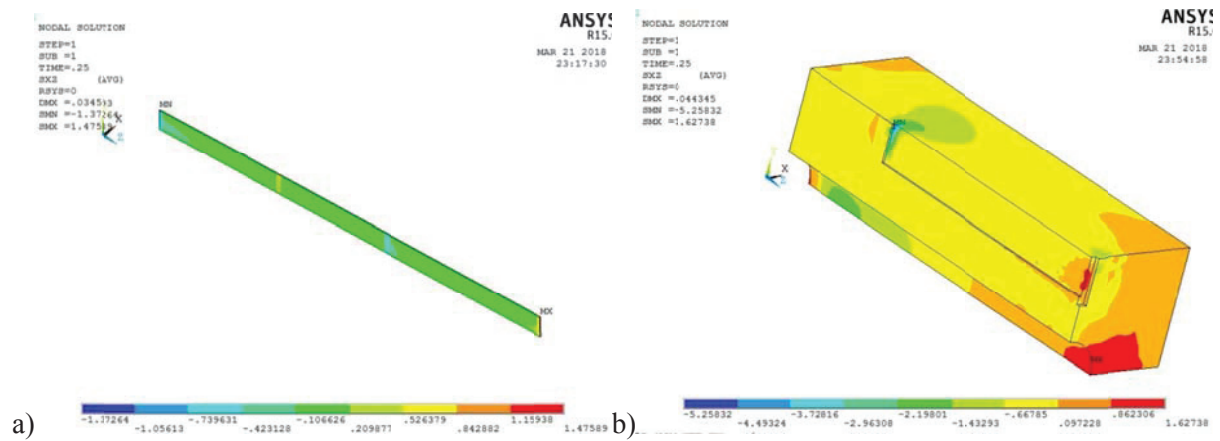


Figure 180: Normal stress σ_{xx} .

a) CFRP; b) concrete

Figure 181: Normal stress σ_{zz} .

a) CFRP; b) concrete

Figure 182: Shear stress τ_{xz} .

a) CFRP; b) concrete

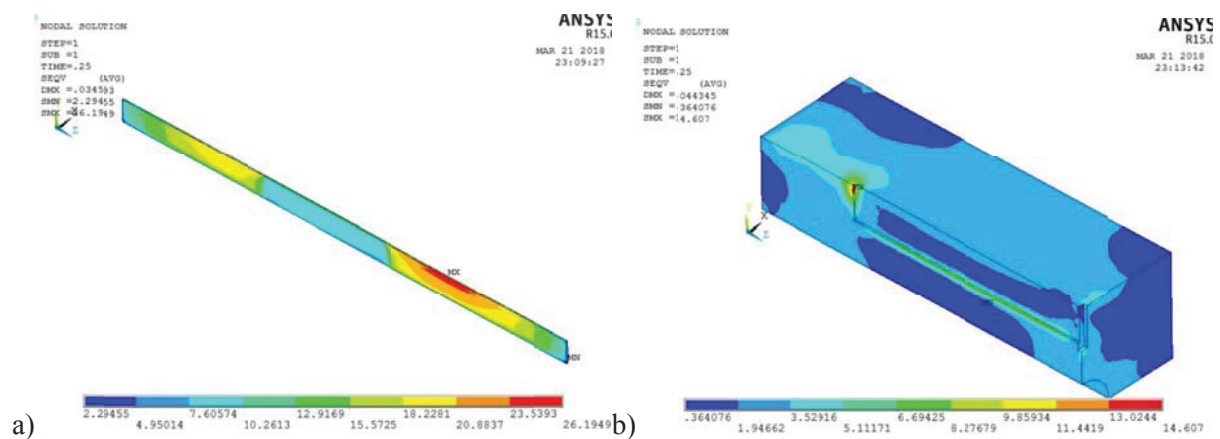


Figure 183: Von-Mises stress.

a) CFRP; b) concrete

Figure 184 displays the predicted result in total-displacement vs. time curves at three investigated mechanical load cases. As can be seen from this figure, at the mechanical load case $F_w=400\text{N}$, the numerical prediction (curve 2) is greater than the experimental results at the beginning part but its later part shows a good agreement with experimental curve (curve 1). At two mechanical load cases: $F_w=840\text{N}$, $F_w=1400\text{N}$, the numerical prediction on the development of total-displacement as time (and also as the increasing temperature; curves 4, 6) are close to the experimental result (curves 3, 5). According to these results, it can be inferred that the total-displacements under the combined effect of mechanical load and increasing temperature are well predicted in three mechanical cases: $F_w=400\text{N}$, $F_w=840\text{N}$ and $F_w=1400\text{N}$.

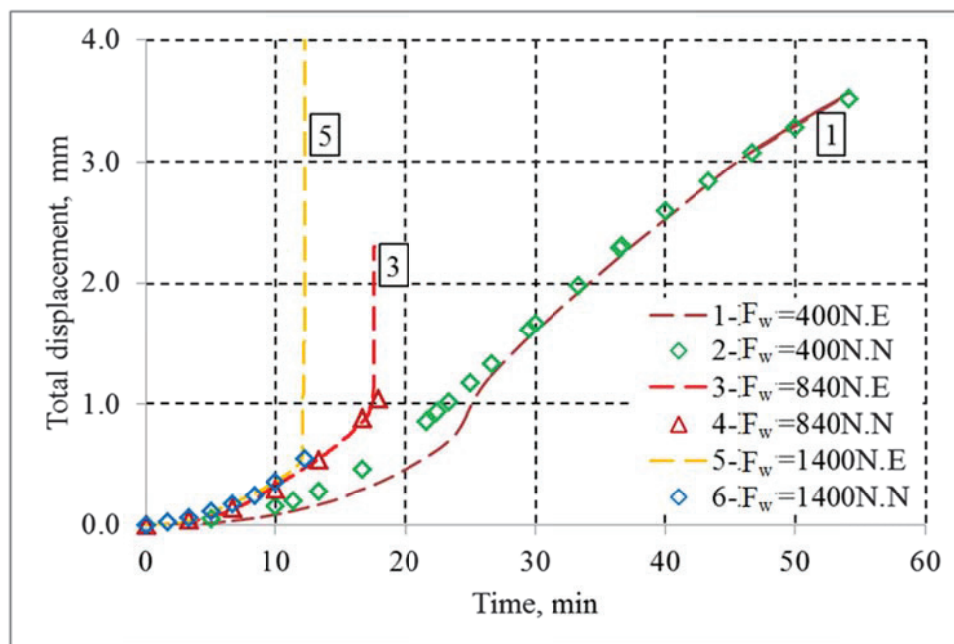


Figure 184: Total displacement – time curves at different mechanical load cases of TM2 regime. (obtained by numerical modelling (*.N) and experiment (*.E))

4.2.6.4. TM2 performance at different mechanical loads as fire curve (ISO 834 condition)

As far as the author's acknowledgement, the elevated temperature performance of the CFRP reinforced concrete structure mainly depends on CFRP-concrete bond which is significantly influenced by the used adhesive (Firmo et al., 2015b). According to analysed result, due to small temperature variation along path CE, the temperature at middle point D of CE path is proposed as a referenced failure criterion for the specimen under the service load and elevated temperature condition. Therefore, under mechanical load $F_w=840\text{N}$, the specimen is assumed to be failed as the temperature at point D (CFRP-concrete interface) exceeds 310°C . Figure 185a presents the temperature evolution at three points obtained from numerical model: side of specimen ($T_{\text{ext.N}}$), concrete-steel interface ($T_{\text{int.N}}$) and at CFRP-concrete interface ($T_{\text{point D.N}}$). Based on the proposed failure criteria for the imposed mechanical load ($F_w=840\text{N}$), the numerical result can estimate the performance of specimen that can be maintained for the duration up to 16.08 minutes (Figure 185a). Figure 185b presents the numerical result of developed model in which the temperature evolution surrounding specimen is adopted from standard fire case, ISO-834 curve. The temperature evolutions at top and bottom of specimen are referred from the experiments. With the proposed failure

criterion (under $F_w=840\text{N}$), the service duration of specimen is up to 6.67 minutes under ISO-834 fire-temperature condition. Based on the numerical results obtained at two other mechanical load cases ($F_w = 400\text{N}$ and $F_w = 1400\text{N}$, see modelling details on Appendix A) verified by experiments, Figure 186 predicts the service duration of CFRP reinforced concrete specimens under different mechanical load status, subjected to standard fire temperature ISO-834 condition. According to the numerical result, the specimens which are under mechanical load $F_w=400\text{N}$, 840N and 1400N can resist the standard-fire temperature ISO-834 for 19.2 minutes, 6.67 minutes and 4.83 minutes respectively. Figure 187 presents the predicted relations between total-displacement vs. time at different mechanical load cases under standard fire-temperature case in 60 minutes (ISO-834 curve).

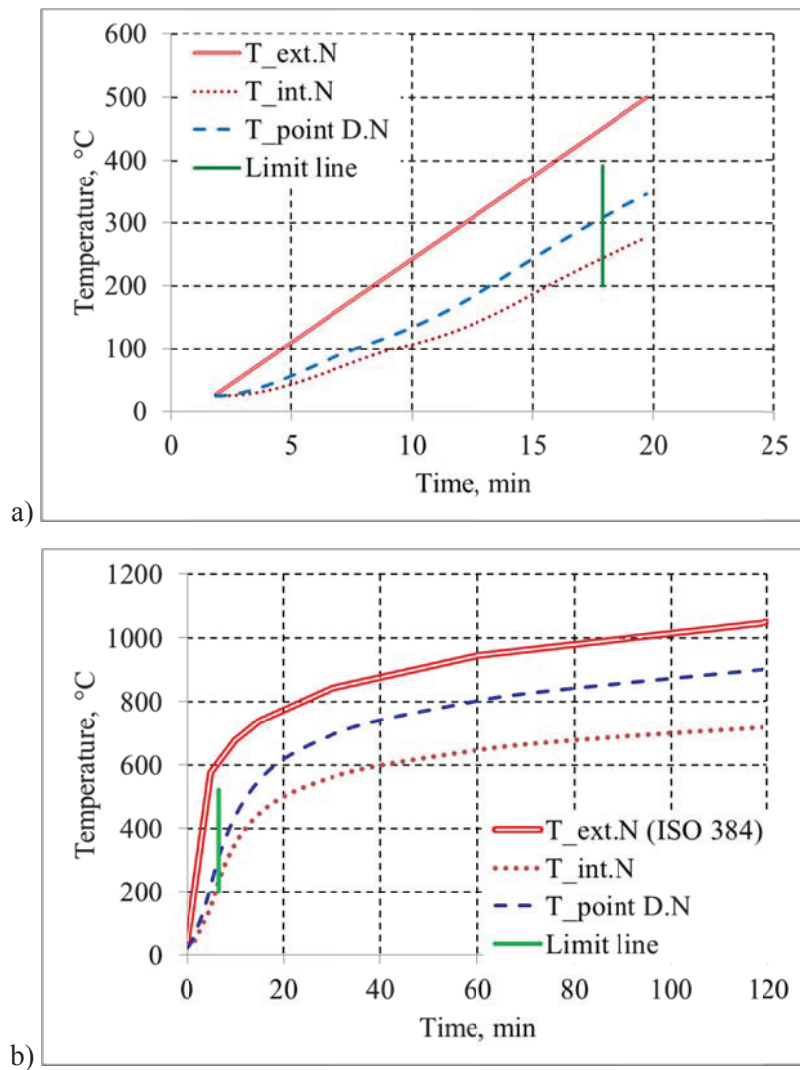


Figure 185 : Numerical temperature evolution of three points obtained with temperature: a) based on experiment; b) based on ISO 384 curve

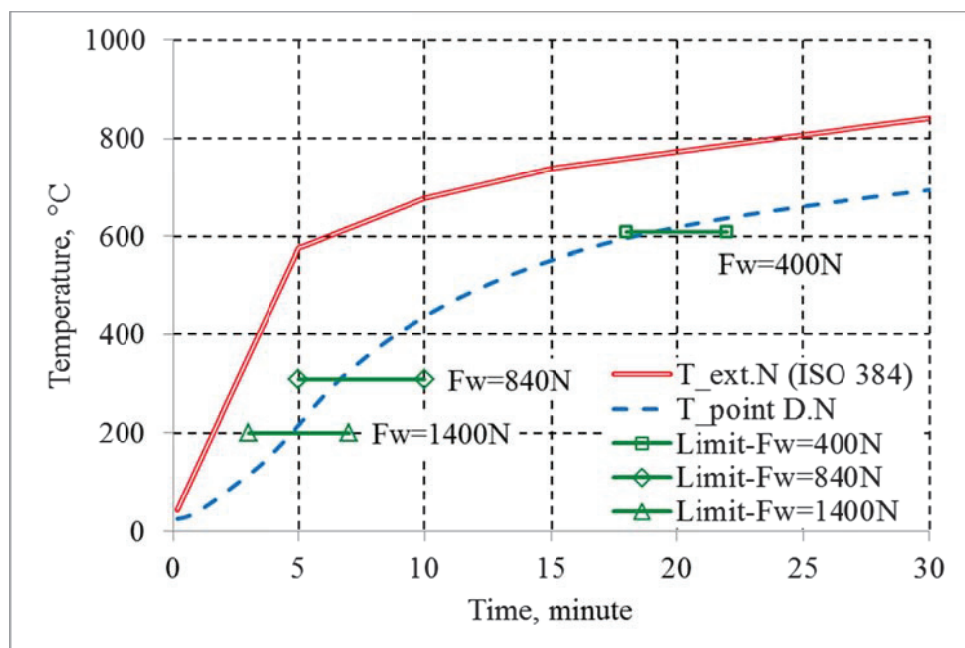


Figure 186: Predicted service duration of CFRP reinforced concrete specimen under different mechanical load case, subjected to standard fire-temperature ISO-834

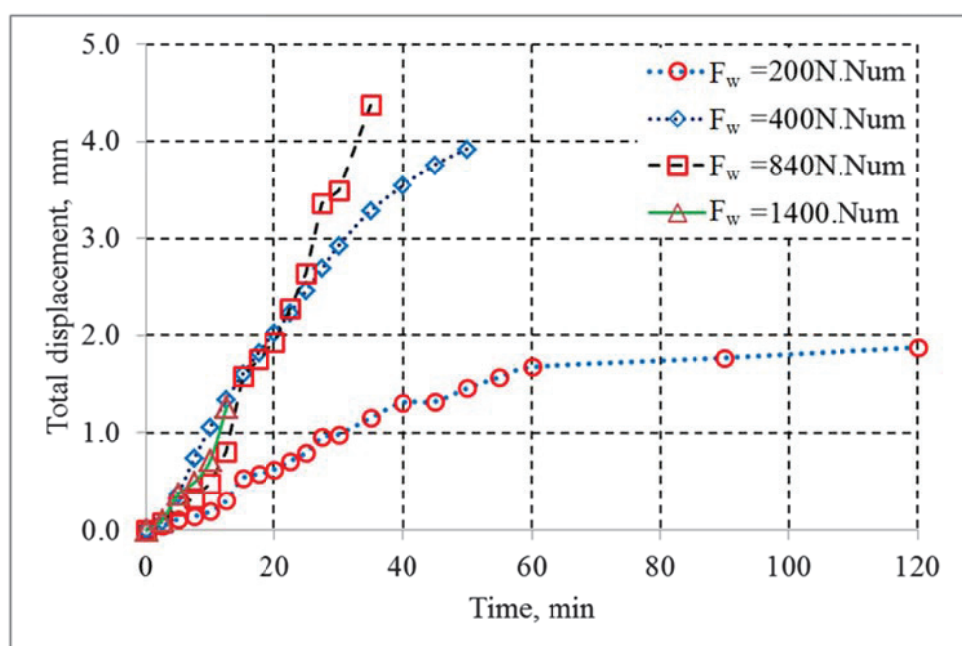


Figure 187: Total-displacement – time curves at different mechanical load cases exposed to standard fire-temperature condition (obtained by numerical modelling (*.N) and experiment (*.E))

4.2.7. Conclusions

This section has successfully numerically investigated the performance of CFRP reinforced concrete specimen, which is simultaneously under service load and elevated temperature condition. The actual temperature evolution and mechanical load acting on the experiment have been considered and then reproduced in simulation models. The simulation results show a good agreement to experimental results in both thermal and mechanical solutions. Based on these results, followings remarks are concluded:

- With adopted material data, the numerical model is able to predict the thermal distribution inside the specimen under elevated temperature condition and also the total displacement of specimen under effects of increasing temperature.
- With NSM reinforcement method, the obtained result shows that the temperature in the adhesive is lower than the temperature surrounding specimen and varies along the bonded interface. The temperature distribution inside the bonding interface can vary up to 150°C depending on the interface geometry.
- Based on the experimental and numerical results, combined with studies in the literature, a thermal-based failure criterion has been proposed to predict the service duration of the mechanically loaded specimen under elevated temperature condition. This numerical model can be developed to evaluate the service duration of concrete structures under fire-temperature condition regarding heat transfer solution.

4.3. Model 2- insulated CFRP

In this subsection, generality about the finite element model used, details of the model used are firstly described. Numerical results and parametric study are then analysed. This subsection ends by discussion on the application of the used insulation in protecting M-CFRP under fire temperature condition.

4.3.1. Generality about the finite element model used

The finite element model has been generated to study the efficiency of the insulation material in different temperature condition. The heat transfer model formerly developed is a finite-volume code, which is capable of predicting temperature in an insulated concrete section. The partial differential equation of heat conduction can be expressed as in Equation 12 (see the subsection 4.2.2).

4.3.2. Details of the model used

The geometry configuration and dimension of the studied insulation material are described in the experimental part (Figure 142): the block of insulation has the length 280 mm, the width 60 mm and the thickness is 40 mm. Due to the symmetry of loading, boundary condition, material and temperature loading, an one eighth model was generated and analyzed using the finite element code ANSYS APDL (Figure 188). Building one eighth model can simplify the computation process by reducing elements while maintain the reliability of analysis with time efficiency. The element type chosen for the transient thermal analysis is SOLID70 (3D 8-nodes thermal solid, Figure 151). With maximum size for meshing element is 2mm, there are 11852 elements for the numerical calculations which simulate the experimental tests.

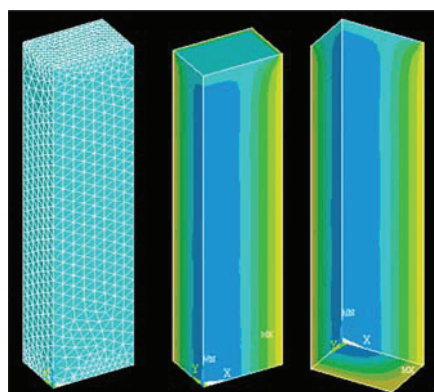


Figure 188: One eighth symmetry model of the insulation material with meshed elements

To obtain an accurate prediction of heat transfer within the insulation material, the thermal properties at 20°C have been adopted from previous study which has the same insulation type (Hawileh et al., 2009): thermal conductivity: $K_o = 2.5 \times 10^{-4}$ W/mmK; specific heat: $C_o = 1654$ J/kg.K; and density: $\rho_o = 2.69 \times 10^{-7}$ kg/mm³. The evolutions of thermal properties as function of temperature of the used insulation material in the literature are previously summarized (Hawileh et al., 2009) (see Table 52). The evolution temperature condition exterior has been modelled as the temperature evolution in the experimental test (Figure 145 and Figure 146). In this section, three cases of transient heat transfer are observed: two cases simulate the two temperature conditions in the experimental part with insulated CFRP material and an extended case for standard fire temperature condition.

Table 52: Evolutions of normalized thermal properties of the insulation material (Hawileh et al., 2009)

Temperature (°C)	20	100	150	200	300	400	500	600	700
Normalized specific heat C/C_0 (20°C)	1.00	3.60	0.80	0.55	0.55	0.50	0.45	0.45	0.45
Normalized thermal conductivity K/K_0 (20°C)	1.00	1.00	0.45	0.45	0.45	0.50	0.60	0.80	0.80

4.3.3. Numerical results

To examine the validity and predictability of the model used, the FE and experimental results were compared. Figure 189 shows the temperature distribution result in the insulation volume of the “C.T.020.Ins” case. Figure 190 and Figure 191 show the temperature evolution of exterior temperature ($T_{ext.-}$) and interior temperature ($T_{int.-}$) in both numerical result (-.N) and experimental result (-.E) of two cases : C.T.020.Ins and C.T.030.Ins. The exterior point is identified as on the middle surface of insulation volume and the interior point is identified as the middle point at the interface between the CFRP material and the insulation material (measured by thermo-couple in the experiment, Figure 142). In the numerical model, the interior point is chosen as 2mm from the axial axis of the volume (correspond to the position of thermo-couple in the experiment).

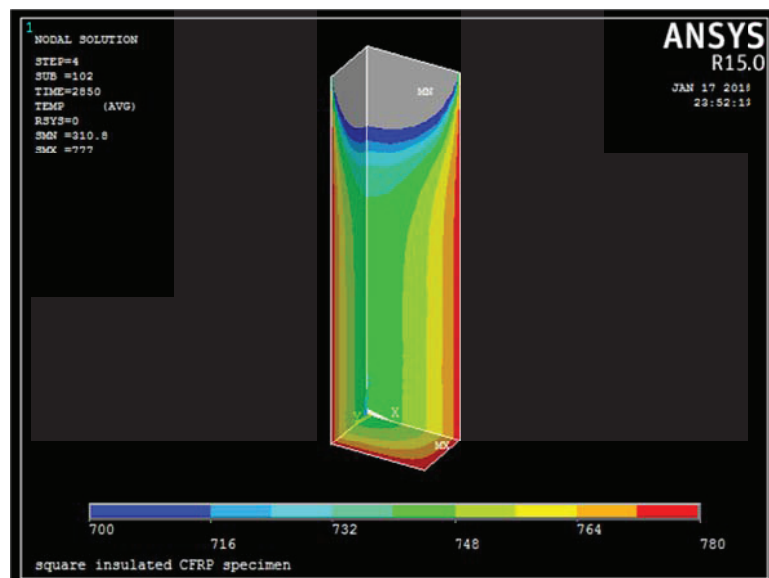


Figure 189 Temperature distribution of the C.T.020.Ins case

As can be seen from Figure 190 and Figure 191, the exterior temperatures in numerical models have been generated according to the exterior temperature obtained in the experiments. The predicted results on interior temperatures in two cases are very close to the obtained results in experiments. In the C.T.020.Ins case, the experimental interior temperature rapidly increases while the numerical value is close but still lower than the exterior temperature. It should be noted that in the numerical model, there is no mechanical load, the insulation material is assumed as continuous and isotropic

material in thermal conduction analysis while in experiments, the CFRP are imposed with mechanical load, which may then influence to the performance of the insulation material.

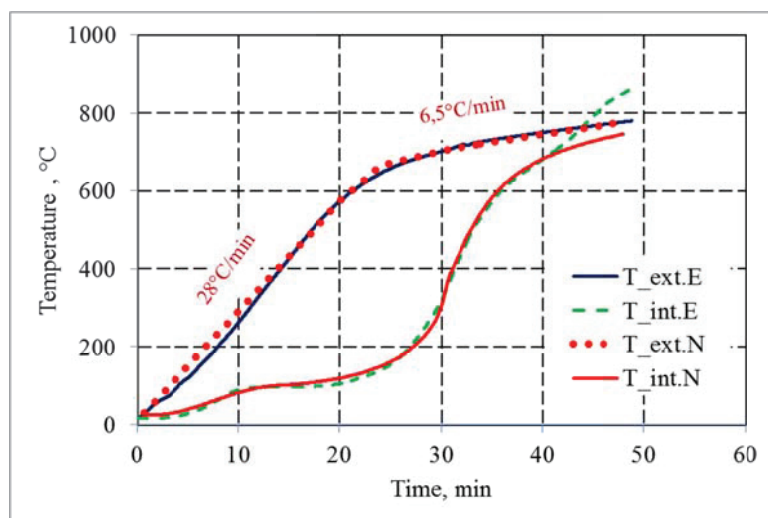


Figure 190 : Temperature evolution of exterior temperature ($T_{ext.-}$) and interior temperature ($T_{int.-}$) of C.T.020.Ins case: numerical result (-.N) and experimental result (-.E)

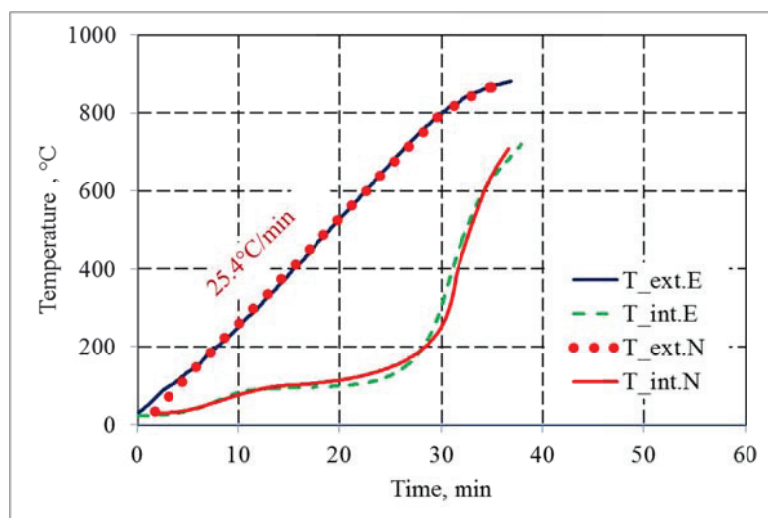


Figure 191: Temperature evolutions of exterior temperature ($T_{ext.-}$) and interior temperature ($T_{int.-}$) of C.T.030.Ins case: numerical result (-.N) and experimental result (-.E)

4.3.4. Parametric study

From the successful calibrated input thermal properties of the insulation material based on comparison between numerical and experimental results (see the subsection 4.3.3), the third model has been generated in order to observe the capacity to protect CFRP of the used insulation material under the temperature condition that is close to fire. The third thermal analysis model has the same material properties but the geometry will vary in term of the thickness of insulation layer. The model will then be applied with thermal load on insulation surface with temperature evolution in accordance to

standard fire curve ISO-834 (ISO-834, 1999). The thickness of insulation layer will vary from 1 cm to 5 cm as in Table 53.

Table 53: Geometry of the fire-testing model (one-eighth dimension)

Thickness of insulation layer, cm		1	2	3	4	5
Specimen dimension, cm	Length	14	14	14	14	14
	Width	2	3	4	5	6
	Thickness	1	2	3	4	5

Figure 192 displays the evolutions of exterior temperature and interior temperature as functions of time in different cases. As can be seen from this figure, the applied temperature on specimen's surface (N.T_ext-ISO 834 curve) in the model is exactly equal to standard fire curve (ISO 834). The interior temperature curves in different thickness cases (N.T_int.Xcm, with X is from 1 cm to 5 cm, Figure 192) show that with the increase in thickness of insulation material, the longer that the heat conduction has been delayed.

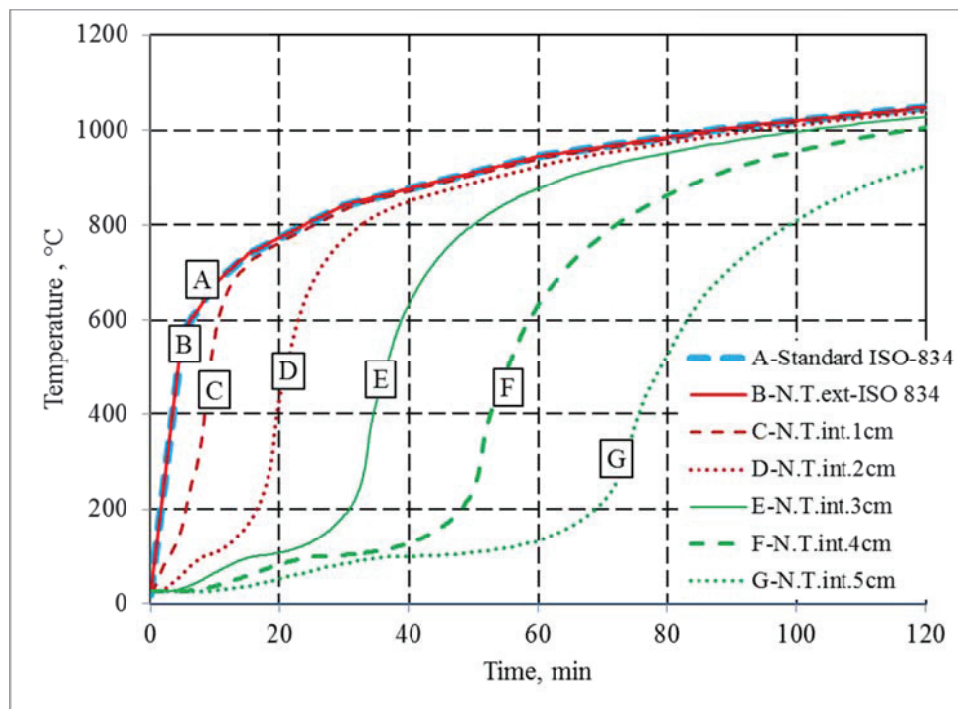


Figure 192: Exterior and interior temperature evolution of insulation volume at different thickness under standard fire temperature condition

4.3.5. Discussion on the application of the used insulation in protecting M-CFRP under fire temperature condition

Table 54 summarizes the average failure temperature of M-CFRP at different cases of applied load ratio (obtained in Table 29). According to this summary, when the applied load ratio increases from 0.1 to 0.5, the failure temperature gradually reduces from 636.4°C to 491.8°C.

Table 54: Thermal resistance of M-CFRP at different applied load ratio

Applied load ratio, f_w	0.1	0.25	0.5
Average rupture temperature, °C	636.4	596.3	491.8

Although the results of insulated M-CFRP tests show that at the time of failure, the temperature on M-CFRP in the case with insulation is higher than that of the case without insulation, further experiments and analysis need to be undertaken in order to confirm this tendency. In civil engineering, when a fire happens, there are several phenomena: structures are subjected with service load, elevated temperature condition, chemical reactions or degradation of material, the existence of toxic smokes. In this research, the authors aim to study the performance of M-CFRP and insulated M-CFRP under condition with combined elevated temperature and mechanical load at the same time without consideration on the other phenomena such as material degradation due to elevated temperature. According to current guideline for fire-design, the main role of insulation material is to protect the structure under the elevated temperature. Furthermore, the mechanical properties of several available insulation materials in commercial market are not significant in comparison to the structure and materials. The result on the performance of M-CFRP under combined mechanical load and temperature load can be applied for evaluation its performance in fire-concerned cases. With the experimental and numerical results on insulation material, the evolution of temperature behind the insulation layer with an identified thickness at different elevated temperature cases can be estimated. The experimental test with insulated M-CFRP shows that the real temperature at M-CFRP surface (under insulation layer) at failure is higher than that of the cases without insulation material. However, if the failure temperature in the case without insulation material is referred as a failure criterion for M-CFRP, then it is possible to apply this criterion to predict the failure of insulated M-CFRP specimens which are simultaneously subjected to both mechanical load and elevated temperature. Therefore, within the objective of this research, it is assumed that the surface temperatures of M-CFRP at the failure in two tested cases (with and without insulation material) are not much different, disregarding the mechanical status. Then, combining with the numerical result in fire-temperature loading case (Figure 192), a proposal thickness of insulation material to protect the M-CFRP under fire-temperature load regarding the mechanical loading status and the requirement to extend the fire-resisted duration as displayed in Figure 193.

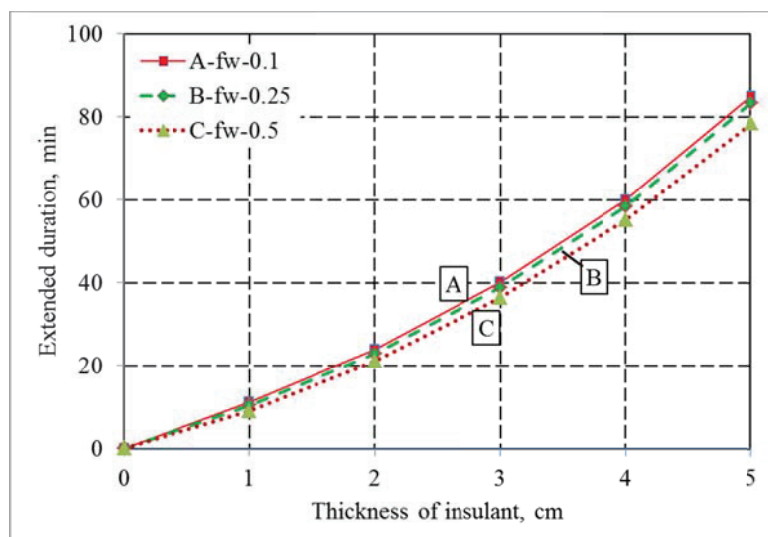


Figure 193 Extending fire performance of M-CFRP based on different thickness of insulation layer

From civil engineering application point of view, in case that the M-CFRP material is imposed with mechanical load up to 50% of the material resistance capacity, with the thickness at about 4.3cm, the used insulation material can protect the M-CFRP under fire-temperature load up to 60 minutes (Figure 193).

4.4. Conclusion

In this chapter, the numerical solution has been considered in investigating the thermal and mechanical behaviours of CFRP reinforced concrete specimen. A thermal analysis has been conducted to preliminary the efficiency of an insulation material in protecting CFRP material, which is under mechanical load, from the effect of elevated temperature. The numerical models can well predict the thermo-mechanical performance the structure under combined elevated temperature and mechanical condition with reliability and acceptable precision. According to the appropriateness of the numerical prediction and experimental result, followings conclusions have been made:

- Although in the numerical solution, the increase temperature applies on the specimen before the mechanical load, which is reversed from the experiment that mechanical load is firstly applied and temperature then increases, these results are well agreeing together. This shows that in the simulation, the order of load type has little influence on the general prediction result.
- Although the non-isotropic material model has not been considered for concrete material at any mechanical load case, the mechanical behaviour of structure specimen (total-displacement vs. time relation) of prediction model shows a good consistence to the experimental curve. It is because at the collapse of specimen, the concrete, CFRP and steel material are little affected and still work in elastic state, only adhesive fails. Therefore, in the numerical model, the properness of the isotropic material is also suitable for the model.
- The temperature distribution at the end of thermal analysis can explain for the reason that NSM specimens experience a better performance at elevated temperature condition in comparison with EBR specimens. In the observed cases, the variation of temperature within the bonded interface can be up to 150°C depending on the geometry of NSM reinforcement.

- Based on two prediction results on CFRP reinforced concrete specimen and insulated CFRP under standard fire-temperature case, it is possible to improve the fire performance of CFRP reinforced concrete by using appropriate reinforcement method and also protect the bond with suitable insulation layer with consideration to the mechanical state of the structure in order to meet with the fire-resistance design standards.
- Of course, there are still differences between the temperature profiles which are experimentally and numerically measured. These differences are attributed to several factors from the numerical model simplifications, the nature of the material heterogeneity and the possible effects of environmental factors and experimental conditions during testing. However, to these numerical values obtained in this study, it clearly requires further test to confirm.
- The combination of two numerical models can be developed for predicting the fire-temperature performance of CFRP reinforced concrete structures that are under mechanical load as well as protecting them to meet the fire-safety requirements according to design guidelines.

Chapter 5:
**Conclusions
& Recommendations**

CHAPTER 5 **Conclusions & Recommendations**

This study presents the experimental and numerical study on the performance of CFRP and CFRP reinforced concrete structures under three different combinations of elevated temperature and mechanical load, including simultaneous and separation cases. To achieve these objectives, an intensive literature review has been conducted in the chapter 1; several experimental tests on CFRP material and CFRP reinforced concrete structure have been observed in the chapter 2 and the chapter 3; numerical simulation has been completed, validated by experiments and used for parametric study in the chapter 4. In this chapter, the general conclusions of the research works are presented first; recommendations for experimental test and engineering design regarding fire concerns as well as research perspectives are respectively presented afterwards.

5.1. Conclusion

Even in research, the status of structure in a real fire is too complicated and thus difficult to thoroughly understand. Regarding the working condition of CFRP in real fire, there may be more effects that can influence to the performance of CFRP for example: the direct contacting to fire or not, duration of exposing to temperature and the history of thermal interaction (such as peak temperature) or cyclic thermal action... Among the factors that influence to the structure during fire, mechanical and thermal factors are mainly and simultaneously accounted for the structure failure, so they are the research objects of this thesis. From the obtained results, conclusions are summarized as followings:

5.1.1. CFRP material

The performance of two types of CFRP (P-CFRP and M-CFRP) at three different cases concerning the temperature range between 20°C to 712°C has been experimentally studied. The performance of the CFRP material is generally reduced as the temperature increases or mechanical status increases. Some findings of this study are summarized:

1. The thermo-mechanical and residual ultimate strengths of P-CFRP decrease by 50% at approximately 300°C and 500°C.
2. The thermo-mechanical and residual Young's modulus of P-CFRP decreases by 50% at approximately 540°C in the thermo-mechanical procedure and at 570°C in the residual procedure.
3. The thermo-mechanical and residual strength of M-CFRP gradually decreases when the temperature increases from 20°C to 700°C. At 400°C, it loses 50% of ultimate strength in thermo-mechanical condition and 45% in residual condition.
4. The Young's modulus of M-CFRP varies little in temperature, ranging from 20°C to 400°C and only decreases 30% at 600°C in thermo-mechanical condition but up to 72% with residual condition.
5. For both P-CFRP and M-CFRP, when the stress ratio increases from 0.1 to 0.5 (P-CFRP) and 0.6 (M-CFRP), the failure temperature and exposure duration gradually reduce and then significantly drop down when the stress ratio exceeds these values. This result contributes to the confirmation of the combined effect of the simultaneousness of thermal and mechanical impacts on the performance of CFRP.
6. The order of loading among the thermal and mechanical effects on CFRP has little influence on the obtained result.

7. The experimental result of P-CFRP at 400°C in two thermo-mechanical conditions confirm that thermo-mechanical ultimate strength and Young's modulus of P-CFRP experience little change with thermal exposure durations between 10 minutes and 90 minutes. This is because the degradation temperature of PAN carbon fiber is about 500-600°C.
8. The heating rate of exterior condition has small influence on the thermal resistance of P-CFRP at the stress ratio of 0.25. It is because that the heat transfer within the material and degradation of carbon fibres at about 500-600°C are independent from the heating condition.
9. When the temperature increases or the mechanical load decreases, the failure mode of CFRP changes from brittle to a more softened shape. This is because that the thermal and mechanical loads have mutual influence to the performance of CFRP material at thermo-mechanical condition. Thus as the mechanical load increases, the thermal resistance of the material reduces.
10. At elevated temperatures higher than the degradation temperature of the polymer matrix of CFRP, smoke releases.. This process can last up to 30 minutes depending on the material composition.
11. The adjusted prediction models (by Gibson and Bisby) with the calibrated coefficients can predict the properties of P-CFRP under thermo-mechanical and residual conditions.
12. A three-degree polynomial analytical model is proposed for CFRP material under thermo-mechanical conditions. The proposed model better fits with the reduction of the ultimate strength of two studied CFRPs and other types of CFRP which have been reported in the literature especially the reduction between temperature range from 200°C to 400°C.

5.1.2. CFRP reinforced concrete structure

Within experiments on CFRP reinforced concrete specimens, following conclusions have been inferred:

1. The compressive state of concrete enhances the mechanical performance of CFRP reinforced specimen up to 38% in comparison with its shear state at ambient temperature. This means that the design of specimen has better exploited the advantage of concrete material.
2. With NSM reinforcement method, the thermal performance of CFRP reinforced concrete specimen increases 3.6 times at low mechanical load state ($NAS = 0.143$ MPa) and 2.2 times at higher mechanical state ($NAS=0.5$ MPa) in comparison with EBR method. This is because that the thermal penetration from environment is delayed and this extends the service duration of the CFRP-concrete bond; while with EBR method, the adhesive is closer to the heat source and thus sooner reduce its strength.
3. The residual mechanical performance of CFRP reinforced concrete specimen is much higher than its thermo-mechanical performance: 2 times higher at 75°C and 10-12.6 times higher at 150°C to 300°C. It is because the recovery of the cooled adhesive in its strength at ambient temperature.
4. When the imposed mechanical status increases, the thermal performance of CFRP reinforced concrete reduces with reduction rate that depends on the reinforcement method and the used adhesive. This shows that the mechanical load has influences on thermal performance of CFRP reinforced concrete. These influences are due to the co-existence of the two factors within the structure.
5. The use of Duralco 4703 (epoxy with Al_2O_3 + metal particles) has significantly improved the failure temperature at low mechanical state; at medium mechanical state, the cement-based adhesive shows a slightly better performance but at substantial mechanical, Eponal 380 is

better . It is because that Duralco 4703 is recommended for temperature up to 230°C thanks to the mixed particles while Eponal is used in ambient temperature condition.

6. The appropriateness of load status, reinforcement method, and bonding adhesive in design can improve the performance (failure temperature and exposure duration) of CFRP reinforced structure under elevated temperature condition that closes to fire.

Within experiments on insulated M-CFRP, the following conclusions about thermal performance of insulation VG can be inferred:

1. The VG insulation material can improve the thermo-mechanical performance of M-CFRP under elevated temperature condition by delaying the heat penetration.
2. The ability to delay the temperature rise depends on the thickness of the used insulation material used in protecting structure.
3. With the protection of the VG insulation material, the temperature at M-CFRP material at failure is higher than that obtained in cases without insulation material.

5.1.3.Numerical model

With the numerical model on CFRP reinforced concrete:

1. The finite element method has successfully evaluated the performance of CFRP reinforced concrete specimen, which is simultaneously under service load and elevated temperature condition, using the material data obtained in the experimental part and in the literature.
2. The numerical model is able to predict the thermal distribution inside the CFRP reinforced concrete specimen under elevated temperature condition and also the total displacement of the specimen under effects of mechanical load and elevated temperature rise.
3. The numerical result shows that the temperature distribution inside the bonding interface can vary up to 150°C depending on the interface geometry. Therefore the temperature in the adhesive is lower than the temperature surrounding specimen and varies along the bonded interface and thus results in the higher thermal performance of CFRP reinforced concrete.
4. The proposed method, based on thermal criterion at different mechanical load cases, is able to predict the service duration of the CFRP reinforced specimen under simultaneous mechanical load and elevated temperature rise. This method can be applied to evaluate the fire performance of CFRP reinforced concrete structures under mechanical loading condition.

With the numerical model on insulated M-CFRP:

1. The finite element method has successfully evaluated the performance of CFRP reinforced concrete specimen, which is simultaneously under service load and elevated temperature condition, using the material data obtained in the experimental part and in the literature.
2. Parametric study based on thermal analysis shows that: it is necessary to consider mechanical loading condition when protecting CFRP with insulation material under fire-temperature to meet the fire safety regulations.

5.2. Recommendation for experimental study on CFRP-concrete bond under elevated temperature and mechanical condition

- The used configuration of CFRP reinforced concrete specimen has converted the specimen failure from shear failure of the concrete in to shear failure of the CFRP-adhesive-concrete interface. This is due to the presence of steel plate at the bottom of concrete blocks in specimen design that has changed shear state into compressive state of concrete, which is also

better method to exploit the strong point of concrete. This allows better characterizing the interface or bond behaviour of near surface mounted method under different complicated condition.

5.3. Recommendation for civil engineering design

The used materials in this research are laminate pultruded CFRP (which is commonly used to externally reinforce structures) and M-CFRP (which is commonly used to strengthening structure in shear, flexural and confined performance). Therefore, the experimental data can be exploited in structure profiles such as concrete structures (beams, slabs,...) and steel structures (beams,...) that are reinforced with CFRP. From an application standpoint, we would like to impress that in the fire engineering domain, there is little guideline for designing, evaluating the fire performance of general structures (beams, slabs, columns) due to dispersed experimental data, especially on material, reinforcement method as well as testing protocol. From the above mentioned conclusions, the author proposes following recommendations for civil engineering design:

1. It is necessary to evaluate the fire performance of CFRP and CFRP reinforced structures based on thermo-mechanical behaviour. The properties obtained from closer-to-fire condition increase the reliability in fire design for civil engineering structure.
2. The residual behaviour of CFRP and CFRP reinforced structures can be applied in fire concerns: evaluating the residual performance of CFRP and CFRP reinforced structure at post-fire situation, for repairing / strengthening / retrofitting or even destructing decision if needed.
3. The experimental residual behaviour of CFRP and CFRP reinforced structures can be applied for fire-performance in design stage if the correlation between two conditions for each material is taken into account.
4. The proposed analytical model is able to predict the reduction of ultimate strength of two studied CFRPs at elevated temperature condition for fire design application. The model can be applied for other type of CFRP in the literature with limited experimental data under thermo-mechanical condition.
5. The analytical models proposed in the literature can be better applied to predict the reduction of Young's modulus of two studied CFRPs at elevated temperature condition for fire design application.
6. For the use of CFRP and FRP in reinforcing concrete structures, it is better to use near-surface mounted method for better fire performance of structures. The geometry of reinforcement method may vary due to the availability of structure dimension with the efficiency can be confirmed with numerical verification.
7. For the use of CFRP and FRP in general, conducting thermal curing can improve the mechanical performance of reinforced structure under ambient temperature situation.
8. The use of Duralco 4703 epoxy can improve the thermo-mechanical performance of CFRP reinforced structures under elevated temperature rise that is close to fire case, respecting the appropriate mechanical load during the elevated temperature rise.
9. For further extending the service duration of CFRP reinforced structures to meet the fire-design regulations, it is better to use the insulation material to protect structure with the consideration on the mechanical status of structures.

5.4. Research perspectives

The study has experimentally characterized the performance of CFRP and small concrete structure reinforced with CFRP under three conditions that simultaneously combine temperature and mechanical loads.

Based on these results on CFRP material, further comparative and analytic study can be conducted for synthesizing and generalizing the performance of FRP and CFRP in particular for different applications concerning fire case.

The new proposed analytical model is based on three-degree polynomial function, which is different from sigmoid function proposed in the literature. The new proposed model is better suit with thermo-mechanical ultimate strength of two studied CFRPs while previous models are more suitable to thermo-mechanical Young's modulus. Therefore, it is also necessary to clarify the suitability of the new proposed analytical model and others proposed in the literature for predicting the reduction of material properties under elevated temperature condition.

Based on the experimental results on CFRP reinforced concrete specimens, further studies can focus on:

1. Influence of thermal effect on performance of CFRP or FRP reinforced concrete structures at ambient temperature condition. This can result in the standard treatment procedure improving the mechanical performance of CFRP reinforced concrete structures.
2. The residual test on CFRP reinforced concrete structure is obtained from cooled specimen after exposing to constant temperature condition, which is not the same as fire-temperature condition. To be applied to estimate the residual performance of CFRP reinforced concrete structures at post-fire situation, it is also necessary to study the residual performance of the near surface mounted CFRP reinforced concrete under mechanical load after exposing to standard-fire history within different durations.
3. Because the experimental tests were conducted with a small scale structure, further confirmations on full scale structure should be studied with comparative analysis. Base on that result, the experiment on small scale, which is easier and cheaper to conduct, can be applied for full scale situation.

Base on numerical results, further developments can be considered:

1. Influence of thermal effect on performance of CFRP or FRP reinforced concrete structures at ambient temperature condition.
2. The concrete model at different temperature conditions should be considered in the continue research for better suiting the different working situations of concrete such as shear and flexural strengthening case.

Appendix: Numerical models

This appendix presents the results obtained from two different numerical cases following TM2 procedure:

I. Result of thermal analysis

A. Thermal analysis result of TM2 condition under $F_w = 400N$

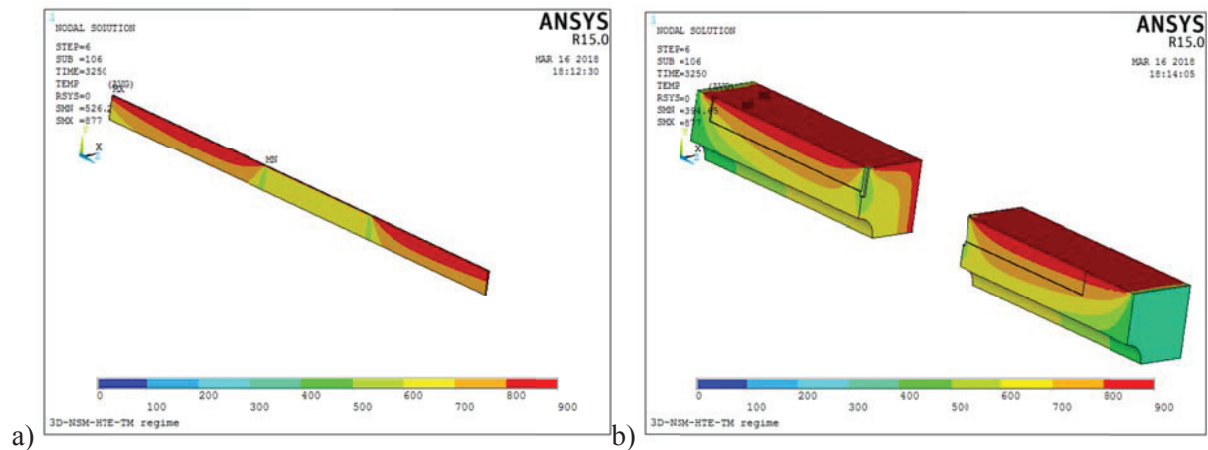


Figure 194 Numerical result of temperature distribution in sample (T2 400N): a) CFRP; b) concrete

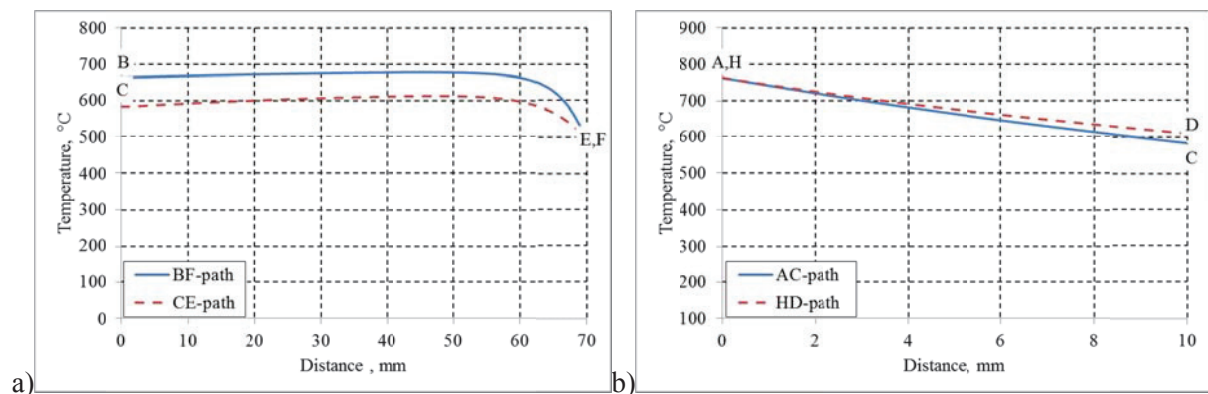


Figure 195 Temperature distribution along four paths on the CFRP-concrete interface at the failure.

B. Thermal analysis result of TM2 condition under $F_w = 1400N$

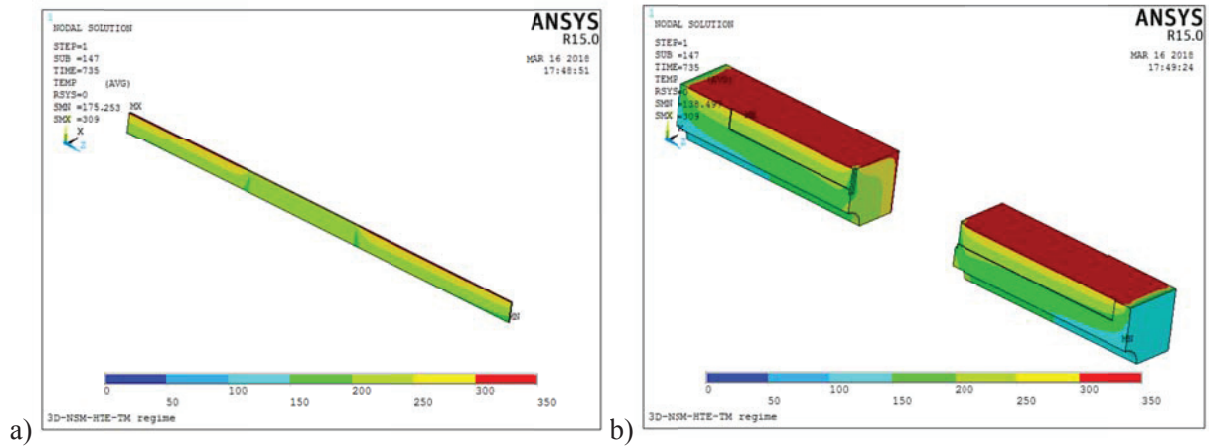


Figure 196 Numerical result of temperature distribution in sample (T2 1400N): a) CFRP; b) concrete

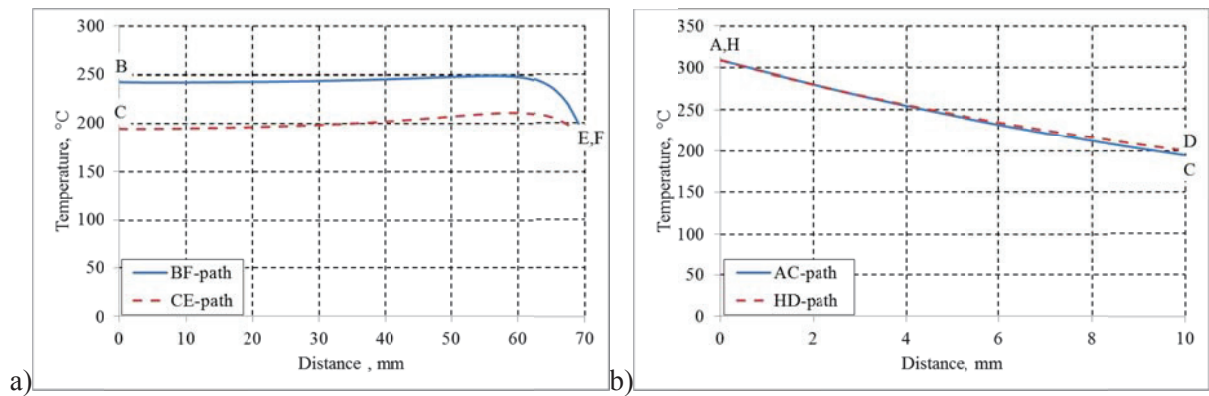


Figure 197 Temperature distribution along four paths on the CFRP-concrete interface at the failure.

II. Result of thermal – mechanical analysis

A. Thermal– mechanical analysis result of TM2 condition under $F_w = 400N$

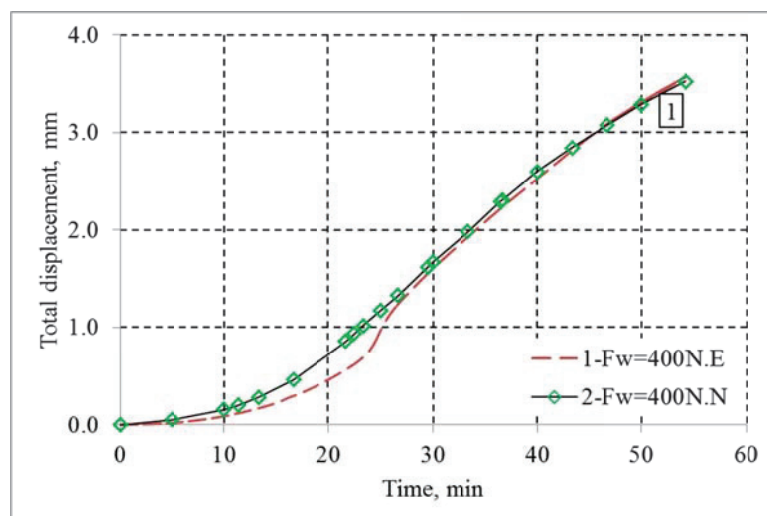


Figure 198: Total displacement vs. time curves at mechanical load $F_w = 400N$ (obtained by numerical modelling (*.N) and experiment (*.E))

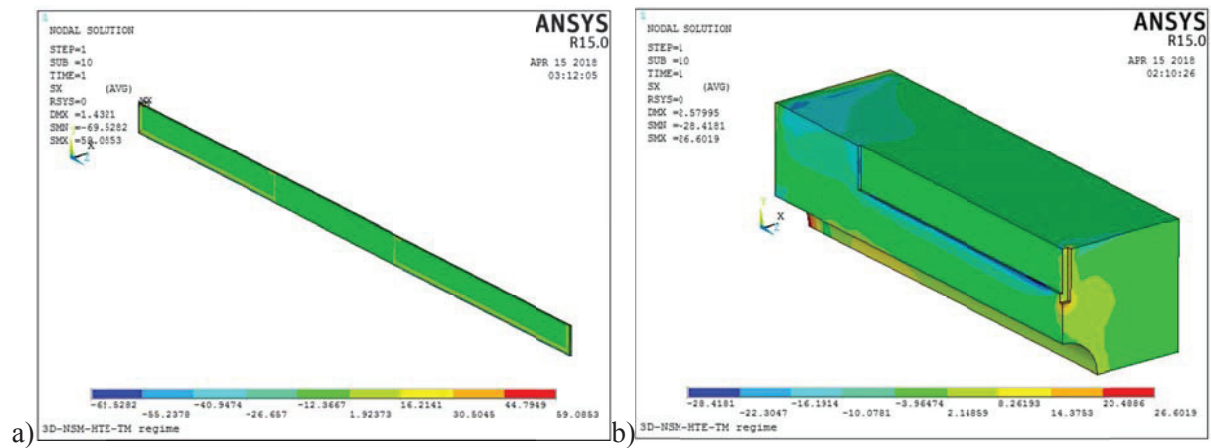


Figure 199: Normal stress σ_{xx} : a) CFRP; b) concrete

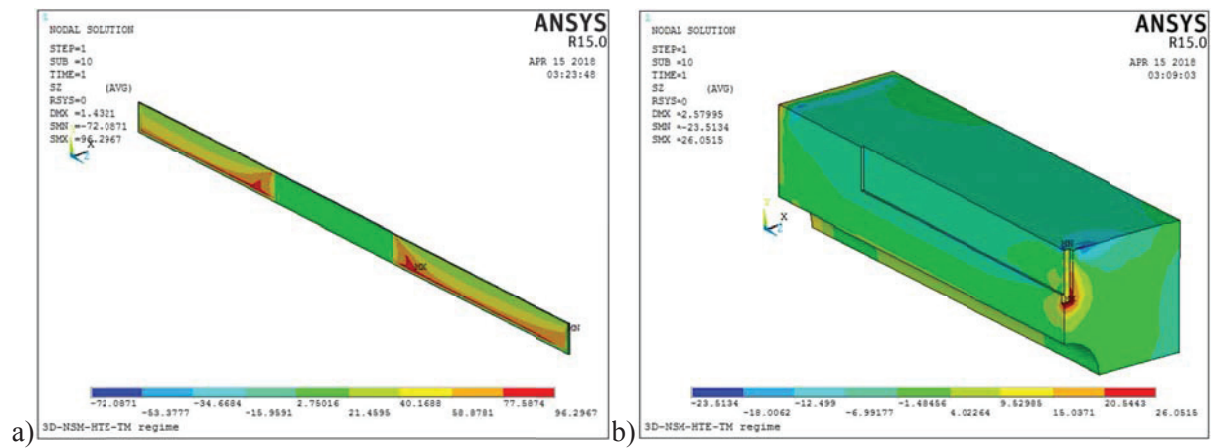


Figure 200: Normal stress σ_{zz} : a) CFRP; b) concrete

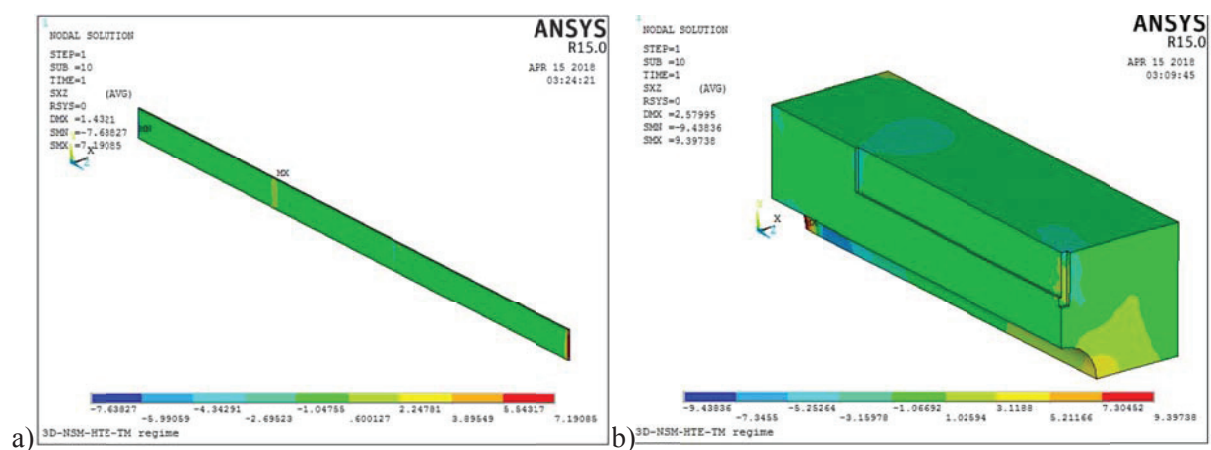


Figure 201: Shear stress τ_{xz} : a) CFRP; b) concrete

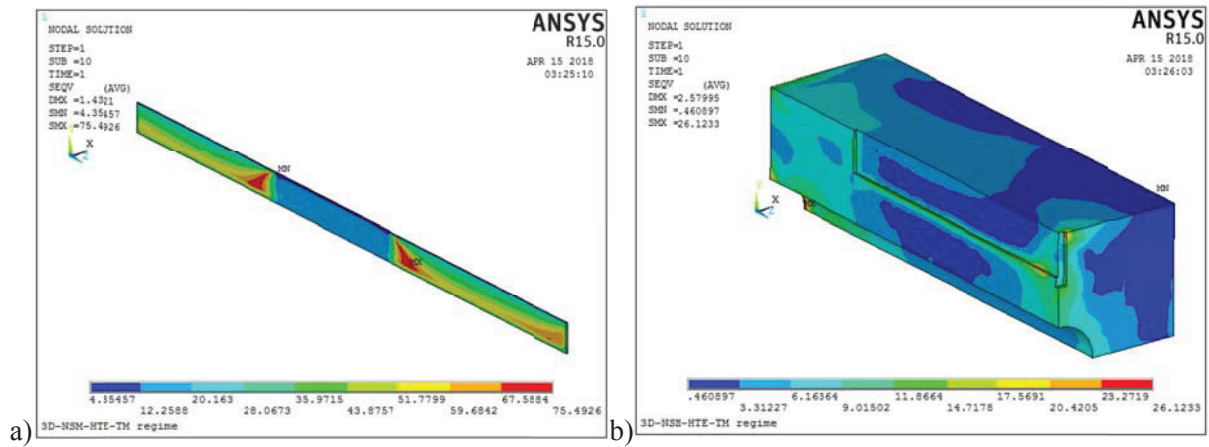
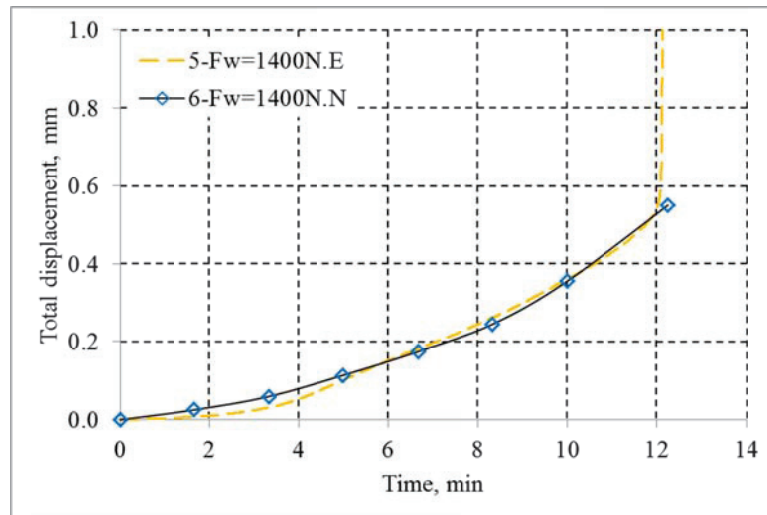
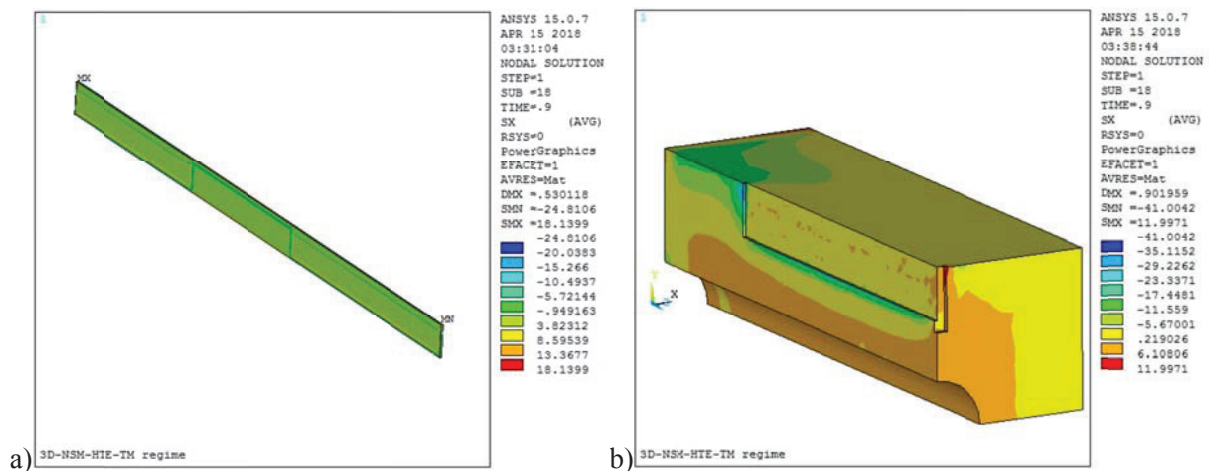


Figure 202: Von-Mises stress: a) CFRP; b) concrete

B. Thermal– mechanical analysis result of TM2 condition under $F_w = 1400\text{N}$


 Figure 203: Total displacement vs. time curves at mechanical load $F_w = 1400\text{N}$ (obtained by numerical modelling (*.N) and experiment (*.E))

 Figure 204: Normal stress σ_{xx} : a) CFRP; b) concrete

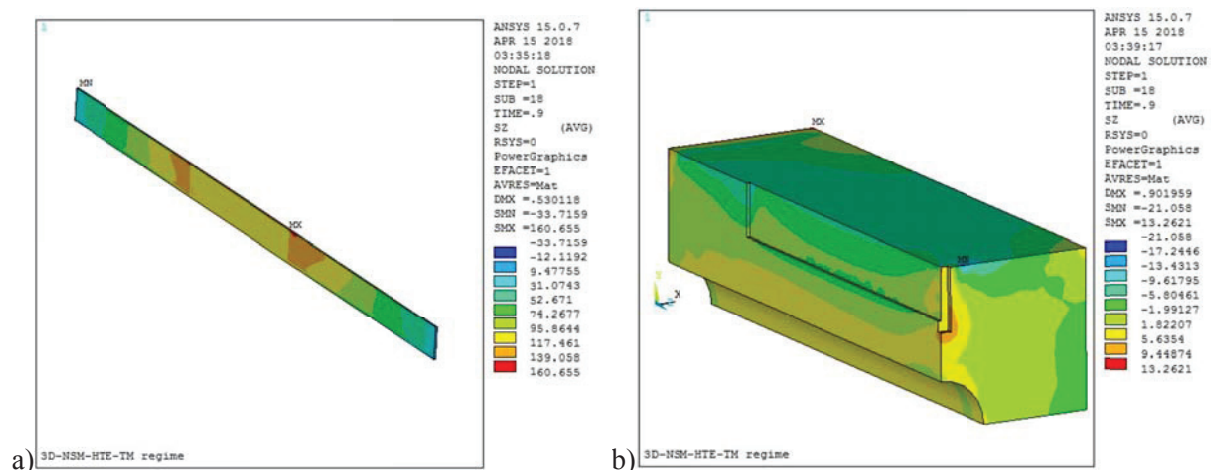


Figure 205: Normal stress σ_{zz} : a) CFRP; b) concrete

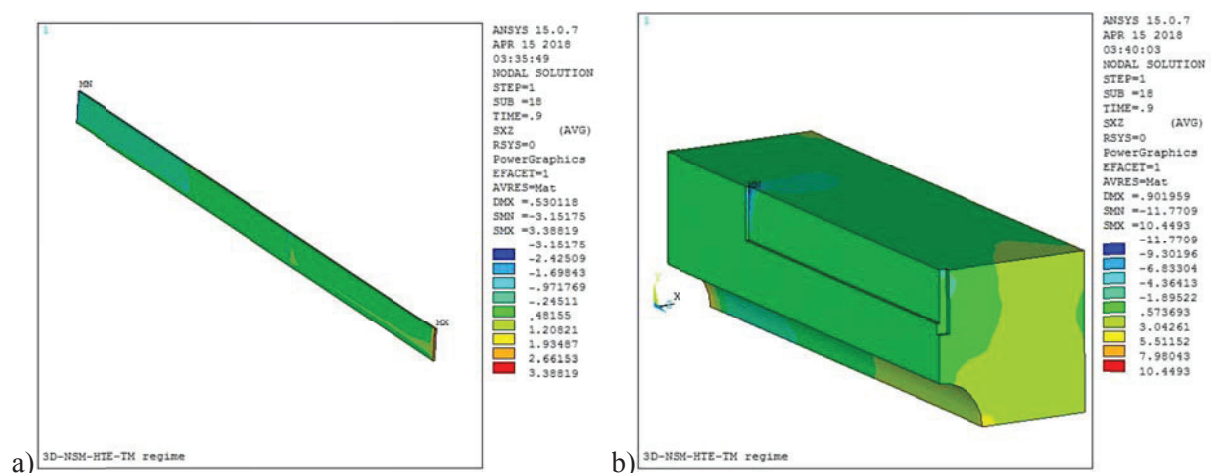


Figure 206: Shear stress τ_{xz} : a) CFRP; b) concrete

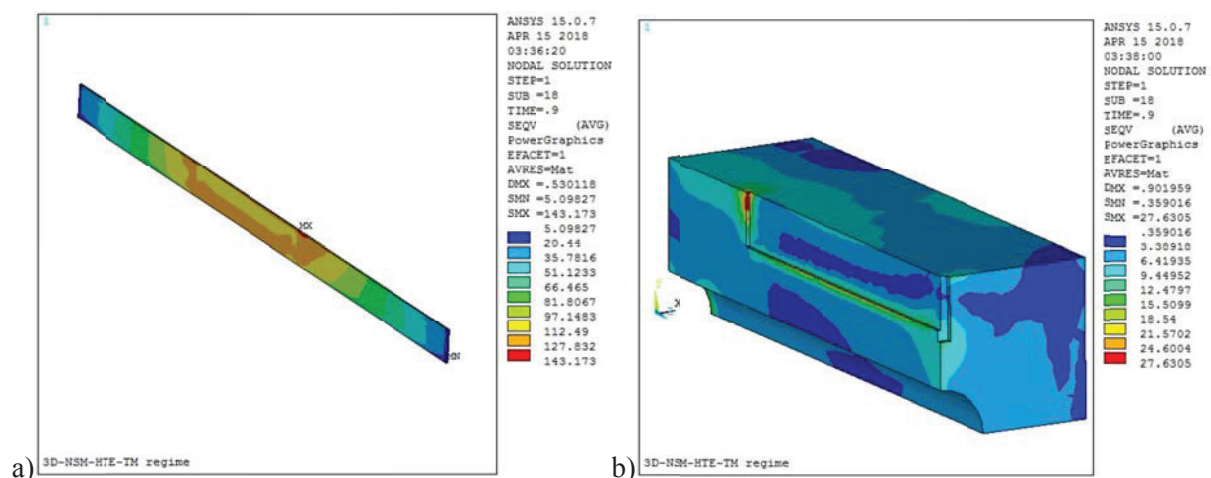


Figure 207: Von-Mises stress: a) CFRP; b) concrete

III. Result of thermal – mechanical analysis for standard fire case ISO 834

A. Thermal– mechanical analysis result of TM2 condition under $F_w = 200\text{N}$

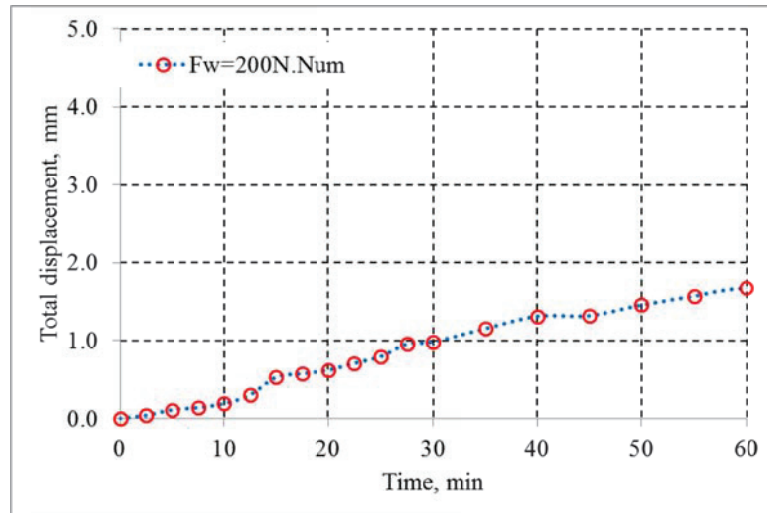


Figure 208: Total displacement vs. time curves at mechanical load $F_w = 200\text{N}$ (obtained by numerical modelling (*.N) and experiment (*.E))

B. Thermal– mechanical analysis result of TM2 condition under $F_w = 400\text{N}$

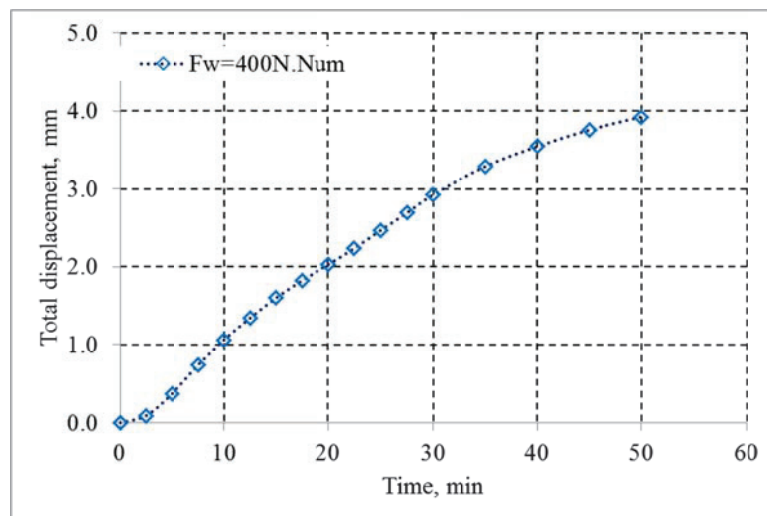


Figure 209: Total displacement vs. time curves at mechanical load $F_w = 400\text{N}$ (obtained by numerical modelling (*.N) and experiment (*.E))

C. Thermal analysis result of TM2 condition under $F_w = 840\text{N}$

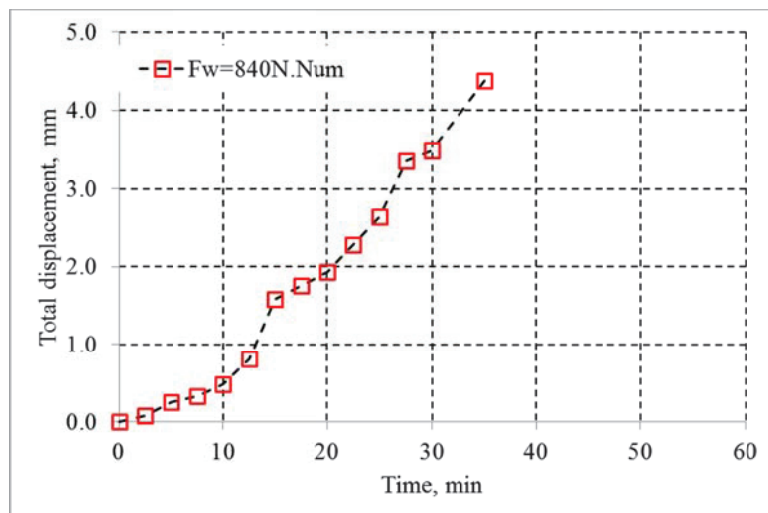


Figure 210: Total displacement vs. time curves at mechanical load $F_w=840N$ (obtained by numerical modelling (*.N) and experiment (*.E))

D. Thermal analysis result of TM2 condition under $F_w=1400N$

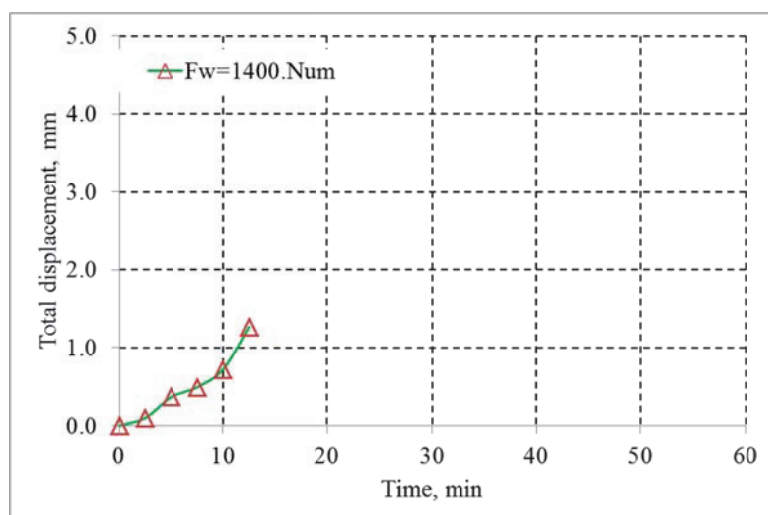


Figure 211: Total displacement vs. time curves at mechanical load $F_w=1400N$ (obtained by numerical modelling (*.N) and experiment (*.E))

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