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State of Art: The Fire Resistance of RC Members Strengthened with CFRP Laminates

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ABSTRACT

The available current research on mechanical behavior of RC structural members strengthened with CFRP material resulting from fire is presented and technically discussed in this paper. This includes design reviews, methods of application and techniques of reinforcing RC members with CFRP. Besides, the review includes the latest developed experimental, numerical, methods and formulation studies. Moreover, most of the studies agreed that there is a need to conduct more parametric numerical analysis in the field for improvement the global thermal response and flexural strength of the RC members strengthened with FRP. Based on the missing research, this review paper propose and suggest a set of very innovative design strategies and methods of application to improve the fire response of FRP laminates in case of fire, such as, (1) a combination design reinforcement technique on RC structural beam members with a combined mechanically anchored 3NSM extruded FRP design, (2) RC structural members external bonded with zigzag shaped FRP strips at the bottom and side soffits, (3) installing steel wire mesh, textile wire mesh and carbon tissues as a reinforcement material in the fire protection layer, (4) testing the fire response of using π-anchor and FRP anchor devices and new shaped memory alloy material in RC structural members strengthened with FRP, (5) u-shaped steel anchorage plate installed in the mid-span of the RC FRP beam, (6) suggesting installing L-shaped steel plate as a form of anchorage tool to support the bottom and the vertical soffits of the extruded FRP and (7) fire response of RC beams strengthened with FRP laminates using 3 different pre-fabricated types of extruded FRP laminates. The aim of this paper is to contribute for a more effective research on this field, leading to a future wide use of this technique in safer RC structures to fire events.

Keywords:

Fire Resistance, RC, Beams, CFRP, Laminates.

1. Introduction

Researching the response of RC structural members strengthened with FRP both experimentally and numerically is a crucial matter to protect both lives and property and to increase the resistance performance of beams under fire loads. It has been observed that there is a lack of studies carried out in this field, especially in terms of presenting new techniques and designs for improving the FRP laminates system which gives the opportunity to carry out more research for improvement. Very few works have been done on the use of FRP as an internal reinforcement material tested against fire. Several investigations were carried out on bond degradation by conducting different pull out tests on RC specimens both numerically and experimentally. In addition, the majority of the research which has been carried out focused on the glass transition temperature of the FRP-concrete bonding adhesive and its behavior under elevated temperatures. Moreover, the majority of the works focused on three FRP design techniques. These are EBR, NSM and with very few work carried out on mechanically anchorage and extruded FRP laminates. Some manuscripts did a comparison between cementitious and epoxy bonding adhesives, while other investigations studied the fire response of FRP laminates with different dimensions and thicknesses. On the contrary, many studies analyzed the use of different types of mortars as a fire protection layer, such as, Vermiculite-Perlite VP, expanded clay aggregates and ordinary Portland cement mortars. A significant achievement in the field was identified by Firmo and Correia (2015) [16] by testing applying thicker thermal insulation layer on the anchorage area to achieve cable mechanism behavior of the FRP during fire. However, the research did not identify a method of application to sustain the second proposed design technique strategy. Generally speaking, the current research which has been carried out in the field so far is very minimalist in terms of presenting and analyzing new designs and techniques for improving the thermal response of RC structural members strengthened with FRP. Accordingly, this review paper aim to suggest innovative designs and technique for future researchers by illustrating the strength and weaknesses of the current investigations. This review paper presents the latest investigations that have been carried out in the field. Moreover, the first section of the review will illustrate the available literature review and summary on the missing research. Additionally, the second section will demonstrate a presentation and discussion on the current available research, such as (1) beams strengthened, (2) bond strength, (3) bond degradation, (4) fire protection layer, (5) experimental and numerical studies and (6) methods and formulations. Each section is followed by a summary on the missing research for each part of the review including results and discussion of the suggestions. Finally, the conclusions and further recommendations for future work will be suggested.

2. State of Art on the Thermal Response of RC Structural Members Strengthened with CFRP

Firmo et al. (2015) [14] published a state of art on the experimental and numerical applications of FRP material as a reinforcement on RC structural elements to protect them in case of fire. The review included the mechanical fire response of FRP and the bonding properties between FRP/concrete under elevated temperatures. In addition, the literature review stated that many impact factors on fire response of RC structural members strengthened with CFRP are mysterious and needs investigation. For instance, the thermal behavior of CFRP is a result of various moisture contents, concrete aging and curing, creeping, loading and geometrical parameters. Lau et al.

(2016) [26] made a state of art on the use of FRP material to rehabilitate and strengthen timber and concrete structures. His review presented current studies conducted on (1) the fire response of FRP material, (2) the damage and de-bonding of the FRP strengthening system, (3) the use of high durable FRP reinforcement techniques and (4) evaluation of the behavior of FRP when induced to harsh environments. Moreover, the review mentioned that the main problem was in the lack of information on the long term serviceability of FRP reinforcement system when exposed to harsh environmental conditions. Also Lau et al. (2016) [26] has suggested more studies to be carried out on the durability of FRP bonding system and there safety ratios under fire endurance. Kalfat et al. (2018) [22] presented a state of art of the latest anchorage system technologies and devices used in RC structural members strengthened with FRP material. The review mentioned that the most efficient FRP anchorage systems are (1) anchors made from FRP material, (2) π anchors and sometimes called Pi anchors and (3) steel anchorage methods. In addition, the presented literature review was very technically detailed and informative. Finally, the review concluded with an assumption that both π and FRP anchors are more reliable in terms of improving the structural performance when compared with the traditional steel anchorage. This is because both the π and the FRP anchors are fabricated from the same FRP material. However, Kalfat et al. (2018) [22] did not mention the anchorage response in fire situations. In the author's point of view, it would be a very new advancement in the structural fire safety field to test the fire response of RC beams strengthened with CFRP laminates and anchored with π and FRP anchorage systems. In addition, the CFRP systems and devices are advancing every day but without testing these new systems under fire. For example, a new pre-stressed CFRP system is currently used in strengthening RC members and structures. However, there is absolutely no work that has been conducted or recommended to test pre-stressed CFRP device and system under fire load and elevated temperatures.

3. Methodology on the Thermal Response of RC Structural Members Strengthened with CFRP

The methods used by researchers in terms of beams strengthened, bond strength, bond degradation, fire protection layer, experimental and numerical studies and methods and formulations is discussed and commented on in this section to show the pros, cons and missing researcher for improving fire endurance and to increase the percentage in strength capacity of RC beams strengthened with CFRP.

3.1. Beams Strengthened

Barros et al. (2006) [6] established an experimental study on RC beams, columns and brick panels strengthened with NSM CFRP strips to determine the efficiency of using NSM in reinforcing and strengthening the structural elements and materials. The interpretation concluded that NSM system improves the flexural resistance and increases load bearing capacity. However, Barros et al. (2006) [6] compared the experimental results between NSM and EBR techniques and judged that the NSM technique is more efficient in increase load bearing capacity. However, his research did not include any numerical simulations to validate his assumptions. Moreover, Barros et al. (2006) [6] did not investigate the fire response of the CFRP strengthened structural members and materials.

Hawileh et al. (2009) [18] conducted numerical modeling investigation on RC T-shaped beam strengthened with CFRP. The study has included a parametric analysis to determine the mechanical and thermal response. The simulations included determining the global heat transfer by applying fire on the bottom and lateral faces of the beam to illustrate a real case scenario. This includes the spread of temperature in the CFRP layer, rebar's, adhesive bondage layer between the concrete soffit and the CFRP sheet. In addition, the numerical results were compared with other experimental results (Fig.1) which were carried out by other researchers. Hawileh et al. (2009) [18] has observed a direct relationship between the increase in the fire time and the increase in deflection in the mid-span of the beam.

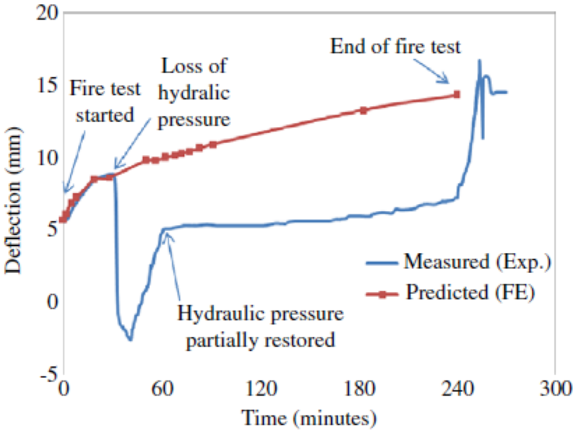
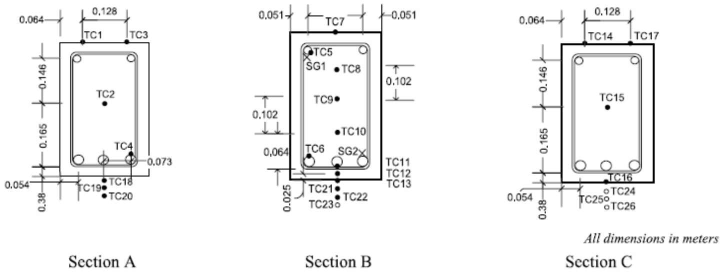
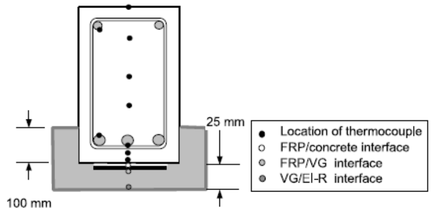


Figure 1. Time (mm) vs. Deflection (mm) forcast graph between experimental and numerical investigations by Hawileh et al. (2009) [18].

Ahmed and Kodur (2011) [3] carried out an experimental research on 5 equally dimensioned rectangular RC beams strengthened with FRP under ASTM E119 standard fire exposure. Four of the tested beams were exposed to fire and serviceability load. The fire response testing of the beams was carried out in accordance to ACI 318/ACI 440.2R provisions. The study analyzed the variables in fire exposure, anchorage zone, insulation type and restraint conditions to evaluate the failure modes, thermal and global structural response. Moreover, the influence of various parameters on the fire performance was conducted for both standard and non-standard fire conditions. This was including experimental testing on different fire scenarios and different support conditions to determine failure time. During the fire testing, the temperature, strains and deflections at various locations in the beam was recorded using Type-K thermocouples as illustrated in Figure 2. Ahmad (2011) has also stated that there is lack of knowledge on the global structural response of RC beams strengthened with FRP under non-standard fire. In addition, to the lack of research carried out using Tyfo®WRAFP as a thermal insulation material in RC members. Moreover, the author recommended using non-combustible and non-flammable material for fire insulation layer. Finally, his study concluded that the fire endurance is based on the rebar temperature (Figure 3) which has a direct relationship with the type of fire insulation. However, Ahmad (2011) did not test his rectangular RC beams strengthened with FRP under non-standard fire. In the author's point of view, Ahmad (2011) conducted further experimental fire testing outdoor to demonstrate a real case situation including other environmental factors such as air and wind.



(b) Cross-sectional details and location of thermocouples and strain gauges.



(c) Mid-span cross section showing location of thermocouples.

Figure 2. Cross section of the distribution of thermocouples in the RC beam by Ahmad (2011) [3].

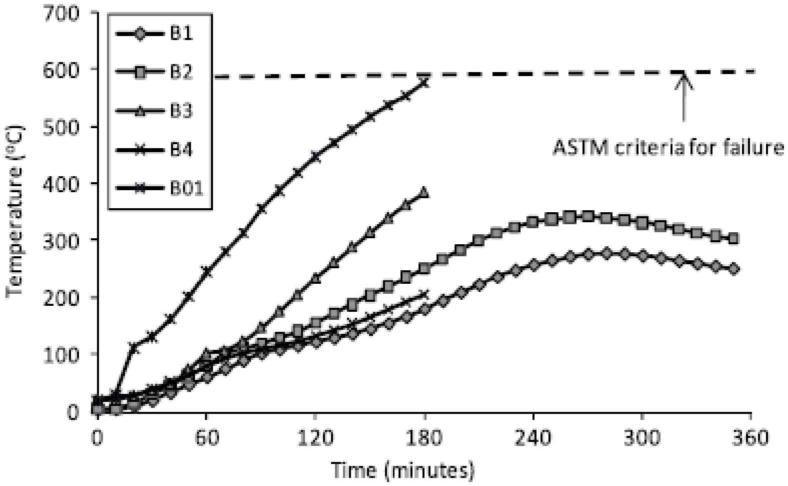


Figure 3. A comparison of the rebar temperature with respect to time between the tested RC specimens by Ahmad (2011).

Yu and Kodur (2013) [34] studied the fire behavior of concrete beams internally embedded with FRP reinforcement rebars by means of FE models (Fig 4 and Fig. 5). The numerical investigation carried out on the developed concrete beams included two types of internal FRP reinforcement materials, CFRP and GFRP. The main objective of the research was to investigate the change of material properties under fire cases. This was performed by monitoring the temperature of rebar, concrete, FRP and adhesive induced slippage during fire application. The findings by Yu and Kodur (2013) [34] stated that the traditional steel reinforcement rebars has higher fire resistance than FRP reinforcement rebars. On the other hand, when comparing the fire response between CFRP and GFRP, it was observed that the application of CFRP reinforcement rebar in concrete beams has higher fire resistance than using Glass fiber strengthened polymer rebars. As part of the drawn conclusions, in terms of concrete cover parametric analysis it was worth mentioning that the thicker the concrete cover the better the fire resisting performance of concrete beams.

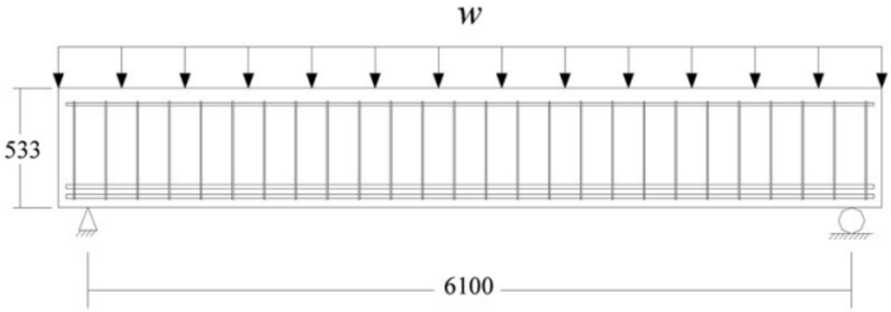


Figure 4. Dimensions and layout of RC beam internal strengthened with FRP by Yu and Kodur (2013) [34].

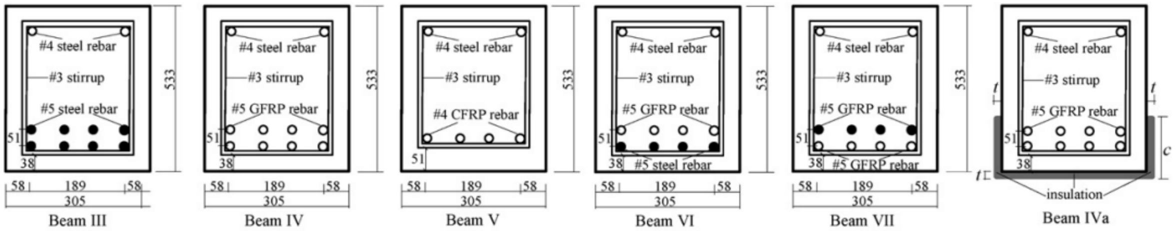


Figure 5. Cross sectional geometry and internal reinforcement distribution of the numerically analised RC beam internal strengthened with FRP by Yu and Kodur (2013) [34].

Petkova et al. (2014) [29] studied experimentally 6 simply supported small scaled beams strengthened with CFRP tested under fire temperature ranging from 50 to 300 C° with a temperature interval of 50C°. Besides, the specimens were left to cool in the laboratory at ambient temperature. Afterwards, the beams were tested in four point bending. The mode of failure analysis included measuring the deformation in the CFRP laminates, deflections in the beams and crack pattern analysis of the fire-damaged CFRP RC beams. However, Petkova et al. (2014) [29] did not test full scale, nor, conducted numerical analysis to validate the experimental results. Firmo et al. (2015) [13] developed a numerical analysis on CFRP strengthened beams to study the mechanism under ambient temperature. His study stated that a thicker fire protection layer at the anchorage area will improve the fire resisting performance of the CFRP laminates. Even though the adhesive will lose its strength in the middle of the beams due to de-bonding as a result of burned adhesive in this zone and exceeding the limit of the glass transition temperature in the mid-span. Additionally, the application of a thick fire protection layer at the anchorage zone and a thinner fire protection layer at the unanchored zones will initiate a cable behavior mechanism of the CFRP laminates. His developed numerical simulations provided a parametric analysis by modeling various FE models (Fig. 6) with different span lengths between two to five meters length with an interval of 1m. Firmo et al. (2015) [13] drawn conclusions based on his achieved numerical results by stating that (1) as the CFRP bonding length lb by span length increases, the reduction in strength decreases, (2) the type of load do not have any effect on the reduction in strength and (3) the near soffit mounted technique performs better in terms of reduction in strength at elevated temperatures than the EBR strengthening technique. Conversely, Firmo et al. (2015) [13] did not carry out any fire response investigations on different steel mechanical anchorage systems and devices with different grades, dimensions and thickness. Accordingly, the study has lack of knowledge on the fire behavior of anchorage systems and devices and needs more parametric investigations in the future.

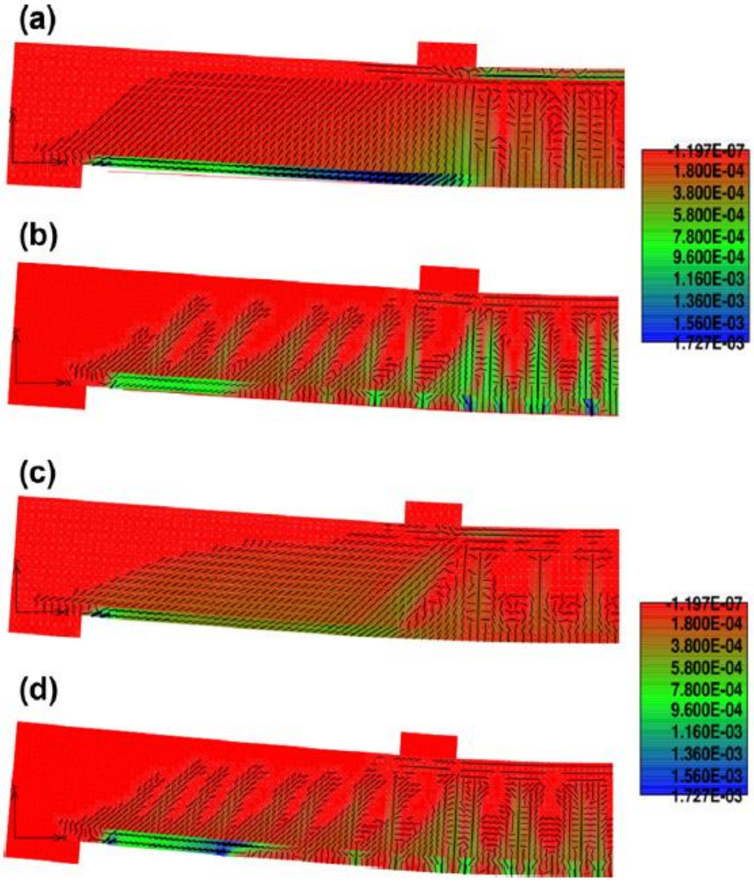


Figure 6. Contour map of the distribution of crack pattern through the CFRP strengthened beams (Inch [m]) perior to failure load, where, (a) for EBR-F technique, (b) EBR-c-1le technique, (c) NSM-F technique and (d) NSM-C-1le technique by Firmo et al. (2015) [13].

Firmo et al. (2015) [12] studied 2D FE modeling of RC beams strengthened with CFRP laminates using externally bonded reinforcement technique. The beams were subjected to ISO 834 standard fire and under service loading. Numerical simulations were conducted by applying thicker thermal insulation layers on the CFRP anchorage zones (Fig. 7). This was carried out to maintain the cable mechanism behavior of CFRP strips when exposed to elevated temperatures. Also the numerical FE models forecasted the initiation of the adhesive de-bonding process when the temperature of the adhesive in the anchored zones is between 1.1 and 1.4 Tg. As such, the numerical results showed good correlation with the experimental results. Accordingly, the researcher proposed a fire protection design strategy to be established on achieving 2 main necessities. The first necessity is to maintain the temperature of the CFRP strips in the mid-span of the RC beam to prevent its early rupture. The second necessity focused on preserving the temperature of the bonding adhesive layer in the anchored area lower than the glass transition temperature of the used bonding adhesive agent. However, Firmo et al. (2015) [12] did not propose any technical method to be used to achieve the second mentioned design necessity strategy. The author's suggest that further investigation should be conducted with fire testing u-shaped steel anchorage plate installed in the mid-span of the RC beam in order to achieve the second proposed design strategy.

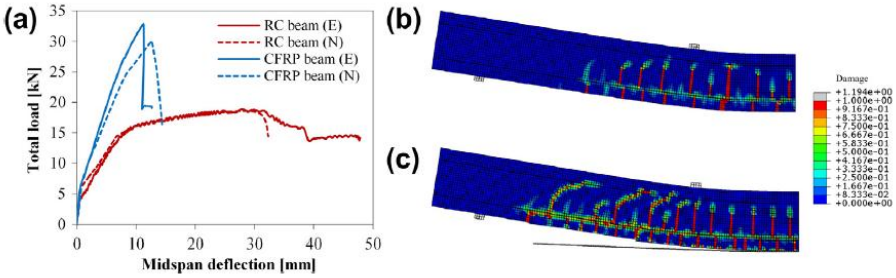


Figure 7. (a) Comparison between Midspan deflection (mm) and applied load (kN)- experimental vs. numerical for un-strengthened RC beams and strengthend RC beams, (b) Contour thermal distribution map for un-strengthened RC beams and (c) Contour thermal distribution map for CFRP strengthened RC beams by Firmo et al. (2015) [12].

Bilotta et al. (2015) [7] researched the difference between NSM and EBR techniques under elevated temperatures. Figure 8 demonstrates EBR and NSM design techniques used by Bilotta et al. (2015) [7]. This was done by constructing and testing 10 RC beams strengthened with CFRP strips and plates. Moreover, different loading shapes were subjected to the specimens and the variance in failure modes was examined. Bilotta et al. (2015) [7] has proved that the near surface mounted technique provides higher fire resistance than the EBR technique. This is because the de-bonding mechanism in NSM is less reactive than in the EBR technique. Additionally, the research indicated that the stiffness of RC beams is more beneficial when using EBR laminates. The author's believe that the research conducted by Bilotta et al. (2015) [7] could have been more original if he had conducted fire response tests on a combination design such as mechanically anchored NSM extruded CFRP combined design technique which has never been done before.

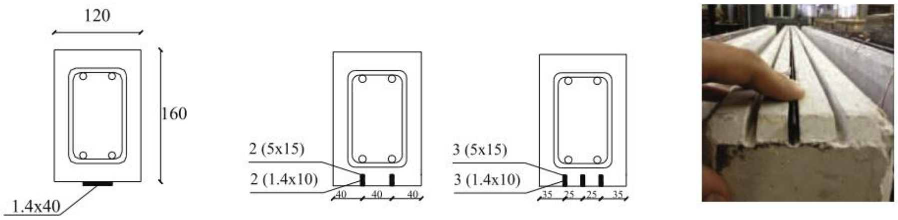
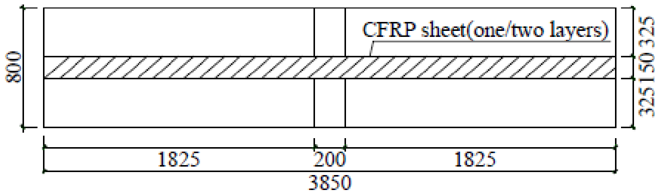
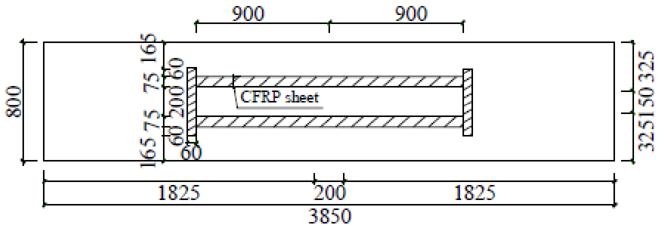


Figure 8. EBR and NSM techniques used by Bilotta et al. (2015) [7], where, (a) EBR CFRP strengthening technique, (b) 2NSM strips strengthening technique and (3) 3NSM strips strengthening technique.

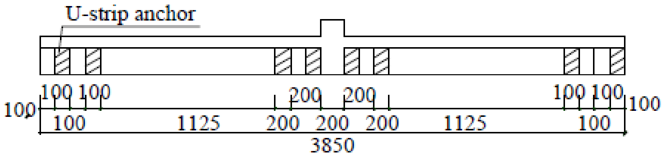
Krzywan (2017) [25] conducted laboratory tests on 15 real scale RC beams, 7 beams were strengthened with CFRP, 7 beams strengthened with SRP tape and one non strengthened beam. He used EBR technique for reinforcing the RC beams subjected to elevated temperatures between 20 and 80 C°. In addition, the temperature of the specimens were monitored under sun heat and presented the temperature of the adhesive layer for CFRP and SRP during selective days. The tested RC beams had the same dimensions (200x300x3000mm), same concrete mix and rebars. Moreover, the beams where loaded monotonically until failure. Furthermore, the types of failure were presented in terms of yield of steel and adhesive/concrete de-bonding. Krzywan (2017) [25] has also mentioned that the adhesive serves only as a fixer between CFRP and concrete. However, his study did not mention other techniques of a CFRP installation nor applying fire heating elevated temperatures on his tested specimens. Kodur and Bhatt (2018) [23] developed a numerical RC slab models strengthened with FRP and analyzed it under fire temperatures. A tracing method was used to monitor and record the thermal mechanical response starting from the early stages of the linear elastic state until reaching the dynamic plastic state and failure point. The models take into account the thermal behavior and global change in the structural material properties in the RC slab. This is including the internal steel reinforcement bars, concrete, FRP and the adhesive bonding agent. Moreover, a parametric study was conducted on various types of fire insulations and different FRP bonding alignment arrangements. The models were numerically analyzed with and without FRP strengthening material for results comparison purposes. Kodur and Bhatt (2018) [23] has found that the RC slabs strengthened with FRP have more fire resistance than the traditional un-strengthened RC beams. Moreover, the bonding alignment arrangement plays a significant role on the fire response of RC slabs externally strengthened with FRP material. Xu et al. (2019) [33] investigated 7 RC fire damaged T-beams and repaired with CFRP sheets. The specimens were exposed to different fire durations and tested to failure. In addition, the tested RC beams were subjected to ISO 834 standard fire for durations of 60 or 90 minutes. Moreover, the research introduced different CFRP external reinforcement techniques, such as, the U-shaped strips anchorage, one and two CFRP layers as shown in Fig.9. Xu et al. (2019) [33] has illustrated the experimentally developed results by means of flexural mode of failure and concluded that the epoxy bonded CFRP laminates has preserved the initial stiffness loss. However, generally speaking there is lack of fire response knowledge concerning various parametric studies on different alignment arrangements of CFRP laminates. The author's suggest the conduction of fire behavior research on RC structural members externally strengthened with zigzag shaped CFRP strips bottom and side anchorages.



(a) bottom CFRP sheets along the spans of SGB1~SGB3



(b) top CFRP sheets over the middle support of SGB2



(c) U-strip anchors

Figure 9. CFRP design alignment arrangement by Xu et al. (2019) [33], where (a) is bottom CFRP arrangement, (b) top CFRP arrangement and (c) U-strip side anchorages.

3.2. Bond Strength

Toutanji et al. (2006) [31] carried out experimental fire response testing on 8 RC beams externally bonded with CFRP sheets. The tested RC beams had one control beam and 7 specimens bonded with 3 to 6 CFRP layers using inorganic adhesive. Moreover, the beams were tested under four point bending. Toutanji et al. (2006) [31] concluded that (1) the load bearing capacity of the structural members increases as the number of CFRP layers increases, (2) organic adhesives has low fire resistance, (3) in-organic adhesives have higher fire resistance when compared with organic adhesives and can sustain high temperatures in fire scenarios. Moreover, Figure 10 illustrates the crack pattern analysis and FRP de-bonding failure of the tested beam by Toutanji et al. (2006) [31]. Finally, the author was not fully certain of the fire response failure modes using inorganic adhesives and suggested further future studies to be conducted to monitor the bond failure modes.

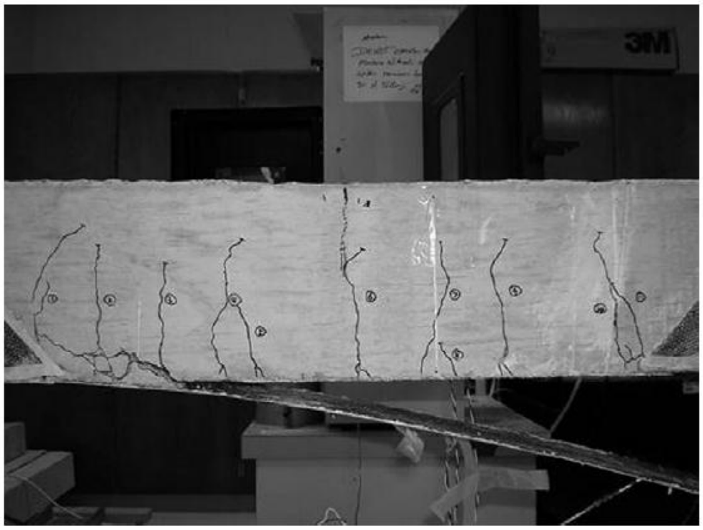


Figure 10. Crack pattern analysis and FRP debonding failure of the tested beam 5L-1 by Toutanji et al. (2006) [31].

Firmo and Correia (2015) [15] has conducted 9 fire resistance tests on RC beams externally strengthened with CFRP strips. The specimens were tested against standard fire ISO 834. Moreover, two different types of epoxy-based adhesives were tested, these were S&P Resin220 (Epoxy 1) and Araldite 2014-1 used for bonding metals (Epoxy 2). To prevent the early de-bonding of the CFRP, an anchorage system was used. In order to the CFRP strips to achieve cable mechanism behavior (Figure 11) during fire, a thicker thermal insulation layer was installed at the anchorage parts. Additionally, the fire insulation system consisted of Calcium Silicate (CS) boards, with a thickness between 25 and 75mm. These insulation boards were applied at the bottom concrete soffit of the beam. Firmo et al. (2014) [10] has also used a bolted steel plate at the edge sides of the installed laminates. On the other hand, the mechanical anchorage system consisted of a steel plate class S235 with dimensions of 60x60mm and 5mm thickness fixed through concrete by 4 self-screwing steel bolts grad 19MnB4 with a diameter of 6mm. As a conclusion of his research J. P. Firmo et al. (2014) [10] has concluded that the strengthening system retained its structural effectiveness through a cable mechanism after the damage of the bonded interface. However, Firmo et al. (2014) [10] did not conduct investigations on full scale RC beams to validate his assumptions, nor he tested other techniques such as NSM.

Figure 11. Cable mechanism behavior of the CFRP laminate after fire exposure by Firmo and Correia (2015) [15].

Arruda et al. (2016) [5] presented numerical analysis on the behavior of bondage layer between CFRP and concrete soffit under various temperatures. A comparison was done to compare the high rise evaluation and bond-slippage failure between NSM and EBR techniques. The method of this research was conducted by heating up the specimens at 20, 55, 90, 120 and 150 C° followed by applied load until reaching the failure mode. Furthermore, simulations on 3D FE models (Fig. 12) were carried out to determine the overall reaction of the bondage layer of the CFRP laminates. This study summarized the findings to a higher maximum shear stresses using NSM technique than EBR CFRP. Accordingly, the NSM bondage layer has a better fire resistance performance than the EBR technique. However, Arruda et al. (2016) [5] has conducted the simulations on simple models with 2 embedded steel strengthened rebar's and did not develop real RC beam models with vertical and horizontal strengthened rebars. Therefore, the models do not demonstrate a real fire response situation of a structural member strengthens with CFRP. More numerical parametric study should have been carried out on different embedded steel reinforcement designs.

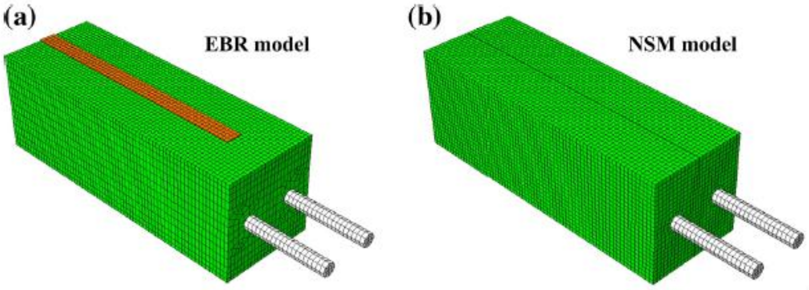


Figure 12. Arruda et al. (2016) [5] 3D numerical model specimens where (a) EBR design and (b) NSM design.

3.3. Bond Degradation

Ahmad (2011) has studied the properties influenced by bond degradation. His investigation included both experimental and numerical model analysis to study the factors which influences the FRP/concrete bond such as the type of FRP, the type of adhesive, thickness of adhesive, compressive strength of the concrete, moisture content, soffit preparation and temperature level. Moreover, Ahmad (2011) used two different aggregate types in the concrete mix, siliceous and carbonate. In addition, his simulations included different parametric investigations on several different concrete covers, FRP and thermal protection thicknesses and various dimensional parametric simulations on RC beams strengthened with FRP to predict there fire response. Ahmad (2011) stated that the time at which the bond slippage occurs when the adhesive loses its ability to effectively transfer the forces between concrete and FRP during fire. Accordingly, the comparison between time vs. deflection graph for different bond slippage dimensions by Ahmad (2011) is shown in Fig. 13. Moreover, the bond degradation depends on the fire insulation thickness and the glass transition temperature of the used adhesive.

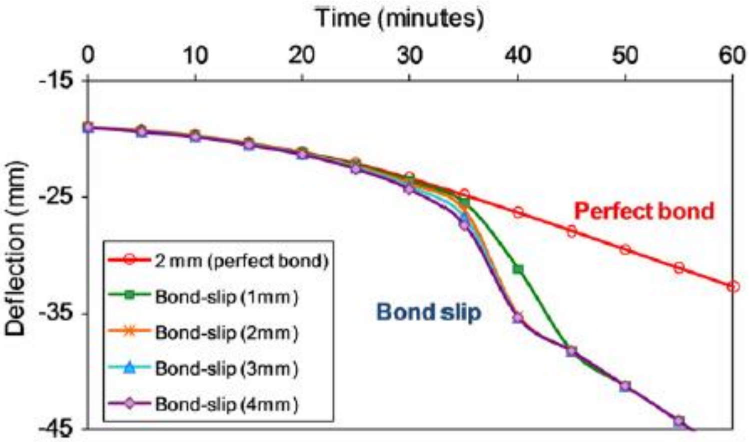


Figure 13. Comparison between time vs. deflection graph for different bond slippage dimensions by Ahmad (2011).

Del Prete et al. (2018) [9] did an experimental study on concrete prism samples by conducting 22 pull out tests on NSM CFRP laminates at ambient temperature. Various types of epoxy and cementitious adhesives were used in bonding CFRP strips in the grooves with a bond length of 300 and 400mm. The author determined that the cementitious bonding adhesives NSM CFRP laminates are more efficient in fire when using ribbed bars. Even though, the cementitious bonding adhesives are less sensitive under elevated temperatures, for they have less strength and rigidity when compared with epoxy adhesives. Furthermore, Figure 14 shows the total slippage image conducted by Del Prete et al. (2018) [9] for different groove fillings. The author's believe that Del Prete et al. (2018) [9] should have carried out more parametric analysis on bonding lengths greater than 400mm. Also, further analysis could been carried out by the researcher by conducting CFRP pull off on RC structural members and not only on concrete prism samples.

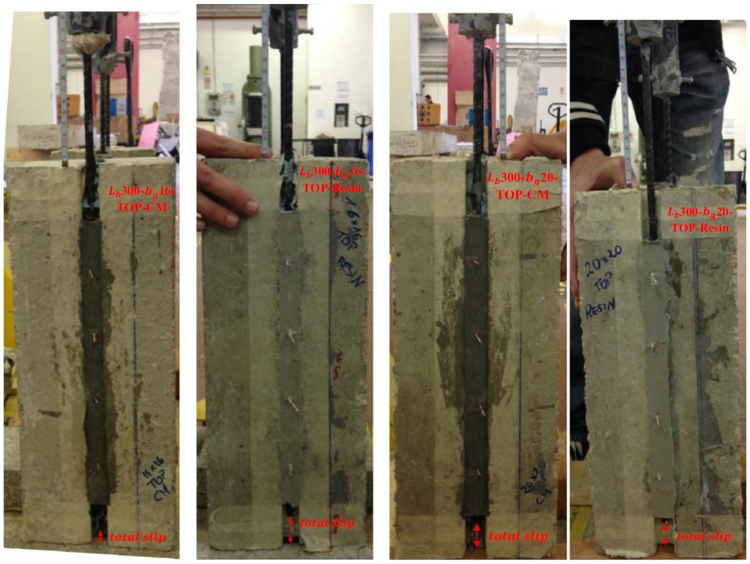


Figure 14. Total slippage image conducted by Del Prete et al. (2018) [9] for different groove fillings where, (a) Lb 300-b, 16 Top cement mortar, (b) Lb 300-b, 16 Top Resin, (c) Lb 300-b, 20 Top cement mortar and (d) Lb 300-b, 20 Top Resin.

3.4. Fire Protection Layer

Al-Salloum et al. (2011) [4] experimentally investigated the fire resistance of 42 cylindrically shaped concrete specimens strengthened with FRP material. The tested specimens consisted of 12 samples un-strengthened, 12 samples strengthened with CFRP sheets and 12 samples strengthened with GFRP material. Furthermore, the concrete samples were subjected to temperatures of 100 and 200C° for a period between one and three hours. The specimens were then axially compressed until destroying their full compression load bearing capacity and failure. An initial reduction in strength was observed in the tested specimens at a temperature of 100 C°. This was due to the consumption of the adhesive bonding strength and initiation of bond slippage mechanism by exceeding the glass transition temperature (Tg) of the adhesive bonding agent. Additionally, the specimens get weaker in terms of their strength when exposed to a fire endurance temperature of 200C°. Moreover, the second part of the experimental research was conducted on three concrete prism samples externally bonded with GFRP from one side and CFRP from the other side. All the specimens were subjected to pull out tests to determine the bonding strength of the FRP sheets under 3 temperature levels, at the room temperature, at 100C°and at 200C°. Furthermore, the pull out testing was in accordance to ASTM D4541-09. Al-Salloum et al. (2011) [4] observed that the strength of the adhesive bond during an induced temperature of 200C° is higher using GFRP sheets than that with CFRP sheets. Also, it could have been more scientifically beneficial to carry out the tests on real structural members and not only on small concrete specimens.

Jiangtao et al. (2017) [20] did an experimental research on 15 RC beams externally strengthened with CFRP beams exposed to ISO 834 standard fire and loaded until reaching the full consumption of the ultimate structural load bearing capacity (failure). The investigator conducted various tests between NSM and EB techniques to proof that the NSM application method performs better under fire. To achieve the main aims of the study, Jiangtao et al. (2017) [20] used two different types of bonding adhesives, magnesium oxychloride cement and epoxy. Additionally, parametric simulations were conducted on thin and thick fire retardant coatings applied on different sides on the concrete soffit of the beam. The application of fire retardant coatings was conducted as below:

- Applied on a single soffit.
- Applied on the bottom soffit.
- Applied on the bottom and horizontal soffits of the beam in a u-shaped form of application.

Nevertheless, the study concluded that by using a suitable fire protection system the RC beam members strengthened with NSM CFRP can sustain more than three hours of standard fire with high loading levels. In addition, it was observed that a u-shaped thermal protection layer improves the fire resistance and increases the heat insulation. On the contrary, the assumptions drawn by Jiangtao et al. (2017) [20] was based on results obtained for only 2 Near Surface Mounted strips. In the author's point of view, the researcher should have extended his investigation on 3 Near Surface Mounted strips. The author's believe that the structural member could have sustained higher fire endurance if the author would have installed a steel wire mesh in exactly the middle depth of the fire protection system. In the author's point of view, the strengthened fire protection system can minimize the risk of early failure of the layer during fire.

Carlos et al. (2018) [8] has experimentally examined the fire response of 9 RC strengthened and thermally protected beams during fire using three different fire insulation materials with 3 different layers for each material. In addition to one RC beam none strengthened and unprotected and used as a control beam. The thermal insulation materials used and tested were (1) vermiculite-perlite VP, (2) expanded clay aggregates and (3) ordinary Portland cement mortars. Each material was analyzed on three thicknesses, at 20mm, 35mm and 50mm. Moreover, the beam and its supports were fully placed inside the testing furnace. The tested CFRP laminates had a width of 50mm and 1.2mm thickness, average tensile strength of 2741.7MPa, modulus of elasticity 170.9GPa, and ultimate strain of 16% at ambient temperature. Moreover, the CFRP laminate was bonded to the concrete soffit using Epoxy adhesive (S&P Resin 220) and had a modulus of elasticity of 8.8GPa and a tensile strength of 17.3MPa. Additionally, all the beams had the same dimensions with a cross section of 150x300mm and a length of 3400mm. A concrete class of C25/30 was used and maintaining a concrete cover of 25mm from all sides. Carlos et al. (2018) [8] concluded that (1) the VP mortar material had the lowest thermal conductivity during fire, (2) the thicker the thermal insulation layer the better the fire insulation and (3) VP mortar is more effective than EC and OP during fire. Furthermore, Figure 15 presents the results of the cross sectional temperature in the RC specimen with respect to time by Carlos et al. (2018) [8]. In addition Carlos et al. (2018) [8] has presented results of the cross sectional temperature in the RC specimens with respect to time for fire protection layer using expanded clay and ordinary Portland materials with different thermal layer thickness. Even though Carlos et al. (2018) [8], has recommended the installation of reinforcement in the fire protection layer to improve the strength of the fire protection system, he did not mention any reinforcement types or materials that could be installed in the fire protection layer. It has been noted that is no research carried out what so ever on strengthened fire protection layer. The author’s believe that further investigations should be carried out on various types of different strengthened fire protection materials, for example, steel wire mesh, textile wire mesh and carbon tissues. In addition, the author’s suggest further parametric studies which have to be carried out on the fire response with different installation depth locations inside the thermal protection layer, for instance, in the centre depth and near soffit mounted with the fire protection layer. However, Carlos et al. (2018) [8] did not test the insulation materials on different installation techniques, such as NSM CFRP or extruded CFRP technique. Nor he investigated different geometrical parametric studies on the efficiency of the test insulation materials.

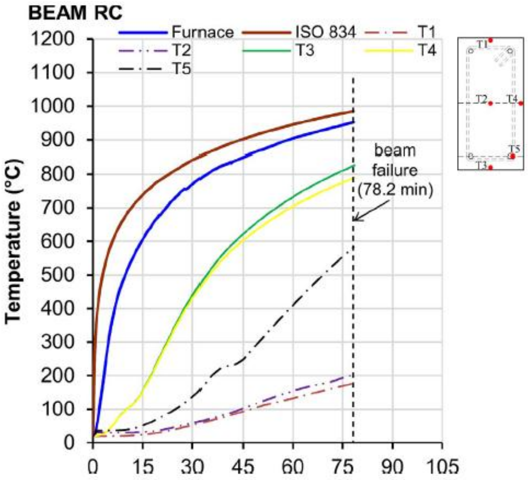


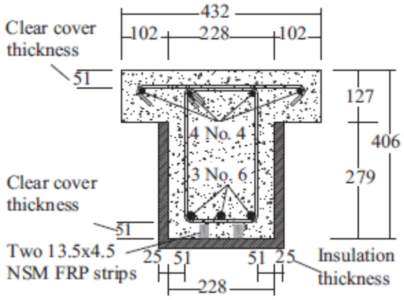
Figure 15. Results of the cross sectional temperature in the RC specimen with respect to time by Carlos et al. (2018) [8].

3.5. Experimental and Numerical Studies

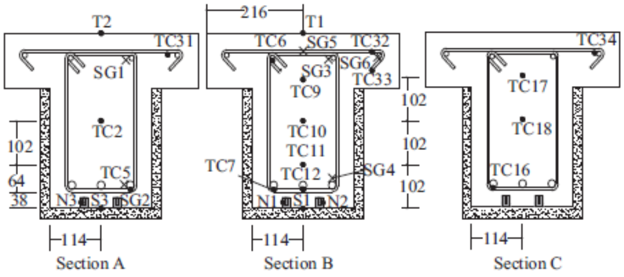
Foret and Limam (2007) [17] conducted both experimental and numerical studies on two way RC slabs strengthened with CFRP rods and laminates using NSM and EB techniques. The results obtained for both techniques were evaluated in terms of elastic behavior and bearing capacity. This study concluded that the two ways RC slab strengthened with NSM CFRP rods increases the bearing capacity and is cheaper than the EB laminates technique. However, the researcher did not apply fire loads or elevated temperatures on the two ways RC slabs strengthened with CFRP rods and laminates using NSM or EB techniques. Firmo et al. (2012) [16] researched both experimentally and numerically the fire response of RC beams strengthened with CFRP laminates. This was conducted by using two different materials in the fire protection layer, calcium silicate boards and vermiculite/perlite cement based mortar. Moreover, each fire protection material was tested on two thicknesses, 25mm and 40mm. The study suggested installing a thicker fire protection layer on the anchorage area. Accordingly, Firmo et al. (2012) [16] found that with this application technique, the thermal response of CFRP acts in a cable mechanism behavior. Also, the paper stated that the vermiculite perlite mortar performs better as a fire insulation material than CS boards. Finally, the experimental results were compared with 2D FE numerical models. In the author’s opinion, Firmo et al. (2012) [16] should have tested more fire insulation materials, such as expanded clay. In addition, a better accuracy could have been achieved if Firmo et al. (2012) [16] extended his 2D FE models to 3D models for more validation accuracy. Likewise, Lopez et al. (2013) [27] performed both similar experimental and numerical simulations on two variance fire protection materials, calcium silicate boards and vermiculite/perlite cement based mortar. The thermal protection materials were installed at the bottom face of the RC slabs and were strengthened with CFRP laminates. In addition, the CFRP strips were mechanically anchored and had a thicker thermal insulation fire protection layer on the anchorage zones. Also the 2D models were developed into 3D FE models with the aim of exploring the fire response of RC slabs strengthened with CFRP laminates and three types of examinations were conducted as below:

- Geometric parametric study on the fire protection layer especially on the anchorage zone.
- Comparison in thermal behavior between NSM and EBR reinforcement techniques.
- The glass transition temperature Tg of the adhesive in the anchored zones.

Lopez et al. (2013) [27] concluded that a fire protection layer of 20mm using either NSM or EBR techniques can structural preserve 90 minutes of fire insulation. Also, it was observed that by applying a 60 or 80mm of fire protection layers on the anchorage zone can sustain the temperature of the bonding adhesive below the Tg for an extra period of 30 minutes. This thermal protection duration of the adhesive can double to 60 minutes when applying 100mm fire protection layer. The research concluded that the NSM technique has a better thermal protection performance than the EBR technique. At the end, the researcher suggested the use of adhesives with higher glass transition temperature to improve the thermal protection of the RC slabs strengthened with CFRP strips. Yu and Kodur (2014) [35] presented both experimental and numerical analysis on 4 tested T-shaped RC beams strengthened with FRP using NSM technique. The specimens were tested under standard fire (ASTM E119) to monitor their fire behavior. Yu and Kodur (2014) [35] stated that the NSM FRP T-shaped beam (Fig. 16) performs well up to 3 hours of applied temperature. At the end, the author concluded that the greater the induced load, the higher the deflection and the lower the fire resistance. Moreover, the author stated that there are no studies which have been carried out on the performance of anchored NSM FRP. However, the paper only presented results conducted on 2 NSM FRP strips and did not conduct research on the fire response of installing three NSM CFRP strips.



(b) Cross section of RC beam



(c) Instrumentation

Figure 16. Detailed cross sectional drawing of the fire protected NSM CFRP strengthened T-beams by Yu and Kodur (2014) [35].

Firmo et al. (2014) [10] conducted both experimental and numerical analyses for further investigation on the CFRP cable mechanism behavior under fire when installing a thicker thermal protection layer on the anchored areas. Accordingly, the CFRP cable thermal response was proved to increase the structural behavior against elevated fire endurance and works efficiently in protecting the thermal insulation system. Moreover, the cable response of CFRP during fire was analyzed for both EBR and NSM techniques. Finally, the researcher suggested further parametric and numerical studies to be carried out in the future to proof the suggested fire safety design strategies. Jadooe et al. (2017) [19] conducted a numerical and experimental research on 8 RC fire damaged beams strengthened with CFRP strips using NSM application method. The specimens consisted of 6 beams tested under ISO-834 standard fire and two beams examined under ambient temperatures. Moreover, the samples were exposed to temperature of 600 and 700C° and their flexural response was examined. Additionally, 4 RC beams were strengthened with CFRP laminates after fire exposure, while the other two RC beams were used as control beams without any CFRP reinforcement. The study determined that the stiffness and the load bearing capacity of the tested RC beams exposed to ISO-834 standard fire decreases when comparing the results with the other two beams which were analyzed under normal temperatures. However, the researcher stated that the stiffness and the load bearing capacity of the damaged beams can be increased when repairing and strengthening them with CFRP strips using NSM technique. Finally, the experimental results showed a good relationship when compared with the numerical FE models results.

Firmo et al. (2018) [11] developed 3D FE models of RC beam strengthened with CFRP laminates using EBR and NSM techniques. The numerical simulations were set to find the global thermal mechanism and alteration in the mechanical properties of structural materials under elevated temperatures. Again with reference to his previous experimental study which was carried out in 2011, Firmo et al. (2018) [11] has confirmed that the application of thicker fire protection layer on the mechanically anchorage system will provide the CFRP laminates with a cable mechanism thermal response. In addition, the investigation stated that the NSM technique has a higher fire resistance than the EBR technique, because the de-bonding occurs earlier during fire exposure in the EBR technique. Nevertheless, it was observed that the average temperatures of the adhesive bonding agent in the anchorage areas are as follows:

- From 1.2Tg to 1.4Tg when using the Epoxy Bonded Reinforcement technique.
- From 2.4Tg to 4.2Tg when using the Near Soffit Mounted technique.

As such, it is worth mentioning that the resistance of the bonding agent during fire has doubled when using the NSM technique.

Truong et al. (2018) [32] simulated an experimental flexural investigation on the fire response of 4 RC beams strengthened with Glass fiber strengthened polymers (GFRP) using NSM technique. The GFRP laminates were bonded using two different types of mortar and epoxy adhesives. Analytical analysis was conducted to validate the experimental results and to determine the deformations and failure modes of GFRP NSM RC beams exposed to elevated temperatures. Truong et al. (2018) [32] observed that the flexural strength is sustained using GFRP laminates bonded with mortar adhesive. The research concluded also that the initial stiffness of GFRP bonded with mortar is higher than that of GFRP bonded with epoxy.

3.6. Methods and Formulations

Nigro et al. (2014) [28] suggested a method of design to calculate the FRP bending moment resistance of RC beams strengthened with FRP bars in fire. His study argued about the shortage of methods of design and lack of details in the Eurocodes about the structural fire response of RC structural members strengthened with FRP material. Teixeira de Freitas et al. (2014) [30] has presented a set of formulations on hybrid FE beam model strengthened with CFRP laminates and subjected to ISO-834 Standard fire temperature. This was analyzed by applying different heat flow fields on the structural element. In addition, numerical simulations were carried out to determine the thermal global response and change in material properties for various element geometries (ISO-parametric boundary conditions). Furthermore, the thickness of the CFRP was studied when applying radiation on both bottom and bottom sides of the beam. The beam was subjected to duration of 5000 seconds of fire temperature near 1000C°. Accordingly, the global thermal distribution in the beam was monitored at 240 to 5000 seconds with an interval of 240 seconds. Teixeira de Freitas et al. (2014) [30] developed a 1D FE model to 2D and 3D models as part of the heat transfer simulations and concluded that the hybrid FE formulations and models gives accurate forecast and stable solutions using coarse mesh of higher-degree elements. Zeng et al. (2016) [36] has analyzed the action of strengthened RC members with FRP using a compressive membrane. By presenting a prediction model and carrying out simulations on how the material properties such as concrete, steel reinforcement and FRP laminates can cause on CMA. His study concluded that applying CMA on RC beams strengthened with FRP can increase the load bearing capacity.

Moreover, his observations from the parametric study has linked a direct relationship between changing material properties and improvement in efficiency of CMA, such as (1) increasing the area and elastic modulus of FRP and reinforcement rebar, (2) increasing the ultimate strain and concrete strength. However, an increase in span to depth ratio would cause a reduction in the effectiveness of CMA. Furthermore, two failure modes were reported by Zeng et al. (2016) [36], which are de-bonding and rupture. The author suggested installing u-shaped FRP anchorage wraps to reduce the failure modes. It was obvious that the prediction model proposed by Zeng et al. (2016) [36] needs to be validated with further research. Zeng et al. (2016) [36] has concluded that the CMA efficiency decreases as the span to depth ratio increases. Accordingly, he recommended more investigation to be carried out on his proposed model and for enhancement of an analytical prediction model to investigate the load-deflection behavior of compressive membrane action in FRP strengthened RC members.Another important research was carried out by Kodur et al. (2017) [24] presenting temperature forecasting formulations which could be used in RC structural members subjected to standard fire loads. However, the numerical formulations which was illustrated by Kodur et al. (2017) [24] did not include RC structural members under non-standard fire loads. Jiangtao et al. (2018) [21] has initiated a proposed algorithm method to predict the fire resistance of RC beams strengthened by NSM-FRP. The main purpose of his method was to theoretically predict the flexural strength and fire resistance capacity of the strengthened beams on the basis of two failure modes. The author's calculation model has taken into consideration the frictional factor of FRP and the global slippage (τ slip). In addition, he has monitored the slippage rate and bond strength between NSM-FRP and the concrete soffit at various ISO834 standard fire stages. The algorithm is also suitable in calculating the flexural strength of RC beams strengthened by NSM-FRP during fire cases. The fire resistance design of a 3 strips NSM-FRP has been illustrated in Figure 17. The 3 strips NSM-FRP were installed in the concrete soffit by pre-cutting grooves and fixed using an adhesive mortar. Two different types of adhesives were used, epoxy resin (ER) and magnesium oxy chloride cement (MOC). A graphical presentation was presented to show the bond-slip relation between the two adhesives under diverse fire levels. A previous experimental study was mentioned in his study which consisted of a set of pull-out tests to investigate the bond slippage of NSM-FRP under different fire rates. For validation purposes Jiangtao et al. (2018) [21] did a comparison between the results obtained from a previous experimental study which was conducted on 10 RC beams strengthened by NSM-FRP and the theoretical results obtained from the algorithm method. However, further studies should be carried out on the method due to the occurrence of high deformation in the correlation between the method calculation results and the experimental results. According to his study, the following conclusions were observed:

- The weakest link was the adhesive due to its glass transition temperature (Tg) properties and shortage in performance during high fire scenarios and early stress relaxation mechanism.
- Near soffit mounted FRP performs better in resisting fire than EB-FRP because the FRP is embedded in the concrete and protected by the concrete cover from direct fire thermal conduction.
- To reduce the frictional strength the FRP could be anchored mechanically instead of adhesively.

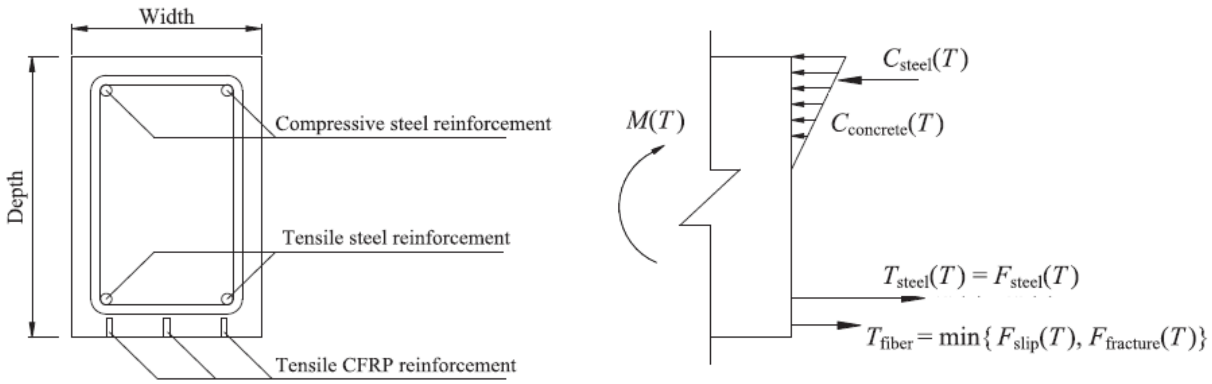


Figure 17. Fire resistance design of a 3 strips NSM-FRP (Jiangtao et al., 2018) [21].

4. Results and Discussion

The current researchers' results have been presented and discussed in this section in terms of (1) Adhesives and Glass transition temperature Tg, (2) FRP strengthening properties and (3) load bearing capacities of beams and shear strength of the interface laminate vs concrete. The findings from this section is the benchmark of this review paper, aim to improve fire endurance and to increase the amount of strength capacity of RC beams strengthened with CFRP as suggested in the conclusions and recommendations for future work section.

4.1. Adhesives and Glass Transition Temperature Tg

The glass transition temperature is the temperature by which a material changes its state and properties to a liquid rubber form. The majority of the researches agrees that the main problem is that once the temperature of the adhesive during fire exceed Tg, early slippage and de-bonding occurs which leads to failure without fully consuming the strength of CFRP material. Since then researchers has been conducting studies to improve the fire performance of the adhesives. According to Ahmed and Kodur (2011) [2], the Tg can be determined either by differential scanning calorimetry (DSC) or thermo-mechanical analysis (TMA). Moreover, the ACI [1] stated that the range of Tg of epoxy adhesives ranges between 62 and 82 C°. As shown in Table 1, the highest adhesive Tg was used by Al-Salloum et al. (2011) [4] with a value of 88 °C. Very recent studies carried out by Jadooe et al. (2017) [19] and Truong et al. (2018) [32] on fire response of cement based mortar adhesives.

Table 1. List of adhesive properties by authors.

Author	Adhesive type	Tg temperature (°C)	Strengthening method	Test method for determining Tg
Al-Salloum et al. (2011)	Epoxy resin	88	Rapped	DSC
Ahmed and Kodur (2011)	Two-component Epoxy	82 exceeded @ 1h	EBR	
López et al. (2013)	Epoxy	55	EBR & NSM	
Petkova et al. (2014)	Two-component			
Thixotropic epoxy	82	EBR & NSM		
Firmo et al. (2015)	EP 1-S&P Resin 220			
	EP 2-Araldite 2014–1	85	EBR	DSC
Bilotta et al. (2015)	Two-component			
	Thixotropic epoxy		EBR & NSM	
Jiangtao et al. (2017)	EP1-Araidite XH111A/B			
	EP2-Araidite XH180A/B	50.16	EBR &NSM	DMA
	MOC			
Krzywoń (2017)	EP1-S&P Resin 55	45	EBR	
	EP-SikaDur®330			
Jadooe et al. (2017)	Epoxy and CBA		NSM	
Truong et al. (2018)	SKRN epoxy and mortar		NSM	
Carlos et al. (2018)	S&P Resin 220	82	EBR	DMA

According to the comparison made between author's adhesives (Table 2), the highest adhesive tensile strength was Araldite 2014–1 which was used by Firmo and Correia (2015) [15] with a value of 10 GPa (Fig. 18). On the other side, the highest adhesive tensile strength was a two-component epoxy used by Ahmed and Kodur (2011) [2] with a value of 72.4MPa (Fig. 19). Moreover, the adhesive which was used by Ahmed and Kodur (2011) [2] had the second highest Tg with a value of 82 °C exceeded in fire at 1 hour.

Table 2. List of adhesive's tensile modulus and strength used by authors.

Author	Test method	Adhesive Tensile Modulus (GPa)	Tensile strength of the interface laminate vs concrete (MPa)
Ahmed and Kodur (2011)	Four-point bending	3.18	72.4
Firmo et al. (2015)	Four-point bending	EP 1 = 10 , EP 2 = 4.4	EP 1 = 14 , EP 2 = 26
Bilotta et al. (2015)	Four-point bending	6	70
Jiangtao et al. (2017)	Three-point bending	N.A.	EP1 = 13.6, EP2 = 55 and MOC = 10.5
Truong et al. (2018)	Three-point bending	N.A.	57.3
Carlos et al. (2018)	Four-point bending	8.8	17.3

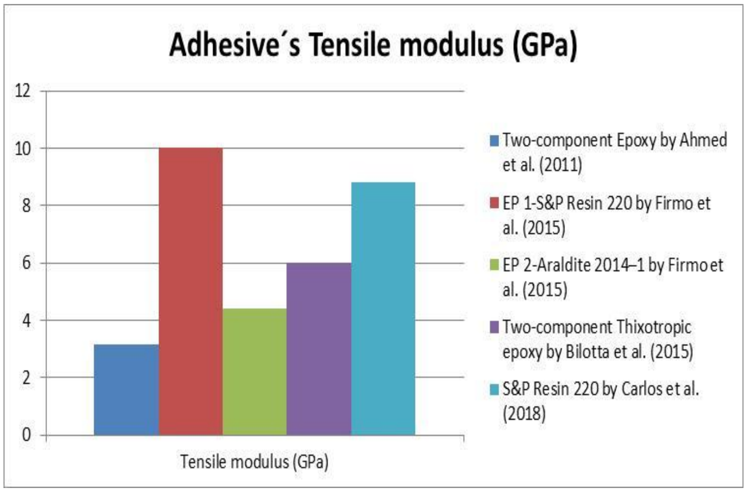


Figure 18. Comparison between adhesive's tensile modulus used by researchers.

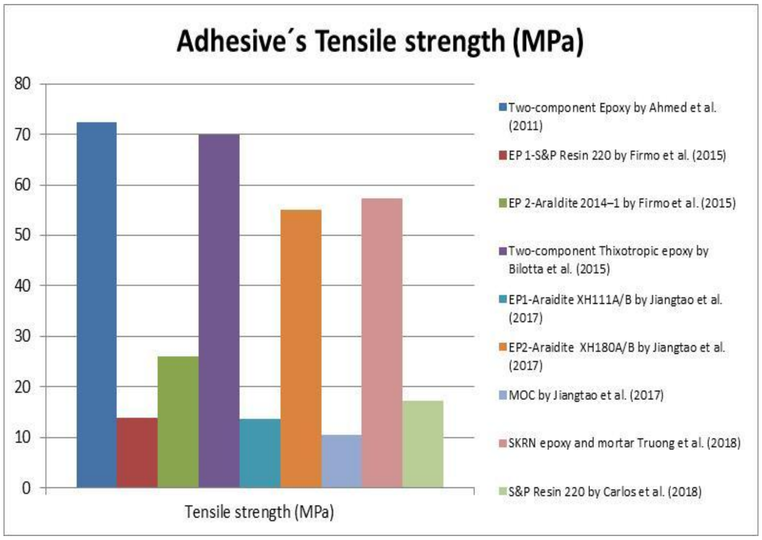


Figure 19. Comparison between adhesive's tensile strength used by researchers.

4.2. FRP Strengthening Properties

Figure 20 demonstrates a comparison between the FRP strengthening properties which was used by researchers. Accordingly, the highest CFRP tensile strength was 2741 MPa used by Carlos et al. (2018) [8]. While the highest CFRP tensile modulus was used by Firmo and Correia (2015) [15] with a value of 189 GPa.

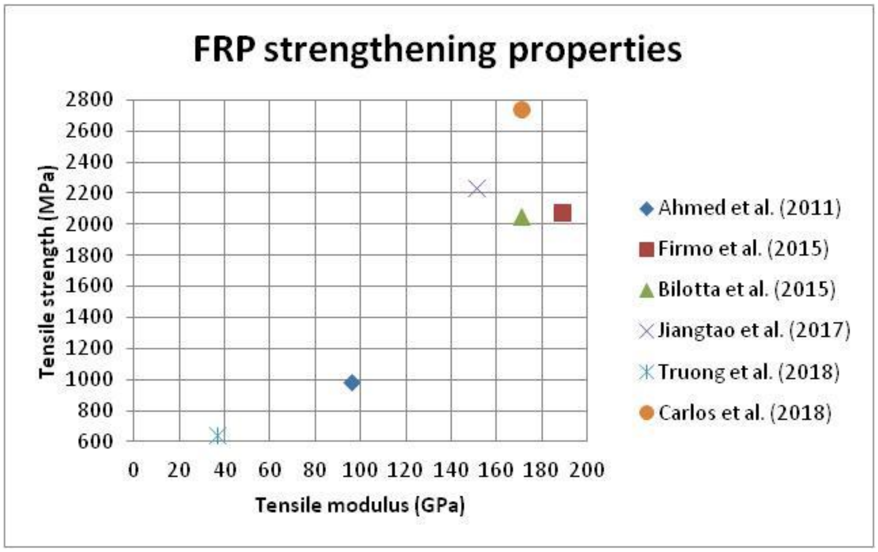


Figure 20. Comparison between FRP strengthening properties used by researchers.

4.3 Load Bearing Capacities of Beams and Shear Strength of the Interface Laminate vs Concrete

A comparison was made between the percentages of increase in strength capacity of RC beams strengthened with FRP (Fig. 21) and showed that the highest was by Firmo and Correia (2015) [15] with 74% increase in strength. In addition, Firmo and Correia (2015) [15] had the longest fire endurance duration of 4 hours and 47 minutes (Table 3). Such a remarkable increase in % of strength and fire endurance was achieved by Firmo and Correia (2015) [15] due to the below successful application techniques:

- Application of thicker insulation layers at anchorage zones which maintained a cable mechanism of CFRP laminate during fire.

- Using Araldite 2014–1 (with the highest adhesive tensile strength among researchers - 10 GPa) as a bonding adhesive with a high Tg value of 85% has eliminated the possibility of an early de-bonding.

- The installation of a high tensile CFRP strengthening laminates (highest tensile modulus among all researchers) with a value of 189 GPa.

However, Firmo and Correia (2015) [15] beams had the second lowest ultimate capacity with a value of 18.9kN as shown in Figure 22. This is because the researchers have used different (1) geometrical dimensions for the tested beams, (2) different internal reinforcement design and (3) different concrete and steel properties. As such the highest ultimate capacity beam was conducted by Ahmed and Kodur (2011) [2] with a value of 140kN. Accordingly, in the author's point of view this review paper is very essential to this field and it is strongly believed that the fire endurance and percentage increase in strength capacity of RC beams strengthened with CFRP can be improved above the results obtained by Firmo and Correia (2015) [15], as well as the elimination of early de-bonding of interface laminate vs. concrete if our suggestions as presented in the conclusions and recommendations for future work section are followed and investigated further by researchers.

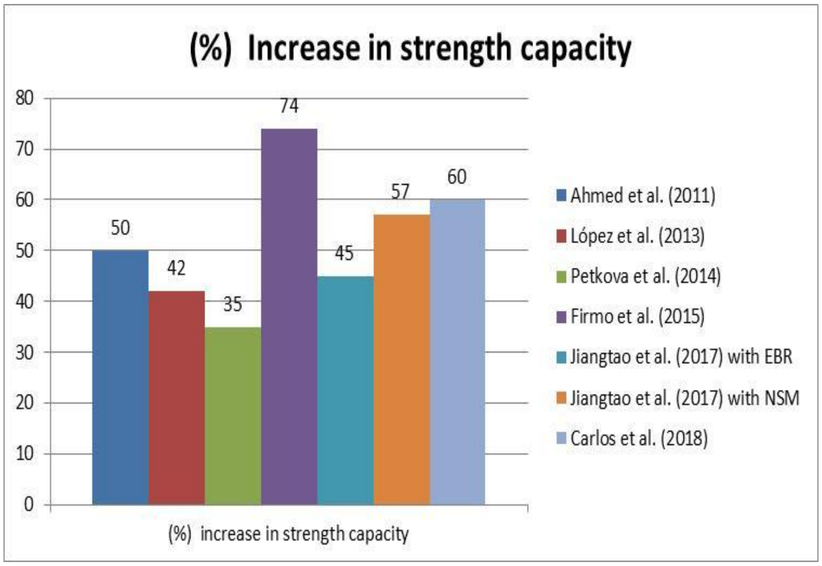


Figure 21. Comparison between % increase in strength capacity for authors CFRP strengthened beams under fire.

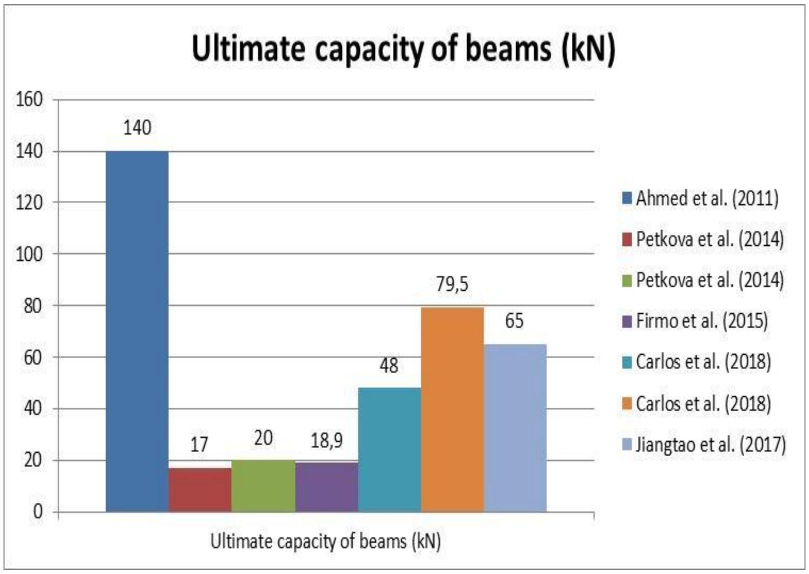


Figure 22. Comparison between ultimate capacity of beams by author.

Table 3. Summary of structural fire results by authors.

Author	Test set up	Longest fire endurance duration (Hours)	Ultimate capacity of beams (kN)	(%) increase in strength capacity
Ahmed and Kodur (2011)	Beam tests	More than 3 hours	140	50
Firmo et al. (2015)	Double lap	4 hours and 47 mins	18.9	74
Carlos et al. (2018)	Beam tests	N.A.	48 and 79.5	60
Jiangtao et al. (2017)	Beam tests	More than 3 hours	65	5 with EBR & 57 with NSM
Petkova et al. (2014)	Beam tests	N.A	between 17 & 20	35
López et al. (2013)	N.A.	120mins	N.A.	42

5. Author's Proposed Design Techniques for Improving the Performance of RC Beam Strengthened with CFRP Laminates

As part of this review, the author has proposed design techniques for improving the fire performance of RC beam strengthened with CFRP laminates. It is believed that the proposed designs would be advancement in the field. The author's proposed designed has considered beams with a dimension of (cross sectional dimension of 150X300mm and a length of 3400mm). Furthermore, the proposed design's beams could be tested under both ISO-834 standard fire and nonstandard fire and loaded until failure. Moreover, four different CFRP strengthening techniques could be applied on the beams (Three repetitions for each technique). The proposed design techniques which could be experimentally tested against fire are 2NSM, 3NSM, extruded CFRP and mechanically bolted techniques. Furthermore, each technique could be tested under (1) ambient temperature, (2) fire protected and (3) unprotected. It is to be noted that the beams which will be tested under fire should have a 30mm expanded clay fire protection layer applied on the bottom and side soffits of the beams. In addition, the fire protection layer could be reinforced with a steel wire mesh (Ø6mm) which might be installed in the middle depth of the fire protection layer at 15mm. Furthermore, the internal reinforcement of the testing beams may consist from four Ø10mm rebars and Ø6mm stirrups every 150mm. In addition, a concrete class 25/30 is advisable to be used in casting the beams. To ensure the quality of concrete, the beams should be cured for a duration of 28 days and 4 cube compressive strength sample's may be extracted during (1) concrete casting, (2) after 7 days, (3) after 14 days and (4) after 28 days. Two types of CFRP laminates and strips might be used depending on the type of technique. For instance, CFRP laminate (50mm x 1.2mm) could be installed for extruded and mechanically anchorage techniques. On the other hand, CFRP strips (13.5mm x 4.5mm) could be applied for 2NSM and 3NSM techniques. Additionally, all the CFRP strengthening materials should be glued to the RC beams using S&P Resin 220 Epoxy adhesive with a Tg of 75 °C with a thickness of 3mm. Thermocouples (Type-K) is the most suitable type to be embedded in the beams in order to monitor the global temperature of the CFRP strengthened beams during fire testing. The distribution of the thermocouples in the beams has been assembled in a way to track the raise of temperature with respect to time during fire in the (1) concrete, (2) steel rebar's, (3) CFRP laminates, (4) fire protection layer and (5) steel wire mesh. Moreover, the thermocouples have been tagged from TC1 to TC13 depending on the location of the indicated thermocouple. Below is a summary of the tag number and location of each thermocouple:

TC1 – Located on the middle top soffit of the concrete beam surface.
TC2 – Located in the middle of the RC beam.
TC3 – Located in the right side of the RC beam.
TC4 – Located in the middle right side of the fire protection layer and attached to the steel wire mesh.
TC5 – Located in the bottom right side of the beam and attached to the bottom longitudinal steel rebar.
TC6 – Located on the middle bottom soffit of the concrete beam surface.
TC7 – Located in the bottom middle side of the CFRP laminates.
TC7a – Located in the bottom middle side of the 2NSM CFRP strip.
TC7b – Located in the bottom middle side of the 3NSM CFRP strip.
TC7c – Located in the bottom middle side of the right 3NSM CFRP strip.
TC8 – Located in the middle bottom side of the fire protection layer and attached to the steel wire mesh.
TC9 – Located in the middle bottom surface of the fire protection layer.
TC10 – Located inside the beam and attached to the right steel rod for the mechanical anchorage system.
TC11 – Located on the right side steel bolt of the mechanical anchorage system.
TC12 – Located in the bottom middle side of the mechanical anchorage system and attached to the steel washer plate.
TC13a – Located in the top middle side of the 2NSM CFRP strip.
TC13b – Located in the top middle side of the 3NSM CFRP strip.
TC13c – Located in the top middle side of the right 3NSM CFRP strip.

The exact distribution of the thermocouples for each proposed design technique has been demonstrated in figures 23, 24, 25 and 28. Moreover, the results which may be obtained from the fire testing and monitored by the above mentioned thermocouples should be compared with the standard fire ISO 834 (Figure 23) Time (Min) vs. Temperature C° graph.

Figure 23. Standard fir ISO 834 Time versus Temperature graph.

5.1. Two Near Surface Mounted CFRP Strengthening Technique

The first proposed strengthening design technique is the 2NSM technique, which consists from 2 CFRP strips (13.5x4.5mm) embedded in the bottom soffit of the concrete beam surface. After casing the beams, two grooves should be drilled in the bottom soffit of the beam to glue the strips inside these grooves. Moreover, the distance between the CFRP strips is 4.1cm. Figure 24 demonstrates the design for 2NSM CFRP strengthening technique and the distribution of thermocouples in the beam. Furthermore, ten thermocouples should be installed for the 2NSM CFRP strengthened beams. These are TC1, TC2, TC3, TC4, TC5, TC6, TC7a, TC8, TC9, TC13a. The thermocouples distribution has been chosen in the arrangement shown in Figure 25 to track the global fire response of the beam strengthened with 2NSM CFRP strengthening technique. In addition, the thermocouple with tag number TC1 serves to monitor the temperature of top concrete surface of the beam to measure the thermal distribution through the concrete when compared with TC2 and TC6. It is believed that this location will have the lowest thermal impact because it is the most far point in the tested beam. On the contrary, thermocouple TC2 serves to investigate the fire response of concrete in the centre of the tested beam as this location is very critical part of the RC beam. Moreover, the location of thermocouple with tag number TC3 has been chosen in order to compare the fire response of the internal concrete and external concrete surface. Furthermore, thermocouple TC4 aims at investigating the fire response of the steel wire mesh on the side soffit of the RC beam. The location of TC4 was chosen to analyse the benefits of using steel wire mesh as reinforcement for the fire protection layer. Additionally, the main purpose of thermocouple TC5 is to study the change of temperature of the steel reinforcement rebar during elevated temperatures. On the other hand, the location of thermocouple TC6 is very important to test the protected bottom concrete surface of the beam. Whilst thermocouple TC8 serves as the base point for fire response tracking of the steel wire mesh of the bottom soffit and will be compared with the results obtained from TC4 to have a full clear idea of the fire behavior of the steel wire mesh. Moreover, the location of thermocouple TC9 has been chosen to monitor the direct fire behavior of the fire protection layer at the bottom soffit of the tested RC beam. Finally, thermocouples TC7a and TC13a aim at tracing the fire behavior of the CFRP strips from the bottom and the top sides respectively.

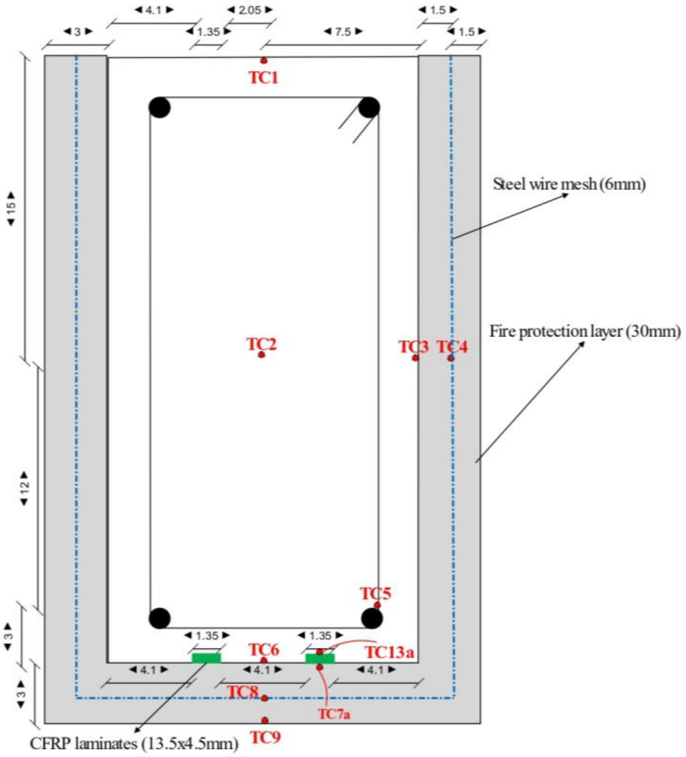


Figure 24. Distribution of thermocouples in the 2NSM CFRP strengthening technique.

5.2. Three Near Surface Mounted CFRP Strengthening Technique

The second proposed strengthening technique is the 3NSM design technique, which consists from 3 CFRP strips (13.5x4.5mm) embedded in the bottom soffit of the concrete beam surface. After casing the beams, three grooves should be drilled in the bottom soffit of the beam to glue the strips inside these grooves Moreover, the distance between the CFRP strips is 2.74cm. Figure 25 demonstrates the design for 3NSM CFRP strengthening technique and the distribution of thermocouples in the beam. Furthermore, eleven thermocouples may be installed for the 3NSM CFRP strengthened beams. These are TC1, TC2, TC3, TC4, TC5, TC7b, TC7c, TC8, TC9, TC13b, TC13c. Unlike the distribution of the thermocouples in 2NSM technique, the TC6 will be replaced with TC7b to monitor the fire response of the centre bottom side of the middle NSM CFRP strip. In addition, thermocouple TC7a has been replaced with TC7c to trace the fire behavior of the bottom right CFRP strip. This is due to an extra CFRP strip addition in this technique which changed the location of thermocouple TC7a. Similarly, thermocouple TC13a has been replaced with thermocouples TC13b, TC13c to observe the transfer of heat in the top side of the middle and right CFRP strips respectively.

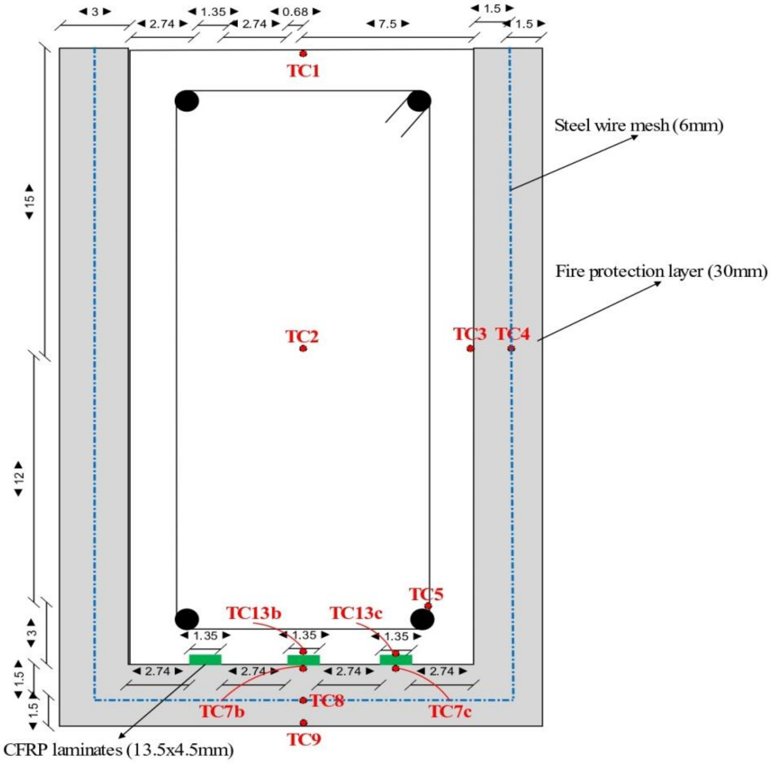


Figure 25. Distribution of thermocouples in the 3NSM CFRP strengthening technique.

5.3. Extruded CFRP Strengthening Technique

The third proposed strengthening technique is the extruded CFRP technique, which consists from a single CFRP laminate (50x1.2mm) installed in the bottom and side soffits of the concrete beam surface. Figure 26 presents the design for extruded CFRP strengthening technique and the distribution of thermocouples in the beam. Moreover, the CFRP laminate should be installed fully on the bottom length of the beam (3400mm) and half of the vertical soffits of the beam at 150mm as shown in figure 27. Additionally, an L-shaped steel plate with dimensions of 150x150x6mm should be fixed on the edges (Figure 28) to join both bottom and vertical CFRP laminates together and to avoid early slippage of the vertical laminates. Furthermore, nine thermocouples should be installed for the extruded CFRP strengthened beams. These are TC1, TC2, TC3, TC4, TC5, TC6, TC7, TC8 and TC9. Similar, thermocouples TC1 to TC6, TC8 and TC9 serve for the same purpose described above. However, there is an extra thermocouple TC7, which will trace the fire behavior of the bottom side of the CFRP laminate.

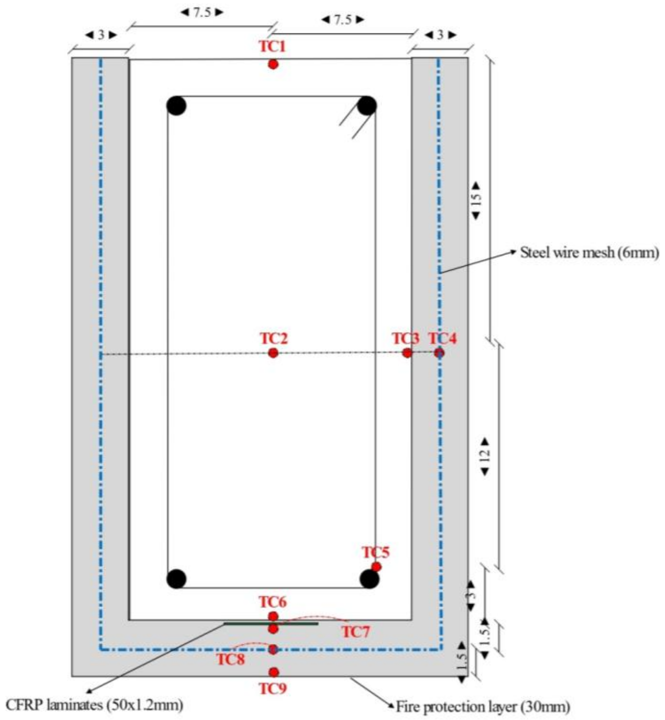


Figure 26. Distribution of thermocouples in the extruded CFRP strengthening technique.

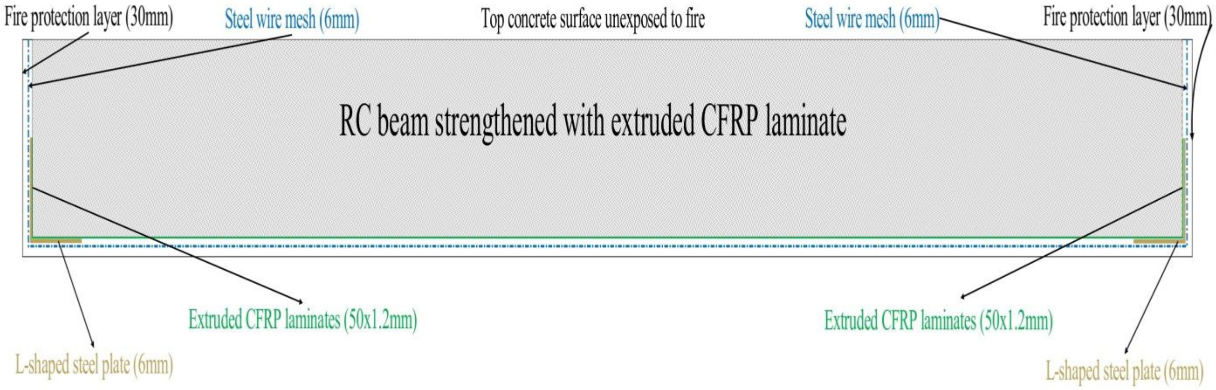


Figure 27. Longitudinal section of the extruded CFRP strengthening technique.

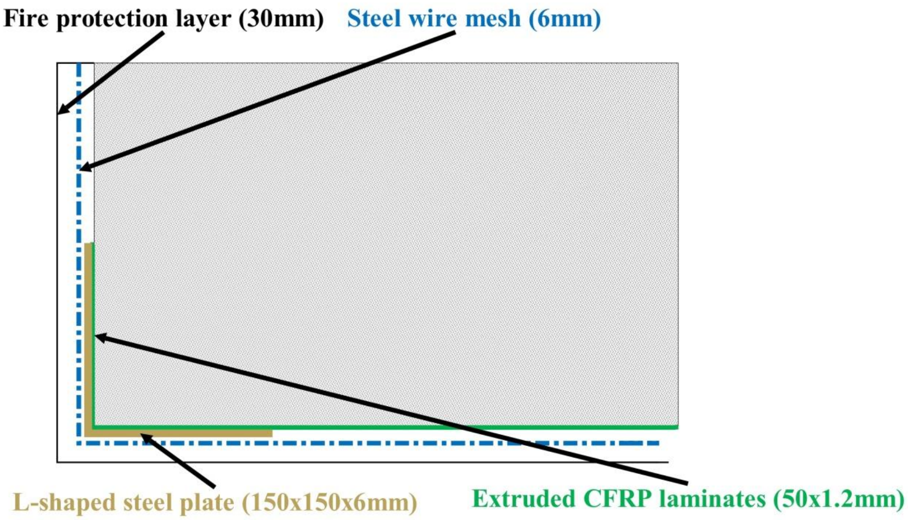


Figure 28. Side section of the extruded CFRP strengthening technique.

5.4. Mechanically Anchored CFRP Strengthening Technique

The fourth proposed strengthening technique is the mechanically anchored CFRP technique, which consists from a single CFRP laminate (50x1.2mm) installed in the bottom soffit of the concrete beam surface. The CFRP laminate should be anchorage with two anchorage devices. Each anchorage system may be installed after a distance of 700mm from each edge of the beam. Moreover, the distance between the anchorage will be 2000mm. Additionally, each anchorage system consists from one steel plate Class S235 60mm x 60mm with a thickness of 5mm, four embedded steel rods (Φ24mm diameter) and four steel screws grade 19MnB4 (Φ6mm diameter). The first phase of the anchorage system installation will be by drilling 4 holes in the center depth of the beam at 150mm. Afterwards, the drilled holes should be cleaned and filled with epoxy resin and steel rods must be fitted in the holes. Then the steel plate has to be fixed on the bottom beam surface by fitting the four holes in the steel plate inside the four embedded steel rods. Furthermore, the steel screws should be tilted on the head of the steel rods until it is fully fixed and tight with the steel plate. Figure 29 presents the design for mechanically anchorage CFRP strengthening technique and the distribution of thermocouples in the RC beam. Moreover, the CFRP laminate have to be installed fully on the bottom length of the beam (3400mm). Furthermore, twelve thermocouples should be installed for the mechanically anchorage CFRP strengthened beams. These are TC1, TC2, TC3, TC4, TC5, TC6, TC7, TC8, TC9, TC10, TC11 and TC12. With the same service purposes indicated in the extruded CFRP strengthening system, thermocouples TC1 to TC9 serves for the same purpose described above. However, there are three extra thermocouples TC10, TC11 and TC12. Furthermore, TC10 will be aiming at tracing the fire behavior in the right embedded steel rod as part of anchorage system. Additionally, thermocouple TC11 will serve to monitor the change in temperature on the bottom of the right steel screw. Moreover, thermocouple TC12 will observe the change of temperature versus time at the bottom of the steel plate.

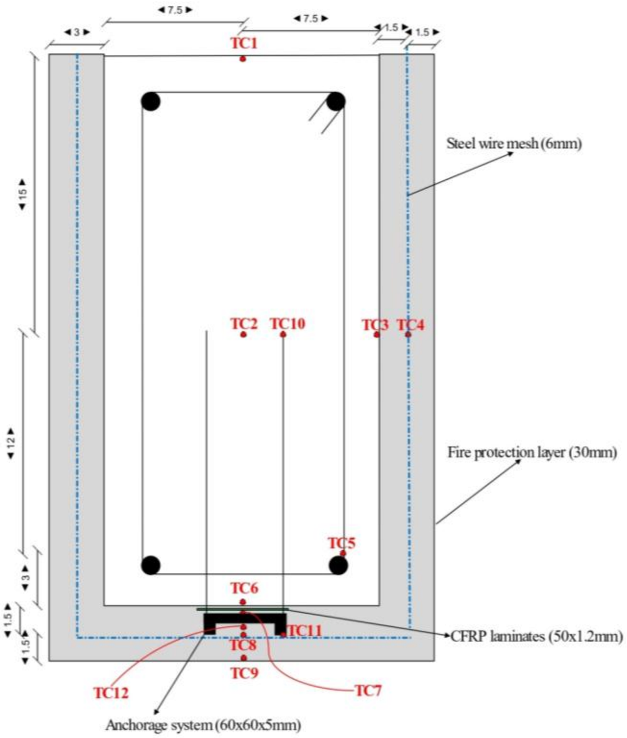


Figure 29. Distribution of thermocouples in the mechanical anchorage CFRP strengthening system.

6. Conclusions and Recommendations for Future Work

This state-of-art review has presented and discussed the available conducted research on the thermal fire behavior of RC structural members strengthened with FRP material in terms of (1) beams strengthened, (2) bond strength, (3) bond degradation, (4) fire protection layer, (5) experimental and numerical studies and (6) methods and formulations. It has been noticed that there is a lack of information and knowledge on testing specimens under non-standard fire. Moreover, the current available research showed a lack of numerical parametric studies and research carried out on RC structural members. In addition, it has been observed that there is a shortage on the fire response knowledge in case of various parametric studies on different alignment arrangements of CFRP laminates. Accordingly, the following future work suggestions have been drawn:

- Suggesting the conduct of fire response investigations on RC structural members external strengthened with zigzag shaped CFRP strips bottom and side anchorages.
- No research has been carried out on strengthened fire protection layer with a personal suggestion of conducting simulations on steel wire mesh, textile wire mesh and carbon tissues to identify the best fire resistance reinforcement type and material. This should also include a parametric simulation study on the installation depth of the reinforcement to determine the best fire resistance performance of the strengthened fire protection system.
- Suggesting testing the fire response of using π-anchor and FRP anchor devices to mechanically anchorage the RC beams strengthened with CFRP laminates.

- Suggesting testing the fire behavior of a combination design reinforcement technique on RC structural beam members with a combined mechanically anchored 3NSM extruded CFRP design.
- Suggesting conducting a parametric study on the fire behavior of RC structural members strengthened with CFRP laminates and mechanically anchorage with steel plates of different grades, dimensions and thicknesses.
- Testing the fire response of pre-stressed CFRP strengthening device system.
- Suggesting the performance of experimental fire testing outdoor on RC structural members strengthened with CFRP to demonstrate a real case situation including other environmental factors such as air and wind.
- Suggesting testing the fire behavior of RC beams strengthened with CFRP using mineral fibers in the fire protection layer mix.
- Suggesting further research to conduct fire testing on u-shaped steel anchorage plate installed in the mid-span of the RC beam strengthened with CFRP laminates in order to achieve the second proposed design strategy which was proposed by Firmo and Correia (2015) [15].
- Suggesting conducting a numerical modeling parametric study on the fire response of RC beams strengthened with CFRP laminates using 3 pre-fabricated extruded CFRP laminates (1) 90˚bended extruded edges, (2) semi-circular bended extruded edges and (3) 3 separated continuous straight. This should also include a parametric analysis on the extruded installation height of the CFRP laminate along the vertical soffits of the RC beam. For example, install the extruded CFRP laminates up to half of the vertical soffits of the RC beam or fully extruded along the full thickness of the beam.
- Suggesting installing L-shaped steel plate as a form of anchorage tool to support the bottom and the vertical soffits of the extruded CFRP. This should include a parametric analysis on the variables in the elevated temperature response when using different L-shaped steel plate thickness and dimensions. Also it could be more informative to analyze the bonding methods that could be applied to bond the L-shaped steel plate with the extruded CFRP. This could be by either using metallic or epoxy adhesives or using drilled mechanical bolts.

7. References

[1]- American Concrete Institute (ACI), 2008, **Guide for the design and construction of externally bonded FRP systems for strengthening concrete structures ACI 440.2R-08. ACI Committee 440**, Farmington Hills (MI), 1–45.

[2]- Ahmed A, Kodur V. K. R., 2011, **Effect of bond degradation on fire resistance of FRP-strengthened strengthened concrete beams**, Composites: Part B, 42: 226–237.

[3]- Ahmed A., and Kodur V., 2011, **The experimental behavior of FRP-strengthened RC beams subjected to design fire exposure**, Engineering Structures, 33: 2201–2211.

[4]- Al-Salloum, Y. A., Elsanadedy, H. M., and Abadel, A. A., 2011, **Behavior of FRP-confined concrete after high temperature exposure**, Construction and Building Materials, 25: 838–850.

[5]- Arruda, M. R. T., Firmo, J. P., Correia, J. R., and Tiago, C., 2016, **Numerical modelling of the bond between concrete and CFRP laminates at elevated temperatures**, Engineering Structures, 110: 233–243.

[6]-Barros, J. A. O., Ferreira, D. R. S. M., Fortes, A. S., and Dias, S. J. E., 2006, **Assessing the effectiveness of embedding CFRP laminates in the near soffit for structural strengthening**, Construction and Building Materials, 20: 478–491.

[7]- Bilotta, A., Ceroni, F., Nigro, E., and Pecce, M., 2015, **Efficiency of CFRP NSM strips and EBR plates for flexural strengthening of RC beams and loading pattern influence**, Composite Structures, 124:163–175.

[8]- Carlos, T. B., Rodrigues, J. P. C., De Lima, R. C. A., and Dhima, D., 2018, **Experimental analysis on flexural behaviour of RC beams strengthened with CFRP laminates and under fire conditions**, Composite Structures, 189: 516–528.

[9]- Del Prete, I., Bilotta, A., Bisby, L., and Nigro, E., 2018, **Ambient temperature performance of cementitious matrices for fire-safe NSM FRP strengthening of concrete structures**, Construction and Building Materials, 193: 42–54.

[10]- Firmo, J. P., Arruda, M. R. T., and Correia, J. R., 2014, **Contribution to the understanding of the mechanical behavior of CFRP-strengthened RC beams subjected to fire: Experimental and numerical assessment**, Composites: Part B 66:15–24.

[11]- Firmo, J. P., Arruda, M. R. T., Correia, J. R., and Rosa, I. C., 2018, **Three-dimensional finite element modelling of the fire behaviour of insulated RC beams strengthened with EBR and NSM CFRP strips**, Composite Structures, 183:124–136.

[12]- Firmo, J. P., Arruda, M. R. T., and Correia, J. R., 2015, **Numerical simulation of the fire behaviour of thermally insulated strengthened concrete beams strengthened with EBR-CFRP strips**, Composite Structures, 126: 360–370.

[13]- Firmo, J. P., Arruda, M. R. T., Correia, J. R., and Tiago, C., 2015, **Flexural behaviour of partially bonded carbon fibre strengthened polymers strengthened concrete beams: Application to fire protection systems design**, Materials and Design, 65:1064–1074.

[14]- Firmo, J. P., Correia, J. R., and Bisby, L. A, 2015, **Fire behaviour of FRP-strengthened strengthened concrete structural elements: A state-of-the-art review**, Composites Part B 80: 198-216.

[15]- Firmo, J. P., and Correia, J. R., 2015, **Fire behaviour of thermally insulated RC beams strengthened with EBR-CFRP strips: Experimental study**, Composite Structures, 122:144–154.

[16]- Firmo, J. P., Correia, J. R., and França, P., 2012, **Fire behaviour of strengthened concrete beams strengthened with CFRP laminates: Protection systems with insulation of the anchorage zones**, Composites: Part B 43:1545–1556.

[17]- Foret, G., and Limam, O., 2008, **Experimental and numerical analysis of RC two-way slabs strengthened with NSM CFRP rods**, Construction and Building Materials, 22:2025–2030.

[18]- Hawileh, R. A., Naser, M., Zaidan, W., and Rasheed, H. A., 2009, **Modeling of insulated CFRP-strengthened strengthened concrete T-beam exposed to fire**, Engineering Structures, 31:3072–3079.

[19]- Jadooe, A., Al-Mahaidi, R., and Abdouka, K., 2017, **Experimental and numerical study of strengthening of heat-damaged RC beams using NSM CFRP strips**, Construction and Building Materials, 154:899–913.

[20]- Jiangtao, Y., Yichao, W., Kexu, H., Kequan, Y., and Jianzhuang, X., 2017, **The performance of near-soffit mounted CFRP strengthened RC beam in fire**, Fire Safety Journal, 90:86–94.

[21]- Jiangtao, Y., Keke, L., Ling-zhi, L., Yichao, W., Kequan, Ya., and Qingfeng, X., 2018, **A simplified method to predict the fire resistance of RC beams strengthened with near-surface mounted CFRP**, Composite Structures, 193:1–7.

[22]- Kalfat, R., Gadd, J., Al-Mahaidi, R., and Smith, S. T., 2018, **An efficiency framework for anchorage devices used to enhance the performance of FRP strengthened RC members**, Construction and Building Materials, 191:354–375.

[23]- Kodur, V. K. R., and Bhatt, P. P., 2018, **A numerical approach for modeling response of fiber strengthened polymer strengthened concrete slabs exposed to fire**, Composite Structures, 187: 226–240.

[24]- Kodur, V. K. R., Yu, B., and Solhmirzaei, R., 2017, **A simplified approach for predicting temperatures in insulated RC members exposed to standard fire**, Fire Safety Journal, 92:80–90.

[25]- Krzywon, R., 2017, **Behavior of EBR FRP strengthened beams exposed to elevated temperature, International Conference on Analytical Models and New Concepts in Concrete and Masonry, Structures AMCM'2017**, Procedia Engineering, 193: 297 – 304.

[26]- Lau, D., Qiu, Q., Zhou, A., and Chow, C. L., 2016, **Long term performance and fire safety aspect of FRP composites used in building structures**, Construction and Building Materials, 126: 573–585.

[27]- López, C., Firmo, J. P., Correia, J. R., and Tiago, C., 2013, **Fire protection systems for strengthened concrete slabs strengthened with CFRP laminates**, Construction and Building Materials, 47:324–333.

[28]- Nigro, E., Cefarelli, G., Bilotta, A., Manfredi, G., and Cosenza, E.,2014, **Guidelines for flexural resistance of FRP strengthened concrete slabs and beams in fire**, Composites: Part B, 58: 103–112.

[29]- Petkova, D., Donchev, T., and Wen, J., 2014, **Experimental study of the performance of CFRP strengthened small scale beams after heating to high temperatures**, Construction and Building Materials, 68:55–61.

[30]- Teixeira de Freitas, J. A., López, C., Cuong Rui Faria, P. T.,2014, **Hybrid finite element thermal modelling of fire protected structural elements strengthened with CFRP laminates**, Composite Structures, 113:396–402.

[31]- Toutanji, H., Zhao, L.,and Zhang, Y.,2006, **Flexural behavior of strengthened concrete beams externally strengthened with CFRP sheets bonded with an inorganic matrix**, Engineering Structures, 28:557–566.

[32]- Truong, G. T., Lee, H., and Choi, K., 2018, **Flexural behavior of RC beams strengthened with NSM GFRP strips after exposed to high temperatures**, Engineering Structures, 173: 203–215.

[33]- Xu, Q., Chen, L., Han, C., Harries, K. A., and Xu, Z., 2019, **Experimental research on fire-damaged RC continuous T-beams subsequently strengthened with CFRP sheets**, Engineering Structures, 183:135–149.

[34]- Yu, B., and Kodur, V. K. R., 2013, **Factors governing the fire response of concrete beams strengthened with FRP rebars**, Composite Structures, 100:257–269.

[35]- Yu, B., and Kodur, V. K. R., 2014, **Fire behavior of concrete T-beams strengthened with near-soffit mounted FRP reinforcement**, Engineering Structures, 80:350–361.

[36]- Zeng, Y., Caspeele, R., Matthys, S., and Taerwe, L., 2016, **Compressive membrane action in FRP strengthened RC members**, Construction and Building Materials, 126:442–452.