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Structural Behavior of Jacketed Fire-Damaged Reinforced Concrete Members: A Review

M. M. A. Alhadid[1], M. A. Youssef[2]
[1]Department of Civil and Environmental Engineering, University of Western Ontario
[2]Department of Civil and Environmental Engineering, University of Western Ontario

Abstract: The production of concrete as a superior building material led to a consequent civilian renaissance in construction. Unfortunately despite the enormous advantages of Reinforced Concrete (RC) structures, they deteriorate and loose part of their strength when exposed to fire. The mechanical properties of concrete and reinforcing steel as well as the interfacial behavior between them pass through several significant changes during the heating and cooling stages. Therefore, a detailed assessment strategy should be carried out to evaluate the overall performance of a fire-damaged structure. The main objective of this paper is to summarize the experimental and analytical research concerned with the behavior of retrofitted fire-damaged RC elements. The paper will present information about the residual strength of fire-damaged RC elements and the expected improvements in their capacities when retrofitted using RC jackets. The information gathered in this paper will provide a strong basis to identify future research needs for assessing the capacity and retrofitting of fire-damaged RC structures.

1 Introduction

The rapid chemical process which involves the oxidation of combustible materials and releases energy in terms of heat and light is widely known as fire. A typical fire event is characterized by three main stages, namely: growth period, burning period and decay period. Although the duration of the growth period is relatively small and produces low temperatures, it is crucial in determining the effective operation period of fire brigades to intervene and distinguish the fire with minimal damage to the properties. Once the combustible materials burn in an active manner, the burning period initiates when a flashover occurs and the temperature starts to increase remarkably in an increasing rate till some point and then in a decreasing rate until the peak temperature is reached. The temperature starts to stabilize again when the heat generated from the combustible materials become equal to the heat loss to the surroundings. After that, the temperature falls down gradually without the need of any further mitigation within the decay period. The temperature in any closed area varies with time and location as well, and thus the reported temperature is usually taken as the average gas temperature within a certain volume (Lie, 1992.)

There is no doubt that reinforced concrete is considered as one of the most widely used construction materials worldwide. The robustness and inherent structural performance of this material motivated the engineers to use it extensively in their designs when larger buildings, higher durability, better seismic performance and even environmentally friendlier materials are considered. In addition to its advancement in structural applications, concrete is a non-combustible material and possesses an outstanding fire resistance and thus it does not contribute to the fire load and does not burn at elevated temperatures. It also provides fire shielding and works as an insulation material for other construction materials such as steel and timber due to its low thermal conductivity. Although the performance of concrete structures exposed to elevated temperatures is good compared to other construction materials, some physical and chemical changes in the concrete material occur and cause significant reduction in its mechanical properties and thus deterioration of the entire structure with time. In addition to pores vapour pressure, the deterioration mechanism at temperatures below 500^oC occurs mainly due to the formation of thermal gradient within the member's cross-section causing internal stresses and consequent thermal cracks. The chemical and physical reactions become more pronounced when temperature exceeds 600^oC where dehydration of cement paste and decomposition of aggregate take place excessively causing structural breakdown of the concrete material (Chang et al., 2006). These changes in concrete structure will cause consequent substantial changes in its compressive strength, tensile strength, strain at peak stress, stiffness, creep behavior, thermal conductivity, ductility, toughness and bond strength with steel reinforcement. Thus, a detailed examination of reinforced concrete in both macro and micro scales should be carried out after fire events to assess its ability to maintain its structural functionality considering the recommended safety factors for the individual elements as well as the structure in general.

To the best of the authors' knowledge, the first known steps in the realm of developing a full understanding of concrete behavior at elevated temperatures has been commenced since at least 1922 by Lea and Stradling. The structural fire protection legislations aim at maintaining the lives of people, controlling the spread of fire and protecting the surrounding environment. Most concrete structures exposed to fire conditions are not fully deteriorated and their structural integrity and mechanical properties can be restored by applying suitable repair methods. According to the European concrete platform ASBL (2007), a Swedish study revealed that only 9% of all burned houses made of reinforced concrete had to be demolished and the remaining 91% were put back to use after being repaired. The detailed assessment of the structural performance after fire events is an essential key to satisfy the current construction practices by choosing a suitable repair and strengthening techniques that conform to the current regulations and provide sufficient fire resistance for other possible fire scenarios.

The strength reduction and softening of the reinforced concrete members exposed to elevated temperatures remain for certain period of time even after the highest fire temperature is reached because of two chief reasons. The first one is that the response of the interior concrete section to the temperature decrease of the surrounding environment is slow as it is thermally protected by the concrete cover. Thus, the heat keeps transferring from the outer concrete layers not only to air, but also towards the concrete core resulting in a further reduction in its mechanical properties. This phenomenon becomes more pronounced as the cross-sectional dimensions of the concrete member increases. The second reason is due to the incomplete strength and durability recovery of the concrete material after the fire is extinguished. The formation of cracks and softening in the stress-strain relationship becomes permanent when the concrete temperature exceeds high temperature values where dissociation in the cement paste components and break up of aggregates take place.

The numerical analysis procedure of reinforced concrete elements follows the same sequence of a typical fire scenario. Firstly, the temperature of the surrounding environment due to fire needs to be identified at different time intervals. Then, the influence of this variation in temperature on the temperature of the concrete section itself is considered by adopting a suitable thermal distribution model. Finally, the behavior of the structural element under consideration is predicted at different locations within the member at any time interval by taking into account an appropriate model relating the mechanical properties to its temperature.

2 Residual Strength and Cooling Effect

The mechanical behavior of concrete as well as steel reinforcement exposed to elevated temperatures is one of the main concerns for researchers worldwide such as Malhorta (1956), Abrams (1971), Schneider (1976), Khoury *et al.* (1985), Lie (1992), Purkiss (1996), Phan and Carino (1998), Hertz (2005), and others. In an attempt to provide a better understanding of concrete subjected to various fire scenarios, Youssef and Moftah (2007) conducted an extensive literature review which discussed in details the general stress-strain relationship of this material when subjected to high temperatures. The significance of the study emerged from its ability to provide a solid basis for designing concrete structures to account for various possible fire scenarios by presenting and comparing the different models used for predicting both the concrete and steel performances and the interfacial behavior between them at elevated temperatures. The study came to a conclusion that the main properties affecting the stress-strain relationship of confined concrete are the concrete compressive strength, modulus of elasticity, strain at peak stress, thermal strain, transient creep strain, steel yield strength and bond strength of the reinforcing bars. Also, it was shown that concrete softens as the temperature increases indicating a proportional reduction in its strength and stiffness accompanied by an increase in the absolute strain at maximum stress value. Based on the findings, the authors proposed and verified different simplified analytical models that can be implemented in any finite element code to describe both the compressive and tensile stress-strain relationships of concrete at high temperatures.

Several studies discussing the residual mechanical properties of concrete after being exposed to elevated temperatures and brought back to room temperature are available in the literature. However, quantitative comparison between these studies cannot be performed accurately due to the variation in specimens' geometries, material properties and testing conditions among the researchers. One of the earliest investigations related to strength recovery of concrete exposed to elevated temperatures was carried out by Crook and Murray in 1970. The performance of concrete blocks under different post-fire curing conditions was evaluated after heating concrete specimens to 620^{o}C and cooling them down to room temperature. The authors noticed that concrete compressive strength was decreased remarkably even after bringing the specimens temperature back to the initial state. However, it was observed that by immersing the samples in water after cooling, the strength recovery was much more evident than that evaluated by air treatment. This observation was justified by knowing that the presence of water motivated the hydration process to reactivate and increase the cement paste strength chemically and physically by forming more hydration products that filled the small pores.

A research by Poon et al. in 2001 was performed in an attempt to figure out the influence of concrete treatment after exposure to various fire scenarios on its mechanical properties and durability. The experimental program encompassed casting and testing concrete cubes of twenty different mixes to cover a wide range of concrete types and curing regimes. The findings showed that the strength and durability regain in the blended concrete was higher than the normal concrete made of Portland cement only. It was also observed that strength recovery of concrete became insignificant when the temperature exceeded 600oC for all specimens as a result of the C-S-H gel decomposition that becomes more pronounced above 550oC. Thus, the authors recommended that in case of any fire scenario, keeping the temperature of concrete members below 600^{o}C would eliminate the need of special repairs to regain the concrete initial strength and durability.

In 2006, Chang *et al.* studied the strain variation with respect to the applied stress on 108 standard concrete cylinders cast with siliceous aggregate. The experimental work commenced by heating the specimens to temperatures ranging from 100^{o}C to 800^{o}C and cooling them gradually to room temperature before testing them in compression to obtain their compressive strength, tensile strength, modulus of elasticity, peak strain ratio and failure patterns. The substantial influence of heat on those mechanical properties was detected by tracking their variation with respect to temperature increase. It was found that the concrete compressive strength decreases in an increasing rate up to 85% loss of the initial compressive strength at 800^{o}C without noticing any effect of the actual compressive strength on this trend. The elastic modulus followed the same behavior of the compressive strength variation until reaching a temperature of 500^{o}C beyond which it kept decreasing but with a decreasing rate. The tensile strength was found to drop steadily from 20% of the initial strength at 200^{o}C to just over 90% at 800^{o}C. Based on the results, the authors recommended the use of a single equation to describe the stress-strain behavior for both heated and unheated concrete by using the same model proposed by Tsai (1988) but with modified parameters.

Zega and Di Maio (2006) investigated the behavior of concrete made of recycled aggregates in terms of its mechanical properties after a full heating and cooling cycle. The experimental work was performed by testing standard cylindrical specimens casted from various concrete mixes with different water/cement ratios and recycled aggregates replacement rates to evaluate their compressive strength and modulus of elasticity. Part of these samples were heated so that the internal temperature reached an average value of 230^{o}C and the remaining ones were heated until their core reached a mean temperature of 450oC before bringing them back gradually to ambient conditions. For the scope of this work, a similar behavior was observed for both the recycled concrete and the normal concrete as a result of the insignificant differences in thermal properties they possessed.

In 2007, Xiao and Zhang conducted an experimental study aiming at assessing the residual compressive strength of concrete made of different proportions of recycled aggregates after being exposed to elevated temperatures. All concrete cubes were heated to a predetermined maximum temperature ranging between 200^{o}C and 800^{o}C and then tested after being cooled to room temperature. The results showed a significant effect of the aggregate replacement ratio on the concrete performance in resisting compressive load after cooling. An increase in the concrete strength compared to the normal concrete was detected when the replacement rate exceeded 50% of the original aggregates and vice versa. This observation was more pronounced when the maximum concrete temperature varied between 300oC and 500^{o}C.

In 2008, Belkacem et al. inspected the behavior of high-performance concrete after being exposed to elevated temperatures and cooled down under various cooling regimes. The extensive experimental program was conducted using 114 cylindrical samples to fully determine the concrete residual mechanical properties after being exposed to maximum temperatures ranging from 200oC up to 1000oC. It was observed that the change in these properties was more pronounced in fast cooling conditions compared to the natural ones. The results indicated that under all cooling regimes, the loss initiation of concrete compressive strength was obvious at relatively low fire temperature whereas the loss in splitting tensile strength became remarkable when the temperature exceeded 400^{o}C.

Klingsch et al. (2009) conducted an experimental study to investigate the concrete compressive strength when exposed to elevated temperatures and after cooling. The experimental program was carried out by heating cylindrical concrete specimens casted from different cement types and testing them at different temperature values. Another set of specimens were heated to the same maximum temperature values of the previous group and then tested in compression after cooling them down to room temperature. By plotting the strength-temperature curves for the different cement types, it was concluded that the concrete compressive strength decreases significantly as the temperature increases and that the residual strength after cooling was further reduced and became more pronounced with higher temperatures. The authors justified this conclusion by the debonding between the aggregates and the surrounding cement paste as was seen from the magnetic resonance imaging.

Tanacan et al. (2009) studied the influence of different cooling conditions on the mechanical performance of aerated concrete subjected to high temperatures. All specimens were heated to a certain maximum temperature ranging from 100oC to 965oC and tested either before or after being cooled to ambient temperature. All specimens were thermally expanded at first and exhibited a small increase in volume before they shrink as the temperature rises. The results showed that the rapid cooling by water caused thermal shock in the specimens and thus led to less residual strength compared to the ones cooled gradually in air taking into account the high porosity of the aerated concrete and the higher susceptibility for water vapor to influence the concrete strength.

Bingol and Gul (2009) underwent an extensive experimental study in an attempt to better understand the influence of cooling regimes on the residual strength of concrete with various water/cement ratios and exposed to high temperatures ranging from 50 to 700^{o}C with a heating rate of 12 to 20^{o}C/min. The unit weight of all concrete specimens was shown to decrease slightly as the heating temperature goes up because of the voids left in the cement paste due to the bound water evaporation. A substantial permanent loss of the concrete compressive strength was noticed in all specimens exposed to high temperatures as a consequence of the different types of cracks developed in the specimen. The residual strength observed in the specimens cooled gradually in air was higher than their counterparts cooled rapidly in water causing thermal shock. Spalling was not encountered in any of the specimens because of the normal density cement paste that contains paths for the water vapor to escape and thus avoid pressure accumulation.

Bingol and Gul (2009b) proceeded their study by investigating the interaction between the steel reinforcement and the surrounding concrete material during heating and after cooling. All heated specimens were reinforced with steel bars with various embedment lengths and cooled down under different cooling conditions. It was shown that the residual bond strength kept increasing up to a temperature of 150oC beyond which it started to decrease consistently by raising the temperature. The concrete compressive strength was linearly proportioned with the bond strength for the range between 20 and 35 MPa. The study also revealed that the influence of the cooling conditions started to become more pronounced when the bar embedment length exceeded 10 cm indicated by the higher bond strength for the water-cooled samples compared to the air-cooled ones.

Wu et al. (2010) studied the performance of reinforced concrete columns exposed to fire scenarios during heating and at the end of the gradual cooling phase emphasizing on both the loading and the axial restraint ratios. The experimental program was carried out under transient heat loading conditions using twelve 2.34 meters long columns with (+), (T) and (L) cross sections. Thermal analysis of the columns was conducted using SAFIR finite element software and revealed that the adopted sections possessed less fire endurance compared to the rectangular columns because of the less sectional thickness they have. Vertical cracks along all columns surfaces were observed at the end of the heating process. The contours of the temperature distribution in the different cross sections varied according to the columns geometry with the (+) section having the least core temperature and the (L) section possessing the highest one. It was also observed that at the initiation of the cooling phase, the concrete outer parts and the steel bars responded promptly whereas the concrete core temperature kept increasing as a result of the continuous heat transfer.

Another research in 2010 was performed by Liu et al. who studied experimentally the behavior of fire-damaged shear walls after cooling and exposure to seismic loading conditions with a deep focus on the influence of steel reinforcement and the loading scenarios. The shear walls were heated for 90 minutes either under stressed or unstressed conditions prior to testing. The specimens were subjected to cyclic lateral load to simulate the behavior of an earthquake. The cracks distribution demonstrated the influence of the elevated temperatures in reducing the shear walls strength and improves their ductility. The inclined cracks were smaller and in some cases insignificant when the cyclic loading was applied on axially loaded fire-damaged shear walls as opposed to the wider cracks observed in the unstressed shear walls. It was shown from the test results that for certain heating conditions, increasing the steel reinforcement causes higher residual ultimate capacity and stiffness of the shear walls due to strength recovery of steel after cooling. The seismic performance of the shear walls was affected negatively when exposed to fire before the application of the cycling loading as indicated by the thinner hysteretic loops produced from the fire-damaged specimens with respect to the intact ones.

Sharma *et al.* (2010) carried out an extensive experimental study in order to assess the influence of confining steel reinforcement on the residual strength and behavior of RC short columns at high temperatures. All 108 cylindrical concrete specimens were 150 mm in diameter and 450 mm in length and varied in their hoop reinforcement spacing, steel yield strength, concrete compressive strength and maximum temperature they were exposed to. The specimens were tested after a full heating and cooling cycle under concentric axial compressive monotonic loading with a rate of 0.1 mm/min. The test results revealed that for both confined and unconfined specimens, the temperature effect started to be pronounced beyond 400^{o}C and the maximum reduction in the mechanical properties of 60% of the unheated specimens where detected at a temperature of 800^{o}C. The overall structural behavior of the confined specimens experienced less deterioration rate and found to be more ductile when the spacing of the lateral steel reinforcement was reduced for all temperature values resulting in higher load carrying capacity and less deformations. Increasing the yield strength of the lateral steel reinforcement resulted in negligible effect for temperatures less than 300$_{o}$C and a small reduction in the axial capacity beyond that. Also, increasing the concrete compressive strength resulted in faster deterioration rate of the specimens' peak capacity at elevated temperatures.

Vieira et al. (2011) conducted an experimental research towards achieving better prediction of the mechanical properties of concrete made of recycled aggregate after being exposed to elevated temperatures. The compressive strength, tensile strength and modulus of elasticity were evaluated for various concrete mixes using the appropriate standard test after bringing the heated specimens back to room temperature. The authors concluded that the residual mechanical performance of the concrete made of recycled aggregate is similar to the normal concrete despite the differences in porosity and thermal properties between them.

In 2011, Dimia et al. numerically investigated the influence of the cooling stage on the behavior of the structural system due to the exposure of the reinforced concrete columns to natural fire. The main focus of this study was on the columns geometrical properties as well as the duration of the fire event. All columns were subjected to fire from three sides and were fully modeled using SAFIR finite element software to determine the temperature distribution in certain sections. The thermal properties of steel were assumed to be fully reversible after cooling whereas the residual thermal expansion and shrinkage were taken into consideration for concrete by assuming its thermal conductivity after cooling was the same as the value reached at the highest temperature during heating. The results of the proposed model showed that the structure remains in risk of collapse throughout the cooling period even after distinguishing the fire due to the continuous heat transfer in the internal parts of the section. According to the authors, this conclusion can be generalized for all solid reinforced concrete columns and is more pronounced in axially loaded columns with low slenderness ratio and exposed to short fire durations.

3 Jacketing of Reinforced Concrete Members

3.1 Jacketing of Undamaged Reinforced Concrete Members

Several studies were conducted to understand the influence of concrete jacketing on the mechanical behavior of various RC elements. For instance, an experimental study by Cheong and MacAlevey (2000) was carried out to investigate the behavior of retrofitted RC beams by RC jacketing. The experimental program was divided into two phases by testing plain concrete prisms with different interface angles in shear and testing retrofitted RC beams with fully and partially roughened interfacial surfaces in bending. The tested beams were either simply supported or continuous and subjected to two point loads. It was noticed that the jacketed beams behaved in a similar manner to their monolithic counterparts in terms of the ductility, cracking and deflection behaviors. Also, due to the observed little difference in the performance of the fully roughened and partially roughened jacketed beams, it was suggested that roughening the surfaces with conventional impact tools does not have significant enhancement to the overall behavior of the retrofitted RC beams.

Altun (2004) performed an experimental study to examine the influence of RC jacketing on the mechanical performance of simply supported RC beams considering the load-displacement behavior, ultimate load, ductility and toughness. The study was conducted by applying flexural load to nine RC beams that vary in their cross-sectional area but having a fixed span length of 2 meters. Then, the four sides of these beams were trimmed, roughened and cleaned off by a strong water jet to remove all the dust and fine materials in order to form a strong bond with the later applied 10 cm thick RC jacket. The test results revealed that the behavior of the jacketed RC beams is similar to the corresponding ordinary ones throughout the testing range where flexural cracks kept growing in size until failure occurred.

Júlio et al. (2005) conducted a research in order to better understand the structural performance of jacketed RC columns with different interface treatments. The columns used in the experimental program were 1.35 meters long and having square cross-sectional area of 200 mm breadth and RC jacket thickness of 35 mm. The experimental measurements were verified by a proposed analytical model assuming either a complete non-adherence or perfect bonding between the original RC column and the surrounding jacket. It was concluded that for undamaged and undeteriorated columns, the interfacial preparation method resulted in insignificant variation in the columns mechanical behavior compared to their monolithic counterparts as long as the surfaces are well roughened.

In another study, Vandoros and Dritsos (2006) investigated the significance of surface preparation of deteriorated concrete columns before applying the new concrete jacketing. The surface treatment was assessed based on the degree of surface roughening and the effect of steel dowels placement. All jacketed specimens had 250 mm x 250 mm core cross-sectional area and 75 mm thick reinforced concrete jacket confining all the four sides. The columns were subjected to a constant 800 kN compressive axial load in addition to a horizontal cyclic loading applied at their upper side. The authors observed a similar failure mechanism for all of the jacketed specimens characterized by the propagation of horizontal cracks above the foundation followed by sequential order of concrete cover spalling, stirrups opening and bars buckling. The results revealed that strength and stiffness of the jacketed columns are less of their monolithic counterparts unless both good surface roughening and sufficient dowels placements are taken into account. The energy dissipation of the jacketed specimens was more pronounced than the monolithic specimens as a result of the interface friction and dowel action contributions.

In 2007, Santos et al. performed pull-off tests and slant shear tests in an attempt to assess the interfacial behavior of jacketed concrete specimens quantitatively as an alternative of the current qualitative methods. The pull-off tests were conducted on concrete cubes of 200 mm side length whereas the slant shear tests were carried out using prismatic specimens having dimensions of 200 x 200 x 400 mm. By observing the results, it was shown that sandblasting provides better performance in terms of both shear and tensile bond strengths compared to some other surface treatment methods such as wire-brushing, water jetting and chipping. Also, it was suggested that the use of sandblasting can eliminate the need for applying epoxy resins at the treated surfaces. The authors introduced certain parameters, such as the peak height and valley depth along the surface, which can be evaluated experimentally to describe the bond strength and interfacial behavior of the jacketed concrete member.

In 2007, Martinola *et al.* conducted a study in an attempt to understand the behavior of RC beams when jacketed with high performance fiber reinforced cementitious composites (HPFRCC) which are characterized by their tensile hardening behavior. The experimental work was carried out by testing one control and two jacketed beams each having a clear span of 4.35 m and cross-sectional dimensions of 300 mm x 500 mm under two point loading set up. The compressive strength of all beams was 25 MPa and the jacketing material was 40 mm thick and made of HPFRCC having compressive strength of 176 MPa. In order to ensure full bond between the new and old concrete materials, sandblasting was performed on the beams' sides before casting applying the jacketing material. Preliminary investigation was carried out on smaller specimens and the no slippage assumption was verified. The results showed that stiffness and cracking load both increased substantially and the peak load was observed to be 2.5 times higher than the unstrengthened RC beam. As a result of the considerably higher stiffness, the midspan deflection at service load was decreased by just over 91% from 6 mm to 0.5 mm. The failure of the jacketed beams was brittle and characterized by yielding of steel reinforcement rather than crushing at the concrete face.

In 2009, Shehata et al. underwent both experimental and analytical studies in an attempt to understand the behavior of RC beams retrofitted with partial jacketing using shear connectors. The research program was carried out by testing eight 4.5 meters long beams having rectangular cross-sectional dimensions of 150 mm x 400 mm with varying amount of original and added reinforcement. The side surfaces of all beams were roughened and expansion bolts were fixed along the entire span before applying the trapezoidal shape RC jacket. The results showed that when using expansion bolts with sufficient shear strength, increasing the steel reinforcement ratio in the jackets caused a substantial increase in both the rigidity and strength of the retrofitted beams. It was also recommended to ignore the concrete contribution in providing shear strength to the interface and to keep the expansion bolts close to the jacket main and shear reinforcement.

An experimental study was carried out by Wang and Hsu in 2009 to investigate the behavior of beam-column connections without horizontal shear studs and the possible enhancement these connections would attain under seismic loading when retrofitted with reinforced concrete jackets. By retrofitting and testing seven beam-column connections, it was noticed that the new concrete should be anchored to the old one by means of dowels in order to eliminate any possible slippage during cyclic loading conditions and hence to improve the connections performance. The shear strength of the jacketed connections was found to be more influenced by the compressive load acting on the columns than the slippage at the interface between the old concrete and its surrounding jacket.

Tsonos (2010) compared the performance of shotcrete and cast-in-place concrete jacketing in retrofitting damaged reinforced concrete columns as well as beam-column connections. For both strengthening techniques, jacketing was executed from four sides for some specimens and from two sides only for the remaining ones in an attempt to model the different constructions in practice. The experimental program was carried out on five columns and beam-column connections by applying a reversed cyclic lateral loading in one direction for the specimens. By examining the results, the authors concluded that the performance of all retrofitted elements under seismic loading scenarios was more satisfactory than the undamaged unrepaired ones in terms of ductility and energy absorption. It was also observed that both retrofitting arrangements contributed to increasing the connections ductility and generating flexural hinges in the attached beams leading to a substantial enhancement in their seismic loading resistance.

3.2 Jacketing of Fire-Damaged Reinforced Concrete Members

Studies related to the performance of jacketed reinforced concrete members after being exposed to elevated temperatures are very limited in the literature. One of the first attempts in this research filed was carried out by Lin et al. (1995) by investigating the mechanical behavior of RC columns after being repaired from severe fire damage. The repair technique was conducted by removing the damaged concrete surface and replacing it with new concrete material especially designed to provide higher strength and more durability than the original concrete in order to compensate for the potential loss in the deteriorated concrete core. Full bond between the new concrete cover and the exposed core was maintained by roughening the surfaces prior to concrete casting. The experimental program was performed by first exposing eleven columns to heat flow according to BS476 temperature curve and then testing them under eccentric axial loading conditions. The main parameters investigated in this study were the columns' gross cross-sectional area, longitudinal steel reinforcement yield strength, fire duration and the location of the applied concentrated load. The load-curvature curves were plotted for undamaged, damaged unrepaired and damaged repaired columns. The results revealed that full or even higher strength regain can be obtained by replacing the outer deteriorated concrete layers with a concrete of higher strength and durability. Surface roughening and preparation was found to be of significant importance in order to avoid premature failure of the repaired columns resulting from spalling of the new concrete cover. The authors provided and recommended the use of an analytical approach, which was verified in view of the experimental results, for future investigations.

Haddad et al. (2007) investigated experimentally the influence of applying high strength fiber reinforced concrete (FRC) jackets on the flexural performance of fire damaged RC beams. The experimental program was carried out by testing fourteen simply supported T-beams having a span of 1400 mm under two point loading system until failure. The beams were first heated for 2.5 hours to a maximum temperature of 600oC and left to cool down before treating their surfaces and applying the FRC jackets at the web's sides and flange's bottom. These jackets were prepared using four different types of fibers; namely: brass coated steel (BCS), hooked steel (HS), glass (G) and high performance polypropylene (HPP). The load deflection curves for the undamaged specimens, fire damaged specimens and retrofitted specimens revealed that the ultimate load capacity, ductility, toughness and stiffness were significantly improved by applying the FRC jackets to the damaged beams. The degree of improvement depends on the type and proportions of the fibers used in the jacketing material. For instance, the ultimate load was increased from 86.29 kN for the fire damaged specimen to 103.3 kN for the GFRC and 121.6 kN for the HBCSFRC jacketed specimens indicating an overall flexural capacity improvement ranging from 19.7% to 40.9%, respectively. The ultimate carrying capacity of the retrofitted beams was pronounced and even exceeded the flexural capacity of the undamaged beams when BCSFRC or HBCSFRC jacketing materials were used. The cracking pattern for the jacketed beams was similar to the undamaged ones where flexural cracks initiated at the beam mid-span and propagating towards the compression face of the beam until concrete crushing. However, the cracking load for the beams was increased by applying the jackets due to the fibers influence on increasing the concrete tensile strength and regaining part or all of the flexural capacity of the undamaged specimen. The authors recommended the use of high strength steel FRC jackets as a repair technique for fire damaged concrete beams since it provides it provides the highest displacement ductility ratio improvement of 112%, the highest stiffness enhancement of 220% and almost full flexural capacity regain relative to the undamaged beam specimen.

Greepala and Nimityongskul (2009) examined experimentally the structural performance of ferrocement jackets when exposed to fire scenarios with a maximum temperature of 1060^{o}C for short duration of 3 hours and long duration of 63 hours. The main objective of the experimental program was to investigate the influence of both the wire mesh volume fraction and mortar thickness on the mechanical properties of the ferrocement panels. The geometry of the ferrocement specimens was 200 mm x 240 mm x 25 mm and they were prepared from hydraulic cement mortar reinforced with multiple layers of steel wire mesh. The specimens were heated in electric furnace for the specified period of time and then left to cool down to room temperature before being tested in flexure. The results revealed that retrofitting the fire damaged RC members with ferrocement jackets would cause a substantial regain in flexural capacity of those members and enhance their resistance against other possible fire events. Also, it was concluded that the influence of wire mesh assemblies on the flexural performance of the ferrocement panels were more pronounced under normal conditions and became almost negligible at elevated temperatures. The effect of mortar covering on the specimens' carrying capacity and toughness was found to be insignificant in all fire exposure conditions. The visual inspection of the fire damaged specimens showed that increasing the wire mesh volume fraction beyond 0.54% or reducing the mortar covering to less than 2 mm resulted in more sever cracking and damage to the ferrocement jackets. The authors recommended the use of ferrocement jacketing with proper wire mesh arrangements as a superior alternative to its plain mortar or concrete cover counterparts currently used in practice.

In 2010, Leonardi et al. conducted an analytical study to evaluate the performance of fire damaged reinforced concrete beams and columns when retrofitted with high performance fiber reinforced concrete (HPFRC) jackets with steel microfibers content of 2.5%, length of 15 mm and diameter of 0.18 mm. It was assumed that the surfaces of fire damaged concrete element were treated and roughened using sandblasting and thus slippage between the old concrete and the jacketing material can be ignored. The first phase of the analytical program was conducted on a beam having a cross-sectional area of 300x500 mm and steel reinforcement ratio of 0.6%. The second phase was concerned with modeling concrete column with the same cross-sectional area and properties of the beam. The concrete material was modeled according to Kent and Park method whereas steel behavior was modeled based on the elastic hardening law. The heat transfer mechanism within the reinforced concrete elements was described by Fourier's equation for the non-steady conditions in terms of the thermal conductivity (λ), specific heat (c) and material density (ρ) as shown in equation [1].

$$[1]\quad \lambda\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2}\right)-\rho\, c\,\frac{\partial T}{\partial t}=0$$

The beams were assumed to be exposed to elevated temperatures from three sides only and the upper side was considered to be in adiabatic conditions; whereas the columns were assumed to be subjected to fire from all four sides. The load carrying capacities of the modeled beam and column decreased substantially as expected due to the decrease in their mechanical properties at elevated temperatures. The beams were repaired using 40 mm thick jacket along the three sides exposed to fire; whereas the jacketing in columns was applied on all four sides. The concrete core was modeled based on the reduced mechanical properties after being exposed to fire while the surrounding jacketing material was modeled considering the actual undamaged conditions. The current provisions recommended by different design codes require that the fire resistance for the repaired structure to be at least equal to the fire resistance of the undamaged one. Thus, the capacity of the repaired beams and columns was assessed for four conditions; namely: undamaged, fire damaged, repaired and repaired fire damaged. The corresponding moment-fire duration curves for beams and interaction diagrams for columns were presented for all conditions. The authors strongly recommend the use of HPFRC jacketing as a retrofitting technique for fire damaged members as it provides higher strength capacity compared to the undamaged members under the normal conditions and provide fire resistance that satisfies the current provisions when exposed again to similar fire scenarios.

Recently in 2012, Guo *et al.* proposed an analytical calculation method to evaluate the capacity of jacketed RC columns subjected to fire scenarios under eccentric loading conditions. The residual mechanical properties of both concrete and steel were calculated at different temperatures using any of the provided models in literature. Spalling and consequently potential reduction in cross-sectional area of the columns was ignored in the analysis. A reduction factor was then introduced by dividing the residual property by its original counterpart prior to fire exposure for each grid element within the cross-section. The strain and stress distributions resulting from the eccentric loading were obtained from sectional analysis of the proposed columns. The steel reinforcement ratio and bars cross-sectional area were chosen so as to eliminate failure of the original column prior to jacketing application. The interaction between the new concrete jacketing and the confined concrete core was determined by comparing the stress state in concrete jacketing to the tensile strength in steel reinforcement bars. The method suggested that columns failure can be modeled as transformed section with known stress-strain distribution assuming full bond between the new and old concrete.

4 Conclusions and Future Work

This paper highlighted the main research experimental and analytical works that were carried out towards the development of better understanding of concrete behavior when exposed to elevated temperatures. A discussion of the residual mechanical properties and stress-strain relationship of both concrete and steel reinforcement in addition to the interfacial behavior between them was first presented. The paper proceeded by discussing jacketing as an efficient strengthening and/or repair technique for enhancing the properties of different reinforced concrete members before and after being exposed to elevated temperatures and various fire scenarios. The results obtained from those researches revealed that with proper surface treatment and under well controlled conditions, the retrofitted members could regain their full or even more of their original strength provided that better concrete quality than the original one is used as a repair material.

The drawn conclusions from the presented research studies are milestones that enrich the literature with significant findings of jacketed fire damaged concrete members; however, further research is needed to fully describe the behavior of such elements. For instance, detailed investigations on the mechanical behavior of jacketed fire damaged beams, columns, slabs and connections need to be carried out both experimentally and numerically. Also, the performance of the repaired members should be investigated when exposed another fire scenario by conducting extensive experimental programs. In addition, the bond characteristics between the damaged concrete core and the new concrete cover need to be analyzed under various surface treatment conditions to provide accurate factors that can be used in other numerical research works.

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