STRUCTURAL FIRE PERFORMANCE OF FIBER REINFORCED POLYMER (FRP) STRENGTHENED HIGH STRENGTH CONCRETE BEAMS USING OPENSEES SOFTWARE

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DEDICATED

TO

MY BELOVED PARENTS AND WIFE

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ABSTRACT

Analysis of structures subjected to extreme static and dynamic loads (such as earthquake, impact, wind and snow) using finite-element software are common and extensively being used in construction industry. However, to study the structural response under fire conditions, highly tedious nature of modeling involving full (often coupled) hydro-thermal-mechanical properties as a function of time under realistic fire scenario is required. OpenSees (Open System for Earthquake Engineering Simulation) developed initially by McKenna (Buchanan 2002; McKenna et al. 2000; Mckenna 1997) at the university of California, Berkeley, USA, is an object-oriented software framework used to create finite element applications to simulate the response of structural systems subjected to an earthquake. OpenSees consists of wide variety of material models which can be customized to one's own material in its ever-growing library. A structural fire research group in School of Engineering, University of Edinburgh (Jiang and Usmani 2013) successfully conducted the research to add structures-in-fire modeling capability into the OpenSees framework by utilizing its well-designed software architecture. By adopting object-oriented programming paradigm, the software structure is consistent with that of the official OpenSees platform, which made it possible to reuse some of the existing components of software whereby introducing fire related components in it.

At present, the use of high-strength concrete (HSC) is becoming popular due to the improvements in structural performance such as high strength and durability that it can provide compared to conventional normal strength concrete (NSC) (Kodur and Dwaikat 2008). However, OpenSees analysis module lacks material properties of many concrete types such as high strength concrete (HSC) and fiber reinforced concrete (FRC). Thus, there is a dire need to incorporate such material properties in existing OpenSees software so that realistic analytical simulations can be performed in predicting the fire response of infrastructure made of a peculiar concrete.

In this research, material models based on mechanical and thermal properties of HSC (Kodur and Khaliq 2010) along with carbon fiber reinforced polymer (CFRP) (Ahmed and Kodur 2010) were added in OpenSees material library for thermal and structural analysis. OpenSees material library was updated for tracing the response of HSC beams strengthened with CFRP under realistic fire, loading and restraint conditions. All of the critical factors, namely; high-temperature material properties, axial restraint force, and different strain components that have a significant influence

on the fire behavior of HSC beams strengthened with CFRP were incorporated in the model. For validation of this modification, developed code was validated against previous available studies and data. The validated model was then applied to conduct a set of parametric studies to quantify the influence of various factors, such as fire scenario, load level, axial restraint and concrete strength; on the fire response of HSC beams strengthened with CFRP.

Results from parametric studies with OpenSees numerical simulations show that fire resistance of CFRP strengthened HSC beam is enhanced under design fire exposures. Different fire scenario has varying impact on fire performance of HSC beam strengthened with CFRP. Provision of insulation of CFRP can enhance the fire resistance of CFRP strengthened HSC beams. Higher load levels decrease time to reach failure state under fire exposure and thus affect fire performance. End boundary conditions also affect the fire performance, lower restraint forces lead to a lower fire resistance in CFRP strengthened HSC beams whereas lower compressive strength of concrete increases the fire performance.

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CHAPTER 1

INTRODUCTION

1.1 General

Concrete is the most common material used all over the world in all kind of weather in a wide range of applications like multi-storey buildings, road pavements, power stations and railway/highway bridges etc. Due to the versatility in application of concrete, it is preferred over all other materials used in construction. It is non-combustible and does not discharge any poisonous gasses, smoke or drip molten particles when exposed to fire. It has excellent fire resistance properties which are because of the concrete constituents (i.e cement and aggregates), when chemically bonded, forms a material that is essentially inert, has poor thermal conductivity and low strength loss properties. Due to this low heat of transfer and strength loss, it makes concrete to be an effective shield between adjacent spaces and also continue to perform load bearing under fire condition.

Over a period of time, a lot of research work has been done to improve the concrete properties. New types of concretes have come up known as high strength concrete (HSC), fiber reinforced concrete (FRC), high-performance concrete (HPC) and ultra high-performance concrete (UHPC). HSC is referred to concrete with higher strength, better workability and durability than NSC. With the passage of time, further research in concrete technology make it easier to obtain increasingly higher strength using innovations, resultantly, classification of HSC is also continuously changing. Generally, for classification of concrete if compressive strength is less than 70 MPa (10 ksi) then it is termed as NSC otherwise HSC (Bilodeau et al. 2004).

Just like all other structural members, the concrete structure must be designed to meet the required safety standards. In order to enhance the safety of users, control the spread of fire and minimize the damage of the building, there is a requirement for provision of safety measures.

1.2 Fire hazards in Pakistan

Despite of invention of very sophisticated and delicate fire alarm and firefighting measures, the fire incidents are on increase and cause loss to human lives and properties. As per Rescue 1122 official website (Rescue 1122, 2016) more than 85,000 fire cases have been reported in last 10 years in Punjab Province only. This number indicates that on average 25 structures catch fire in a day in Punjab only and many other minor cases go unreported as well. These fires cause not only loss of many precious lives but damage to property as well. Fire cases may be because of multiple reasons including faulty electric connections, flammable/combustible materials, human error/negligence and arson. Pakistan being a developing country has just adopted a National Fire Safety Policy to regulate any untoward situation related to fire in 2017. These fire incidents in Pakistan are causing an average death of 16,500 people and causing injuries or disabled 164,000 every year. It leads to property loss and insurance claims of worth Rs 400 Billion. The urban areas, including Islamabad, Rawalpindi, Lahore and Karachi are witnessing many fire incidents but the basic factors mostly remain unknown or usually named as short-circuiting. The country witnessed the worst fire incident in Baldia Town Factory Karachi in Sep 2012 that claimed around 300 lives. In addition to this, many incidents occurred in the Federal Capital of Pakistan Islamabad which experienced fire incidents at Marriott Hotel, UBL Building, Shaheed-e-Millat building and commercial plazas.

A lot of research has been carried out for improvement of fire safety design in last century. Active fire safety systems are being introduced by focusing on reducing the life loss. These active fire safety systems are generally self-triggered in the case of fire in the building. In 1913, the death rate due to fire in the United States was 9.1% per 100,000 people. However, the use of fire-resistant material and the improvements in design (including smoke detectors) reduced that rate to 2% per 100,000 people in 1988 (Williams 2005). Generally, the major cause of most fatalities and injuries is toxic smoke evolving during a fire event. However, some of these deaths and injuries, particularly among first responders, were due to structural collapse/damage under fire conditions (Fahy et al. 2008).

1.3 Concrete structure under fire

Reinforced concrete has been widely used as a construction material during the last century. The superior characteristics of reinforced concrete and the increasing need for construction has led to the mass consumption of concrete in infrastructure; however the continuation of this trend of production and consumption of concrete needs to be considered attentively. One factor out of many other factors is its fire safety. This fire safety is to provide sufficient warning time to the occupants without collapsing or failure so that they can move to a safer distance. For fire safety of structure, there is a requirement to design its members (beam, column and slabs etc) in a way to with stand at against fire induced elevated temperatures.

1.4 Reinforced concrete (RC) beams under fire hazard

With the increase in temperature due to fire, the temperature of concrete and beam starts increasing. This causes degradation in the constituent materials and reduction in beam strength and stiffness. With the passage of fire exposure time, beam mid-span deflection starts increasing due to the reduction in the beam stiffness. Creep due to high-temperature creeps also becomes significant especially at later stages of the fire exposure. When deflection, stresses, and loading applied reaches the beam nominal capacity, the beam is considered to have failed. Fire resistance of the beam is time duration from the start of fire exposure to the failure. With the degradation of strength and stiffness, fire-induced spalling also occurs. It is caused by pore pressure in the concrete of the beam. The applied loads on the beam also have the effect on the fire resistance. Higher load levels decrease time to reach failure state under fire exposure and decrease fire performance.

1.5 Behavior of fiber reinforced polymer (FRP) RC beams under fire

RC beam can be further strengthened in bending usually by application of thin layers of FRP sheets on tension face (beam soffit). Beam shear strength is improved by applying FRP on both sides of the beam. This technique has wider acceptance than the use of steel plates and external post-tensioning techniques due to ease of application. Application of FRP sheets on beam soffit can considerably improve the flexural capacity of a retrofitted beam. When exposed to fire, FRP-strengthened RC beams behave differently from that at ambient temperature since beam stiffness and strength (including FRP) keeps on degrading with respect to rising temperature. The loss in beam stiffness and strength properties causes the decrease in load carrying capacity. Beam failure occurs when moments and stresses induced deflection because of the loading applied increases, thus decreasing RC beam bending capacity. Factors affecting the fire behavior of an FRP-strengthened concrete beam depend on:-

- Type of loading
- Fire exposure loading type

- Beam end restraint conditions
- High-temperature properties of constitutive materials

Generally, FRP-strengthened RC beams experience higher stresses when compared with a beam that is without FRP since the load level on a strengthened beam is relatively higher. The higher stress level in the beam can lead to early strength failure in case of no fire protection since FRP starts to burn in the first 10-15 minutes. So, application of insulation on external surfaces is critical to achieving reasonable fire resistance in FRP-strengthened beams (Williams et al. 2006). There is very little information on the required level of insulation under realistic fire, loading, and restraint levels. Flexural strengthening of beams is bond-critical application in which FRP is attached to the tension surface of the beam using polymer adhesive. At very high temperatures, concrete and FRP bond is a critical aspect that disturbs the behavior of beam strengthened with FRP. In most of the previous studies, a perfect bond was assumed at the face of FRP and concrete up to the glass transition temperature of the adhesive and thereafter, the bond was assumed to be completely lost. The bond degradation is gradual during start of fire exposure (lower temperature increase at interface) and its properties drop significantly in the region of polymers T_g. However, unidirectional FRP continue to be structurally effective (contribute to strength capacity) at temperatures above T_g. Therefore, for a realistic assessment of fire performance of strengthened members, degradation in bond with temperature has to be taken care of. Capturing degradation of bond due to raised temperature in full scale fire tests is not easy due to lack of instrumentation (strain gauges) that can survive rapid rising high temperatures. However, numerical models can be effectively used to predict bond degradation, provided bond properties at high temperature are known. Axial restraining force can influence the fire response of a strengthened beam. Numerous studies have been conducted to trace the response of FRP-RC members at ambient conditions.

These studies addressed overall structural response of FRP-strengthened members (Kodur and Ahmed 2010; Kodur et al. 2006; Williams et al. 2008), creep and fatigue effects (Scott et al. 1995; Zhang et al. 2004), and factors contributing to durability enhancement (Green et al. 2000; Waldron et al. 2001).

1.7 What is OpenSees

OpenSees is full form of Open System for Earthquake Engineering and Simulations, a powerful program written in object oriented language C++. It is a software framework for simulating the seismic response of structural and geotechnical systems. OpenSees was originally developed by Frank McKenna (McKenna et al. 2000) at University of California Berkeley. OpenSees is not a code, it's a robust tool which can perform nonlinear incremental dynamic analysis and performance based design with less effort and time because of the coding loops that can be made. The software is designed for parallel computing to allow scalable simulations on high-end computers or for parameter studies. OpenSees is providing beam-column elements and continuum elements for structural and geotechnical models. A wide range of uniaxial materials and section models are available for beam-columns.

OpenSees consists of wide variety of material models which can be customized to one's own material in its ever-growing library. A structural fire research group in School of Engineering, University of Edinburgh (Jiang and Usmani 2013) successfully conducted the research to add structures-in-fire modeling capability into the OpenSees framework by utilizing its well-designed software architecture. By adopting object-oriented programming paradigm, the software structure is consistent with that of the official OpenSees platform, which made it possible to reuse some of the existing components of software whereby introducing fire related components in it.

As part of this research, it is proposed to undertake studies to develop an understanding of the behavior of HSC beam strengthened with FRP under realistic fire and loading conditions.

1.8 Aims and objectives

It is clear that there have been very less research work and lack of knowledge about OpenSees use in the structural behavior of beam strengthened with FRP under fire. This numerical study examines the implications of high temperature thermal susceptibility on currently used FRP materials in civil engineering applications and on structural behavior of FRP-strengthened RC beams. To achieve this objective, extensive literature review followed by development of numerical model and parametric studies on HSC beam strengthened with FRP have been conducted. Specific objectives of this research are:

- Incorporate thermal and mechanical properties in the existing material library of OpenSees.
- Incorporate CFRP properties into the existing material library of OpenSees
- Conduct fire analysis of HSC using newly incorporated various concrete materials in OpenSees
- Compare the effectiveness of use of CFRP in case of fire

1.9 Organization of thesis

The work presented in this thesis involves study of OpenSees software, incorporation of new material properties into existing material library and full scale fire analysis. As part of analysis, RC beam strengthened with FRPs and one control RC beam were analyzed under applied loads to evaluate fire response. For analysis of RC beam strengthened with FRP, OpenSees material library was updated. The software was validated by using the test data available in the literature. The validated software was then applied to undertake parametric studies to quantify influence of various factors on fire response of FRP-strengthened RC beams. The thesis is organized into five chapters.

Chapter 1 introduces about the thesis work, chapter 2 presents extensive review of the literature related thermal and mechanical properties of HSC and FRP as material and as a component of a structural member. Detailed discussion on elevated temperature properties related to steel, concrete and FRP along with insulation is presented. The chapter also includes summary of experimental and numerical modeling work that has been performed previously on NSC beam strengthened with FRP. Chapter 3 deals with study of OpenSees software and its validation, where predictions from the model are compared with the test data from literature, as well as with data obtained from tests conducted as part of this research.

Chapter 4 covers fire analysis of NSC beam strengthened with FRP and discusses results of parametric studies undertaken to quantify influence of various factors on fire performance of FRP-strengthened RC beams. Chapter 5 provides conclusions based on this thesis and recommendations for future work. An appendixes is included that provides detailed information not presented in the main body of the text.

CHAPTER 2

LITERATURE REVIEW

2.1 General

This chapter provides the review of literature about fire vulnerability and methods developed with passage of time in order to deal with fire analysis. Concrete generally exhibits good fire resistance properties and thus finds wide applications in buildings and other built infrastructure, where fire safety is one of the primary considerations. However, recent studies show that structural members made of new concrete types (HSC, SCC and FAC) known as HPC, may not have same level of fire resistance like conventional concrete (NSC) (Bamonte et al. 2010; Dwaikat and Kodur 2009). Typically, new types of HPC have lots of applications in members of building because of the advantage of higher strength which is utilized to reduce size (cross-section) of beams/columns. The fire resistance of concrete structural members is governed by high temperature thermal and mechanical properties of constituent concrete. For predicting fire resistance of concrete structural members, knowledge of high temperature material properties is very critical which includes thermal, mechanical and deformation properties. In addition to that, fire induced spalling might significantly influence the fire resistance of HSC, therefore properties related to spalling are also important and should be known (Khaliq and Kodur 2011).

FRP materials were originally developed in early 1960's and 70's by aerospace and defense industries for specific applications such as aircrafts, ships and military hardware's. Therefore, significant information is available on FRP properties at room temperature (Davies et al. 2006). In the last three decades, FRP is being used for wide ranging application to civil infrastructure. Due to ease of its application, cost effectiveness and efficient performance, FRP is frequently used for retrofitting and strengthening of concrete structures. These unique properties of FRP are widely used in strengthening and retrofitting techniques widely utilize externally bonded composites (Bakis et al. 2002). At initial stages of FRP applications, FRP was used in RC column confinements and beam / bridge girders flexural strengthening. Now a day, different structural element like columns, beams, slabs, shear walls, domes and trusses are strengthened using FRP.

2.2 Effects of fire on structures

The common viewpoint regarding fire is that it occurs in a room or an enclosed section of the building which are known as compartment fires. If a fire ignites in a compartment due to any reason, it will expand by burning the fuel available in the room. If sufficient combustible materials exist; temperatures will rise especially in the upper air layers in the room. If the temperature is high enough, the ambient heat flux reaches a critical level where all combustible items in the compartment will begin to burn. This leads to a sharp rise in both heat release rate and temperature. This transition is called “flashover” and the fire is called “post flashover fire” or a “fully developed fire” (Buchanan 2002).

The behavior of the fire will be less predictable in rooms which have large floor areas, high ceilings or irregular arrangement of fuel or openings. Maximum temperature of a post-flashover fire will rarely exceed 1000ºC (Alfawakhiri et al. 2002), while in the case of not fully developed fires the temperature will not exceed 550 °C. The elevated temperature during the fire is the major factor affecting the safety and performance of the structure.

Simulation of temperatures in a realistic fire is very complicated due to the multiplicity of variables involved. Design codes and standards, however, use standard fire tests to measure the performance of the structural members in fire. Although they may not represent a real fire incident, standard fire tests could be used to assess and compare the level of performance of structural members in fire. An actual fire will have a slower growth phase and will experience temperature fluctuations, thus the standard temperature-time curve is somewhat conservative because it corresponds to a severe fire, but not the severest possible fire event (Khoury 2000).

2.3 Material behavior at high temperatures

Fairly adequate information is available about the behavior of concrete and steel at high temperatures; while there is limited data on behavior of FRP, insulation and adhesive.

2.3.1 Concrete

Rise in temperature affects the stress strain behavior of concrete. Experimental results reported by (Schneider 1988) for concrete in uniaxial compression at different temperatures are plotted in Figure 2-1. It could be observed from the diagram that a rise in temperature results in a degradation of compressive strength and stiffness of the concrete. Meanwhile the increase in temperature affects the ductility of the concrete.

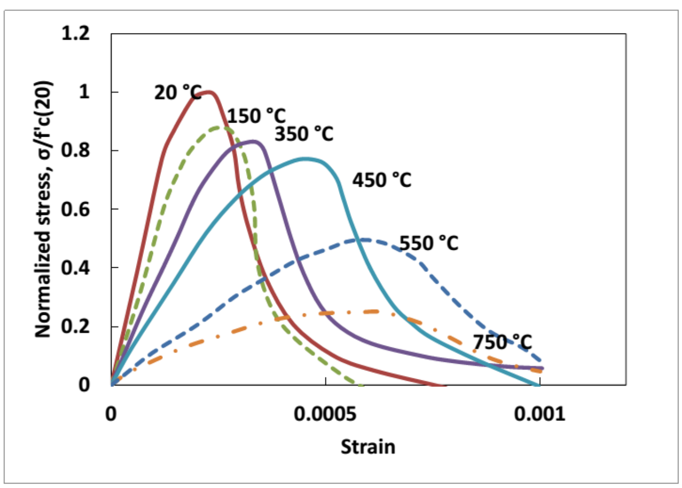


Fig. 2.1 Stress-strain relationship for NSC derived in strain – rate controlled tests (Singh et al. 1988).

Concrete response to uniaxial loading at high temperature is dependent on many factors like aggregate type, water content etc. and concrete response is also dependent on the applied compressive stress during heating (Ehm and Schneider 1985) or in other words the loading history has an effect in behavior of the concrete. To account for this phenomenon, an additional strain component is defined in heated concrete. This strain is called "transient creep strain" or "transient strain" or "load induced thermal strain (LITS)".

2.3.2 Steel

A glance at literature suggests that models for yield and ultimate strength of steel vary considerably because these properties depend on steel composition and the definition of yield strength (Buchanan 2002). Curves for the stress-strain relation of mild steel at various temperatures are shown in Figure 2-2. It can be seen that the yield strength decreases with temperature and there is a yield plateau at lower temperatures which disappears at higher temperatures. Considering the residual strength of the reinforcing steel, the reinforcing steel recovers most of its original yield strength after cooling when the maximum strength experienced by it remains below 500°C (Neves et al. 1996). The percentage of strength and modulus recovery depends on the highest temperature experienced by reinforcing steel. When steel is subjected to temperatures above 500°C a gradual decrease in residual strength is observed. Extensive research has been performed to evaluate the performance of structural steel at fire. In general, at approximately 1000 °F (538 °C), steel loses approximately 50 % of its room-temperature strength and modulus of elasticity, see Figure 2-3.

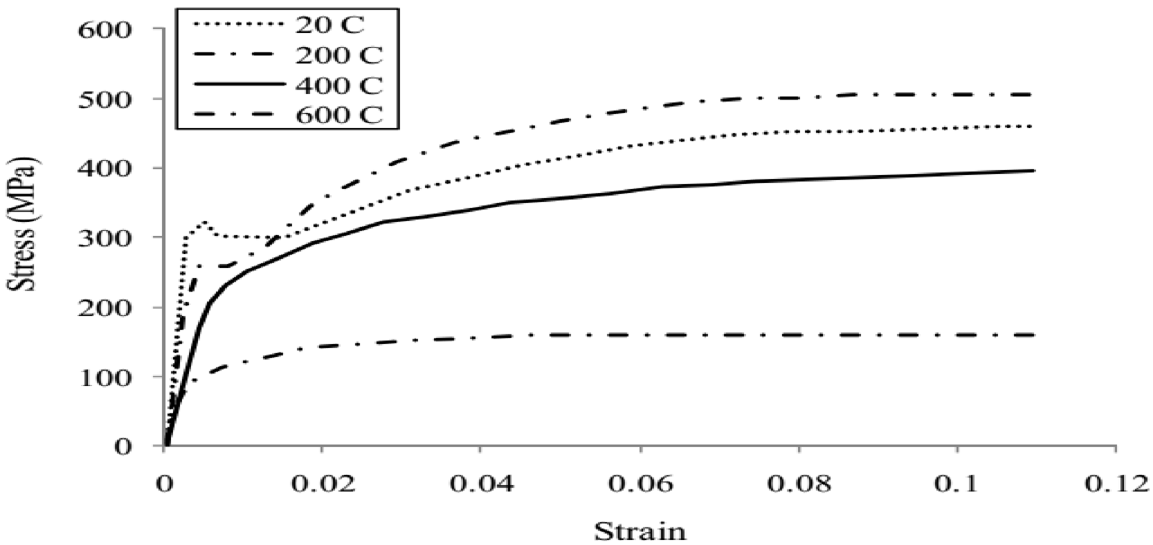


Fig. 2.2 Stress-strain curves for steel (fy = 300 MPa) at different temperatures (Lie 1992)

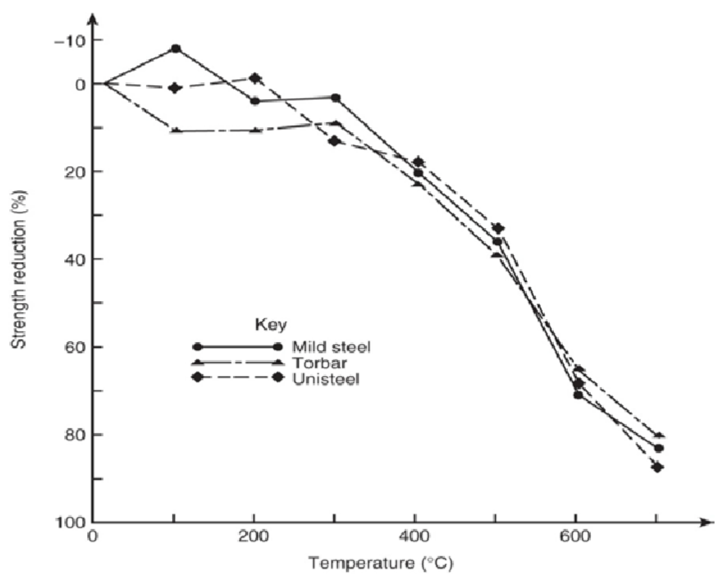


Fig. 2.3 Variation of strength of reinforcement steel (Holmes et al. 1982)

2.3.3 FRP

Thermal and mechanical properties of FRPs are dependent on the properties of their constituents i.e. fiber and matrix. Volume fraction of fibers and matrix also influences the behavior of the FRPs (Sorathia et al. 1992). Glass and carbon FRPs generally produce less smoke than aramid fiber.

Fiber type also considerably influences thermal conductivity of FRPs. Carbon FRPs have higher thermal conductivity than glass and aramid FRPs. Studies show that carbon fibers experience little to no change in their tensile strength up 1000 °C (Rostasy et al. 1992), and they have better performance at high temperatures than steel. Glass fibers lose almost 50% of their original tensile strength at 550°C (Dimitrienko 1999) and (Sen et al. 1993), which is similar to steel behavior at high temperatures. FRP on the other hand loses most of its strength when the temperature reaches the glass transition temperature (Tg) of its adhesive/matrix. At this temperature, the resin softens and the resin will no longer be as effective in transferring stresses between fibers. As far as fire behavior of FRP is concerned, glass transition temperature is the most important property of any FRP.

2.4 Fire performance of FRP strengthened beam

There are lots of studies in literature concerning the fire behavior of externally FRP strengthened beams.

- There has been observed an increase of about 160% in beam capacity (Meier and Kaiser 1991), however, due to ductility and serviceability constraints, maximum increase limits to 40%. Typical response is shown in fig 2-4
- (Deuring 1994) tested six beams (300mm by 400mm by 5m) where four of them were strengthened with CFRP sheets and were subjected to sustained loading. Insulated beams showed satisfactory fire endurance in the tests. The uninsulated beams had a fire endurance of 81minutes while the insulated beams gave an endurance of 146 minutes. Interestingly the endurance of insulated CFRP plated beam was larger than that of the un-strengthened RC beam.

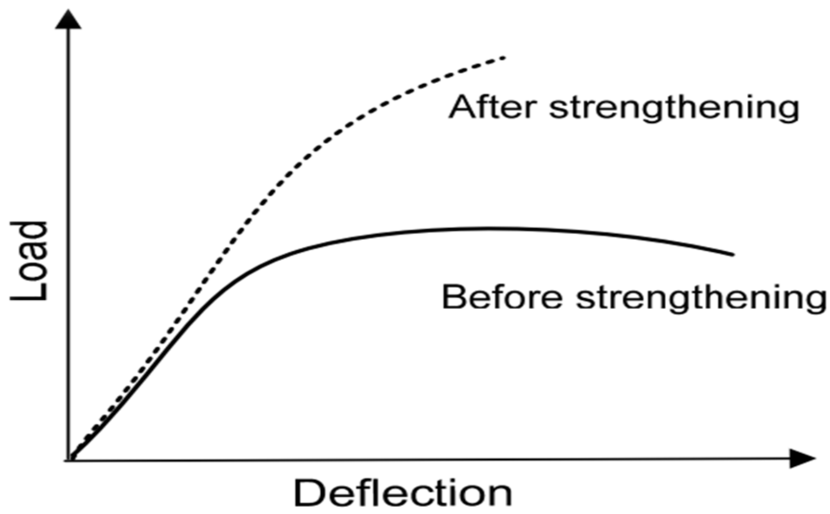


Fig. 2.4 Typical response (load-deflection curve) of FRP-strengthened and un-strengthened (control) RC Beam

- (Blontrock et al. 2000) tested CFRP plated beams using multiple insulation schemes. During the experiments once the temperature of FRP reached Tg, the load bearing contribution of FRP was significantly reduced. Overall the fire endurance observed in the tests was not sufficient.
- (Chowdhury 2005) tested full scale insulated T-beams and intermediate scale slabs. Beams were subjected to sustained load but slabs were tested without loading (Williams, Kodur et al. 2008). Length of the beams was 3.81m and the web and flange width were 1220 and 300 mm respectively. Beam depth was 400mm. Dimensions of the intermediate slabs were 954 by 1331mm. They concluded that beams and slabs with sufficient insulation could achieve fire endurances of more than 4 hours.

- (Stratford et al. 2009) studied the performance of bonded FRP strengthening in real compartment fire (the Dalmarnock Fire Tests). They applied near surface mounted and externally bonded FRPs. They also used intumescent coating and gypsum boards as insulation materials. They concluded that FRP reinforcements are vulnerable during a real compartment fire.
- (Palmieri et al. 2011) performed fire tests on six near surface mounted FRP strengthened concrete beams with different insulation systems. They achieved 2-hour fire endurance in their experiments.

2.5 Insulation Techniques

Fire proofing is essential for structural elements with low fire resistance. This could be done by applying a coating of fire suppressing materials or materials with low thermal conductivity. The insulation materials could be applied as pre-made boards or they could be sprayed on the structural member. Different types of fire proofing are available. Performance of a number of common insulating materials will be discussed below.

2.5.1 Concrete

Concrete among construction material is a good insulator however the use of concrete as insulation has been reduced recently while lighter and more cost effective insulation techniques are prevalent. Concrete encasing is time consuming and adds considerable weight to the member. Another problem could be the possibility of explosive spalling. Despite disadvantages concrete is durable and resistant to impact, abrasions, and weather exposure.

2.5.2 Sprayed Insulation

There are two major types of spray applied insulation materials, cementitious and mineral fiber. The mineral-fiber mixture combines fibers, mineral binders, air and water. In its final cured form, the mineral-fiber coating is lightweight, non-combustible, chemically inert and a poor conductor of heat. Cementitious coating usually incorporates lightweight aggregates, like vermiculite, in a heat-absorbing matrix of gypsum or Portland cement. Some formulations also use magnesium oxysulfate, magnesium oxychloride or calcium aluminate (Gewain et al. 2003). The sprayed insulation is cost effective compared to most other systems.

2.5.3 Board insulation systems

Gypsum boards are considered the most common type of fire protection boards. Their fire resistance greatly relies on the chemically-combined water, which is approximately one fifth of the weight of the boards. When the board system is exposed to fire, the water gradually evaporates in a process that consumes heat, and thus keeps the temperature of the protected structural element relatively low. When all the water evaporates, the temperature of the structural element starts to increase slowly based on the thermal conductivity of the dry gypsum boards. Less common types of boards include vermiculite boards. Vermiculite boards are made by pressing vermiculite particles into board form. These boards can withstand thermal shocks and temperatures up to 1100°C.

2.5.4 Intumescent coating

Intumescent coating is a paint-like material. When exposed to high temperature (200 to 250 ºC) it swells and produces a charred layer with very low conductivity. Despite its low conductivity intumescent coating usually provides limited fire resistance of 1 hour or less. In the charring process a series of decomposition reactions happens. Initially the inorganic salt in the presence of an amide is decomposed. Following this, the carbonific agent is decomposed which produces a large amount of char. Eventually the char expands due to temperature as the blowing agent starts to expand. The final result of these reactions is a solidified material with a very low thermal conductivity.

2.6 Previous studies on OpenSees

OpenSees (Open System for Earthquake Engineering Simulation) developed initially by McKenna (McKenna et al. 2000; Mckenna 1997) at university of California, Berkeley, USA, is an object-oriented software framework used to create finite element applications to simulate the response of structural systems subjected to an earthquake. OpenSees consists of wide variety of material models which can be customized to one's own material in its ever-growing library. A structural fire research group in School of Engineering, University of Edinburgh (Jiang and Usmani 2013) successfully conducted the research to add structures-in-fire modelling capability into the OpenSees framework by utilizing its well-designed software architecture. By adopting object-oriented programming paradigm, the software structure is consistent with that of official OpenSees platform, which made it possible to reuse some of the existing components of software whereby introducing fire related components in it.

2.7 Summary

Literature review carried out in this chapter shows that

- Simulation of temperatures in a realistic fire is very complicated due to the multiplicity of variables involved. Design codes and standards, however, use standard fire tests to measure the performance of the structural members in fire.

- Fairly adequate information is available about the behavior of concrete and steel at high temperatures; while there is limited data on behavior of FRP, insulation and adhesive.
- There are very few studies in literature concerning the fire behavior of externally FRP strengthened beams.
- Fire proofing is essential for structural elements with low fire resistance. This could be done by applying a coating of fire suppressing materials or materials with low thermal conductivity.
- OpenSees (Open System for Earthquake Engineering Simulation) is an object-oriented software framework used to create finite element applications to simulate the response of structural systems subjected to an earthquake. However, software framework has been extended to carry out thermal analysis of by adding thermal classes in its material library.

CHAPTER 3

COMPUTATIONAL MODELING OF STRUCTURES IN OPENSEES AND ITS VALIDATION

3.1 General

Analysis of structures subjected to extreme static and dynamic loads (such as earthquake, impact, snow and wind) using finite-element software are common and extensively being used in construction industry. However, to study the structure response of fire, very complex nature of modelling of a realistic fire scenario, heat transfer to structure and structural response is required.

OpenSees is full form of Open System for Earthquake Engineering and Simulations, a powerful program written in object oriented language C++. It was initially developed by Frank McKenna (McKenna et al. 2000; Mckenna 1997) at university of California, Berkeley, USA. It is an object-oriented software framework used to create finite element applications to simulate the response of structural systems subjected to an earthquake. OpenSees consists of wide variety of material models which can be customized to one's own material in its ever-growing library. A structural fire research group in School of Engineering, University of Edinburgh (Jiang and Usmani 2013) successfully conducted the research to add structures-in-fire modelling capability into the OpenSees framework by utilizing its well-designed software architecture. By adopting object-oriented programming paradigm, the software structure is consistent with that of official OpenSees platform, which made it possible to reuse some of the existing components of software whereby introducing fire related components in it.

OpenSees is not a code, it's a robust tool which can perform nonlinear incremental dynamic analysis and performance based design with less effort and time because of the coding loops that can be made.

3.2 Why OpenSees

It consists of wide variety of material models and one can also customized one's own material, and its ever growing library. It has numerous options to define the element from elastic to non-linear, from lumped plasticity to concentrated plasticity and from force based to displacement based. Intricate linear or nonlinear structural and geotechnical modeling can be done. It is very robust tool for simulations capable of performing static pushover; static reversed cyclic, dynamic time history analysis, and uniform support excitation, multi support excitation and incremental dynamic analysis.

Structural response to real fires is very complex in nature and it becomes very difficult to carry out analysis using commercial software. OpenSees has the capability to link with computational fluid dynamic (CFD) packages to model the whole problem. It can solve multi-hazard modelling situation like fire followed by earthquake. OpenSees is also developing an international community of researchers and collaborators around one common computational tool.

3.3 Research methodology

OpenSees software is a robust tool for extreme static and dynamic load analysis. However, it lacked thermal analysis capability which was required to be incorporated. A group of researchers (Jiang and Usmani 2013) at university of Edinburg added two material classes which are

- Steel01Thermal
- Concrete02Thermal

This team incorporated mechanical and thermal material properties of NSC in OpenSees material library. In this research, modification in material library has been carried out by adding HSC mechanical and thermal properties. Theses HSC thermal and mechanical properties were taken from previous research works (Khaliq and Kodur 2011). After modification in the material library, this was validated by comparing the results with existing results (Ahmed and Kodur 2010).

After validation of modified material library, a beam was modelled in OpenSees of most common used dimensions and criteria. This beam was externally wrapped with FRP on tension face with use of adhesives. This beam was analyzed by OpenSees with variables conditions which we encounter in our daily life. At the end, this analysis has been discussed in details.

3.4 Modification in material library

Existing layout of OpenSees material class hierarchy after modification by group of researchers from university of Edinburgh is as under:-

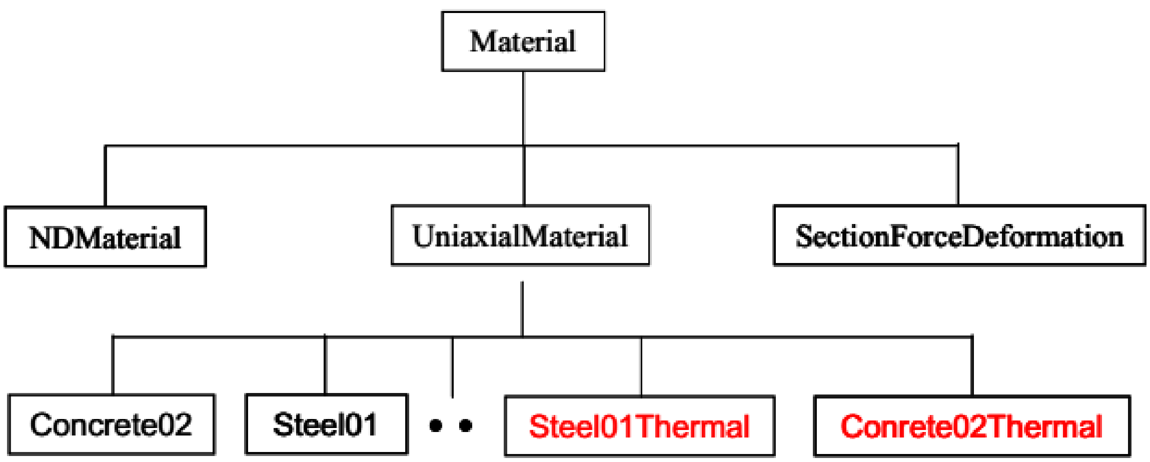


Fig. 3.1. Existing material class in OpenSees by (Jiang and Usmani 2013)

OpenSees material library has multidimensional materials, Uniaxial Materials and Section Force Deformation components. In Uniaxial materials, it already had concrete and steel material properties for earthquake analysis; however, it was not having capability of thermal analysis. In 2013, few developments works at university of Edinburgh were carried out. Team added two material classes to incorporate thermal capability.

- Steel01Thermal
- Concrete02Thermal

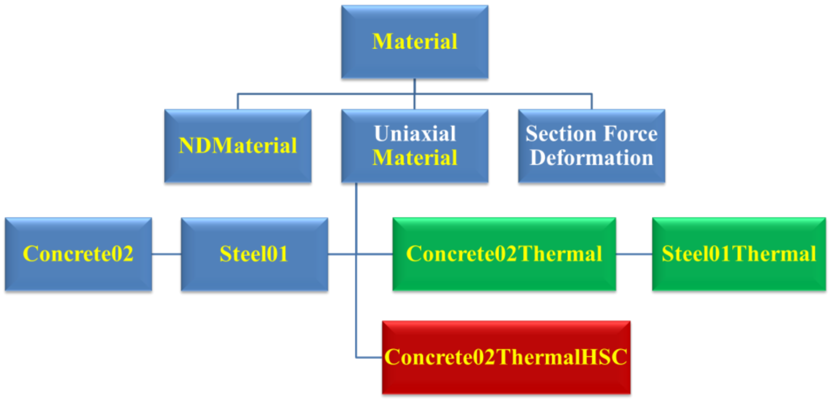


Fig. 3.2. Modified material class in OpenSees

In this work, another material class was added <concrete02thermalHSC> properties to add HSC thermal capability in OpenSees as shown in fig 3.2.

During this modification, Over 13,000 files were downloaded through subversion, these files are all linked with each other because when the software runs, it checks the compatibility of all the files and ensures that there is no buck or changing exist in the files.

Linkages were understood and the code that how it interacts with in the files and how it reads the properties and formulae from the files.

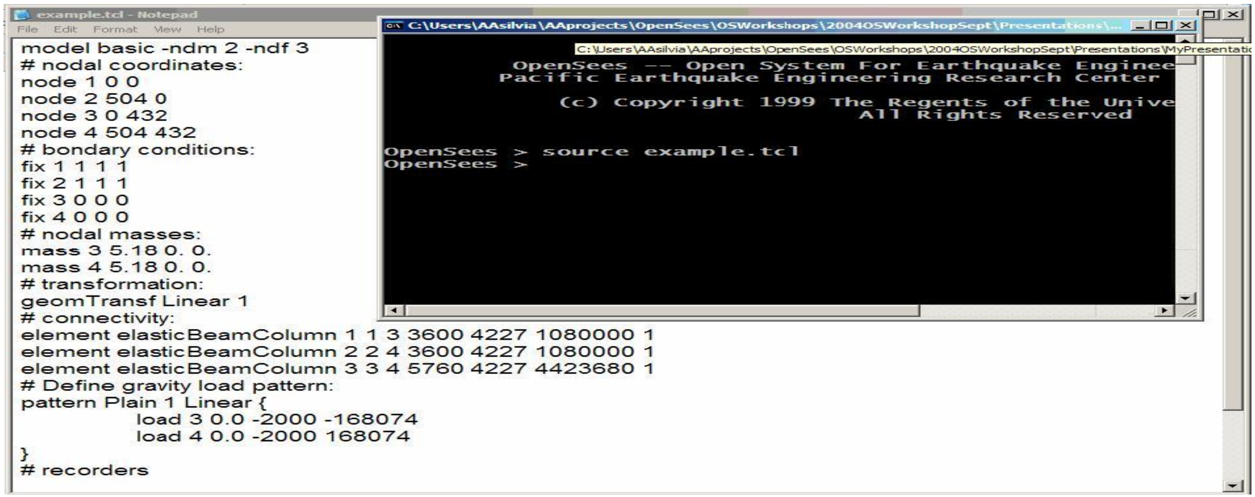


Fig. 3.3. Downloading of files through subversion

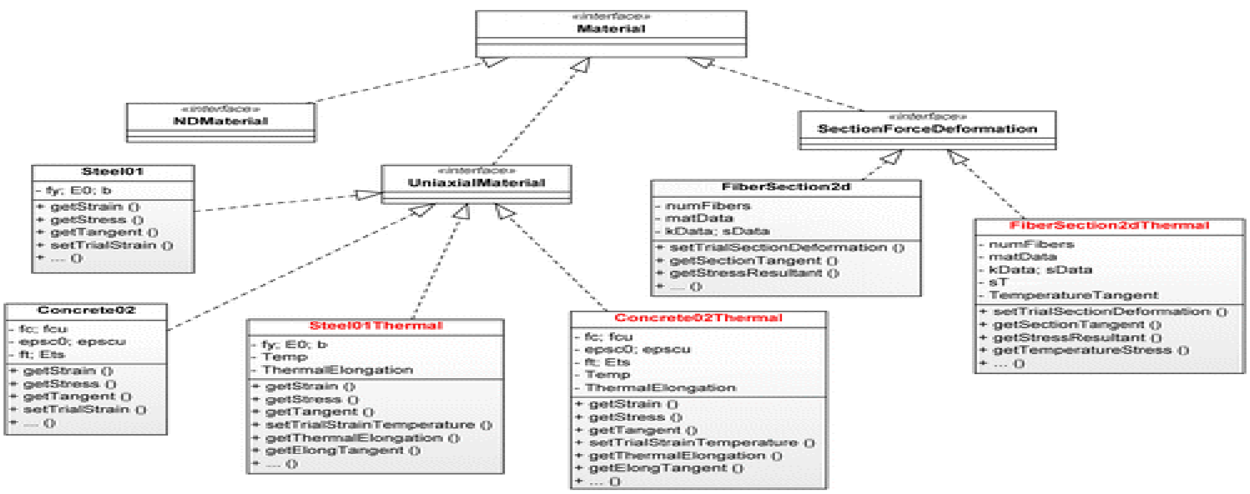


Fig. 3.4. Linkages in between the material classes, section classes and element classes

There are few other sets of files like section classes and element classes which are also modified accordingly to be able to incorporate the properties modified in concrete02thermal material. After understanding the code, modified the code of concrete02thermal material into concrete02thermalHSC, in this few of the properties modified are shown here.

3.4.1 Thermal properties

The relations of thermal property are proffered with respect to different temperature ranges in Table 3.1.

Table 1.1 Relationship of thermal properties with respect to different temperature ranges (Khaliq and Kodur 2011)

Property	Concrete type	Relation
Thermal conductivity (W/m-°C)	HSC	k_t = 3.12-0:0045T 20°C≤T≤400°C 3-0:0025T 400°C≤T≤800°C
Specific heat (MJ/m^3-°C)	HSC	cp = 2.4 + 0.001T 20°C≤T≤400°C 0.6-0.006T 400°C≤T≤800°C
Thermal expansion (%)	HSC	εth = 0 20°C -0.1 + 0.0015T 20°CbT≤800°C
Compressive strength	HSC	βT , compression = 1.0 20°C 0.99-0.002T 100°C≤Tb200°C 0.73-0.0005T 200°C≤T≤800°C
Splitting tensile strength	HSC	βT , tensile = 1.0 20∘C 0.99-0.001T 100°C≤T≤800°C
Elastic modulus	HSC	βT , modulus = 1.0 20°C 0.84-0.001T 100°C≤T≤800°C
Thermal conductivity (W/m-°C)	HSC	k_t = 3.12-0:0045T 20°C≤T≤400°C 3-0:0025T 400°C≤T≤800°C

3.4.2 Mechanical properties

Due to least difference in variation in elevated temperature compressive strength of SCC, single representative relation is presented for f_c',T. However, because of significant difference in variation of high temperature splitting tensile strength and elastic modulus, separate relationships are presented for SCC.

$\beta_{T,compressive}$ = f'_c,T / f'_c

$\beta_{T,tensile}$ = f'_t,T / E_c

$\beta_{T,modulus}$ = E_c,T / f'_c

Table 3.2 Reduction factor (βT) of compressive strength, tensile strength and elastic modulus with respect to different temperatures of SCC

Temperature °C	**Reduction factor (βT)**		
	Compressive strength SCC	Tensile strength	Elastic modulus
20	1	1	1
100	0.79	0.95	0.74
200	0.59	0.9	0.64
300	0.56	0.8	0.54
400	0.53	0.7	0.44
600	0.43	0.5	0.34
800	0.33	0.3	0.04

Conventionally, concrete tensile strength should usually be ignored. The tensile strength reduction $f_{ct,T}$ of a concrete at high temperature is defined by the reduction factor

$k_{ct}=f_{ct,T}/f_{ct}$, it is stated as

For 20°C ≤ T ≤ 100°C

$$k_{ct} = 1$$

For 100°C < T ≤ 600°C

$$k_{ct} = 1 - \frac{T - 100}{500}$$

The concrete thermal elongation strain ε_{cth} can be found as follows:

Siliceous aggregates:

For $20^oC \leq T \leq 700°C$:

$$\varepsilon_{cth} = -1.8x10^{-4} + 9x10^{-6}T + 2.3x10^{-11}T^3$$

For $700^oC < T \leq 1200°C$:

$$\varepsilon_{cth} = 1.4x10^{-2}$$

Calcareous aggregates:

For $20^oC \leq T \leq 805^oC$:

$$\varepsilon_{cth} = -1.2x10^{-4} + 6x10^{-6}T + 1.4x10^{-11}T^3$$

For $805^oC < T \leq 1200^oC$:

$$\varepsilon_{cth} = 1.2x10^{-2}$$

3.5 Testing of developed codes in OpenSees

The key features of structures in fire are presented first followed by the analytical solutions of the deflection and reaction force of an individual beam subjected to different boundary and thermal load conditions. These analytical solutions are derived to judge the performance of the developed OpenSees when temperature independent linear elastic material is used. In the developed OpenSees is used to analyze the behavior of a single beam under fire conditions. These cases include a fully restrained beam partly subjected to a uniform temperature increase, a single beam with finite translational and rotational end restraint subjected to uniform distributed load and a thermal gradient through the section depth. In these cases a temperature dependent elastic material is used and the OpenSees results are compared with the examples given in the already studies carried out.

In this work HSC has been incorporated with and without fibers into the existing material library of OpenSees. The method used to incorporate the new material (HSC) is attached as Appendix B. The amended Code used for HSC is attached as Appendix A.

Geometric properties of cross section used in validation of the incorporated material is shown in Table 3.3 and the drawing is shown in Fig. 3.23. The comparison of beam deflection under temperature loading is shown in Fig. 3.24. Result shows the complete conformity with the practical example.

Table 3.4. Geometric properties of cross section applied in testing

Property		**Nomenclature / Dimension**
Cross section (mm)		400 x 600
Length (m)		5 m
Reinforcement	Top bars (# 5 grade 60 bars)	2 x 15.8 mm
	Bottom bars (# 8 grade 60 bars)	4 x 25 mm
f'_c (N/mm^2)		90 MPa
f'_y (N/mm^2)		414 (Grade 60)
Applied total load (kN/m)		60
Bottom concrete cover thickness (mm)		50
Top concrete cover		40
Support condition		SS
Fire type		ASTM E119

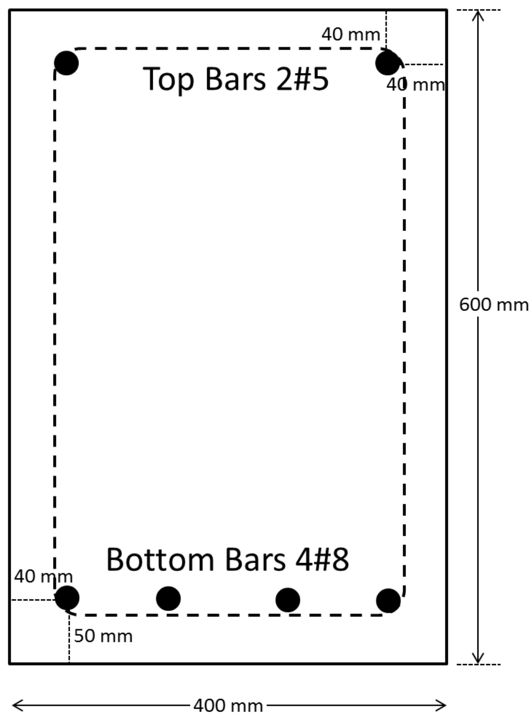


Fig. 3.23 cross section of validation beam

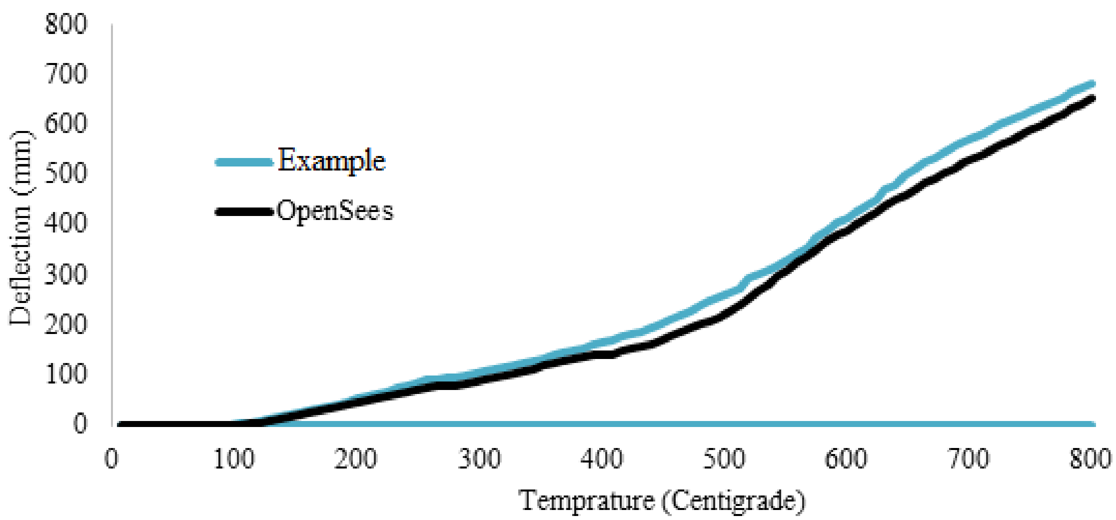


Fig. 3.5 Validation of newly incorporated material class in OpenSees

CHAPTER 4

ANALYSIS AND RESULTS

4.1 Introduction

The previous studies indicate that fire response of FRP strengthened HSC beam is complex in nature. There are number of factors which influence the fire behavior of FRP strengthened HSC beam. Many of these factors and their effects are interlinked as well. Out of all these factors have been analyzed in this work, which are the effect of FRP, different fire scenarios, concrete strength and load level.

4.2 Analysis details

4.2.1 Significant factors

The literature review clearly specifies that the fire resistance performance of FRP-strengthened beams is influenced by many aspects and many of these aspects are associated with each other. It was shown through qualitative parametric studies (Ahmed and Kodur 2010) that RC beam strengthened with FRPs fire response is affected by the main factors which are:-

- Fire scenario
- Load level
- Strength of Concrete

Using OpenSees, the effect of these factors, fire resistance analysis has been conducted by varying above parameters using OpenSees.

4.2.2 Selection of beam

A simply supported (SS) FRP-strengthened HSC beam was selected as primary beam for the fire resistance analysis. The beam details are as under (refer to Fig. 4.1);-

- Length (L) 6.1 m (20ft)
- Cross section 380×610 mm (15"x24")
- The flexure strengthening of beam by CFRP (three layers of unidirectional CFRP) at bottom face of the beam.
- For fire protection, Tyfo ® VG insulation is applied at the bottom of the beam that extends 105 mm on both sides of the beam cross section.
- The thickness of insulation is kept 20 mm (constant) except when specified. The details of geometric properties are tabulated in Table 4.1.

Table 4.1. Summary of properties for FRP strengthened beam

Property		Nomenclature / Dimension
Cross Section (mm)		380 x 610
Length (m)		6.1
Reinforcement	Top bars	2 x 15.8mm
	Bottom bars	4 x 25 mm
f'_c (N/mm^2)		40 - 90 MPa
f'_y (N/mm^2)		414 (Grade 60)
Applied Total Load (kN/m)		60
Concrete Cover Thickness (mm)		40
Aggregate type in concrete		Carbonate
FRP type		CFRP
FRP thickness (mm)		3
FRP ultimate tensile strength (kN/mm^2)		0.65
Modulus of elasticity FRP (kN/mm^2)		38.6
Rupture strain of FRP (mm/mm)		1.7%
Insulation Thickness (mm)		20
Insulation type		VG-EI-R

4.2.3 Material properties

The beam has High strength concrete (HSC) with a compressive strength of 70 MPa (10 ksi) and carbonate aggregate. The beam has four 25 mm (#8bar) reinforcing rebar at the bottom (flexural reinforcement) with yield strength of 414 MPa and 2% yield strain. The CFRP composite has ultimate tensile strength of 650 MPa, an elastic modulus of 3860 MPa and rupture strain of 1.7%. For analysis, thermal and mechanical properties as suggested by (Lie 1992) are used for concrete and reinforcing steel whereas for FRP and insulation these properties are obtained from semi-empirical relationships proposed by (Bisby 2003). It is assumed that the insulation does not crack and remain intact for the duration of fire test. It has no strength contribution towards capacity of the beam. Unless specified, the insulation thickness is assumed to be 20 mm.

4.2.4 Failure criteria

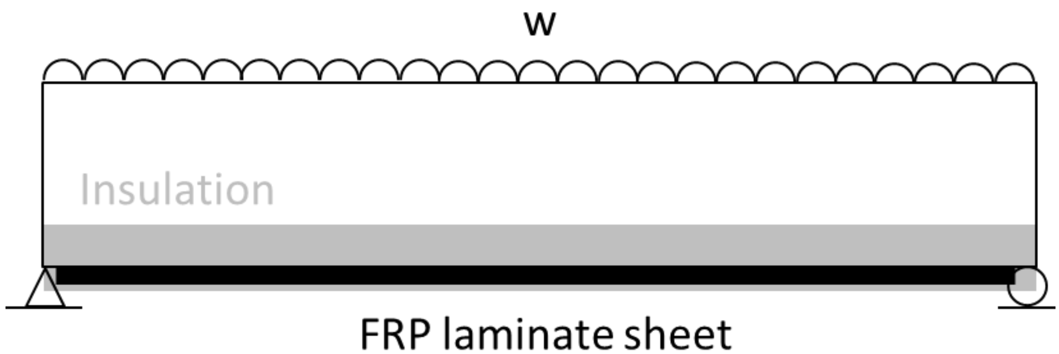
The fire resistance for analyzed beam is computed according to three failure criteria, namely strength, deflection and temperature in steel reinforcement.

4.2.5 Range of parameters

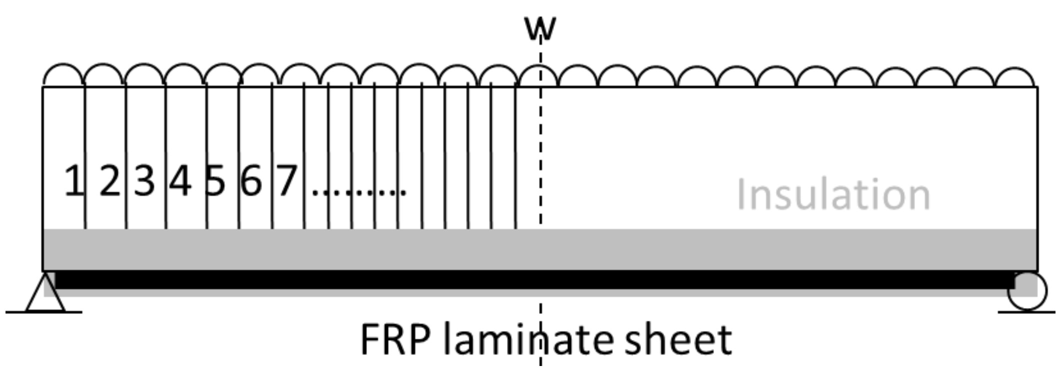
The parameters varied in the analysis include

- Load ratios (30, 50 and 70%) of nominal strength
- Simply Supported and Fixed Ends
- Three types of beams, namely; un-strengthened RC beam, un-strengthened and insulated RC beam and FRP-RC beam with applied insulation
- The analysis includes fire behavior of FRP-strengthened beam with a perfect bond and also while accounting for bond degradation with temperature

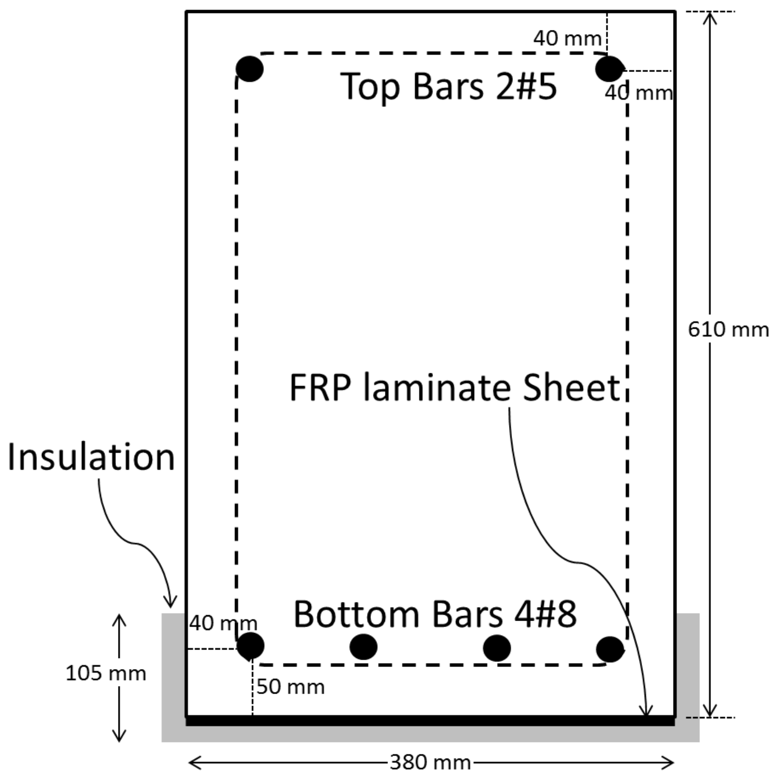
- To study the effect of fire scenarios, FRP-RC beams were analyzed under two standard fire exposures (ASTM E119) standard fire and ASTM E1529 (1993) hydrocarbon fire) and design fire exposures (Euro Code).
- The time temperature curves for the fire scenarios are given in Fig. 4.2. The fire resistance of this beam was evaluated based on thermal, strength, and deflection failure criteria.



(a) Elevation of SS FRP RC Beam



(b) Nodes along the beam



(b) Cross sectional Elevation

Fig. 4.1. Longitudinal and cross sectional for fire resistance analysis

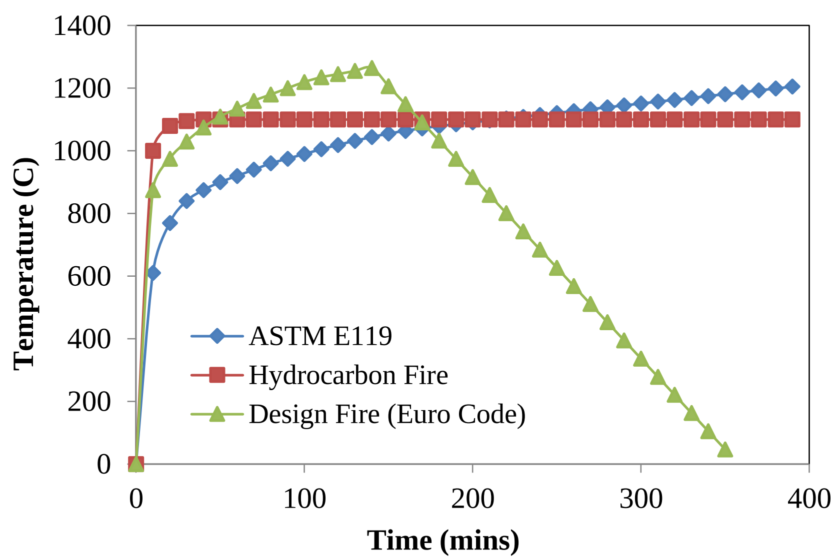


Fig. 4.2. Time – temperature curves for different fire scenarios

4.3 Results from parametric studies

The effect of the studied parameters on structural response of FRP-strengthened RC beam (time-deflection curves) is included in the discussion. The thermal response of the beam (rebar and concrete temperatures) is not presented here explicitly except for the parameter of fire scenario because many of these parameters such as load ratio, axial restraint do not influence the thermal response of the analyzed beams especially when the FRP-strengthened beam is provided with insulation. The effect of each of the parameters on the fire response of the beam is discussed below.

For analysis, 4 x beams were selected, one beam is of NSC and remaining 3 are HSC beams. Each beam has same fire exposure. 2 x beams have FRP on beam soffits and two are without FRP. 3 x beams are simply supported and 1 x beam is having fixed ends. All beams have same loading of 60 KN. Summary is shown in table 4.2.

Table 4.2. Summary of beams with fire exposures and support conditions

Beam	**Concrete Type**	**Fire Exposure**	**FRP 3mm**	**Support Conditions**	**P (KN)**
B1	NSC	ASTM E119	No	SS	60
B2	HSC	ASTM E119	No	SS	60
B3	HSC	ASTM E119	Yes	SS	60
B4	HSC	ASTM E119	Yes	Fixed	60

4.3.1 Effect of FRP strengthening

The effect of different section types on fire response can be gauged from graph shown in fig 4.3 that shows three cases comparison of deflection-time response for FRP-strengthened HSC beams, namely;

- HSC and NSC beams without FRP.
- HSC beam with and without FRP.
- HSC beam reinforced with FRP having a perfect bond and with temperature induced bond slip.

In order to carryout analysis comparison, load level was taken same in these cases.

- During early phases of fire exposure, rate of deflection of Non-FRP beams having NSC and HSC is very high because there is no external fire protection available on the both beams. Due to non-availability external fire protection, mechanical properties of concrete and steel degrade quickly which leads to greater deflection.
- NSC beam performs better than HSC beam due to its low density and higher pores as compared to high strength concrete. With less density and more porous NSC beam, the rate of flow of temperature is also less.
- HSC Beams with FR show stiff response at early phase of fire exposure period. i.e very less deflection as compared to non-strengthened HSC beam. It is because of high stiffness and strength properties provided by FRP material.
- Response of beam with perfect bond is stiffer i.e less deflection in entire fire exposure period as compared to the FRP-RC beam with bond degradation. This is because performance of the beam (deflection) mainly depends on good elevated temperature properties of FRP.
- Fire behavior of beam B3 having slip in between beam bottom concrete surface and wrapped FRP is questionable in OpenSees analysis which is against the literature and previous studies carried out. More investigation is required on slip and no slip of FRP on concrete surface.

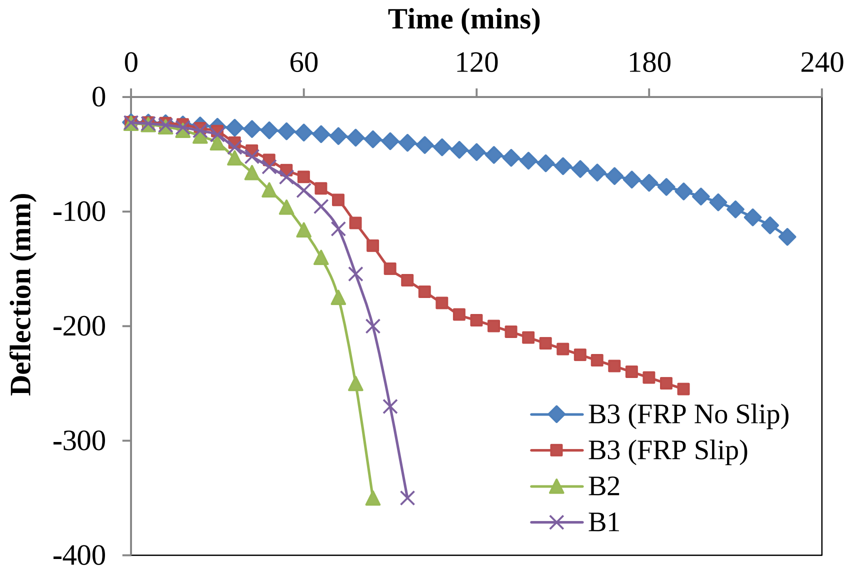


Fig. 4.3. Comparison of mid span deflection by FRP strengthening on fire behavior of HSC beams.

4.3.2 Effect of fire scenario

Comparative response of different fire scenarios have been studied which has been shown in fig. 4.4. Three types of fires have been used in analysis.

- ASTM E119
- Hydrocarbon fire (ASTM E1525)
- Design Fire (Euro Code)

Simply supported HSC beam was strengthened with FRP in all fire scenarios along with same loading through out of this parameter study. In standard fires, there is no decay phase however, design fires which are closer to actual fire has decay phase.

- Mid span deflection of HSC beam strengthened with FRP under standard fires is less than other two fire as the temperature rise is slow in early stages of fire exposure which causes less thermal strains means less deflection.

- In case of Hydrocarbon and Design Fire scenarios, the cross sectional temperature increases faster in early stages of fire exposure and thus leads to relatively large deflections resulting from high thermal strains.
- Under ASTM and hydrocarbon fire, deflection increase is considerable after 180 minutes into the fire. This can be attributed to no decay phase.

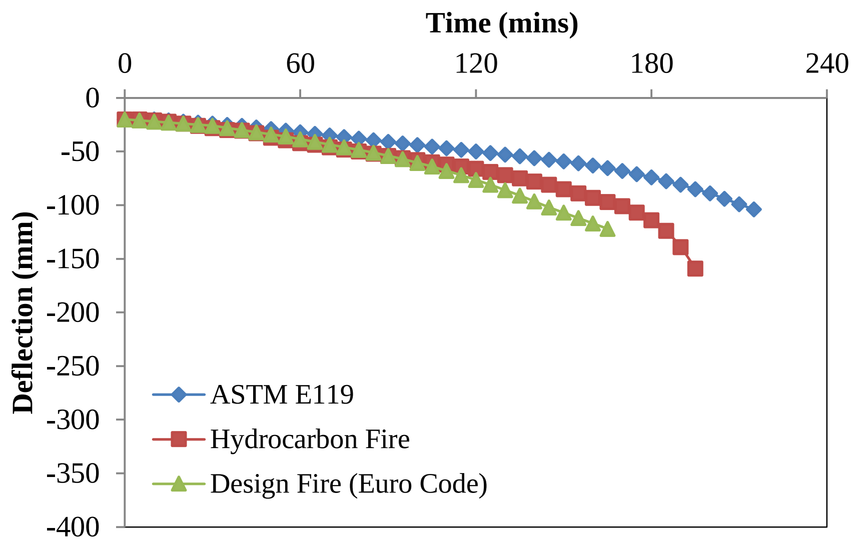


Fig. 4.4. Fire situations effects on mid-span deflections of FRP-strengthened HSC Beam

- Lowest fire resistance is achieved under design Fire as compared to hydrocarbon and ASTM E119 standard fires. This can be attributed to faster degradation in mechanical properties of constitutive materials in first 120 minutes due to a higher rate of increase in fire temperatures.

4.3.3 Effect of load level

Load ratio has significant effect on fire performance of HSC beam strengthened with FRP. Load ratio is the ratio of ratio of applied load to the nominal capacity of the beam at room temperature.

In this scenario, load ratio was varied as 30%, 50%, 70%. In addition to this, HSC beam with FRP (B2) with 50% load ratio was also analyzed in order to check the effectiveness of FRP. The effect of load ratio on the fire response of FRP-HSC beam is illustrated in Fig. 4.5.

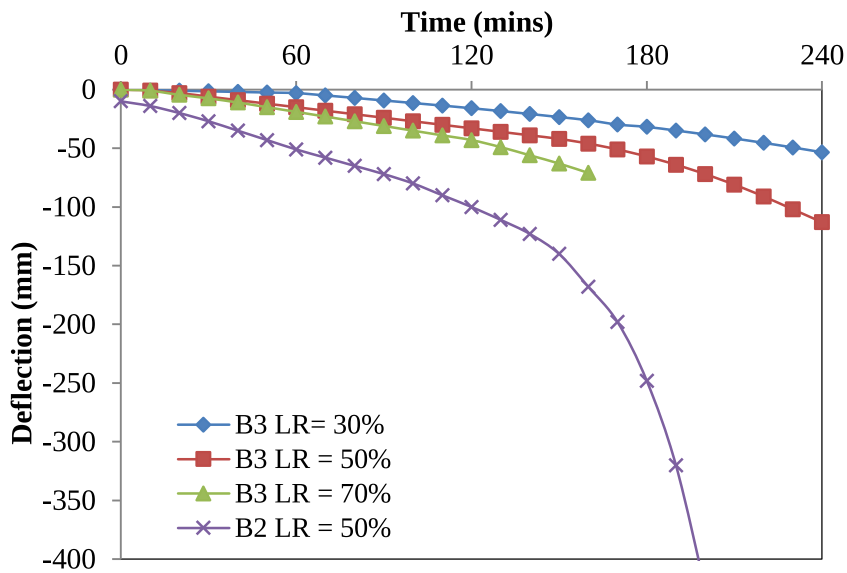


Fig. 4.5. Effect of load on mid span deflection of FRP-Strengthened HSC Beam exposed to fire

It can be seen from results that the fire resistance decreases with increasing load ratio. This is mainly due to the fact that at higher loads, the strength and stiffness properties of materials degrade significantly with temperature and beam will experience higher stresses and moments leading to early strength failure.

4.3.5 Effect of concrete compressive strength

Fig. 4.8 shows the effect of compressive strength of concrete (fc') on fire resistance of FRP-strengthened RC beams. Three different strengths of concrete (fc'=40, 50, 70 and 90 MPa) were analyzed and results are plotted in Fig. 4.8. It can be seen that concrete strength does not have greater effect on fire response of FRP-strengthened HSC beam.

Performance of CFRP strengthened HSC beam increase with the increase in compressive strength; however, RC beam without FRP performs exactly opposite to this i.e with the increase of compressive strength, performance reduces.

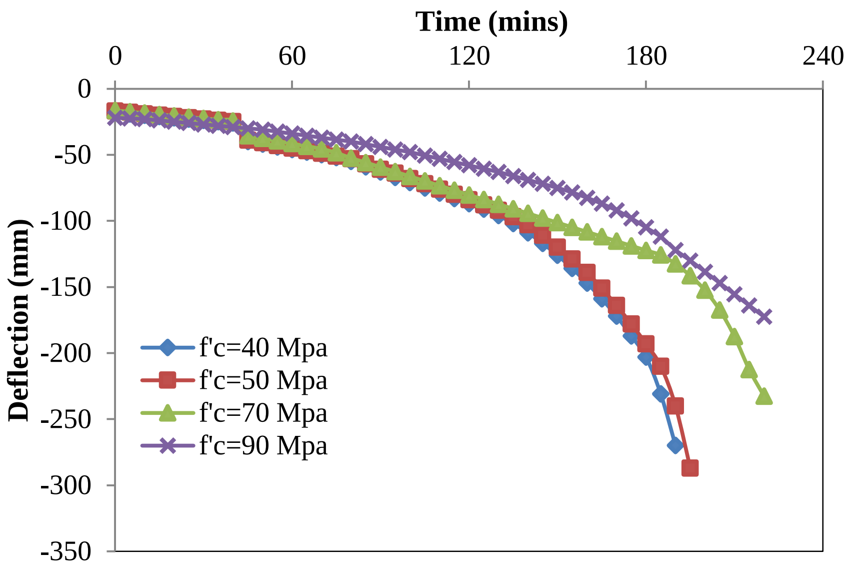


Fig. 4.6. Effect of f'_c on mid-span deflection of FRP strengthened reinforce concrete beam exposed to fire

4.4 Summary

A parametric study keeping in view the different fire scenarios, load level, axial restraints and compressive strength of beam, were carried out in this chapter has following summarized points:-

- RC stiffness is increased with use of FRP on tension face.
- HSC beam with FRP performs better under design fire than standard fire
- With the increase in load ratio of nominal capacity, fire performance reduces.

CHAPTER – 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Introduction

The main aim of this work to carry out the fire analysis of CFRP strengthened HSC beam using OpenSees under realistic fire and loading conditions. HSC beam strengthened with FRP was modelled in OpenSees to trace the response under realistic fire, loading, restraint conditions, and different concrete strengths. The different critical factors, which are; material properties at elevated temperature, axial restraint force, and components having significant influence on the fire behavior of FRP-strengthened HSC beams were incorporated in analysis. For model validation, existing data HSC beams was used, then was analyzed to compare the results under fire loading. Then a parametric analysis was carried out keeping in view the significant factors.

5.2 Key conclusions

Keeping in view the analysis carried out in this thesis, following key factors can be concluded:

- Fire performance of HSC without FRP is less effective than NSC and if strengthened with FRP, its performance is almost doubled
- The fire type has main impact on the fire performance of FRP strengthened HSC beams. FRP-strengthened HSC beams perform better under design fires as compared to a standard fire exposure.
- Higher load level leads to a lower fire resistance of FRP-strengthened beams, if load ratio is increased from 30% to 70%, fire performance is reduced almost 35%

5.3. Recommendations

After going through this study following is recommended for future research works

- More work is required to understand and accurately model the insulation behavior in terms of bond strength (mechanical properties) with concrete and FRP and possible mechanisms of delamination at elevated temperatures, crack formation and propagation
- Experimental validation may be carried out in subsequent works
- Software expert may be involved in further improvements in software

APPENDIX A

Addition of Materials in OpenSees Material Library

```
// this is addition of Concrete02ThermalHSC, the interface of it is same
with concrete02.
#include <stdlib.h>
#include <Concrete02ThermalHSC.h>
#include <OPS_Globals.h>
#include <float.h>
#include <Channel.h>
#include <Information.h>
#include <elementAPI.h>
#include <OPS_Globals.h>
void *
OPS_NewConcrete02ThermalHSC()
{  // Pointer to a uniaxial material that will be returned
  UniaxialMaterial *theMaterial = 0;
  int    iData[1];
  double dData[7];
  int numData = 1;
  if (OPS_GetIntInput(&numData, iData) != 0)
{    opserr << "WARNING invalid uniaxialMaterial Concrete02ThermalHSC tag"
<< endln;
    return 0;  }
  numData = OPS_GetNumRemainingInputArgs();
  if (numData != 7) {
    opserr << "Invalid #args, want: uniaxialMaterial Concrete02ThermalHSC
" << iData[0] << "fpc? epsc0? fpcu? epscu? rat? ft? Ets?\n";
    return 0;  }
  if (OPS_GetDoubleInput(&numData, dData) != 0) {
    opserr << "Invalid #args, want: uniaxialMaterial Concrete02ThermalHSC
" << iData[0] << "fpc? epsc0? fpcu? epscu? rat? ft? Ets?\n";
    return 0;  }
 // Parsing was successful, allocate the material
  theMaterial = new Concrete02ThermalHSC(iData[0], dData[0], dData[1],
dData[2], dData[3], dData[4], dData[5], dData[6]);
  if (theMaterial == 0)
{    opserr << "WARNING could not create uniaxialMaterial of type
Concrete02ThermalHSC Material\n";
    return 0; }
  return theMaterial;}
Concrete02ThermalHSC::Concrete02ThermalHSC(int tag, double _fc, double
_epsc0, double _fcu,
double _epscu, double _rat, double _ft, double _Ets):
UniaxialMaterial(tag, MAT_TAG_Concrete02ThermalHSC),
 //fc(_fc), epsc0(_epsc0), fcu(_fcu), epscu(_epscu), rat(_rat), ft(_ft),
Ets(_Ets)
  fcT(_fc), epsc0T(_epsc0), fcuT(_fcu), epscuT(_epscu), rat(_rat),
ftT(_ft), EtsT(_Ets) //JZ
{//JZ 07/10
////////////////////////////////////////////////////////////start
  fc = fcT;
  epsc0 = epsc0T;
```

```
  fcu = fcuT;
  epscu = epscuT;
  ft = ftT;
  Ets = EtsT;
//JZ 07/10
////////////////////////////////////////////////////////////end
  ecminP = 0.0;
  deptP = 0.0;
  eP = 2.0*fc/epsc0;
  //eP = 1.5*fc/epsc0; //for the euro code, the 2.0 should be changed into
1.5
  epsP = 0.0;
  sigP = 0.0;
  eps = 0.0;
  sig = 0.0;
  e = 2.0*fc/epsc0;
  //e = 1.5*fc/epsc0;//for the euro code, the 2.0 should be changed into
1.5
  //if epsc0 is not 0.0025, then epsc0 = strainRatio*0.0025
  strainRatio = epsc0/0.0025;
  ThermalElongation = 0; //initialize
  cooling=0; //PK add
  TempP = 0.0; //Pk add previous temp   }
Concrete02ThermalHSC::Concrete02ThermalHSC(void):
  UniaxialMaterial(0, MAT_TAG_Concrete02ThermalHSC)
{ Concrete02ThermalHSC::~Concrete02ThermalHSC(void)
{
  // Does nothing
}
UniaxialMaterial*
Concrete02ThermalHSC::getCopy(void)
{
 Concrete02ThermalHSC *theCopy = new Concrete02ThermalHSC(this->getTag(),
fc, epsc0, fcu, epscu, rat, ft, Ets);
   return theCopy; }
double
Concrete02ThermalHSC::getInitialTangent(void)
{  return 2.0*fc/epsc0;
}
int
Concrete02ThermalHSC::setTrialStrain(double trialStrain, double
FiberTemperature, double strainRate)
{  double  ec0 = fc * 2. / epsc0;//?
 // double ec0 = fc * 1.5 / epsc0; //JZ. 27/07/10 ??
 // retrieve concrete hitory variables
 ecmin = ecminP;
 dept = deptP;
 // calculate current strain

 eps = trialStrain;
 double deps = eps - epsP;
 // if the current strain is less than the smallest previous strain
 // call the monotonic envelope in compression and reset minimum strain
```

```
 if (eps < ecmin) {
 this->Compr_Envlp(eps, sig, e);
 ecmin = eps;
 } else {;
// else, if the current strain is between the minimum strain and ept
// (which corresponds to zero stress) the material is in the unloading-
// reloading branch and the stress remains between sigmin and sigmax
// calculate strain-stress coordinates of point R that determines
// the reloading slope according to Fig.2.11 in EERC Report
// (corresponding equations are 2.31 and 2.32
// the strain of point R is epsR and the stress is sigmR
double epsr = (fcu - rat * ec0 * epscu) / (ec0 * (1.0 - rat));
double sigmr = ec0 * epsr;
// calculate the previous minimum stress sigmm from the minimum
// previous strain ecmin and the monotonic envelope in compression
double sigmm;
double dumy;
this->Compr_Envlp(ecmin, sigmm, dumy);
// calculate current reloading slope Er (Eq. 2.35 in EERC Report)
// calculate the intersection of the current reloading slope Er
// with the zero stress axis (variable ept) (Eq. 2.36 in EERC Report)

    double er = (sigmm - sigmr) / (ecmin - epsr);
    double ept = ecmin - sigmm / er;
    if (eps <= ept) {
      double sigmin = sigmm + er * (eps - ecmin);
      double sigmax = er * .5f * (eps - ept);
      sig = sigP + ec0 * deps;
      e = ec0;
      if (sig <= sigmin) {
      sig = sigmin;
      e = er;      }
      if (sig >= sigmax) {
      sig = sigmax;
      e = 0.5 * er;      }
    } else {
      // else, if the current strain is between ept and epn
      // (which corresponds to maximum remaining tensile strength)
      // the response corresponds to the reloading branch in tension
      // Since it is not saved, calculate the maximum remaining tensile
      // strength sicn (Eq. 2.43 in EERC Report)
      // calculate first the strain at the peak of the tensile stress-
strain
      // relation epn (Eq. 2.42 in EERC Report)
      double epn = ept + dept;
      double sicn;
      if (eps <= epn) {
      this->Tens_Envlp(dept, sicn, e);
      if (dept != 0.0) {
      e = sicn / dept;
      } else {
      e = ec0; }
      sig = e * (eps - ept);
```

```
      } else {
      // else, if the current strain is larger than epn the response
      // corresponds to the tensile envelope curve shifted by ept
      double epstmp = eps - ept;
      this->Tens_Envlp(epstmp, sig, e);
      dept = eps - ept;}
  return 0;
}
double
Concrete02ThermalHSC::getStrain(void)
{  return eps;
}
double
Concrete02ThermalHSC::getStress(void)
{  return sig; }
double
Concrete02ThermalHSC::getTangent(void)
{  return e; }
double
Concrete02ThermalHSC::getThermalElongation(void) //***JZ
{  return ThermalElongation; }
double
Concrete02ThermalHSC::getElongTangent(double TempT, double& ET, double&
Elong, double TempTmax) //PK add to include max temp
{  //material properties with temperature
  Temp = TempT;  //make up the 20 degree which is minus in the class of
thermalfield
  Tempmax = TempTmax; //PK add max temp for cooling
  // The datas are from EN 1992 part 1-2-1
  // Tensile strength at elevated temperature
   //if (Temp >= 1080) {
  //    opserr << "temperature " << " " << Temp <<endln;
  //}
  if (Temp <= 100) {
        ft = ftT;  }
  else if (Temp <= 800) {
        ft = (0.99 - (0.001*Temp))*ftT;
        Ets = (1.0 - 1.0*(Temp -80)/500)*fcT * 1.5 / epsc0T;
        //Ets = (1.0 - 1.0*(Temp -80)/500)*EtsT; }
  else {
        ft = 1.0e-3;
        Ets = 1.0e-3;
        //ft = 0;
        //Ets = 0;}

  // compression strength, at elevated temperature
  //   strain at compression strength, at elevated temperature
  //   ultimate (crushing) strain, at elevated temperature
  if (Temp <= 0) {
        fc = fcT;
        epsc0 = -0.0025;
        fcu = fcuT;
        epscu = -0.02;
```

```
        //Ets = EtsT;  jz what is there the statement? }
  else if (Temp <= 100) {
        fc = fcT;
        epsc0 = -(0.0025 + (0.004-0.0025)*(Temp - 0)/(80 - 0));
        fcu = fcuT;
        epscu = -(0.0200 + (0.0225-0.0200)*(Temp - 0)/(80 - 0)); }
  else if (Temp <= 200) {
      fc = fcT*(0.99 - (0.002*Temp));
        epsc0 = -(0.0040 + (0.0055-0.0040)*(Temp - 80)/100);
      fcu = fcuT*(1 - (Temp - 80)*0.05/100);
        epscu = -(0.0225 + (0.0225-0.0200)*(Temp - 80)/100);  }
//  //else if (Temp <= 280) {
//    //  fc = fcT*(0.95 - (Temp - 180)*0.1/100);
//      //epsc0 = -(0.0055 + (0.0070-0.0055)*(Temp - 180)/100);
//      fcu = fcuT*(0.95 - (Temp - 180)*0.1/100);
//      epscu = -(0.0250 + 0.0025*(Temp - 180)/100);
//  }
//  //else if (Temp <= 380) {
//      fc = fcT*(0.85 - (Temp - 280)*0.1/100);
//      epsc0 = -(0.0070 + (0.0100-0.0070)*(Temp - 280)/100);
//      fcu = fcuT*(0.85 - (Temp - 280)*0.1/100);
//      epscu = -(0.0275 + 0.0025*(Temp - 280)/100);
//  }
//  else if (Temp <= 480) {
//      fc = fcT*(0.75 - (Temp - 380)*0.15/100);
//      epsc0 = -(0.0100 + (0.0150-0.0100)*(Temp - 380)/100);
//      fcu = fcuT*(0.75 - (Temp - 380)*0.15/100);
//      epscu = -(0.03 + 0.0025*(Temp - 380)/100);
//  }
//  else if (Temp <= 580) {
//      fc = fcT*(0.60 - (Temp - 480)*0.15/100);
//      epsc0 = -(0.0150 + (0.0250-0.0150)*(Temp - 480)/100);
//      fcu = fcuT*(0.60 - (Temp - 480)*0.15/100);
//      epscu = -(0.0325 + 0.0025*(Temp - 480)/100);
//  }
//  else if (Temp <= 680) {
//      fc = fcT*(0.45 - (Temp - 580)*0.15/100);
//      epsc0 = -0.0250;
//      fcu = fcuT*(0.45 - (Temp - 580)*0.15/100);
//      epscu = -(0.035 + 0.0025*(Temp - 580)/100);
//  }
//  else if (Temp <= 780) {
//      fc = fcT*(0.30 - (Temp - 680)*0.15/100);
//      epsc0 = -0.0250;
//      fcu = fcuT*(0.30 - (Temp - 680)*0.15/100);
//      epscu = -(0.0375 + 0.0025*(Temp - 680)/100);
//  }
  else if (Temp <= 800) {
      fc = fcT*(0.73 - (0.0005*Temp));
        epsc0 = -0.0250;
        fcu = fcuT*(0.15 - (Temp - 780)*0.07/100);
        epscu = -(0.04 + 0.0025*(Temp - 780)/100);  }
//  else if (Temp <= 980) {
```

```
//      fc = fcT*(0.08 - (Temp - 880)*0.04/100);
//      epsc0 = -0.0250;
//      fcu = fcuT*(0.08 - (Temp - 880)*0.04/100);
//      epscu = -(0.0425 + 0.0025*(Temp - 880)/100);
//  }
//  else if (Temp <= 1080) {
//      fc = fcT*(0.04 - (Temp - 980)*0.03/100);
//      epsc0 = -0.0250;
//      fcu = fcuT*(0.04 - (Temp - 980)*0.03/100);
//      epscu = -(0.045 + 0.0025*(Temp - 980)/100);
//  }
  else  {
      opserr << "the temperature is invalid\n";   }
//jz assign a miner to the valuables
 // epsc0 = epsc0T*strainRatio;
 // epscu = epscuT*strainRatio;
 // caculation of thermal elongation
        if (Temp <= 1) {
              ThermalElongation = (Temp - 0) * 9.213e-6;    }
  else if (Temp <= 680) {
      ThermalElongation = -1.8e-4 + 9e-6 *(Temp+20) + 2.3e-11
*(Temp+20)*(Temp+20)*(Temp+20); }
  else if (Temp <= 1180) {
      ThermalElongation = 14.009e-3;  //Modified by Liming,2013 }
  else {
        opserr << "the temperature is invalid\n";  }
  ET = 1.5*fc/epsc0;
  Elong = ThermalElongation;
  //For cooling to exist T must go to Tmax and then decrease
//if cooling the factor becomes 1
 //if (Temp = Tempmax) {
    //cooling=1;
 // }
///PK COOLING PART FOR DESCENDING BRANCH OF A FIRE////
// If temperature is less that previous commited temp then we have cooling
taking place
  if (Temp < TempP) {
//opserr << "cooling " << Temp << " " << TempP << endln;
  double kappa;
  double fcmax; //compr strength at max temp
  double fcumax; //ultimate compr strength at max temp
  double fcamb; //compr strength at cooled ambient temp
  double fcuamb; //ultimate compr strength at cooled ambient temp
  double epsc0max; //strain at compression strength for the max temp
  double epscumax; //ultimate strain at ultimate compression strength for
the max temp
  if (TempP == Tempmax) {
  //opserr << "cooling,T,TP,Tmax " << Temp << " " << TempP << " " <<
Tempmax <<endln;  }
  // PK Determine residual compressive strength of concrete heated to the
max temp and then having cooled down to ambient
  // This will be the same for all the timesteps during the cooling phase
```

```
  // PK 1st step is to determine Kc,Tempmax according to table in 3.2.2
(EN1994-1-2:2005)
    if (Tempmax < 0) {
    opserr << "max temperature cannot be less than zero " << " " <<
Tempmax <<endln; }
  else if (Tempmax <= 80) {
    kappa = 1;
    fcmax = fcT;
    fcumax = fcuT;  }
  else if (Tempmax <= 180) {
    kappa = 1 - (Tempmax - 80)*0.05/100;
    fcmax = fcT*(1 - (Tempmax - 80)*0.05/100);
    fcumax = fcuT*(1 - (Tempmax - 80)*0.05/100);  }
  else if (Tempmax <= 280) {
    kappa = 0.95 - (Tempmax - 180)*0.1/100;
    fcmax = fcT*(0.95 - (Tempmax - 180)*0.1/100);
    fcumax = fcuT*(0.95 - (Tempmax - 180)*0.1/100); }
  else if (Tempmax <= 380) {
    kappa = 0.85 - (Tempmax - 280)*0.1/100;
    fcmax = fcT*(0.85 - (Tempmax - 280)*0.1/100);
    fcumax = fcuT*(0.85 - (Tempmax - 280)*0.1/100); }
  else if (Tempmax <= 480) {
    kappa = 0.75 - (Tempmax - 380)*0.15/100;
    fcmax = fcT*(0.75 - (Tempmax - 380)*0.15/100);
    fcumax = fcuT*(0.75 - (Tempmax - 380)*0.15/100); }
  else if (Tempmax <= 580) {
    kappa = 0.60 - (Tempmax - 480)*0.15/100;
    fcmax = fcT*(0.60 - (Tempmax - 480)*0.15/100);
    fcumax = fcuT*(0.60 - (Tempmax - 480)*0.15/100);  }
  else if (Tempmax <= 680) {
    kappa = 0.45 - (Tempmax - 580)*0.15/100;
    fcmax = fcT*(0.45 - (Tempmax - 580)*0.15/100);
    fcumax = fcuT*(0.45 - (Tempmax - 580)*0.15/100);  }
  else if (Tempmax <= 780) {
    kappa = 0.30 - (Tempmax - 680)*0.15/100;
    fcmax = fcT*(0.30 - (Tempmax - 680)*0.15/100);
    fcumax = fcuT*(0.30 - (Tempmax - 680)*0.15/100);  }
  else if (Tempmax <= 880) {
    kappa = 0.15 - (Tempmax - 780)*0.07/100;
    fcmax = fcT*(0.15 - (Tempmax - 780)*0.07/100);
    fcumax = fcuT*(0.15 - (Tempmax - 780)*0.07/100);  }
  else if (Tempmax <= 980) {
    kappa = 0.08 - (Tempmax - 880)*0.04/100;
    fcmax = fcT*(0.08 - (Tempmax - 880)*0.04/100);
    fcumax = fcuT*(0.08 - (Tempmax - 880)*0.04/100);  }
  else if (Tempmax <= 1080) {
    kappa = 0.04 - (Tempmax - 980)*0.03/100;
    fcmax = fcT*(0.04 - (Tempmax - 980)*0.03/100);
    fcumax = fcuT*(0.04 - (Tempmax - 980)*0.03/100);  }
  else  {
    opserr << "the temperature is invalid\n";   }
  // PK 2nd step is to determine compressice strength at ambient after
cooling as shown in ANNEX C (EN1994-1-2:2005)
```

```
  if (Tempmax < 0) {
    opserr << "max temperature cannot be less than zero " << " " <<
Tempmax <<endln;  }
  else if (Tempmax <= 80) {
    fcamb = kappa*fcT;
    fcuamb = kappa*fcuT;  }
  else if (Tempmax <= 280) {
    fcamb=(1-(0.235*(Tempmax-80)/200))* fcT;
    fcuamb=(1-(0.235*(Tempmax-80)/200))* fcuT;  }
  else if (Tempmax <= 1080) {
    fcamb = 0.9*kappa*fcT;
    fcuamb = 0.9*kappa*fcuT;  }
  else {
    opserr << "the temperature is invalid\n";  }
  // Calculation of current compressive strength
  // linear interpolation between ambient and maximum compressive strength
(after and before cooling)
  fc = fcmax - ((fcmax-fcamb)*(Tempmax-Temp)/Tempmax);
  fcu = fcumax - ((fcumax-fcuamb)*(Tempmax-Temp)/Tempmax);
  // Calculation of epsc0 for Tempmax and then keep it the same for all
next time steps
  if (Tempmax < 0) {
    opserr << "max temperature cannot be less than zero " << " " <<
Tempmax <<endln; }
  else if (Tempmax <= 80) {
    epsc0max = -(0.0025 + (0.004-0.0025)*(Tempmax - 0)/(80 - 0));
    epscumax = -(0.0200 + (0.0225-0.0200)*(Tempmax - 0)/(80 - 0));  }
  else if (Tempmax <= 180) {
    epsc0max = -(0.0040 + (0.0055-0.0040)*(Tempmax - 80)/100);
    epscumax = -(0.0225 + (0.0225-0.0200)*(Tempmax - 80)/100);  }
  else if (Tempmax <= 280) {
    epsc0max = -(0.0055 + (0.0070-0.0055)*(Tempmax - 180)/100);
    epscumax = -(0.0250 + 0.0025*(Tempmax - 180)/100);  }
  else if (Tempmax <= 380) {
    epsc0max = -(0.0070 + (0.0100-0.0070)*(Tempmax - 280)/100);
    epscumax = -(0.0275 + 0.0025*(Tempmax - 280)/100);}
  else if (Tempmax <= 480) {
    epsc0max = -(0.0100 + (0.0150-0.0100)*(Tempmax - 380)/100);
    epscumax = -(0.03 + 0.0025*(Tempmax - 380)/100);  }
  else if (Tempmax <= 580) {
    epsc0max = -(0.0150 + (0.0250-0.0150)*(Tempmax - 480)/100);
    epscumax = -(0.0325 + 0.0025*(Tempmax - 480)/100);  }
  else if (Tempmax <= 680) {
    epsc0max = -0.0250;
    epscumax = -(0.035 + 0.0025*(Tempmax - 580)/100);  }
  else if (Tempmax <= 780) {
    epsc0max = -0.0250;
    epscumax = -(0.0375 + 0.0025*(Tempmax - 680)/100);  }
  else if (Tempmax <= 880) {
    epsc0max = -0.0250;
    epscumax = -(0.04 + 0.0025*(Tempmax - 780)/100);  }
  else if (Tempmax <= 980) {
    epsc0max = -0.0250;
```

```
    epscumax = -(0.0425 + 0.0025*(Tempmax - 880)/100);  }
  else if (Tempmax <= 1080) {
    epsc0max = -0.0250;
    epscumax = -(0.045 + 0.0025*(Tempmax - 980)/100);  }
  else  {
    opserr << "the temperature is invalid\n";   }
  //make eps0 = eps0max
  epsc0 = epsc0max;
  // Calculating epscu
  epscu = epsc0 + ((epscumax-epsc0max)*fc/fcmax);
  ft=0;
 // Make thermal elongation zero during the cooling phase
 // Elong =0;    }
   if (Temp > 0) {
//cooling=1;
//opserr << "Heating,T,TP,Tmax " << Temp << " " << TempP << " " << Tempmax
<<endln;   }
  return 0; }
int
Concrete02ThermalHSC::commitState(void)
{  ecminP = ecmin;
  deptP = dept;
   eP = e;
  sigP = sig;
  epsP = eps;
  TempP = Temp; //PK add set the previous temperature
  return 0; }
int
Concrete02ThermalHSC::revertToLastCommit(void)
{  ecmin = ecminP;;
  dept = deptP;
   e = eP;
  sig = sigP;
  eps = epsP;
  //Temp = TempP; //PK add set the previous temperature
  // NA ELENXW MIPWS EDW XANETAI TO TEMP LOGW MIN CONVERGENCE
  return 0;
}
int
Concrete02ThermalHSC::revertToStart(void)
{  ecminP = 0.0;
  deptP = 0.0;
  eP = 2.0*fc/epsc0;
  epsP = 0.0;
  sigP = 0.0;
  eps = 0.0;
  sig = 0.0;
  e = 2.0*fc/epsc0;
  return 0; }
int
Concrete02ThermalHSC::sendSelf(int commitTag, Channel &theChannel)
{  static Vector data(13);
  data(0) =fc;
```

```
  data(1) =epsc0;
  data(2) =fcu;
  data(3) =epscu;
  data(4) =rat;
  data(5) =ft;
  data(6) =Ets;
  data(7) =ecminP;
  data(8) =deptP;
  data(9) =epsP;
  data(10) =sigP;
  data(11) =eP;
  data(12) = this->getTag();
  if (theChannel.sendVector(this->getDbTag(), commitTag, data) < 0) {
    opserr << "Concrete02ThermalHSC::sendSelf() - failed to sendSelf\n";
    return -1;  }
  return 0;}
int
Concrete02ThermalHSC::recvSelf(int commitTag, Channel &theChannel,
     FEM_ObjectBroker &theBroker)
{  static Vector data(13);
  if (theChannel.recvVector(this->getDbTag(), commitTag, data) < 0) {
    opserr << "Concrete02ThermalHSC::recvSelf() - failed to recvSelf\n";
    return -1;  }
  fc = data(0);
  epsc0 = data(1);
  fcu = data(2);
  epscu = data(3);
  rat = data(4);
  ft = data(5);
  Ets = data(6);
  ecminP = data(7);
  deptP = data(8);
  epsP = data(9);
  sigP = data(10);
  eP = data(11);
  this->setTag(data(12));
  e = eP;
  sig = sigP;
  eps = epsP;
  return 0;}
void
Concrete02ThermalHSC::Print(OPS_Stream &s, int flag)
{  s << "Concrete02ThermalHSC:(strain, stress, tangent) " << eps << " " <<
sig << " " << e << endln;}
void
Concrete02ThermalHSC::Tens_Envlp (double epsc, double &sigc, double &Ect)
{/*-----------------------------------------------------------------------
! monotonic envelope of concrete in tension (positive envelope)
!  ft    = concrete tensile strength
!   Ec0   = initial tangent modulus of concrete
!   Ets   = tension softening modulus
!   eps   = strain
!   returned variables
```

```
!    sigc  = stress corresponding to eps
!    Ect  = tangent concrete modulus
!-------------------------------------------------------------------------*/
    double Ec0  = 2.0*fc/epsc0;
      // double Ec0  = 1.5*fc/epsc0;
  double eps0 = ft/Ec0;
  double epsu = ft*(1.0/Ets+1.0/Ec0);
  if (epsc<=eps0) {
    sigc = epsc*Ec0;
    Ect  = Ec0;
  } else {
    if (epsc<=epsu) {
      Ect  = -Ets;
      sigc = ft-Ets*(epsc-eps0);
    } else {
      //      Ect  = 0.0
      Ect  = 1.0e-10;
      sigc = 0.0;    }
 { return;}
void
Concrete02ThermalHSC::Compr_Envlp (double epsc, double &sigc, double &Ect)
{
/*-------------------------------------------------------------------------
! monotonic envelope of concrete in compression (negative envelope)
!   fc    = concrete compressive strength
!   epsc0 = strain at concrete compressive strength
!   fcu   = stress at ultimate (crushing) strain
!   epscu = ultimate (crushing) strain
!   Ec0   = initial concrete tangent modulus
!   epsc  = strain
!   returned variables
!   sigc  = current stress
!   Ect   = tangent concrete modulus
-------------------------------------------------------------------------*/

  double Ec0  = 2.0*fc/epsc0;
  //double Ec0  = 1.5*fc/epsc0;
  double ratLocal = epsc/epsc0;
  if (epsc>=epsc0) {
    sigc = fc*ratLocal*(2.0-ratLocal);
    Ect  = Ec0*(1.0-ratLocal);
  } else {
  //   linear descending branch between epsc0 and epscu
    if (epsc>epscu) {
      sigc = (fcu-fc)*(epsc-epsc0)/(epscu-epsc0)+fc;
      Ect  = (fcu-fc)/(epscu-epsc0);
    } else {
   // flat friction branch for strains larger than epscu
      sigc = fcu;
      Ect  = 1.0e-10;
      //       Ect  = 0.0    }
  {  return; }
int
```

```
Concrete02ThermalHSC::getVariable(const char *varName, Information
&theInfo)
{  if (strcmp(varName,"ec") == 0) {
     theInfo.theDouble = epsc0;
     return 0; } else if (strcmp(varName,"ElongTangent") == 0) {
     Vector *theVector = theInfo.theVector;
     if (theVector != 0) {
       double tempT, ET, Elong, TempTmax;
       tempT = (*theVector)(0);
         ET = (*theVector)(1);
         Elong = (*theVector)(2);
       TempTmax = (*theVector)(3);
       this->getElongTangent(tempT, ET, Elong, TempTmax);
         (*theVector)(0) = tempT;
       (*theVector)(1) = ET;
       (*theVector)(2) = Elong;
         (*theVector)(3) = TempTmax;  }
     return 0; }
  return -1;}
//this function is no use, just for the definiation of pure virtual
function.
int
Concrete02ThermalHSC::setTrialStrain(double strain, double strainRate)
{ opserr << "Concrete02ThermalHSC::setTrialStrain(double strain, double
strainRate) - should never be called\n";
  return -1;}
```

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