Seismic and Fire Behaviour of FRP Strengthened Reinforced High Strength Concrete Structures—An Overview

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Abstract The development of Fibre Reinforced Polymer (FRP) can be traced to the expanded use of composites after the World War II in the early 1940s, though the use of FRP was considered seriously for use as reinforced concrete until 1960s. Fibre Reinforced Polymers are well recognized as an effective seismic retrofit/fire resistant material for existing concrete buildings. This strengthening domain in civil engineering, a critical part of overall lifecycle aspect of any infrastructure, is more than two decades old and several successful projects have been installed using FRP as reported in several literatures. Many of these retrofitted buildings have experienced significant earthquakes and performed as designed, validating the effectiveness of the FRP and technology. Extensive laboratory testing and actual earthquakes have led to the growth of dependable design methodologies and guidelines for FRP to be used by the engineering fraternity. FRP materials have a high strength-to-weight ratio, which make them a perfect material for seismic retrofit. Although they do not add significant mass to a structure, they certainly enhance the capacity of various structural components. This also avoids the mandate of performing the analysis again without appreciable weight change and further consequential effect on foundation after due strengthening. FRP possesses innate characteristics to deal with fire and heated environment. This article is an attempt to highlight some of the features of FRP Reinforced High-Strength Concrete Structures from both Seismic and Fire viewpoints.

Keywords Concrete · Ductility · Design · Materials · Seismic performance · Fire · FRP

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1 Background and Introduction

The need for new materials and new versions of existing materials has been growing at an accelerated rate. Out of all characteristics, the most sought after and indispensable material characteristics in the construction industry are high workability and high strength, as far as concrete is concerned. Also, the growing need of tall buildings requires that the structural designs are optimized to perfection (no more and no less), thereby instilling the need for research in search of high-performance concrete. Consequently, new versions of concrete such as High Strength Concrete, High-Performance Concrete, and Ultra-High-Performance concrete have emerged. The primary reason behind the application of such performance concrete is to build structures with minimum material use and maximum performance level. Under severe earthquake loading or fire, ductility is highly desirable and is focussed on profoundly during the design stage itself.

Failures due to severe heating environment: It is reported in literature that about 25,000 persons die due to fires and related causes in India. According to literature, about 45% of the claims are due to fire losses and about Rs. 1000 crores are lost every year due to fire. Electric defaults are the one of the primary reasons in initiating fire. Many a times, beams with openings meant to carry electric lines and AC ducts are susceptible to such failure. In terms of the potential risk, ‘Fire’ has been ranked fifth and according to National Crime Record Bureau (NCRB), a total of 18,450 cases of fire accidents were reported in India in 2015, with 1,193 persons injured and 17,700 killed during the disaster. After the 9–11 attack on the World Trade Centre, interest in the design of structures for fire has greatly increased.

However, in May 2018, a 26-storey high-rise building has collapsed in Brazil in 90 min as building was unable to resist the severe heating environment. In the year 2017, a two-storeyed building in West Delhi collapsed after fire supposedly due to faulty wiring in the air-conditioning system. In June 2018, major fire broke in G + 5 building and subsequently building collapses. Incidentally, this building was already considered dangerous and such un-demolished building poses severe danger for the pedestrians who are passing nearby the dangerous buildings. The schools where mid-day meals are cooked are potential locations of fire hazards. In commercial establishments, major fires start in storage area and warehouses than production areas. The threat posed by fire following an earthquake has been highlighted by the occurrence of a number of past earthquakes [27], notably those witnessed in San Francisco (1906), Northridge (1994), Los Angeles (1994), and Kobe, Japan (1995).

Incidence of a fire may be pointedly riskier under post-earthquake circumstances rather than under usual conditions and thereby creating a greater need for Ductile design. Ductile detailing requires good amount of reinforcing bar to create good confining effect but has the potential to naturally creating congestion in the structural member for concreting to take place. Under such circumstances, the need for high workability and flowability of concrete using high-range water reducers is mandated to meet the construction requirement.

Concrete is widely appreciated in the construction industry. Indeed, it is the most consumed material in the world after water but its major disadvantage is its brittle nature, which is attributed to its poor resistance to crack formation, low tensile strength, and strain capacities. In the last two decades, the construction of high-rise buildings using high-strength concrete has grown significantly in many residential and commercial sectors due to paucity of land. Though HSC is preferred from strength and durability point of view in ambient temperature conditions, normal strength concrete exhibits good performance under fire situations. However, the use of high-strength concrete in RC members cannot be avoided as it keeps the structural size to the optimum level. On the other hand, with the introduction of high strength concrete, structural members have become very thin and hence less fire resistant. The concrete's physical, chemical and mechanical properties do undergo extraordinary modifications when subjected to elevated temperatures and a considerable loss in strength occurs when concrete is heated above 300 °C [16]. Instead of conventional steel reinforcement, this article attempts to highlight the features of FRP reinforced high-strength concrete structures.

2 Firm Choice of Comfort in FRP

The retrofitting of existing concrete structures to counteract high design loads, correct strength loss due to deterioration, correct design or construction deficiencies, or increased ductility has traditionally been accomplished by the use of established construction materials and techniques. Steel plates with external bonding, use of steel/concrete jackets, and external post-tensioning are a few such techniques currently being deployed. Orthodox methods of seismic assessment and design of buildings with RC walls were challenged after the peculiar failure modes observed in RC structural walls in the 2010 Chile and February 2011 New Zealand (NZ) earthquakes. While some of the existing methods are also good at improving the specific building performance, these methods lack overall resilience in terms of completing the task with minimum disturbance in day-to-day operations. Composites made of fibres in a polymeric resin, also known as fibre-reinforced polymers (FRPs), have been developed as an alternative to conventional materials for repair and rehabilitation (ACI 440–2R3). In the last decade, the acceptance of the usage of FRP as a structural repair is beyond doubt.

3 Few Inherent Capabilities of FRP (As Per ACI–440)

- The greater interest in strengthening of RC columns by external wrapping since 1980s have led to the investigation in the direction towards the confinement of concrete with FRP laminates.

- Ductility has also been a concern where FRP is primarily used. It was highlighted that the strength gain is often complimented by a reduced deflection at failure (ductility). Nevertheless, the proper design is extremely essential to ensure that the steel reinforcement in the beam yield before failure, giving advanced cautioning prior to failure of the beam.
- The fact that shear strength in concrete is resisted by diagonal tension means that the FRP can be used as shear reinforcement. The design guidelines with respect to limiting low value of the allowable strain in the FRP for shear ensures that shear crack does not become too wide and thereby ensuring the keeping intact of aggregate interlock.
- Complete wrapping of the FRP laminate around the section is the most efficient wrapping technique and is most frequently used in column applications where all four sides of the column can generally be accessed. It is impractical to completely wrap beam members due to the presence of an integral slab; therefore, the shear strength can be enhanced by wrapping the FRP laminate on three sides of the member (U-wrap) or pasting on two opposite sides of the member.
- The existing method of formulating FRP RC design guidelines by adjusting conventional RC guidelines may seem reasonable, but it is not fully appropriate. The basis of this statement is that conventional RC design guidelines assume that the principal mode of failure is always ductile, due to flexural reinforcement yielding. However, the same cannot be assumed for FRP RC; FRP RC guidelines assume that brittle failure would be sustained because of either concrete crushing or FRP reinforcement rupture.
- FRP bars are anisotropic in nature and can be manufactured using a variety of techniques such as pultrusion, braiding, and weaving. The characteristics of FRP bar are largely influenced by fiber volume, fiber type, resin type, fiber orientation, dimensional effects, and quality control during manufacturing. Hence, it is suggested that manufacturer's material data should be consulted for specific product properties.

4 Literature Review—Fire Resistance

An analytical model, developed by [10], based on extensive experimental investigation of the structural response of beams subjected to the elevated temperature simulating the fire loading indicated that the significant shear cracks were developed much early near the continuous support, thus highlighting the importance of considering fire in the design of concrete structures. However, the concrete reported in the study was of normal-weight concrete.

Zhang et al. [35] investigated the performance of retrofitted RC deep beams using Carbon Fibre Reinforced Polymer (CFRP) laminates and observed the significant improvement in ductility and shear strength.

Evaluation of the fire endurance of FRP reinforced concrete slabs by [17] highlighted the factors to be considered for the fire resistant design. The type of reinforcement, concrete cover and type of aggregate were the important factors reported in the study. The differences in the critical temperature of the steel reinforcement and FRP reinforcement were also reported in this paper. It was also highlighted that the aggregate type has moderate influence on the fire resistance of FRP reinforced concrete slabs. It was found that concrete made of carbonate aggregate has 10% greater fire resistance as compared to siliceous aggregates; this was seen in terms of the degree of temperature rise in specimen concrete slabs. Moreover, with higher concrete cover, the higher fire resistance can be obtained as advocated in the study and hence spalling characteristics are considered to be important.

In the past, engineers have endorsed the use of advanced analytical models to determine fire growth within a compartment using the finite element models of structural components to evaluate the temperatures of many structural elements within a component by heat transfer analysis [6]. The literature advocates that the input heat, thermal expansion, degradation in strength and stiffness of materials at elevated temperatures are required to be factored into the design of building components [9].

Another work highlighting the influence of reinforcement type on fire resistance was reported in [20] and it was widely considered that FRP reinforced concrete elements have lower fire resistances than conventional steel reinforcement due to the sensitivity of FRP to the change in tensile and bond strength under severe elevated temperature conditions. Kabay (2014) reported that the addition of basalt fibres in normal as well as in high strength concrete can lead to massive improvement in flexural strength (9–13%), fracture energy (126–140%) and reduction in abrasion wear (2–18%). However, it may also be noted that the compressive strength of concrete generally decreases on addition of basalt fibres.

It was also reported in [24] that at elevated temperatures, the moisture evaporation takes place and moisture transportation in concrete has been reported to be a complex phenomenon, not essentially controlled by temperature, pore pressure and vapor content

Zaidi et al. [33] highlighted the influence of FRP properties on the numerical deformations in FRP bars-RC elements in heated temperature and observed that circumferential thermal deformations increase, profoundly with the increase of elasticity modulus in the transverse direction of concrete especially in high temperature zone. It was also highlighted that the concrete cover thickness has no big effect on the circumferential thermal deformations of FRP bar-reinforced concrete cylinders.

The detailed study was reported by [5] by investigating the influence of cracking on the heat propagation in RC structures (beams, columns and frames) experimentally and analytically and predicted that the cracked regions are susceptible to the increase in the rate of heat propagation. It was concluded that the temperature distribution needs to be different for different nature of sections in order to arrive at the safe design.

The demand for high-strength concrete (HSC) has increased in recent years with the increase of modern construction projects (e.g., long-span bridges, super high-rise buildings, offshore platforms and underground structures). It is well understood that improving the performance of concrete can enhance the lifespan of concrete structures (Wang et al. 2017).

The growing global population and the enormous economic development in areas prone to calamities have amplified the chance of several catastrophic incidents, which lead to disruption of buildings and infrastructures. Marasco et al. [21] discussed the importance of hazard analysis of hospital building in an effort to improve structural safety and resiliency and also to reduce the building life-cycle costs.

In the recent past, it was reported that development of Steel-Carbon FRP Composite Bars (SCFCB) actually makes up for the lack of ductility of FRP rebars to certain extent and thereby reducing engineering costs [30]. The results also indicated that under the same conditions of reinforcement ratios, the SCFCB-reinforced beams exhibit better performance than CFRP-reinforced beams, and stiffness is slightly lower than that of steel-reinforced beams.

Tariq and Bhargava [28] highlighted the importance of dealing with aggressive corrosive environment and subjected to accidental fire. It was highlighted that accidental fires can cause irreparable damage to the construction. The load–deflection characteristics of structural elements were studied under the influence of corrosion-temperature interaction.

Gedam [13] proposed the performance-based fire resistance design method for evaluating the flexural carrying capacity of reinforced concrete beams. It was observed that the developed method is capable of predicting fire-resistance rating of RC beams. The type of aggregate plays a crucial role in the flexural carrying capacity at fire lad.

Cao and Nguyen [7] highlighted the importance of flexural performance of post-fire Reinforced Concrete Beams as a part of retrofitting strategy. It was observed that the ductility of post-fire specimens was decreased by up to 61.1%. Apart from ductility, yield strength, yield stiffness and yield deflection were also affected.

5 Literature Review—Earthquake Resistance

Erkmen and Saatcioglu [11] studied the seismic performance of carbon fiber reinforced polymer concrete frame buildings. It was found that upon applying cyclic dynamic loading, seismic force demand can be lesser than that computed through equivalent static load analysis using experimentally determined period values. This highlights the significance of FRP as a material as a choice for earthquake resistance as well.

Eslami and Ronagh [12] performed a numerical examination of the enhancement in seismic performance of RC buildings having glass and carbon FRP wrapping: both code-complying and poorly-confined reinforced concrete buildings were considered. Non-linear analysis showed that the GFRP and CFRP wrappings are incapable of enhancing the ductility of code-complying structures, but they significantly enhanced the ground motion resistance of poorly-confined buildings.

A study reported by [27] highlighted the influence of ductile detailing on the performance of RC building frame subjected to earthquake and fire and concluded that the ductile detailing was found essential in arresting the fire damage and the extensive spalling. A full-scale fire test was conducted on an already damaged RC frame. A non-ductile detailing resulted in the higher temperatures and thermal damages in the RC frame and its constituent elements. It was also highlighted that the threat posed by post-earthquake fire scenario such as San Francisco (1906), Northridge, Los Angeles (1994), and Kobe (1995) resulted in massive failure of buildings and loss of human lives. Until the mid-1970s, the engineering community knew little about how to design structures to resist earthquake loads safely. As a result, the entire global inventory of buildings and bridges that were constructed prior to those dates are unsafe for resisting earthquake loads. This is evident by the large number of older buildings that have collapsed or were severely damaged in recent earthquakes.

Salem and Issa [26] performed non-linear finite element analysis of high and ultra-high strength concrete beams reinforced with FRP bars and observed that concrete strength has a small effect on the ultimate capacity. However, the deflection is higher for beams with lesser strength. It was also observed that CFRP reinforced beams showed higher capacity and lesser ductility, while GFRP reinforced beams showed lesser capacity and higher ductility.

Del Zoppo et al. [8] observed from his experience on earthquakes and also through experimental analysis that use of external reinforcement systems, such as CFRP, is herein experimentally investigated as a reliable method for enhancing the capacity of short RC members and also helps in preventing the undesirable brittle shear failure. It was also highlighted that L'Aquila earthquake (2009) confirmed the high incidence of columns brittle failure due to shear, especially in case of reduced shear length (i.e. band-type windows, semi-basement, etc.). 56 out of 284 heavily damaged RC buildings were susceptible to shear failure of columns. Also, shear failures were also observed in slender columns for those structures designed using "first-generation" seismic codes, non-conforming to present day requirements.

Lee et al. [18] proposed a novel sprayed FRP strengthening technique for RC columns. Different permutations and combinations of chopped glass and carbon fibers with epoxy/vinyl ester resin were gushed onto the RC columns and dynamic loading was applied. The shear strength and deflection capacity of the column increased pointedly upon the usage of FRP; the most optimum mix was found to be the one having glass and carbon fibers mixed with resin in a 1:2 proportion. The shear strength of the FRP-strengthened specimens, on average, was found to be 31% greater than the control columns.

Zeng et al. [34] studied the seismic behavior of basalt **F**ibre reinforced Polymer-**R**ecycled Concrete Aggregate-**S**teel **C**olumns (FRSCs) having shear connectors. FRSCs are capable of withstanding significant lateral loads, have very high ductility. The presence of shear connectors on the inner steel tube was observed to be instrumental in opposing the buckling of steel, and enhancing the lateral load capacity.

Mincigrucci et al. [23] conducted a comparative study between GFRP, RC and steel frames subjected to seismic loading. Using GFRP decreased the base shear by approximately 40% in comparison to steel and by 88.5% in comparison to reinforced concrete. The Von Mises equivalent stress time histories reveal that the FRP frames exhibit more regularity in behaviour than steel and RC. However, the FRP frames show a less uniform stress distribution than steel and RC.

6 Literature Review—High Strength Concrete

ASCE [3] defines sustainability as a combination of economic, environmental, and social circumstances in the society has the capability and possibility to maintain and enhance its quality of life for the upcoming generations without deteriorating the quantity, quality, or accessibility of resources. Even though the embodied energy of concrete is among the lowest compared to other engineering materials [4], the concrete industry is still one of the significant industrial pollutants. The cement industry alone is accountable for approximately 5–8% of the world's CO_2 emissions [22]. It is also to be noted that most materials used in construction are still natural and non-renewable.

Sustainable Ultra High-Performance Concrete (UHPC) is defined as that UHPC whose fresh-state and hardened-state properties can be tailored to meet design specifications including sustainability [31]. The partial utilization of agricultural and industrial waste as alternatives for cement, aggregate, and rebar materials in the manufacture of sustainable UHPC can be the solution. ACI 239R (ACI 2018) defines UHPC as a fiber-reinforced concrete that has a compressive strength of at least 150 MPa with specific durability, ductility, and toughness requirements. Also, according to ACI 363R (ACI 2005), high-strength concrete is concrete having a compressive strength of 55 MPa or greater.

Though UHPC is having many benefits in terms of certain characteristics such as impermeable, ductility, energy absorption, it may also potentially cause shrinkage problems and can be very fragile without any steel fibre [29]. There is a great need to reduce the cost of such HPC by looking for materials that not only satisfy technical needs, but also satisfy the budgetary constraints. UHPC certainly has teething issues and needs further refinement before being put into practice in masses.

7 Literature Review—Basalt Fibre—Sustainable Construction Material of the Future

Basalt fibre was originally developed in the Soviet Union during the 1960–1980s. Basalt fiber is a material made from extremely fine fibers of basalt, which is composed of the minerals plagioclase, pyroxene, and olivine. Basalt is usually black or dark gray

Fig. 1 Chopped basalt fibers

and relatively featureless. It is composed of mineral grains which are mostly indistinguishable to the naked eye. Basalt may also contain volcanic glass (Fig. 1) (based on Zhang et al. [36]).

Basalt fiber is an inorganic material produced from volcanic rock called basalt. The production of basalt fibers does not create any environmental waste and it is nontoxic and biodegradable. Basalt fiber has been considered to be environmentally safe and noncorrosive with good insulating characteristics and thermal endurance. It is stable in all aggressive environments, does not conduct electricity, and possesses a high tensile strength. It is believed that basalt fibre-reinforced concrete (BFRC) takes the pole position in the construction industry because it is cheaper, greener, lighter, and eliminates the problem of corrosion of reinforcement bars and corrosion-led damages in concrete structures. Currently, basalt chopped fibres are available in various lengths ranging from 12 to 100 mm and various diameters ranging from 10 to 20 μm.

The use of high-performing materials (HPM) such as high strength concrete (HSC) and fibre-reinforced polymers (FRP) have sneaked their way into the construction world in the recent years. The reason for the emergence of FRP is primarily from the durability (non-corrosive) point of view. Carbon and Glass fibres are two of such materials which have gained significant attention due to their exceptional mechanical performance and durability. However, their use is still a concern from environment perspective as incineration of discarded fibres generates plenty of smoke and unhealthy odours. To overcome such environmentally hazardous concerns, basalt has emerged as a suitable type of fibre, which has found multiple applications in many fields. In 1990s, Basalt found its way in multiple applications of Civil Engineering field and is now recognized as ‘The twenty-first century non-polluting green material’. The use of continuous basalt fibre, considered to be the potential fire resistant material, has already been explored as an alternative to the steel reinforcement in achieving the desired strength and ductility characteristics under very severe temperature conditions.

Table 1 Chemical composition of basalt fibre

Name of the chemical compound	Percentage
SiO_2	49.58
TiO_2	2.08
Al_2O_3	14.48
Fe_2O_3	4.42
FeO	9.43
MnO	0.17
MgO	5.10
CaO	8.50
Na_2O	1.89
K_2O	1.12
P_2O_5	0.35

Basalt is an igneous rock that contains more than 45 and less than 52% of SiO_2 and less than five percent of total Alkalies ($K_2O + Na_2O$) (Table 1) (based on Yuvaraj et al. [32]).

Yoder and Tilley (1962) developed Basic Tetrahedron model (Dhand et al. 2015) for the classification of minerals that constitute basalt rocks. The four corners of the tetrahedron represented the four major constitutive minerals i.e. Forsterite (Olivine), Diopside (Pyroxene), Nepheline (Feldspathoid) and Quartz. Chemically, basalt rocks cover almost 70% of the earth's surface and mainly contain Silica (SiO_2), Alumina (Al_2O_3), Ferrous Oxide (FeO), Calcium Oxide (CaO), Magnesium Oxide (MgO) etc. These rocks are classified as alkaline, mild-acidic and acidic basalts according to the variation in the SiO_2 content. Generally, only acidic basalt (SiO_2 content > 46%) qualifies as suitable for the preparation of basalt fibre, as high silica content is required to develop glass network. Moreover, SiO_2 is also responsible for strength, hardness and thermal characteristics of basalt. The brittleness of basalt is due to the crystalline nature of SiO_2. Al_2O_3 and FeO, on the other hand, are responsible for imparting characteristics like wear resistance, alkali and acid resistance, thermal stability, stiffness etc. [25]. The brown colour of basalt fiber is due to the presence of FeO [19]. CaO provides strength and bonding nature to basalt. MgO is responsible for Its chemical stability at elevated temperatures and moisture resistance.

8 Manufacturing of Basalt Fibres

Basalt rock is principally composed of silica, alumina, with lime, magnesium oxide and ferric oxide found in lesser percentages. For fabrication of continuous basalt fibre (CBF), the quantity of each material needs to be controlled. Mineralogically speaking, basalt is primarily constituted of plagioclase, pyroxene and olivine. To create basalt fibre, the basalt rock is mined and crushed into basalt fractures. Batches of basalt fractures are sorted and mixed in order to achieve the desired composition. These blended fractures are then melted in a furnace. Once the basalt fractures are heated to an optimal temperature of between 1400 and 1600 °C, the molten basalt is extruded into continuous filaments with a diameter of 12–18 μm. CBF may be formed into chopped basalt fibre strands, basalt fabrics, basalt wires or meshes, which can then be used in a wide range of application areas. It is similar to fiberglass, having better physico-mechanical properties than fiberglass, but being significantly cheaper than carbon fibre.

9 Summary and Conclusions

This paper presents overview of the importance of considering various aspects of Fire and Seismic behavior and also the usage of FRP, especially the Basalt Fibre. The high-strength and high-performance concrete are going to be unavoidable in future because of multiple constraints and expectations in the construction industry.

FRP as a material has a potential to excel in many areas including durability, corrosiveness, fire resistance etc. Also, basalt, which is considered as a green and sustainable material has excellent capability in dealing with fire. It also possesses better physico-mechanical properties and hence suitability is non-negotiable.

Strength, durability, stiffness, and ductility are few of the capabilities that are sought in structural members. The design of FRP can be done in such a way that it satisfies good number of characteristics and thus making it a viable material to be used in the construction of buildings. A high strength to weight ratio is very promising, and hence the issue of weight increase due to FRP does not emerge as a discussion point.

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