Composites Science and Technology

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Fiber Reinforced Polymeric Materials and Sustainable Structures

Springer

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Preface

At the outset, it was our great privilege to extend a hearty welcome to all participants and invited speakers to the US2020 Partnership Workshop on "FRP Materials and Sustainable Structures," organized by the Department of Civil Engineering, Birla Institute of Technology and Science, Pilani, Pilani Campus (Rajasthan), India, on March 4th, 2022, leading to the creation of this book.

As we know that the COVID-19 pandemic has engulfed the whole world and the big question is whether the world population have enough sustainable resources and strategies in place to safeguard themselves from COVID-19 and similar infectious diseases. The entire scientific community is worried about the sustainability of resources for the future generations to come which includes sustainable civil engineering infrastructure systems in the post-COVID conditions.

The infrastructure in the form of buildings, bridges, roads, railways, airports, power plants needs to satisfy all the requirements of safety while being cost-effective and sustainable. The greater awareness of the world's limited natural resources and the desire for state-of-the-art systems necessitate new materials to be adopted in design and retrofitting of structural systems. Also, the ever-increasing world population coupled with the movement of people toward urban world has resulted in an unprecedented demand in terms of new infrastructure systems being built in a place that is likely to experience multiple natural hazards such as earthquakes, hurricanes, wind storms, flooding, and fire. Many new fields with innovative materials are born in the civil engineering domain such as structural health monitoring that essentially reflects the need for continuous monitoring of structures for sustainability, and advanced composite materials such as FRPs and development of design approaches to cater for the new construction materials.

In recent years, advent of advanced composite materials such as carbon fiber reinforced polymer (CFRP), glass fiber reinforced polymer (GFRP), aramid fiber reinforced polymer (AFRP), and basalt fiber reinforced polymer (BFRP) systems has provided solutions to the many problems related to deteriorating health of civil engineering infrastructures such as reduced strength, stiffness, and most importantly durability. Furthermore, the development of natural fiber-based composites has led to the cost-effective as well sustainability-based design of FRP reinforced and/or

FRP strengthened concrete infrastructures. These advanced and natural fiber-based composites have great potential for upgrading the strength, stiffness, and resilience of the structural systems in particular and civil engineering infrastructures in general.

Thus, this book is based on presentations made at one-day international workshop at BITS Pilani on the development of innovative FRP materials using different types of fibers and polymeric systems/resins for structural applications. In addition, this book also deals with current design practice for using different kinds of FRP materials for improving strength, stiffness, durability, resilience, and sustainability of structural systems. Further, emphasis is placed on the use of agricultural waste-based fibers for developing green composites for civil engineering infrastructures. Moreover, FRP material characteristics, manufacturing techniques, background and history of its use with its advantages and disadvantages along with design of retrofitting and rehabilitation of structures using FRP are presented in detail. Hence, researchers and the practicing engineers working in the broad field of design of civil infrastructures can significantly gain by keeping abreast of the latest trends and developments in the field of FRP materials for design of high-performance structural systems with adequate sustainability and durability. We are thankful to all speakers and authors who have contributed their valuable chapters for bringing out this wonderful book.

Finally, we do hope that all the valuable chapters from eminent speakers and authors will be beneficial to the researchers, practitioners, and academicians and will create further opportunities to enrich their knowledge in the field of FRP materials and sustainable structures with primary aim of fabricating the structures with lowest carbon footprint and reduced greenhouse gas emissions.

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Contents

Fire Resistance Requirements for Bio-Based Fiber-Reinforced Polymer Structural Members

Venkatesh Kumar R. Kodur, S. Venkatachari, Vasant A. Matsagar, and Shamsher Bahadur Singh

Abstract In this chapter, the fire resistance requirements for structural components incorporating bio-based fiber-reinforced polymer composites are presented. The factors that are to be accounted for in evaluating the performance of fiber-reinforced polymer (FRP) structural members at elevated temperatures are discussed. In addition, the various steps associated with evaluating the fire resistance, both experimental and numerical, are outlined. The application of a numerical procedure for evaluating the fire performance of a typical bio-based FRP-strengthened concrete beam is illustrated through a case study. It is shown that the fire resistance of the bio-based FRP-strengthened beam can be much lower than a similar concrete beam strengthened using conventional glass- or carbon-based FRP. Further, it is shown that the fire resistance of bio-based FRP-strengthened concrete members can be enhanced through the application of supplementary fire insulation.

1 Introduction

The use of sustainable material alternatives is gaining significant attention in various sectors due to rising environmental concerns on carbon-di-oxide (CO_2) emissions

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arising from the use of petroleum-based products, depletion of non-renewable resources, and increasing waste generation. Natural fibers, derived from agricultural waste (or by-products) are being considered as a potential alternative, in place of petroleum-based synthetic fibers (such as glass or carbon-based fibers), for the development of bio-based composite materials for use in civil engineering applications. Natural (or bio-based) fiber-reinforced polymers (NFRP) offer several advantages over traditional FRP materials, including cost savings, relatively lightweight, appreciable strength and stiffness properties, and environment friendly benefits. Furthermore, finding such applications for agricultural waste will lead to reduced carbon emissions, energy savings, and economy in the construction sector.

NFRP composites are currently being used in some engineering applications. Table 1 shows the properties of various traditional FRP and NFRP fibers and their composites at room temperature as reported in published literature [1–5]. NFRP composites incorporating jute, hemp, kenaf, and bamboo fibers are used in the manufacture of automotive parts, packaging, and to a limited extent in structural components (such as wall panels, bricks, window frames, etc.) [4, 6]. In addition, NFRP composites are also finding increasing applications in the fabrication of electrical and electronic components, sports equipment, and aerospace components. The use of NFRP composites in these applications is due to their low specific weight, low cost, locally sourced materials, and resistance to corrosion and fatigue. However, the high moisture absorption, poor thermal performance, and variable quality of the NFRP composites limit their wider use [7–9].

While the use of NFRPs is, at present, mainly in non-structural applications, there is enormous potential for its use in buildings, especially in strengthening and retrofitting applications, where the span of structural members is small and the required strengthening requirements are low to moderate. When used in buildings, structural members must be designed to satisfy the appropriate fire resistance requirements, in addition to other requirements such as flammability and smoke development criteria specified in building codes [1]. These fire resistance requirements are included in the codes on the premise that when other measures of controlling fire fail, structural integrity is the last line of defense. Currently, one of the main impediments to using bio-based FRPs in buildings is the lack of knowledge about the fire performance of bio-based FRP composites.

In this paper, the fire resistance requirements for bio-based FRP composites are discussed. The factors that differentiate the performance of NFRP at elevated temperatures, as compared to that of traditional materials, such as concrete, steel, and conventional FRP are discussed. The general procedures associated with evaluating the fire resistance, both experimental and numerical, are outlined. Through a case study, the application of the numerical procedure for evaluating the fire performance of a NFRP-strengthened concrete beam is illustrated.

Table 1 Room temperature material properties of synthetic and natural fibers and their composites

Fiber or composite	Density (g/cm^3)	Tensile strength (MPa)	Elastic modulus (GPa)	Elongation at break (%)
Carbon	1.7	4000	230–240	1.4–1.8
E-glass	2.5	2000–3500	70	2.5
S-glass	2.5	4570	86	2.8
Aramid	1.4	3000–3150	63–67	3.3–3.7
Cotton	1.5–1.6	287–800	5.5–12.6	7.0–8.0
Jute	1.3–1.45	393–773	13–26.5	1.16–1.5
Flax	1.5	345–1100	27.6	2.7–3.2
Hemp	1.48	550–900	70	1.6
Sisal	1.45	468–640	9.4–22	3–7
Coir	1.15	131–175	4–6	15–40
Carbon/epoxy	1.5–2.1	1050–1500	180	0.5–1.8
Glass/epoxy	1.25–2.5	700–1050	42–55	1.2–5
Aramid/epoxy	1.25–1.45	1400	76	1.4–4.4
Jute/unsaturated polyester	–	50	8	–
Flax/epoxy	–	132–160	15–27	–
Hemp/polypropylene	–	52	4	
Sisal/epoxy	–	330–410	6–10	–
Kenaf/polypropylene	–	46	5	–

2 Need for Fire Resistance in Bio-Based FRP Composites

For structural applications, conventional FRP composites offer several advantages over traditional construction materials like steel and concrete [1]. However, unlike steel and concrete, the FRP composites are highly combustible and burn when exposed to fire. Flame spread and toxic smoke generation are two major issues that limit the application of FRP composites in building applications, and the extent of flame spread largely depends on the type and composition of the specific FRP material.

Owing to their combustible nature, the FRP composites begin to decompose even at low to moderate temperatures in a fire scenario. In addition, the strength and stiffness properties of the FRP undergo rapid degradation with a moderate temperature rise of 200 to 300 °C. Further, the interfacial bond properties of the FRP composites also experience drastic degradation with temperature rise that affects the load (or stress) transfer between the FRP and concrete. Due to these issues concerning the high-temperature behavior, the FRP composites demonstrate poor fire resistance properties.

Much like the traditional FRP composites, NFRP composites are also highly susceptible to flaming, charring, material degradation, and rapid loss of strength and stiffness properties when exposed to elevated temperatures [8, 10, 11]. NFRP composites also have lower initial strength and stiffness at ambient conditions in comparison to traditional FRPs. In addition, the degradation in material properties in the case of NFRPs can be more drastic since the NFRPs incorporate natural fibers (such as hemp, jute, rice husk, etc.) in place of synthetic fibers (such as carbon or glass).

To illustrate the difference in the behavior of FRP at elevated temperatures, the variation of strength and stiffness with temperature for conventional and bio-based FRP are presented in Fig. 1 along with other traditional construction materials. In the figure, the ratio of strength at elevated temperature to that at room temperature is plotted. As is the case with steel, concrete, and wood, the strength of FRP also decreases with increasing temperature. While the data for concrete, steel, wood, and conventional FRP is well documented in the literature [1], there is no reliable data for the properties of NFRP at elevated temperatures. Based on the limited information available at room temperature conditions, the NFRPs have much lower strength and stiffness as compared to conventional FRPs, such as CFRP, GFRP, etc. Also, since the NFRPs incorporate plant-based fibers, the drop in strength and stiffness is likely to occur early (at a lower temperature rise) and at a more rapid pace than conventional FRPs. With these considerations, the probable trends for strength and stiffness degradation of NFRP are shown in Fig. 1. As can be seen in the figure, the rate of strength and stiffness loss is much greater for FRP than that of concrete and steel. In the case of concrete, the 50% strength loss does not occur until about 600 °C whereas for steel the corresponding temperature is 500 °C. The critical temperatures (50% strength loss) of CFRP and GFRP are 250 °C and 325 °C, respectively [12]. The critical temperature of NFRPs is expected to be much lower than that of conventional FRP. In addition, the strength and stiffness characteristics of the NFRP can vary significantly depending on the type and composition of the FRP, and the quality of the natural fibers used in the composite.

3 Fire Resistance Requirements

Structural members are to be designed to satisfy the requirements of serviceability and safety limit states. One of the major safety requirements in building design is the provision of appropriate fire resistance to structural members. Structural members are required to meet the criteria for flammability, smoke development, and fire resistance ratings prescribed in building codes and standards.

Since the FRP materials are highly combustible, a large extent of toxic gases, heat, and flame spread can get generated during the burning of the FRP. The emitted smoke and flame spread can hinder the occupant evacuation and firefighting operations during a fire incident. For these reasons, construction materials are classified based on flame spread index (FSI) and smoke-developed index (SDI) for use in

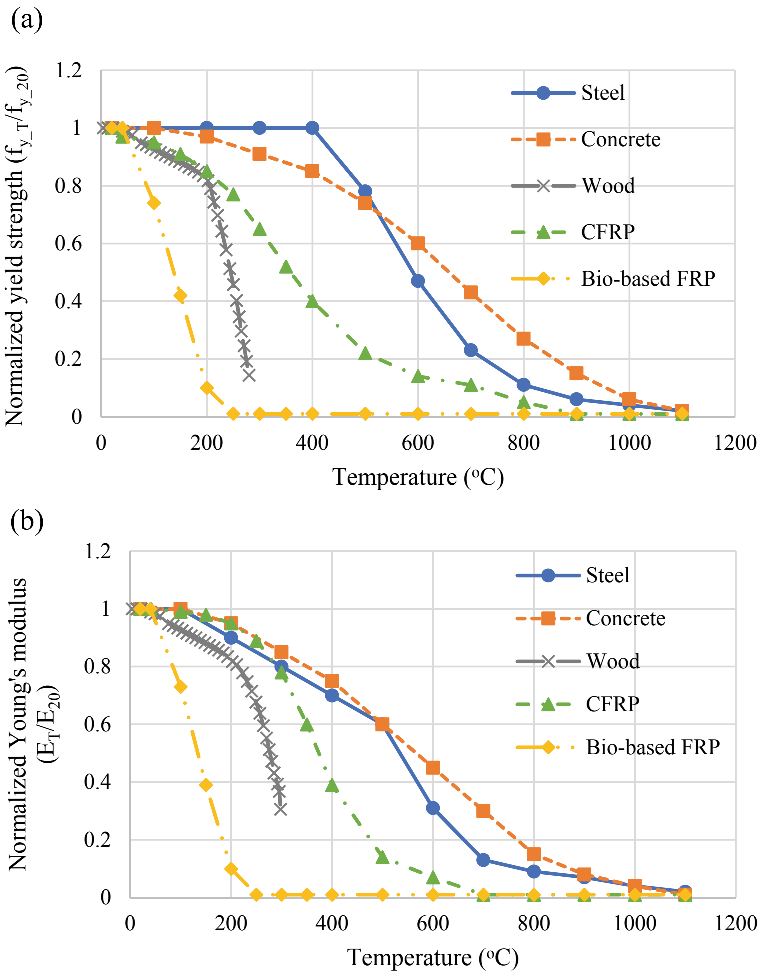


Fig. 1 Variation of **a** strength and **b** stiffness with temperature for different materials

building applications. Evaluation of flame spread and smoke development is undertaken through standard tests as per test procedures recommended in different standards such as the American Society for Testing and Materials (ASTM) and National Fire Protection Association (NFPA) standards. The test procedures for measuring FSI and SDI for different building materials are specified in ASTM E84 [13] and NFPA 255 [14] standards. In these test methods, the surface burning behavior of a material is evaluated using a Steiner Tunnel setup, which is available in certain laboratories such as the Underwriters Laboratories (UL) in Northbrook, IL, USA. Additional characteristics such as specific optical density of smoke generated and surface flammability of building materials can be obtained using ASTM E662 [15] and ASTM E162 [16] testing protocols. Typically, the FSI and SDI classifications for FRP materials are provided by the manufacturer in directories such as UL and also in some building codes based on the standard testing protocols discussed above. Currently, such classifications are not available for NFRP materials and need to be generated for their use in buildings.

In addition to the above requirements for flammability and smoke development, the structural members in buildings are also required to satisfy minimum fire resistance ratings. Fire resistance is defined as the ability of a structural member to carry its service loading at elevated temperatures that could be encountered in a fire. It is the time during which a structural member exhibits resistance to failure. On the other hand, building codes specify a minimum time for which a structural member has to withstand the effect of fire, without experiencing failure. These times are expressed in hours (1, 1.5, 2, 3, and 4 h) and are referred to as fire resistance ratings. Typical fire resistance rating requirements for specific structural members in a building are specified in building codes, such as the International Building Code (IBC) 2021 [17] and National Building Code of India 2016 [18]. Generally, the fire resistance rating of a structural member is a function of applied load, member type (e.g., column, beam, wall), member dimensions, probable fire intensity, and type of construction material (concrete, steel, or wood). In addition, the ratings also depend on the type of occupancy, the number of stories, and the floor area in a building. For instance, the fire resistance ratings required for columns in multi-story buildings vary from 1 to 4 h while primary beams are required to have a fire resistance rating of 1 to 3 h (IBC 2021 [17]).

The fire resistance of a structural member depends, in part, on the materials used in its construction. Structural components made of bio-based FRP should also satisfy the fire resistance requirements. While the commonly used fire protection techniques for concrete and steel can also be adapted for achieving the required ratings of NFRP structural members, in general, there are some major differences associated with FRP as a material. In steel-reinforced and prestressed concrete structural members, the concrete cover thickness requirements, for the steel reinforcement, are complemented, to a certain extent, by the requirements for corrosion control. For FRP-reinforced concrete structural members, no special concrete cover thickness provisions are required for corrosion control. However, the size of the concrete section, cover thickness, and insulation (if any) needs to be determined based on the strengthening requirements and limiting the temperature rise in the FRP reinforcement. Since the NFRP composites have lower initial strength and stiffness as compared to conventional FRPs, a larger thickness (or more number) of NFRP reinforcement may be needed to achieve similar performance as that of conventional FRP composite members.

Also, where NFRP sheathing or externally bonded NFRP sheets are used as external reinforcement in the repair or rehabilitation of a structural member, fire performance characteristics of the concrete member might be affected due to the flammable nature of the FRP composite. In this case, the building codes also require that the overall structural assembly satisfy appropriate fire safety requirements. This can be achieved by applying a layer of fire insulation to the FRP-strengthened member.

4 Fire Resistance Assessment

The fire resistance of structural members can be determined through standardized fire resistance tests; however, such tests are costly and time-consuming. Alternatively, rational methods can be applied to evaluate the fire resistance of structural members. These methods can be carried out at a simplified level or an advanced level through numerical analysis. In these methods, the sectional temperatures that develop in a fire-exposed member and the degradation in the structural behavior are traced to evaluate the fire resistance of the member. In this section, the steps associated with evaluating fire resistance, both testing and numerical methods, are outlined.

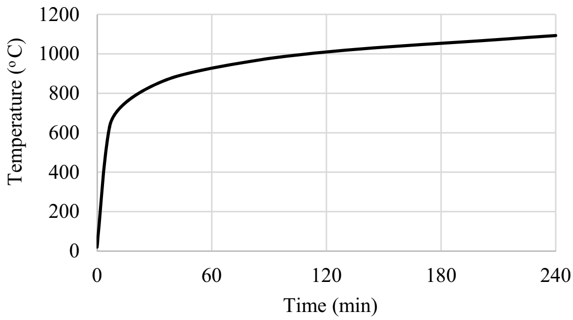
4.1 Testing

A common method to assess fire resistance is by subjecting building elements, such as beams, slabs, or walls to a standardized fire test. Data from these tests can be used to develop fire resistance ratings of different structural members. The fire resistance of bio-based FRP composite structural members (or components) can be evaluated through fire tests as per specifications in codes and standards in a particular country such as ASTM E119 [19], NFPA 251 [20], ISO 834 [21], etc.

During a test, the specimen is exposed to a standard fire in specially built test furnaces. Figure 2 shows the standard time–temperature curve as per ASTM E119 specifications [19]. The test furnace is designed to reproduce conditions that a member might be exposed to during a fire, which includes temperature, structural loads, and heat transfer. In addition, the test specimen needs to be fabricated to ensure normal quality and condition at the time of testing. Depending on the size of the furnace, the dimensions of the FRP composite member that can be tested can vary.

Several fire tests have been carried out on conventional FRP-strengthened concrete members to develop fire resistance ratings [22–26]. In these tests, FRP-strengthened concrete members with different types of strengthening methods, insulation schemes,

Fig. 2 ASTM E-119 standard fire time–temperature curve for testing building elements



and fire scenarios have been tested. These tests indicate that FRP-strengthened reinforced concrete members with supplemental fire protection can achieve the required fire resistance ratings (up to 4 h) under standard fire exposure. However, such fire test data is unavailable for NFRP composite members.

In the fire test method, the fire resistance rating is expressed as the time that the specimen reaches specified limiting criteria of performance during exposure to a standard fire. There are three performance criteria in the standard test method. These are related to load-bearing capacity (strength), insulation, and integrity criteria [1]:

Load-bearing capacity: For load-bearing constructions, the test specimen shall not collapse in such a way that it no longer performs the load-bearing function for which it was constructed.

Insulation: For constructions such as floors and walls that have the function of separating two parts of a building, the average temperature rise at the unexposed face of the specimen shall not exceed 139 °C, the maximum temperature rise at the unexposed face of the specimen shall not exceed 181 °C.

Integrity: For constructions such as walls, floors, and roofs, the formation in the test specimen of openings through which flames or hot gases can pass shall not occur. Failure of integrity is deemed to have occurred when a specified cotton wool pad applied to the unexposed face is ignited.

In many cases, not all criteria have to be satisfied. Beams, for example, are required only to demonstrate the load-bearing capacity criteria; the ability to carry loads for the fire resistance period. Non-load-bearing walls, if used as fire separations, have only to meet the requirements of integrity and insulation. Load-bearing fire separations, however, have to meet all three criteria of performance.

Results, obtained from the standard tests, can be used as a basis for developing fire resistance ratings for NFRP-strengthened concrete members. These ratings are given in the tabulated form in terms of minimum dimensions to obtain specific fire resistance ratings. For concrete walls, for example, the minimum thickness of the concrete to obtain specific fire resistance is given. For concrete floors, the minimum thickness of the floor and the minimum thickness of the concrete cover to the reinforcing steel are given.

4.2 Numerical Modeling

Evaluating the fire resistance ratings through fire tests is quite expensive, complicated, and time-consuming. Numerical modeling, on the other hand, is an effective alternative to evaluating the fire performance of bio-based FRP composite members. In addition, the numerical model also allows quantifying the effect of various governing parameters, such as the type and composition of the FRP composite, different types of strengthening methods and fire insulation schemes.

Numerical models, capable of simulating the behavior of structural members under fire conditions, have been developed for predicting the fire resistance of conventional FRP-strengthened concrete members [27, 28]. Such models can be applied for evaluating the fire resistance of bio-based FRP-strengthened concrete members through appropriate material properties, discretization, and fire limits for the natural fiber-based composite members. A flow chart, illustrating the calculation procedure employed in such models, is shown in Fig. 3. The calculation of fire resistance is performed in three steps:

1. calculation of the fire temperature,

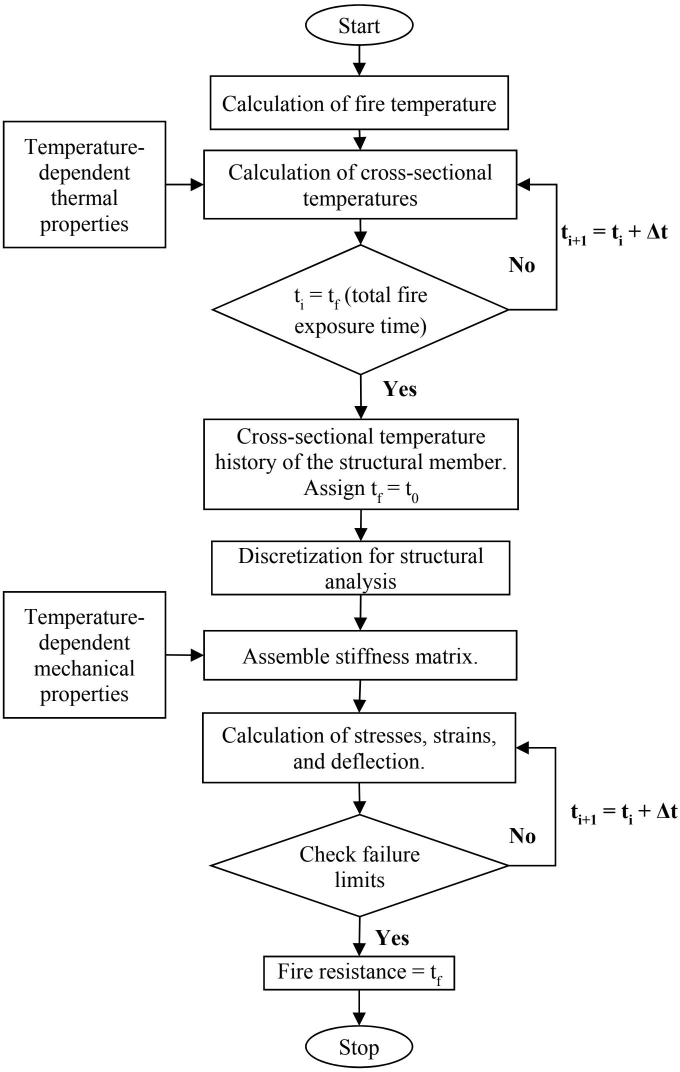


Fig. 3 Flowchart showing numerical procedure for evaluating fire resistance of structural members incorporating bio-based FRPs

2. calculation of temperature in the fire-exposed FRP-strengthened member, and
3. calculation of capacity and deformations of the FRP-strengthened member during the exposure to fire.

Fire Temperature: At present, in calculations of fire resistance of NFRP-strengthened concrete members, the fire temperature course is assumed to follow the ASTM E119 standard or equivalent temperature–time relation. For evaluating the performance of the structural member under more realistic fire severities, other design temperature–time relationships such as the parametric fire curves in Eurocode 1 [29] or design fire scenarios generated as per the recommendations in the SFPE Handbook [30] can be utilized.

Structural Member Temperature: The next step in the procedure is the calculation of the temperatures of the fire-exposed member. These temperatures are calculated using a 2-D heat transfer analysis. In this method, the cross-section of the member is divided into a number of elemental regions, which may have various shapes such as squares or rectangles, depending on the geometry of the member. For each element or layer, a heat balance is made. By solving the heat balance equations for each element or layer, the temperature history of the member can be calculated.

Strength: In the third step, a structural analysis is conducted to determine the capacity and deformations in the member during exposure to fire. The FRP-strengthened member is discretized into several segments along the length of the member, and the cross-section at the center of each segment is divided into several elements (same as the heat-transfer analysis). Moment–curvature relations are derived for various segments of the member by applying force equilibrium and strain compatibility. These time-dependent moment–curvature relations are used to generate the moment and deflection at different segments as a function of fire exposure time.

The response parameters obtained from the numerical analysis include the cross-sectional temperatures, stress and strains, moment capacity, and deflections. These response parameters are compared with the different failure limits, as prescribed in ASTM E119 [19]. The fire resistance is obtained by determining the time at which the failure limit states are reached. The temperature, strength, and deflection-based failure limits are given below.

1. The temperature in the tensile reinforcing steel reached 593 °C.
2. The average temperature on the unexposed surface of the slab exceeds 139 °C or the temperature at any one point on the unexposed surface exceeds 181 °C above the initial temperature (applicable only to slabs and walls).
3. The moment carrying capacity of the structural member falls below the moment due to applied loading.
4. The mid-span deflection exceeds $L^2/400d$ (mm), and the rate of deflection exceeds $L^2/9000d$ (mm/min), where L and d are the span (mm) and effective depth (mm) of the structural member.

To calculate the fire resistance of the FRP-reinforced structural members, knowledge of the relevant thermal and mechanical properties of the constituent materials at elevated temperatures is essential. Thermal and mechanical properties of various traditional materials, such as concrete and steel rebar at elevated temperatures, are given in codes and standards such as Eurocode [31] and ASCE manual [32] and also in various published papers [33]. Only limited high-temperature material property data is available for FRP composite, and even these are for conventional FRPs [34, 35]. Methods to determine the high-temperature properties of FRP composites, including those of bio-based FRPs, are discussed in a recent publication (Kodur et al. [36]).

5 Case Study

To assess the fire performance of bio-based FRP concrete structural members, a feasibility study is undertaken with the main emphasis on the fire resistance of NFRP-strengthened concrete beams. The numerical model developed by Kodur and Ahmed [27] using the FORTRAN program and further extended by Kodur and Bhatt [28] is applied to evaluate the fire resistance of NFRP-strengthened concrete beams. Using the model, the temperature gradients in the cross-section of the member, available moment capacity, and mid-span deflections, as functions of fire exposure time, and the fire resistance of the beam can be computed. Realistic strength and deflection-based limit states are used to determine the failure of the beam. The numerical model has been validated previously against fire test data on conventional FRP-strengthened concrete members and complete details of the validation studies can be found in [27, 28, 37].

The model is applied to compare the fire performance of a NFRP strengthened concrete beam with that of a conventional FRP-strengthened beam. Two beams, one strengthened with carbon fiber-reinforced polymer (CFRP) (B1), and the other strengthened with hemp-based FRP (B2), are analyzed. Figure 4 shows the details of the beam considered for this study. The FRP reinforcement for strengthening is selected to achieve a 25% increase in the moment capacity of the beams. The tensile strength and elastic modulus of the CFRP strip are taken as 1170 MPa and 96.5 GPa, respectively and the corresponding values for the NFRP strip are taken as 52 MPa and 6.8 GPa, respectively. The strength and modulus properties of NFRP are taken based on the room temperature values reported for hemp-based FRP composites [38]. No fire insulation is applied to these beams. The beams are exposed to standard ASTM E119 fire temperatures for 240 min or until failure occurs.

The results from the thermal analysis are shown in Fig. 5 where the temperatures in the steel reinforcement, mid-concrete layer (evaluated at the mid-point of the concrete section), and FRP reinforcement are plotted against time. The critical temperature at which failure is assumed to occur, for the steel and FRP reinforcement, is also shown in the figure. For NFRP, the critical temperature is assumed as 150 °C, which corresponds to 50% tensile strength loss in hemp-based FRP. Based on the limited studies reported in the literature for NFRP composites, it is expected that the natural fiber-based composite will degrade at a faster pace than conventional FRPs and the

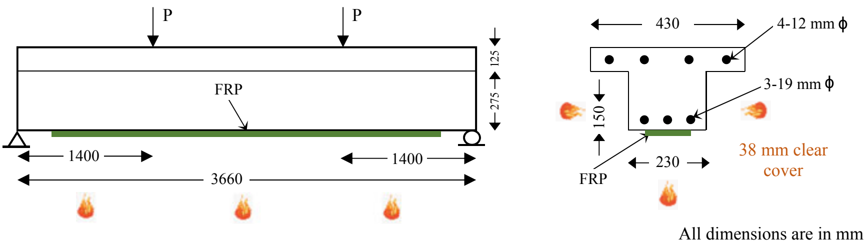


Fig. 4 Elevation and cross-section of reinforced concrete beam strengthened with CFRP or NFRP reinforcement

critical temperature can range anywhere between 125 °C and 200 °C depending on the type and composition of these composites. The critical temperature of 150 °C chosen in this study can result in a conservative estimate of the fire resistance of NFRP-strengthened concrete members. The critical temperatures for reinforcing steel and the CFRP strip are taken as 593 °C and 250 °C, respectively. The temperatures in the beam section increase rapidly with fire exposure time as can be seen from Fig. 5. The temperature in the NFRP strip is slightly lower than the CFRP strip due to the higher thickness of the NFRP (10 mm) used in comparison to that of CFRP (1 mm).

To illustrate the variation of the structural response during fire exposure, the moment capacity degradation and enhanced mid-span deflections of the beams are plotted in Fig. 6. It is seen that both beams experience rapid degradation in the moment capacity and increased deflection right from the start of fire exposure time, with the trends being more rapid for the NFRP beam. The failure or the fire resistance of the CFRP-strengthened beam is 165 min, while that for the NFRP-strengthened beam is 140 min based on the deflection limit state. The NFRP beam loses much

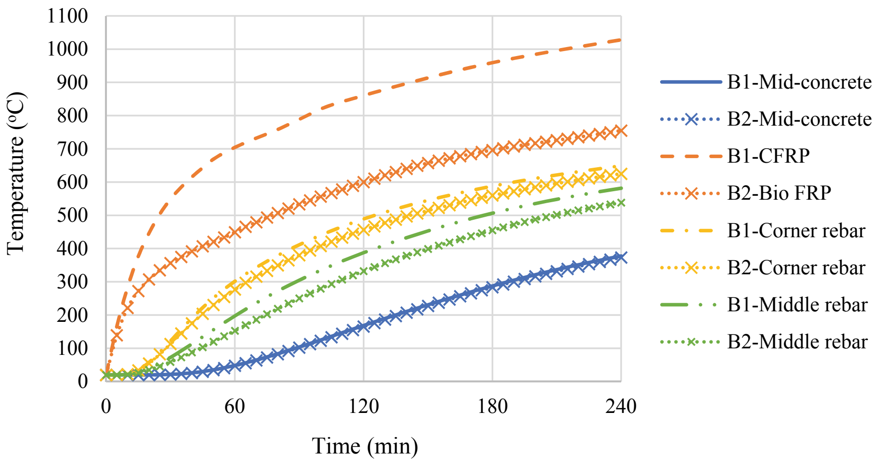
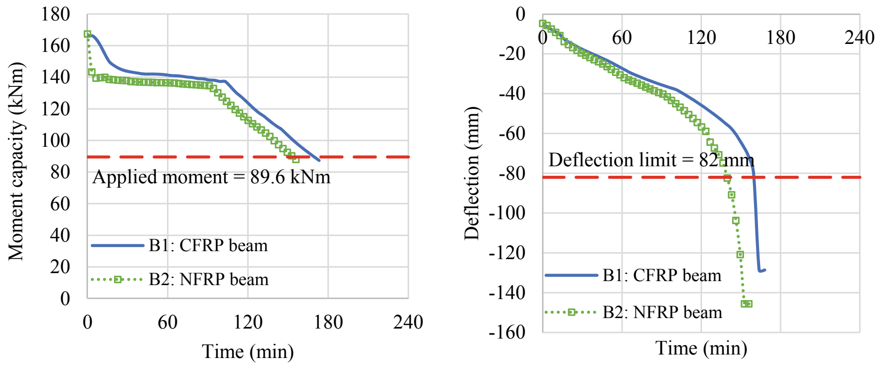


Fig. 5 Thermal response of concrete beams strengthened with CFRP or NFRP reinforcement



(a) Moment capacity (b) Mid-span deflection

Fig. 6 Structural response of concrete beams strengthened with CFRP or NFRP reinforcement

of the strengthening within 5 min of fire exposure, whereas it takes about 25 min for the CFRP beam to lose its strengthening as seen from Fig. 6. This is because of the faster degradation of strength and stiffness properties of the bio-based FRP with temperature rise as compared to the CFRP strip. Beyond these times, the FRP-strengthened beams act like regular concrete beams without any contribution from the FRP reinforcement. The fire resistance times of 140 min and 165 min in the NFRP and CFRP-strengthened beams are obtained mainly due to the resistance of the concrete section.

Application of fire insulation can delay the temperature rise in the FRP, steel rebar, and the overall concrete section, and thus increase the fire resistance of the FRP-strengthened member. When a layer of fire insulation of 19 mm thickness is applied to the NFRP-strengthened beam, it was observed that the fire performance improved significantly. The NFRP beam was able to retain its strengthening for about 40 min and experienced a more gradual increase in deflections with fire exposure time. The beam did not undergo failure for the entire duration of fire exposure of 240 min. Currently, these numerical studies are being refined and expanded to evaluate the effect of various factors including the presence of fire insulation, strengthening method, and type of FRP on the fire resistance of FRP-strengthened concrete members.

6 Research Needs

As discussed earlier, there is a lack of data on the fire performance of structural members incorporating bio-based FRPs. The fire resistance performance of NFRP structural members can be established through fire tests and calculation methods. Existing test methods and numerical models can be extended to assess the effect of fire on NFRP members. However, for evaluating the fire resistance of NFRP structural members, high-temperature material properties and material models for NFRP are required as part of the input data. While the material properties of conventional FRPs at elevated temperatures are available in the literature [39], very little information is available on the properties of NFRP composites at room and elevated temperatures.

For bio-based FRP, the effect of temperature on the following properties must be determined as a function of temperature:

- Flammability properties: Flammability index and smoke development classification
- Thermal properties: thermal conductivity, specific heat, and glass transition temperature
- Mechanical properties: tensile strength, compressive strength, modulus of elasticity, stress–strain relations, bond strength, and bond-slip relations
- Deformation properties: thermal expansion and creep

The properties of the bio-based FRP composite together with those of the steel reinforcement and concrete, as a function of temperature, can be used as input data for the numerical model. Through numerical studies, the main variables influencing the fire performance of the NFRP-reinforced concrete members can be established.

The main factors influencing the fire performance of the NFRP-reinforced concrete members, as obtained from the preliminary numerical studies, can be taken into account in designing specimens, such as beams and slabs, for fire tests. The specimens, after sufficient curing, can be tested in a specially built furnace by subjecting them to fire, according to specified time–temperature relations, under design loads. The data recorded during the fire tests will include the history of temperatures along the cross-sections, deflections, and the ultimate fire resistance of the structural members.

Data obtained from the fire tests can be used to establish the validity of the numerical model for the NFRP structural members. These numerical methods can then be used to carry out detailed parametric studies to determine the extent of influence of different parameters, such as the dimensions of structural members and concrete cover, the number (and thickness) of NFRP reinforcement, the thickness and type of fire insulation, etc. on the fire performance of the NFRP structural members.

Results from these studies can be used to make design recommendations, including optimum fire protection measures, for improving the fire performance of NFRP structural members. In addition, data obtained from the parametric studies can be used to develop simple design equations or design charts for calculating the fire resistance ratings, which can be incorporated into the building codes. Such a study on NFRP structural members, which is in progress at Michigan State University, will result in cost-effective, sustainable, and fire-safe construction, and lead to its application in buildings.

7 Summary

Based on the information presented in this paper, the following points can be drawn:

- Very limited information is available on the high-temperature properties of bio-based FRPs and fire performance of bio-based FRP structural components.
- Data on the variation of properties of bio-based FRP (thermal, mechanical, and deformation) at elevated temperatures is required for evaluating the fire resistance of structural members incorporating bio-based FRPs.
- The bio-based FRP-strengthened concrete members exhibit lower fire resistance in comparison to concrete members strengthened with conventional FRP composites.
- Supplementary fire insulation is to be applied on the bio-based FRP-strengthened members to meet the required fire resistance ratings for their use in building applications.

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Methodologies for Evaluating FRP-Concrete Interfacial Bond Strength at Elevated Temperatures

P. P. Bhatt and Venkatesh Kumar R. Kodur

Abstract The strength of interfacial bond between fiber reinforced polymer (FRP) and concrete substrata influences the capacity of FRP-strengthened concrete structure both at ambient and fire conditions. Evaluation of bond strength is a challenging task at elevated temperatures and requires specialized test setup and a complex set of procedures. In this chapter an innovative test setup and procedure for evaluating the FRP-concrete interfacial bond strength at elevated temperature is proposed, wherein double lap shear tests are conducted on concrete blocks strengthened with FRP sheet. The applicability of the procedure is illustrated by testing the concrete prisms strengthened with carbon FRP sheet at four different temperature levels. The results from the test indicated that the bond strength decreases by 35% at temperatures close glass transition temperature of bonding adhesive.

Keywords FRP-concrete bond strength · Fire resistance · High temperature properties · Bond strength test methods

1 Introduction

The potential of fiber reinforced polymer (FRP) as a strengthening and repair material in retrofitting of concrete structures is well established. Use of FRP offers advantages such as, high strength-to-weight ratio, corrosion resistance, and ease of application, over other traditional strengthening systems [1]. In majority of strengthening and retrofitting applications, FRP sheets or laminates are externally applied to the surface of concrete member using an organic polymer based bonding adhesive such as epoxy resin. The bonding adhesive serves as a medium for transfer of stresses from concrete

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to FRP, and therefore, the FRP-concrete interfacial bond is critical for effectively carrying the load on the member.

At ambient conditions current design procedures account for interfacial bond by premature debonding through limiting the tensile and shear strains at the level of FRP-concrete interface. However, under fire conditions the bond starts degrading rapidly due to softening of bonding adhesives at temperatures close to the glass transition temperature (T_g), which is in the range of 60–82 °C [2]. The rapid degradation of bond reduces the structural effectiveness of the strengthening system at a faster rate, which in turn leads to rapid reduction of the moment (or shear) capacity of the strengthened structural member, thereby resulting in earlier failure under fire conditions [3, 4]. Thus, temperature induced bond degradation has significant influence on the fire performance of FRP-strengthened concrete structural members. In fact, several experimental studies [5–10] on fire response of FRP-strengthened concrete beams have identified temperature induced bond degradation as a primary reason for early failure of FRP-strengthened beams under fire conditions. Therefore, knowledge of FRP-concrete interfacial bond behavior at elevated temperatures is a key factor in the fire design of strengthened concrete structures and must be evaluated.

Despite the severity of the issue, limited studies have been reported in the literature evaluating the behavior of FRP-concrete interfacial bond at elevated temperatures [11–17]. Different test setups were used in these studies to determine the FRP-concrete bond strength at elevated temperatures. For instance, Gamage et al. [14] and Carlos et al. [16] conducted single lap shear tests, whereas all the other studies conducted a double lap shear test (DST) on concrete blocks strengthened with FRP sheets or strips to evaluate the bond behavior at elevated temperatures. Further, these studies were conducted with different FRP materials and bonding adhesives with T_g ranging from 47 to 85 °C (measured using different methods). Additionally, due to lack of standard test procedures different types of specimens, heating rates, and load levels were considered in these studies. As a result, there exists a wide variation in the reported results, as shown in Fig. 1.

In each of the aforementioned studies, the authors reported a high scatter in the bond strength measured at same temperature level. Moreover, the bond behavior

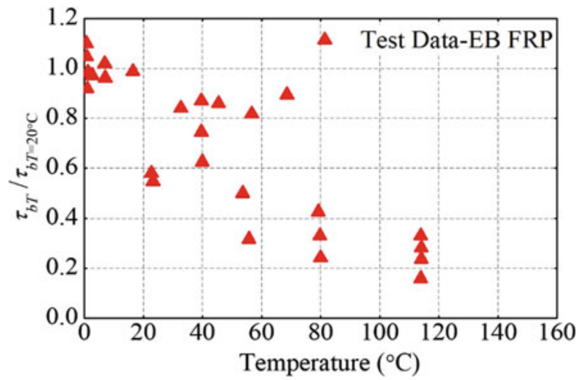

Fig. 1 Variation of bond strength with temperature as reported in various studies

reported in each of these studies was also significantly different. For instance, Blontrock [11] and Klamer et al. [12] reported an increase in the bond strength until the T_g of the adhesive followed by a sharp decrease at temperatures beyond T_g. Whereas Wu et al. [13], Gamage et al. [14], Firmo et al. [16], and Carlos et al. [17] reported a consistent decrease in the bond strength with increase in temperatures below or above T_g of the adhesives. On the other hand, Leone et al. [15] reported a decrease in bond strength until T_g of adhesive followed by an increase in bond strength beyond T_g of adhesive. Thus, it is evident from the above discussion that the results reported in the above-mentioned studies do not provide a clear understanding of the FRP-concrete interfacial bond behavior at elevated temperatures. Further, there are no recommended standardized test methods and procedure for undertaking bond strength tests at elevated temperatures [18]. To address this concern and to evaluate the bond behavior at elevated temperatures a unique test procedure is proposed in this chapter.

2 Limitations of Current Test Method

The FRP-concrete bond behaviour is primarily evaluated using direct shear test methods involving single lap shear test or double lap shear test setup. In a single lap shear test, a portion of FRP sheet is bonded to one side of the concrete block, which is held in position using a steel frame, while the other end of the FRP sheet is clamped and pulled by means of testing machine. In case of double lap shear tests, two concrete prisms are joined by an FRP sheets on two opposing faces and moved apart by means of steel rebar anchored within the blocks or through steel plates connected by bars clamped in wedges of testing machine.

The single lap shear test although easier to implement requires specific attention to maintain the alignment for ensuring pure shear stress in the bonded region. Further, the inherent eccentricity between the tensile load in FRP sheet and restraint provided by the concrete substrate often results in normal stresses in the bonded region which in turn affect the failure mode of the bond. Moreover, due to the direct clamping of the FRP sheet by the testing machine, premature failure of sheet prior to failure of bond is often observed. The double lap shear test removes the disadvantages of load eccentricity and clamped grips, but the specimen is too heavy to handle, and requires specialized equipment for measuring slip at bonded region. Moreover, the symmetrical geometry doesn't guarantee equal load distribution on either side resulting in unrealistic predictions. To address these limitations, an innovative double lap shear test method is proposed here.