State-of-the-Art on Fire Resistance Aspects of FRP Reinforcing Bars

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Abstract. The behaviour of Fibre-Reinforced Polymer (FRP) bars and Fibre-Reinforced Polymer reinforced concrete (FRP-RC) members under fire exposure is quite different from conventional means. This may be attributed to the complex behaviour of the bars when they are subjected to fire, as well as to the complexity of fire test procedures. The thermomechanical properties of FRP bars depend on the chemical composition of their constituents, their interface performance and the production process. The choice of the type of fibres and matrix with characteristics suitable for the desired purpose, as well as their balanced proportions in FRP bar can be the key factors affecting the overall resistance of an FRP element in the event of fire. The work presents a theoretical background and is intended to identify existing gaps in knowledge to justify the need for the present study.

1. Introduction

The rapidly growing interest in application of Fibre-Reinforced Polymers (FRP) reinforcement for reinforced concrete (RC) structures indicates the increasing potential of these materials from both practical and theoretical perspectives. Due to their superior properties and properties of their constituents, FRP reinforcement possess numerous advantages over steel reinforcement, such as high tensile strength, lightweight, low conductivity, ease of handling and transportation, but above all a relatively high corrosion resistance [1, 2].

Choice of particular type of FRP composites constituents and the way of their application can be done basing on considered design purpose [3, 4]. Fibres dispersed in concrete can improve the fracture mechanics parameters and post-cracking behaviour of Fibre-Reinforced Concrete (FRC) structures [5]. FRP reinforcing bars become to be used more often and nowadays the FRP bars can be found in a diverse range of applications.

Strength requirement, service life and cost are the issues that need to be addressed for the design of Fibre-Reinforced Polymers reinforced concrete (FRP-RC) structures. The maintenance of conventional steel RC structures is a major problem which requires costly-to-rectify solutions [6, 7]. The relatively non-corrosive behaviour of the fibres allows for significant reduction of concrete clear cover without compromising the material’s durability [8].

However, there are many remaining issues which have not yet been thoroughly addressed in available standards and literature. These issues, among others, include the brittle nature of FRP composites, long-
term durability, hybrid composites performance, fire resistance, etc., that might hinder widespread applications of FRP bars in the construction industry [6, 9].

The fire and elevated temperatures may cause significant damage of RC structures, therefore a reliable and accurate estimations of possible risks is a real necessity [7, 10]. However, the available data related to fire resistance aspects on FRP reinforcing bars and FRP-RC members at high temperatures are still scarce. The behaviour of the bars is atypical comparing to steel bars and mainly depends on the properties of reinforcing fibres, matrix and the volume ratio of constituents.

The matrix can be seriously affected at elevated temperatures, most of the matrices types are flammable and produces large amount of poisonous smoke. Glass transition temperature for most common use matrices are not higher than 200°C. After this threshold, stresses in FRP bars are transmitted only by fibres, for which upper use temperature point may be higher than 1000°C.

Figure 1 shows Hybrid Carbon/Basalt FRP (HC/BFRP) bars, which were uncovered by removing the concrete clear cover. The temperature caused a burning of the FRP bars that resulted in the evaporation of the matrix in the bars. The analysed HFRP bars were composed of carbon-to-basalt fibres (volume fraction 1:3) and epoxy resin [2]. As it can be seen from the figure, a major part of the fibres remain in the same place and continued to sustain the load. The temperature, however, caused debonding with concrete, completely separating the reinforcement with the concrete surface.

Figure 1. HFRP Bars of 8mm Diameter
(Research on HFRP Bars Conducted at Warsaw University of Technology)

Experimental work on FRP bars have shown that the transverse coefficient of thermal expansion (CTE) of FRP bars is typically much higher than its longitudinal CTE. Carbon Fibre-Reinforced Polymers (CFRP) have CTE in the longitudinal direction, $\alpha_L$, close to zero (from $-9 \times 10^{-6}/{^\circ}C$ to $0/{^\circ}C$), CTE transverse direction from $74 \times 10^{-6}/{^\circ}C$ to $104 \times 10^{-6}/{^\circ}C$ [11, 12]. Aramid Fibre Reinforced Polymers (AFRP), on the other hand, have a negative coefficient varying from $-2 \times 10^{-6}/{^\circ}C$ for Arapree and to $-15 \times 10^{-6}/{^\circ}C$ for Technora, CTE transverse from $60 \times 10^{-6}/{^\circ}C$ to $80 \times 10^{-6}/{^\circ}C$ [12, 13]. For glass fibre reinforced polymers (GFRP) bars, whilst the longitudinal coefficient, $\alpha_L$, is similar to that of concrete (from $6 \times 10^{-6}/{^\circ}C$ to $12 \times 10^{-6}/{^\circ}C$), the transverse CTE coefficient, $\alpha_T$, is ranges from $21 \times 10^{-6}/{^\circ}C$ to $23 \times 10^{-6}/{^\circ}C$ [12, 14]. Thermal incompatibility in the transverse direction may create significant bursting stresses within the concrete members around the FRP reinforcement under temperature increase or separation of the bars from the concrete under temperature decrease. The FRP-to-concrete bond performance plays a key role because it build better understanding of behaviour of complete structural system [3].
The available technical literature indicates that there is a wide gap in the current research on FRP-RC at elevated temperatures. Currently, the use of FRP reinforcement for RC structures is limited and includes only cases when fire resistance aspects are not particularly meaningful.

2. Thermomechanical Properties of FRP Reinforcing Bars

In the matter of fire safety, it is practical to divide constituents of FRP bar into fibres and matrix. Fibres have load bearing role, while role of resin is to redistribute stresses of external loads among fibres and to protect them. To understand behaviour of FRP reinforced members in fire conditions, there is necessity to understand behaviour of single FRP bar, which is associated with understanding of the behaviour of individual constituents at elevated temperatures. Thermomechanical properties of constituents depends mainly on the chemical composition and the production process.

There are four main types of fibres that are commercially available for production of FRP bars – carbon, glass, aramid and basalt. All of them are characterised by different thermomechanical properties, therefore problems causing limitation of their application in constructions due of fire risk are solved with different approaches. Carbon and aramid fibres have much smoother surface in comparison to other types. Surface treatment of fibres can improve connection with interphase, consequently increasing FRP bar strength at high temperature. Main problem related to basalt fibres is non-homogenous character of melting of fibres and gradual crystallization with rise of temperature [15]. Glass fibres are valid in wide range of subtypes and improving their properties is mainly focused on changes in chemical composition [16].

Three of these types are included in many norms and standards related to FRP composites, however BFRP composites are included only in a few. One of the reasons for its absence can be due to the differing characteristics of basalt rock depending on its origin. Therefore, currently the majority of studies focus on FRP applications involving materials such as Carbon FRP (CFRP), Glass FRP (GFRP) and Aramid FRP (AFRP).

Figure 2 describes the variation in elastic modulus and tensile strength for different unidirectional FRPs being subjected to elevated temperature. The plots are based on experimental data presented in the literature and assembled by Bisby (2003) [17].

![Figure 2](image-url)  
**Figure 2.** Variation in (a) Elastic Modulus and (b) Tensile Strength vs. Temperature for Unidirectional CFRP, AFRP and GFRP [17]
In addition, internal stress distribution of FRP bar is highly dependent on bonding interphase, not only on individual properties of matrix and fibres. Loads, which can be transmitted by FRP bars are higher than these, which can be carried by separate constituents. Chemical bond and at the same time shear forces between fibres and matrix can be strengthened with addition of coupling agents [16]. Improving thermomechanical properties of FRP bars at high temperatures is connected with assurance of strong bonding interphase that can be extremely important, when exposed to high temperature.

2.1. Thermomechanical Properties of Constituents of FRP Bars

2.1.1. Polymer Matrix

The matrix is considered to be the most combustible material in FRP composites from the point of fire resistance aspects. Therefore improving thermomechanical properties of FRP bars is mainly connected with improving properties of matrix. Fardis and Khalili (1982) [18] suggested that fire properties of FRP based components can be improved by increasing glass transition temperature of matrix or by making short-term strength of the bar independent to loss of the matrix. Change of composition of matrix with use of additives or its chemical modification may result in improved resistance to flames, limitation in oxidation and in smoke generation.

Polymer matrices may be categorized as thermoplastic and thermosetting types. The first one soften or melt when are exposed to high temperature, what limit their usage in construction application, due to fire safety reasons. Thermosetting polymers exhibits good thermal properties, they decompose instead of melt, when are subjected to high temperatures. However, there is growing interest towards polymers, because of possible benefits, resulting from their usage. Many researches have been investigated the topics related to improving characteristics of polymers at elevated temperatures in recent years [19-24].

The most common matrices that are currently used in production of FRP bars are epoxy, polyester resins and vinyl esters. All of them are characterised by different thermomechanical properties, decomposition mechanisms and way of processing. Most epoxy resins and vinyl esters have better thermomechanical properties than polyesters resins, but usually their cost is higher. These three types of polymers are thermosetting polymers - their load-bearing performance is superior at very high temperatures in comparison to thermoplastic polymers. They also have high chemical resistance, good thermal stability and reduced stress relaxation [25].

Thermosetting polymers typically have amorphous structures, which is characterized only by a glass transition temperature, \( T_g \). Changes of their properties at the glass transition temperature are not very significant because of high degree of cross-linking. After reaching this value, their mechanical properties are decreasing linearly to growth of temperature.

Polyester resins are characterised by high flammability and heat release in comparison to epoxy resins and vinyl esters. Their decomposition process begins at temperature range of 330-360°C for most non-modified polyester resins and 90-95% of the original mass undergo decomposition into oxygenated volatile gases during the initial stage. Improving properties of polyester resins is mainly focused on their chemical modification with use of flame retardants, for which product of decomposition is char, not volatiles. Gases formed during the combustion process of polyester resins are toxic and temperature plays key role in their generation [26].

In past decade a lot researches concerning improvement of thermal properties of epoxy resins had been performed. Gao et al. (2008) [19] studied thermomechanical properties of different types of epoxy resins, based on reactive monomer, which contain 2.5% phosphorous and can reach 30.2% limiting oxygen index. The results show that with increase of phosphorous content, glass transition and decomposition temperatures decrease slightly. Positive change is limitation of generated smoke, lower heat peak release rate and overall heat release rate.

Epoxy resins are available in the wide range of types with various viscosities. They stand out with very good thermomechanical properties, therefore are widely used as matrices for high performance composites. Long cure reactions of epoxy resins, cause that their processing is costly and takes a long time. Most of their types require post-cure heating to achieve desired temperature performance. Essential
The moment of decomposition of epoxy resins occur in temperature range of 380-450°C and is associated with loss of approximately 75% of their original mass. During decomposition process 10-20% of epoxy resin mass is transformed into porous char, while the rest decompose into volatile gases (with toxic character as in case of polyester resins) [27].

Zhou et al. (2008) proposed to use epoxy resin modified with carbon nanotube, which have extremely high thermal conductivity, strength and thermal stability equal to 2800°C. Result of Authors experiment prove, that carbon nanotube content in epoxy resin matrix can increase $T_g$ by 17°C and storage modulus by 90% [20].

Thermomechanical properties of polyester resin can be improved by addition of halogens or nanoclays, especially in flammability aspects. Nazare, Kandola and Horrocks (2006) conducted experiments to analyse effect of silicate nanoclays addition on thermal properties of polyester resin. They suggested, that 5% nanoclay content in matrix reduces the peak heat release rate by 23-27%, total heat release by 4-11% and fire growth index by 23-30%. Authors also proposed addition of other flame retardants, which can decrease peak heat release rate by 60-70% and limit smoke release [23].

Many researchers believe that vinyl esters are most suitable matrix materials for application in common FRP reinforced structures, due to their mechanical and chemical properties, toughness, flexibility and improved retention of properties in aggressive environments. Their behaviour in case of fire is similar to polyester resins, with slightly higher smoke generation and heat release. During decomposition process 90-95% of the vinyl ester mass is decomposed into volatile gases and the rest into char. Vinyl esters are derivatives of epoxy resins and therefore modification of their thermal properties proceeds in similar way [16].

Sultania, Rai and Srivastava (2010) synthesized cardanol-based vinyl ester and tested influence of high temperature on its properties. During experiment at elevated temperature, modified vinyl ester was stable when heated up to 260-285°C, then started slowly decomposing. Significant, rapid mass lost took place in temperatures ranging from 350°C to 500°C. Measured values are promising parameters in matter of fire safety [24].

Table 1 describes basic mechanical and thermal properties of commonly available thermosetting polymers.

|                          | Epoxy resin | Polyester resin | Vinyl ester | Polyamide resin a |
|--------------------------|-------------|-----------------|-------------|-------------------|
| Tensile Strength, MPa    | 55-130      | 34.5-103.5      | 73-81       | 95                |
| Young’s Modulus, GPa     | 2.75-4.1    | 2-4.4           | 3.0-3.5     | 2.76              |
| Thermal expansion, $10^6/°C$ | 45-65       | 55-100          | 53          | 63                |
| Glass transition temperature, °C | 100-250 | 75-150 | 220-320 | Up to 316 |

a can be also thermoplastic.

Thermoplastic polymers have semicrystalline structure. They behave in similar way to thermosetting polymers to the point of $T_g$ (in which they are slightly loosing bearing properties) and for some time after. With further increment of temperature, thermoplastic polymers reach melting temperature, $T_m$ - their properties drop drastically in relatively short time. Significant changes in elastic modulus, $E_m$, of thermoplastic polymers, when subjected to elevated temperature, cause change of their state from glassy to rubbery flow, having specific, prolonged transitional behaviour. Decrement of $E_m$ of the thermosetting polymers is not notable, the rapid drop occurs only in the moment just before decomposition [28].

2.1.2. Reinforcing Fibres

Mechanical properties of each type of fibres are affected in different way, when subjected to elevated temperature. Type of fibre have very high influence on behaviour of FRP bar exposed to high temperature; specific heat, thermal diffusivity, thermal expansion and thermal conductivity are main parameters of fibres, determining effectiveness of their usage in FRP bars.
Carbon fibres are type of fibres with highest thermal stability, i.e. up to 2500°C. They can be classified basing on tensile strength and modulus. The high strength carbon fibres are heat treated at temperatures in range from 1200-1500°C, while high modulus carbon fibres at higher temperatures [29]. C. Pradere et al. (2009) measured specific heat and thermal diffusivity of three different kinds of carbon fibres in order to obtain data allowing for analyse of behaviour of carbon fibres at elevated temperatures. Authors used differential scanning calorimetry and drop calorimetry techniques to measure specific heat of fibres at temperatures reaching 2730°C. It was so far first test conducted on single carbon fibres at extremely high temperatures. Thermal diffusivity was measured by innovative method, allowing for performing test on single fibre at temperature up to 2230°C. During tests there were analysed raw carbon fibres and heat treated carbon fibres at temperature of 2230°C [30].

Lynn Penn et al. (1979) performed thermal analysis tests of organic Aramid (Kevlar 49) fibres, characterised by high tensile strength and Young’s modulus. Aramid fibres keep their volumetric stability unchanged (100%) up to 520°C, then their volume decomposed with small temperature increment by 35%, up to 560°C. Further decomposition was proceeded gently to 40% of loss of volume at 650°C [31].

Song He et al. (2017) proposed surface modification of Kevlar 29 aramid fibres with use of silica aerogel to reduce their thermal conductivity. As a result thermal conductivity of modified fibres decreased by 24% in comparison to raw aramid fibres. Their volumetric stability in relation to elevated temperature was also examined, both types of fibres behave almost similar manner. For both raw and modified fibres, loss of volume was equal to 5% at 500°C, then dropped enormously to 90% at 640°C and stayed with this value up to 800°C [32].

Basalt fibres have better failure strain and produces less poisonous smoke in comparison to carbon fibres in fire conditions, however their tensile strength is equal to approximately 30% of carbon fibres strength. Sim, Park and Moon (2005) conducted experimental works concerning among others thermomechanical properties of basalt, carbon and glass fibres. All types of fibres has been heated in furnace for two hours at temperatures of 100, 200, 400, 600, 1200°C and then used for tensile strength test after one day cooling. The loss of strength of investigated types of fibres was irrelevant up to 200°C, then it started decreasing up to 600°C. The reduction of basalt fibres tensile strength at 600°C was equal only to 7%, while for carbon and basalt fibres was equal to 40% and 45% respectively. Test at 1200°C shows that basalt fibres have less volumetric loss at the same time having highest heat resistance. Glass fibres tend to soften very slowly starting at temperatures of 1200°C, but are not significantly fluid up to 2000°C [33, 34].

3. Conclusions

The widespread use of FRP for RC structures is hindered by several factors, including their low fire resistant characteristics, which limit their use to situations where fire resistance aspects are not particularly meaningful. The main focus in previous and ongoing research related to FRPs at elevated temperatures is the investigation on their mechanical parameters at the specific temperatures. Attention has also been given to the changes in the bond characteristics between FRPs and the concrete surface. Mechanical properties of bars in the transverse direction are more affected by elevated temperatures than the longitudinal due to the anisotropic properties of materials.

The mechanical properties of each type of fibre are affected in different ways when subjected to elevated temperatures, however it is well established that commonly available fibres are relatively resistant to high temperatures. The degradation of mechanical properties is caused mainly due to the deterioration of the polymer matrix. The assumed critical temperature is taken to be the glass transition temperature, T_g, of the polymer matrix, and is typically in the range of 40-120°C for matrices used for infrastructure applications.

Therefore, the appropriate selection of a matrix with desired properties can significantly influence thermomechanical characteristics of the FRP bars. As it is suggested from literature, the modification of polymer matrices can be a potential solution for improving FRP bars at elevated temperatures.
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