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Fire performance of FRP systems for infrastructure: a state-of-the-art report

Bisby, L. A.; Williams, B. K.; Kodur, V. K. R.; Green, M. F.; Chowdhury, E. U.

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Publisher’s version / Version de l'éditeur:
https://doi.org/10.4224/20377587
Research Report (National Research Council Canada. Institute for Research in Construction); no. RR-179, 2005-03-01

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RR-179

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FIRE PERFORMANCE
OF
FRP SYSTEMS FOR INFRASTRUCTURE:
A STATE-OF-THE-ART REPORT

by

Bisby, L.A, Williams, B.K, Kodur, V.K.R., Green, M.F., and Chowdhury, E.

Research Report 179

Queen's University, Kingston
and
National Research Council, Ottawa

MARCH 2005

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

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Executive Summary

Widespread deterioration of infrastructure resulting from corrosion of reinforcing steel in concrete has led recently to the use of fibre reinforced polymers (FRPs) in a number of infrastructure applications. A significant research effort over the past fifteen years has shown that FRP materials can be effectively used to reinforce and/or strengthen deteriorated or under-strength reinforced concrete structures. However, the performance of FRP materials in fire remains a serious concern, which needs to be addressed before these materials can be used with confidence in applications where fire endurance is a design criterion (i.e. buildings, parking garages, etc.). This report presents a review of the literature with respect to the fire and high-temperature behaviour of FRP composites as is relevant to the design and construction of FRP-strengthened or reinforced concrete structures.

After a general overview of the motivation for this report which is provided in Section 1.0, Section 2.0 provides a description of FRP materials, their composition and properties, and the roles of each of their material components. Section 3.0 presents an overview of the various uses of FRPs in civil engineering applications, with a focus on their use as reinforcement and/or strengthening of reinforced concrete structures. Section 3.0 also presents a discussion of the various concerns associated with the use of FRP materials in situations where fire poses a threat, and briefly comments on the economics of the use of FRP in various applications. Section 4.0 presents a detailed summary and discussion of the thermal and mechanical properties of FRP at elevated temperature or in fire. Additional discussions are provided on bond behaviour, smoke generation and toxicity, ignition and flame spread, and barrier treatments to improve fire performance. Section 5.0 presents an overview of the philosophies and criteria used to define the fire endurance of structural members. An understanding of fire endurance design is important before moving to Section 5.1, in which results of previous testing programs to investigate the fire performance of FRP-strengthened or reinforced concrete members are provided. Section 6.0 provides an overview of current research in this area being performed at the National Research Council of Canada, Section 7.0 gives a summary and conclusions from this report, and section 8.0 gives a series of recommendations for further research.

1.0 General

The deteriorated and/or under strength state of the world's reinforced concrete buildings and infrastructure has forced the development and implementation of new and innovative repair and rehabilitation techniques for reinforced concrete structures. Additionally, the civil engineering industry is being forced to examine new materials and methods of construction to ensure that new structures are capable of living long with healthy service lives. Fibre-reinforced polymers (FRPs), a relatively new class of materials in civil engineering applications, have received widespread attention in recent years, both for repair and rehabilitation and for new construction of reinforced concrete, and more recently steel, structures. However, there is a legitimate concern that structures strengthened and/or reinforced with FRPs may be damaged by exposure to high temperatures, such as would be expected in the case of fire.

This report presents a review of the literature with regard to FRPs as a class of materials, their applications in civil engineering, and concerns associated with their behaviour in fire, particularly when used as reinforcement for concrete. Also included for completeness is a discussion of the current philosophy and methodologies used to evaluate the fire endurance of reinforced concrete members.

2.0 Fibre-Reinforced Polymers

FRPs are not new materials; they have been used in the automotive and aerospace industries for over 40 years, where their high-strength and light-weight can be used to the greatest advantage. In the last fifteen years or so, the civil engineering community, spurred by soaring infrastructure repair and replacement costs, has begun to use FRPs in a variety of structural engineering applications.

FRPs are a subgroup of the class of materials referred to as composites. Composites are defined as materials created by the combination of two or more materials on a macroscopic scale, to form a new and useful material with enhanced properties that are superior to those of its constituents (Neale and Labossière, 1991). An FRP is a two-component material, consisting of high strength fibres embedded in a polymer matrix.

The study of FRPs is invariably complicated by the innumerable combinations of materials that can be combined to create an FRP composite. This is both an advantage and a disadvantage for FRP as an engineering material. FRPs can be tailored to suit virtually any application. However, this versatility leads to an enormous range in properties, making it extremely difficult to arrive at generalizations with regard to a number of important issues; behaviour at elevated temperatures is one important example.

2.1 Composition and Properties of Fibre-Reinforced Polymers

Because FRPs are typically composed of two distinct materials, their material properties depend primarily on those of the constituents.

2.1.1 Fibres

The fibres provide the strength and stiffness of an FRP. Because fibres used in most structural applications are continuous and are oriented in specified directions, FRPs are orthotropic, and much stronger and stiffer in the fibre direction(s). In the event of a single fibre break, force transfer to adjacent fibres through shear stresses that develop in the polymer matrix prevents failure of the overall FRP composite. It is interesting to consider that this force transfer depends primarily on the shear strength of the matrix material, which can be severely degraded at high temperature.

In civil engineering applications, the three most commonly used fibre types are carbon, glass, and to a lesser extent, aramid (Rostasy, 1993). While the various fibre types all have advantages and disadvantages, carbon fibres are rapidly becoming the material of choice for structural composites for rehabilitation, due mainly to their high stiffness, low relaxation, and superior fatigue and durability characteristics. A complete review of fibre types and properties is avoided here, since this information is available in most composite materials textbooks (e.g. Schwartz, 1997). A more complete discussion of fibre properties as they relate to FRP behaviour at high temperature is presented in Section 4.3.

2.1.2 Matrix

The matrix is the binding material for an FRP and generally has poor mechanical characteristics. Matrix materials are required to support and protect the fibres, to transfer and distribute forces to the fibres, and to disperse and separate the fibres (Hollaway, 1990). Matrix materials should also be as thermally compatible as possible with the fibres to reduce the magnitude of stresses resulting from differential thermal expansion, although in most cases the coefficients of thermal expansion of the fibres and matrices actually differ substantially. A major selection criterion for matrix materials is that they have a low density, usually considerably less than the fibres, such that the overall weight of the composite is minimized (Neale and Labossière, 1991).

Matrix materials for FRPs can be grouped into two broad categories: thermoplastics and thermosetting resins. Thermoplastics include such polymer compounds as polyethylene, nylon, and polyamides, while thermosetting materials include epoxies, polyesters, and vinyl esters. Thermosets are used almost exclusively in structural applications (Blontrock et al. 1999). They have good thermal stability and chemical resistance, and low creep and relaxation in comparison with thermoplastics. However, thermosets have a short shelf life after mixing, lower strains at failure, and lower impact strengths than thermoplastics (El-Hacha, 2000). Both thermoplastics and thermosets are characterized by very low thermal conductivities (Cengel, 1998).

In terms of the fire behaviour of FRPs, it is the polymer matrix that is the problematic component. Polymers are sensitive to both temperature and rate of loading. Thus, at elevated temperatures, deterioration of the matrix mechanical properties and creep, neither of which are fully understood (Neale and Labossière, 1991), can be a serious concern. Again, a detailed discussion of matrix properties is avoided here, but additional information on matrices relevant to the behaviour of FRP in fire is presented in Section 4.2.

2.1.3 Fibre-Reinforced Polymers

Although the strength and stiffness of an FRP are governed by the fibres, the overall material properties depend also on the mechanical properties of the matrix, the fibre volume fraction, the fibre cross-sectional area, the fibre orientation within the matrix, and the method of manufacturing (Jones, 1975). The current report focuses exclusively on unidirectional FRPs, which are typically used for concrete reinforcing applications.

A wide variety of FRP formulations are available for use with reinforced concrete structures. Glass and carbon are the two most commonly used fibres in North America, and matrices are typically epoxies or vinyl esters. Glass is widely used because of its comparatively low cost, and because there is historically much more experience with it (El-Hacha, 2000). However, glass fibres have demonstrated certain significant disadvantages, such as a relatively low elastic modulus and durability concerns in alkaline environments (Uomoto, 2001). These disadvantages have made carbon FRPs, with elastic moduli that compare more closely with steel, more attractive, even given their higher cost. The primary concerns with aramid FRPs are that they are sensitive to creep (Hollaway, 1990; Uomoto, 2001) and have displayed poor durability characteristics resulting from their propensity for moisture absorption (Braimah, 2000; Uomoto, 2001).

Figure 1 shows the stress-strain behaviour of various FRP materials. Also included in the figure is a stress-strain curve for mild steel. Some commonly available FRPs and their properties are listed in Table 1. It is evident that both glass and aramid FRPs have moduli that are considerably less than steel in the pre-yield zone, but that carbon FRPs have moduli that are comparable to, or even higher than, steel in some cases. Also evident is that FRPs have ultimate strengths that can be many times greater than steel.

The most significant characteristic of the stress-strain behaviour of FRPs as compared with steel is their linear elastic nature. FRPs do not display the post-yield behaviour observed for steel, and generally have much lower strains at failure. Consequently, the safe use of FRPs as reinforcement for concrete is complicated by the lack of ductility inherent in the materials. It has been shown however, that adequate ductility can be obtained for FRP-reinforced concrete members provided they are properly detailed using the concept of deformability (ACI, 2002; ISIS 2001a,b). Table 2 gives a qualitative comparison of the three main types of FRPs based on a number of important criteria.

3.0 Fibre-Reinforced Polymers in Civil Engineering Applications

Reinforced concrete continues to be one of the most popular construction systems for buildings, bridges, and other infrastructure worldwide. The most pressing problem reinforced concrete structures face is the electrochemical corrosion of conventional reinforcing steel, which is difficult to prevent and can cause severe deterioration of concrete structures through expansion and cracking, invariably leading to spalling of the concrete cover and/or loss of tensile reinforcement. FRPs are non-corrosive and thus present a potential alternative to steel as tensile reinforcement for concrete structures. FRPs have also demonstrated enormous potential as materials for repair and rehabilitation of existing corrosion-damaged and/or under strength concrete structures (Meier, 2000; Munley and Dolan, 2001; Neale, 2000; Taly and GangaRao, 1999).

Various techniques for using FRPs in lieu of steel for reinforced concrete construction have been gaining acceptance in the civil engineering community. Some examples of FRP applications in reinforced concrete repair, rehabilitation, and construction include: external post-tensioning of damaged or under strength concrete girders (Burgoyne, 1993; El-Hacha, 1997), plating for flexural or shear strengthening of reinforced and/or prestressed concrete beams (ACI, 2002; Deniaud and Cheng, 2000; El-Hacha et al., 2001; Hazen et al., 1998; Ichimasu et al., 1993; ISIS, 2001a,b; Labossière et al., 2000; Labossière et al., 1997; Meier et al., 1992; Nanni, 1997; Rostasy et al., 1992; Steiner, 1996; Walser and Steiner, 1997), wrapping for confinement and/or ductility enhancement of reinforced concrete columns (ACI, 2002; Challal and Shahawy, 2000; Fam and Rizkalla, 2001; ISIS, 2001a, b; Karbhari and Gao, 1997; Lavergne and Labossière, 1997; Lee et al., 2000; Liu and Foster, 1998; Mirmiran and Shahawy, 1997; Mirmiran et al, 1998, 1999, 2000; Monti et al., 2001; Parent and Labossière, 2000; Purba and Mufti, 1999; Saaman et al., 1998; Sheikh and Yau, 2002; Spolestra and Monti, 1999; Theriault and Neale, 2000, 2001; Xiao and Wu, 2000), and internal reinforcement for shear, non-prestressed, and prestressed reinforcement for new concrete structures (ACI, 2002; Benmokrane et al, 2000; CSA, 2001, 2002; Hassan et al, 2000; ISIS, 2001a, b; Shehata et al., 2000; Tadros, 2000). In some cases, FRPs can be used in combination with fibre-optic sensors (FOS) to create smart structures and allow for remote monitoring, which has recently received widespread attention (Benmokrane et al., 2000; Meier, 2000).

The advantages of FRPs over conventional reinforcing steel are cited often in the literature and include:

- FRPs are non-corrosive, although they may be susceptible to other forms of equally damaging environmental distress, usually caused by elevated temperatures and/or moisture
- high strength-to-weight ratios, as much as 10 to 15 times greater than steel
- excellent fatigue characteristics, particularly carbon FRPs
- electromagnetic neutrality, which can be extremely useful in some special structures
- high tensile strength as compared with steel
- rapid and easy installation, significantly lowering construction costs and downtime.

There are however, a number of disadvantages to using FRPs. Some of the most pressing concerns include:

- high material cost, although prices have dropped drastically in the past 10 years as use has increased (El-Hacha, 2000)
- low strain at failure, requiring new design approaches and raising concerns over insufficient member ductility
- extremely low lateral load capacity due to the relatively poor mechanical properties of the matrix
- excessive creep and relaxation in some cases, particularly for aramid FRPs
- the potential for ultra-violet (UV) degradation of polymer matrices in external applications
- expansion and deterioration due to moisture-absorption, particularly for aramid FRPs
- lack of clear guidelines for design with and use of these new materials, although this problem has been addressed recently by several organizations (ACI, 2002; CSA, 2001, 2002; ISIS, 2001a, b).
- rapid and severe loss of bond, strength, and stiffness at elevated temperatures, as would be expected in the case of fire.

The final disadvantage listed above is extremely significant and is at the core of the work presented in this report. Sorathia et al. (2001) present a gap analysis for durability of FRP composites for civil infrastructure, in which they include a chapter on the effects of fire. They state that an enormous amount of additional information is required in terms of: flame spread, fire endurance, smoke generation and toxicity, and heat release, before many infrastructure applications using FRPs can be implemented safely and with confidence. Munley and Dolan (2001) point out that fire endurance uncertainties associated with the use of FRPs may be addressed, for the time being, through a rational set of design limitations. This approach has indeed been taken by the ACI Committee 440 (ACI, 2002), whose design guidelines state that the load factors for a structure that is retrofitted with bonded FRP reinforcement be set to 1.2 and

0.85 for dead and live loads respectively. It is intended that these load factors prevent collapse by assuming that the FRP is lost completely during a fire. The ACI 440 documents further state that the existing strength of a structural member with a specified fire-resistance rating should satisfy fire endurance requirements under the contemplated increased loads if it is to be strengthened with an FRP system. The service load effects in this case should be determined using the current load requirements for the structure. If the FRP system is meant to allow greater load carrying capacity, such as an increase in live load, the load effects should be computed using these greater loads (ACI, 2002). However, while such an approach is certainly conservative, it makes FRP materials less cost-effective as they otherwise might be. Munley and Dolan also comment that the professional community would be far more comfortable with a set of full-scale fire endurance tests.

Although FRPs have been used in a wide variety of applications for reinforced concrete construction, repair, and rehabilitation, the focus in this report is on two specific, yet fundamentally different classes of application: FRP bars for internal reinforcement of concrete slabs, and externally-bonded FRP sheets for strengthening of reinforced concrete beams or columns. Both applications are discussed in detail in the following sections.

3.1 FRP Bars for Beam and Slab Reinforcement

Because of the widespread and costly problems associated with corrosion of reinforcing steel in concrete structures, a great deal of research in recent years has focused on the use of FRP bars as a substitute for conventional tensile and temperature and shrinkage reinforcement for concrete beams and slabs (Benmokrane and Rahman, 1998; Benmokrane et al, 2000; Neale and Labossière, 1992; Saadatmanesh and Ehsani, 1996; Taerwe, 1995). Recently, there have been several field applications using FRPs for non-prestressed slab reinforcement in bridge decks (ACI, 2002; Benmokrane et al., 2000; Hassan et al., 2000).

Some of the initial factors that were considered in investigating the suitability of FRP bars, rods, and grids, for slab and beam reinforcement have included: creep (Ando et al., 1997; Currier and Dolan, 1995; Matthys and Taerwe, 1998; Plevris and Triantafillou, 1994; Rostasy, 1988; Saadatmanesh and Tannous, 1999a, 1999b; Seki et al., 1997; Sen et al., 1999; Uomoto, 2001), fatigue (Adimi et al., 1998; Hayes et al., 1998; Rahman and Kingsley, 1996; Rahman et al., 1997; Rostasy, 1997; Saadatmanesh and Tannous, 1999a; Uomoto, 2001; Yagi et al., 1997), durability (Benmokrane and Rahman, 1998; Hamilton and Dolan, 2000; Uomoto, 2001), bond and development (Bakis et al., 1998a, b; Bank et al., 1998; Freimanis et al., 1998; Katz, 1998, 1999, 2000; Nanni et al., 1997), and failure modes and ductility (Jaeger et al., 1995; Newhook et al., 2000), to name only a few. An exhaustive review of the literature in this area is not presented here, because it is now relatively widely recognized that internal FRP reinforcement can be used for concrete slabs and beams, provided that certain design guidelines are adhered to. FRP bar-reinforced concrete structures can be designed with the aid of draft design guidelines such as the Guide for the Design and Construction of Concrete Reinforced With FRP Bars (ACI, 2002), Reinforcing Concrete Structures with Fibre-Reinforced Polymers (ISIS, 2001a, b), The Canadian Highway Bridge Design Code (CSA, 2001), or CSA-S806: Design and Construction of Building Components with Fibre-Reinforced Polymers (CSA, 2002).

3.2 Strengthening with Externally-Bonded FRPs

While the above section discussed FRP bars for new construction applications, externally-bonded repair systems using FRPs, such as bonded plates for external strengthening or column wrapping for confinement, currently show the greatest potential for the use of FRPs in the construction industry. Indeed, such systems are currently competing economically with conventional repair and retrofit solutions (Munley and Dolan, 2001).

In the case of FRP sheets for strengthening reinforced concrete columns, FRP sheets are applied to the exterior of reinforced concrete columns in either the longitudinal direction (to provide additional flexural capacity) or in the circumferential direction (to provide additional confining reinforcement which increases both the ductility and the compressive strength). Although steel casings have been widely used for confinement of concrete columns, they are difficult to install, heavy, and prone to corrosion. Steel encasements are also isotropic (the casing ends up taking a significant portion of the axial load) and have a high Poisson's ratio (resulting in separation of the tube from the concrete under axial load (Karbhari and Gao, 1997)). FRPs offer an ideal alternative material, since they are non-corrosive, lightweight, easy to install, and orthotropic, with negligible strength in the direction perpendicular to the fibres.

Over the past ten years, numerous research studies and field applications have demonstrated that FRP-wrapping can significantly increase both the strength and ductility of reinforced concrete columns (ACI, 2002; Callery, 2000; Challal and Shahawy, 2000; Demers and Neale, 1994; Fam and Rizkalla, 2001; Hosotani et al., 1997; ISIS, 2001a, b; Karbhari and Gao, 1997; Lavergne and Labossière, 1997; Lee et al., 2000; Liu and Foster, 1998; Mirmiran and Shahawy, 1997; Mirmiran et al, 1998, 1999, 2000; Monti et al., 2001; Parent and Labossière, 2000; Pilakoutas and Mortazavi, 1997; Saadatmanesh et al., 1994; Saaman et al., 1998; Santarosa et al., 2001; Sheikh and Yau, 2002; Soudki and Green, 1997; Spolestra and Monti, 1999; Suter and Pinzelli, 2001; Theriault and Neale, 2000; Theriault et al., 2001; Watanabe et al., 1997; Xiao and Wu, 2000). The observed increases in strength and ductility can be attributed to the fact that the FRP wrap generates a confining pressure on the dilating concrete core, which places the concrete in a triaxial state of stress and increases both the ultimate strength and strain of the concrete in compression by reducing shear stresses and controlling crack initiation. Numerous analytical models for the stress-strain behavior of FRP-confined concrete are available in the literature (Cusson and Paultre, 1995; Fam and Rizkalla, 2001; Fardis and Khalili, 1981, 1982; Hoppel at al. 1997; Karabinis and Rousakis, 2001; Karbhari and Gao, 1997; Lam and Teng, 2001; Manfredi and Realfonzo, 2001; Mirmiran and Shahawy, 1997; Miyauchi et al., 1997; Parent and Labossière, 2000; Saafi et al., 1999; Saaman et al., 1998; Spolestra and Monti, 1999; Toutanji, 1999; Vintzileou, 2001; Xiao and Wu, 2000), and design guidelines for confinement of reinforced concrete columns have recently been published by the American Concrete Institute (ACI, 2002), ISIS Canada (ISIS, 2001a), and the Canadian Standards Association (CSA, 2002).

In the case of concrete beams and slabs strengthened in flexure or shear with externally-bonded FRP plates or sheets, the FRP materials are bonded to the tension face (flexural strengthening applications) or side faces (shear strengthening applications) in such a way as to supplement the tensile reinforcement provided by the internal reinforcing steel. This technique, which can be used to increase both the strength and stiffness of concrete beams and slabs, is often preferable to more conventional techniques involving bonded steel plates, external steel post-tensioning, or steel shear bolts.

Numerous research studies have demonstrated the effectiveness of FRP materials in repair of RC beams to achieve increased flexural strength (Dortzbach, 1999; Grace et al., 1999; Grace, 2001; Mayo et al., 1999; Shahrooz et al., 2002; Tadros et al., 1999;) and shear capacity (Deniaud and Cheng, 2001; Hsu, 2003; Hutchinson and Rizkalla, 1999; Okeil et al., 2001; Triantafillou, 1998). Near surface mounted (NSM) FRP bars are also being applied to achieve improved shear and flexural strengthening (De Lorenzis and Nanni, 2001; Rizkalla and Hassan, 2002). Design guidelines in this regard have been developed by several organizations (ACI, 2002; ISIS, 2001a; CSA, 2002). In addition, prestressed FRP rods, cables and sheets have shown great potential for use in concrete beam construction and rehabilitation (Abdelrahman et al., 1995; Dolan, 1999; El-Hacha, 2000; Grace and Singh, 2003; Iyer, 1993; Okamoto et al., 1993).

Research efforts in this area include work on the overall behaviour of FRP-strengthened members (Aprile et al., 2001; Arduini et al., 1997; Challal et al., 1998), the characterization of FRP bond with concrete (Bisby et al., 2000; Lee et al., 1999; Toutanji and Ortiz, 2001), the attainable strength increases due to FRP (Khalifa et al., 1998; Norris et al., 1997), fatigue performance (Yang and Nanni, 2002), creep behaviour (Scott et al., 1995) and durability (Green et al., 2000; Neale et al., 2001; Toutanji and Gomez, 1997; Waldron et al., 2001).

3.3 Concerns with FRPs in Fire

Assuming that durability, fatigue, bond and development, and creep rupture problems can be avoided, generally through using appropriate FRP fibre/matrix formulations and by limiting service stress levels in the FRP reinforcement – sometimes severely – the major concerns during a fire when reinforcing with FRP bars as opposed to steel are:

> *Reduction in Strength and Stiffness*: The strength and stiffness of FRP materials decreases with increasing temperature. When the matrix is called upon to transfer loads, the strength will be drastically reduced at temperatures of about 300°C for most conventional FRP materials, with decreased stiffness being observed well below that.
>
> *Loss of Bond*: Because of the susceptibility of matrix materials to high temperature, loss of bond will occur for fire-exposed composite bars and wraps within minutes. In cases where bond is relied upon to transmit shear stresses, the FRP will be rendered ineffective at temperatures below 300°C (Blontrock et al., 2000). In cases where the bond is not critical to the performance of the FRP, as would be the case in a filament wound concrete column or a multi-bay concrete slab, loss of bond is not as critical (assuming anchorage is provided, see below). Loss of bond in this case would essentially create an unbonded FRP that would still be able to provide significant confinement or tensile reinforcement (Fardis and Khalili, 1982).
>
> *Supplemental insulation*: Tests on FRP-plated reinforced concrete beams (Blontrock et al., 2000) have shown that, when the anchorage of the FRP material can be maintained through fire protection in the form of insulation, the FRP reinforcement will perform in a similar manner to the case of an FRP insulated along its full length. Thus, it is conceivable that a concrete member reinforced or wrapped with continuous fibres could maintain some

increased level of strength up to temperatures well above 1000°C (for carbon FRPs), as long as loss of bond is prevented (possibly by insulating only the anchorage regions against fire).

Insulating Effect: One factor that should be considered is the potential insulating effect of an externally applied composite wrap on the reinforced concrete member. FRPs generally have very low transverse thermal conductivities (Mallick, 1988) and would thus tend to insulate the reinforced concrete member, possibly increasing its fire endurance.

Potential for Increased Spalling: Tests on the effect of FRP-wrapping on corrosion rates in reinforced concrete columns (Debaiky, 2000) have indicated that the FRP wraps form an impermeable membrane around the column, preventing the transport of moisture and oxygen into (or out of) the concrete. While an advantage in terms of corrosion prevention, this is a concern in fire. As a concrete member is heated in fire, it will expel moisture when its temperature reaches approximately 100°C. If moisture is prevented from exiting the column, pressure might be developed internally which could potentially lead to explosive failures when the wrap eventually loses its confining capabilities.

Development of thermal stresses resulting from differential thermal expansion between the concrete and the FRP can be a concern. Minimum concrete covers are specified to ensure that cracking will not occur as a result of differential thermal expansion. However, the current draft codes consider thermal expansion due to temperature differences that could be expected under normal service conditions, and no mention is made of the extreme temperature differentials that could be expected in a fire.

Fire endurance concerns are commented on in several of the draft codes. The approach for fire design in conventional (steel-reinforced) slab design is to specify required concrete covers for particular fire endurances based on thermal protection for the tensile reinforcement. In the case of steel-reinforced concrete the design guidelines are based on the observation that steel loses about 50% of its room temperature yield strength at 593ºC – its critical temperature. For FRPs it is difficult to establish the acceptable critical temperatures given the wide variety of FRP materials currently available. Further testing will be required in this area before simple design charts can be used with confidence.

3.4 Economic Considerations

In many cases, especially in repair and rehabilitation applications, FRPs are the only viable material. In some cases, however, as in new construction or in certain external plating applications, a choice must be made between FRPs and more conventional techniques.

FRP materials are more costly on a per-weight basis than steel. However, the costs of FRPs have dropped drastically in the past few years, and this trend should continue to some extent as use of these materials becomes more widespread. For example, Buyukozturk et al. (1999) reported that the price of raw carbon fibres dropped from US$ 20/lb to US$ 6.50/lb in the years between 1990 and 1999, with projections for a cost of US$ 5/lb by the end of 2000.

It is also important, in today's economic climate, to consider factors other than capital cost when selecting materials for construction. If a comparison is made on a cost per force basis, then the cost discrepancy diminishes due to the extremely high strength-to-weight ratios of FRP materials (El-Hacha, 2000). From a construction point of view, costs can also be reduced when using FRPs due to the lightweight nature and ease of application, which can significantly reduce both construction time and costs associated with downtime of the structure in repair applications. Finally, life cycle costs should be considered wherever possible. Structures built using FRPs are presumably non-corrosive and should have service lives that exceed those of conventionally reinforced concrete structures, with repair and maintenance costs that are also considerably less. When FRPs can be combined with fibre optic sensor (FOS) technologies, intelligent sensing, and remote monitoring, inspection and servicing costs can also be reduced.

4.0 FRP Properties at Elevated Temperature

An understanding of material behaviour at high temperature is essential to experimentally or analytically investigate the fire endurance of structural members. The properties that are of interest for structural materials can be divided into two broad categories: thermal and mechanical. Important thermal properties include: thermal conductivity, specific heat, emmissivity, and density; while mechanical properties include: thermal expansion, creep, and stress-strain behaviour. The above mentioned properties are discussed in the following sections as they apply to FRPs at high temperature. It should be noted that conventional infrastructure materials such as steel and concrete do not combust, and hence will not contribute fuel to a fire, evolve toxic gases, or generate smoke. This is not typically true in the case of FRPs, most of which are combustible.

4.1 General

As early as 1982, it was recognized that fire posed a significant risk to FRP-reinforced concrete members. In their pioneering work on FRP-wrapped concrete columns, Fardis and Khalili (1982) included a section that discussed various concerns associated with the flammability of the polymer matrix and the consequences for reinforced concrete structures. At that time, they suggested the use of flame retardant additives and fillers to improve the fire performance of polymer matrices, but did not attempt to improve or test fire performance themselves. It is interesting to note that relatively few studies have been conducted to investigate the fire resistance of FRPs for structural applications in the twenty-two years since.

Two types of performance against fire are extremely important (Tanano et al., 1999): performance against initial fire and performance in the post-flashover stage. Performance against initial fire includes: flammability, which affects the spread of fire (non-combustibility and flame retardency), and smoke and gas-generating properties, which affect the ability to safely evacuate a building. The performance against fire in the post-flashover stage includes: heat-insulating, flame resisting, and smoke barrier properties of separating members, such as floors or walls, and structural safety (or load-bearing capability) of framing members, such as columns and beams.

Fibre-reinforced polymers display a high temperature performance that is drastically different than steel. All polymer matrix composites will burn if subjected to a sufficiently high heat flux. In addition, commonly used matrix materials such as polyester, vinyl ester, and epoxy not only support combustion, but evolve large quantities of dense black smoke (Sorathia et al., 1992). Compared to non-filled plastics however, thick FRPs have two advantages with regard to their involvement in fire. First, the non-combustible fibres (with contents as high as 70% by weight) displace polymer resin, making less fuel available for the fire. Second, when the outermost layers of a composite lose their resin due to combustion, the remaining fibres act as an insulating layer for the underlying composite, significantly reducing heat penetration to the interior (Sorathia et al., 2001).

The properties of FRP elements at high temperature have not been extensively studied in the literature, and what little work has been done does not provide data that are readily applicable to the wide range of FRP composites used in civil engineering applications. Before detailed numerical studies on the structural fire endurance of FRP-reinforced concrete elements can be conducted with confidence, a more complete understanding of the thermomechanical properties of these materials would be beneficial. Approximate empirically-derived equations have been developed by the authors to describe the reductions in strength, stiffness and bond with temperature (refer to Figures 2-6). The following sections outline the results of studies performed to date to investigate the high temperature behaviour of FRP materials.

4.2 Matrix Behaviour

The wide variety of available matrix materials and additives make it extremely difficult to provide generalizations with respect to their high temperature behaviour. However, this section gives a brief synopsis of the somewhat limited work that has been done in this area. For a detailed discussion of matrix materials and their properties, the reader should consult Bakis (1993).

As far as the fire endurance of FRP-reinforced or strengthened concrete is concerned, some of the more important matrix properties are the thermal conductivity, the glass transition temperature (T_g), the coefficient of thermal expansion (CTE), and the flame resistance.

The burning characteristics of thermoplastics and thermosets differ significantly. Sorathia et al. (1992) offer a review of the fire behaviour of different resin types used for FRPs in marine applications. They state that thermosets will degrade, thermally decompose, or char when exposed to fire, but will not soften or melt like thermoplastics. In general, thermosets burn for a shorter duration than thermoplastics, and have much higher heat release rates. Thermoplastics, on the other hand, tend to soften when exposed to high temperature due to their primarily linear chain molecular structure. Thermoplastics burn longer and release less heat than thermosets. Currently, thermosets are most often used in civil engineering applications.

With respect to thermosets, Bakis (1993) states that polyesters can be made quite resistant to fire, and that their upper use temperatures are about 100°C to 140°C. Vinyl esters have advantages over polyesters in terms of high temperature resistance, with upper use temperatures in the range of 220 to 320°C. Epoxy resins, the most versatile FRP resins and subsequently the most widely used in structural applications, can have upper use temperatures anywhere from 50°C to 260°C depending on the particular formulation and resin additives. Polyamide resins, which can be either thermoplastic or thermosetting, have maximum use temperatures as high as 316°C. Thermoplastics can have upper use temperatures anywhere from 85°C to 277°C, but have rarely been used in structural applications to date.

Probably the most important property of the matrix material, as far as fire behaviour in reinforced concrete applications is concerned, is the glass transition temperature, T_g. Drastic changes in the strength and stiffness properties of matrix materials occur at temperatures close to T_g (Bakis, 1993). Reductions in elastic and shear modulus of a factor of 10 to 100 have been observed in a temperature interval of 10°C to 20°C around T_g (Blontrock et al., 1999). The magnitude of the reduction in mechanical properties of a matrix at temperatures near T_g depends heavily on the degree of cross-linking of the polymer, a discussion which is beyond the scope of this report.

The T_g for a particular FRP is the temperature at which the amorphous polymeric regions of a material undergo a reversible change from hard and brittle to viscous and rubbery (Bank, 1993). These changes are due to changes in the molecular structure of the material. T_g for resins used in commonly available FRPs are relatively low, typically less than 200°C, while the fibres can withstand comparatively high temperatures (more than 1000°C in the case of carbon). Because the GTT of a polymer is specific to that material, it is virtually impossible to make generalizations with regard to safe temperature ranges for the enormous variety of FRPs currently available for structural applications.

Plecnik et al. (1986) investigated the fire behaviour of epoxy resins as repair materials for concrete members. A series of tests were performed (tensile, compressive, and shear) to evaluate the high temperature mechanical properties of the resins. Their results indicated that the strength of these materials dropped off very rapidly at temperatures near T_g, and that the strength was negligible at temperatures 100°C greater than T_g. Dimitrienko (1999) conducted a series of tests to determine thermomechanical properties of a variety of matrix materials. His tests, on a specific epoxy material that is not described in detail, indicate a reduction in the elastic modulus of about 50% at 150°C and about 95% at 300°C. Dimitrienko also found that the rate of reduction in strength depended on the heating rate, and was greater for higher rates of heating.

Numerous resin additives are available for enhancing the resistance of matrix materials to flames, smoke generation, oxidation, and heat. For example, phosphorus-based flame-retardant additives function by developing a protective char that insulates the unburned polymer from the flame. Hydrate-based flame-retardants, such as aluminum trihydrate, undergo exothermic reactions and release water upon heating, thereby quenching combustion reactions. These specific additives each function differently and it is difficult to make generalizations with respect to their behaviour. In most cases however, resin additives result in a reduction in the room temperature mechanical properties of the resin material, making many of them unsuitable for FRP applications. A more complete discussion of resin additives can be found in Mallick (1988).

4.3 Fibre Behaviour

The three commonly used fibre types have significantly different thermomechanical properties at high temperature. Aside from a tendency to oxidize at temperatures above 400°C, some carbon fibres have shown negligible strength loss up to temperatures of 2000°C. Aramid fibres have a high thermal stability, but oxidation limits their use above 150°C. Glass fibres will not oxidize, but tend to soften at temperatures in the range of 800°C to 1000°C (Bakis 1993).

Rehm and Franke (1979) tested the tensile strength, as a function of temperature, of different kinds of glass fibres. It was found that at 550°C the tensile strength was reduced to half of its value at room temperature. Rostasy (1992) conducted a series of tests to examine the effect of temperature on the tensile strength of carbon, glass, and aramid fibres. The tests indicated that the tensile strength of aramid fibres was more dependent on temperature than glass fibres, but the tensile strength of carbon fibres seemed to be affected only slightly by temperatures up to 1000°C. Sen et al. (1993) performed tests on a variety of different glass fibres at high temperature. They concluded that the strength of glass fibres was reduced to about half of the room temperature value at about 550°C, and that the strength reduction was independent of the type of glass fibre being used. Sumida et al. (2001) tested the tensile strength of both carbon and aramid fibres at high temperature and determined that, while carbon fibres are unaffected by temperatures up to 300°C, aramid fibres experience an almost linear decrease in strength at temperatures above 50°C with a strength reduction of 50% at 300°C. Dimitrienko (1999) provides experimental data from tests on a variety of fibres at temperatures up to 1400°C. Tests were performed on carbon, glass, and aramid fibres in pure tension under exposure to elevated temperature. It was determined that carbon fibres were relatively insensitive to high temperature, with strength and stiffness actually increasing at temperatures above 600°C up to 1400°C. Glass fibres were found to weaken and soften at temperatures above 400°C, with a reduction of 20% in both strength and stiffness at 600°C and of 70% at 800°C. Glass fibres showed negligible strength and stiffness at temperatures above 1200°C. Aramid fibres performed very poorly, with significant reductions in strength and stiffness at temperatures above 100°C. Aramid fibres demonstrated a 20% decrease in strength and stiffness at 250°C, and a 70% decrease at 450°C.

Figure 2 shows the temperature dependence of the tensile strength of a number of different fibre materials based on tests conducted by a variety of authors. It is evident that, while all fibres seem to be affected by elevated temperatures, aramid is the most severely affected with reductions of over 50% at 500°C, and carbon is the least with reductions of less than 5% at the same temperature.

Sorathia et al. (1992) state that the type and quantity of the fibre will significantly influence the fire performance of an FRP composite. Glass and carbon FRPs generally smoke less, and give off less heat than those with organic fibres such as aramid. The fibre type also significantly influences the thermal conductivity of FRP, with carbon FRPs having higher thermal conductivities than glass (particularly in the fibre direction).

4.4 Thermal Properties

4.4.1 Thermal Expansion

Thermal expansion is potentially a very important factor to consider in the fire behaviour of FRP-reinforced concrete members, since the coefficient of thermal expansion (CTE) of concrete may differ substantially from that of a particular FRP. The potential consequences of differential thermal expansion between FRP and concrete include spalling of concrete cover (due to the development of internal pressure when FRPs are used as internal reinforcement) or the development of shear stresses within the adhesive layer (possibly contributing to bond damage or failure) when FRPs are used in external applications. Although differential thermal expansion of concrete and FRP may not be a primary concern for the temperature ranges commonly encountered in service, the temperature variation experienced during fire could be in the order of hundreds of degrees, causing significant differential thermal expansion. Because of the concerns associated with thermal expansion of FRP, it has been studied quite extensively in the literature.

The CTEs of FRP materials are highly directionally dependent, and can also vary depending on the type and proportion of constituent materials present. The CTE of unreinforced polymers is generally higher than that of reinforcing steel (Mallick, 1988). However, the addition of fibres to a polymer matrix reduces the CTE. Depending on the fibre type, orientation, and volume fraction, the CTE of an FRP can vary widely, as shown in Table 3, which provides typical CTEs for various FRP materials. It is evident that the transverse CTEs are generally much higher than the longitudinal. This is because the longitudinal properties of a unidirectional FRP are dominated by the fibre properties, whereas the transverse properties are dominated by the matrix (the CTEs of fibres are generally much less than for commonly used polymer matrices). Hence, the concerns associated with spalling of concrete cover when FRP bars are used internally are highlighted.

Rahman et al. (1993) determined the CTE for a carbon/glass/vinyl ester hybrid grid FRP reinforcement in the range of -30°C to +50°C and found it to be 8.39e-6/°C, or about 84% that of concrete. Silverman (1983) conducted tests on a series of glass FRP reinforcements with a variety of different resins, and found that the transverse (matrix dominated) CTE for the GFRP material was not constant, but rather increased with increasing temperature. Drastic increases in the CTE were observed in the 150 to 200°C temperature range, and were thought to be associated with the attainment of the glass transition temperature of the resin materials, established as 185°C. Gentry and Hudak (1996) experimentally determined the CTEs of two different glass/vinyl ester composite rods and found them to be 4.8 με/°C and 8.2 με/°C in the longitudinal direction in the temperature range 0°C to 60°C and 38 με/°C and 32 με/°C in the transverse direction. This highlights both the high directional dependence of the CTE and the inconsistency in CTE values for FRPs of similar composition. Gentry and Hussain (1999) studied the thermal compatibility of concrete and composite reinforcements using both a thermoelastic solution and a numerical finite element approach. They concluded that it is likely that some cracking due to differential thermal expansion of the bars and concrete could result if small covers and bar spacings were used.

Because of the potential for cracking and spalling associated with thermal expansion of FRP reinforcement, several researchers have attempted to determine the critical concrete cover required to prevent cracking. Matthys et al. (1996) performed a finite element analysis to study the effects of transverse thermal expansion of FRP reinforcement. They considered aramid FRP prestressing bars and strips in a temperature range of 20 to 80°C, and determined that the critical concrete cover was about 3.5 to 5 times the bar diameter, depending on the concrete strength and the shape of the FRP element. Aiello et al. (1999) performed an evaluation of the effects of temperature variation on glass and aramid FRP-reinforced concrete elements. Their study confirmed the influence of temperature variations on the state of thermal strain and stress within FRP-reinforced concrete, and the necessity of a minimum concrete cover to prevent cracking.

The above mentioned studies demonstrate that thermal expansion of FRP reinforcement in concrete can cause tensile stresses to develop. If these stresses are large enough and the concrete cover is small enough, cracking or failure of the cover may occur. Experimental work in this area has been limited at present to consider temperature variations that are likely to be experienced under normal service conditions. Few attempts have been made to consider the effects of extreme temperature variation, as would occur in a fire, on the potential for spalling of the concrete cover. Indeed, the potential for damage under high temperatures is increased by the fact that the CTE of some FRP materials has been shown to increase rapidly at temperatures above the GTT of the matrix (Gentry and Hudak, 1996).

4.4.2 Thermal Conductivity

In the study of the high temperature behaviour of FRP bar or grid-reinforced concrete, thermal conductivity of FRPs is not a primary consideration because the amount of FRP in a concrete member will be small in comparison to the amount of concrete. Hence, the FRP's contribution to the overall heat transfer within the member will be negligible. When used as external reinforcement, however, the effect of wrapping or plating may play a role given that the low transverse thermal conductivity of FRPs may act to insulate the substrate concrete from fire.

In general, polymers have comparatively low thermal conductivities (Mallick, 1988), which is one reason that polymers are used as insulating materials for wires and cables. The thermal conductivity of an FRP depends on the resin type, the fibre type and orientation, and the fibre volume fraction. For unidirectional composites used in civil engineering applications, the fibres control the longitudinal thermal conductivity and the matrix controls the transverse thermal conductivity. Some typical values of thermal conductivities for various FRP materials at room temperature are given in Table 4, although again, generalizations are difficult to make. Thermal conductivities of FRPs are generally comparatively low, with the exception being CFRPs in the fibre direction (due to the high thermal conductivity of carbon fibres themselves).

Little work on the variation of thermal conductivity and other thermally important properties, such as density and specific heat, are available for FRPs in the literature. Griffis et al. (1984) conducted tests on a specific carbon/epoxy FRP used in the aerospace industry by subjecting specimens to radiant heat by laser irradiation up to temperatures of 3000°C. The results of these studies are shown in Figure 7, and indicate that the thermal and physical properties of the FRP vary a great deal with temperature. Scott and Beck (1992) also conducted tests on a carbon/epoxy FRP used in the aerospace industry. They found that the thermal conductivity of the FRP varied almost linearly from 0.77 W/m°C to 0.85 W/m°C between the temperatures of 30°C and 135°C. For FRPs to be properly accounted for in heat transfer analyses, more detailed information on their thermal conductivity is needed.

4.4.3 Specific Heat

The rate of heat transfer through a material depends to a great extent on its specific heat. Because of the complex chemical reactions that take place in an FRP at high temperature, it is extremely difficult to determine the variability of specific heat with temperature. Griffis et al. (1984) suggested the use of specific heats that varied as shown in Figure 7 for heat transfer calculations in a carbon/epoxy FRP. In the development of this curve, the specific heat was artificially increased in the temperature range 343°C to 510°C to simulate the thermal degradation effect of the epoxy. Scott and Beck (1992) provide specific heat data that agree well with Griffis et al. (1984), although over a much smaller range of temperatures.

4.5 Mechanical Properties

It is well established that there is a general deterioration in the mechanical properties of most engineering materials with increasing temperature. The somewhat limited work that has been performed in the area of FRP materials at elevated temperatures suggests that the same holds true for FRP composites. Deterioration in mechanical properties in the case of FRP reinforcement for concrete structures is extremely important, since decreases in elastic modulus and strength during a fire could lead to unserviceable deflections, loss of tensile or confining reinforcement, and eventually collapse.

Bank (1993) states that all of the mechanical properties of an FRP are functions of temperature. The critical temperature will usually be the T_g of the matrix; although degradation in both strength and stiffness may be observed well before the T_g is reached. Because of the anisotropy of FRP materials, the transverse (matrix dominated) properties are more affected by elevated temperatures than the longitudinal (fibre-dominated) properties. Thus, for a unidirectional FRP, the transverse strength and stiffness decrease rapidly as the temperature approaches the T_g of the polymer matrix.

4.5.1 Strength and Stiffness

Gates (1991) investigated the variation in the longitudinal, transverse, and shear moduli of a carbon/thermoplastic FRP and a carbon/bismaleimide thermoset FRP in the temperature range of 23°C to 200°C. No significant trend was observed in the longitudinal modulus up to 200°C for either FRP, although the transverse and shear moduli appeared to be affected at elevated temperatures. This result agrees well with the notion that matrix-dominated properties are more severely affected by elevated temperature. It is important to note that the T_g for the resin used in these tests was unusually high, quoted as 220°C. Gates also studied the stress-strain response of the two CFRPs at elevated temperatures, and observed a significant reduction in strength with increasing temperature. The reduction was about 40 to 50% at 125°C and 80 to 90% at 200°C, which indicates extreme strength degradation at temperatures well below the matrix T_g. The anchorage zones were protected from high temperature during this testing, so anchorage effects (loss of bond) is presumably be reflected in the data.

Sorathia et al. (1992) conducted residual flexural strength tests on a variety of FRP panels after 20 minutes of exposure to flame. The tests indicated residual flexural strengths of only about 21% of the original for thermoset matrix FRP. The reader will note that the flexural strength of an FRP is dependent largely on the shear strength of the matrix.

Kumahara et al. (1993) conducted a detailed study on the tensile strength and longitudinal modulus of a variety of continuous glass, carbon, and aramid FRP bars at high temperature. They found that aramid fibre bars showed the most pronounced changes in properties due to heating, with tensile strength values that dropped by 20% at 100°C, and by about 80% at 400°C. The Young's modulus also dropped by 15% at 100°C, and decreased to about 30% at 250°C. Glass fibre bars demonstrated somewhat different behaviour depending on the type of matrix used. The tensile strength of the glass/vinyl ester FRP decreased by 20% at temperatures of 100°C. At 250°C, the tensile strength of the GFRP had decreased by 40%, and at 400°C, the reduction was 60%. In contrast, glass/polyphenylene sulfide (PPS) bars demonstrated little reduction in strength at temperatures up to 250°C. The authors stated that the binder used in the glass/vinyl ester FRP rods was less resistant to heat than that used in the glass/PPS material. No significant reduction in the elastic modulus was observed for the GFRP materials up to temperatures of 250°C. Tests on carbon/epoxy FRP showed a tensile strength reduction of 0 to 25% by 100°C, and 0 to 50% at 250°C. A strength loss of at least 40% was observed at 400°C. The Young's modulus of the carbon FRP did not appear to change significantly up to temperatures of 250°C. The anchorage zones of the FRPs tested in this study were isolated from high temperature. The authors concluded that the tensile strength and modulus of FRP bars was significantly affected by exposure to high temperature, and that the type of fibre and resin used was a key factor in high temperature performance of FRPs. In particular, it was deemed important to use a matrix with as high a T_g as possible.

Fujisaki et al. (1993) conducted heat resistance tests on grid-shaped FRP reinforcement composed of carbon, glass, or carbon/glass hybrid fibres with a vinyl-ester resin. Two types of heating tension tests were conducted on carbon/glass hybrid FRP grid reinforcement: a series of tension tests at high temperature, and a series of residual strength tests performed after heating and cooling. Experimental results indicated that the residual strength of the specimens after heating did not seem to be affected by temperatures up to 250°C. However, the strength during heating was reduced by about 40% at 100°C, and remained about 60% of the unheated strength up to 250°C. Again, the anchorage zones of the FRPs were insulated in this study. This finding could be important for the fire behaviour of FRP-reinforced structures in that the residual strength of the members might not decrease significantly, allowing members to retain much of their strength after exposure to high temperature. The residual strength of FRP-reinforced concrete members and FRP reinforcing materials certainly warrants further study.

Uematsu et al. (1995) used uniaxial tension tests on carbon/poly-ether-ether-keytone (PEEK) FRP. The longitudinal elastic modulus was found to be relatively insensitive to temperatures up to 200°C, demonstrating a loss of less than 10% at that temperature. However, the matrix-dominated properties showed a significant deterioration at temperatures above 100°C. For example, the shear modulus decreased by 5% at 100°C, 55% at 150°C, and 85% at 200°C.

Dimitrienko (1999), in an attempt to develop analytical models to describe the high temperature thermomechanical properties of FRP materials, conducted tests on a number of epoxy matrix FRP products. His tests indicated severe reductions in the elastic and strength properties of carbon and glass FRPs at temperatures below 300°C. Both types of FRPs displayed strength and stiffness reductions of 20% at 200°C and about 40% at 250°C. No mention is made in this study of a provision for thermal protection of the FRP anchorages during these tests, and hence it is not clear if thermal degradation of the shear properties of the polymer matrix at the anchorage were responsible for the apparent deterioration in overall tensile properties.

Alsayed et al. (2000) found that, at 350°C, carbon FRP retained about 35% of its room temperature tensile strength and 40% of its tensile modulus. The corresponding percentages for aramid FRP were 15% and 40%.

Sumida et al. (2001) conducted a test program to investigate the heat resistance of FRP rod reinforcements available in Japan. They conducted tensile tests on both carbon/epoxy and aramid/epoxy FRP rods at elevated temperature and after exposure to high temperature. Tests at high temperature, with the anchor zones insulated from heat, indicated tensile strength reductions of approximately 40% and 60% respectively, for carbon and aramid FRP rods at 260°C, with essentially linear trends of strength loss with increasing temperature. Residual strength tests after heating indicated less than 10% reduction in tensile strength at heating temperatures up to 300°C for both carbon and aramid FRP rods.

Kodur and Baingo (1998) conducted a detailed literature survey on the properties of FRP reinforcement at high temperature, and subsequently presented a numerical model to describe the heat transfer behaviour of FRP bar-reinforced concrete slabs which has been used to provide design guidance in CSA S806: Design and Construction of Building components with Fibre Reinforced Polymers (CSA, 2002). Based on their work, they suggested a strength versus temperature curve for glass FRP reinforcements subjected to fire. Figure 8 shows the variation of strength with temperature for GFRP, timber, concrete, and steel based on their survey of the literature, which predicts a strength loss for FRP of about 15% at 100°C and 75% at 250°C.

An extensive study was performed by Wang et al. (2003) in an effort to define the critical temperature for FRP reinforcing bars; that is, the temperature at which only 50% of the original strength remains. Based on 57 tension tests conducted at various temperatures, it was determined that carbon and glass FRP lost 50% of their original strength at 250ºC and 325ºC, respectively. Stiffness appeared to suffer negligible losses up to about 400ºC, at which point it decreased rapidly.

Based on the experimental data discussed above, a database of test results on the strength and stiffness properties of various fibre and FRP types was assembled. This database has been used to develop semi-empirical analytical expressions that describe the reduction of strength and stiffness of FRP materials at elevated temperatures. Based on the database, the temperature dependant behaviour of carbon, glass, and aramid FRP elements compiled from a number of different studies is shown in Figures 3, 4, and 5 respectively. Variation in the elastic modulus of different FRP materials is shown in Figure 6. It is evident that all types of FRPs show diminished strength and stiffness properties with increasing temperature, although there is a great deal of scatter in the results – as should be expected given the wide range of possible matrix formulations, fibre orientations, and fibre volume fractions represented in the data. The data also indicate that a significant reduction in strength should be expected for any FRP material at temperatures well below 500°C. This would indicate that the *critical temperature* for FRP reinforcement is significantly less than that for steel (593°C).

4.5.2 Creep

Creep can become a critical factor in the design of FRP-reinforced concrete in that excessive long-term deformations can lead to unserviceable structures or to creep-rupture of FRP reinforcement. One concern that has been raised when FRPs are exposed to elevated temperatures, as in the case of fire, is that thermally accelerated creep may be severe and could lead to large deflections and/or failure.

Creep is caused by a combination of elastic deformation and plastic flow. It is widely recognized that creep strain in polymers and polymer composites is dependent on temperature (Mallick 1988). In general, creep strain of FRPs increases with increasing temperature and is largely dependent on the matrix material. Also, highly cross-linked thermoset matrices with a higher T_g exhibit less creep than thermoplastics. Fibre orientation greatly influences the temperature dependence of the creep characteristics of FRPs. If the fibres are in the loading direction, creep in the fibres governs creep in the composite, and it has been observed that commercially available fibres do not creep significantly, with the exception of some aramid fibres (Mallick 1988).

Rahman et al. (1993) conducted tensile creep tests on a uniaxial carbon/glass hybrid FRP loaded to 40% of its ultimate strength for 175 days at room temperature, and determined that the creep in the fibre direction was only 1.8% of the initial strain. Thus, with the exception of aramid fibres, little temperature dependence of creep is expected in the fibre direction, and thermally accelerated creep during fire should not be a significant problem in civil engineering applications, where uniaxial composites are the FRPs of choice.

4.6 Bond Properties at Elevated Temperature

The bond between FRP and concrete is essential to transfer loads, through shear stresses that develop in the polymer matrix or adhesive layer, from the FRP to the concrete and vise-versa. In the event of fire, changes in the mechanical properties of the matrix material have the potential to cause loss of bond at modestly increased temperatures, and result in loss of interaction between FRP and concrete. The result could be catastrophic, both for internally FRP-reinforced concrete and for externally FRP-wrapped reinforced concrete, since loss of interaction could very rapidly lead to loss of tensile or confining reinforcement, and subsequent failure of the concrete member.

Katz et al. (1998, 1999) and Katz and Berman (2000) studied the effect of elevated temperature on the bond properties of FRP bars in concrete. They investigated the pullout strength of glass FRP reinforcement, with six different types of surface textures, subjected to temperatures up to 250°C and found that the bond strength of FRP bars decreased as the surrounding temperature increased. Up to 100°C, the loss of bond was found to be similar to that observed in steel-reinforced concrete, but at temperatures of 200°C to 220°C, the bond strength decreased dramatically to a value of about 10% of the original. The authors commented that the reduction in bond strength was likely due to changes in the properties of the polymer matrix at the surface of the rod.

Sumida et al. (2001) conducted bond strength tests at high temperature on carbon and aramid/epoxy FRP rods, and found large bond strength reductions at rod temperatures above 100°C. They concluded that the surface temperature of FRP rods should be kept below 100°C when subjected to high levels of permanent stress, and that advanced resins with superior high temperature properties are required to improve the fire resistance of FRP reinforcing materials.

In the case of externally bonded FRP reinforcements, no work has been done on bond at high temperature. Temperature effects are more critical in externally bonded applications, since loss of bond would result in complete loss of FRP reinforcement, and further work is required in this area.

4.7 Smoke Generation and Toxicity

The temperature at which a polymer matrix will ignite, the flame spread characteristics, and the amount and toxicity of smoke produced, are all dependent on its particular formulation (Nelson, 1995). Smoke toxicity is potentially a major concern for the fire resistance of FRP reinforcements for concrete, and there is a definite absence of published research in this area, likely because most of the research to date has been performed by the defense and aerospace industries, and the results are not available to the wider research community.

Combustion gases from burning FRPs create a toxicity hazard for humans, and can be highly corrosive to equipment and electronics. Although smoke from burning resins may be toxic and corrosive, it has been stated in the past that the level of hazard is low because FRP repairs are normally in the open or the amount of material is small (Ballinger et al., 1993). This is not the case when concrete elements are reinforced or strengthened with FRPs in buildings. Neale and Labossière (1991) comment on the problem, stating that polymers will generally produce large quantities of very dense, sooty, black smoke. Some components of the smoke, such as carbon monoxide, may be toxic, and other toxic gases such as hydrogen cyanide may also be produced, depending on the component materials used in the manufacture of the FRP.

Sorathia et al. (1992) studied the smoke generation and toxicity characteristics of a variety of FRP materials for use in marine and offshore applications. They conducted optical smoke density tests according to ASTM E662-97 (ASTM, 1997). The results, shown in Figure 9, demonstrate that thermoset resins commonly used in structural FRPs (vinyl ester in particular) generate unacceptable quantities of smoke. The limits quoted by the authors for smoke density in this study were 100 within the first 300 seconds and 200 at any point during the test. Tests were also conducted to determine the nature of combustion gases for a variety of FRPs. The results are shown in Table 5 and indicate that: thermoplastics generate significantly lower concentrations of carbon monoxide during combustion, burning fluorocarbons produce hydrogen fluoride, chlorinated resins produce hydrogen chloride, sulfur-containing compounds produce hydrogen sulfide, and nitrogen containing resins produce hydrogen cyanide, all of which are potentially harmful compounds.

Smoke toxicity is obviously most critical in cases where the FRP is installed on the exterior of a concrete member, although internal reinforcement may generate smoke that could escape through cracks in the concrete at high temperature. More work is required to adequately characterize the gases released and the temperatures at which smoke generation will occur for FRPs in civil engineering applications.

4.8 Ignition and Flame Spread

The impact of a severe fire on an unprotected polymer matrix FRP may be substantial and obvious. Widespread charring, melting, delamination, bucking, and ignition may occur depending on the severity of the fire. Auto-ignition has been observed for FRP composites exposed to high levels of irradiation. Typically, pyrolysis – the process by which solid organic materials are converted into gases, liquids, and a solid char – is initiated between 200°C and 300°C for organic matrix materials (Milke and Vizzini, 1990). During a fire, the FRP matrix will be the most at risk of ignition, due to its high content of carbon, hydrogen, and nitrogen, all of which are flammable. The higher the hydrogen-to-carbon ratio in the polymer matrix the greater is its tendency to burn, and so different matrices may have entirely different susceptibilities to ignition. Despite this disadvantage, the reader should recognize that polymer matrix materials tend to have higher ignition temperatures than wood or other cellulose materials (Neale and Labossière, 1991).

Sorathia et al. (1992) conducted a series of flame spread tests on a variety of different FRP materials according to ASTM E162-98 (ASTM, 1998), which covers the measurement of surface flammability of materials and is not intended for use as a basis of ratings for building code purposes. The results indicated relatively poor flame spread characteristics for vinyl ester and epoxy as compared with other matrix materials.

It should be noted that there exists a number of resin additives that can significantly increase the ability of polymer materials to resist ignition, although these additives generally cause reductions in the mechanical properties which discourages their use in structural applications. Additives may also be incorporated to increase the resistance of FRPs to flames, heat, smoke generation, moisture absorption, oxidation, various chemical actions, and shrinkage. Because of the enormous variety of possible additives, and their effects on the various properties of FRPs, no further discussion of this topic is included here.

4.9 Barrier Treatments

The performance of fire-exposed FRP systems can be improved by the use of barrier treatments or coatings. These treatments function either by reflecting radiant heat back towards the heat source, or by delaying heat penetration to the FRP through their insulative and/or ablative properties (Sorathia et al., 1992).

Sorathia et al. (1992) studied the effectiveness of a ceramic fabric, a ceramic coating, and several intumescent coatings (silicon foam, ablative materials, and phenolic resin as a sacrificial fire barrier), in protecting vinyl ester/glass and epoxy/carbon FRPs exposed to a radiant heat source. For the vinyl ester/glass FRP, ignition times were increased by a factor of 20 using a water-based intumescent coating. For epoxy/carbon FRP, use of an ablative layer with a phenolic skin increased the ignition time by a factor of 10 and reduced the heat release rates significantly.

Apicella and Imbrogno (1999) conducted flame spread and smoke generation tests according to ASTM E84-95 (ASTM, 1995) on a carbon/epoxy FRP wrap. They also investigated the ability of three different fire coatings: an intumescent latex coating, a flame-retardant latex, and an exterior grade acrylic latex, to delay or suppress flame spread. Tests demonstrated that the FRP system without protection achieved only a UBC class III rating, with an ASTM E-84 flame spread index of 155 and a smoke development index of 405. However, with the intumescent latex protective layer, the same system was able to achieve an UBC class I rating, with a zero flame spread index and a smoke development index of 20. The UBC Classifications for interior finishes are shown in Table 6. Class III materials are approved for use in factories, storage areas, and industrial rooms, Class II materials are approved for use in institutional rooms and spaces, and Class I materials are approved for use in critical areas like unsprinkled stairwells and exit ways (Apicella and Imbrogno, 1999). No results were reported with regard to ignition temperature or smoke toxicity.

5.0 Fire Endurance

The discipline of fire engineering is primarily concerned with the protection of life and property from fire (Lie, 1992). The high temperatures experienced during a fire in a building can cause dramatic changes in member behaviour and cause safety or ultimate limit states to be exceeded. Provision for adequate fire endurance of structural members is required to ensure that, when all methods of fire containment fail, structural integrity is maintained for an adequate period of time. Design for fire safety is an extremely complex and rapidly evolving discipline, which requires consideration of a wide range of factors, from materials, to sprinkler systems, to exit signage, to structural integrity. In what follows, we are concerned with *structural* fire endurance requirements as they apply to buildings.

Fire endurance requirements for buildings are specified in building codes such as the National Building Code of Canada (NRC, 1995). They are generally expressed in terms of minimum allowable times to reach specified failure criteria. The prescribed time to failure is chosen based on a number of factors, such as the building size and occupancy, and is a function of: applied load, member type and dimensions, fire intensity, and the materials involved. For traditional structural materials and methods of construction (structural steel, timber, and reinforced concrete), behaviour in fire has been extensively studied and is *relatively* well understood. However, full-scale fire endurance tests are time-consuming and costly, and for new materials and construction methods, fire endurance requirements are not well established in most cases.

When examining the fire endurance of reinforced concrete members, three basic types of members must be considered: beams, slabs, and columns. Each member type has specific requirements in terms of the applicable failure criteria and the required time to reach said criteria. For instance, columns, which are the primary load bearing members in a structure, tend to have the highest required fire ratings (up to 4 hours) whereas slabs, the failure of which would likely be more localized, have comparatively low fire ratings (as low as 1 or 2 hours) (Lie, 1992). There are essentially three distinct failure criteria for different types of reinforced concrete members: loss of load bearing capacity, loss of insulating capacity, and loss of integrity or separating capacity (Kodur, 1999).

Loss of load bearing capacity refers to structural failure (or collapse) such that a member no longer performs the structural task for which it was constructed. Loss of insulating capacity refers to floors or walls that are required to provide fire separation in a building. The particular requirements in Canada (NRC, 1995) are such that the maximum temperature rise at the unexposed face of the specimen shall not exceed 181°C, and that the average temperature rise at the exposed face shall not exceed 139°C. Loss of integrity refers to walls, floors, and roofs and states that no openings or holes should form that would allow fire to move through the assembly. All three criteria do not apply to all types of members. Obviously, a column must only satisfy load-bearing requirements.

The behaviour of reinforced concrete in fire has been studied quite extensively in the literature (Abrams, 1977; Khoury, 2000; Lie, 1992). Concrete has a relatively low thermal conductivity, and it therefore experiences elevated internal temperatures far more slowly than steel. Concrete members can consequently achieve very high fire ratings with no supplemental fire protection, a factor that has contributed to the success of concrete as a structural material during the last century. Adequate fire endurance for reinforced concrete members is usually ensured by providing a sufficient concrete cover to the steel reinforcement. The low-conductivity concrete cover acts as insulation for the internal steel reinforcement, and ensures that the temperature in the reinforcement does not exceed its critical temperature (defined as the temperature at which the reinforcement loses about 50% of its room temperature strength). However, it is difficult to evaluate the fire performance of load-bearing members by heating tests when the permissible temperatures for the reinforcing materials are unknown (Tanano et al., 1999). The critical temperatures for reinforcing and prestressing steel have been established as 593°C and 426°C respectively (Kodur, 1999). No such critical temperatures have yet been established for the wide variety of available FRP reinforcements, although Kodur and Baingo (1998) suggest a temperature of 250°C for internal GFRP reinforcement, based on a review of the literature. The lower critical temperature suggested for FRP reinforcement is highly significant to structural designers, since much larger concrete covers (or supplemental insulation) would be required to achieve similar fire endurance ratings as would be achieved with steel-reinforced concrete.

In externally-bonded FRP-strengthening applications there is no concrete cover, and hence there is no insulation for the FRP reinforcement (unless supplementary insulation is installed). Additionally, in steel-reinforced concrete design there is a provision for concrete cover for corrosion protection, which is usually sufficient to satisfy fire endurance requirements. For FRP-reinforced concrete there is no such corrosion provision (Kodur and Baingo, 1998), although most design guidelines suggest minimum concrete covers to FRP reinforcement based on the prevention of concrete cracking resulting from thermal incompatibility. Thus, the thickness of concrete cover might be less in FRP-reinforced concrete than in steel-reinforced concrete. In cases where the cover cannot be relied on to provide adequate insulation, it is likely that additional fire insulation will be required.

There are a variety of options as far as supplemental fire insulation is concerned; gypsum board, mineral wool, low-density shotcrete, spray-up cellulose, and vermiculite plaster are all possible insulative materials, as are a wide variety of currently available intumescent coatings. Because of the wide variety of insulating materials available, and because they are for the most part proprietary products, a detailed discussion of supplemental insulation methods is avoided here.

5.1 Fire Endurance Tests on Reinforced Concrete Members

Fire endurance tests on a wide range of reinforced concrete members and assemblies have been performed over the last thirty years. These tests have examined a variety of factors and have led to the development of design codes for reinforced concrete members. Some of the more important factors that influence the fire behaviour of reinforced concrete are the cover to the steel reinforcement, the size of the member, the aggregate type, and the concrete compressive strength. In recent years, the primary purpose in conducting full-scale fire endurance tests has been to validate numerical models, such that parametric studies can subsequently be performed at little additional cost. For a comprehensive review of test methods and results, the reader is referred to Lie (1992) and Khoury (2000).

5.2 Fire Endurance Tests on FRP-Reinforced Concrete Members

Studies investigating the thermal and structural behaviour of FRP-reinforced concrete elements are extremely scarce. The few tests results that have been presented in the literature represent tests on specific FRP reinforcing systems and materials, and are not generally applicable to many different FRP-reinforced concrete elements.

5.2.1 Fire Endurance Tests on FRP Bar-Reinforced Concrete

NEFCOM Corporation (1998) conducted fire endurance tests on concrete slabs that were internally reinforced with either glass or carbon FRP grids produced under the trade name NEFMAC^{TM}. A total of ten 3500mm by 500mm, 120mm thick, slabs were exposed to fire on one side for a maximum duration of 2 hours according to the Japanese Industrial Standard (which is essentially equivalent to the CAN/ULC S101 standard fire up to 2 hours). Parameters that were varied in the experimental program included the load intensity, the type of reinforcement (GFRP, CFRP, GFRP/CFRP in combination, or conventional reinforcing steel), the type of polymer matrix used (vinyl ester or unsaturated polyester), the bar size of the grids, the thickness of concrete cover, the presence of a construction joint, and the presence of supplemental insulation in the form of a 25 mm thick rock wool board. Deflections, cross-sectional temperatures, and reinforcement temperatures were all monitored during the tests.

It was observed that the deflection of all slabs increased dramatically when the temperature at the bottom of the reinforcement reached 600°C. This was due to a severe drop in the stiffness of the FRP grid at these elevated temperatures. The performance in fire of the FRP-reinforced slabs did not appear to be affected by the type of resin used in the fabrication of the FRP grid. The rise in temperature in the FRP grid, for the same concrete cover thickness, did not appear to be affected by the type of fibre used. However, the temperature rise at the level of the reinforcement for the steel-reinforced slab was slower than for the slabs reinforced with NEFMAC^{TM}. It is not clear in the NEFCOM study exactly where thermocouples were located in the slabs. If the thermocouples measuring reinforcement temperature was placed at the bottom of the reinforcement (the side closest to the fire), then the slower temperature rise in the reinforcement observed for the steel reinforced slab was likely due to the higher thermal conductivity and heat capacity of steel, such that it acted as a thermal sink to draw heat further into the slab, and thus reducing the observed temperature at that location. Slabs with construction joints failed, before the bottom surface of the reinforcement reached 600°C, because of rapid thermal degradation of the epoxy joint filling agent, resulting in very high temperatures at the location of the joint. The insulated slabs showed substantially higher fire endurance than those without insulation. After two hours of the test, the temperature in the reinforcement in the insulated slab was only 170°C and the deflection only 25mm, as opposed to 600°C and 73mm in the uninsulated slabs. Specimens with higher applied loads showed lower fire endurance based on the time to reach a limiting deflection of 73 mm. The authors concluded that there was no recognizable difference in the fire deflection behaviour of slabs reinforced with NEFMAC^{TM} or with steel.

The most interesting information presented in the above paper is that the NEFMAC^{TM} grid reinforcement was apparently able to maintain strength and stiffness until it reached a temperature of 600°C. Most FRP materials should have lost a significant portion of their strength and stiffness at temperatures well below 600°C. While these results seem contradictory, it is possible that special chemical additives were incorporated in the FRP matrix to improve the fire behaviour, although the authors do not comment in this regard.

Tanano et al. (1995) performed a study on the fire behaviour of FRP-reinforced concrete beams in Japan. Their study focused on the residual strength of beams *after* exposure to fire and did not investigate the structural behaviour of the elements *during* exposure while under load. In this study, 3m long beams with a 200 mm by 300 mm cross-section, and reinforced with either carbon, glass, or aramid FRPs, were heated in a furnace according to a modified version of the Japan Industrial Standard heating curve, such that their temperature reached some specified value in one hour, and was then maintained at a constant level for one and a half hours until the temperature at the level of the internal tensile reinforcement reached 250°C, 350°C, or 450°C.

The authors observed several explosive failures during the heating. It was noted that, because these failures were only observed in beams with an epoxy matrix FRP, the explosive failures were not thought to be associated with generation of steam within the specimens, but with the use of epoxy matrix FRP with a spiral configuration. The specific cause of the explosive failures remains unknown.

After heating, the beams were returned to room temperature and tested in four-point bending. It was observed that bond strength and stiffness decreased for epoxy matrix FRP-reinforced concrete beams as the heating temperature increased, but that the rate of decrease was different depending on the type of FRP used. The rates of decrease in both strength and stiffness were greater for epoxy matrix FRP-reinforced beams than for those reinforced with conventional reinforcing steel. Beams reinforced with an inorganic matrix FRP showed only a small reduction in residual strength after exposure to temperatures of 250°C and above. The residual tensile strength of the FRP reinforcement decreased as exposure temperature increased for all materials, as evidenced by a change in failure mode of the beams from compression failure in the concrete to tensile failure of the internal reinforcement.

Fujisaki et al. (1993) conducted fire endurance tests on FRP-reinforced concrete panels in an attempt to justify the use of FRP-reinforced precast concrete curtain walls. The grid-shaped FRP reinforcement was composed of carbon, glass, or carbon/glass hybrid fibres with a vinyl ester resin.

Thirty-minute fire endurance tests were conducted on precast concrete panels with the grid shaped FRP reinforcement in accordance with the Japanese Industrial Standard. All three types of FRP material (glass, carbon, and carbon/glass hybrid) were examined in a single test. The test results indicated that the maximum temperature on the exposed face of the 150mm thick lightweight concrete slab remained below 260°C, and the maximum temperature observed in the internal reinforcement was 300°C, at which point its strength was assumed to be equal to 60% of the unheated tensile strength based on preliminary testing. The maximum out of plane deflection at the center of the slab was 14 mm, and the maximum crack width was 0.55mm. Based on the results of the tests, the authors concluded that it was not necessary to test the structural capacity as well as the fire-resistance for the members, and judged that the panels displayed sufficient fire-resistance characteristics to be used for curtain wall elements.

Okamoto et al. (1993) conducted a series of full-scale fire endurance tests on partially prestressed concrete beams reinforced and prestressed with braided FRP bars. Braided aramid/epoxy or carbon/epoxy FRP bars were used as the main tendons and transverse reinforcement. Two specimens, one with aramid FRP reinforcement and the other with carbon, were tested. The beams were heated according to the Japanese Industrial Standard heating curve and subjected to a constant load in four-point bending.

It was evident in the tests that heating significantly increased the deflection of the FRP-reinforced concrete beams. The time to failure for both beams tested was 114 minutes, and no explosive failure of the concrete cover was observed. Temperature profiles at different locations were measured throughout the tests, and it was noted that the temperature of the FRP tendons did not exceed 120°C. The authors concluded that the FRP-prestressed beams should be considered able to resist fire for about two hours, although they stated that the residual strength of these beams warranted study.

Kodur and Baingo (1998) conducted a literature review and a numerical parametric study in order to examine the fire endurance of FRP-reinforced concrete slabs. In their study, a numerical finite difference procedure was used to study the time-temperature response of an internally FRP-reinforced concrete slab under exposure fire. The numerical procedure essentially gave fire endurance ratings based on the achievement of a critical temperature of 250°C in the internal FRP reinforcement. The choice of 250°C as the critical temperature was based on what the authors referred to as a worst-case scenario for GFRP chosen after a review of the scarce literature in this area. Some of the more important conclusions of their study were that: FRP-reinforced concrete slabs have a lower fire endurance than slabs reinforced with conventional reinforcing steel; higher fire endurance for FRP-reinforced concrete slabs can be obtained by using a thicker concrete cover and by using carbonate aggregate concrete; data on the material properties of FRPs at elevated temperatures are required; and structural fire endurance tests are required to validate the numerical models.

Sakashita (1997) investigated the effect of fire on concrete beams reinforced with carbon, glass, and aramid FRP rods with different surface textures and fibre orientations (braided, spiral, or straight). The behaviour of these beams was compared to that of a conventionally reinforced concrete beam in a fire test. All specimens were heated to 100ºC for three hours prior to testing and then heated to 1000ºC under load in 180 minutes. It was found that, at a furnace temperature of 350ºC, specimens containing aramid FRP experienced a sudden increase in vertical deflection. These beams failed at a furnace temperature of 500ºC. However, specimens containing glass or carbon FRPs, or conventional steel, completed the 180-minute test without failure. At the end of the tests, it was observed that the average midspan deflections and temperature at the bottom face of the beams were 160 mm and 680ºC for GFRP, 30 mm and 700ºC for CFRP, and 100 mm and 680ºC for conventional reinforcing steel.

Nakagawa et al. (1993) performed a fire test on an FRP-reinforced concrete curtain wall section. The curtain wall was a 75 mm thick concrete slab and was reinforced with a 3-D carbon FRP grid. Fire endurance tests of 60 minutes duration were conducted on two specimens according to the Japanese Industrial Standard. A maximum temperature of 516°C was recorded in the FRP reinforcement and of about 110°C on the unexposed face of the slab. Based on the results of heating tests on the specific FRP reinforcement, which indicated a loss of about 50% of the room temperature tensile strength at 400°C, it was concluded that the reinforcement was damaged by the extremely high temperatures recorded during the test, although the panels (which were tested under load) did not fail. No cracks or fractures due to differential thermal expansion were observed. The authors concluded that the wall panels displayed an adequate fire endurance of more than 60 minutes.

Kodur and Bisby (2005) present the results of an experimental and numerical study performed to investigate the performance in fire of concrete slabs reinforced with steel, glass FRP rebars, or carbon FRP rebars. Fire tests, performed in accordance with ASTM E119, were conducted on eight intermediate scale reinforced concrete slabs. A number of parameters were varied among the slabs, including: the slab thickness, the rebar type, the aggregate type, and the thickness of the concrete cover to the reinforcement. In addition, a finite difference numerical heat transfer model was developed and verified against the test data, and was shown to agree satisfactorily with the results.

The primary conclusions reached in the Kodur and Bisby (2005) study were that: the qualitative fire performance and heat transfer behaviour of FRP-RC slabs appears similar to slabs reinforced with steel bars; the reinforcement type has a significant effect on the predicted fire resistance of RC slabs, with FRP-RC slabs having much lower fire resistance as compared to those reinforced with steel; slab thickness does not have a significant effect on the fire resistance of the concrete slabs; concrete cover thickness has a significant influence on the fire resistance of RC slabs; and aggregate type has a moderate influence on the fire resistance of FRP-RC slabs. The authors note that higher fire resistance for FRP-RC slabs can be obtained by using larger concrete cover thickness or through the use of carbonate aggregate concrete. They also state that fire design and testing guidelines in North America do not currently consider the effects of two important factors on the fire endurance of RC slabs, namely applied load and reinforcement bond degradation. Full-scale tests on loaded FRP-RC slabs are thus required to determine whether bond degradation, which can be expected to be severe at only mildly increased temperatures, might cause premature structural failure during fire. The reader will note that the spalling of the concrete cover resulting from differential thermal expansion between the FRP and the concrete did not appear to be exacerbated by the presence of the FRP reinforcement in this study.

5.2.2 FRP-Plated or -Wrapped Reinforced Concrete

In concrete members externally reinforced with FRP, unless an insulating or intumescent protective layer (or both) is applied, the FRP would be immediately exposed to the heat of the fire, likely resulting in rapid loss of composite action. In these cases, it is required that the reserve strength of the member, which would revert to a conventional steel-reinforced concrete member, would be relied on to carry the necessary loads for the duration of the fire. Few tests on externally FRP-reinforced concrete have been reported in the literature. Only three previous studies have been reported examining the behaviour in fire of externally FRP-strengthened concrete beams and slabs, and two preliminary studies have examined the fire behaviour of FRP-wrapped columns.

In terms of tests on beams and slabs, Deuring (1994) studied flexural strengthening with externally bonded FRP materials on six concrete beams during exposure to fire. One beam was unstrengthened, one was strengthened with an adhesive bonded steel plate, and four were strengthened with CFRP plates. Two of the FRP plated beams were tested without insulation and two were protected with insulating plates of a different thickness. The results of this initial test program demonstrated the need for thermal insulation of the FRP plates. Bond between the FRP and concrete was lost very rapidly (within minutes) for the unprotected specimens but occurred after about an hour for those with supplemental insulation.

In an effort to gain further insight into the behaviour of FRP-plated reinforced concrete beams during fire, a second study was conducted by Blontrock et al. (2000). The focus of this test program was to investigate a number of different thermal protection materials and layouts. The program included tests on a total of ten beams. An unstrengthened reference beam and a strengthened reference beam were statically tested to failure in four point bending, two unprotected and unstrengthened beams were loaded to full service load and tested under fire exposure, and six strengthened and protected beams were loaded to full service load and tested under fire exposure. The protection schemes were different for all six protected beams and consisted of gypsum board/rock wool combinations. All strengthened beams were strengthened using the Sika CarboDur^{TM} carbon/epoxy FRP strengthening system.

The fire endurance tests were conducted in accordance with the International Standards Organization (ISO) test method 834 for fire testing of concrete members, which is essentially the same as the Canadian CAN/ULC S101 fire testing procedure. A summary of the test results is presented in Table 7. The U-shaped protection scheme shown in Figure 10 was most effective at prolonging the time before loss of interaction between the plate and the concrete. This scheme had the additional advantage of lowering the temperature of the internal reinforcing steel, thus contributing to lower deflections throughout the tests.

Blontrock et al. (2001) conducted a series of fire endurance tests on externally CFRP-reinforced concrete slabs in an effort to evaluate their fire endurance. As was the case in the beam study discussed above, various fire insulation schemes (consisting of rock wool and/or gypsum board layers) were implemented to prevent debonding of the carbon FRP plating material. A total of ten slabs were tested including: unstrengthened and strengthened reference slabs tested at room temperature, unstrengthened and unprotected slabs tested under exposure to fire, and strengthened and protected slabs tested under exposure to fire.

Some of the more important conclusions reached in these studies were that: thermal protection is required in order to maintain the interaction between the FRP plates and the concrete; without protection it is impossible to achieve the same fire endurance as for the unprotected and unstrengthened beams; interaction between the externally glued composite and the concrete was lost when the temperature in the epoxy adhesive reached temperatures of 66°C to 81°C for the Sika^{TM} CFRP product, and 47°C to 69°C for an S&P Laminates^{TM} CFRP product; partial protection of the external strengthening system (applied to the anchorage zones only) was able to maintain interaction between the FRP and the concrete; and the fire endurance for the strengthened and protected beams was at least the same as for the unstrengthened unprotected beams.

To the knowledge of the authors no full-scale fire endurance tests on FRP-wrapped reinforced concrete columns have been reported in the literature. Saafi and Romine (2002) conducted a series of residual strength tests on FRP-wrapped reinforced concrete cylinders after exposure to elevated temperatures. A total of 40 cylinders, wrapped with two layers of a unidirectional glass/epoxy FRP, were tested in axial compression after exposures of up to three hours at 90°C, 180°C, and 360°C. The results of these tests indicated significant reductions in the overall strength and ductility of the wrapped cylinders at exposure temperatures at or above the 180°C (the GTT for this system). However, this study is not particularly useful for a variety of reasons. First, the authors observed several explosive failures of their cylinders, which would indicate that the cylinders were not allowed sufficient time to dry before testing. In addition, the temperature regimes were not nearly severe enough to be representative of a building fire, and the tests were conducted after the cylinders had returned to room temperature, a condition which is not representative of a severe building fire.

6.0 Current Research: NRC-ISIS-Industry Collaboration

This state-of-the-art report is one component of an ongoing research program that is currently underway at the National Research Council of Canada (NRC) in collaboration with the Intelligent Sensing for Innovative Structures (ISIS) Research Network of the Canadian Network of Centres of Excellence (NCE), and industry partners. The current project is aimed at examining the performance in fire of externally-bonded FRP strengthening systems for reinforced concrete members. To this end, a number of intermediate-scale and full-scale fire endurance tests have been conducted on insulated FRP-strengthened reinforced concrete slabs, beams, and columns. Various FRP systems and supplemental fire insulation systems and thicknesses have been investigated. A suite of numerical fire simulation models has also been developed, and has been verified against the results of the fire tests. This project is ongoing, and to date only the results of initial column and slab tests have been reported in the literature.

6.1 Column Test Program

The column test program to date has consisted of full-scale fire tests on three FRP-strengthened and insulated reinforced concrete columns (Bisby, 2003; Bisby et al., 2001, 2002, 2004a, 2004b). Two of these columns were circular and were strengthened with carbon FRP wraps. The third column was square and was strengthened with glass FRP wraps. In all three cases the columns were protected with a supplemental fire insulation system applied to the exterior of the FRP wrap. The fire protection was developed specifically for this application by an industry partner, and consisted of a two-part system comprised of a layer of a modified vermiculite-gypsum plaster with a surface coating of epoxy paint. Further information on the insulation system is given in Bisby (2003). In conjunction with the full-scale fire tests, numerical models were developed that can predict the heat transfer within and load capacity of these members under exposure to the standard fire. The models can be used to predict the fire endurance of insulated FRP-strengthened columns with satisfactory accuracy.

Without getting into the details of the test program, the overall conclusions reached during the initial column test program can be summarized as follows:

> The unique two-component insulation system used in this study is an effective fire protection system for FRP-wrapped reinforced concrete columns. The insulation remained intact during exposure to the standard fire, and provided outstanding thermal protection for externally-bonded FRP materials. FRP-strengthened columns protected with this system are capable of achieving satisfactory fire endurance ratings.
>
> The numerical model developed can satisfactorily predict both the heat transfer within, and load capacity and deformation of, FRP-wrapped and insulated reinforced concrete columns during exposure to a standard fire.

6.2 Slab Test Program

The slab test program to date has consisted of intermediate-scale fire tests on two FRP-strengthened and insulated reinforced concrete slabs (Williams et al., 2002, 2004). The slabs were 150 mm thick, were reinforced internally with conventional reinforcing steel, and were strengthened with carbon FRP wraps. The slabs were protected with different thicknesses of the same supplemental fire insulation system as was used to protect the columns. In this case the fire tests were used as a means to evaluate the performance of the supplemental fire insulation system, and the slabs were tested in the unloaded condition. Numerical models were also developed to predict the heat transfer within these members under exposure to the standard fire. The models can be used to predict the fire endurance (based on thermal criteria only) of insulated FRP-strengthened slabs with satisfactory accuracy.

Again, without getting into the details of the test program, the overall conclusions reached during the initial slab test program can be summarized as follows:

> According to ASTM E119 temperature-based fire endurance criteria, a four-hour fire endurance rating can be achieved with 38mm of the insulation scheme examined. A smaller thickness of insulation (19mm) provided approximately two hours of fire protection for slabs resisting only their self-weight.

Observations from the fire tests indicate that providing sufficient insulation thickness is important in minimizing cracking and preventing possible delamination of the fire protection.

The heat transfer model can provide reasonable estimates of the temperature within the insulated, FRP-strengthened RC slabs during fire exposure.

While it will likely be very difficult to maintain the effectiveness of externally-bonded FRP systems during fire, it appears possible to achieve satisfactory fire performance for these members, provided they are appropriately designed and adequately insulated. Tests on full-scale insulated FRP-strengthened RC slabs under full service load are required to confirm this conclusion.

7.0 Summary and Conclusions

It is evident from the material presented in this chapter that information on the fire and high temperature behaviour of FRPs and FRP-reinforced concrete members is extremely scarce. At elevated temperatures, all FRP materials currently available for civil structural applications will experience a reduction of both strength and stiffness. They may experience significant transverse thermal expansion leading to cracking or spalling of the concrete cover or to the development of shear stresses in their adhesive layer. They may ignite. Upon ignition, they may emit dense smoke and toxic gases. They may lose their bond with the substrate or surrounding concrete. All of these concerns have not, at present, been adequately studied or addressed by current design guidelines.

The development of standard tests for FRP materials are required both at room and high temperatures, with both static and dynamic loading and temperature regimes, such that a database of test results can be formulated and expanded on an international scale. The mechanical and thermal behaviour of FRP materials currently available in industry must be accurately ascertained, such that experimental and parametric numerical studies can be executed with accuracy. Detailed models must be developed and continually updated in order to study the effect of varying a wide range of parameters on the fire behaviour of FRP-reinforced and FRP-prestressed concrete members. Finally, full-scale fire endurance tests are required in order to validate numerical procedures, and to raise awareness of and confidence in FRP reinforcing materials in the construction industry.

Eventually, it is hoped that research will lead to the development of complete design guidelines for the use of FRP-reinforced concrete in buildings and structures. Only when such a design code is produced and sanctioned with confidence by the engineering research community will the use of FRPs for reinforcement and strengthening of concrete gain widespread acceptance and implementation.

8.0 Recommendations

As is evident in this report, while a number of significant conclusions have been drawn from research conducted to date, a great deal of further research is required before rational and realistic fire design recommendations for FRP-reinforced or wrapped concrete members can be suggested with confidence. Some of the most important recommendations for further research into the fire behaviour of FRP-strengthened reinforced concrete structures include:

Further full-scale fire endurance testing of FRP-wrapped reinforced concrete columns is required, both to ensure repeatability of the experimental results from the two tests conducted to date, and to provide additional validation data for the numerical fire simulation models.

Full scale fire tests should be conducted on FRP-strengthened reinforced concrete members to investigate a variety of important issues, including: member type, strengthening scheme (externally bonded versus near surface mounted), load intensity, combined axial and bending loads, fibre type, matrix type, etc.

Research has indicated that both the overall fire endurance of FRP-strengthened members and the ability of fire simulation models to predict internal temperatures depend on the prevention or minimization of crack formation in supplemental insulation materials as the fire progresses. New installation approaches should be developed that promote the formation of fewer and smaller cracks in insulating materials.

Further work is required, both analytical and experimental, to accurately model the behaviour in fire of the various currently available insulation systems for FRP-strengthening schemes. A more complete understanding of the variation in thermal properties with temperature, and the movement of moisture within the pores of insulation materials, and its effect on thermal properties, is essential for accurate modelling of insulated members in fire.

Existing fire simulation models for FRP-strengthened concrete members do not account for moisture migration in the concrete. It is suggested that an attempt be made in the future to numerically account for moisture migration in the concrete (and in insulation materials when present). This extension of the models' capabilities would also be of benefit to researchers investigating the fire behaviour of conventionally reinforced concrete structures, and steel structures insulated with supplemental systems.

With regard to the fire behaviour of FRP bar-reinforced concrete members, the following are recommendations for further research:

Fire endurance tests on FRP bar-reinforced slabs and beams under sustained load are required to investigate the structural behaviour of these members during fire exposure. Test data are also required to validate numerical fire simulation analyses.

Further research is required to determine rational methodologies for assigning critical temperatures of FRP reinforcing bars. This work must account for the differences in design approaches and failure modes for FRP-reinforced members as compared with steel reinforced members, and will require that full-scale fire endurance tests on FRP-reinforced members under sustained load be conducted.

Further research is required to determine both the nature and magnitude of FRP-concrete bond degradation at high temperature (for both internal reinforcing and externally-bonded applications), and the effects of bond degradation on the flexural capacity of FRP bar-reinforced concrete members. In addition, tests to determine residual bond characteristics would be beneficial in the evaluation of fire-damaged FRP bar-reinforced concrete structures.

The following are general recommendations for further research into the fire behaviour of FRPs and FRP-reinforced concrete:

A more complete understanding of the thermal and mechanical properties of FRP materials at high temperature is required. The mechanical and thermal behaviour of FRP materials currently available in industry must be accurately ascertained, such that experimental and parametric numerical studies can be executed with confidence and accuracy. In addition, the residual (post-fire) mechanical properties of FRP materials require investigation, such that fire damaged FRP-reinforced or wrapped concrete members can be evaluated and repaired if necessary.

The development of standard test methods for FRP materials are required both at room and high temperatures, with both static and dynamic loading and temperature regimes, such that a database of test results on the high-temperature behaviour of FRP materials can be formulated and expanded on an international scale.

To date, virtually no consideration has been given to the potential environmental effects of FRP combustion and decomposition during a building fire. The potential for the generation of significant amounts of dense smoke and toxic gas is a significant concern when FRPs are used in buildings. Further research is required to characterize the nature and amount of gaseous FRP decomposition products produced in fire, such that environmental threats to building occupants can be addressed.

Detailed information on the variation of several thermally important properties (thermal conductivity, specific heat, density) with temperature is extremely scarce for most currently available fire insulation materials. In the near future, given the current shift toward objective-based design codes, it is likely that numerical fire modelling will become a much more important research tool for fire protection engineers. Research is required to develop test methods to determine these thermally significant properties at a variety of temperatures. Once these test methods are in place, a significant research effort is required to obtain and compile thermal data for the wide variety of insulating materials currently available in industry.

Research studies conducted to date on the fire performance of FRP-reinforced and/or strengthened reinforced concrete structures have used standard fires in an attempt to characterize behaviour. The response of FRP materials and FRP-reinforced concrete structures under exposure to real building fires, which can be substantially different than standard fires, requires evaluation, particularly given that the combustible nature of FRPs will actually alter the development of fires when FRPs are left unprotected.

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Table 1: Selected FRP materials currently available for civil engineering applications

Name	Fibre	Matrix	Fibre Content (%)	Modulus (GPa)	Ultimate Stress (MPa)	Poisson's Ratio	CTE (μ /°C)		Shape
							Longitudinal	Transverse	
C-Bar B1 (#12)[1]	Glass	Vinyl ester (VE)	60 by weight	42	770	0.27	8	32	Rod
ASLAN 100 (#12) [1]	Glass	-	70 by weight	40.8	690	-	6-10	21-23	Rod
ISOROD [1]	Glass	VE or polyester	-	37.43	635-747	0.27-0.29	8.9-9.1	16.9-21.2	Rod
	Carbon	Vinyl ester	-	111.1	1596	-	-	-	Rod
NEFMAC[1]	Glass	-	-	30	600	-	-	-	Grid
	Carbon	-	-	100	1200	-	-	-	Grid
	Aramid	-	-	54	1300	-	-	-	Grid
	Hybrid	-	-	37	600	-	-	-	Grid
ROTAFLEX[1]	Glass	Epoxy	80 by weight	56	1800	-	-	-	Rod
LEADLINE[1]	Carbon	Epoxy	65 by vol.	147	2550	-	0.7	-	Rod
CFCC[2]	Carbon	Epoxy	53.2 by vol.	137	1750	-	.6	-	Rod
Arapree[2]	Aramid	Epoxy	45 by vol.	125	2860	0.38	-2	-	Strip
FiBRA[2]	Aramid	Epoxy	60 by vol.	69	1400	0.6	-5.2	-	Rod
Technora[2]	Aramid	Vinyl ester	65 by vol.	54	2150	-	-3	-	Rod
SIKA CarboDur S[3]	Carbon	Epoxy	68 by vol.	> 155	> 2400	-	-	-	Strip
SikaWrap Hex 100G[3]	Glass	Epoxy	-	26.1	600	-	-	-	Sheet
Mitsuishi Replark 20[3]	Carbon	Epoxy	-	235	> 3000	-	-	-	Sheet
M-Brace CF 130[3]	Carbon	Epoxy	-	227	3800	-	-	-	Sheet
M-Brace CF 530[3]	Carbon	Epoxy	-	373	3500	-	-	-	Sheet
M-Brace AK 60[3]	Glass	Epoxy	-	120	2000	-	-	-	Sheet
M-Brace EG 900[3]	Aramid	Epoxy	-	72.4	1520	-	-	-	Sheet
Tyfo SEH-51	Glass	Epoxy	-	26.1	575	-	-	-	Sheet
Tyfo SCH-41S	Carbon	Epoxy	-	72.4	876	-	-	-	Sheet
Tyfo SCH-35	Carbon	Epoxy	-	78.6	991	-	-	-	Sheet
Tyfo SEH-51A	Glass	Epoxy	-	26.2	575	-	-	-	Sheet
Tyfo SCH-30T	Carbon	Epoxy	-	90.2	1351	-	-	-	Sheet

(1) ISIS, 2001A
(2) Braimah, 2000
(3) ISIS, 2001b
(4) http://www.fyfeco.com/tyfosys.html

Table 2: Qualitative comparison of different FRP types (Meier, 1994)

Criterion	**Fibre Type**		
	Carbon	**Aramid**	**Glass**
Tensile Strength	Very Good	Very Good	Very Good
Compressive Strength	Very Good	Inadequate	Good
Modulus of Elasticity	Very Good	Good	Adequate
Long Term Behaviour	Very Good	Good	Adequate
Fatigue Behaviour	Excellent	Good	Adequate
Bulk Density	Good	Excellent	Adequate
Alkaline Resistance	Very Good	Good	Inadequate
Price	Adequate	Adequate	Very Good

Table 3: CTEs of various unidirectional FRPs and building materials (Mallick, 1988)

Material	**Coefficient of Thermal Expansion (10^{-6} / °C)**	
	Longitudinal	**Transverse**
Glass/Epoxy	6.3	19.8
Aramid/Epoxy	-3.6	54
High Modulus Carbon/Epoxy	-.09	27
Ultra-High Modulus Carbon/Epoxy	-1.44	30.6
Boron/Epoxy	4.5	14.4
Aluminum	21.6 – 25.2	
Steel	10.8 – 18	
Epoxy	54 – 90	

Table 4: Thermal conductivities of various unidirectional FRPs and building materials (Mallick, 1988)

Material	**Thermal Conductivity (W/m· °C)**	
	Longitudinal	**Transverse**
Glass/Epoxy	3.46	0.35
Aramid/Epoxy	1.73	0.73
High Modulus Carbon/Epoxy	48.44 – 60.55	0.87
Ultra-High Modulus Carbon/Epoxy	121.1 – 129.8	0.04
Boron/Epoxy	1.73	1.04
Aluminum	138.4 – 216.3	
Steel	15.57 – 46.71	
Epoxy	0.346	

Table 5: Gases released during combustion of FRP (Sorathia et al., 1992)

Fibre/Matrix	**Carbon Monoxide (ppm)**	**Carbon Dioxide (% volume)**	**Hydrogen Cyanide (ppm)**	**Hydrogen Chloride (ppm)**
Glass/Vinyl Ester	230	0.3	NONE	NONE
Glass/Epoxy	283	1.5	5	NONE
Glass/Phenolic	300	1.0	1	1
Glass/BMI	300	0.1	7	TRACE
Glass/PEEK	TRACE	TRACE	NONE	NONE

Table 6: UBC classifications for interior finishes (Apicella and Imbrogno, 1999)

Interior Finish Classifications	ASTM E-84 Flame Spread Index	ASTM E-84 Smoke Developed Index
Class I	0-25	0-450
Class II	26-75	0-450
Class III	76-2000	0-450

Table 7: Summary of results from fire tests on FRP-plated reinforced concrete beams (Blontrock et al., 2000)

Beam Number	Time to Loss of CA* (min)	Temp. in FRP at Loss of CA (°C)	Midspan Defl. @ 90 min (mm)	Temp. in Internal Steel @ 90 min (°C)
3	-	-	56.0	536.2
4	-	-	49.4	547.5
5	7	61.2	-	-
6	38	65.2	15.3	137.3
7	26	52.1	26.1	212.8
8	39	57.4	-	-
9	18	54.9	47.7	466.4
10	22	56.0	40.7	419.5

* CA – Composite Action

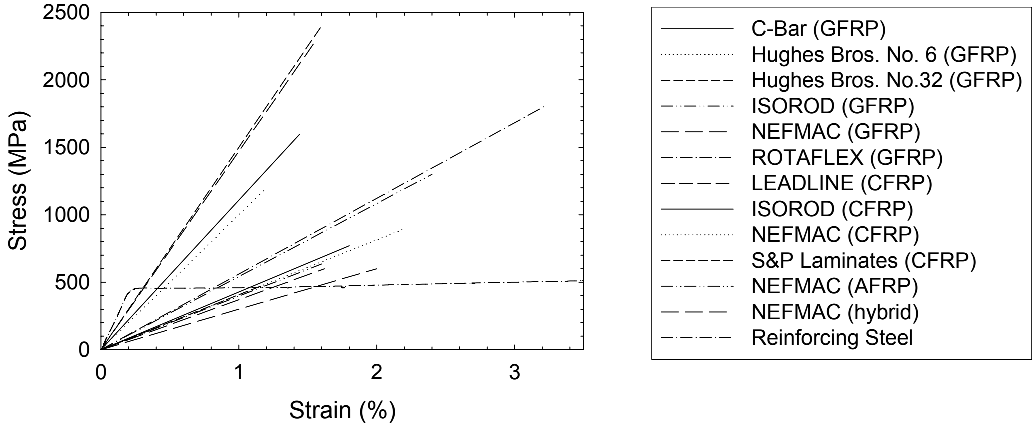


Figure 1: Manufacturer specified stress-strain behaviour of various currently available FRP reinforcing products (reproduced after ISIS, 2001a)

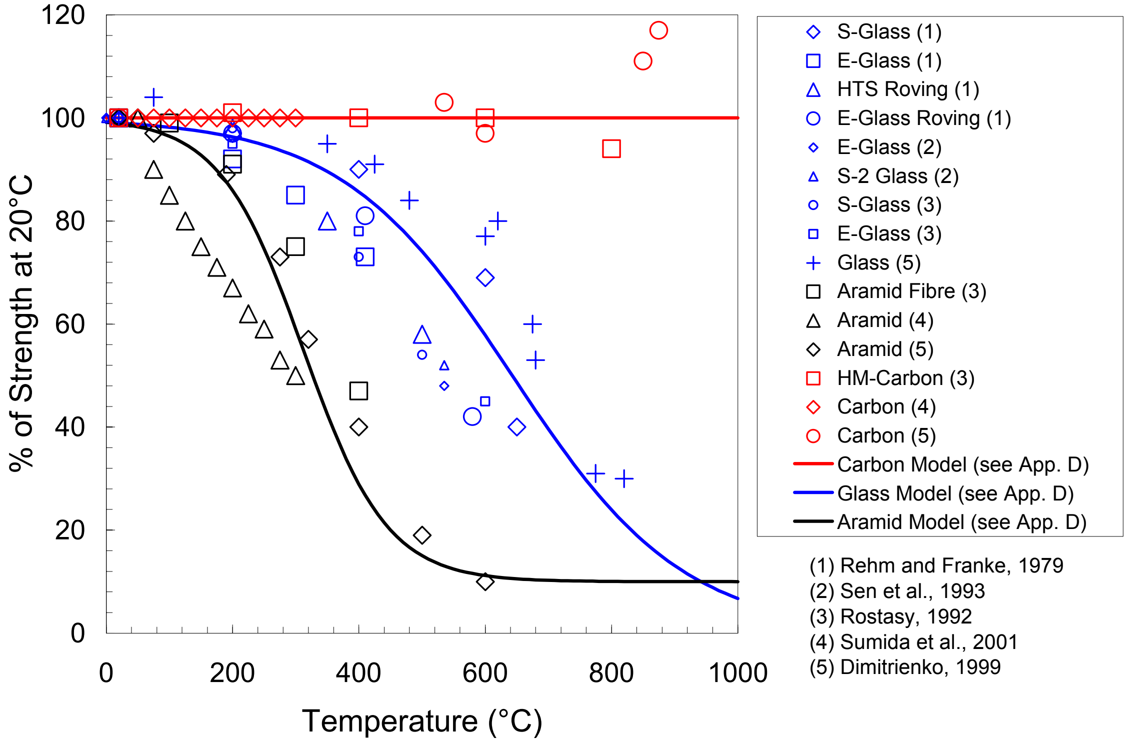
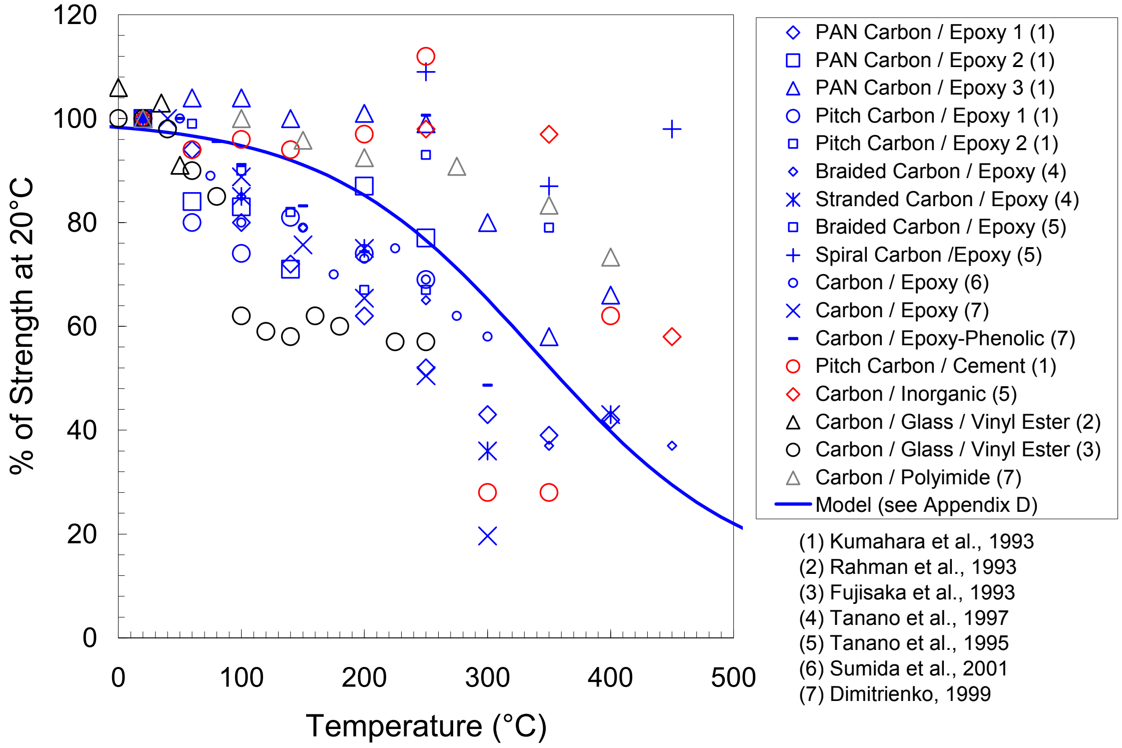
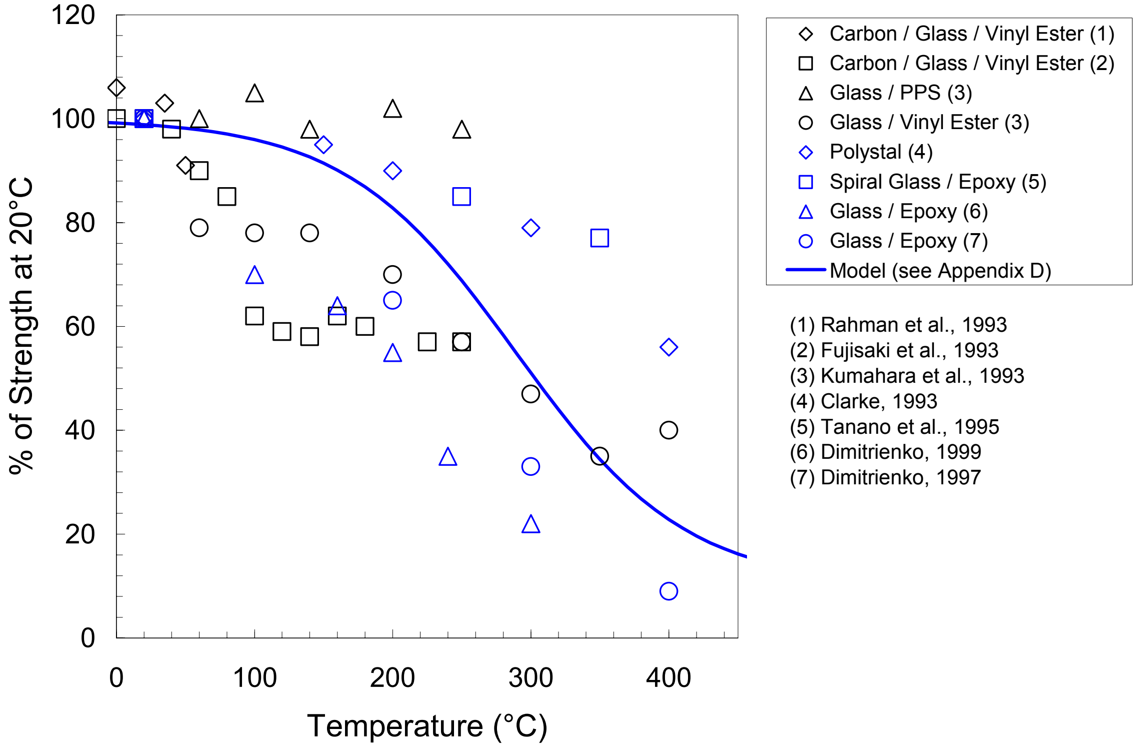


Figure 2: Variation in tensile strength of various fibres with temperature



(1) Kumahara et al., 1993
(2) Rahman et al., 1993
(3) Fujisaka et al., 1993
(4) Tanano et al., 1997
(5) Tanano et al., 1995
(6) Sumida et al., 2001
(7) Dimitrienko, 1999

Figure 3: Variation of strength of various carbon FRPs with temperature



(1) Rahman et al., 1993
(2) Fujisaki et al., 1993
(3) Kumahara et al., 1993
(4) Clarke, 1993
(5) Tanano et al., 1995
(6) Dimitrienko, 1999
(7) Dimitrienko, 1997

Figure 4: Variation of strength of various glass FRPs with temperature

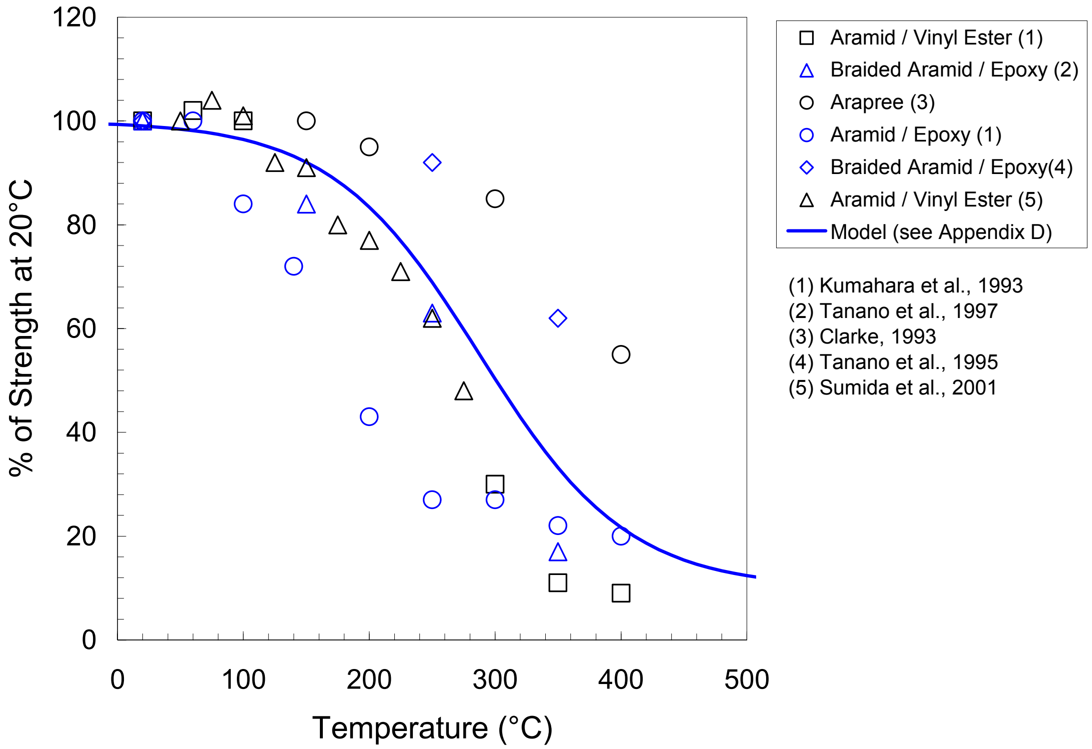
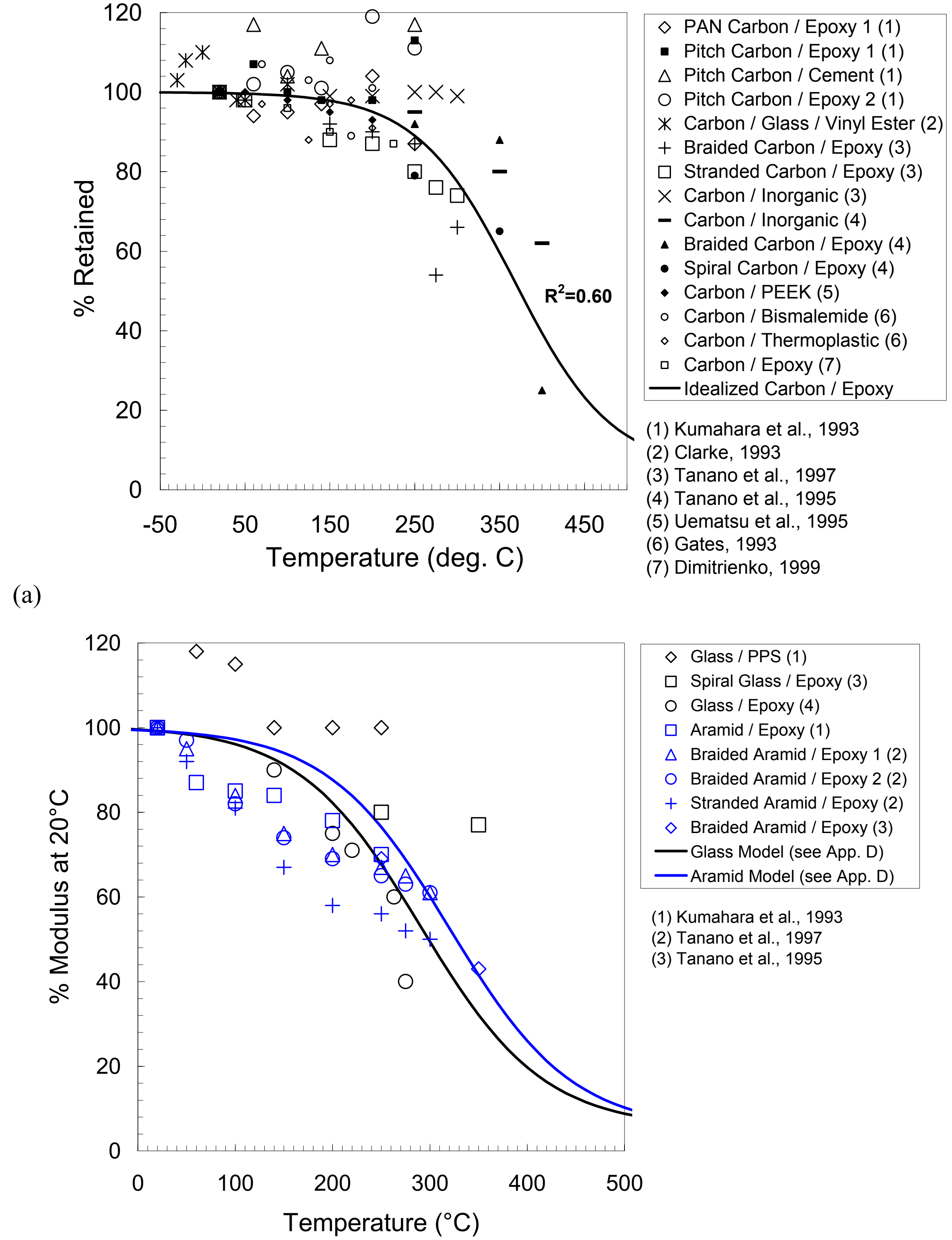


Figure 5: Variation of strength various aramid FRPs with temperature



(a)

(b)

Figure 6: Variation of elastic modulus of (a) carbon (b) glass and aramid FRPs with temperature

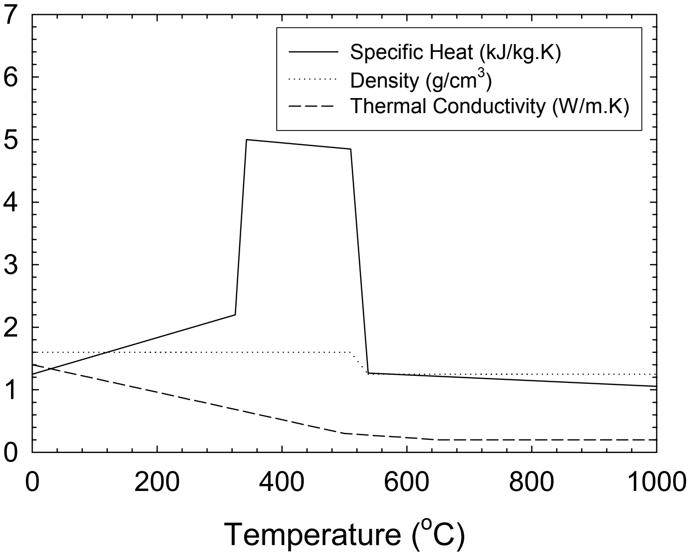


Figure 7: Variation of thermal conductivity, density, and specific heat with temperature for carbon/epoxy FRP (after Griffis et al., 1984)

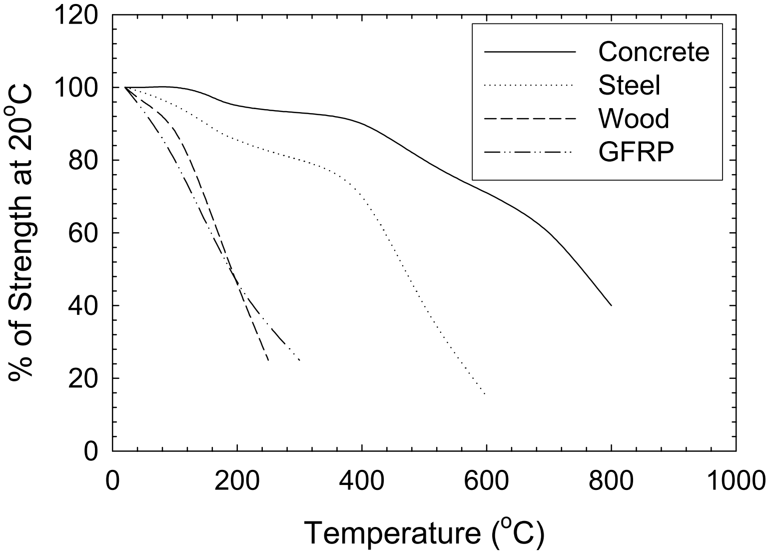


Figure 8: Variation of strength with temperature for GFRP, timber, concrete, and steel (reproduced after Kodur and Baingo, 1998)

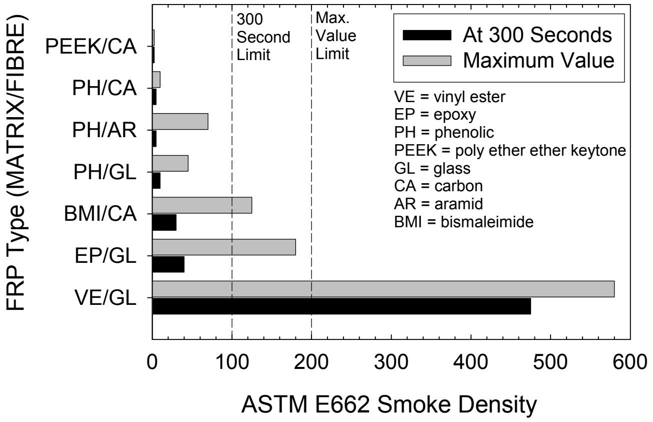
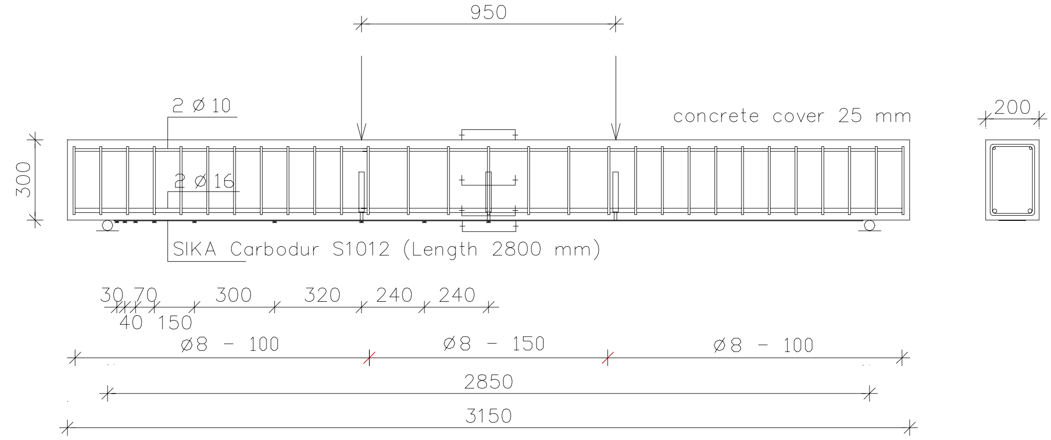
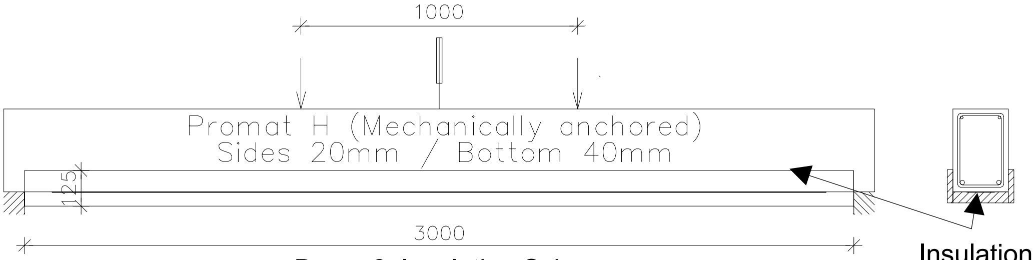


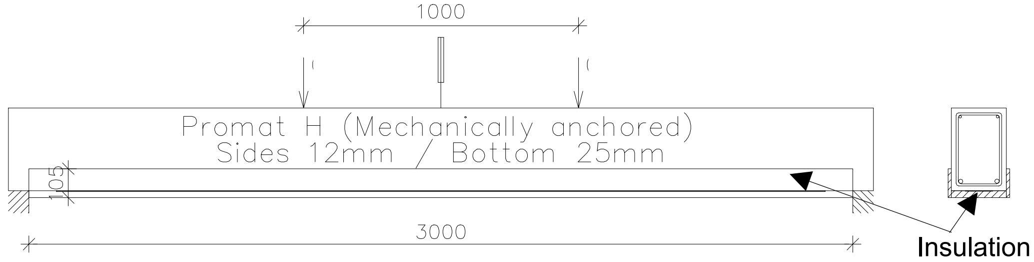
Figure 9: Results of smoke generation tests on various FRPs (after Sorathia et al., 1992)



Beam Dimensions and Reinforcement Details



Beam 6: Insulation Scheme



Beam 7: Insulation Scheme

Figure 10: Details of selected FRP plated beams fire tested by Blontrock et al. (1999)