1 Introduction

1.1 Background

Nature resources, energy shortage, and global warming are recognized as the major issues faced in the twenty-first century. It was reported that buildings expend 32% of the world's resources in construction, consume approximately 40% of global energy, and produce approximately 40% of total greenhouse gas emissions [1]. Steel and concrete dominate the construction market of civil infrastructure, with current consumption of 1 m^3 per person/year for the latter (which is always reinforced with steel reinforcements) [2]. Steel is an unrenewable resource in nature and its manufacturing is very energy intensive leading to a high carbon footprint. Ordinary Portland cement, as an essential component in concrete, has high embodied energy and contributes approximately 5–7% of global anthropogenic CO_2 emissions.

The choice of materials in construction of civil infrastructure therefore becomes an important decision. Embodied energy associated with a material that accounts for the total energy necessary of an entire product lifecycle as well as associated carbon footprint must be considered [3]. The way to construct civil infrastructure is of further concern. Today, it appears that almost all types of industry have adopted automated processes to speed up, optimize, and economize production. Construction industry, however, seems to be an exception. Bridges and buildings are still cast on-site using scaffolding and formwork and employing cumbersome wet-in-wet processes with increasingly unacceptable consequences regarding cost, quality, and safety [4].

The arrival of new materials in the field of civil construction such as fiber-reinforced polymer (FRP) composites may provide a solution for all those challenges. Compared with steel, FRP composites have similar strength but lighter weight (1/4–1/6 of steel). FRP composites may also exhibit advantageous environmental characteristics, particularly if glass fibers (glass fiber-reinforced polymer, GFRP) such as low carbon dioxide emissions, are used. The embodied energy analysis further indicates that GFRP material is a clear winner in structural applications as compared to steel [5]. These lightweight and high-strength materials can be formed into complex shapes, and are therefore compatible with industrialized prefabrication and rapid installation. The applications of such

High Temperature Performance of Polymer Composites, First Edition. Yu Bai and Thomas Keller.

materials in engineering structures are expected to contribute significantly to profound innovations and benefits in different economic, environmental, and social levels.

In order to successfully implement FRP composites in civil infrastructure construction, the performance of FRP composites under elevated temperatures and fire must satisfy the corresponding requirements such as structural adequacy, integrity, and insulation [6]. The thermophysical and thermomechanical behavior of an FRP composite depends mainly on its resin component. The material state and material properties of a polymer composite remain fairly stable in the low temperature range before the glass transition of the resin occurs, after which however they undergo significant changes. When temperature continuously increases, the resin decomposes, resulting in further changes in material state and material properties.

These physical and chemical processes lead to an obvious degradation of the stiffness and strength of FRP composite materials. Figure 1.1 shows a cross section of the lower face sheet of a DuraSpan® bridge deck (E-glass fiber-reinforced polyester resin) subjected to an ISO-834 (International Standards Organization) fire curve on the underside. It can be seen that almost all the resin was decomposed, leaving only the fibers in the pultrusion direction. But, as these fibers no longer provide composite action, the load-bearing capacity of such a deck is considerably reduced. If FRP composites are to be used in load-bearing structural applications, it must be possible to build structures that resist such extended excessive heating and/or fire exposure and also to understand, model, and predict their endurance when subjected to combined thermal and structural loads. The application of FRP

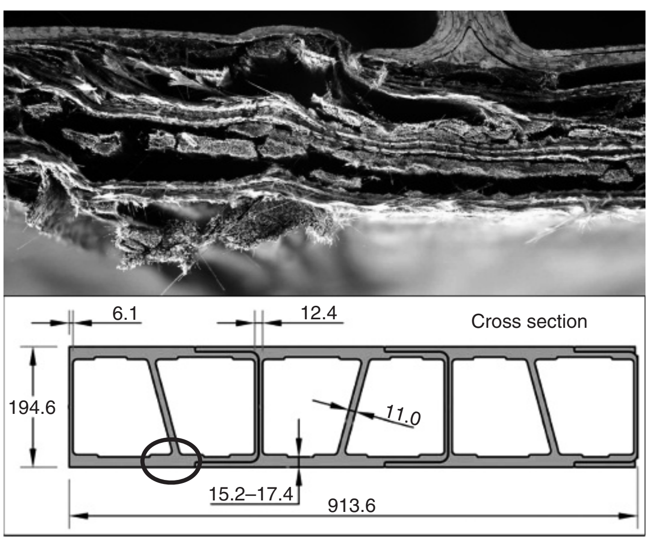

Figure 1.1 Cross section of a FRP profile after fire exposure. (With permission from EPFL-CCLab.)

materials in structures requiring extended excessive heating resistance and/or fire resistance, such as in building structures, necessitates the study of the thermal and mechanical responses of large-scale and complex composite structures over longer time periods [8].

Most of the previous studies concerning FRP composites under elevated and high temperatures involve military applications, aerospace, and marine and offshore structures. The required endurance times for marine and offshore composite structures are longer than those for the initial military applications, although they are still low in comparison to those required for civil infrastructure, especially in building construction [8]. For example, most multistory buildings are required to resist 90 min of fire exposure in many countries. It has been recognized that structural system behavior under excessive heating and fire conditions should be considered as an integral part of structural design, whereas only very limited research has been conducted concerning the progressive thermomechanical and thermostructural behavior of FRP composites for building construction.

Although several thermochemical and thermomechanical models have been developed for the thermal response modeling of polymer composites, most are based on thermophysical and thermomechanical property submodels without a clear physical and chemical background (empirical curves from experimental measurements). Very few have considered the thermomechanical response of composites subjected to excessive heating and/or fire exposure lasting longer than 1 h. Existing thermochemical or thermomechanical models cannot adequately consider the progressive material state and property changes and structural responses that occur during the extended excessive heating and/or fire exposure of large-scale FRP structures. In addition, after excessive heating or fire exposure, the condition of these load-bearing composite structures has to be assessed. Very often, the major parts of a structure will not be decomposed or combusted, but only experience thermal loading at elevated and high temperatures. Information and models relating to the assessment of post-fire properties for load-bearing FRP structures are still lacking [8].

In this book, it is intended to provide the reader with useful and comprehensive experimental data and models for the design and application of FRP composites at elevated temperatures and fire conditions. The progressive changes that occur in material states and the corresponding progressive changes in the thermophysical and thermomechanical properties of FRP composites due to thermal exposure will be discussed. It will be demonstrated how thermophysical and thermomechanical properties can be incorporated into heat transfer theory and structural theory. The thermal and mechanical responses of FRP composites and structures subjected to hours of realistic fire conditions will be described and validated on the full-scale structural level. Concepts and methods to determine the time-to-failure of polymer composites and structures in fire will be presented, as well as the post-fire behavior and fire protection techniques.

1.2
FRP Materials and Processing

1.2.1
FRP Materials

FRPs are composite materials made of a polymer matrix reinforced with fibers. In comparison to concrete (that is also a composite material), the fibers may carry and transfer both compressive and tensile stresses. The polymer matrix bonds these fibers together, prevents buckling of the fibers in compression, transfers stresses between discontinuous fibers, protects the fibers from environmental impact, and maintains the overall form of the resulting composite material.

Polymer matrix materials are categorized into thermoplastics and thermosets. Thermoplastics soften and melt above a specific temperature and become solid when cooled. They can be formed by repeated heating and cooling. In contrast, thermosets normally cure by irreversible chemical reaction (between two components, a resin and a hardener, for example, for epoxy (EP)) and chemical bonds are formed during the curing process. This means that a thermoset material cannot be melted and reshaped once it is cured. Thermosets are the most common matrix materials used for FRP composites in construction nowadays. The most common thermosets are unsaturated polyester (UP), EP, and vinylester (VE) [9]. Because of their organic material nature, all of these matrix materials are sensitive to elevated temperatures and fire.

Major fiber types used for FRP composites in construction are glass, carbon, and aramid. Properties of these fibers are given in Table 1.1 [9]. Glass fibers are most commonly used in structural applications because of their low manufacturing cost and their high strength to weight properties. They are made by melting glass or other raw materials to liquid form, then extruded through bushings into filaments and coated with a chemical solution. Different types of glass fibers exist, among them E-glass fibers (aluminoborosilicate glass with less than 1% alkali oxides) are the most popular ones in structural applications [10]. Commercial E-glass fibers are

Table 1.1 Mechanical properties of glass, carbon, and aramid fibers.

Property	E-glass fibers	Carbon fibers	Aramid fibers
Tensile strength (MPa)	3500	2600–3600	2800–3600
Young's modulus (GPa)	73	200–400	80–190
Elongation at failure (%)	~4.5	0.6–1.5	2.0–4.0
Density ($g\,cm^{-3}$)	2.6	1.7–1.9	1.4
Coefficient of thermal expansion ($10^{-6}\,K^{-1}$)	5–6	Axial −0.1 to −1.3, radial 18	−3.5
Fiber diameter (μm)	3–13	6–7	12
Fiber structure	Isotropic	Anisotropic	Anisotropic

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3–13 μm in diameter. They are isotropic, stronger, and lighter than steel by weight, but not as stiff (i.e., lower *E*-modulus) as steel. Carbon fibers are very strong, stiff, and light. They are anisotropic (reduced radial strength) and associated with high cost of production. Aramid is a synthetic fiber that has a high tensile strength. The disadvantages of aramid fibers are their low compressive strength, reduced long-term strength (stress rupture), and their sensitivity to UV radiation [9].

FRP composites, as a combination of fibers and polymer matrix, show also lightweight and high strength. In addition, because of the polymer matrix, they present high corrosion resistance and low thermal conductivity. Table 1.2 shows a comparison of basic material physical properties of FRP composites and other common constructive materials [11].

In comparison to steel and steel reinforced concrete, a distinction of FRP composites is their usually orthotropic mechanical behavior. The strongest direction is always in parallel to that of the fiber direction. Strength and stiffness of a FRP component depend on the orientation of the fibers and quantity of fibers oriented in each direction. Bundles of parallel fibers are called *roving*. Different textiles

Table 1.2 Approximate material physical properties of common constructive materials and FRP composites.

Material	Density (kg m^{-3})	Thermal conductivity (W (m K)$^{-1}$)	Specific heat capacity (J (kg K)$^{-1}$)
Steel	7850	45.8	460
Concrete	2100	1.0	880
Wood (pine)	670	0.14	1170
FRP	1870	0.35	640

According to [11].

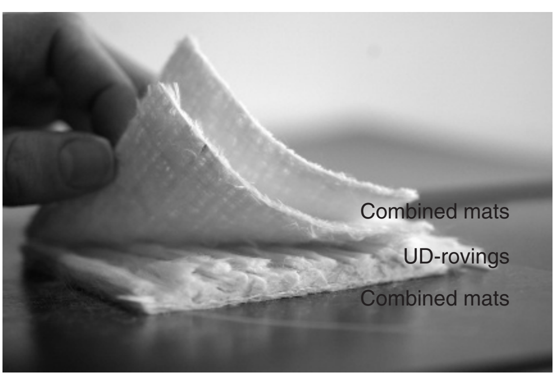

Figure 1.2 Fiber architecture of a 10 mm GFRP plate after matrix burn-off. (With permission from EPFL-CCLab.)

are manufactured from rovings such as multiaxial nonwoven fabrics, grid fabrics (e.g., for grid reinforced concrete), continuous-fiber mats, fleeces from chopped glass fibers, and three-dimensional woven fabrics. Figure 1.2 shows the fiber architecture of a 10 mm GFRP plate after burn-off of the polymer matrix, with a layer of unidirectional rovings sandwiched by two layers of mats [12].

1.2.2 Processing Technologies

There is a variety of processing technologies that can be used to manufacture FRP composites. This section briefly introduces some common ones.

Hand lay-up is probably the easiest way to produce FRP composites as no special equipment is required. The process is first to apply the resin on the surface of a mold (before that a release agent may be necessary to help removing the completed product from the mold), and subsequently place a layer of fibers. This can be followed by further additions of resin and fiber layers. However, air must be removed between the fibers within the matrix, using a roller, for example.

Vacuum-assisted resin transfer molding (VARTM) is a process to form and shape FRP composites. Fibers are layered on a solid mold base and covered by a vacuum bag. By generating a vacuum, the vacuum bag is compacted owing to the action of atmospheric pressure, and, therefore, air bubbles are eliminated. Porous fabrics absorb excess resin and the entire material is cured to obtain better mechanical properties. This processing technology is suitable to a certain level of automation and ensures a good geometrical control and a smooth surface.

Filament winding is an automatic process to produce FRP structural components. It consists of winding continuous-fiber tow around a mandrel to form a tubular structure. The fiber-spinning unit is synchronized to move (back and forth longitudinally) during the rotation of the mandrel. Fibers impregnated with polymer resin are thus laid down in a desired pattern. The advantages of filament winding are its high automation and production rate and low manufacturing cost.

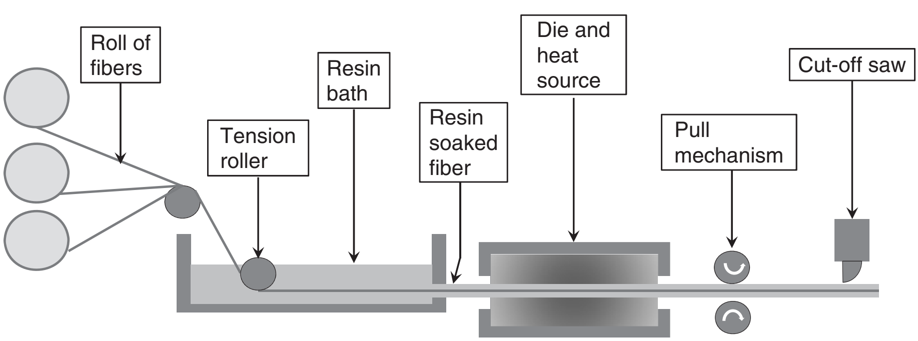

Figure 1.3 Illustration of a pultrusion process where fibers are pulled through a die where the matrix material is injected and cured.

Pultrusion is also a highly automatic process to manufacture FRP structural components. As shown in Figure 1.3, fibers are pulled through a resin bath and then through a heated die for curing and shaping [9]. The pultrusion process is similar to the extrusion process used for aluminum except that the fibers are pulled rather than pushed. Pultrusion can produce complex cross sections as those produced by extrusion. Pultruded structural components therefore exhibit high potential in civil infrastructure applications with a variety of profiles. Most profiles are similar to standard steel sections such as I-sections or tubes, as shown in Figure 1.4, where an even larger range of irregular-sectional and corrugated shapes may also be available.

1.3 FRP Structures

FRP composites have been increasingly used in civil engineering in recent years, not only to repair or strengthen existing structures [13] but also for load-bearing structures especially in bridge construction [9]. Relevant projects in the context of load-bearing FRP composite structures developed at the Composite Construction Laboratory EPFL, Switzerland, are briefly introduced in the following section.

1.3.1 Pontresina Bridge

The Pontresina Bridge is an all-FRP composites pedestrian bridge crossing the Flaz creek in Pontresina that is located in the Swiss Alps at an altitude of 1790 m. The bridge is only temporary, as it is used only during the winter for ski touring. It requires removal in the spring owing to high water and is reinstalled each year in the autumn. Built in 1997, the bridge has been installed and removed several times. Figure 1.5a shows the bridge during service in the winter, while Figure 1.5b shows the bridge placed on the banks during the summer.

Figure 1.4 Standard pultruded GFRP shapes (Fiberline Composite A/S, Denmark) [12]. (With permission from EPFL-CCLab.)

(a) (b)

Figure 1.5 Pontresina bridge (a) during winter and (b) during summer [14]. (With permission from ASCE.)

The conceptual design of the bridge resulted from three main constraints at that time: (i) the low clearance above water that required a load-carrying structure above the walkway, (ii) the annual cycles of installation/removal, and (iii) the available pultruded GFRP shapes provided by the manufacturer (Fiberline Composites, Denmark). The choice of GFRP materials was based mainly on their low self-weight for the installation and removal cycles, and the expected low to zero maintenance [14].

From these constraints, a two-span bridge of 2 m × 12.50 m resulted with 1.48 m deep truss girders on the lateral sides of the walkway. The total width is 1.93 m, while 1.50 m is the clearance between the girders. Each span weighs 16.5 kN (12 kN shapes, 3 kN gratings, 1.5 kN steel supports and bolts) and can be easily removed and installed in one piece by a helicopter, as shown in Figure 1.6.

The bridge was built up from only five different pultruded GFRP shapes and a GFRP grating, as shown in Figure 1.7a,b. The joints in one span are bolted, while the joints in the second span are adhesively bonded with a two-component EP adhesive. Since it was the first time that adhesive bonding was used in primary load-carrying joints, the adhesive joints were secured with back-up bolts. The bolts were also able to facilitate joint fixation during adhesive curing. Crushing of the tubes during bolt tightening was prevented by spacer tubes, through which the bolts were pushed.

The pultruded GFRP profiles consisted of E-glass fibers embedded in an isophthalic polyester resin. The environmental exposition of the GFRP profiles corresponds to a typical alpine climate. The mean annual temperature is approximately 4 °C with maximum values of approximately 25 °C in the summer and a minimum of −20 °C in winter. The annual hours of sunshine are approximately 1700 and the average annual rainfall is 1000 mm. The alpine location exposes the white colored bridge to high UV radiation. A layer of dense snow normally covers the walkway [14].

However, as a temporary pedestrian bridge, no certain fire resistance were required, therefore, no specific fire safety considerations were made.

Figure 1.6 One span of Pontresina Bridge removed by a helicopter [15]. (With permission from Elsevier.)

1.3.2 Eyecatcher Building

FRP composites have demonstrated their success in bridge construction [16]. In building construction, however, FRP composites have not yet received the same success, although they offer the same high strength and lightweight advantages, and in *addition* low thermal conductivity (for GFRP composites).

A demonstration of using FRP composites in building structures was made through the construction of the 15 m tall, five-story ''Eyecatcher'' at the Swiss Building Fair 1999 in Basel (Figure 1.8) that is still the tallest FRP building in the world [17]. Similar to the Pontresina Bridge, it is composed of pultruded GFRP profiles. While for the Pontresina Bridge, the low self-weight and corrosion resistance were factors that determined the choice of material, for the Eyecatcher building, it was the low thermal conductivity that was foremost. More specifically, the GFRP composites do not create thermal bridges and can be integrated directly into the façade. A multilayered façade construction is therefore not required.

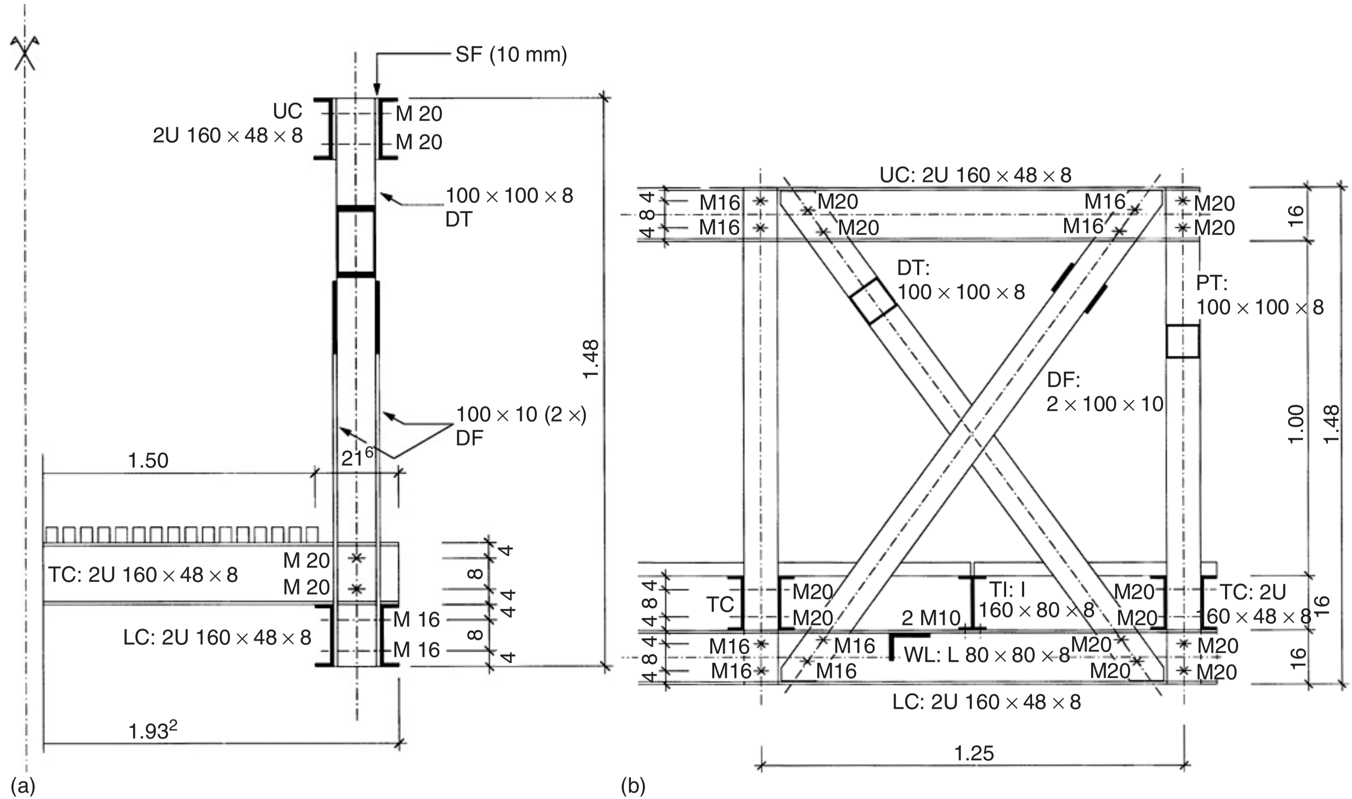

Figure 1.7 (a) Typical cross section and (b) right end portion of longitudinal section, where UC and LC are for upper and lower chords with two U channel sections, DT and DF are for diagonal tubes in compression and diagonal flat sections in tension, PT is for vertical posts, TI is for transverse I beams between joints and TC for transverse beams with two U channel sections at joints, and SF is for spacer plates with flat sections [14]. (With permission from ASCE.)

Figure 1.8 Eyecatcher building.

This reopens the lost conceptual and structural possibilities of the ''bauhaus'' architectural style for architects, and reduces construction costs [18].

The primary load-carrying structure of the Eyecatcher consists of three parallel trapezoidal GFRP frames (see one in Figure 1.9) connected by wooden decks. The structural joints in the frame were bolted in order to facilitate dismantling of the reusable structure. Because the selection of cross-sectional shapes and sizes of the girders and columns was limited at that time, project-tailored cross sections were designed by assembling individual standard pultruded shapes. Three cross sections were built up using adhesive bonding as shown in Figure 1.10 [18]. Those sections were further experimentally examined in full scale under four-point bending for safety evaluation [17].

Translucent sandwich panels for the side-facades were also made of glass-fiber-reinforced polyester composites (see Figure 1.8). The sandwich panels consisted of two layers separated by a composite fiber sheet with trapezoidal corrugations. The surface of the façade panels was finished with fleeces that also provide resistance to aging and UV radiation. As the main function of these façade elements was thermal insulation, the sandwich panels were filled with aerogels. They were therefore able to provide a K-value of 0.4 W m^{-2} K^{-1} with a panel thickness of only 50 mm [18]. In terms of building fire considerations, a sprinkler system was installed as an active fire protection.

1.3.3 Novartis Main Gate Building

Recently in 2006, a lightweight GFRP sandwich roof structure was designed and built for the new Main Gate of the Novartis Campus in Basel, Switzerland, as

Figure 1.9 Frame construction.

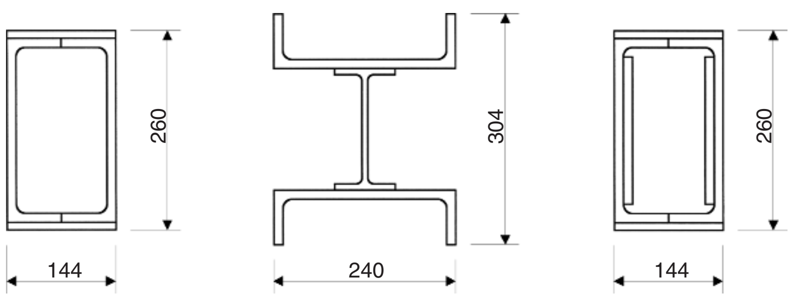

Figure 1.10 Typical adhesively bonded cross sections of Eyecatcher girders and columns.

shown in Figure 1.11 [19]. The building is covered with a 21.6 m × 18.5 m function-integrated GFRP sandwich roof structure that integrates load-carrying, physical and architectural functions into one single-layer building envelope.

The rectangular floor plan of 17.6 m × 12.5 m is formed by four glass walls. The walls consist of insulating glass and, as shown in Figure 1.12, are stiffened every 1.7 m with vertical twin glass stiffeners. The glass walls and stiffeners are connected with structural silicone and carry the GFRP sandwich roof without any other

Figure 1.11 Novartis Campus Main Gate Building with GFRP sandwich roof, view from the south [19]. (With permission from ASCE.)

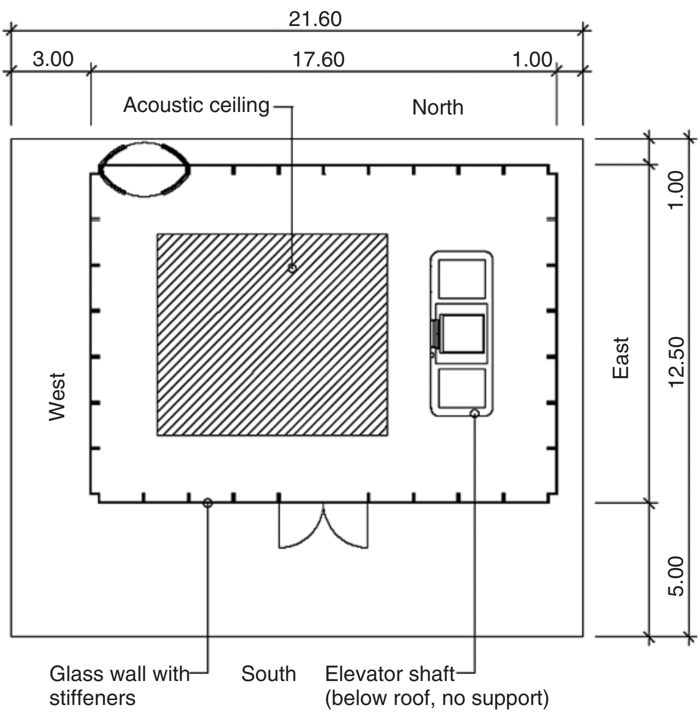

Figure 1.12 Plan view with glass walls, glass stiffeners, and roof cantilevers [19]. (With permission from ASCE.)

structural elements. The GFRP roof structure has overhangs on all four sides to protect the glass walls from direct solar radiation. The largest overhang of 5.0 m is to the south, followed by 3.0 m to the west, and 1.0 m to the north and east. The roof plan is 21.6 m × 18.5 m, as shown in Figure 1.12. On the basis of esthetic considerations, the roof has the form of a wing that tapers off from a maximum thickness of 620 mm in the middle to 70 mm thin edges at the overhang ends. The surface appearance is similar to that of a sailplane wing: white in color, very smooth, and glossy [19].

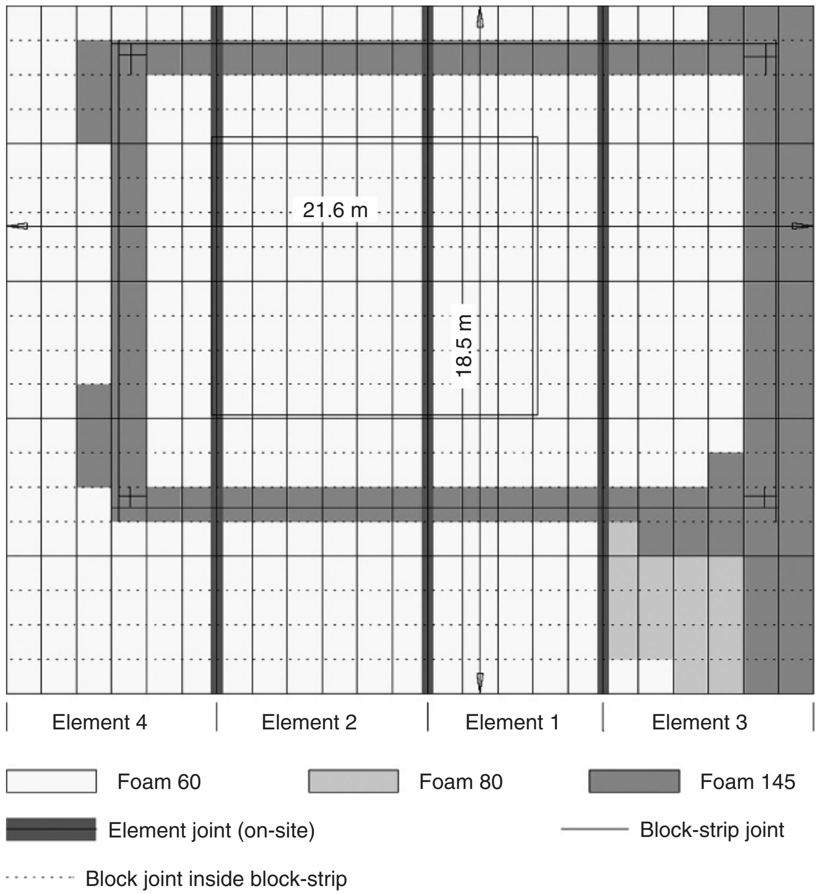

Figure 1.13 Plan view with internal web grid, core density distribution, block, block strip, and element arrangement [19]. (With permission from ASCE.)

The aforementioned architectural and esthetic considerations presented several constrains for the following structural design and construction. The roof must be lightweight owing to the limited load-carrying capacity of the glass walls, and, at the same time, it must provide thermal insulation and waterproofing for the building. Together with the desire of a complex double-curved geometry, the use of a GFRP sandwich structure of variable depths was decided. The sandwich core consists of a polyurethane (PUR) foam of three different densities and strengths. As the shear load-carrying capacity of even the densest foam core was not sufficient, the core had to be reinforced by an internal system of orthogonal GFRP webs spaced at 925 mm. Figure 1.13 shows a plan view of the roof with the internal web grid and the distribution of the core densities (maximum density over the supporting glass walls).

The roof structure was assembled on-site by four roof elements through adhesive bonding at the element joint positions, as shown in Figure 1.13 (where the element joints separated the entire structure into four). Each element was composed of series of sandwich block strips (each block strip was formed by a group of four blocks) and prefabricated in a factory. During prefabrication, adhesive bonding was used to connect the webs of the block strips, thereby, providing continuity of the longitudinal and transversal webs. The resulting self-weight of the entire roof structure is 28 ton or an average of 70 kg m^{-2} [19].

In terms of fire resistance considerations, as E-glass fibers and a polyester resin were used, a filled, low viscosity, and self-extinguishing polyester resin was adopted that further showed low flammability and medium smoke formation. As fire is an accidental action, the partial load factors could be reduced to 1.0 in the structural design according to the Swiss code. A consideration in the structural design of fire situation was that a surface of $2.0\,\mathrm{m} \times 2.0\,\mathrm{m}$ of the lower face sheets could fail without collapse of the roof structure. This further took into account the reduction of 50% in material strength and stiffness for a 1.0 m wide strip around this surface [19].

1.4 Structural Fire Safety

Fire is a dangerous and potential threat to the built environment and it may turn into a disaster if not well controlled. In any case, fire safety must be considered at the design stage of new buildings. The principles of fire-safe design are outlined in this section.

1.4.1 Possible Fire Threats

Building fires threaten both life and property in numerous ways. In order to design adequate protective measures, it is first necessary to identify possible threats that building fires present.

Heat and flames may be most direct threats. Contact with an object at 65 °C may cause burns within 1 s. Air heated above 150 °C may cause edema (blockage of the respiratory tract), exhaustion, and dehydration. However, direct contact with flames (which are more than 10 times hotter) may cause immediate burns [20].

During fire, a fatal threat to human lives is oxygen depletion. Normal air contains roughly 21% oxygen. If the fire consumes enough oxygen that the level drops down to 17%, muscular dexterity degrades through anoxia. If it drops further to 14%, mental capacity and decision making are impaired. A further reduction to 8% causes death within 6–8 min [20]. Other threats to human lives are any toxic combustion products and smoke. Smoke, by limiting visibility, may hinder the escape of occupants or inhibit the efforts of rescuers. Although hundreds of gasses produced during combustion have been proven to be toxic at sufficient concentrations, carbon monoxide (CO) causes fire-related deaths more than any other toxic product or even any other threat [20]. Other common poisons are carbon dioxide (CO_2), nitrogen dioxide (NO_2), sulfur dioxide (SO_2), hydrogen chloride (HCl), and formaldehyde (CH_2O) [21].

Structures may collapse during fire exposure that in most cases is catastrophic. In addition to the collapse of a whole building, failure of any individual building components, such as a floor deck or column, can lead to death by direct physical trauma or by the obstruction of escape routes. The objective of fire safety measures is to reduce these threats to the levels that are deemed acceptable by building fire standards. Those standards are laws or regulations and must be followed in the design and construction of building structures, as briefly introduced in the following section.

1.4.2
Building Fire Standards

Building fire standards are a special type of building codes intended to ensure fire safety of building structures. In general, two types of fire codes exist: prescriptive and performance-based codes. Prescriptive codes are an early version that specifies the exact details of how to achieve fire safety goals for the building category and usage, in terms of materials and products, assembly methods, and overall building design [7]. Prescriptive codes are usually straightforward to follow because very little evaluation or analysis is required and only a certain number of options are acceptable. However, innovation is discouraged by such codes. It can be prohibitively difficult to obtain certification for products and assemblies that are not specifically described in a prescriptive-based code.

A later version of building fire codes is developed based on the evaluation of structural performance through the definition of the exact fire safety goals and the criteria to determine whether those goals are met [22]. The manner in which the goals are achieved is, however, not specified. The transition from prescriptive to performance-based standards, therefore, encourages innovations and provides flexibility in the selection of new structural materials, including FRP composites. Following performance-based standards, new products may receive certification or a rating through validated models or standardized tests. Organizations such as the ISO, ASTM (American Society for Testing and Materials), UL (Underwriter's Laboratories), and DIN (Deutsches Institut für Normung) develop and publish standard testing procedures. The tests are performed for fire reaction properties, such as but not limited to the following:

- ASTM E1354-04 (standard test method for heat and visible smoke release rates for materials and products using an oxygen consumption calorimeter) and ISO 5660-1:2002 (reaction-to-fire tests – heat release, smoke production, and mass loss rate – part 1: heat release rate, cone calorimeter method) for heat release and oxygen consumption.
- ASTM E2102-11a (standard test method for measurement of mass loss and ignitability for screening purposes using a conical radiant heater) and ISO 5657:1997 (reaction-to-fire tests – ignitability of building products using a radiant heat source) for material ignitability.

- ASTM E2102-11a (standard test method for measurement of mass loss and ignitability for screening purposes using a conical radiant heater) and ISO 5660-1:2002 (reaction-to-fire tests – heat release, smoke production, and mass loss rate – part 1: heat release rate, cone calorimeter method) for mass loss.
- ASTM E662-13 (standard test method for specific optical density of smoke generated by solid materials) and ISO 5659-2:2012 (plastics – smoke generation – part 2: determination of optical density by a single-chamber test) for smoke production.
- ASTM E1321-09 (standard test method for determining material ignition and flame spread properties) and ISO 5658-1:2006 and ISO 5658-2:2006 (reaction-to-fire tests – spread of flame – part 1: guidance on flame spread and part 2: lateral spread on building and transport products in vertical configuration) for flame spread.

Another group of tests are standardized in order to determine fire resistance characteristics of structural members, such as but not limited to the following:

- ASTM E119-12a (standard test methods for fire tests of building construction and materials).
- ISO 834 (fire resistance tests – elements of building construction – part 1–12).
- EN 1365 (fire resistance tests for load-bearing elements – part 1–6).

In these fire-related tests, the experimental procedures are specified and standardized clearly for measuring certain fire reaction and resistance characteristics, so that the measured characteristics and the resulting material ratings according to such standard tests can be referenced later by a building code. For example, a typical performance-based building code may require that all doors that form part of a fire compartment should achieve an F-90, that is, 90 min endurance rating under ASTM E-119-12a [7].

In the European Union, the current code that relates to fire safety in the design and construction of buildings is Eurocode 1 – actions on structures: part 1.2: actions on structures exposed to fire [23]. This code was first released in 1990. Two forms of design fires are considered within the code: normative and parametric. The normative design fire is used in the prescriptive portion of the code and refers to the time-temperature curves provided by the ISO 834 standard. The parametric portion of the code provides a performance-based design approach. Rather than using standard time–temperature curves, realistic fire scenarios can be considered using a choice of simple or advanced fire models [7].

In Eurocode, the required performance of building components is denoted by the function that the component serves and the duration of fire exposure it must withstand. Three functions are considered for building components, with *R* for retention of structural resistance (i.e., the ability of a load-bearing structural element to support a load), *E* for retention of the component integrity (i.e., the ability of a structural element to resist the passage of flames and hot gases from one space to another), and *I* for retention of thermal insulation (i.e., the ability of a structural element to maintain a temperature on the surface that is not exposed to the furnace, below the limits specified). These letters are followed by a number (in minutes in multiples of 30) that denotes the minimum duration that these functions are retained when a building component is subjected to fire conditions [23]. For example, a rating of REI30 may be required for walls that are both load-bearing and form part of a fire compartment [7].

In Switzerland, the design and construction of buildings is governed by the Normes Suisses (SN), published by the Swiss Society of Engineers and Architects (SIA). The current code that relates to fire safety in the design and construction of buildings is SIA 183 (La Protection Contre l'Incendie dans la Construction). This code is used in conjunction with the design methods outlined in the European Standard (Eurocode 1: Part 1.2). The fire endurance requirements defined in SIA 183 for load-bearing components are summarized in terms of building height as below [24]:

- Single-story buildings: no requirements
- Two-story buildings: 30 or 60 min, depending on the building size, usage, and so on
- Three-story buildings: 60 min (30 min with sprinklers)
- Taller than three stories: 90 min (30 min with sprinklers).

In Australia, the requirements for the fire resistance of the building are prescribed in the Building Code of Australia (BCA), where 10 classes of buildings were defined according to their uses. In addition, three structural types are defined to determine the level of fire resistance that particular elements of the building must achieve (namely A, B, and C) according to the building's class and rise in storys. Type A includes buildings that have a higher risk such as high rise and high occupant buildings, and is thus of the highest fire resistance. Type C includes buildings that have a lower risk and is thus the least fire resistant. Similarly to Eurocode, the fire resistance level measured in minutes is also defined in terms of structural adequacy (resistance), integrity, and insulation. A 90/30/60 fire resistance means that an element must achieve a level of 90 min for structural adequacy, 30 min for integrity, and 60 min for insulation.

The fire resistance level of building materials, components, and structures is evaluated according to the test standard AS 1530.4-2005 [6]. In this standard, the ISO 834 time–temperature curve is suggested for the test procedure. Alternative heating conditions and other procedures may be adopted to evaluate the performance of structural elements under fire conditions as specified by the applicant, including hydrocarbon fire curve, slow heating establishment phase fire for barrier systems, and radiation external fire spread regimes. The failure criteria of structural and construction elements are accordingly categorized into structural adequacy, integrity, and insulation. Therefore, fire requirements are to ensure that not only a building maintains structural stability during a fire to allow for occupants to evacuate, but also the fire spreading from one building to another is prevented.

1.5 Summary

FRP composites appear to be relatively new materials with the potential to lead to substantial innovations and environmental benefits in the building domain. The materials are introduced on the constituent level (fiber and polymer matrix), and on the structural component level that can be produced through different manufacturing processes. Representative structures composed of FRP composites from own experiences are presented in this chapter. In these examples, the use of FRP composites offers the potential to contribute to the emergence of a new generation of engineering structures that ideally are multifunctional, safe and reliable, durable, adaptable or mobile, sustainable, economical, and esthetic [4]. However, these examples are demonstrative and fire situation is either an noncritical scenario (for the Pontresina Bridge as a temporary pedestrian bridge), or tackled by an active protective system (for the Eyecatcher building as a five-story office building), or taken into account through specific structural design considerations (for the Novartis Main Gate building with a GFRP roof structure).

In order for these materials to be fully exploited for applications in engineering structures, one challenge is to understand and predict the behavior of FRP materials and structures under elevated temperatures and fire. The fire requirements for structural members are an important and indispensable part in building specifications and standards.

In the following Chapters 2 and 3, a mechanism-based approach to describe the thermally induced changes of the status of FRP materials is developed. The resulting temperature and time dependent thermophysical and mechanical properties are introduced and modeled in Chapters 4 and 5. Integrating those material properties into a heat transfer governing equation and structural theory, enables the modeling of thermal and mechanical responses of FRP composites under elevated and temperatures and fire, which is presented in Chapters 6 and 7. The modeling results are further verified through full-scale fire endurance experiments on FRP structures as presented in these two chapters. The assessment and modeling of post-fire behavior of FRP composites will be addressed in Chapter 8. Finally, possible ways and practices to improve the fire resistance performance of FRP structures are introduced in Chapter 9.

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