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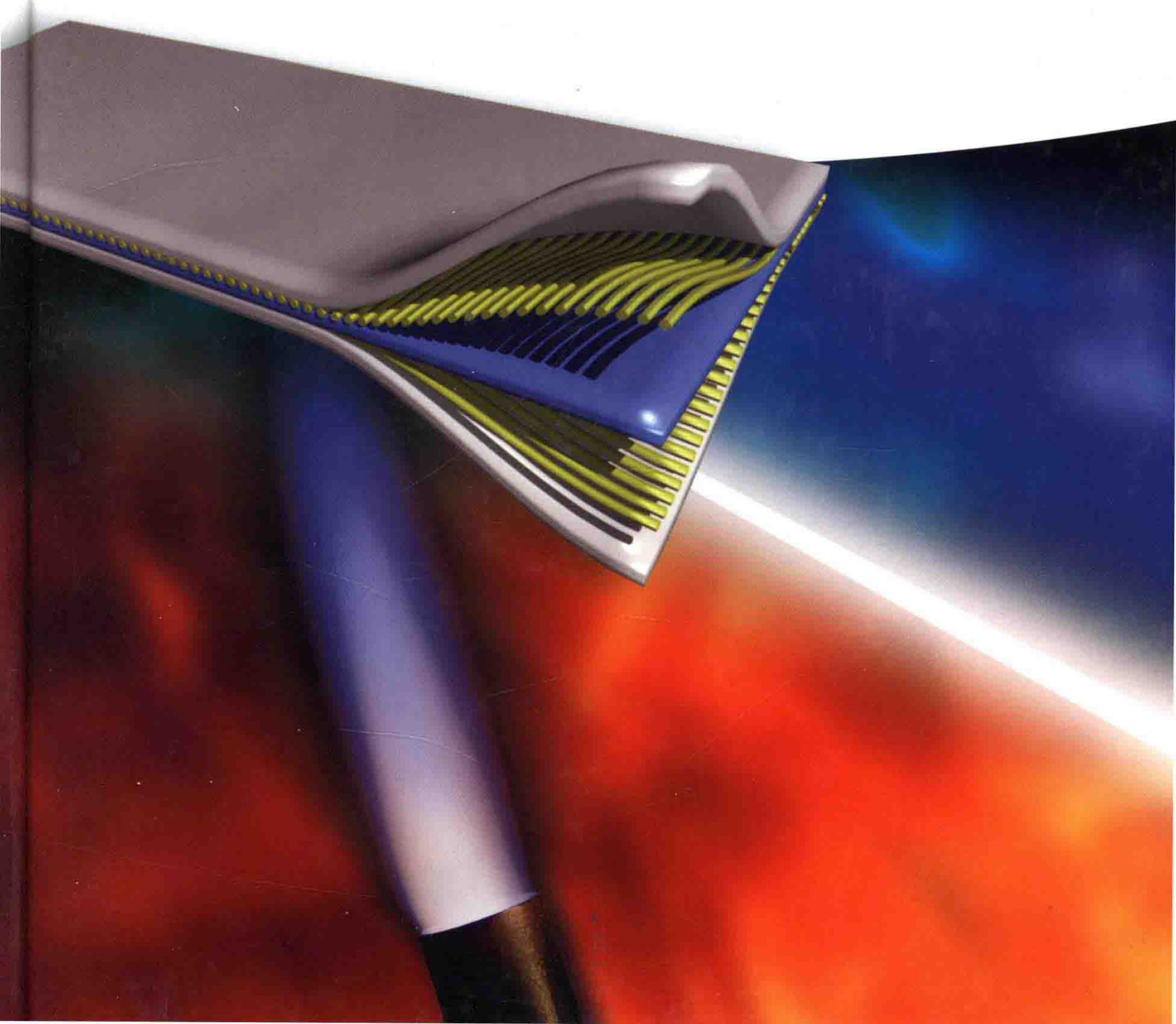
High Temperature Performance of Polymer Composites



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Authors

Dr. Yu Bai
Monash University
Faculty of Engineering
Department of Civil Engineering
VIC 3800 Clayton
Australia

Prof. Thomas Keller
Ecole Polytechn. Fed. Lausanne
CC Lab, Station 16
1015 Lausanne
Switzerland

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Preface

As the range of applications for fiber-reinforced polymer (FRP) composite materials in civil engineering constantly increases, there is more and more concern with regard to their performance in critical environments. The high temperature behavior of composite materials is especially important, as fire is a potentially dangerous scenario that must be considered at the design stage of civil infrastructure.

When a thermoset polymer resin is subjected to elevated and high temperatures, it undergoes complex physical and chemical processes such as glass transition and decomposition. These processes can very likely lead to significant changes in thermophysical properties and can also result in considerable losses of stiffness and strength. Experiments at the material level are necessary to quantify the changes of the thermophysical and thermomechanical properties of the material across a full temperature range, covering both its physical and chemical processes. Equally important, theoretical modeling is required to predict such material properties under elevated and high temperatures based on the description of these physical and chemical processes.

The above understanding forms the basis for the development of thermophysical and thermomechanical property sub-models for composite materials at elevated and high temperatures, and also for the description of the post-fire status of the material. By incorporating these thermophysical property sub-models into heat transfer theory, thermal responses can be calculated using finite difference method. By integrating the thermomechanical property sub-models within structural theory, the mechanical responses can be described using finite element method and the time-to-failure can also be predicted if a failure criterion is defined.

Full scale experiments on FRP structural members subjected to realistic fire exposure are also necessary. Not only does this supply valuable results and provide confidence for the fire performance of FRP structural members to be used in civil engineering, it also validates the above modeling concepts on the structural level. Similarly, as performed in the fire design of structures made by traditional materials such as steel and reinforced concrete, active and passive fire protection techniques may be necessary for prolonging resistance time of composite materials in fire. Such techniques are reviewed and compared, particularly with regard to their applications for composite materials.

The majority of this work was performed during the PhD study (2005–2009) of Dr. Yu Bai with Prof. Thomas Keller at the CCLab of EPFL. The financial support received from the Swiss National Science Foundation at that time is appreciated. Thanks also go to the Australian Research Council for the inaugural DECRA fellowship, which was awarded to Dr. Yu Bai in 2012 for him to continue his research in this field.

During the course of this work, we have been supported by a large group of colleagues and friends. We thank Dr. Erich Hugi in the Laboratory for Fire Testing, EMPA Switzerland, Prof. Xiao-Ling Zhao in the Department of Civil Engineering, Monash University Australia, Prof. Yong Chang Wang in the School of Mechanical, Aerospace and Civil Engineering, University of Manchester UK, and Prof. Jack Lesko and Dr. Nathan Post at Virginia Tech USA for their assistance, suggestions, and comments on this work. We especially thank Dr. João Correia in the Civil Engineering and Architecture Department, Technical University of Lisbon, Portugal, who provided valuable results that have been depicted in Chapter 9.

Finally, we greatly enjoyed working with Ms. Bernadette Gmeiner in the editorial office of our Publisher, Wiley-VCH, and thank her for her patience, again and again, with our revisions to improve the quality of this work.

Melbourne, Lausanne, July 2013

Yu Bai
Thomas Keller

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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

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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

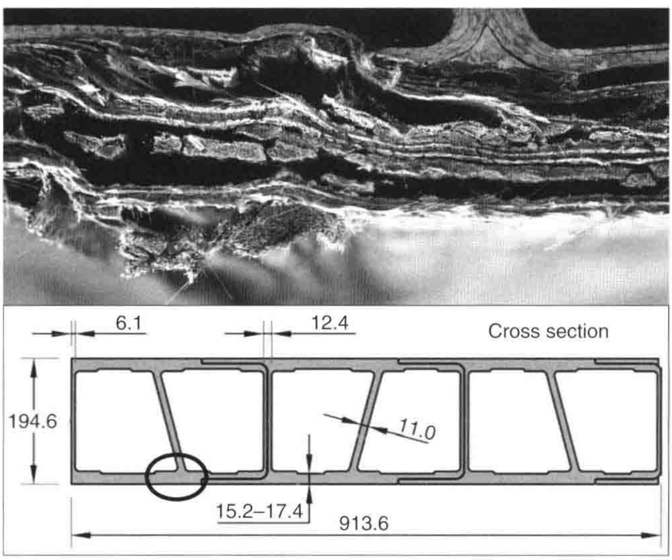

Figure 1.1 Cross section of a FRP profile after fire exposure. (With permission from EPFL-CCLab.)

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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