Chapter 10

Fire safety

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Abstract

This chapter deals with the fire safety of multifunctional composite materials. The chapter starts with a brief description of possible fire hazards that may arise from the use of multifunctional polymer composite materials and relevant fire safety regulations, explaining why fire safety of composites is important. Following an introduction of the combustion mechanism, fire safety strategy is introduced. It then presents properties used to evaluate fire performance of multifunctional composite materials. Lastly, it provides details about fire retardants for improving the fire safety of multifunctional polymer composites.

10.1 Introduction

Polymer matrix composite (PMC) materials also called *fiber reinforced polymer* (FRP) composites are being increasingly employed in many engineering applications where the structural functions are met with a reduced specific weight. In addition to offering the lowest possible specific weight, PMCs can offer many other advantages, such as multiple function integration, corrosion resistance, and better fatigue resistance and durability when properly designed and constructed. However, in terms of fire safety, the polymer matrices in PMCs have limited usage in applications where fire safety requirements are constricted, e.g aircrafts, trains, buildings, and ships. Because polymers are combustible, although they are reinforced with non-combustible fibers, their composites will decompose, generate heat and flame, and yield smoke/gases when exposed to sustained heating or fire conditions. After ignition, the burning polymers will act as fuels that can help the growth and spread of the unwanted fire. After a certain time, the PMC structure will possibly collapse under combined mechanical and thermal loads. As a result, PMC composites may be dangerous and even deadly to passengers or occupants in many structures. Concerns about fire safety of PMC materials have adversely prevented wider application to structures where fire risk is high.

Fire performance of PMC materials can be assessed by two factors: reaction-to-fire and fire resistance. *Reaction to fire* is related to fire growth (e.g., ignitability, flame spread, and heat release) and fire effluents (e.g., smoke opacity and toxicity). *Fire resistance* indicates how a structure resists fire and usually measures three parameters: insulation, integrity, and load bearing capacity (for load-bearing elements). PMC materials must be demonstrated to meet the fire safety requirements set forth by fire safety regulations. For example, building fire safety in the US is regulated by building codes and fire codes that are developed through the code consensus process and adopted and enforced by local government (usually at the state level). For PMC to be used in buildings, they must meet all fire safety requirements as described in applicable provisions in the adopted fire and building codes.

To meet the fire safety requirements one needs to satisfy either the prescriptive-based design requirements or the performance-based design requirements [1, 2]. When using the prescriptive-based approach, PMC materials are required to meet the performance criteria described in the referred standard fire tests, such as ASTM E84 for flame and smoke development, and ASTM E119 for structural fire resistance. When using a performance-based approach, the behavior of the designed PMC materials and structures in fire must be evaluated against design fire scenarios to meet all performance criteria set by the project stakeholders [3]. For non-load bearing applications, a fire growth analysis must be performed to estimate fire development and fire products generation. When used for load-carrying applications, a complete analysis should be performed to examine the mechanical and structural responses of PMC structures in fire. Typical fire performance criteria include two categories, life safety (or tenability) criteria and non-life safety criteria. Life safety criteria address the survivability of persons exposed to fire and its products, for example, air temperature, radiant heat flux, concentrations of *carbon monoxide* (CO), *carbon dioxide* (CO_2) and *oxygen* (O_2), and smoke obscuration (or visibility). Non-life safety criteria include structural integrity and continuity, fire spread, damage to exposed properties, and damage to the environment. An acceptable design must satisfy all fire performance criteria against all anticipated fire scenarios during the trial design evaluation process.

By regulation, PMC materials are required to meet fire safety requirements before they can be used in specific applications. If the virgin PMC material cannot meet fire safety requirements, then *fire retardants* (FRs) can be added to improve its flammability performance. Flammability performance concerns “reaction-to-fire”, rather than “fire resistance”. Thus the term “retardant”, which refers to delaying the ignition and flame spread, as well as reducing heat and smoke release and toxicity.

Numerous fire retardants are available to improve the fire performance of PMC materials, such as *halogen-based fire retardant* (HFR), *phosphorus-based fire retardants* (PFR), *intumescent fire retardants* (IFR), and *mineral filler fire retardants* (MFR). However, usually this improvement of fire performance may compromise mechanical properties. Nanocomposites have shown great improvements in flammability while maintaining excellent mechanical properties compared with original resins. However, nanofillers alone hardly can improve the flammability to pass the standard tests. Usually nanofillers need to synergize with traditional FRs, which seems to be a promising approach to improve both fire and mechanical properties of PMC composites.

Fire safety standards or regulations change with our increasing knowledge in fire and safety. For example, fire retardants are now required to be environmental friendly [4]. Some of the HFRs were banned due to environmental and health threats [5, 6]. It is imperative that the PMC community continuously develop high performance materials that meet the most recent fire safety requirements and regulations.

This chapter presents basic information about the fire safety of multifunctional composite materials. It starts with a brief introduction of combustion mechanism for PMCs. It then presents fire safety objectives and strategies for ensuring fire safety requirements for engineering applications. Following that, it gives a brief description of fundamental fire properties of PMC materials and traditional methods to improve them. Finally, a review on recent developments for improving the fire safety of multifunctional polymer composites is provided.

10.2 Mechanisms of ignition and fire growth

Ignition is an oxidized chemical reaction that takes place fast enough to rise temperature and usually yields light as a flame. Depending on whether the flame exists, the ignition is divided into flaming and smoldering. Depending on whether a pilot exists or not, flaming ignition is divided into piloted ignition and spontaneous ignition. For ignition to occur, the following three elements must present: fuel, heat, and oxidizer (usually oxygen in air). These three elements can be illustrated through the *fire triangle* concept as shown in Figure 10.1.a. Ignition occurs when the three elements are present and combined in the right mixture. On the other hand, a fire can be prevented or extinguished by removing any one of the three elements in the fire triangle.

Once the ignition has occurred, the combustion process may grow or extinguish. If the resulting exothermic chain reaction can sustain the combustion process, the fire will continue. If resulting exothermic chain reaction cannot sustain the combustion process, or any element of the fire triangle is removed or (blocked), the fire will extinguish. The Fire Tetrahedron model in Figure 10.1.b represents the three elements already present in the fire triangle, plus another component, the chemical chain reaction. In fact, a growing fire is a continuous combustion process in which the chemical reaction feeds the fire more heat energy and thus allows it to continue and grow. Unwanted sustained or established fires are safety hazards. Fortunately, when one of the tetrahedron elements is removed, combustion will stop. Thus, both

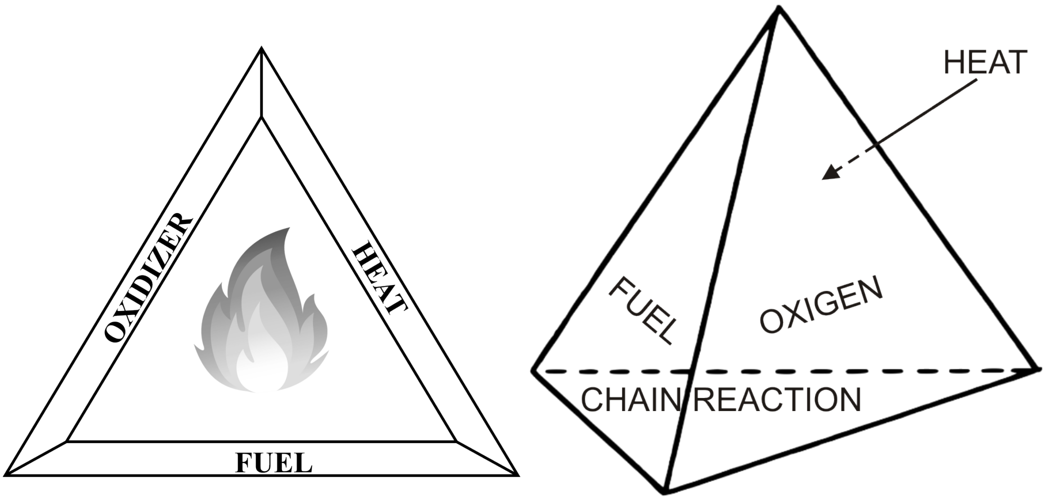

Figure 10.1: (left) Schematic diagram of fire triangle, and (right) Fire tetrahedron.

the fire triangle and the fire tetrahedron models provide us with a fundamental understanding of ignition and fire growth. They serve as bases for ways to prevent or extinguish an established fire. The Fire Tetrahedron model will guide us in inventing ways to improve performance of multifunctional polymer composites.

10.3 Fire safety objectives and strategies

Fire safety strategies in general should ensure the following four fundamental objectives: life safety, property protection, continuity of operations, and environmental protection [3]. Depending on the specific application, some projects may require additional related objectives such as heritage conservation of a special structure. When competing or conflicting objectives are present, the stakeholders should work together to prioritize their fire safety objectives. Once they are determined, all fire safety objectives must be met.

The development of fire safety strategies can be tracked back to our understanding of the fire triangle and the fire tetrahedron models as we discussed in the previous section. Based on the fire triangle model, the *National Fire Protection Association* (NFPA) has developed NFPA550 Guide to the Fire Safety Concepts Tree, a tool for planning fire safety strategies to meet fire safety objectives. NFPA550 suggests that we prevent fire from occurring in the first place. When we do have a fire, then we should manage fire impact. The top gates of the Fire Safety Concepts Tree are shown in Figure 10.2. Using the fire triangle model, one can control heat-energy sources, control heat source and fuel interaction, or control the fuel. Since most structures are already exposed to air, little we can do to control the oxidizer (oxygen in the air).

When applying fire safety strategies to multifunctional composites, the *prevent fire ignition* branch should be our focus, i.e., we should design materials or struc-