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RESPONSE AND FAILURE OF COMPOSITE STRUCTURES EXPOSED TO FIRE

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ABSTRACT

A methodology for evaluating the performance of composite structures subjected to simultaneous mechanical loading and fire exposure is presented in this paper. The experimental procedure (along with the newly-developed equipment required for these tests) is described. A series of computer models used to simulate the entire fire exposure, material degradation, and structural failure processes is discussed. Experimental results for composite structures under various degrees of mechanical loading and subjected to fires of various intensities are then presented and discussed. The results indicate that the durability of composite structures in a fire is strongly influenced by the interaction between the fire characteristics, the initial mechanical load level, and the material degradation mechanisms thereby making it unwise to apply conclusions drawn from specific experiments to the general problem of structural response to fire.

KEYWORDS

fire, composites, durability, material simulation

INTRODUCTION

The work presented in this paper focuses on evaluating the response of composite structures to simultaneous mechanical loading and fire exposure. The work represents several "firsts" for the fire research community. It is the first attempt to experimentally evaluate the thermo-mechanical response of loaded structures exposed to a real fire source (as opposed to radiant heat sources that don't accurately represent the time and space-varying nature of heat fluxes from fires). Also, it is the first attempt to integrate a series of computer models, each of which simulates a specific phenomenon relating to fire exposure, in order to simulate the entire exposure process (from fire evolution, through material degradation and the associated stress re-distribution within the structure, and ending with structural failure). The experimental procedures and equipment, along with the simulation methodologies and computer models should not only serve to expand the base of knowledge on the behavior of composites in fire, but should also prove valuable to the fire research community in general by providing meaningful ways to assess the response of any structure to any fire.

In this paper, the experimental equipment and procedures that have been developed, as well as the computer models used for the analysis, are discussed. Some results are then presented and interpreted to illustrate some complications that arise when predicting the response of a loaded structure to fire exposure that don't arise in more typical engineering analyses.

BACKGROUND

As composite materials continue to gain popularity and more serious consideration for use in applications that have long been served by metals, new design issues and constraints are inevitably encountered. This fact is clearly illustrated by efforts within the military, infrastructure, and transportation communities to replace traditional metallic structures and components with lighter and more corrosion-resistant polymer-matrix composite (PMC) parts. While this will likely lead to savings in cost and weight, there is legitimate concern about the durability of polymeric materials in the presence of fire (an issue of little concern when designing with metals). Concerns stem not only from the fact that many polymers release toxic fumes upon burning, but also that polymers (and PMCs) are known to lose structural integrity at much lower temperatures than metals.

Despite these major concerns, the potential advantages are great enough that the Navy has devoted a large amount of time and money to studying the behavior of composites exposed to fire [1]. Most of the fire studies have focused on the flammability and burning characteristics of composites. There has been only limited work aimed at evaluating the mechanical response of composite structures exposed to fire [2,3,4]. Much of this work focused on the degradation of mechanical properties by comparing measurements taken *before* and *after* fire exposure (providing no information about the performance of the material *during* fire exposure). Some work in which simultaneous exposure to "fire" and mechanical loading was considered is deficient in that the "fire" conditions to which the loaded structures were exposed involved steady-state and uniform heating (which is not at all representative of the conditions encountered in a real fire).

The aim of the work presented here is to expand the limits of past fire research and perform as complete an analysis as possible of the fire exposure and subsequent material degradation and failure processes associated with composites in a fire. On the experimental side, unique equipment and procedures were developed to enable simultaneous mechanical loading and real fire exposure while also allowing for observation and measurement of the structure's response. On the theoretical side, a complete set of computer models was developed to describe the entire fire exposure and thermo-mechanical response process. The set of models assembled for this work is more complete than any developed previously to simulate the response of a loaded structure to fire. The final result of this research will be the capability to predict the service-life of a loaded composite structure in the presence of fire and the experimental procedures and equipment needed to validate the predictions. In this paper, some preliminary experimental results, along with descriptions of the models used for the analyses are presented.

EXPERIMENTAL

Clearly, one of the reasons simultaneous exposure to fire and mechanical loading has never previously been considered is the danger and difficulty associated with testing with real fire. Typical experimental procedures, equipment, and instrumentation are inadequate when the intense heat fluxes and temperatures resulting from real flames are introduced. A novel experimental technique, along with the required equipment, was thus developed as part of this research.

To apply a mechanical load to the composite specimens for this work, thin layers of composite material (with total length $L = 200$ mm) are bent out-of-plane and constrained between 2 stationary supports (subjecting them to large deflections and a non-uniform state of stress along the length of the sample). This method of testing was adopted by Mahieux et. al. [5] and provides a very simple way to load the samples without the use of expensive instrumentation or equipment that could be damaged by the intense heat. The loaded specimens are placed above a diffusion burner (fed at controlled flow-rates by a liquid propane fuel supply). The sample and burner are both housed within a specially-designed fire chamber to contain the heat from the fire and subject the specimen to fire conditions representative of those it could experience in service. Figure 1. shows a schematic of the experimental set-up.

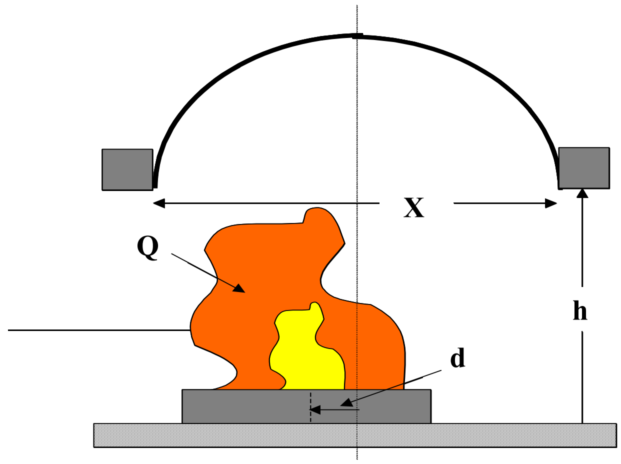

Figure 1: Schematic of experimental set-up

For the work reported here, 3 experimental parameters were varied. Experiments were performed for 2 initial load levels (X/L = 7/8 and X/L = 6/8), 2 fire sizes (Q = 0.176 kW and Q = 0.247 kW), and 2 distances between the sample and the burner (h = 127 mm and h = 178 mm). At least 3 replicates were performed at each of the 8 conditions. For each case, both the time-to-failure and the temperature distribution along the length of the sample were measured.

THEORETICAL

In order to accurately predict the thermo-mechanical structural response observed during the experiments, it is necessary to simulate the entire fire exposure and degradation process – a feat never previously accomplished for structures exposed to real fires in a confined chamber. To accomplish this, a set of 5 distinct models has been assembled, each of which addresses a specific process and feeds information to the next model in the series. The 5 models are briefly described in the sub-sections below.

Model 1 – fire model to predict conditions in chamber

A sophisticated computational fluid dynamics model developed by the National Institute of Standards and Technology has been adopted for this simulation. This model, known as the Fire Dynamics Simulator (FDS), accepts information about the chamber geometry and contents of the chamber (such as the loaded sample) as well as the fire size and location and outputs the ambient temperatures and heat fluxes (both radiative and conductive) to the specimen.

Model 2 – thermal response model

A heat transfer model was developed to accept the time-dependent heat flux and ambient temperature distributions over the length of the sample and compute the evolution of the material temperature distribution over time.

Model 3 – temperature-property model

A scheme to represent the temperature-dependent property distribution within the composite specimen is applied. This model accepts the non-uniform temperature profiles over time and computes the non-uniform stiffness profiles over time in a manner introduced by Mahieux [6].

Model 4 – mechanical response model

This model accepts the non-uniform stiffness distributions computed by Model 3 as well as the initial load level and sample geometry (input by the user to match the experimental conditions). The model utilizes a numerical scheme (shooting method employing a 4th order Runga-Kutta integration scheme) to solve the exact, non-linear differential equation for bending of the beam with non-uniform stiffness. The model outputs the shape profile and the stress and strain distributions along the length of the sample over time.

Model 5 – material failure model

Several material failure models deemed appropriate for the experiments and materials of interest here are used to define the deteriorating strength of the thermally and mechanically-loaded specimens. The predicted strengths from this model are compared with the evolving stress profiles (from Model 4). The time at which the increasing local stress in a critical material element exceeds the decreasing material strength in that element is defined as the time-to-failure. These time-to-failure predictions can be compared with the time-to-failure measurements for a range of fire sizes, fire locations, and initial load levels.

RESULTS & DISCUSSION

As the deformed composite specimens are exposed to fire over time, the material begins to degrade and stresses are re-distributed within the samples. This induces changes in the deformed shape of the loaded specimens. Eventually, the local state of stress or strain in the deforming sample is significant enough to exceed the strength of the degrading material. The time at which this occurs is defined as the time-to-failure. Time-to-failure measurements for the range of conditions investigated during these experiments are shown in Figure 2.

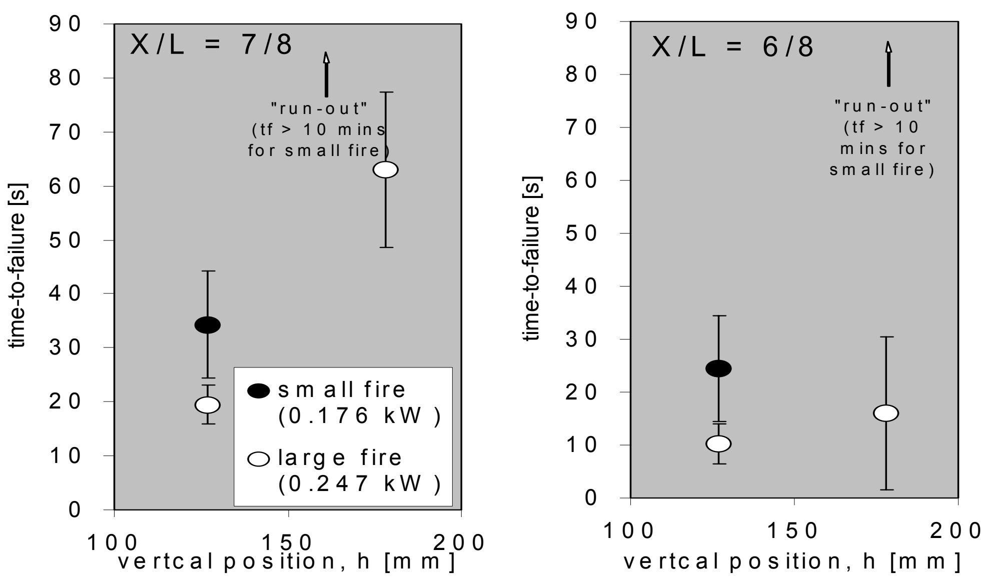

Figure 2: Time-to-failure measurements

First considering the low initial load level (X/L = 7/8), it is shown that increasing the fire size decreases the time-to-failure from an average of 29 s to an average of 19 s when the samples are positioned 127 mm from the surface of the burner. When the samples are moved 178 mm from the surface of the burner and exposed to a large fire, the time-to-failure dramatically increased to an average of 68 s. Samples positioned 178 mm from the burner and subjected to small fires, however, survived longer than 10 min (defined as "run-outs") without failing.

Similar behavior was observed for the samples loaded to a greater initial load level (X/L = 6/8). Loading the samples more severely in the presence of both large and small fires (with the samples positioned 127 mm from the burner) slightly reduced the measured times-to-failure. Moving the samples exposed to large fires a distance of 178 mm from the burner only slightly increased the times-to-failure for the case of severe initial loading (as opposed to the strong effect observed for more moderate mechanical loading). Again, when the samples were placed 178 mm from the burner and subjected to the smaller fire, they survived more than 10 mins without failing.

Consideration of the measured temperature distributions at the time-of-failure for these samples reveals additional information about the nature of the failures. Consider, for example the 4 conditions (2 fire sizes and 2 sample heights) for the case of low initial loading. The measures temperature distributions at the time-of-failure (or at run-out) for samples subjected to each condition are shown in Figure 3.

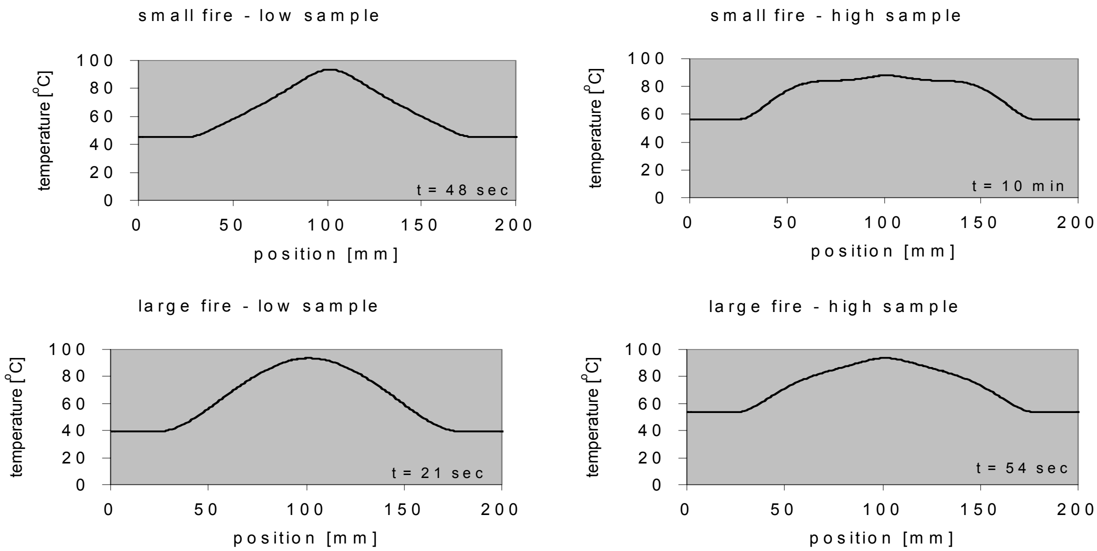

Figure 3: Measured temperature and computed stiffness distributions at time-of-failure (or at run-out)

It is shown that the maximum temperature achieved for the samples positioned closer to the fire (for both large and small fires) is approximately 95°C (~ T_g of the composite). Also, the peaks in the temperature distribution near the center of these samples (where the flame is centered) are quite sharp. Moving the samples farther from the burner serves to flatten out these sharp temperature peaks. It is interesting that sample positioned close to the burner and exposed to the large fire to induce failure also failed with a maximum temperature of 95°C, although the temperature distribution was much different than those positioned close to the fire. The sample positioned far from the fire but exposed to a smaller fire achieved a slightly lower maximum temperature (T_{max} = 90°C) than those that failed. It is interesting that this maximum temperature should still have weakened the material significantly, though the sample ran-out without failing.

An effort is made to explain this phenomenon by considering not only the temperatures, but also the strains at failure. The measured temperature profiles and computed stiffness profiles (from Figure 3) were input to Model 4 in order to obtain the strain distributions for each specimen at the time-of-failure (or run-out). The results are shown in Figure 4.

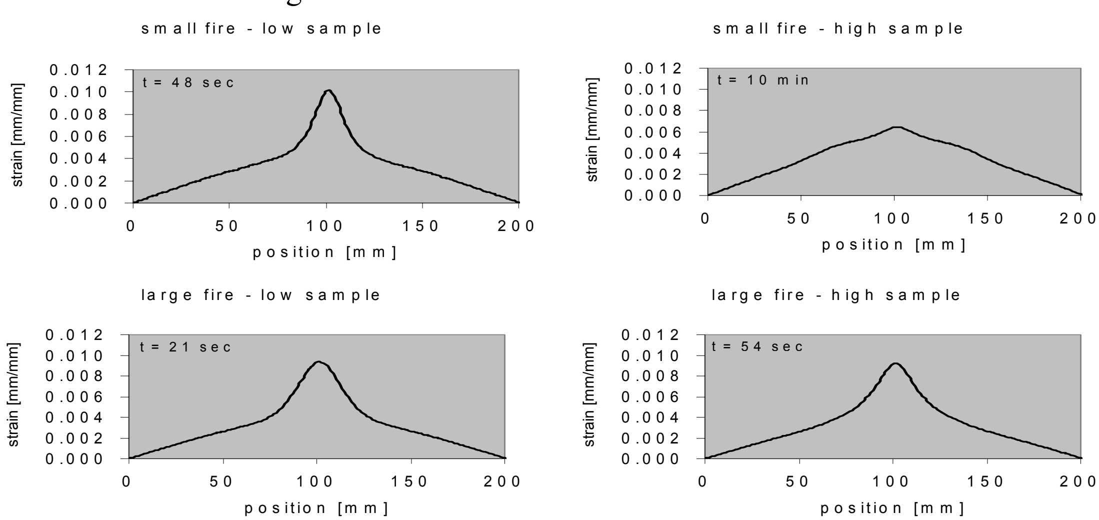

Figure 4: Computed strain profiles at time-of-failure (or at run-out) based on measured temperatures

It is shown that the 3 samples that failed (all with $T_{max} = 95^oC$) also exhibited approximately the same maximum strain at the time-of-failure ($\varepsilon_{max} \sim 1.0\%$). The run-out sample (with T_{max} only slightly lower than 95^oC) only achieved $\varepsilon_{max} = 0.62\%$. It appears (based on this limited data) that there is some critical strain that cannot be exceeded in order for the loaded sample to survive, regardless of fire size or fire location.

It is interesting that although the maximum temperature of the run-out sample considered here was nearly as high as the samples that failed, the fact that the temperature distribution was more uniform for this case actually prevented a sharp strain concentration from forming. Interpretation of this result leads to a somewhat surprising conclusion. The sample that absorbed a large amount of thermal energy actually survived much longer than a sample that absorbed a much smaller amount of thermal energy under identical initial mechanical loading conditions. It is this type of interaction between fire size, fire location, and mechanical loading that complicates studies of structural response to fire.

SUMMARY

The work described in this paper represents several "firsts" in the field of fire research. The experiments performed here are the first in which structures have been subjected to simultaneous mechanical loading and real fire exposure. Also, the models developed and assembled for this work provide the very first complete simulation of the entire fire exposure and structural response and failure processes. The experimental data reported here indicates that the durability of a loaded composite structure in the presence of fire depends very strongly on the interactions among initial mechanical loading, the characteristics of the fire, and the way in which the material from which the structure is made deteriorates as a result of the heat from the fire (leading to re-distribution of the stresses within the structure and degradation of the structure's strength). It is clear that applying conclusions drawn from a specific set of experiments to more general conditions can be quite dangerous. This fact highlights the importance of the simulation scheme being developed from the 5 models discussed in this paper. This will ultimately enable predictions of the service life of any loaded composite structure to any fire, hopefully reducing the need to rely on expensive and inconvenient experiments.

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