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THE EFFECTS OF SIMULATED FIRE EXPOSURE ON GLASS-REINFORCED THERMOPLASTIC MATERIALS

James A. Milke
Assistant Professor
Department of Fire Protection Engineering

Anthony J. Vizzini
Associate Professor
Department of Aerospace Engineering

Composites Research Laboratory
University of Maryland
College Park, Maryland

SUMMARY

The influence of a modest thermal insult from a fire on glass-reinforced thermoplastics is explored experimentally and analytically. A first-order thermomechanical model was formulated to investigate the thermomechanical response of asymmetrically heated glass-reinforced, thermoplastic composites under tensile load. Failure predictions can be summarized with a three-dimensional failure surface comprised of load, heat flux and time-to-failure for composite material systems exposed to localized overheating. This paper provides an overview of the preliminary results from a series of small-scale experiments and application of a thermomechanical model.

BACKGROUND

Proposed applications for composite materials are continually expanding due to the numerous advantages they offer, such as weight reduction and corrosion resistance. However, along with the expansion in the market for composites comes a commensurate increase in the risk of deficient performance resulting from exposure to various hazards. Some organic composites are suitable for use in high temperature environments while others are unable to withstand even modest changes in temperature. Thus, a wide range of responses to overheating from fire is possible.

On transportation vehicles, composites have been proposed for use in fire resistant separations. Fire resistance requirements range from five minutes to one hour, depending on the type of transportation vehicle, *i.e.* surface ship, submarines, or aircraft[1-3].

The results from a fire resistance test on a glass reinforced polyester wall panel following ASTM E-119 is reported by Williamson and Baron[4]. The wall panel was observed to satisfy the test criteria for a time period of 30 min. Although surface temperatures and the transverse deflection were measured, no engineering analysis was conducted to evaluate the structural performance of the wall assembly.

The impact of a severe heat exposure on an organic composite is likely to be substantial and obvious, *e.g.*, chemical degradation of the matrix, widespread charring, melting, delamination and cracking. Conversely, exposure to minor heating exposures is not likely to affect adversely the structural performance of a composite. However, subjecting a composite to modest exposures may induce damage solely within the interior of the assembly or on the unexposed side without necessarily producing any visually detectable effects on the exposed side of the composite. As such, modest heating exposures are of particular interest since the effects on structural performance may be substantial in terms of performance degradation, yet be very difficult to detect via visual inspection in the absence of appreciable surface melting or charring. Specific interest in the problem of exposures to modest heating conditions represented by moderate severity fires was expressed in a 1985 workshop sponsored by the Naval Air Systems Command[5]:

> "The third confirmed hazard is the susceptibility of composites near fires to subtle non-visual fire damage. The primary countermeasure is careful inspection. The plan in this area is to develop improved inspection procedures that will determine the extent of subtle fire damage and to develop firefighting procedures to prevent, or at least reduce, the extent of subtle fire damage."

Some of the effects, *e.g.* thermal strains, caused by the fire exposure are reversible. However, should threshold temperatures be exceeded, the effects become irreversible, *e.g.* pyrolysis, thermoset materials exceeding glass transition, ablation, delamination and ply buckling. As such, the effects of overheating should be conducted simultaneously with the imposition of load.

Failure of structural composites exposed to fire conditions is a function of the loading conditions and the temperature distribution within the assembly. The temperature distribution within the assembly depends on the incident heat flux, duration of exposure, environmental conditions and the properties of the assembly. The presence of a temperature rise will result in interlaminar stresses. An originally symmetric composite will be transformed into an asymmetric composite if only one side of the laminate is heated due to material property changes. As a consequence of a temperature gradient within a laminate and differences in the coefficient of thermal expansion (CTE) between the matrix and the fibers or between laminae are hypothesized as being principal causes for some of the noted effects. Local ply buckling may result from in-plane temperature gradients and property discontinuities across boundaries of pyrolyzed and original material.

Failure predictions can be summarized through the use of a three-dimensional failure surface for specific composite assemblies exposed to overheating. The failure surface is defined by three coordinates: load, thermal insult and time-to-failure. In this study, thermal insult is represented by the incident heat flux. Given any two of the three coordinates, a range of values of the third coordinate can be determined which will lead to failure, *e.g.* given the heat flux and time, the critical or minimum load can be determined which will cause failure.

A unique failure surface needs to be formulated for each combination of the type of composite assembly, loading conditions and heat transfer conditions. The type of composite assembly is described in terms of the material composition, layup, dimensions, shape and orientation. Relevant loading conditions include the type of applied loads, *i.e.* forces and moments, and their point(s) of application. The mode of heat transfer (conduction, convection or radiation) and the distribution of the incident heat flux on the surface(s) of the assembly define the heat transfer conditions.

Review of Previous Studies

Several researchers have utilized small-scale tests to examine the impact of severe radiant heating exposures on the structural behavior of composite laminates[6,7]. These studies involved small-scale experimental and analytical evaluations of graphite-epoxy composites (AS/3501-6) exposed to laser irradiation with heat fluxes ranging from 5 to 25 MW/m^2. As a result of this extreme thermal insult, structural degradation and appreciable material loss occurred, sometimes to the point of localized burn-through. Most failures occurred within 60 s, with failure of the specimens attributed to localized burn-out and extreme temperatures[6].

Formulation of a failure surface to document the structural performance of heated composites was constructed based on a limited number of small-scale experiments supplemented by a numerical analysis[6,7]. The experimental program consisted of applying a designated tensile load on test coupons. Next, the test coupons were exposed to an extreme incident heat flux, ranging from 5 to 25 MW/m^2. Test samples consisted of thick laminates, ranging from 20 to 96 plies. The tensile load ranged from 21 to 50 percent of the ultimate tensile strength at ambient temperature. A two-dimensional failure surface was constructed for each applied load relating times-to-failure with the exposure duration. The times-to-failure increased with increasing thickness and decreasing incident heat flux.

The structural response of the exposed laminate was examined using a finite element model with each ply represented by plate elements. A one-dimensional temperature distribution was assumed through the thickness of the laminate[6]. The maximum stress criterion was used to predict the failure of individual plies. Discounting failed plies, the analysis was reiterated to investigate progressive failure of additional plies until the entire laminate failed. Errors in the modeled time-to-failure were attributed to the large deflections observed. This source of error was inherent in the analytical approach since large deflections are not properly modeled using plate theory. In addition, the assumption of a one-dimensional temperature distribution may also have contributed to the errors since a three-dimensional temperature distribution actually resulted within the laminate, given the localized irradiation on one surface of the laminate.

Recently, a similar semi-empirical approach has been applied to formulate a three-dimensional failure surface consisting of load, heat flux and time-to-failure for a glass-reinforced thermoplastic exposed to a range of heat fluxes associated with a modest fire exposure[8]. The range of exposures was insufficient to cause ignition or burn-through of the specimens, thereby inducing relatively subtle structural flaws. As in the previous two studies, the recent effort involves formulation of the failure surface through coordinated experimental and analytical efforts. First, a series of small-scale experiments were performed to observe failure mechanisms and obtain data to later check the predictive capabilities of the model. Next, a thermomechanical model was applied to simulate the performance of the laminate. This paper provides an overview of the recent, coordinated experimental and analytical efforts[8].

Terminology to describe the layup of composites addresses the number of plies, to address characteristics in the thickness direction and ply orientation to address in-plane characteristics. The in-plane directions are referred to as the longitudinal and transverse directions. The longitudinal direction is defined as being parallel to the fibers, the transverse direction is in the plane of the plies, but perpendicular to the fibers and the normal direction is in the thickness direction.

EXPERIMENTAL PROGRAM

The experimental program consists of small-scale tests to determine ply and laminate properties required as input for either a thermal or structural analysis. The glass-reinforced thermoplastic (glass volume fraction of 53%) was selected because of its thermal stability at relatively high temperatures, according to the manufacturer. Ply properties were determined experimentally using specimens which were 38 by 760 mm, comprised of 4 or 10 plies. Three layups were used for the material property tests: $[0]_4$, $[90]_{10}$ and $[\pm45]_8$[1]. (Note that $[0]_4$ denotes a laminate comprised of four plies, all with the fibers parallel to the longitudinal axis. Alternatively, $[0/\pm45/90]_8$ relates to a laminate of eight plies (with the angle noted relative to the longitudinal axis): 0, +45, -45, 90, then a symmetric set of plies, i.e. 90,

-45, +45, 0.)

Acquired material property data is evaluated considering each ply of the unidirectional composite laminate to be a homogeneous, transversely isotropic material. In principal, the macroscopic properties are determined by assuming that the microscopically defined properties for each of the ply constituents are smeared uniformly throughout the ply. Further, since the macroscopically defined properties are evaluated for an entire ply, they implicitly account for the imperfections that are present.

The ply material properties of interest for a thermomechanical analysis include both mechanical and thermophysical properties. Mechanical properties include the elastic moduli, CTE's, and strengths. Thermal conductivities, specific heat and density comprise the needed thermophysical properties. Endothermic or exothermic reactions within the matrix can be addressed by artificially altering the value of the specific heat. Relevant properties need to be evaluated for the longitudinal, transverse, and normal directions.

A heat-load sequence was used to evaluate the in-plane tensile ply mechanical properties at elevated temperatures. The heat-load sequence consists of increasing the temperature of the sample to a predetermined value, then applying an increasing tensile load until failure occurs. The property tests were limited to 204°C to avoid melting the matrix. Results of the ply mechanical property tests are presented in Figures 1-4. In Figures 1 and 4, the longitudinal properties and Major Poisson's ratio are only slightly influenced by temperature, as expected due to the fiber dominance of both properties. In Figures 2 and 3, the matrix-dominated transverse and shear properties decrease with temperature, with appreciable decreases indicated near the glass transition temperature. Above the glass transition temperature, the decline of the transverse and shear properties is expected to continue, reaching near-zero values at the melting temperature.

The second set of experimental evaluations consisted of a series of small-scale tests involving the imposition of a thermal insult while a glass-reinforced, thermoplastic test specimen was under tensile load. These tests were conducted to determine the laminate property of residual longitudinal strength while subjected to the heating exposure. This data was required to evaluate the predictions of the failure surface by the thermomechanical model. The load-heat sequence utilized in these tests consisted of applying a tensile load to the sample first, then exposing the sample to the thermal insult.

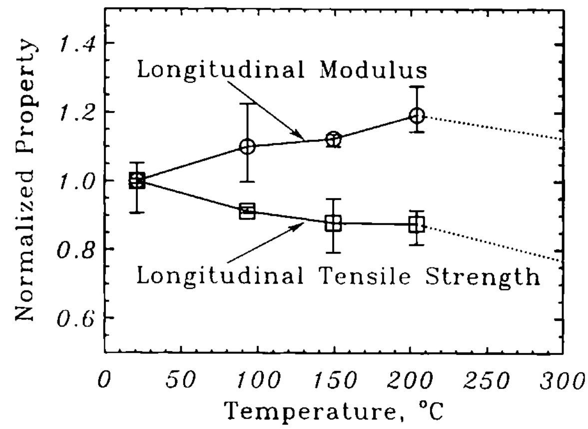

Figure 1 - Longitudinal properties vs. temperature.

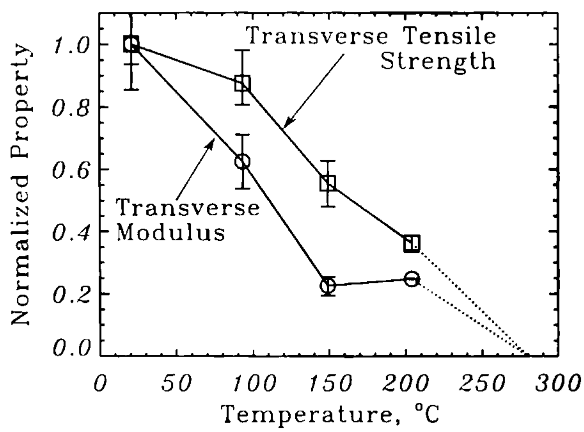

Figure 2 - Transverse properties vs. temperature.

The second series of tests were conducted on three different laminates over a range of loads and heat fluxes. The 13 mm-thick test specimens consisted of the following layups: $[90_8/0]_{11s}$, $[0/(\pm60/0)_{11}]_s$, and $[0/(\pm30/0)_{11}]_s$. The dimensions of the test specimens are 38 by 380 mm. Tensile loads were applied representing 25, 35 and 50 percent of the nominal ultimate tensile strength at ambient temperature of the $[90_8/0]_{11s}$ laminate and 23, 32 and 46 percent of the nominal ultimate tensile strength at ambient temperature of the $[0/(\pm60/0)_{11}]_s$, and $[0/(\pm30/0)_{11}]_s$ laminates. The tensile load was applied following a computer-controlled, programmed sequence consisting of a linear increase of 89 N/s to a pre-set load, followed by the load being maintained at a steady value for the remainder of the test.

One side of the test specimens was subjected to a heat flux using a resistance strip heater for a period up to one hour, or until failure of the specimen. The actual heat flux supplied by the heater varied as a function of temperature and surface conditions of the specimen. Installation of the resistance strip heater on the laminate is indicated in the schematic diagram provided in Figure 5. The dimensions of the strip heater was 38

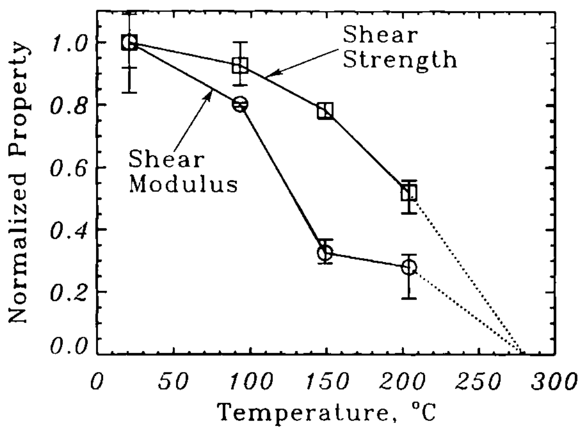

Figure 3 - Shear properties vs. temperature,

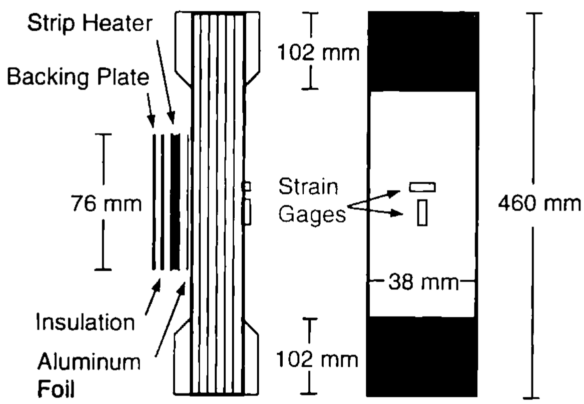

Figure 5 - Schematic diagram of residual strength specimen.

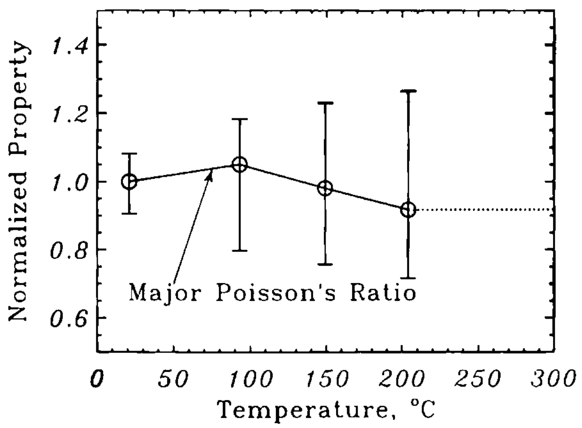

Figure 4 - Major Poisson's ratio vs. temperature.

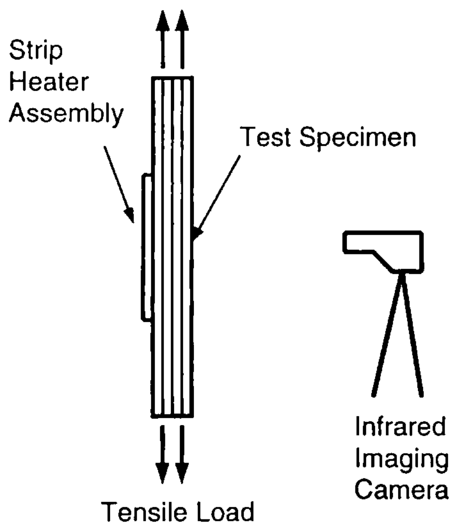

Figure 6 - Schematic diagram of experimental set-up for residual strength evaluation.

by 76 mm. Prior to each test, the strip heater was clamped to the test specimen using the two binder clips, one positioned on each side of the specimen. A schematic diagram of the experimental setup is provided in Figure 6.

Failure of the test specimen was defined as a stroke of 0.0127 m. Considering a nominal test section length of 0.180 m, this maximum stroke is equivalent to a longitudinal strain of approximately 7.1 percent. The one hour limit was selected as the maximum duration for the test because, as indicated previously, that was the most stringent fire resistance requirement for assemblies on transportation vehicles (References 1-3).

Data in the form of load, stroke and strain were acquired via an automated data acquisition system. In addition, the temperatures of the exposed and unexposed surfaces were monitored with a surface-mounted thermocouple and an infrared imaging system, respectively. These temperature measurements were used along with a three-dimensional thermal response model of the specimen (described in the next section) to determine a nominal, steady heat flux. The heat flux provided to the thermal response model that yielded the best agreement in the unexposed surface temperatures was defined as the nominal, steady heat flux (hereafter referred to as *heat* flux). The applied heat flux ranged from 15 to 40 kW/m^2. The heat flux was relatively uniform under all parts of the heater[8].

The test program in this second series of small-scale tests consisted of starting with the high heat flux, high load combination, *i.e.* 30 kW/m^2 and 46 or 50 percent of the ultimate load. Subsequent tests were continued at the same flux level, decreasing the load until runout occurred ("runout" refers to those cases where failure did not occur within the hour). Once runout occurred, testing at that flux level was terminated. The heat flux level was then reduced by 5 kW/m^2 for the next test, with the load returned to the maximum load level. Subsequent tests at this flux were continued, decreasing the load until runout was observed again. In addition, testing was stopped if the load decreased to a value that provided runout at a greater heat flux. This test plan assumed that failure would not occur at a lower flux or load than a previous test in which runout had occurred. Results of the test program are summarized in Table 1.

Table 1
Experimental Time-to-Failure(s)

% of Nominal Ultimate Load	Nominal Steady Heat Flux (kW/m^2) 40	30	25	20	15
$[90_2/0]_{11S}$					
50	93	238	345	Runout	
35		468	Runout		
25		1058			
$[0/(\pm60/0)_{11}]_S$					
46		343	612	1031	Runout
32		928	Runout	Runout	
23		1243			
$[0/(\pm30/0)_{11}]_S$					
46		330	669	Runout	
32		818	1367		
23		1609	Runout		

The results from this second set of tests were expressed in the form of a three dimensional failure surface to indicate the dependence of the residual longitudinal strength on the heat flux and duration of exposure. An example of a three-dimensional failure surface relating the parameters of load, heat flux and time-to-failure for the $[0/(\pm60/0)_{11}]_s$ layup resulting from the tests is presented in Figure 7. The discontinuities in the figure are indicative of the experimental data points. Cross-sections of the failure surfaces for each laminate are interposed for constant heat flux (30 kW/m^2) in Figure 8 and constant load (at the maximum value of 46 or 50 percent) in Figure 9.

Although each layup has a unique failure surface, there are some common features shared by all three failure surfaces. The time-to-failure increases with decreasing flux for all laminates since the temperature gradients (which affect the thermally-induced stress) and damage level decrease with decreasing flux. Failure modes varied for each layup, dependent on the load level. Failure was initiated on the unexposed side of the specimen for the tests conducted with

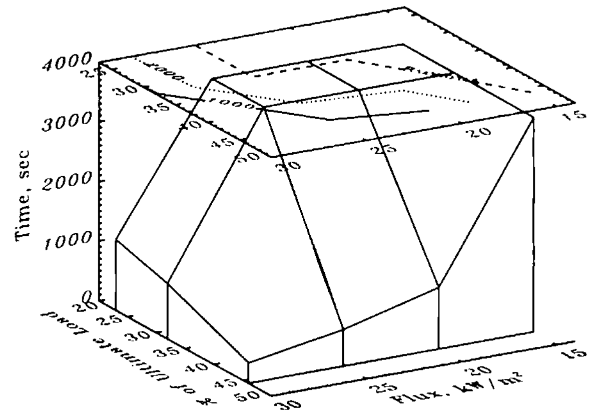

Figure 7 - Failure surface of $[0/(\pm 60/0)_{11}]s$.

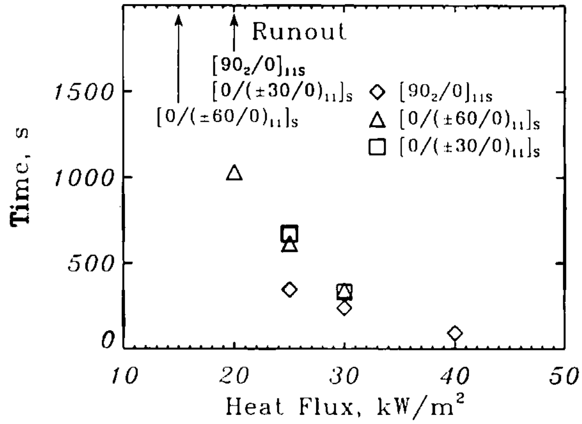

Figure 9 - Time-to-failure for 46% or 50% of ultimate load.

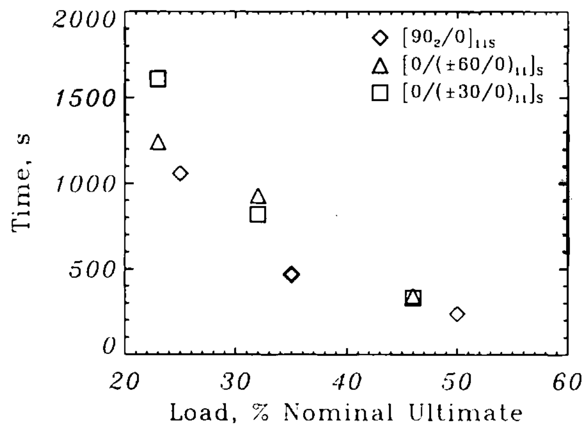

Figure 8 - Time-to-failure for 30 kW/m² heat flux.

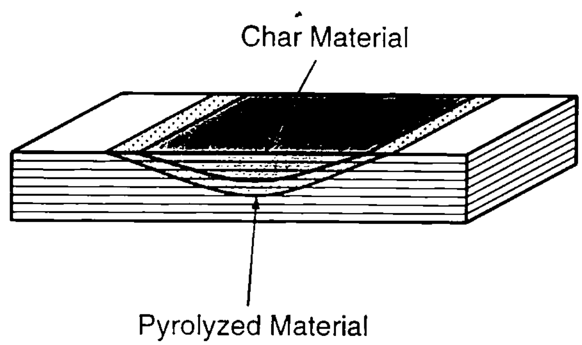

Figure 10 - Char picture.

the greatest applied load, *i.e.* 46 or 50 percent of the ultimate tensile strength at ambient temperature. Also, these failures occurred suddenly, without warning. All failures at the lower loads were initiated on the exposed side and progressed slowly.

Differences in the time-to-failure indicated in Figure 8 for the three layups decrease with increasing load. Thus, because the time-to-failure is appreciably different for the layups at low load levels, the phenomenon is multi-dimensional at low loads. Similarly, in Figure 9, the differences in the time-to-failure for the three layups increase with decreasing flux. Thus, because the time-to-failure is different for the layups at low flux levels, the phenomenon is again multi-dimensional; whereas, at high flux levels, failure is one-dimensional, being dependent primarily on the thickness of the sample.

As the angle of the laminate decreases, *i.e.* the laminate becomes more unidirectional, the time-to-failure increases for a given load and heat flux since the laminate properties become more fiber dependent. This agrees with observations from the elevated temperature property tests where the fiber was demonstrated to be influenced by a lesser degree by the thermal insults than the thermoplastic matrix.

Visual observations detected ply buckling near the interfaces between unmelted and melted regions and between charred and uncharred regions as a result of in-plane temperature gradients. A typical char pattern is indicated in Figure 10. Also, local delaminations were evident near the same interfaces resulting from discontinuities in the coefficient of thermal expansion between plies.

Failure was noted to be independent of measured char depth. Differences in char behavior were documented for samples that failed and those that continued to sustain the load for the entire one hour duration as indicated in Figure 11. A linear correlation of the char depth with the net input heat was developed based on an elementary thermodynamic analysis. In this analysis, the amount of heat needed to increase the temperature of the charred region to the char temperature was estimated. The charred region was approximated as a rectangular solid with a depth equal to the maximum char depth and the cross-sectional area equal to that of the strip heater. As a consequence of agreement with the linear correlation, charring is predominantly a one-dimensional phenomenon.

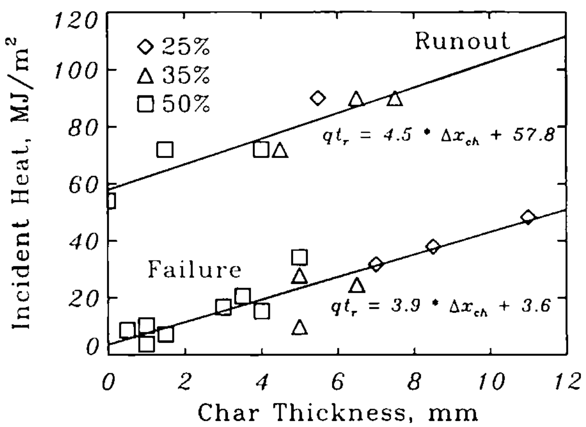

Figure 11 - Char thickness vs. thermal insult.

As compared to the samples which did not fail, samples that failed required much less heat to achieve a particular char thickness. Samples that failed had numerous transverse surface cracks on the exposed side. These surface cracks are considered to have aided in the heat transfer to the interior of the sample to promote charring. Consequently, char behavior appears to be related to crack formation and the overall failure process.

Thermomechanical Model

The thermomechanical model consists of a first-order analysis. Based on the experimental observations, failure of the laminate is assumed to result from in-plane effects, principally fiber failure. This assumption is supported from the post-mortem examinations of the failed test coupons. Consequently, inter-laminar effects such as delaminations were neglected. As a result of the assumed failure mechanism and the localized thermal insult, a three-dimensional analysis is important to evaluate the in-plane thermal strains, especially near material discontinuities, *i.e.* near boundaries of melted and unmelted or pyrolyzed and original material.

Three submodels are contained within the thermomechanical model. One submodel is the thermal response model consisting of a semi-empirical, three-dimensional heat transfer model. The model uses an implicit finite difference scheme to provide a three-dimensional temperature distribution within the composite as a function of time. The predictive capability of the thermal response model has been described previously[10]. The thermal response model investigates the transient heating of angle-ply laminates exposed to asymmetric, incident heat fluxes. In addition, the model can account for temperature dependent material properties and a wide range of convective or radiative boundary conditions.
Another submodel consists of an existing finite element model, NASTRAN, which predicts a three-dimensional state of stress within the composite as a result of the applied loads and the temperature distribu-

tion (obtained from the output of the thermal response model)[11]. This submodel comprises the core of the structural response analysis. Modeling each ply with a separate layer of elements would have an appreciable amount of computation time and memory. Consequently, sublaminate elements were constructed representing three or four plies to decrease computational requirements, as is often done for analyses involving composite laminates[12]. Sublaminate elements representing three plies [±60/0] were used in the interior of the laminate. The regions near the exterior surfaces of the laminate were represented by sublaminate elements representing four plies [0/±60/0]. In-plane properties for the sublaminate elements were determined using classical laminated plate theory and evaluated based on the temperature in the middle of the sublaminate.

Available thermophysical property data utilized in the analysis is indicated in Table 2[7]. Properties for the char layer (represented by temperatures in excess of 540°C) are effective properties, accounting for material changes as well as the presence of cracks. Matrix-dominated properties were assumed to be negligible for temperatures greater than the melting point of the matrix. Spikes in the specific heat were provided to simulate internal energy changes associated with energy of decomposition or phase changes. High temperature fiber properties were determined by adopting the properties of E-glass at 540°C[13]. The longitudinal modulus and strength for E-glass at 540°C are 81.3 GPa and 1725 MPa, respectively.

The resulting high temperature mechanical properties are plotted as a function of temperature in Figures 1-4. Using an assumption of transverse isotropy, properties in the normal direction were equated to those in the transverse direction.

Pre- and post-processor software developed as part of this study interfaces with the existing finite element model conducting the structural analysis. The pre-processor constructs the input data file for the finite element model. Input for the model consists of geometric characteristics, layup, elevated temperature mechanical properties, applied loads and the three-dimensional temperature distribution determined by the thermal response model.

The third submodel consisting of the post-processor analyzes the output of the structural analysis using the maximum stress criterion to determine ply failure[6,14]. The maximum stress criterion is summarized in Table 3. As expressed in the table, the maximum stress criterion establishes the limits for the ply stresses in order to avoid failure.

The post-processor also conducts the progressive failure analysis on a ply-by-ply basis using the output from both the finite element model and the thermal response model to account for failed plies. The progressive analysis is an iterative procedure which excludes failed plies by setting ply moduli

Table 2.
Thermophysical Properties

Temperature (°C)	Longitudinal Conductivity (W/m-K)	Transverse Conductivity (W/m-K)	Density (g/m³)	Specific Heat (J/g-K)
10	0.36	0.39	2.4	0.6
250				1.0
260				6.0
270				1.0
280	0.40			
480				1.0
500				
540		0.70		20.0
660				5.0
1100	0.40	0.70	2.4	5.0

Table 3.
Maximum Stress Criterion

Criterion
$X^t > \sigma_{11} > X^c$
$Y^t > \sigma_{22} > Y^c$
$Z^t > \sigma_{33} > Z^c$
$\lvert S^{12} \rvert > \sigma_{12}$
$\lvert S^{23} \rvert > \sigma_{23}$
$\lvert S^{31} \rvert > \sigma_{31}$

and strengths in the failed directions to negligible values. After excluding the failed plies, the finite element model is re-applied. Then, the postprocessor is re-applied to determine if any additional plies fail. If so, another iteration of removing plies and re-applying the finite element model is conducted. The iterations are continued until no additional plies fail, *i.e.* load transfer is accomplished to the remaining plies without inducing the failure of additional plies.

The thermomechanical model is applied to determine the tensile load required to cause failure, given an incident heat flux and duration of exposure. Following repeated applications of the thermomechanical model, a failure surface can be created for each composite laminate exposed to a wide range of heat fluxes and tensile loads.

The developed analytical model is general in nature. In principle, the formulation is applicable to any type of composite, loading condition or heat flux. However, the present application of the thermomechanical response model was limited to determining the failure surface only for one glass-reinforced, thermoplastic composite, with a layup of $[0/(\pm 60/0)_{11}]_s$.

Inasmuch as the thermal model provides input to the structural model, the two models are not coupled. Changes in geometry, such as curvature, necking and crack formation are not addressed in the thermal analysis. Further, surface recession due to material loss from melting or charring is not accounted for in the structural model. The only effects of charring or melting included in the structural analysis are the reduction of the strength and stiffness of the relevant plies.

A comparison of the failure surface determined by the thermomechanical model with that determined from the experimental program for heat fluxes of 20 to 30 kW/m^2 is presented in Figure 12. Agreement with the experimental data appears quite satisfactory, especially for the cases involving the heat flux of 30 kW/m^2. The improved agreement at the greater heat flux may be attributable to the failure being dominated by ply effects. Interlaminar effects may be more dominant at the lower flux levels where laminate failure was observed in the experiments for the load levels indicated to be due to load transfer problems. Even so, the agreement between the predictions and the experimental data is noteworthy considering the first-order nature of the calculations.

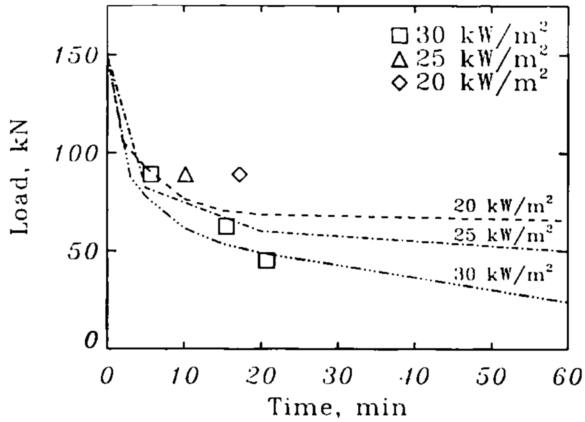

Figure 12 - Measured vs. predicted load vs. time-to-failure for $[0/\pm 60/0)_{11}]$s.

Consequently, the thermomechanical model may be applied to conditions beyond the bounds of the experimental data to determine failure loads of interest for fire resistance considerations on transportation vehicles. The results of the extended investigation are presented in Figure 13. The loads have been normalized by the ultimate load at ambient temperature determined by the model. This figure is presented to show trends from an analysis of a limited number of conditions. The number of conditions was limited because of the excessive computation time required for each simulation. The trends indicated in the figure should be considered preliminary, pending additional experimental data, especially at the high heat fluxes.

As is evident in the figure, the composite laminate can maintain its structural integrity up to the noted exposure durations, as

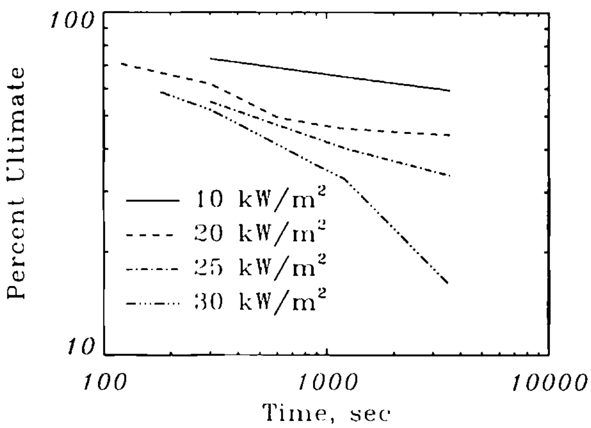

Figure 13 - Predicted load vs. time-to-failure for [0/(±60/0)$_{11}$]s.

long as the load is kept below that required for failure. Application of the model to estimate laminate performance is restrained primarily by available material property data, especially at extreme temperatures. Applications involving severe heat fluxes which induce extreme temperatures on the exposed surface are likely to challenge the material property data base.

Conclusions

The effect of a thermal insult on the structural response of a composite has been shown to depend on the heating conditions, applied loading and characteristics of the composite. Heating conditions, as well as radiant and convective losses, serve to define the boundary conditions for the thermal response analysis. The applied loading defines the structural end conditions. The relevant characteristics of a composite laminate include the geometry of the laminate and the material properties.

As a result of the combined experimental and analytical programs, the performance of the glass-reinforced thermoplastic specimens for these layups is well characterized. However, any conclusions are limited to the material system and layups investigated. Observations pertaining to the performance characteristics of the tested laminates are:

1. Both the thermal and structural response are multi-dimensional phenomena. Application of one-dimensional models may neglect relevant phenomena associated with in-plane temperature gradients and material property changes.

2. The discontinuities caused by melting or charring of the composite leads to stress concentrations and subsequent failure. Thus, these phenomena must be modeled accurately and the physical availability of properties for melted and charred materials are important.

3. Char depth is an inadequate predictor of failure. Char depth is a function of the thermal insult in addition to the damage state. Development of surface cracks is believed to cause more extensive char depths in failed specimens as compared to those proceeding to runout. As a result, a key protection strategy is to prevent surface cracks from developing.

4. Temperature at a single point is an inadequate predictor of failure for a composite laminate. Instead, the temperature distribution within the laminate is necessary.

5. Loaded composite specimens failed as a result of the thermal insult from only modest heat fluxes. Consequently, use of this material system in an assembly subject to fire exposure must be protected with an insulating material.

The modeling effort enabled predictions to be made to provide a broader understanding of the performance of the tested laminates over a much wider range of conditions. As a result of applying the model for the noted laminate, the model can also be reliably applied to other layups of the same laminate, thereby significantly decreasing the number of required tests.

NOMENCLATURE

S shear strength
X longitudinal strength
Y transverse strength
Z strength in thickness direction
σ applied stress

super- and subscripts

1 longitudinal direction
2 transverse direction
3 thickness direction
c compressive
t tensile

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