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EXPERIMENTAL FIRE PERFORMANCE OF THERMOSET CARBON FIBER EPOXY PANELS UNDER VARIOUS TYPES OF STRUCTURAL LOADING

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ABSTRACT

The structural response of three types of composite panels under tension, compression, torsion, and no force with an imposed heat flux are examined. The panels decomposed by pyrolysis and oxidative reactions which resulted in flaming and glowing combustion. The current paper focuses on the structural loading response from the test series. Most of the panels incurred distortions caused by relaxation of the imposed loading in response to the combined structural and thermal environment. One panel type did not distort at all under compression and no force, but distorted under tension and torsion. All panel types were least resistant to forces in torsion. Most panels exhibited minor residual strength, even after significant heating. The behavior of the three different types of panels was appreciably different, suggesting that additional work is needed to understand the relevant parameters that affect structural response in fire-like environments behavior.

INTRODUCTION

Composites are being used increasingly in the design and construction of aircraft. As Sandia has a need to assess the safety of various types of hazardous aircraft cargo for adverse environments, the transportation fire environment created by composite aircraft is important. There is a significant lack of data on the behavior of composite materials in fire. We have begun to examine the response of composites in fire at a range of scales (Brown et al., 2011[1]; Hubbard et al., 2011[2]). Significant findings from these tests describe the decomposition behavior of panels under 20-30 kW/m^2 flux from the radiant heat tests (Hubbard et al., 2011[2]). Spontaneous flaming is not assured at any of the conditions tested without a pilot. Also, the 25-40 kg bulk burn tests suggest that peak heat fluxes from the burning composite are not higher than those achieved from wood or hydrocarbon fuel burns (Brown et al., 2011[1]). The duration of the burns is found to be very long, lasting 5-8 hours under controlled conditions. This test series also found that the decomposition of bulk materials is not dissimilar from that found from thermo-gravimetric analysis (TGA) in that the pyrolysis occurs chronologically first, followed by a long-term glowing oxidation phase.

In addition to our ongoing efforts, there are instances of relevant data in the literature. Keller and Bai (2010)[3] recently put out a review article on this very topic, which cites many of the articles discussed here. Elmughrabi et al. (2008)[4] performed relevant work to the work we present in this paper. They converted a cone calorimeter to accept a loaded test article of vinyl ester and polyester glass laminates. Test articles were stressed in compression and tension near failure stress and heated at several thermal flux levels. They found a small effect of the stress on the decomposition heat release rate, smoke generation, and time to ignition. Tension tends to enhance decomposition rate, while compression has the opposite effect. Their test design prohibited simultaneous mass loss measurements, although they were able to evaluate heat release rates in the calorimeter apparatus. Another review by Mouritz et al. (2009)[5] is focused on modeling and consequently has a lot of relevant citations and information pertinent to this work. Included in the larger body of work that studies composites under thermal and structural combined load, Cao et al. (2009)[6], Burns et al. (2010)[7], Kwon et al. (2006)[8], La Delfa et al (2009)[9], Liu et al. (2011)[10] and Sorathia (1993)[11] evaluated composites with carbon fibers of varying types. Kawai et al. (2001, 2009)[12,13] also examined carbon fiber epoxy materials; they were unidirectional layers not rotated in the matrix, but rotated on the structural rig. This is not as is normally the practice in aviation composites, but allows for a better understanding of the importance of fiber directionality. High temperature in these studies is considered 100ºC, which is low compared to many other studies. Kandare et al. (2010)[14] tested custom glass-based samples and afterwards measured structural integrity. They conclude that char formation enhances strength after fire damage. Indeed, much of the material science literature (not all cited here) is focused on finding additives to enhance charring of the binder to reduce volatile emissions and retain strength. Feih et al. (2008)[15], La Delfa et al. (2009)[9], Liu et al. (2011)[10], and Lua (2011)[16] looked at sandwich materials. In none of the above cases, except in our recent tests (Brown et al., 2011)[1], were the fibers or char intentionally heated to their decomposition temperatures. Experiments found in the literature were often performed at fluxes as high as 75 kW/m^2, which should be high enough to induce oxidative reactions. However generally, the tests were concluded once structural strength was lost in the materials and before the fiber decomposition could ensue.

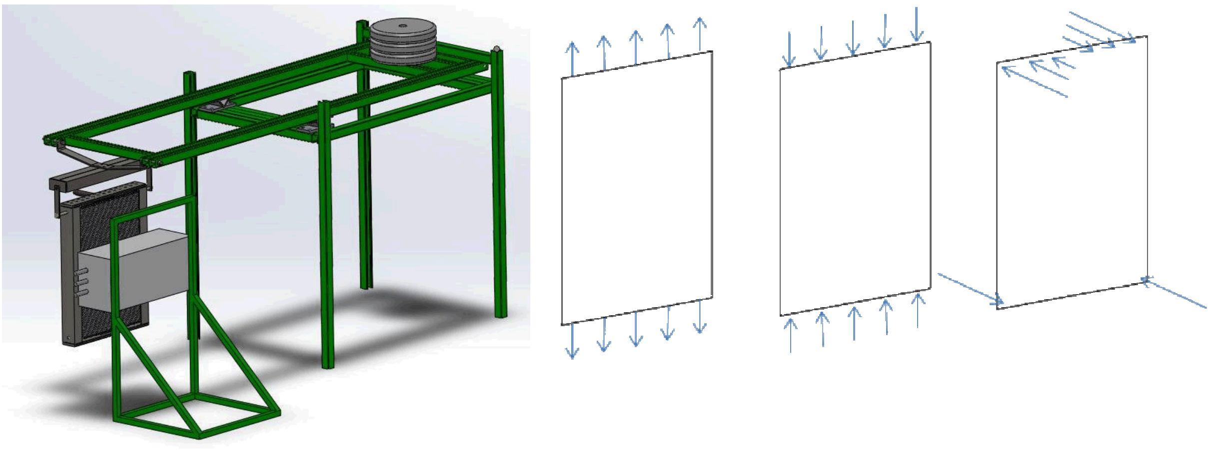
Aircraft often contain large quantities of composite material in large sheets, which differs from the small samples traditionally analyzed as described above. In bulk, the decomposition behavior is not expected to be governed by the same physical mechanisms as with small samples. We are fortunate to have a supply of size-appropriate materials either purchased or supplied from parts fashioned as part of an instruction course. Based on previously detailed work, we anticipate finding the bulk decomposition behavior to be influenced by the types of stresses imposed on the panel. This work aims to quantify this effect on panels of practical size. We also seek to simultaneously measure time-dependent mass loss for the panels to characterize the behavior of large panels in fire conditions. Fiber and char oxidative reactions were demonstrated in an extreme fire environment (Brown et al. 2011)[1], but have not been widely examined in other testing. The conditions under which this type of reaction is initiated and sustained is not well described, and will be explored in this test series.

This report presents a series of discovery tests to explore the structural behavior of typical carbon fiber epoxy materials in a fire-like environment. The findings of Elmughrabi et al. (2008)[4] are a motivating factor for this work. They found structural loading to be functionally related to decomposition rate during the pyrolysis phase. Upon structural failure, their tests were generally concluded. To our knowledge nobody has tested the decomposition rate under loading for full-scale panels as are found on the skins of aircraft. Further, the propensity for glowing combustion exists in an unmitigated fire scenario. The Elmughrabi et al. (2008)[4] dataset does not address that phase of burning, the rate of which might potentially be augmented if structural forces cause dramatic changes in the surface area available for oxidative reactions. Nor does the dataset provide detailed information for lower stress levels, believed to be common under normal (non-flight) environments. This report is a companion report to the work previously documented in Brown and Dodd (2013)[17], which focused on the thermal reactions of the composites from the same test series. This report focuses on the structural response.

METHODS

The test apparatus as designed is illustrated in Figure 1A. A beam balance is placed on a stand structure. The composite holder frame is hung from one end, and is used to impose forces as high as 900 N (200 lbs) on the panels. A counter-balance (illustrated by the gray cylindrical weights) on the opposite end is used to zero the weight measurement, which is taken by a load cell at that same end of the frame. The load cell had a range of +/- 2.27 kg, and is positioned far enough away from the test to remain cool and to give a consistent reading throughout the test. It was generally capable of reading mass changes of approximately 4 grams. Adjacent to the test apparatus is a custom designed 3-rod resistively heated oven generating the thermal environment for the test.

Figure 1. An illustration of the test configuration and sample holders.



Three principal materials are the subject of this testing. One is a 45.7 cm by 61.0 cm (18" x 24") panel, approximately 8 mm thick consisting of rotated layers of Cytec 5208 carbon fiber woven fabric and weighing approximately 4.1 kg (9 lbs). The precise lay-up was not given, but examination of the decomposed panels suggests a similar pattern to that of the other 5208 panels that originated from the same manufacturers. The number of layers was not known, but was sufficient to achieve the stated panel thickness. The second material is a sandwich board composed of rotated unidirectional layers of Cytec 5208/T-300-12 (about 1.5 mm thick; +45/ -45/ 0/ 90/ 90/ 0/ -45/ +45), a HRP-3/16 core (NOMEX, about 25 mm thick), and an 8-layer fabric Kevlar epoxy (about 1 mm thick). This panel is nominally 30.5 cm by 45.7 cm (12" x 18") in dimension, and weighs about 0.45 kg (1 lb). The third material consists of 16 layers of a unidirectional IM7G/8551-7A Hercules carbon fiber, and is 3.2 mm thick, and 48.7 cm x 61.0 cm in dimension (1/8" thick, and 19 3/16" x 24"; [0/90/-45/+45/-45/+45/90/0/0/90/+45/-45/+45/-45/90/0]×2), weighing approximately 1.4 kg (3 lbs). Table 1 lists some basic detail about the panels for these tests and gives the common designation for the panels used throughout the rest of this report in the PANEL column. Since these panels are significantly different from each other in several ways, comparisons between panel types is not advised.

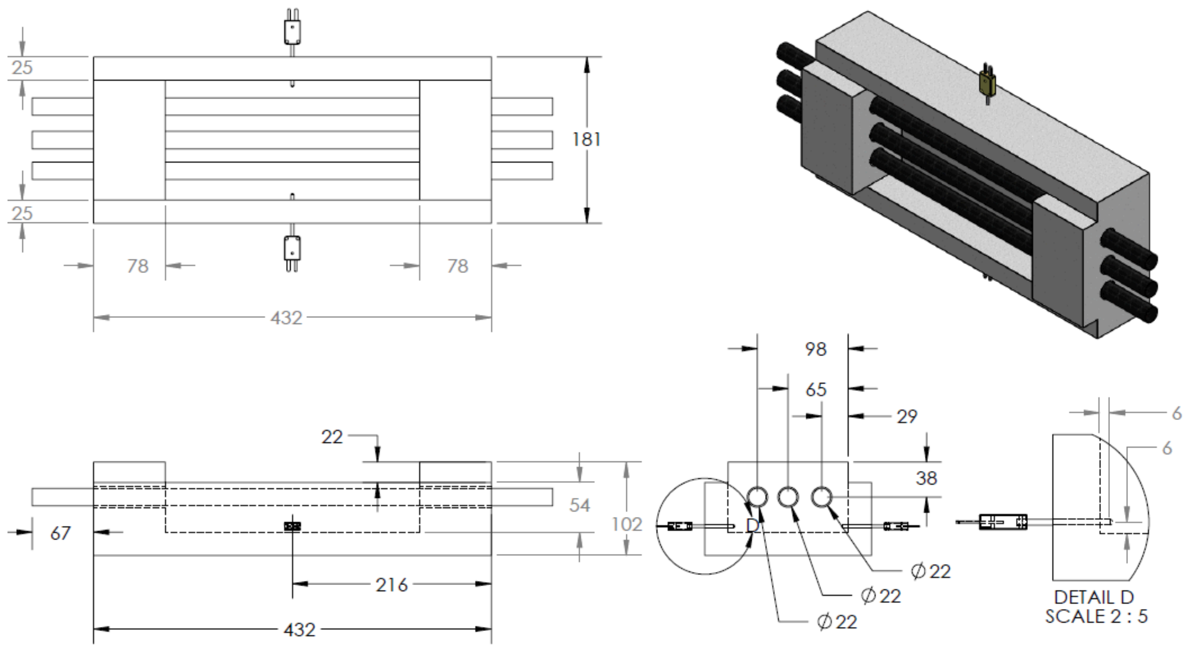
Table 1. The three types of panels in this study.

PANEL	EPOXY	CARBON FIBERS	AVERAGE WEIGHT (kg)	DIMENSIONS (cm)	TYPE
ABDR Sandwich	Cytec 5208	T-300-12 Uni	0.753	30.5 x 45.7 x 2.8	Sandwich
19x24 thin	Hercules 8551-7A	IM7G	1.354	48.7 x 61.0 x 0.32	Flat Panel
18x24 thick	Cytec 5208	T-300-12 Fabric	4.070	45.7 x 61.0 x 0.8	Flat Panel

Three structural loading configurations were designed to impose three basic types of stress, and are illustrated above for the '18x24 thick' composite panels. In each case, retaining bolts are used to compress springs, which provide a measured load and a linear decrease in the load over several centimeters as the applied force relaxes. Total force imposed was as high as 890 N (200 lbf, or 90.7 kg equivalent). The first configuration used in testing is designed to put the panel in tension as it is subjected to the fire. In this case, holes were drilled into the composite to allow the panel to be held firmly. A depiction of the imposed forces is illustrated in Figure 1B. The second configuration is compression, configured with the panel being compressed on two ends. It is illustrated in Figure 1C. The third configuration is bending, which is designed to impose a complex torsional loading on the test object. It is illustrated in Figure 2D. A fourth configuration existed, which was a panel in the support frame with no force imposed. This condition served as a control, providing data for the decomposition of a panel under no external loading other than what naturally exists in the support of its own weight. These were designed to be simple abstractions of the more complex structural environments expected to be imposed on panels of actual aircraft. Forces were imposed by springs located at the bottom of each panel holder. Corresponding engineering drawings of the sample holders are found in Brown and Dodd (2013)[17].

The heat source for this test series was a critical aspect of the tests. An oven was constructed to impose a repeatable thermal environment on the panels. The box was constructed from Pyrotherm I-14 insulation board from PyrotekTM. Manufacturer specifications suggest a density of 288 kg/m^3, heat capacity of 1.09 kJ/kgK, and conductivity at 204 ºC of 0.088 W/mK, with the conductivity varying from 0.078 to 0.105 W/mK for the range of 93-427 ºC. Three silicon carbide rod heating elements were electrically powered to provide the heat source. These are marketed as Starbar® brand 10 inch rods. Their diameter is 19 mm, and advertised heated length was 254 mm. Due to manufacturing variability, the peak heated length could be as much as 20% lower than the total advertised heated length. According to the manufacturer specifications, the heated zone has a resistance of 0.00341 ohms/mm, while the remaining rod is about two orders of magnitude below that. Rods were wired in series, and electrically powered from a 480 volt AC wall outlet through a Silicon Controlled Rectifier (SCR) where current was controlled by a 4-20 mA control box. Separate instrumentation was used to record the current and voltage. The average power thus calculated for the tests was 6,700 Watts, with a standard deviation of 366 Watts.

Figure. 2. A drawing of the oven assembly; all dimensions in mm



A drawing of the oven assembly is found in Figure 2. The oven is constructed of insulation board and held together with standard iron based board screws. The vertical orientation of the oven with respect to the panel was such that the center of the oven was 15.2 cm (6 in) from the bottom of the panel. The center of the rods was located 89 mm away from the front face of the composite at the start of the test. Two thermocouples were placed at fixed locations within each oven as illustrated in Figure 2. These monitored the temperature of the oven, and provided an indicator of repeatability and test to test variation. The oven and rods have a finite lifetime. The thermal environment was controlled by the electrical supply settings (i.e. current, voltage), which were actively measured. Current was shown to be consistent from test to test to within two decimal places, with voltage differences resulting in a variability of approximately 5%.

More detail on the oven thermal characterization are found in Brown and Dodd (2013)[17]. Herein, fewer details are presented. Under typical conditions, the rods were measured by IR cameras and IR thermography to achieve approximately 1400ºC, and the oven thermocouples typically recorded temperatures in a 150 degree range between 1000-1200ºC. Radiometers suggested peak fluxes as high as 160 kW/m^2, and these may be estimating low because of spot shielding and other effects. We believe (based on previously described work; Brown and Dodd, 2013[17]) the peak fluxes to be on the order of 220 kW/m^2. The flux to the panel varies from the peak directly across from the center of the oven, to much lower fluxes away from the oven.

Panels were structurally loaded well before the thermal portion of the test began. An active measurement of the force on the panels was available by monitoring the displacement of the springs. Video cameras recorded this motion and also captured the dynamics of flaming and oxidative reactions. Motion was tracked from two cameras, one with a tight focus on the springs and another wide angle focused on the full panels. Pre-test fiducials were used to calibrate the post-processing. Post-test analysis yielded the active force on the panels as a function of time. The test matrix consisited of the three panels. Tests were performed sequentially according to their number in the Table 2 test matrix, and were repeated for many of the panel configurations to provide confidence and uncertainty bounds.

Table 2. The test matrix listing the corresponding test numbers under each test type

PANEL TYPE	COMPRESSION	TENSION	NO FORCE	TORSION
ABDR SANDWICH COMPOSITE	24,27	31,32	25,33	43
18x24 THICK COMPOSTE	26,34	29,35	30	
19x24 THIN COMPOSITE	(38) 39,45	41	37,40	42

RESULTS AND DISCUSSION

ABDR Sandwich Panels

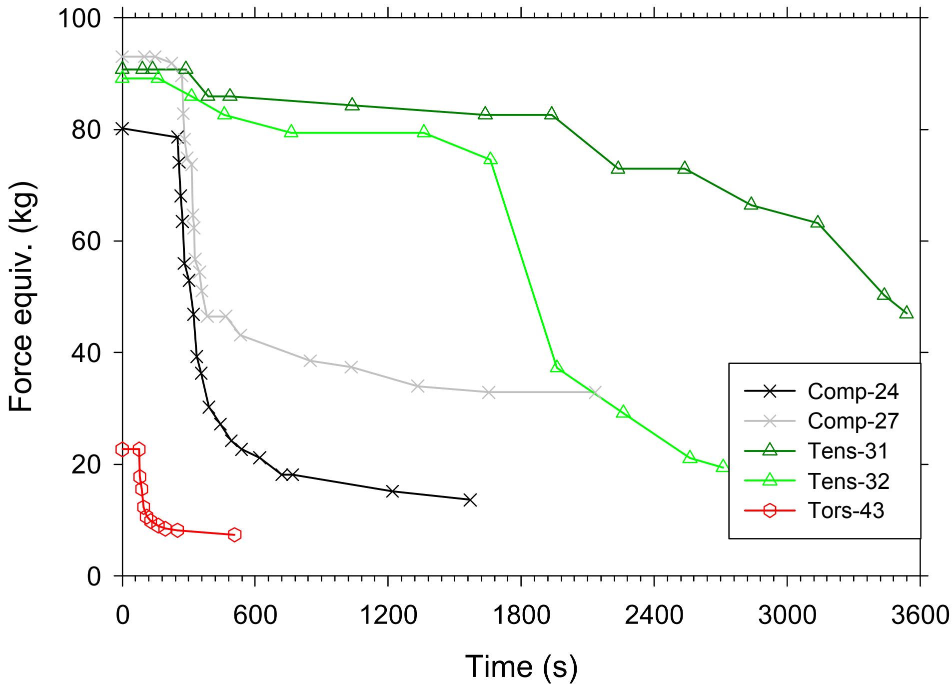
The ABDR sandwich panels were the lightest and tended to burn completely through in 20-40 minutes. The ABDR panels exhibited interesting behavior with respect to the structural loading placed on the panels. Detailed results were determined by examining the back-side camera images and are found in Table 3. Here it can be seen that the compressive and torsional deformations occur early in the event, whereas tension deformations occur later.

The tension tests were clearly differentiated from the compression and torsion cases, in that they were able to support the full load of the frame through a large portion of the test. The torsion and compression tests exhibited movement very early in the test. The torsion test did not exhibit much strength, but there was clearly residual compressive strength through a good portion of the compression tests. This finding is not particularly surprising, as the epoxy is relied upon to provide a greater fraction of the structural strength to compressive and torsional loads. In tension, the fibers most closely aligned with the direction of force are believed to provide strength after the epoxy softens or degrades due to the thermal environment. Hence, the panel exhibits greater resistance to motion in the tension scenarios.

Table 3. ABDR spring movement summary.

Test	Force Type	First Movement	Last Movement	Nature of Movement
24	Compression	1 min 48 sec	19 min 52 sec	Smooth changes at early times, diminishing at late times
27	Compression	2 min 58 sec	36 min 16 sec	Big steady movements for the first 4 minutes, small movements for the next 17 minutes, panel collapsed and fell out of top holder at about 34.5 minutes.
31	Tension	36 min 9 sec	End of test	Minor movement (thermal expansion) before first significant movement, small regular movements until test end.
32	Tension	24 min 32 sec	42 min 21 sec	A tear opened up over the last half of the test, with periodic small movements over this time frame.
43	Torsion	2 min 37 sec	3 min 22 sec	Steady movements for about a minute, slowing afterwards to a creep.

Figure 3. Mass equivalent force on the ABDR panels as a function of time.



Analysis of the spring cameras gives a more complete picture of the estimated load on the panels during the test. The force equivalent mass was deduced from the spring constant of the springs. This is used to report the structural load on the panels instead of stress because the panels were degrading during the tests, making selection of a representative cross-section difficult. There is a degree of subjectivity to this analysis, and these results should be taken as accurate only to within 10% of the initial reading. Even though spatial fiducials were used to provide a reference length scale in the videos, some degree of uncertainty remains from case to case due to combinations of movement in the cameras after the fiducial frames were taken and also due to the perspective. Maintaining a consistent measuring point was also challenging sometimes due to optical quality of the images and changing light sources. Quantified data are found in Figure 3. For the most part, the force was uniformly applied across the ABDR panel base, and the springs released force at about the same time. The torsion test used only one spring, which is why the initial force is about ¼ that of the other tests. The panel hit the back-plate, which is why further movement was not found for this test.

Some discrepancies exist between the results of Table 3 and Figure 3. The start times in Table 3 were subjective and based on a wider angle view in the table. The figure reflects a more detailed view of the occurrence. More subtle motion is captured in the figure. It is possible that the subtle early motion in tension not noticed in the wide-angle extraction (Table 3) is due to thermal expansion and not caused by structural deformations.

An important note with respect to torsion Test 43 is that the data became obscured because a sheet of carbon fiber came loose and rested on the spring holder. This is illustrated in Figure 4. Subsequent motion could not be quantified. All the ABDR tests showed propensity for significant fiber movement on the front face. A point about Test 27 results is that the springs appear to have significant residual force at the end of the test. Yet in that test, the top part of the panel actually fell out of the holder at the end of the test. The residual strength cannot therefore be attributed to the panel. Minutes later, the springs relaxed slightly. The residual strength may be attributed to sticking or some other residual force in the test rig itself. This is one of the reasons the data are not believed to be more than about 10% accurate.

Figure 4. Photographs of the Test 43 ABDR panel in torsion before (left) and after (right) the first significant movement of the fibers.

19x24 Thin Panels

The 19x24 thin panels typically burned through in approximately 60 minutes. These panels were unique in that they did not tend to move significantly with the force imposed. Compression tests exhibited full loading at the end of each test, despite a large (20 cm or greater) hole having been formed in the panel. Tests were terminated when two oven rods were clearly visible from the back side. The tension test did not exhibit stretching or tearing like the ABDR tests, rather the material softened around the bolt holes and the panel sheared across the bolts. This was not the desired behavior and possibly would not have happened except that the three bolts were placed as centered as possible on the panel. Had they been spaced wider or cooled (ideas for subsequent work), the panel might not have behaved the same way. The torsion test did not exhibit significant movement because this panel would not hold much torsional force. The spring would not compress more than a few millimeters, as the panel deformed with the smallest imposed force. Consequently, the deformation data in this section is not as interesting as was found in the other sections. Details on the structural response for the tests are found in Table 4.

It is in a way fortuitous that the compression tests did not deform, as this presumably gave better repeatability in the thermal data. Without significant deformations, the effect of the deformations on the reaction rate (detailed in Brown and Dodd, 2013[17]) due to material moving closer to the oven is minimized. However, the difference in behavior of these tests compared to the tests with the other two panels is surprising and difficult to attribute.

Table 4. 19x24 thin panel spring movement summary.

Test	Force Type	First Movement	Last Movement	Nature of Movement
39	Compression	-	-	None
41	Tension	15 min 48 sec	19 min 28 sec	Shearing from the bottom bolts at a slow pace over about 3.5 minutes.
42	Torsion	3 min 3 sec	12 min 28 sec	Steady movements for about six or seven minutes, slowing afterwards to a creep.
45	Compression	-	-	None

Figure 5. Mass equivalent force on the 19x24 thin panels as a function of time.

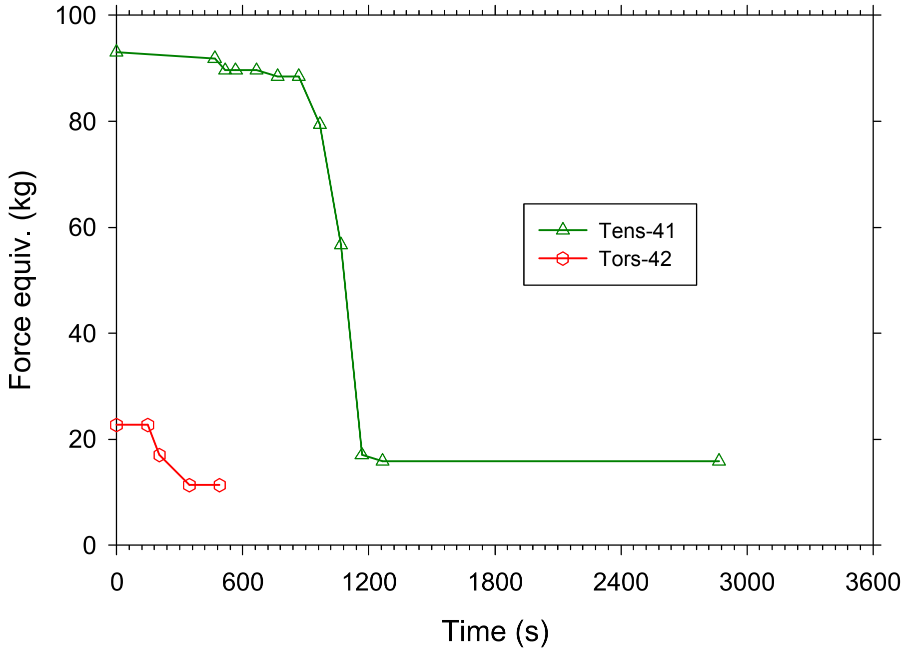


Figure 5 shows a more detailed view of the movement in the two tests where movement occurred. The tension panel was mostly rigid until about 15 minutes, after which rapid movements ensued as the panel pulled clear of the retaining bolts. The torsion test results look very similar to those of the ABDR panel. The panel was unable to support much force in torsion and was heavily distorted from flat before any thermal loading was imposed.

18x24 Thick Panels

Contrary to the previous two panels, the 18x24 thick panels did not burn through all the layers, despite approximately four hours of exposure to the oven. Table 5 shows a general description of the movement of the panel in response to the spring force. As with previous sections, these data were extracted from the back-side camera. On Test 29, the exact movement times are not well understood, as a blown fuse as the oven was initially turned on resulted in a synchronization error between the cameras and the data. It is important to note that after about 30 minutes, there was a significant reduction in the force on all of the panels. This is contrary to the findings for the 19x24 thin panels, which were able to maintain force throughout the test in compression. Details of the imposed force on the panel can be found in Figure 6, as extracted from the spring camera. Even though these panels had much more mass, they appear to have deformed much earlier in the tests compared to the other two panels. Furthermore, their deformations finished earlier. The compression test appears to retain more residual strength at the end of the test compared with the tension tests, as the final force on the panels is still moderately high for those tests. These panels exhibited more uneven distribution of the force than the previous tests. Test 29 and 26 in particular manifested this behavior (test 34 to a lesser degree). These results are shown in Figure 7. In this figure legend, the R and L indicate right hand and left hand side looking at the back side of the panel. In Test 26, the left hand side moved earlier, and in test 29 the right hand side moved earlier.

Table 5. 18x24 thick panel spring movement summary.

Test	Force Type	First Movement	Last Movement	Nature of Movement
26	Compression	4 min 9 sec	15 min 49 sec	Periodic spurts of movement over the indicated time.
29	Tension	Early	around 30 min	Some panel stretching early before back-side flaming at ~16.5 min. Some shearing from the bottom bolt during back-side flaming. After back-side flaming, shearing from the top bolts.
34	Compression	5 min 4 sec	6 min 33 sec	Rapid movement over a short time. The panel bent in the middle, distorting away from the oven.
35	Tension	3 min 22 sec	15 min 10 sec	Lower panel stretching occurs first, followed by big movements around 12 minutes as the panel shears from the top bolts. Final movements are mostly done by about 15 minutes.

Figure 6. Mass equivalent force on the 18x24 thick panels as a function of time.

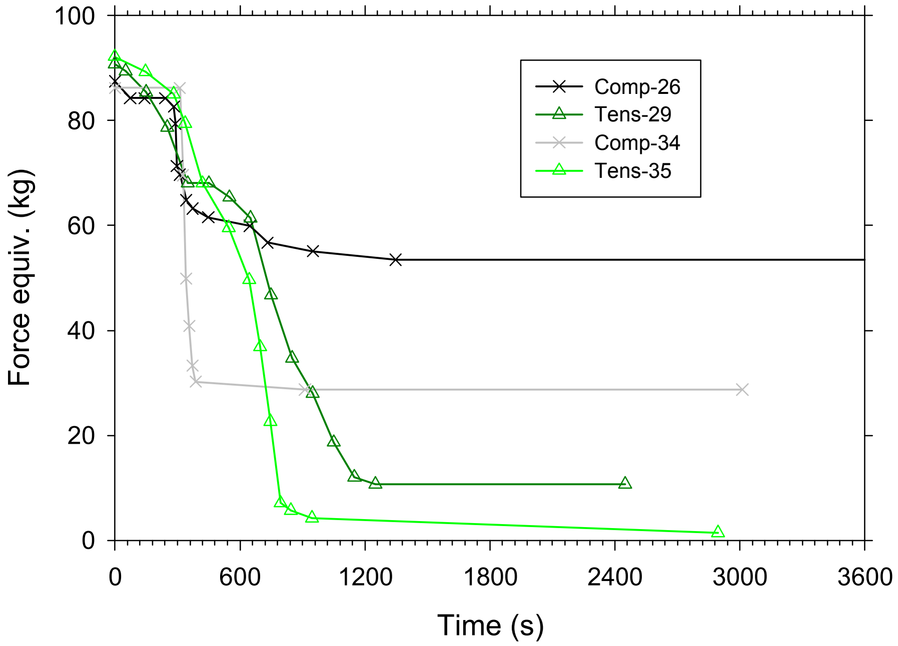
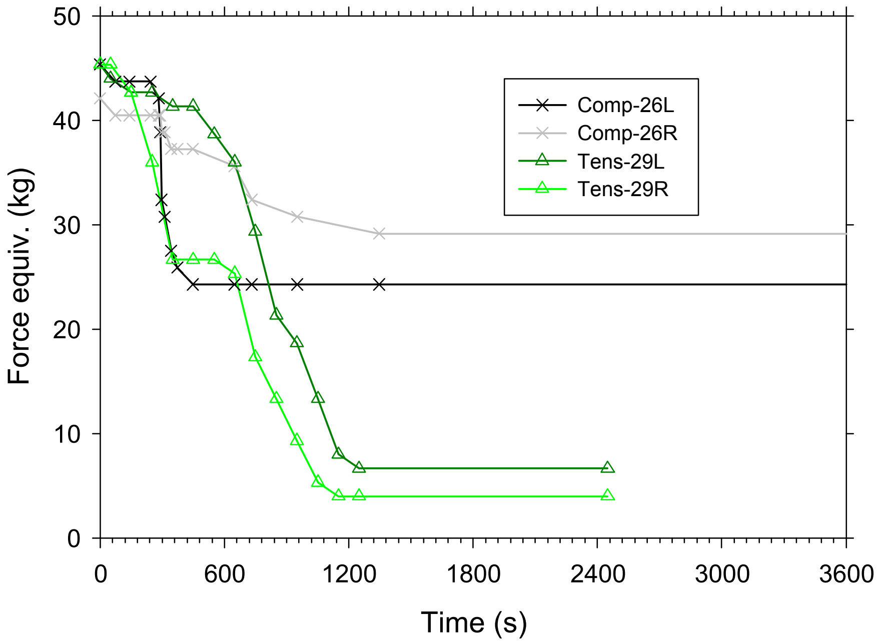


Figure 7. Force mass equivalent broken out by side of panel for two tests to show details of the uneven force distribution.



Discussion

A curious finding from the results is that there is not a simple way to predict beforehand the structural behavior of the panels. The thermal environment resulted in fairly reproducible behavior in the panels in terms of flaming initiation and termination. However the structural results were somewhat unexpected. After performing the 18x24 thick panel tests, it was expected that the 19x24 thin panels would distort under compression much like all others had previously, or perhaps more readily. Yet they did not. The reason the 19x24 thin panels were apparently stronger in the fire environment merits some consideration. The 18x24 panels were thicker and slightly narrower than the 19x24 thin panels. They flamed for a much longer time, perhaps due to the quantity of volatile in the thicker materials. This longer flaming period could create an increased damage state caused by a longer exposure to the flames, weakening the entire structural matrix sooner. Inorganic residues were found for the 18x24 thick panels and not for the 19x24 thin panels, another suggestion of significant differences in the materials of origin contributing to the observed behavior. It is also important to note that the 19x24 thin panels were made from a different grade of binder material (still primarily thermoset epoxy) and from unidirectional fibers. The 18x24 thick panels were made from woven fabric. What effect this could have relative to the structural strength is not clear. One possibility is that the fabric because of the tighter weave makes a better gas seal, and that the decomposition deep in the layers creates higher and more destructive pressures. Carbon fiber epoxy composite conductivity can vary by about two orders of magnitude depending on the fiber orientation. Heat transfer differences caused by the fibers could play a role in this finding. The width difference between the two panels was minor, but the 19x24 thin panels were able to distribute the weight in the compression tests around the holes that eventually formed, whereas the 18x24 thick panels grew weak at the edges. It is important to note that the 18x24 thick panels failed fairly early, which means that the fact that they failed had nothing to do with the extended time that the panels were exposed to the oven compared to the 19x24 thin panels. The lack of uniformity between the samples makes accurately ascribing the reasons for this finding difficult.

The significant differences in compression results among the panels suggests a somewhat counter-intuitive finding, which is that there may be an intermediate material thickness that produces the best structural strength in a fire. This could be seen as a compromise between thermal degradation due to flaming of off-gassing volatiles and bulk strength. Since there were many differences between the two panel types, this test series will not be able to fully explain if this is the driving factor, or if one of the other factors mentioned above is more significant. More work with additional panel types and configurations will need to be done to better understand the structural behavior found in these tests.

If one considers strength in fire on the basis of the weight of the panel, the ABDR panels performed well. Even with significant loading, they were able to hold the full compressive load for a couple of minutes and retained residual strength for 20-30 minutes. The 18x24 thick panels lost strength in a similar time frame, despite being much heavier. The 19x24 thin panels were considerably more resistive to movement in tension and compression than the other two panels, despite having an intermediate weight. In tension, these panels remained stout under the load for at least 20 minutes, also longer than the other two panels. Neither of the panels tested in torsion did particularly well with that type of force under fire conditions.

A couple of other observations in regard to the structural response of the panels are worth noting. The panel did not yield abruptly in any experiment, as tended to be the case in the Elmughrabi (2008) work[4]. The failure was often times rapid, but never an instantaneous move from full strength position and shape to a final deformation. This was true regardless of the panel type or type of structural loading. At these loading levels, as the composites weaken in a fire, they deform gradually in a plastic-like creep. The imposed forces for these tests are probably representative of some of the forces on real transportation vehicles during normal operations. Such forces are significantly below the normal (room-temperature) structural failure point. We therefore hypothesize that a long-term fire involving a composite structure may cause the airframe to soften and droop with time like a plastic airplane in an oven. Real-time evaluations of the videos from these panels could not always detect the motion without careful and precise references on the monitor screens.

CONCLUSIONS

These discovery tests have exhibited some at present difficult to attribute behavior in the decomposition of structurally loaded panels. Shape, size, and material types likely influence the behavior during decomposition. These parameters should be better explored to better understand their influence on the decomposition dynamics.

- In these tests, panel deformation was unique to the type of panel employed.
- Differences in panel materials and construction appear to be important, as decomposition behavior appears to be specific to the type of panel evaluated, not necessarily scaling with panel thickness or initial stress.
- The morphology of the deformation may play a role in how they react in a fire, although these tests did not find clear quantitative evidence in this regard.
- In the fire environment, a panel resists early deformation due to tension better than compression. Torsional forces imposed in these tests resulted in the earliest deformations due to the thermal environment, despite the fact that the torsional force imposed was a quarter that of the other two types of force.
- Structural force-induced motion tended to be gradual with time given the force levels (well below ambient temperature yield limits) imposed in these tests.

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