EVALUATION OF FIRE PERFORMANCE OF COMPOSITE MATERIALS FOR AIRCRAFT STRUCTURAL APPLICATIONS

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SUMMARY: This paper presents a methodology for evaluation of the fire performance of composite material designs for aircraft structural applications. While compatible with civil aviation authority requirements, the tests outlined are intended primarily for screening various potential design options rather than for certification purposes. The developed test approach is demonstrated via a study of design options for a 'fireproof' composite aircraft engine enclosure. This study demonstrates that various composite material designs offer significant potential for fire containment, but also shows that the level of strength retained by composite structures during a fire event is very low in the area of flame impingement.

KEYWORDS: aerospace structures, fire performance, residual strength, structures, fire damage, certification

INTRODUCTION

In order to contain and isolate engine fires, civil aviation regulations require that aircraft powerplant enclosures be sealed from the rest of the aircraft and be 'fireproof'. As outlined in FAA Advisory Circular AC 20-135 [1], a structure is considered to be fireproof if it can withstand a 1093 +/- 83 ºC (2000 ºF +/-150 ºF) flame for a minimum of 15 minutes, while still fulfilling its design purpose and resisting flame penetration. Given that this temperature is greater than the melting point of aluminum alloys, aircraft designers have generally met this fireproofness requirement through the use of titanium or steel enclosures or via incorporation of significant insulating/shielding elements. Any of these approaches, however, result in both increased structure cost and a significant weight penalty. A promising approach to addressing both cost and weight problems is application of advanced composite materials.

Considerable effort has been expended by various research groups in examining the fire performance of composite materials, both for aerospace and naval applications. The large majority of the work performed to date, however, has focused on survivability issues related either to flame penetration *into* an occupied area (typically for external aircraft fires), or FST

(fire, smoke and toxicity) issues for a fire within an enclosed, occupied space such as an aircraft cabin [e.g. 2-4]. Of greater relevance to the case of an engine enclosure is the work of Sorathia and co-workers [e.g. 5-6], who have examined the post-fire residual strength of a number of structural composite materials, although under different conditions to that specified by AC 20-135. The resistance of structural composites to flame penetration under AC 20-135 conditions has also been examined by researchers [7-8], but residual strength was not measured in these cases.

This paper presents a simple methodology for evaluation of the fire performance of structural aerospace composite materials, with a focus on a case study examining various design options for a powerplant enclosure. It should be emphasized that the presented tests are not suitable for airworthiness certification purposes as critical application-specific issues such as structural configuration, vibration, external airflow, and flight-representative loads are not considered. However, these tests should prove useful for rapid screening of potential design options and provide valuable insights that may be used in follow-on certification testing.

ENGINE ENCLOSURE DESIGN OPTIONS

The first step in evaluation of the fire performance of composite engine enclosure designs was definition of feasible design options. Given the limited amount of available data on the fire performance of structural aerospace composites, it was decided to evaluate as wide a range of material and design options as possible (within the limited available resources). In addition to such factors as structural performance, weight, and material cost, other considerations used in evaluation of design options included:

- *Life cycle cost* – In addition to base material and fabrication costs, this includes material and structural certification, maintenance and repair costs.
- *Material availability* – Only commercially available materials were considered.
- *Track record* – Materials and designs were favored which were similar to those employed in certified aircraft applications, particularly fireproof applications.
- *Structure inspectability* - Designs should be amenable to inspection by either NDI or (preferably) visual methods.
- *Vibration tolerance* - Some fire-barrier materials (e.g. ablatives) are known to be susceptible to flaking under vibration during a fire event and were therefore avoided.
- *Environmental resistance* - Designs must be capable of withstanding an elevated temperature environment after prolonged exposure to aircraft fluids as well as moisture.

Based on these considerations, a total of nine different designs were selected for evaluation, as outlined in Table 1. These included both thin-skin and sandwich constructions, glass and carbon fibre reinforcement and epoxy, polyimide, phenolic and BMI matrices. In all cases, fabric reinforcement was used, based on work indicating superior fire performance as compared to unidirectional reinforcement [5,9]. Some designs included an integral fire barrier of a single ply of Nextel™ ceramic fabric (from 3M), since this material had been shown previously to provide excellent resistance to flame penetration [7].

Based on weight considerations (compared to a baseline titanium structure) a nominal thickness of 1.5 mm was chosen for all thin-skin constructions and most sandwich face sheets. The only exception was the BMI foam – filled sandwich in which 1.27 mm facesheets were used due to weight considerations. In all cases, as close as possible to a balanced, symmetric

quasi-isotropic layup was attempted.

Table 1: Composite Material Design Options Selected for Fire Testing

Thin-skin constructions				
No.	**Fibre**	**Matrix**	**Fire Barrier**	**Layup**
1	Glass	Epoxy	Nextel (1 ply)	[45] Nextel + [0/-45/-45/0/45] Glass/Epoxy
2	Glass	Polyimide	Nextel (1 ply)	[45] Nextel + [0/-45/90/-45/0/45] Glass/Polyimide
3	Glass	Phenolic	-	[45/0/-45/-45/0/45] Glass/Phenolic
4	Carbon	Phenolic	-	[45/0/-45/-45/0/45] Carbon/Phenolic
5	Carbon	BMI	-	[45/0/-45/90/90/-45/0/45] Carbon/BMI
6	Carbon	BMI	Nextel (1 ply)	[45] Nextel + [0/-45/90/90/-45/0/45] Carbon/BMI

Sandwich constructions					
No.	**Fibre**	**Matrix**	**Fire Barrier**	**Core**	**Layup**
7	Glass	Phenolic	-	½” Nomex	[45/0/-45/-45/0/45] Glass/Phenolic + Core + [45/0/-45/-45/0/45] Glass/Phenolic
8	Carbon	BMI	Nextel (1 ply)	½” Glass/ Phenolic	[45]Nextel + [0/-45/90/90/-45/0/45] Carbon/BMI + Core + [45/0/-45/90/90/-45/0/45] Carbon/BMI
9	Carbon	BMI	-	¼” Nomex/BMI foam core	[45/0/-45/-45/0/45] Carbon/BMI + Core + [45/0/-45/-45/0/45] Carbon/BMI

TEST DEFINITION AND DESIGN

In accordance with AC 20-135, two separate but related measures were employed to evaluate the relative fire performance of the various identified design options. The first was the ability of the constructions to meet the minimum ‘fire containment’ criteria outlined in the FAA standard. This requires that a structure prevent flame penetration and resist backside (i.e. the side away from the fire) ignition for 15 minutes when subjected to specified fire conditions. In addition to containing an internal fire, a fireproof structure must also retain sufficient strength during (and following) the fire event to fulfill its design function. Thus, the retained strength of each design *after* fire testing was also evaluated.

Fire Test Design

The primary driver in fire test design was achieving the minimum temperature and heat flux conditions outlined in AC 20-135. This document specifies that the flame must produce a temperature of 1093 +/- 83 ºC (2000 ºF +/-150 ºF) 6.4 mm (0.25 in.) above the specimen surface while maintaining a minimum heat flux density of 105.6 kW/m^2 (9.3 BTU/ft^2-sec). Although AC 20-135 requires that these conditions be maintained over a 12.5 cm x 12.5 cm (5 in. x 5 in.) area, a smaller target of a 5 cm – 7.5 cm diameter area was set for this case. This target was set in order to reduce the fire-damaged area so that valid residual strength tests could subsequently be performed on a specimen of reasonably small size. With this target size in mind, a specimen size of 30.5 x 30.5 cm (12 x 12 in.) was chosen. Assuming that flame temperature would drop off quickly outside the impingement zone, this would leave an undamaged (or lightly damaged) area of at least 10 cm along each side of the panel.

Other considerations in fire test design included avoiding excessive fixture warpage and preventing ‘wrap-around’ of the flame from the front of the panel to the back side. The test was also designed to facilitate rapid testing of a large number of specimens as well as quick

and easy flame calibration. It was also decided to incorporate a technique for measuring the backside temperature of each specimen throughout the fire test without affecting specimen behaviour.

A schematic of the developed fire test design is shown in Fig.1. As illustrated, specimens were mounted vertically in removable test frames made of 3 mm thick mild steel sheet. The specimens were held in place by a steel plate bolted to the back of the test frame, leaving an area of 25 cm x 25 cm exposed to the front-side flame. Specimen edges were sealed against the test frame using an intumescent mat material that expanded to fill any gaps created by frame warpage. The combination of this sealant material and a light (finger-tight) bolt clamping pressure resulted in a moderate level of in-plate constraint on the specimens during test.

Several different burner configurations were tried in an attempt to meet the requirements of AC 20-135. As shown in Fig. 1, the final choice consisted of a 2.5 cm diameter steel pipe, with air induction holes at the back end and moderate pressure (appx. 175 kPa) propane gas introduced through a valve. A pilot light was permanently positioned at the mouth of the burner to ensure flame stability. The heat flux and temperature of the flame impinging on the test panels were adjusted by changing the distance from the burner to the test frame, and by changing the air and fuel flows. Although this configuration resulted in a much larger than desired flame impingement area (20 cm – 25 cm in diameter), the required temperature and heat flux levels could not be reliably maintained using a smaller burner diameter.

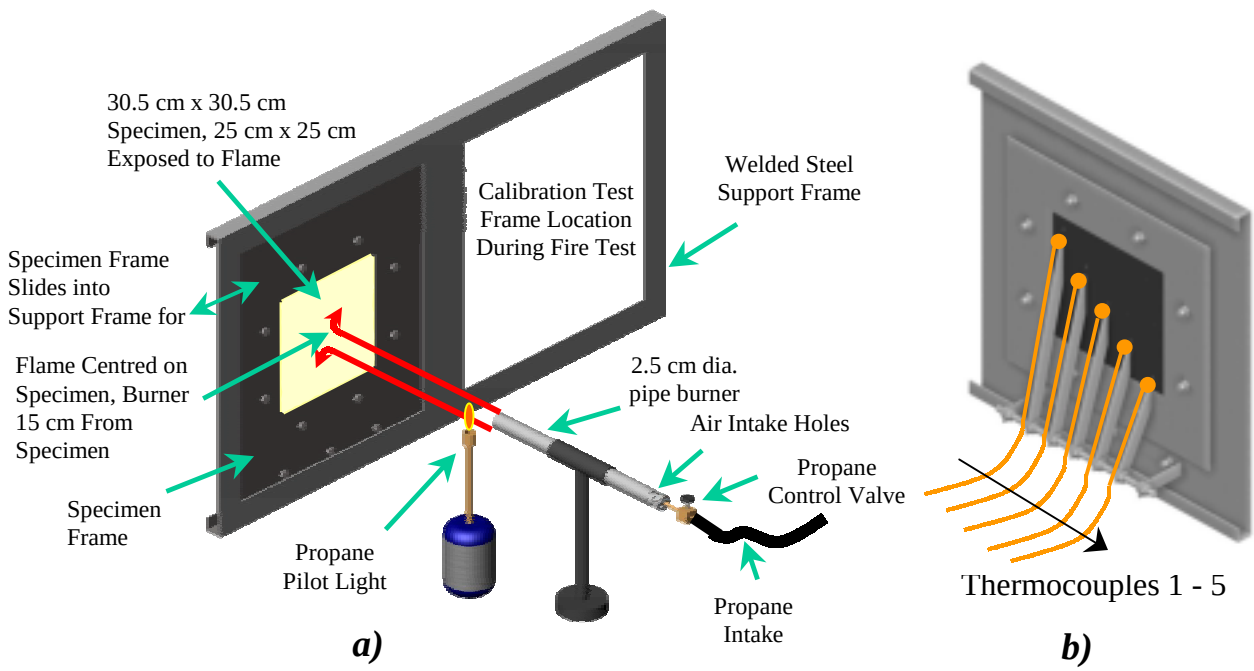

Fig. 1 : Schematic of fire test setup; a) Front view, including frame support, b) Rear view of test frame, showing back-side thermocouples. Note that for each 30 cm x 30 cm specimen, only 25 cm x 25 cm is exposed to the flame, the rest being shielded by the frame.

Calibration

Before and after every series of fire tests, a calibration was performed to ensure that the flame was within specification. This was done using a calibration test frame supporting a water-cooled heat flux meter (Model 64-20-18 from Medtherm Corp., Huntsville, Alabama) and a diagonal arrangement of eight K-type thermocouples. After setting the fuel flow at the

beginning of each test session, it was found that the temperature and heat flux requirements of AC 20-135 could be consistently maintained on an area approximately 10 cm in width.

Backside temperature measurement

In addition to simply containing a fire, it is also important in many applications that the back-side (i.e. away from the fire) temperature of a structure be maintained below a certain level in order to provide protection to passengers, fuel lines or equipment. To record back-side temperatures of the tested specimens, a set of five steel arms was mounted on the back of the test frame. These arms supported and maintained K-type thermocouples in a diagonal pattern across the back of the specimen, as shown in Fig. 1b. The weight of these arms provided sufficient pressure to ensure continual thermocouple contact, without damaging the specimens or interfering with their movement during fire test. All temperature measurements during testing were collected using a PC-based data acquisition system.

Residual Strength Test Design

Following fire testing, the residual strength of the fire-damaged specimens was measured to evaluate the amount of capability each would retain for supporting flight loads. Rather than testing small coupons from various regions of the damaged specimens, full-size 30.5 cm x 30.5 cm (12 in. x 12 in.) specimens were tested in order to evaluate the strength retention of the full structure. Although a difficult test for large, thin panels, specimens were tested for compressive strength. Since the primary effects of a fire on most advanced composites are degradation of the matrix resin and ply delamination, this method was chosen as a conservative measure of strength retention compared to alternatives such as tension or flexural tests.

Specimen geometry and the existence of a fire-damaged zone required that a custom set of fixturing be developed for this test, as illustrated in Fig. 2. Important considerations in test design included:

- *Suppression of large-scale (Euler) buckling, especially in the fire-damaged zones*. This was accomplished through the use of 1.5 cm thick steel anti-buckling plates spanning the whole width of the specimens. To minimize interference with the specimens, these plates were suspended from hanger frames, and sheets of Teflon were sandwiched between the plates and specimens.
- *Smooth introduction of compressive loads into the specimen ends*. In order to avoid brooming failure and reduce stress concentrations the loaded edges of the specimens were potted in aluminum C-channels as illustrated in Fig. 2b. Large epoxy fillets were used to assist in smooth load introduction.
- *Accurate specimen alignment with loading axis*. A number of measures were taken to ensure accurate alignment of the specimen with the loading axis. Vertical alignment fixtures were used to provide a reference plane for the anti-buckling plates and to ensure alignment was maintained during test. A spherical bearing was placed between the actuator and the end of the specimen to compensate for small misalignments. Finally, great care was taken during potting of the specimen edges to ensure that they were both flat and parallel.

Tests were conducted using a four-post MTS hydraulically-actuated load frame (model 931.64) with a 900 kN (200,000 lb) capacity. Load measurements were taken using an MTS

electronic load cell (model 661.31A-05) with a 450 kN (100,000 lb) capacity. Actuator stroke was also measured and recorded using a computer data acquisition system.

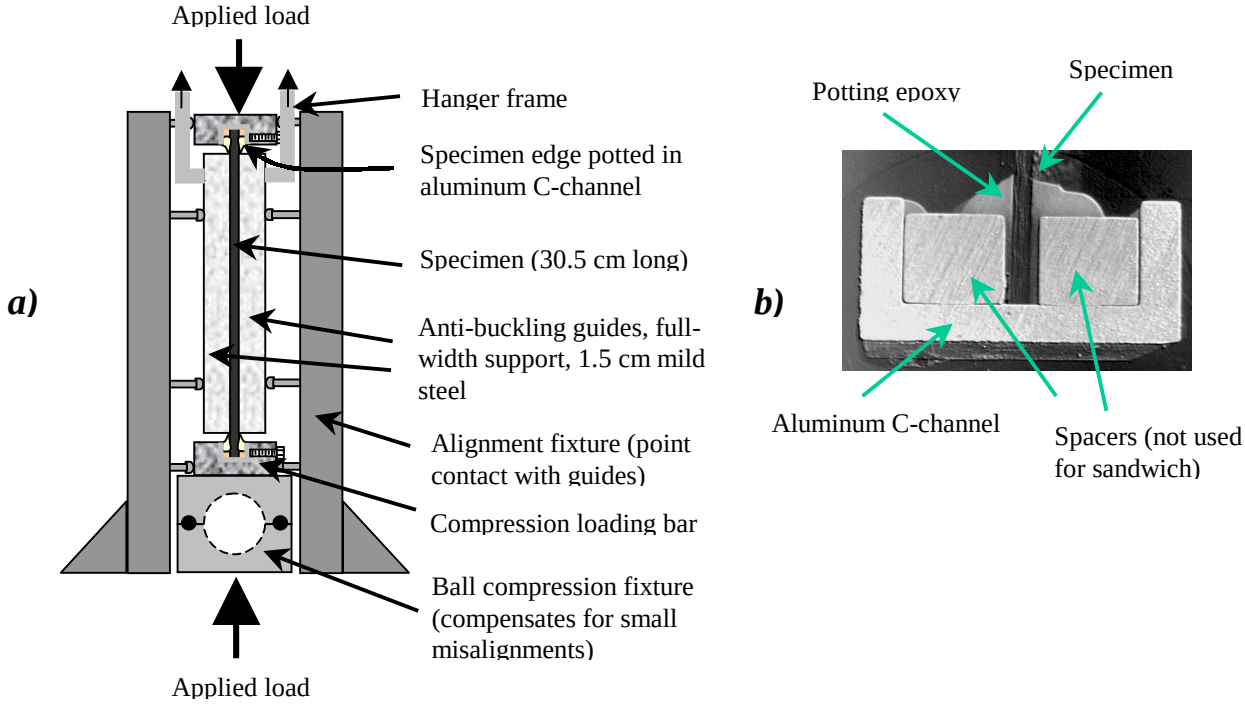

Fig. 2 : Post-fire compression testing; a) Schematic of test fixture, b) Photo of end of specimen potted in aluminum c-channel.

EXPERIMENTAL RESULTS

Between four and six (depending on the amount of available material), 30.5 cm x 30.5 cm (12 in. x 12 in.) specimens were fabricated for each of the composite designs using an autoclave and supplier-recommended cure cycles. Following processing, all specimens were trimmed to size and shape using a diamond saw and inspected using ultrasonic c-scan. Unresolved voiding issues revealed during these inspections resulted in deferral of fabrication and testing of phenolic specimens (designs 3, 4 and 7) due to the potential impacts on specimen residual strength measurements. For each of the successfully-fabricated designs, half of all specimens were subjected to both fire testing and residual strength testing with the remainder used as controls to establish undamaged specimen strength.

Fire Test Results

A series of photos showing the progression of a typical fire test is provided in Fig. 3. As illustrated in this figure, front-face ignition occurred quite early in the test (i.e. before 1 minute) in each case. All specimens, including those with Nextel fire barriers, exhibited extensive front-face damage including delamination of several plies and complete absence of resin in the area directly impacted by the flame. In all cases the damage zone extended across the width of the test frame opening and included all areas above the flame impact point (see Fig. 3c). The size of the damaged area on the back side of the panels varied from almost zero for the sandwich panels (designs 8 and 9) to areas similar in size to that of the front-face for some thin-skin panels. Despite this extensive damage, however, backside plies remained intact at the end of the test in all cases and *all tested specimens* met the basic fire containment criteria outlined in AC 20-135 including no flame penetration, no backside ignition, and no

generation of excessive smoke. Indeed, although warpage of the fire test frame was observed, no flame appeared on the backside of the frame in any case, due to the seal provided by the intumescent material.

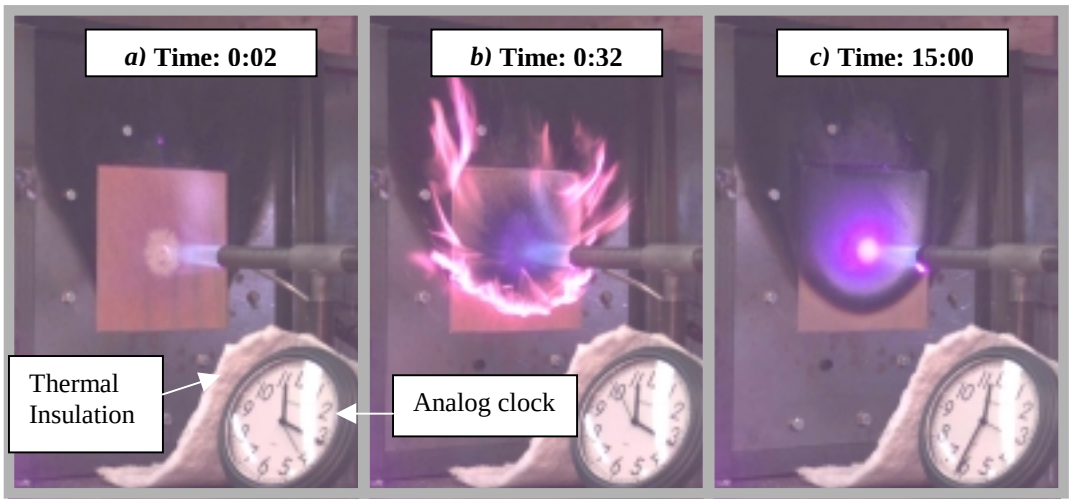

Fig. 3 : Photos illustrating a 'typical' fire test, a) test start, b) front face ignition, c) test completion (panel passes burn-through test).

A quantitative comparison of the relative fire resistance of each of the specimen design types can be made by examining the backside temperatures measured during test. A typical plot for a thin-skin panel is shown in Fig. 4. As shown in this figure, in the early part of the test temperatures rose smoothly and rapidly until the specimen began to delaminate due to resin loss and differential thermal strains in successive plies. These delaminations, which invariably formed early in the test (i.e. before 5 minutes), increased specimen effective thermal resistance and resulted in a reduction in the rate of temperature increase. By about five minutes into the test, temperatures began to stabilize, after which time only very small, gradual increases were observed. Similar trends were observed for all specimen designs, including sandwich panels and absolute maximum backside temperatures were found to be very consistent for all specimens of a given type. In no case for any specimen did backside temperatures exceed 300 ^{o}C, representing a reduction of about 800 ^{o}C versus front-face temperatures.

In general sandwich panels exhibited lower backside temperatures than thin-skin panels; a not altogether unexpected result given their greater thickness. However, an interesting exception to this rule was provided by the glass/polyimide panels (type 2) which consistently showed the lowest back-side temperatures of any specimen type. This was attributed to a very large delamination bubble that appeared on the front face of these specimens during test. Another interesting observation was made by comparing maximum backside temperatures in tests of panel types 5 and 6, which differed only by the substitution of a single carbon fabric ply in panel type 5 with a ply of Nextel in panel type 6. This comparison showed that the Nextel fire barrier material does indeed provide a measure of additional thermal protection, reducing maximum backside temperature in this case by about 70 ^{o}C.

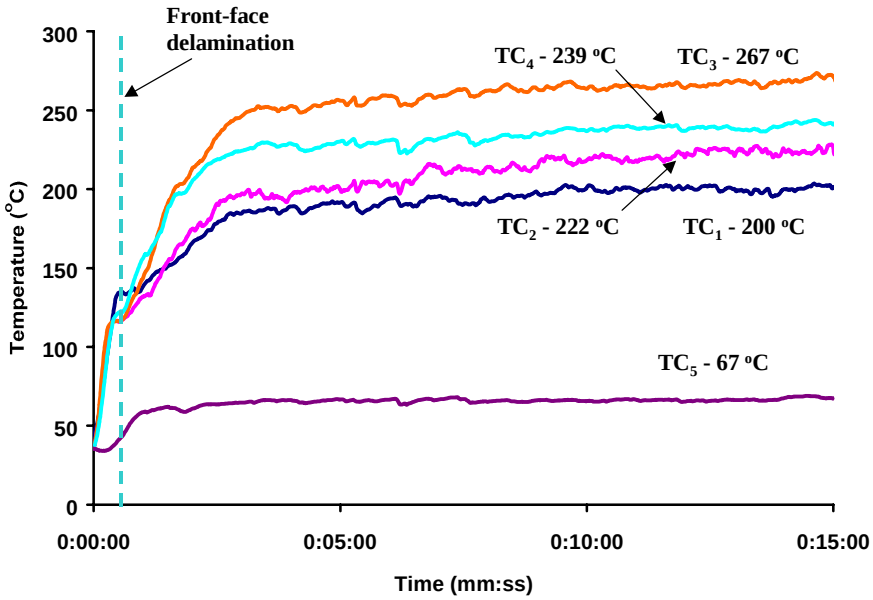

Fig. 4 : a) Backside temperatures during a typical fire test.

Residual Strength Test Results

Following fire testing, specimens were cleaned and their ends were trimmed with a diamond saw to compensate for any test-induced warpage. The top and bottom edges (relative to the fire test) were then potted in aluminum C-channels using a purpose-designed potting fixture. Specimens were then mounted in the compression fixture illustrated in Fig. 2 and loaded to failure.

Fig. 5a shows a typical load-displacement plot for a fire-damaged panel. In general, very consistent failure loads were observed for all panels of a given type (including both damaged and control). Other than deviations caused by damage growth, the load-displacement behaviour of the specimen in Fig. 5a can be seen to be quite linear up to failure, indicating that bending of this thin panel was successfully suppressed. This was true for the majority of both damaged and control specimens, although some bending was apparent for the very stiff thin-skinned carbon fibre / BMI panels (types 5 and 6).

Failure modes were also quite consistent for all specimens of a given type. As illustrated in Fig. 5b, a typical failure mode for fire-damaged panels consisted of micro-bucking failure in one of the undamaged edge regions, followed (apparently) by propagation through the damaged area to the opposite side where global (Euler) buckling failure occurred in the opposite edge region. Undamaged (control) specimens failed by microbuckling across their entire widths, indicating the successful suppression of Euler buckling by the test fixturing. However, while failure of damaged panels generally occurred within the fire-damage zone, failure of controls were observed in most cases quite near the loaded ends. This indicates that load introduction may have been somewhat imperfect.

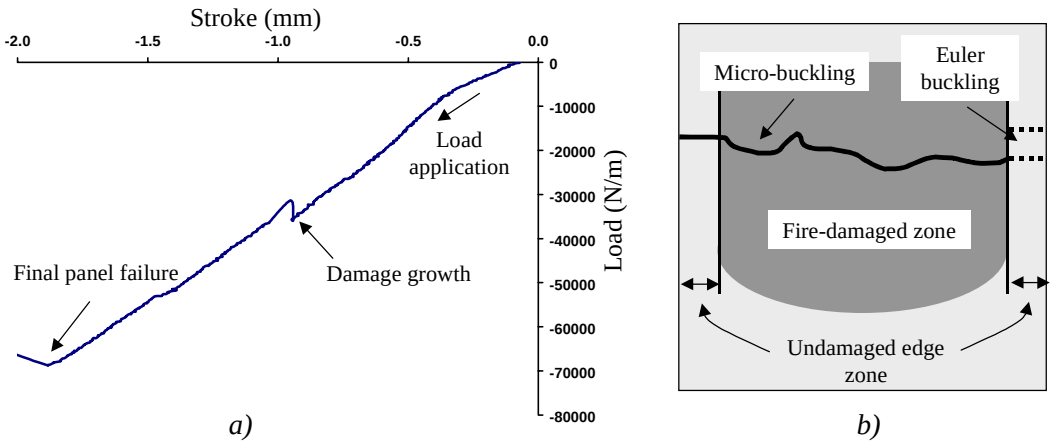

Fig. 5: a) Typical load-displacement plot for fire-damaged specimen, b) Schematic of fire-damaged specimen after compression testing, showing typical failure mode.

Failure for the damaged specimen in Fig. 5a occurred at a load of about 68.8 kN/m, as compared to a measured average value of 364 kN/m for the controls. Accounting for the protected 2.5 cm strips on either edge of the panel, this indicates a residual strength in the unprotected area of about 2% of the undamaged strength. Although this was the lowest value for any tested panel type, residual strength in the fire-damaged zone was very low in all cases.

Even with the relatively low data scatter observed, few definitive conclusions can be drawn regarding the relative residual strength performance of various panel types, other than that the glass/polyimide panels (type 2) performed the best of all thin-skin panels. It is also interesting to note that despite the very good integrity of their back-side skins, the sandwich panels performed little better than the thin-skin panels in this test configuration. This was largely due to the fact that failure of the fire-side sandwich facesheet was quickly followed by buckling of the back-side facesheet due to asymmetric loading. It is anticipated that these panels would perform much better in other loading cases.

DISCUSSION AND CONCLUSIONS

Based on the results obtained from the outlined tests, it was concluded that the developed approach was a useful and appropriate method for evaluating the fire performance of aircraft composite structure design options. The fire test methodology proved useful for rapidly evaluating flame-penetration resistance and thermal protection. The developed compression test also provided valuable data on the residual compressive strength of design options following a fire event.

While the developed test methodology proved useful for screening purposes, further investigations are planned, both to permit more direct use of obtained data (such as residual strength) for design purposes, and to permit testing of actual aircraft structural elements, rather than simplified test panels. Some required modifications would include reduction of the ratio of the area of the flame impingement zone to that of the panel. This would provide better data on the relative damage extent for different types of designs and consequently the effect of fire damage on overall structure performance. Techniques for improved suppression of bending in stiff undamaged thin-skin panels and more smooth introduction of compressive loads will also be investigated.

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