STRUCTURAL INTEGRITY IN FIRE: AN INTERMEDIATE-SCALE APPROACH

A. Hörold, B. Schartel*, V. Trappe, M. Korzen, M. Naumann

BAM Federal Institute for Materials Research and Testing, Unter den Eichen 87, 12205 Berlin, Germany
**bernhard.schartel@bam.de*

Keywords: intermediate-scale test method, structural integrity investigation, fully developed fire, carbon fibre reinforced plastics CFRP.

Abstract

A test method in the intermediate-scale was developed to investigate the structural integrity under fully developed fire. Carbon-FRP sandwich specimens (500 x 500 x 20 mm) were used to examine critical failure loads under compression, structural failure and times to failure. Obtained results were compared to a study in the bench-scale using identical material (150 x 150 x 20 mm). With this study it is demonstrated that the specimen size influences the time to failure and the load bearing capacity dramatically. Thus, larger scale tests of composites are needed to perform more realistic investigations.

1 Introduction

Fibre reinforced plastics or polymers (FRP) captured a brought spectrum of application (aviation, naval, construction etc.) as material of choice. However, fire behaviour is believed to be the single most important factor limiting the wider use of composites in particular as elements for structural application, [1]. Since fuselage for passenger aircrafts like Boeings 787 are designed and built of carbon-FRP they have to meet burn-through resistance for thermal/acoustic insulation materials as well as conventional structures, [2]. The burn-through time represents a critical value enabling people a safe escape after surviving an aircraft accident accompanied by fire, since interior ignition is caused by external jet fuel fire, [3]. Composite structures promote burning by themselves during fire with a burn out of the polymeric matrix. Persisting fire the non-combustible fibres (glass, carbon) function as a protection layer to attain a strongly decreased burn-through hazard, [4]. Conversely the matrix affected by the enhanced temperatures obtains a dramatic loss in mechanical properties before being burnt out. Missing of the fibre supporting matrix immediately diminishes the stability of the composite dramatically.

With respect to lightweight structures the areas under compressive loading are more critical to failure than the areas under tensile loading. The additional fire load leads to a increased hazard of structural failure in the areas under compressive loading with regard to the integrity of the whole component. As a result investigating the structural integrity under fire is becoming the main purpose for wider use of FRP in all fields of application.

Experimental approaches in the small-scale have been proposed to investigate the structural integrity of FRP under fire in the past [4-6].Whereas exposure to fire is typically simulated by a burner or a radiant heater, mechanical load in terms of tensile, bending and compression is applied by a testing machine. Either post-fire testing, taking into account better mechanical properties after cooling down and simultaneous testing under mechanical and fire load have been examined. Heat fluxes between 10 and 280 kW/m² have been applied onto one side of the specimen representing fire scenarios from small trash can fires to fully developed gas-jet fires, [7, 1]. Investigating times to failure, temperature distributions inside FRPs and critical failure loads are from major interest. Especially times to failure are strongly affected by the type of load applied to the structure. Whereas tensile loading is less critical due to the load-bearing capacities of the neat fibres compressive loads tend to a much faster collapse. However, small-scale investigations may neither represent satisfactorily the mechanical properties of real components nor fully developed fires.

The aim of this study is to introduce a test setup in the intermediate-scale which gives us the opportunity to perform more realistic investigations. Tests were conducted in compression due to more critical material response using a furnace compression testing machine. Simultaneously a fully developed fire is directly applied onto one side of the specimen by the same oil burner used to determine the burn-through resistance. The main part of the test setup is the compression device constructed to apply load from the furnace compression testing machine onto the specimen. With its 3.6 m height the device has a weight of 2 tons to resist up to the maximum failure load calculated at 1 MN, figure 1. Specimens can either have the sizes 500 x 500 mm or 500 x 1000 mm with a maximum thickness of 50 mm. In the first test series carbon-FRP sandwich panels (500 x 500 x 20 mm) were investigated with varying compression load. Fire load remained unchanged regarding times to failure, structural failure and critical failure loads. Results were compared to analog investigations in a bench-scale test setup (specimen size 150 x 150 x 20 mm) using identical carbon-FRP sandwich panels.

Figure 1: Test setup (compression device and furnace compression testing machine) with a carbon-FRP sandwich panel (500 x 500 x 20 mm)

2 Materials and testing methods

2.1 Sandwich composites

Structural integrity investigations in the bench- and intermediate-scale were performed using specimens cut from 1100 x 700 x 20 mm sandwich panels (Carbon-Werke Weißgerber GmbH

& Co. KG). The symmetrical sandwich composite consisted of carbon-fibre epoxy laminate skins and a core of poly(methacrylimide)-based (PMI) foam (Rohacell® 71 IG, Gaugler & Lutz OHG). The foam had a thickness of 17 mm and a closed cell structure with a density of 75 kg/m³. The skins with a thickness of 1.35 mm were fabricated using two different prepregs. Starting from the surface the sandwich consisted of a woven fabric (0°/90°) with a fibre areal weight of 0.245 kg/m² (Sigratex Prepreg CE 8201-245-45S, SGL Group) and two layers of an unidirectional prepreg (Sigratex Prepreg CE 1754-600-35, SGL Group) with a fibre areal weight of 0.6 kg/m² in 90° and 0° direction. Epoxy resin (E 201) was used in both types of prepreg. Specimens either 500 x 500 x 20 mm or 150 x 150 x 20 mm were cut with a large-scale cut-off saw (Diadisc 5200, Mutronic GmbH & Co. KG) equipped with a diamond cutting disc. The used foam is classified as “normal flammable” according to the B2 test of DIN 4102. Typically for these sandwich panels is their application as structural component in aviation, aerospace, naval and transportation, although they are not equipped with appropriate flame retardancy.

2.2 Bench-scale compression test under fire and failure load

Schartel et al. conducted investigations in the bench-scale at the University of Newcastle upon Tyne using carbon-FRP specimens (150 x 150 x 20 mm) described previously, [8]. Results were used for comparison in this study. A small compression test rig was used to perform structural investigations under fire using a 295 kN hydraulic machine, [5]. The specimens were simply supported in force direction, whereas the sides remained unsupported. Low cost propane burner equipment was used to provide a heat flux of 200 kW/m² to the front side of the specimen. Direct flame was set according to the heat flux measurement of Browne, [9]. Furthermore, the sides of the specimens were insulated by kaowool to hinder direct contact between flame and foam.

Failure loads were determined with an Avery Denison machine and an Instron machine using strain gages on both sides of the specimen with a crosshead speed of 0.5 mm/min.

2.3 Intermediate-scale compression test under fire and failure load

Our approach enables structural investigations under fire with specimens either 500 x 500 mm or 1000 x 500 mm and a total thickness up to 50 mm. Test were conducted in a furnace compression testing machine (Schenck POZ 913) at BAM. Thus, this machine is equipped with waste gas extraction system. A special constructed compression device with 2 tons weight was built to apply adequate loads up to 1 MN from the furnace compression testing machine onto the specimens (Figure 1). The attachment and vertical alignment of the specimens is also realized by the 3.6 m high compression device. The specimens were clamped in force direction (top and bottom) whereas they are simply supported at the sides. During the experiments the compression device is isolated. Additionally it is temperature monitored and can be water-cooled in the vicinity of direct fire exposure. A fully developed fire is directly applied onto one side of the specimen by an oil burner. Developed to achieve a good reproducible and homogeneous heat flux of 182 kW/m², this NexGen burner is used to determine the burn through resistance of thermal/acoustic insulation materials in aviation (Federal Aviation Regulations 25.856 (b)). Our burner is operated with similar parameters due to a different test setup to the FAA. Fire tests were conducted in force control with previous described carbon-FRP specimens (500 x 500 x 20 mm) regarding times to failure. After defined loads were applied, the burner was allowed to heat up for two minutes and swivelled onto the specimen afterwards. Temperatures were measured inside the foam and on the back side of the specimen.

Failure loads were determined with the 25 MN Large-scale testing machine at BAM and the furnace compression testing machine with a crosshead speed of 0.5 mm/min. Displacement was measured with cable actuated linear position sensors (ASM WS10SG-250-10V-L10). Additionally strain gages (HBM 6/120LY43-2-0.5M) were applied on both sides of the specimen.

3 Results and Discussion

3.1. Compression tests under fire in different scales

The failure loads of carbon-FRP sandwich specimens have been determined in the intermediate-scale (500 x 500 mm) and compared to a study in the bench-scale (150 x 150 mm) [8]. Whereas failure for small specimens occurs at 117 kN, specimens with the size 500 x 500 x 20 mm attain a failure load of 394 kN. Carbon-FRP specimens fail in both test setups due to reaching the compression strength of the sandwich structure at 63 % of the calculated value. Global buckling or core shear failure was not observed. Thus, the failure mechanisms without fire load are identical for the specimens utilized in the bench- and intermediate-scale.

The structural integrity investigations under fire were carried out in both studies using a burner to simulate a fully developed fire. High heat fluxes were applied to specimens in the perpendicular position. For the experimental setup in the intermediate-scale time to failure was recorded and defined as the time needed for both faces to fail. Results were compared to the study in the bench-scale. The load bearing capacity of specimens in the intermediate-scale is three times as high as for specimens in the bench-scale. This is changed dramatically when fire load is applied to the specimens. After only 6 seconds the load bearing capacity of the specimens is identical, shown in figure 2. Longer periods of flame exposure show a clear advantage for the small specimens, although applied stresses are in the range of 60 % to 80 % of the failure load. Whereas specimens in the intermediate-scale attain failure times of 98 s carrying only 40 kN (10 % of their failure load), specimens in the bench-scale are nearly able to sustain twice the load (68 % of the failure load).

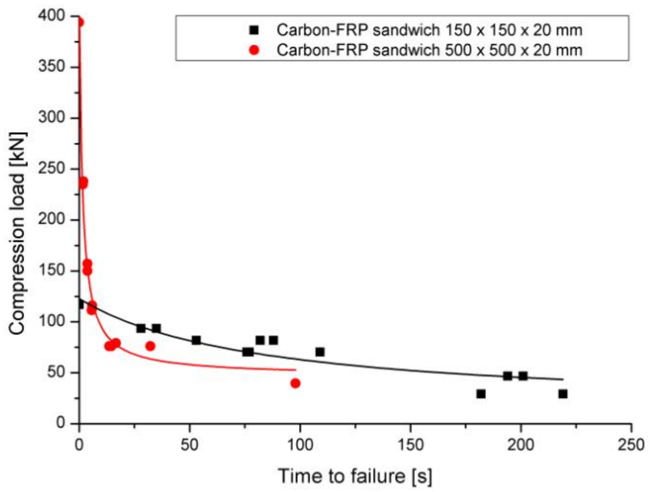

Figure 2: Comparison of structural integrity tests under fire for both specimen sizes regarding time to failure

The better performance of smaller specimens can be explained with respect to the buckling behavior. Specimens in the bench-scale have a higher buckling load normalized to the failure load. Figure 3 shows how this factor is influenced by the depth of damage. Since the sandwich structure is identical for both test setups, only the specimen attachment and the width of the specimen are influencing the buckling load. For simulation both specimens were fixed in force direction and simply supported at the sides. Depth of damage is simply considered by reducing the whole face exposed to fire.

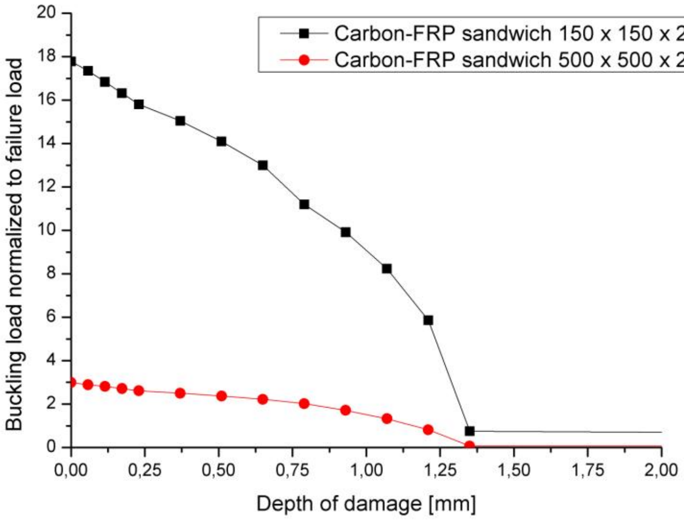

Figure 3: Comparison of buckling load normalized to the failure load for both specimen sizes regarding damage to fire

A depth of damage of 1.35 mm represents a total loss of the load bearing capacity of the face expose to fire. At this time load is only carried by the unexposed face stabilized by the foam. Under these circumstances specimens in the small-scale are still able to carry 45 % of the theoretical failure load, whereas specimens in the intermediate-scale are only able to sustain 4.3 % of their theoretical failure load. This represents that specimens in the intermediate-scale are much more sensitive to compressive loads especially accompanied by fire. Thus, the size of the specimen influences times to failure and failure modes. For this reason the test setup with component-like dimensions was built up to allow realistic investigations up to structural failure in absence of fire and structural investigation in presence of fire load. Also Delfa et al. have announced that it is evident that larger scale test of composites are needed, [5].

3.2. Structural failure and burning behavior of experiments in the intermediate-scale

Experiments in the intermediate-scale were conducted with the NexGen burner. After warm-up the burner was swiveled to the centre of the loaded specimen. The spacing between burner and cone was 100 mm. The duration of the tests was shorter as expected from previous experiments in the bench-scale. Failure occurred with a rapid loss of the load bearing capacity accompanied with an acoustic event. Instantaneously the burner was turned off. After a short time specimens were self-extinguishing. Experiments were conducted with preset compressive loads between 10 % and 60 % of the failure load showing different failure mechanisms.

Specimens with preset loads of 235 kN (60 % of the failure load) failed after only 1.7 s. Although flame was touching the specimen very short the resin was ignited and the woven fabric delaminated at the centre of the specimen. Generated by fire the local defect induced global buckling with a brittle fracture of both faces at the same time. Further delaminations were observed between the foam and the faces. A simply supported specimen attachment should be considered for additional interpretation concerning tests with high loading levels, because the specimen has moved in the attachment. Figure 4 (1c) shows that the clamped parts of the sandwich are displaced against each other. The unexposed face as well as the foam are intact except in the vicinity of the rupture.

Specimens with preset compressive loads of 250 kN (40 % of the failure load) demonstrate a failure mechanism with 2 steps. After ignition of the first layer the woven fabric delaminates. Two seconds after the start of test the fire exposed face fails accompanied with an acoustic event. Due to the elevated temperatures of the resin the front face softens. Furthermore the front face delaminates from the foam which decreases the stability of the sandwich. The buckling load of the remaining sandwich reaches the applied load after 3.7 s. Then the load bearing back face attains brittle failure whereas the front face is plastically deformed, figure 4 (2b, 2c).

Specimens with preset compressive loads of 40 kN (10 % of the failure load) show failure of the first face between 5 s and 24 s with several slight acoustic events. In comparison to the experiments with 60 % and 40 % of the failure load applied, the fire exposed face of this specimen was burnt out, figure 4 (3a). Furthermore, the foam was pyrolysed and burnt out except in the region of the specimen attachment, figure 4 (3c). Due to elevated temperatures provided by the burning foam and the continuous reduction of the support effect of the foam the back face softened and wrinkling occurred after 98 s.

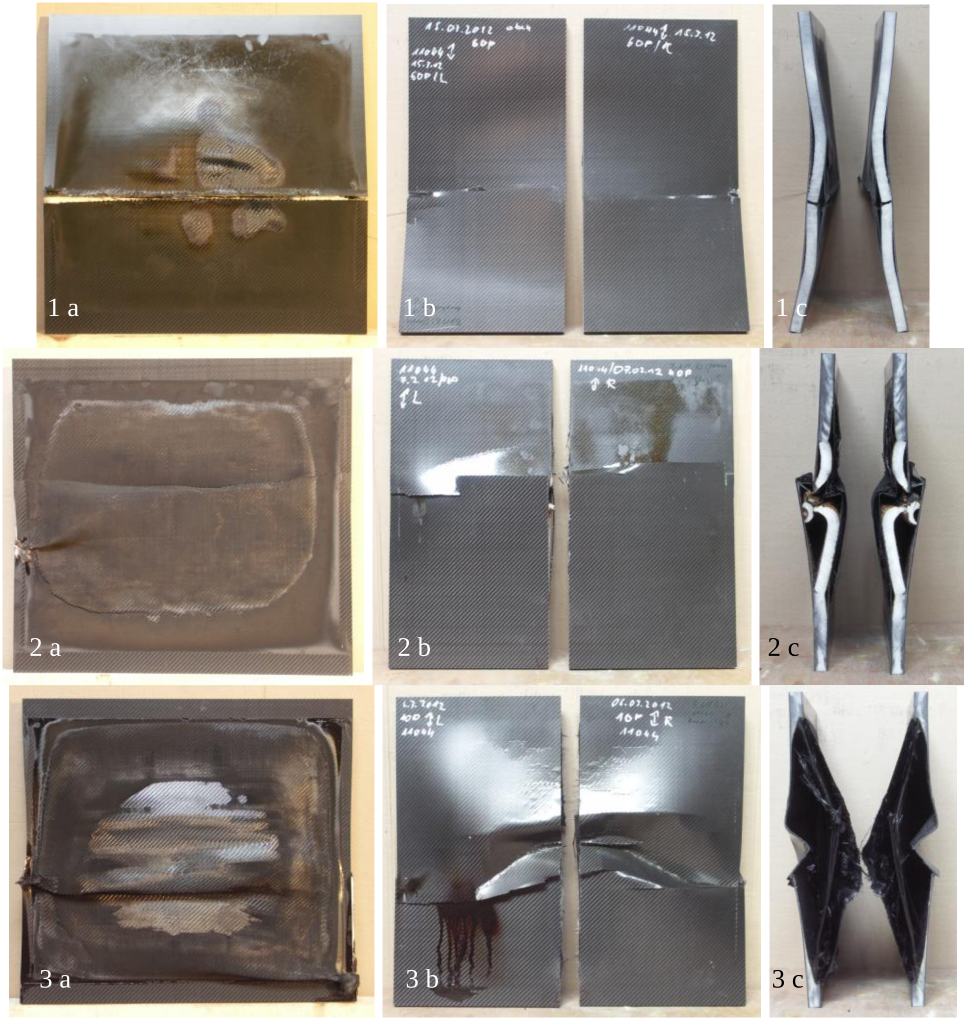

Figure 4: Carbon-FRP Specimens after compression tests under fire: 1) 60 % of the failure load, 2) 40 % of the failure load, 3) 10 % of the failure load. The pictures show a) face exposed to fire, b) unexposed face cut in 2 pieces, c) cross section view, faces exposed to fire stand towards each other.

The specimen attachment functions as described in paragraph materials and testing method applying 40 % of the failure load or less onto the specimen. The fixed attachment at the top and bottom has a positive effect on the buckling behavior leading to a higher buckling load and thus to longer times to failure.

However, promising results were obtained with the component-like test setup. More realistic investigations were conducted on specimens closer to real components indicating a large influence of the applied compressive load on the time to failure.

Conclusion

In this study a new developed test method in the intermediate-scale was introduced to investigate the structural integrity of carbon-FRP sandwich specimens under fully developed fire. Failure loads and times to failure were determined under compression and compared to a study in the bench-scale using identical material [8]. Investigations showed that buckling loads normalized to the size of the specimen are much higher for specimens in the bench-scale. The additional fire induced local damage results in strongly reduced times to failure for specimens in the intermediate-scale. These specimens are able to maintain moderate applied loads for only some seconds, whereas specimens in the bench-scale resist the same level of loading for a few minutes.

Structural failure was examined in the new test setup with varying compressive loads and a constant heat flux. Different failure mechanisms were observed. Global buckling occurred for high compressive loads after a very short time. Both faces failed simultaneously as a result of the fire induced local damage. Reduced compressive loads lead to longer times to failure and to a two-step failure mechanism. Failure of the fire exposed face occurs shortly after the start of test due to delamination and local damage. The load bearing face unexposed to fire fails when the buckling load of the remaining specimen is reduced to the applied load by delamination, softening and burn out of the fire unexposed face and the foam.

The developed test setup is highlighted as a unique instrument to investigate the structural integrity of component-like specimens under fire. It presents the possibility to examine structural failure in absence of fire and structural investigations in presence of fire load. Investigations lead to a deeper understanding of the failure mechanisms of FRP specimens under compressive load accompanied by fully developed fires. Thus, a tool to carry out more realistic experiments in the intermediate-scale with complex structures is introduced successfully.

Acknowledgements

The authors are thankful to the colleagues at BAM especially Sven Riemer, Kai-Uwe Ziener, Stefan Hickmann, Ingo Feick and Patrick Klack for their support. We further thank Arthur Geoff Gibson for the help to get in the topic. With respect to bench-scale used for comparison we thank James K. Humphrey, Richard Warhurst, Wiliam Cragie and Arthur Geoff Gibson at Newcastle University.

References

[1] Mouritz, A.P. *Fibre Properties of Polymer Composite Materials.* Springer, Dordrecht (2006).

[2] FAA FARS 14 CFR Part 25 Appendix F7. *Test method to determine the burnthrough resistance of thermal/acoustic insulation materials* (2007).

[3] Marker T.R. Sarkos C.P., Hill R.G. *Full-scale test evaluation of aircraft fuel fire burnthrough resistance improvement* in “Book of Abstracts of *Annual Conference on Fire Research*”, Gaithersburg, USA, (1996).

[4] Mouritz A.P., Mathys Z., Gibson A.G. Heat release of polymer composites in fire. *Composites Part A-Applied Science and Manufacturing*, **37** pp. 1040-1054 (2006).

[5] La Delfa G., Luinge J.W., Gibson A.G. Integrity of composite aircraft fuselage materials under crash fire conditions. *Plastics Rubber and Composites,* **38**, pp. 111-117 (2009).

[6] Mouritz A.P., Feih S., Mathys Z., Gibson A.G. Mechanical Property Degradation of Naval Composite Materials. *Fire Technology*, **47** pp. 913-939 (2011).

[7] Seggewiß P. Experimentelle und numerische Untersuchung des Verhaltens kohlenstoffverstärkter Epoxidmatrix-Systeme unter einseitiger thermischer und gleichzeitiger mechanischer Belastung. Verlag Dr. Hut, München (2011).

[8] Schartel B., Humphrey J.K., Gibson A.G., Hörold A., Trappe V., Osterod F., Gettwert V. Mechanical failure of carbon fibre sandwich panels under fire: bench scale approach. In preparation.

[9] Browne T.N.A. A Model for the structural integrity of composite laminates in fire. Dissertation, Newcastle University upon Tyne (2006).