STRUCTURAL INTEGRITY IN FIRE: AN INTERMEDIATE-SCALE APPROACH ON PLAIN AND SHELL-STRUCTURED COMPOSITES

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Abstract

The intermediate-scale test setup is successfully operating to investigate the fire stability of composite materials. To obtain realistic failure behavior the test specimen´s size is in the intermediate-scale (500 mm x 500 mm or 500 mm x 1000 mm). During fire test, the specimen is compressed and exposed to a fully developed fire at the same time. The vertically displacement and the surface temperatures on the back side of the specimen are measured. Investigations on carbon fiber reinforced epoxy resins show a dramatic loss in structural stability after a short period of time exposed to fire.

1. Introduction

Fiber reinforced polymers (FRP) are increasingly applied as material of choice for structural applications in construction and transportation. Especially in aviation carbon fiber reinforced polymers (CFRP) have nowadays a very large field of application. The latest aircraft technology is represented by the Airbus A350 which is built up to over 50 % with CFRPs. The fire behavior of these materials is an important issue restricting their usage for structural applications in transportation and construction [1]. Due to their high carbon or glass fiber content, composites represent efficient barriers against burn-through phenomena. Nevertheless, at between 300 °C and 400 °C the matrix starts to decompose. At temperatures of 100-200 °C the glass transition temperature of the polymer matrix is reached and the result is a dramatic loss in the mechanical properties [1, 3]. The application of fire and mechanical loads at the same time induces a characteristic failure of components made from composites. Under fire the structural integrity is highlighted as target for the enhanced use of composites as structural elements in many fields of application.

The intermediate-scale test bench developed at the BAM proofed its functionality and performance in fire load tests with several carbon composites [2]. The approach of this study is to investigate the fire stability and fire resistance of CFRP airframe structures with boundary conditions of an aeronautical post-crash fire. Therefore fire tests with shell-structured CFRPs will be performed which have a curvature comparable to the fuselage of a modern commercial aircraft.

2. Carbon fiber reinforced polymer (CFRP)

2.1 CFRP plate failure load

Within the meaning of a preliminary investigation of CFRP airframe structures and a calibration of the intermediate-scale test bench, four CFRP plates (CP) were tested at the BAM. These specimens are built up each with 32 preimpregnated carbon layers (prepreg) in directions of 0°, 45°, 90° and 135° and result in a thickness of 4 mm. This composition is comparable to CFRP airframe structures applied in modern composite aircrafts and is assumed as quasi-isotropic. The specimens were precisely tailored to an intermediate scale of 500 mm x 500 mm to ensure a homogeneous transfer of the compressive force while tests are performed.

The failure load of the CFRP plate was determined at room temperature integrated into the intermediate-scale test bench. The horizontal edges of the specimen are fixed with two 10mm thick metal sheets from the front and back side to prevent that the specimen slips out of plane. The vertical edges of the specimen are simply supported by four metal sheets with very sharp tips to ensure hinged mounting of the specimen. For the detection of the stability failure load, two strain gauges were fixed in the geometrical center of the specimen on the front and back side to measure the mechanical strain. The failure load detection was performed with two out of four available specimens. Additional a displacement sensor was attached at the intermediate-scale test bench to measure the vertically displacement between the two slidable compression parts of the test bench. The specimen CP1 failed at a compressive load of 323 kN and the second specimen CP2 failed at 300 kN (Figure 1). The inspection of the tested specimens reveals that the specimens failed due to a global stability failure. The cracks are mainly located close to the area where the lateral support of the specimen has a gap which is indispensable due to constructive considerations.

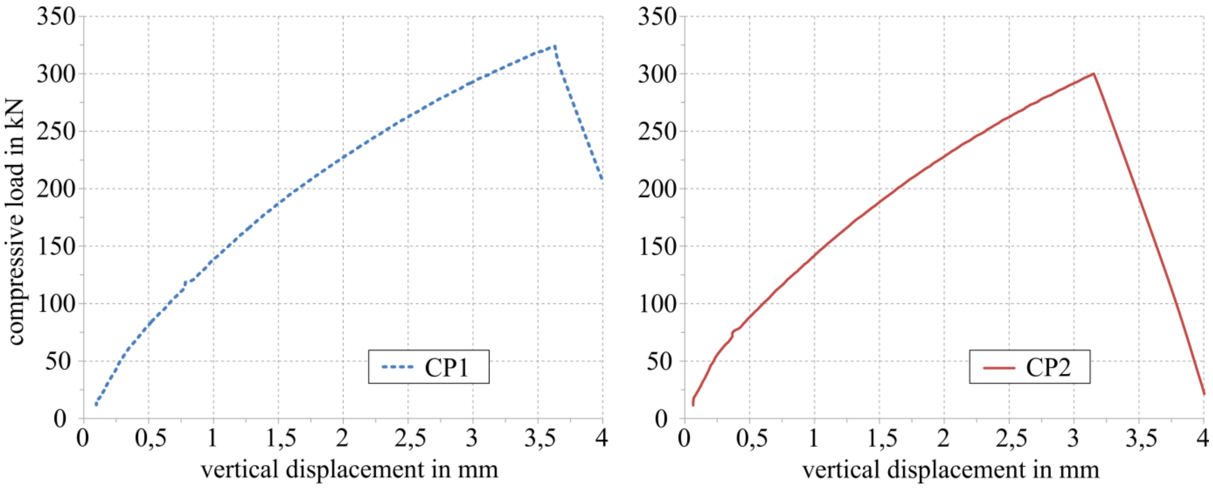

Figure 1. Compressive load plotted against the vertically displacement of the specimens CP1 (left) and CP2 (right)

The calculated buckling load of approximately 40 kN is verified by interpreting the strain measurement on the front and back side of the CFRP plate specimen (Figure 2). At a compressive load of approximately 45 kN the stability failure load is reached and the specimen starts a global buckling which is indicated through a negative strain at the back side and a positive strain at the front side of the specimen CP1. Until a compressive load of 45 kN the two curves behave nearly parallel which indicates that the specimen is compressed linear.

Above this stability failure load the curves separate from each other. At the front side a positive strain is measured which means the outer layer of the specimen senses a tensile force. The negative strain at the back side means that the outer layer gets compressed. The gradients of the curves are not equal because with an increasing total compressive load the specimen senses a global negative strain. That explains the increase of negative strain at the back side and the decrease of the positive strain gradient at the front side with higher compressive loads. The stability failure load of CP2 was detected at a compressive load of 43 kN.

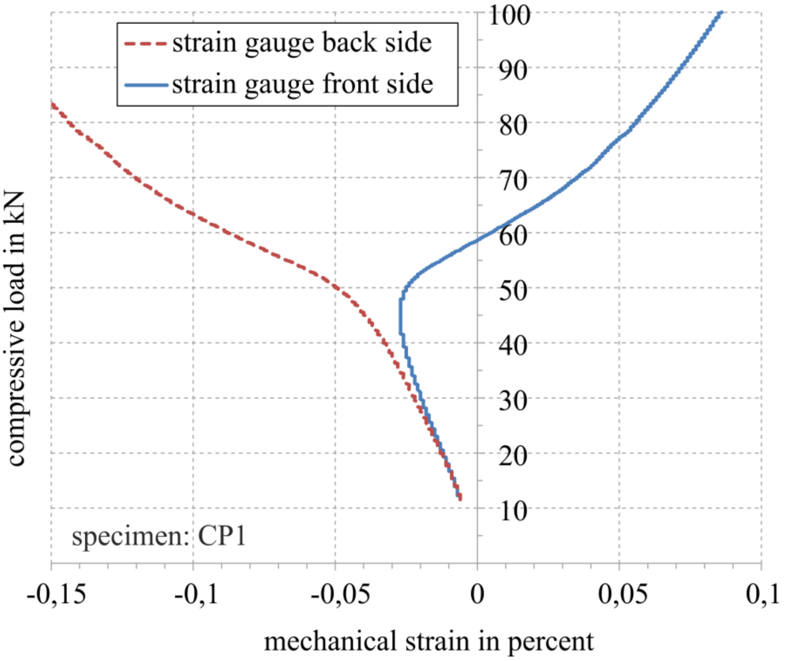

Figure 2. Compressive load plotted against mechanical strain at front and back side of specimen CP1

2.2 CFRP plate structural integrity investigation under fire load

The fire tests were performed with the intermediate-scale test bench with an adequate compressive load of 25 % of the stability failure load at room temperature. The fire testing procedure is heavily dependent on the adjustment and the handling of the Next Generation Burner. The Federal Aviation Administration (FAA) developed guidelines for the usage of the burner during fire tests to produce international comparable results. Before the flame of the Next Generation Burner is directed onto the specimen the burner has to warm up for 120 seconds in an upper position without influencing the specimen. After exposing the specimen to the fully developed fire of the burner, the time to failure was measured. The moment of failure was detected by measuring the displacement between the two slidable compression parts of the intermediate-scale test bench (Figure 3).

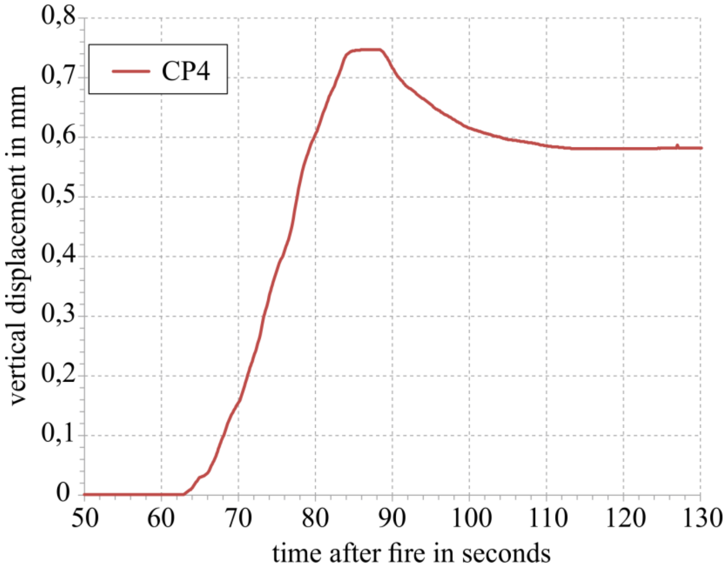

Figure 3. Vertical displacement plotted against the time after exposing the specimens to fully developed fire

An increasing vertically displacement of the slidable compression parts of the intermediate-scale test bench indicates a stability failure of the tested specimen. The tested specimen CP4 shows a stability failure after 65 seconds. The failure process takes approx. 20 seconds which is explained by the relatively low compression force and a high support of the specimen´s edges. With an increasing temperature of the specimen the resin weakens above its glass transition temperature of about 180 °C and the structural integrity starts to decrease because of the missing support of the resin.

On the back side of specimen CP4 the surface temperatures were measured with four thermocouples at certain positions (Figure 4.).

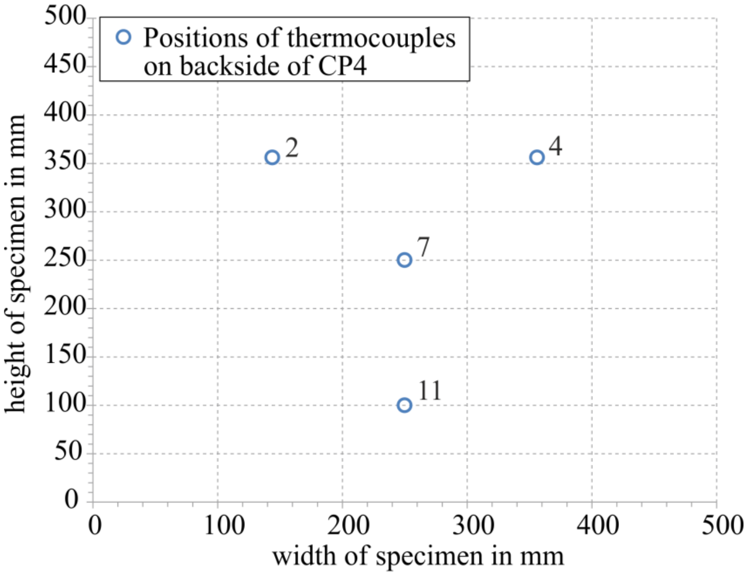

Figure 4. Positions of thermocouples on back side of specimen CP4

Figure 5. shows the behavior of the temperature on the back side of CP4 at different selected positions. After a slight increase of the temperature for the first 10 seconds, the gradient of the temperature at all positions increases rapidly and after 60 seconds the glass transition temperature of 180 °C is reached at all positions on the back side of the specimen. After 80 seconds the back side surface layer of specimen CP4 starts to delaminate and inclusions of air

form up. These inclusions of air are responsible for the nearly constant temperature behavior from 80 to 120 seconds. After 160 seconds the burner was turned off and the temperature decreases slowly.

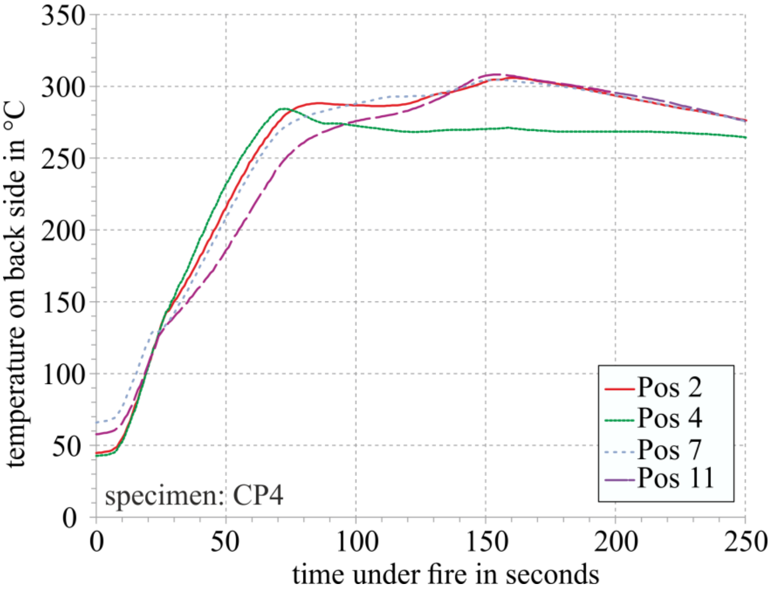

Figure 5. Temperature on back side of specimen CP4 at certain positions plotted against time under fire

3. Carbon fiber reinforced shell structured composite

Modern aircrafts are mainly built up with carbon composites to profit from the reduction in weight with a constant or even better mechanical strength. The aim of these investigations is to understand the failure mechanisms and the behavior of the structural integrity of carbon composites in fire comparable to an aeronautical post-crash scenario with an aircraft fuselage exposed to fully developed fire caused by leaking fuel.

Before fire tests will be performed with the intermediate-scale test bench, it is necessary to understand the stability behavior of shell structured composites to assume adequate boundary conditions for fire tests. Therefore it is fundamental to define the level of curvature of a shell structured composite, as presented by Timme et all [4], (Figure 6.)

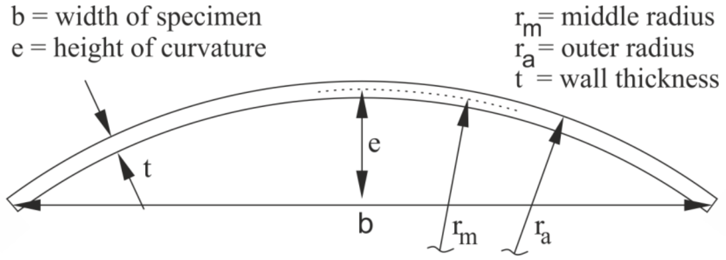

Figure 6. Definition of level of curvature for a shell structured composite

The level of curvature q is defined to (1):

$$q = \frac{e}{b} \cdot 100 \tag{1}$$

For q = 0 a plate is described and q = 50 represents the semicircle, the maximum level of curvature. Considering the level of curvature, an analytical buckling study for different wall thicknesses and material compositions is performed [4] to assume the required compression loads for fire tests. Using original shaped airframe shell structures of the latest commercial aircrafts in an intermediate scale of 500 mm x 500 mm, the level of curvature of the according specimen is calculated to q = 2.1. Figure 7. represents the result of the analytical buckling study [5] for a carbon fiber reinforced shell structure with a fiber volume fraction of 0.5 and an orientation of the carbon layers comparable to a fuselage carbon laminate.

By increasing the level of curvature the critical buckling load growths disproportionately. For a wall thickness of 4 mm the critical buckling load of a shell structured carbon composite with a level of curvature of q = 2 is as double as high compared to carbon plate composite.
For q = 10 the critical buckling load is 12 times higher than the one of a carbon plate composite. With this understanding, the modification of the intermediate scale test bench will be completed and fire tests on carbon shell structured composites will be performed.

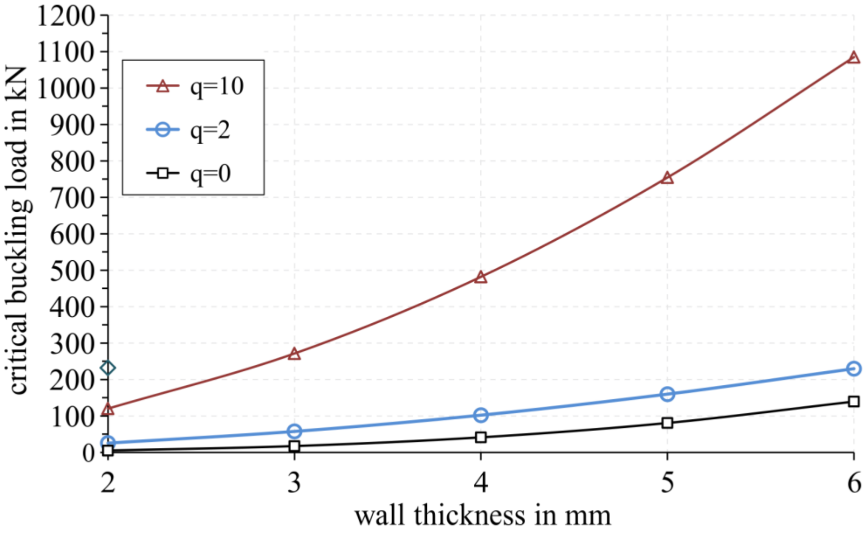

Figure 7. Critical buckling load. Carbon fiber reinforced shell structure with different level of curvature plotted against the wall thickness. Fiber volume fraction of 0.5 and fiber orientation: 45°/-45°/90°/0°/0°/90°/-45°/45°

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