DELAMINATION BEHAVIOR OF ASYMMETRIC SANDWICH SHELLS UNDER AXIAL COMPRESSIVE LOADING

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Abstract
This work covers the experimental and numerical analysis of asymmetric sandwich shells introduced as innovative fuselage structure for transport aircraft in the research program "Citizen-friendly Aircraft". The shells consist of a CFRP skin carrying the main loads, a rigid closed cell PMI foam core and a thin aluminum layer. The manufacturing process is illustrated and several test specimens are damaged by predefined delaminations in between the aluminum skin and the foam. It is shown that face sheet delaminations can significantly reduce the structures' load bearing capacities and propagate suddenly through the entire structure when reaching the critical load. Comparison with a FE simulation showed good morphological agreement, however, the prediction of failure loads and out-of-plane deformation of the buckling skin can be improved.

1. Introduction

The development of modern transport aircraft significantly aims at increasing their efficiency. Besides improving the aerodynamic and engine characteristics the reduction of mass is a major contributor for reaching this goal. Assuming adequate application carbon-fiber-reinforced plastics (CFRP) are able to further increase the load bearing capacities of aircraft structures while reducing the structural weight due to their high specific stiffness and strength [1]. However, they are quite sensitive to stability-driven problems because of the potential risk of interlaminar delaminations and therefore the number of stiffeners (e.g. stringers and frames in aircraft fuselages) cannot be reduced [2]. One possibility to improve this behavior is the use of sandwich constructions which consist of two thin but stiff skins and a relatively thick lightweight core in between them. Due to their high bending stiffness critical loads regarding stability will be raised and therefore stringer and frame pitches can be increased leading to potential mass reductions [3]. A current approach for the application of sandwich technology in aircraft fuselages is the use of an asymmetric sandwich shell for fuselage structures of transport aircraft, see figure 1. It is based on a concept of the German Aerospace Center (DLR) [4]. It consists of an inner CFRP skin, carrying the main loads, a PMI-foam core and a very thin outer aluminum skin. The separation of functions of the single sandwich components leads to further advantages. Core and aluminum serve as impact protection for the CFRP skin and as acoustic and thermal insulation. The aluminum acts as layer for failure detection, lightning protection and electromagnetic compatibility. Due to the multi-layer set-up damages within sandwich structures may be difficult to detect. Therefore and because of the general requirement of damage tolerant structures in aircraft design, comprehensive examinations regarding skin delamination are necessary. In the past, several papers discussed the behavior of symmetric delaminated sandwich structures, e.g. [6-11], by performing experiments and analytical and numerical calculations. In contrast, asymmetric sandwich structures have not been studied widely. This work analyzes the influence of face delaminations on the described asymmetric sandwich configuration. Several test specimens with predefined delaminations of the aluminum skin with diameters of 10 to 50 mm are manufactured and tested under axial compressive loads until failure of the entire structure. Furthermore, numerical analyses are performed in order to establish simulation models for future investigations.

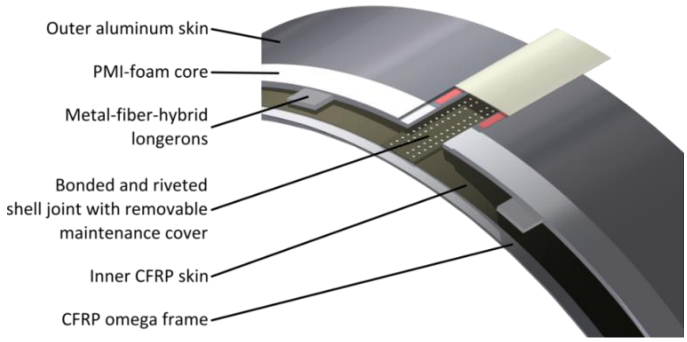


Figure 1. Approach for the use of asymmetric sandwich shells in primary fuselage structures [5].

2. Sandwich shells

The sandwich shells used for the experimental testing are manufactured in-house by processing its components and adhesively joining them to the final part. First, the CFRP-shells are fabricated by curing a prepreg system consisting of 15 layers of HexPly® 8552/IM7 with predominant ±45°-layers (thickness: 1.95 mm after curing). The foam core (ROHACELL® RIST 71) is thermoformed in a high temperature heating cycle by placing it on a curved aluminum mold and deforming it with a vacuum bag. The radius of the aluminum mold measures 1950 mm, leading to a fuselage outer radius of about 1980 mm which is typical for a standard single aisle aircraft. The aluminum layer consists of a 0.3 mm thin sheet of 2024-T3.

Figure 2. Asymmetric sandwich shell after manufacturing [2].

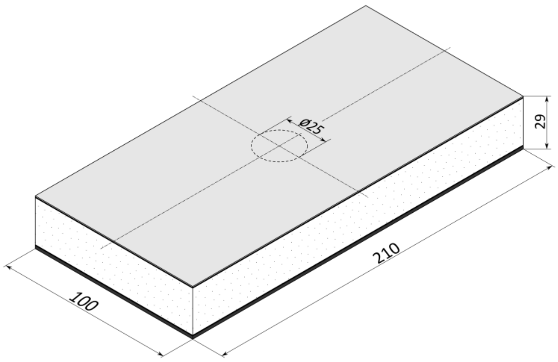


Figure 3. Sketch of a test specimen with a circular delamination (ø 25 mm) of the aluminum layer.

All layers are glued using the two component epoxy adhesive Scotch-Weld™ DP490 in a 2-hour-curing cycle at 65°C and vacuum condition, see figure 2 for a finished shell. To create the predefined delaminations of the aluminum skin two pieces of Teflon foil are placed concentrically within the glue layer in order to create a separation of the adhesive bonding. The delamination of the aluminum skin is chosen because of its very thin thickness and the consequential tendency to buckle at low loads. Finally, test specimens with sizes of approximately 210 x 100 mm (length x width) are cut out of the sandwich shells, see figure 3.

Specimen Number	Size of Delamination Diameter
2_5_0	No Delamination
3_1_10	10 mm
2_1_25	25 mm
3_6_50	50 mm

Table 1. Tested specimens with number and size of predefined delaminations.

3. Experiments

A total of sixteen specimens are tested of which four are presented here exemplarily (see table 1). The sandwich shells are fixed in a clamped support in a Zwick 1484 screw-driven testing machine (see test setup in figure 4) with a crosshead speed of 0.5 mm/min and loaded in axial compression. Similar tests can be found in [12]. Taken measurements are the axial force by the testing machine, a displacement measurement by an inductive displacement sensor, axial strain by a strain gauge on the CFRP face and the deformation of the aluminum layer by the digital image correlation (DIC) system ARAMIS® by GOM. The latter enables the possibility to get a detailed view of the behavior of the buckling delaminated skin.

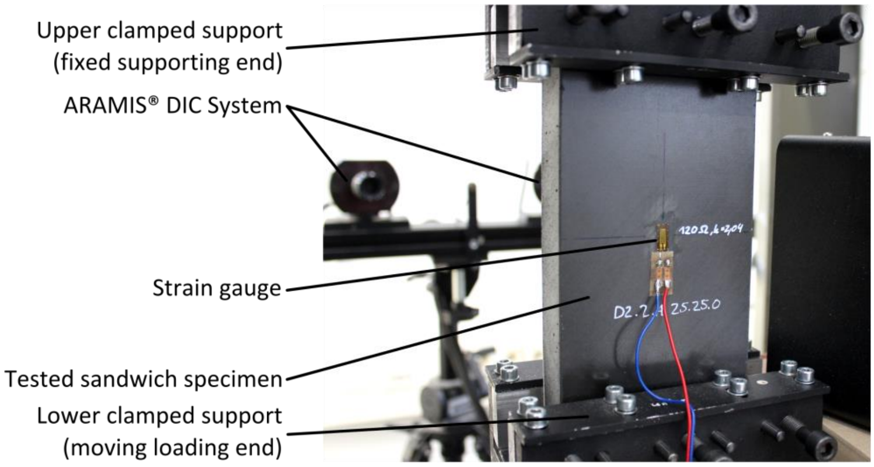


Figure 4. Test setup for experimental examinations of axial compression loadings.

Test results can be seen in figure 5. The applied load is normalized to the exact width of each tested specimen in order to ensure accurate comparability between them and plotted versus the responding displacement in the given diagram. As can be seen, after a certain amount of material setting all specimens deform nearly linearly until first failure. The undamaged specimen (“2_5_0”) carries the highest loads (672 N/mm) without any visible sign of fracture. The failure occurs by sudden and simultaneous delamination and buckling of both face layers, see figure 6 a). Curve “3_1_10” implies a decreasing influence of the inherent delamination on the load bearing capacity. However, as can be shown by repeating the tests, the different behavior lies within the tolerance created by the manufacturing of the shells. The specimen fails similar to the undamaged one not by single face delamination but by global failure of the entire sandwich, figure 6 b). Therefore, small delaminations within the adhesive layer (e.g. pores, manufacturing deficits) can possibly be tolerated by the presented asymmetric sandwich construction. However, larger damages significantly decrease the structure's load bearing capacity. The delamination with a diameter of 25 mm reduces the initial failure load to 391 N/mm (curve "2_1_25"). Failure begins by buckling of the delaminated part of the aluminum skin and the succeeding sudden propagation of the delamination through the entire sandwich perpendicular to the load direction. Subsequent to this the intact rest of the structure is able to carry a load up to 428 N/mm where the CFRP-face delaminates and buckles, see figure 6 c). Increasing the delamination size to 50 mm (curve "3_6_50", figure 6 d) leads to the same behavior as with 25 mm. However the failure loads are reduced significantly. The delamination propagation of the aluminum skin occurs suddenly at 287 N/mm, the global failure of the sandwich takes place at nearly the same load as with 25 mm (417 N/mm). This implies that the size of the delamination of the aluminum skin affects the propagation onset of the delamination but not the global failure.

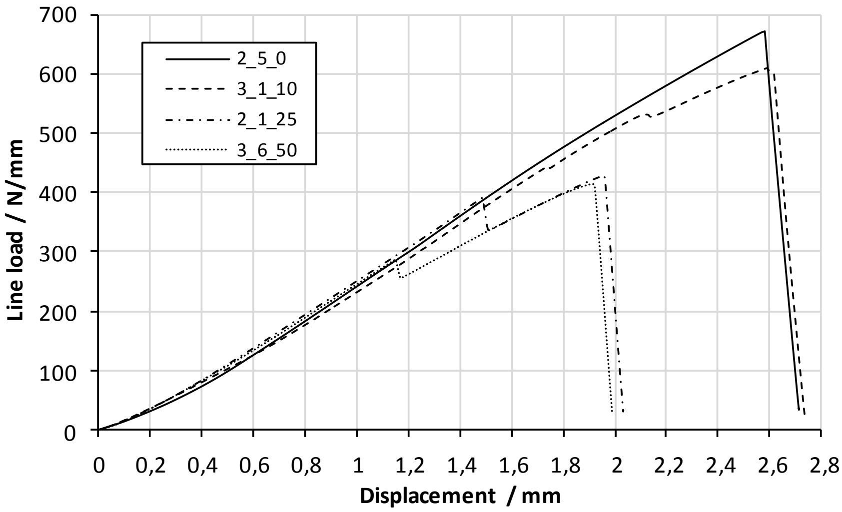
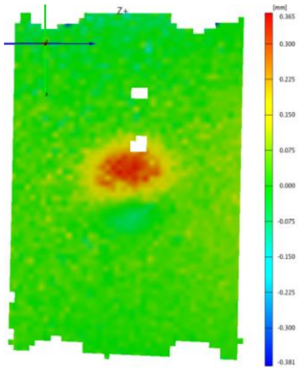


Figure 5. Line load over displacement for tested sandwich shells with different sizes of delaminations of the aluminum skin (no delamination, 10 mm, 25 mm and 50 mm).

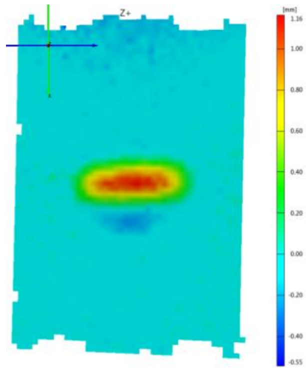
a) No delamination b) 10 mm delamination c) 25 mm delamination d) 50 mm delamination

Figure 6: Tested asymmetric sandwich specimens with different sizes of predefined delaminations.

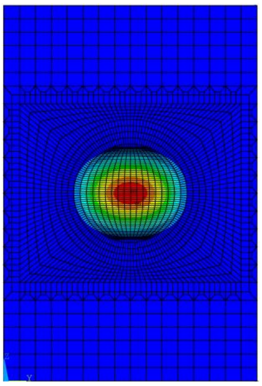
Morphologically the buckling delamination shows a typical behavior as can be shown by the analysis of the DIC system, see figure 7 a) and 7 b). At relatively low loads the buckle is nearly circular and narrows to a more elliptical shape with increasing load. At the left and right tip of this ellipse the delamination starts to propagate.



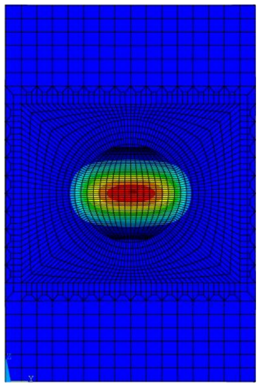
a) DIC plot of shell 3_6_50 at 36 % of failure load



b) DIC plot of shell 3_6_50 at moment of failure



c) Simulation of 50 mm delamination at 37 % of failure load



c) Simulation of 50 mm delamination at moment of failure

Figure 7: Comparison of the out-of-plane-deformation of the delaminated aluminum skin (diameter 50 mm) in experimental tests (a, b) and numerical simulations (c, d) at different loads.

4. Numerical simulation

One of the primary goals of the research project is the development of a valid FEM simulation that can be used in future examinations. Therefore, a parameterized numerical sandwich model is created with a Python script and imported in ANSYS® (figure 8). While the foam core is modeled using SOLID186-elements, the face layers are created by SHELL281-elements. The foam material and the aluminum are isotropic. The CFRP material properties are homogenized. According to the expected large strains during buckling the entire stress-strain-curve including plasticity is considered for the aluminum. For the purpose of simplification the modelling of the adhesive layer is neglected. The element separation necessary for the delamination is introduced by duplicating corresponding nodes and redistributing them to the correct elements. Contact elements (CONTA174, TARGE170) within the gap prevent overlapping of finite elements. The considered load case is identical to the experiments and therefore is axial compression. The examination of different delamination geometries shows a good agreement between simulation and experiments regarding the morphological physical behavior. In figure 7 c) and d) the top view of the out-of-plane deformation is shown. Compared to the DIC plots in figure 7 a) and b) it can be seen that the FE model shows the same narrowing buckle as measured in the experiments. Figure 9 illustrates the buckling of the delaminated aluminum skin as cross section. In larger delaminations (here diameter 50 mm) the mentioned contact elements are necessary to prevent the skin from buckling inwards and overlapping with the core. In order to determine the initial failure load of the FE model, the following three different failure criteria are used. The CFRP fails at a certain strain in any direction and the aluminum failure is defined by the von-Mises-criterion due to the multi-axial stress state.

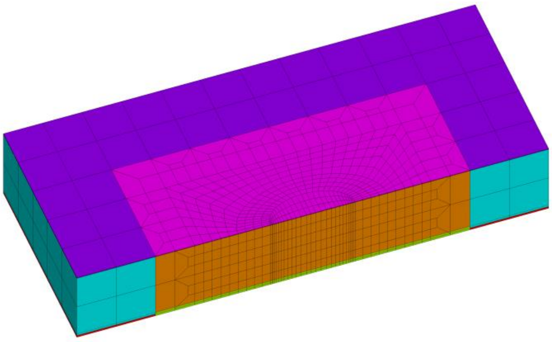


Figure 8: Cross section of a FE model of a delaminated sandwich structure.

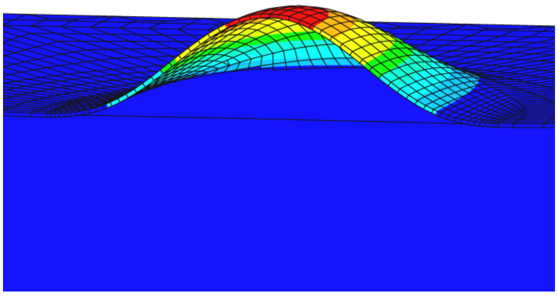


Figure 9: Scaled plot (10x) of the out-of-plane-deformation of a buckling aluminum skin (50 mm).

Because of the asymmetric behavior of the foam material regarding tension and compression the classic von-Mises-criterion is not suitable to produce good results in this case. Therefore another failure criterion, developed for closed cell rigid foam, is used [13].

$$\sigma_v = \frac{\sqrt{(12a_2+12a_1+12)I_2+(4a_2^2+(4a_1+4)a_2+a_1^2)I_1^2}+a_1 I_1}{2a_2+2a_1+2} \tag{1}$$

Similar to the von-Mises-criterion it is based on the calculation of invariants. Here they are

$$I_1 = \sigma_{11} + \sigma_{22} + \sigma_{33} \tag{2}$$

$$I_2 = \frac{1}{3}\left[\sigma_{11}^2 + \sigma_{22}^2 + \sigma_{33}^2 - \sigma_{11}\sigma_{22} - \sigma_{11}\sigma_{33} - \sigma_{22}\sigma_{33} + 3\left(\sigma_{12}^2 + \sigma_{13}^2 + \sigma_{23}^2\right)\right] \tag{3}$$

Following these calculations multi-axial stress states can be considered which is essential for the correct failure prediction within the delamination front. The variables a_1 and a_2 contain information about the foam material.

$$a_1 = \frac{k^2(d-1)}{d} \qquad a_2 = \frac{k^2}{d} - 1 \tag{4}$$

where

$$k = \sqrt{3}\frac{R_{12}}{R_{11}^+} \qquad d = \frac{R_{11}^-}{R_{11}^+} \tag{5}$$

with the foam's tensile strength R_{11}^+, compression strength R_{11}^- and shear strength R_{12}. If plotted at the calculated moment of failure for a sandwich structure with a delaminated aluminum face (diameter 50 mm), figure 10 appears. It can clearly be seen, that the highest stresses occur at the left and right edge of the delamination. This is in good agreement with the experiments, since the propagation of the delamination starts exactly in these areas. In general it can be stated, that the FE model is capable of predicting the correct area of failure and failure mode. However, when comparing the quantitative aspects, discrepancies become apparent. First, the calculated failure load (11.8 kN) is significantly lower than the one reached in the experiments (30 kN). The reason for this behavior is seen in the missing consideration of the adhesive layer in the FE model. Since the current manufacturing process required the delamination (introduced by a Teflon foil) to be within the adhesive layer, the stress peaks of the delamination front are also within the adhesive. Therefore it can be concluded that the plastic deformation of the ductile adhesive dissipates a certain amount of deformation energy before the delamination propagates into the foam core. This dissipation is not covered by the FE simulation. Furthermore, the out-of-plane deformation is overestimated.

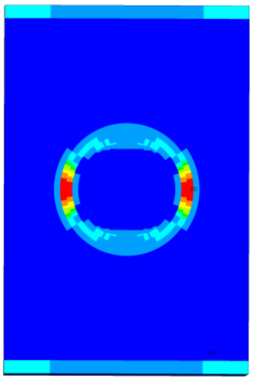


Figure 10. Stress criterion in sandwich foam core at moment of failure. Asymmetric sandwich structure with delamination of aluminum layer (diameter 50 mm) under axial compression.

Figure 11 shows the out-of-plane-deformation of the buckling aluminum skin for the tested specimen ("3_6_50") at 11.8 kN and 30 kN and the corresponding FE simulation. It becomes apparent that the deformation in the experiment is less than the calculated one when comparing both curves at 11.8 kN. Again the delamination within the adhesive is assumed to be responsible since not only the aluminum skin buckles but also half of the adhesive layer bond to the face sheet. Currently, following examinations are performed to prove these assumptions and will be published.

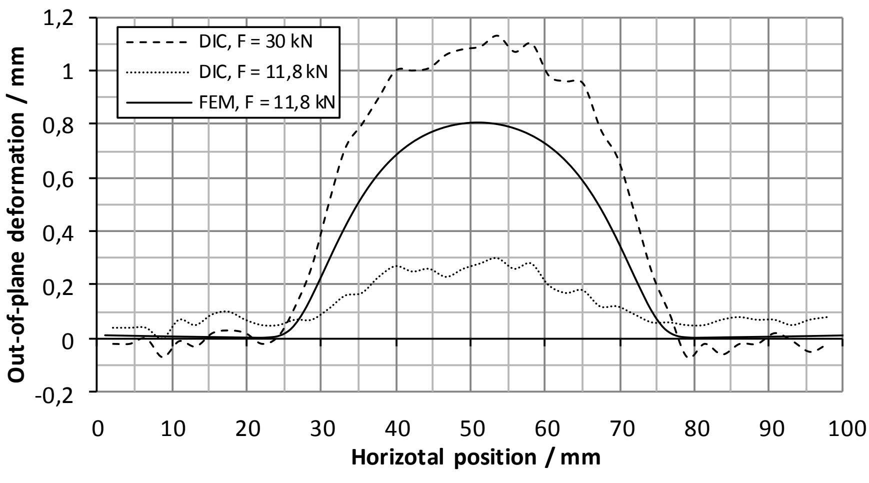


Figure 11. Out-of-plane deformation of the delaminated aluminum skin (diameter 50 mm) over horizontal position for a tested sandwich shell and the corresponding FE simulation.

5. Conclusions

Asymmetric sandwich shells are manufactured consisting of a stiff CFRP skin, a rigid PMI foam core and a thin aluminum skin. Some of the tested specimens are pre-damaged by circular delaminations of the aluminum skin with diameters from 10 to 50 mm introduced by a Teflon foil. Loaded under axial compression could be shown that delaminations above 10 mm significantly reduce the load bearing capacities of the structures. The delaminated skin buckles outwards and the failure is initiated by the sudden propagation of the delamination through the entire shell. Afterwards the structure will carry increasing loads until its global collapse. A FE model is developed for the purpose of performing future examinations and validated with the experiments. The analysis of displacement, strain and DIC data shows good agreement of the morphological behavior. Especially the buckling of the delaminated skin and its shape changing with increasing load is reproduced well. However, failure loads and out-of-plane deformation are not predicted correctly which is assumed to be caused by the missing modelling of the adhesive layer. Future examinations will be carried out to verify this assumption.

Acknowledgements

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