DEFORMATION AND FAILURE BEHAVIOR OF PREDAMAGED FOAM-CORE SANDWICH STRUCTURES IN A FOUR-POINT BENDING CONFIGURATION

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Abstract
This article deals with the investigation of the mechanical behavior of predamaged foam-core sandwich structures. A four-point bending fixture was used to investigate the influence of application-specific loads on a sandwich structure with low velocity-impact damage. A typical sandwich failure mode is the occurrence of damages in the skin, the core and in the interface between both, caused by an impact. Impact damaged aircraft structures have to demonstrate sufficient level of damage tolerance and finally residual strength to endure typical damage scenarios without structural failure below the required load level.
Currently, for predamaged sandwich structures there is no standardized test available to evaluate deformation behavior and certain residual strength. The main point in this investigation is to develop a significant test setup for a foam-core sandwich structure to observe the deformation and residual strength behavior after a low velocity impact occurred. Finite Element computations were made prior to the test to support specimen design that will show valid failure mode in the compression loaded skin area between the inner force stamps. Predicted specimen internal loads and deformation were reflected by the tests. An applicable specimen dimension and four-point bending test scheme could be proposed for testing of impact damaged foam-core sandwich elements.

1. Introduction

Sandwich structures offer a high lightweight potential. Especially foam-core sandwich structures are providing a good ratio of bending stiffness and strength to weight. Using closed-cell rigid foam-cores of Polymethacrylimid (PMI) with face-sheet layers made of fibre reinforced polymer, low priced, high integral structures can be built up by a vacuum infusion process which is an efficient liquid composite moulding technology. That is why they are on focus to be used for aircraft structure applications. The closed-cell foam also allows a certain range of geometric features by a preforming process (milling, cutting, thermoforming). Due to their high bending stiffness sandwich structures are predestinated for use in large shell-like structures which are at risk to fail in buckling. Hence, sandwich structures qualify for application in shells of commercial aircraft (wings, fuselage, tail planes, etc.) [1].
These structures are on the other hand subjected to local impact loads (tool drop, bird strike, hail, etc.), which can cause local impact damages in terms of damages in the face-sheet, in the foam-core and in the interface between them. That is why there is a strong need for experimental evaluation of predamaged sandwich structures in terms of their mechanical behavior. Especially deformation behavior and residual

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strength and lifetime under both static and fatigue loads are of strong interest. The compression after impact test (CAI) is well known and well established for composite materials, especially for laminates. For predamaged sandwich structures there is no standardized test available to evaluate certain residual strength. Apart from that the bending test could be realized much more easily and represents a more major load case for such a structure. That is why the standardized four-point bending (4PB) test is used with a modified sandwich specimen to evaluate the deformation behavior of a predamaged foam-core sandwich structure. Not only to observe the residual strength after a low velocity impact occurred but more to observe the deformation behavior in the area of compression load.
Freeman [2], Goettner [3] and Klaus [4] also developed tests for sandwich structures after a low velocity impact has occurred, they use the residual strength and fatigue life time behavior to evaluate the structure performance, but did not focused to take local effects in to account. The damage in the interface between face-sheet and core can be treated by fracture mechanics principles and related test methods performed on precracked sandwich specimens for evaluation of fracture toughness [5–7].

2. Materials

2.1. Material and specimen manufacturing

The sandwich structure consists of Glass Fiber Reinforced (GFRP) face-sheets and a Polymethacrylimide (PMI) rigid foam-core. For the design and dimensioning of the sandwich specimen for the 4PB-test finite element calculations where used, varying the foam-core density and the reinforcement in the shear loaded area in order to ensure a stress concentration in the compression loaded area, where the impact damage will be applied.
The foam-core sandwich structure was manufactured by a vacuum assisted resin infusion process. The sandwich core is made of a Polymethacrylimide (PMI) ROHACELL® HERO rigid foam, bi-axial GFRP-layers of Non Crimp Fabrics (NCF) and a matrix of epoxy resin RTM6 from HEXCEL®. Table 1 is shown the asymmetric sandwich lay-up related to a certain aircraft structure element. Prepared for

Table 1. Sandwich lay up

Layer	Orientation	Thickness
top ply 1	-45/+45	0.2 mm
top ply 2	0/90	0.2 mm
top ply 3	+45/-45	0.2 mm
top ply 4	90/0	0.2 mm
top ply 5	+45/-45	0.2 mm
	ROHACELL®HERO	30 mm
bottom ply 1	-45/+45	0.2 mm
bottom ply 2	-45/+45	0.2 mm
bottom ply 3	+45/-45	0.2 mm

the four-point bending test the foam-core was reinforced at load introduction to avoid premature failure in loading area and to enforce failure in the specimen middle area loaded by constant bending moment. Therefore the foam-core was built from 70 kg/m^3 density grade in between the inner load bearings and 150 kg/m^3 grade in the shear loading zones. The length of the 70 kg/m^3 density grade core portion is estimated to be 200 mm. The core geometry is shown in Fig. 1. Specific care was taken during bonding of the core components in order to ensure appropriate quality and to avoid premature core specimen failure

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during later test. The specimen were cut from a one-shot infused sandwich panel. To ensure defect-free and shear-crack free specimen a non destructive (NDT) inspection was done by an air coupled ultrasonic system after manufacturing.

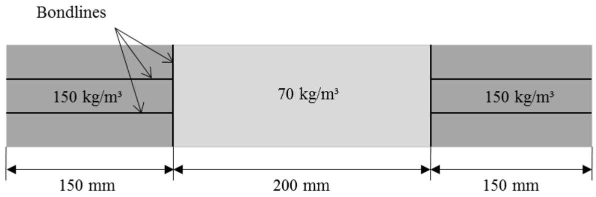

Figure 1. Foam-core geometry with bondlines, front view of cross section

2.2. Specimen design via FEA

The specimens were previously designed by a FEA. An FE mesh density level of 4 has been applied within this study. With increasing core material stiffness, increasing core shear stresses are observed as higher load portion is attracted with stiffer core. In the range of meaningful core stiffness value (CM-1 to CM-3), relatively small core shear stress variation is observed, being in average at around 1 MPa. As expected with displacement controlled loading regime, similar maximum displacement and upper skin strain values are observed, independently from core material stiffness setting. Following FE element formulations are applied:

- Sandwich Core: 8-node FE brick elements
- Sandwich Skins: 4-node FE shell elements
- Rollers: Rigid Body Formulation

The mesh density is controlled with following parameters: element edge length of the skin, element edge length of the core and the element edge length of the rollers. The core material properties are varied in test zone and loading zone as follows:

- CM-1 HERO70 (test zone), HERO70 (loading zone)
- CM-2 HERO150 (test zone), HERO150 (loading zone)
- CM-3 HERO70 (test zone), HERO150 (loading zone)
- CM-4 Extreme property E_core = 5 MPa
- CM-5 Extreme property E_core = 8000 MPa
- CM-6 Extreme property E_core = 80000 MPa

The skin thickness is varied with respect to number of NCF plies; 2, 3 and 5 plies of GFRP NCF. One ply of GFRP NCF has a stacking of [+45; −45] and is assumed to an overall thickness of 0.2 mm.
Study CM-4 is seen as outlier showing significant smaller result values for maximum displacement, skin strain and core shear stress. In deformation plot, significant local deformations in the vicinity of the load introductions are observed. The behavior is interpreted due to extremely low core stiffness and subsequent convergence problems in the non-linear FE analysis run. Table 3 is shown the results of maximum displacement, skin strain and core shear stress of the CM-study.

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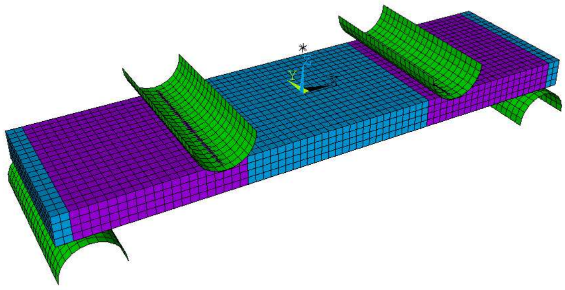

Figure 2. FE-Model of 4PB-specimen with load areas

Table 2. Results of mesh density, sensitivity study

Mesh Density Level	Displacement [mm]	Skin Strain [μ ϵ]	Core Shear Stress [MPa]
1	23	11300	1.10
2	21	10500	0.84
4	20	11500	0.93
8	20	10400	0.80

Table 3. Core material (CM) study - absolute result data

	max. Displacement [mm]	Skin Strain [μ ϵ]	Core Shear Stress [MPa]
CM-1	19.9	9650	0.76
CM-2	20.6	10250	0.94
CM-3	19.9	9650	0.75
CM-4	12.75	2753	0.24
CM-5	20.85	10855	8.3
CM-6	20.6	10609	62.4

3. Experiments and Results

3.1. Impact test and NDT

A drop weight tower was used to impact the sandwich specimens with various impact energies. Typical low-velocity impact damages were introduced, as they do occur i.e. during tool drop and in-service scenarios. Three of the prepared specimen were impacted using a rigid sphere impact-tool geometry with 25.4 mm diameter at 10 J, 20 J and 35 J at a velocity of about 5 m/s. The impact energy was determined in the range of visible impact damages between 10 J and 35 J. The impacts were applied to the tool-side of the sandwich specimen. The test scheme ensures the impacted skin at the compressive side in the course of the test. The impact damage was generated by impact drop on the rigidly supported

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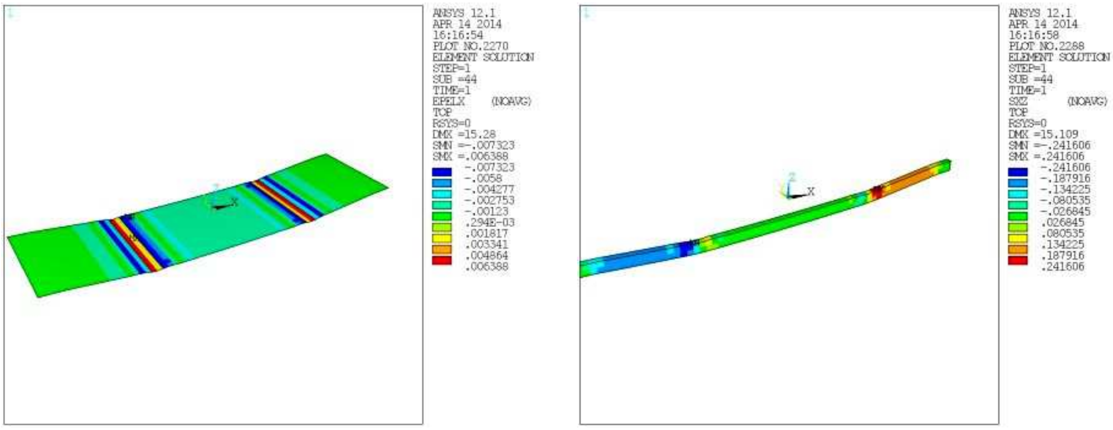

Figure 3. FE-Modell CM-4: skin strain (left), core shear stress (right)

specimen. Impact damage shall be clearly visible but shall not include core shear crack damage mode. The impact energy and damage extension was documented appropriately. Fig. 6 shows the c-scan of the ultrasonic inspection of the herein observed impact damages.

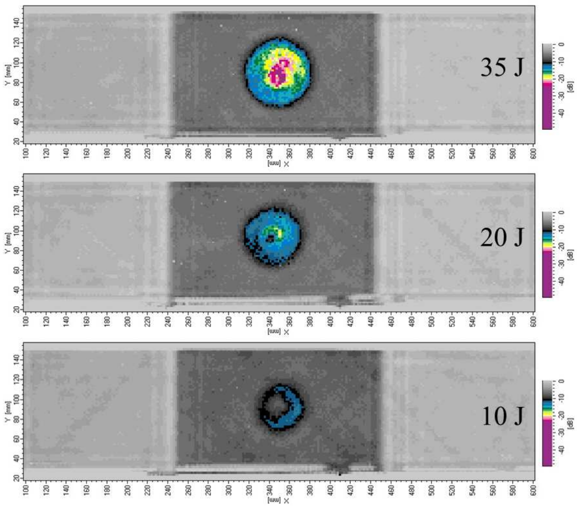

Figure 4. Ultrasonic c-scan of foam-core sandwich specimen after impact, top view

3.2. Four-point bending test

The four-point bending test was performed according to the AITM 1-0018 standard, requested for foam-core sandwich specimen. Two different series of specimen were tested in a standardized 4PB test set-up. The series-01 was used to compare undamaged versus impact damaged sandwich structures. The series-02 was used to compare the behavior of impact damaged sandwich specimen with different specimen width. A strain gauge was applied at the compressive skin of each specimen, as it is shown in Fig. 5 and Fig. 6.
The first series test specimens featured a width of 150 mm (series-01). It was found that an impact of 35 J generates a large damaged area that is incapable to sufficiently redistribute skin loads and resulting in a premature face-sheet near disbonding-like failure. For that a second specimen series was manufactured featuring varying specimen widths between 200 mm and 250 mm. All of these specimen were impacted by 35 J. Fig. 7 shows a predamaged specimen inside the four-point bending (4PB) test rig. Fig. 9 shows

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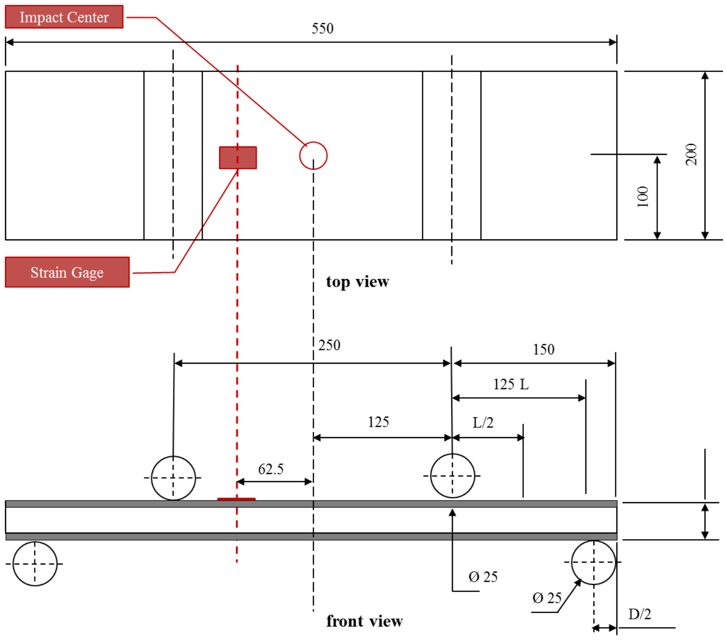

Figure 5. 4PB-specimen with impact center and strain gauge application

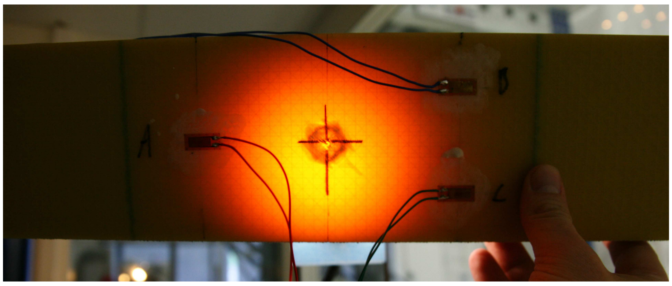

Figure 6. Impact damage and additional strain gauge applications, highlighted background

all specimens after the 4PB test procedure, comparing the specimen failure modes of the series-01 impacted and non-impacted specimen (left) versus the ones of the series-02 featuring increasing specimen widths (right). Significant difference between impacted and non-impacted specimen is observed. With series-02 specimen, the expected failure mode of skin fracture has been found, where in series-01 an invalid skin disbonding-like failure mode is observed. It was shown that in case of a specimen width of 250 mm the 35 J impact has only a little effect on the strength, about 5 % the strength is reduced compared to the undamaged specimen. In case of the 200 mm specimen width, significant effect of a 30 % strength reduction is observed compared to the undamaged specimen. Fig. 8 (left) shows the force-deflection results between undamaged and 35 J predamaged series-02 sandwich specimen. The local strain deformation data confirms the observed strength trend, shown on the right side, and shows that minimum (with impacted) and maximum (with non-impacted sample) skin failure strains are achieved with the 200 mm width specimen. Comparing the FE analysis results versus achieved test data shows, that the predicted specimen displacements and skin compressive strains do meet acceptably good the test recorded data at circa 20 mm and skin 10000 microstrains.

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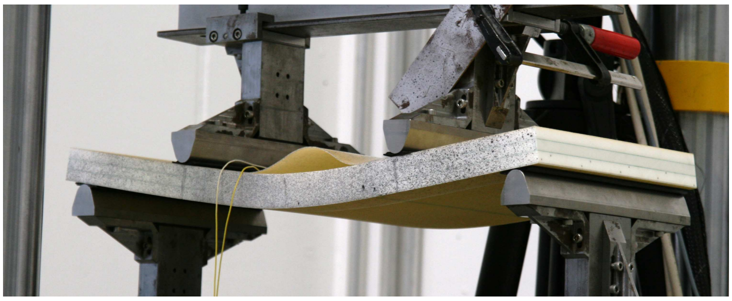


Figure 7. 4PB test with predamaged specimen of series-02

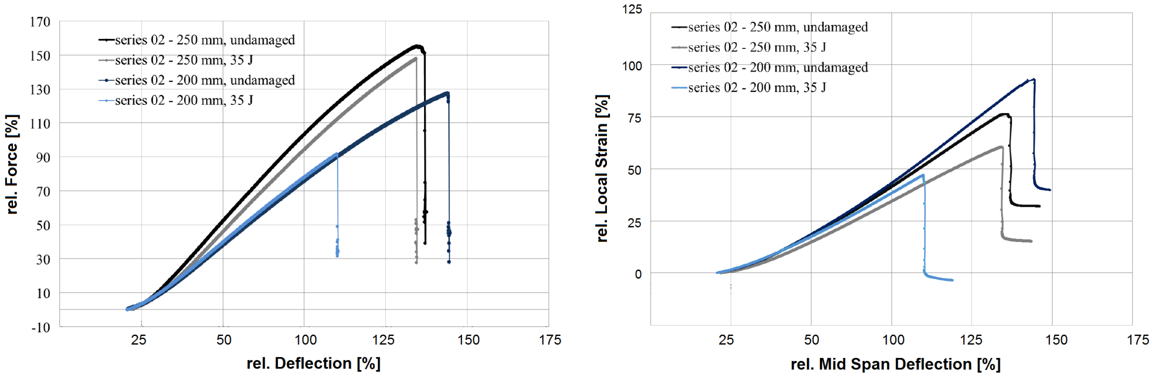
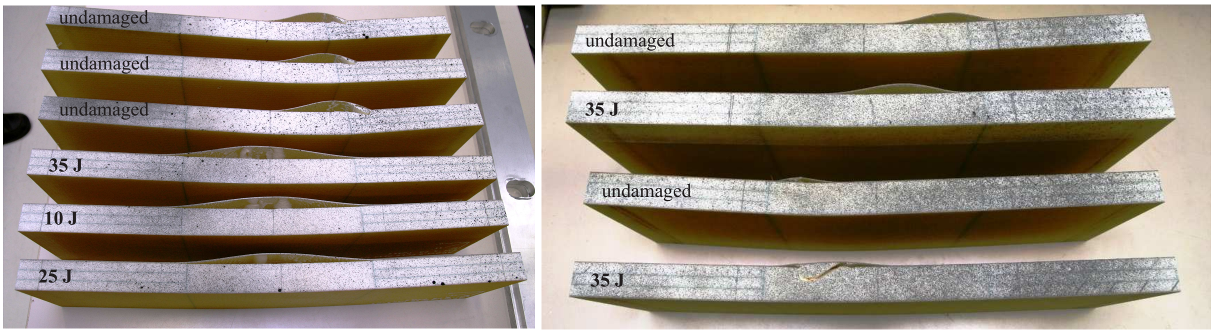


Figure 8. Force-deflection data from 4PB test of series-02 (left) and strain-deflection-data of series-02(right)



series-01: 150 mm specimen width

series-02: 250 mm and 200 mm specimen width

Figure 9. Specimen of series-01 (left) and series-02 (right) after testing

4. Conclusion

Impact damage is a typical scenario for aircraft structure applications, occurring during tool drop as well as in in-service scenarios. Typical sandwich structure is found sensitive to such local out-of plane loads, that is why the strength behavior of impact-damaged sandwich structures needs specifically to be addressed during a component sizing procedure. For residual strength testing, depending on the pre-dominate loading regime, compression after impact (CAI) or bending after impact test schemes may be applied. On the opposite, there is actual only little test standards available specifically applicable to sandwich structures to find valid and reproducible test results. Present work investigated different sandwich four-point bending configurations to find a valid test setup on impact damaged sandwich samples. Foam-cored sandwich specimen equipped with GFRP Non-Crimp Fabric skins have been investigated

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featuring a low velocity impact damage to the compressive side of the 4PB test setup. The specimen were specifically reinforced by high-density foam core portions in the load introduction area in order to avoid premature foam-core failure. 35 J impact damaged specimen have been compared with non-impacted samples of same size with respect to failure load and failure strain. A preceding FE analysis was used to appropriately predict specimen deformations and load levels to be expected with the anticipated test setup. In the test, with present material selection, geometry and loading scenario, a sample width of 150 mm has been found to be non-representative as resulting in an invalid disbonding-like failure mode. A specimen width of 200 mm is identified for appropriate size, demonstrating sufficient load redistribution capabilities by valid skin fracture failure modes, while maintaining a sufficient level of conservatism with respect to achieved failure load levels. For potential application, found test setup and dimension needs to be cross-checked versus further sandwich materials and combinations of different thickness, stiffness and strength properties. Constraints and limitations of the test setup should be investigated and determined.

Despite actual FE prediction is in relative good agreement to the final test data, certain deviations can be observed on strain level and sample deformation with respect to specimen size and resulting stiffness. Future modeling work may comprise representative FE idealizations for the impact damage geometry and strength modeling. Additionally introducing fracture mechanical principles for the analysis of the loads at the impact crack trip may further enable the numerical prediction of skin strength failures.

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