COMPARING UNREINFORCED AND PIN-REINFORCED CFRP/PMI FOAM CORE SANDWICH STRUCTURES REGARDING THEIR DAMAGE TOLERANCE BEHAVIOUR

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ABSTRACT

Foam Core Sandwich Structures are offering a good ratio of bending stiffness- and strength-to-weight. By using closed-cell rigid foam cores of Polymethacrylimid (PMI), low priced and highly integral structures could be built in a vacuum infusion process. Therefore the investigated sandwich structures are suited for primary structure applications in commercial aircrafts. Foam core sandwich structures consist of two CFRP-face sheets and a PMI foam core. Structures without foam core reinforcement were compared to structures with CFRP pin-reinforcement. The CFRP-pins can be used to increase the out-of-plane properties of the sandwich structure and particularly the Damage Tolerance (DT) behaviour. One of the important specific values concerning the Damage Tolerance is the critical Energy Release Rate (ERR) G_{IC}, which has to be determined. In case of very thick and stiff face sheets the climbing drum peel test is not suited for such structures. Currently there is no other standardised test available to evaluate the G_{IC} value for sandwich structures. That is why the Single Cantilever Beam (SCB)-test is used to determine G_{IC} here. The SCB-test was optimised to be used for sandwich structures. Two different methods of G_{IC} evaluation from the SCB-test data, using force, deflection and crack length, are analysed. Afterwards the pros and cons of the used Compliance Calibration Method (CCM) and of the Area Method (AM) are discussed. Beside the method validation, the structures without reinforcement and with pins of two different patterns are compared to each other. It becomes apparent that the Energy Release Rate (ERR) can be increased threefold by special CFRP-pin configuration.

1 INTRODUCTION

Using CFRP/PMI foam core sandwich structures for primary structures in commercial aviation a lot of advantages could be provided. With the cost-effective manufacturing process of vacuum infusion several integral structures with high light weight potential can be built [1].

Face sheet/ core disbonds in sandwich structures, caused by impacts in service or manufacturing faults, decrease the sandwich stability and may reduce the structural reliability significantly. Since local face sheet/core disbonds are a common failure event and due to their complicated detectability, face sheet/core disbonds must be taken into account during the design process, in particular in the aircraft industry. A disbond between face sheet and core occurs as a crack, so that fracture mechanical methods are used to evaluate its criticality in structures and components. Since the face sheet opening mode (Mode I) is the most relevant mode for face sheet/core disbands, the Mode I fracture toughness is determined using the Single Cantilever Beam Test (SCB) [2,3].

To increase the damage Tolerance (DT) performance and the critical Energy Release Rate (ERR) of the CFRP foam core sandwich structure, a foam integrated pin-reinforcement of CFRP could be used. An aim of this work is to proof this assumption.

2 MATERIALS AND PROCESSES

The manufacturing process of the sandwich structure is a vacuum assisted resin infusion process which belongs to the category of liquid composite moulding techniques. It is a dry and simple lay-up of the sandwich components and can be realized by a simple open mould and an oven. The triaxial non crimped fabrics of carbon fibre and the core of Polymethacrylimid (PMI) closed cell foam are stacked dry to a symmetrical sandwich and sealed by a vacuum bag, shown in Figure 1. After evacuating the resin HexFlow®RTM6 and the sandwich lay-up, the infusion process starts at 120°C. The following curing is proceeded at 180°C. After cooling down to ambient room temperature the sandwich specimen can be unzipped out of the vacuum packaging [1].

In case of a pin-reinforcement a stitched foam core is used. Therefore the foam core is pierced by a needle with dry CFRP-rovings in the required direction, angel and distance before the sandwich lay-up is made and the infusion process is started. Afterwards the CFRP-rovings are infused by resin contemporaneously with the resin infusion of the face sheet layers.

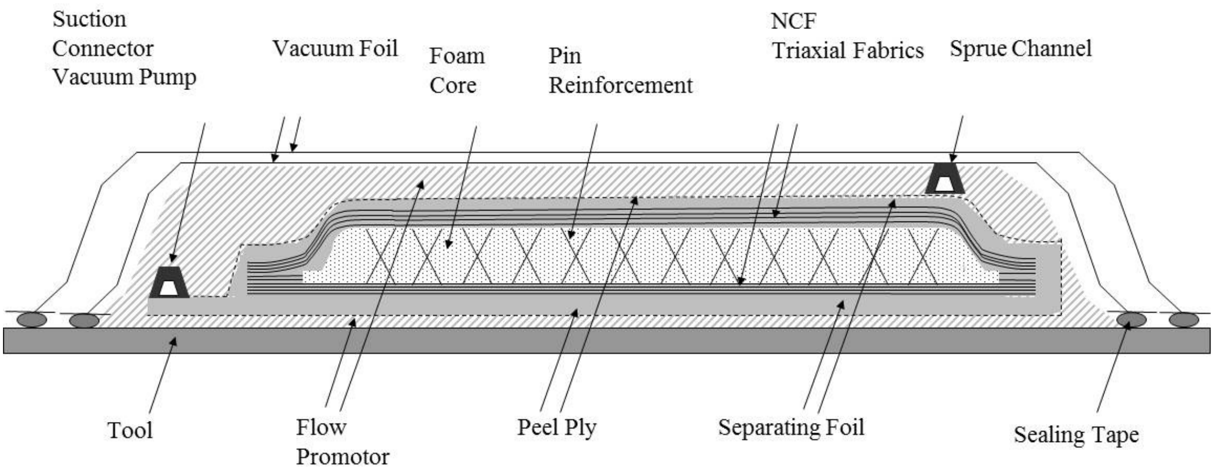

Figure 1: Schematically vacuum assisted infusion process at sandwich manufacturing

3 DAMAGE TOLERANCE BEHAVIOUR

An essential requirement for the use of any structure as a primary structure in an aircraft application is the Damage Tolerance [7]. A disbond between face sheet and core can be caused by impact loads like hail, bird strike and stone chipping in service or tool drop during maintenance, which has to be taken into consideration during the Damage Tolerance evaluation of the structure. A local disbond after an impact occurs as a typical sandwich failure mode [8].

The impact resistances as well as the crack growth behavior are two specific properties characterizing the Damage Tolerance behavior of a structure. In Figure 2 an air-coupled ultrasonic C-scan after a low velocity impact with a diameter of 25.4 mm is shown, which occurs at 50 J (left side) and 70 J (right side). With an air-coupled ultrasonic system only the largest failure areas can be detected. But obviously a relative small impact diameter could cause comparative large area damage at the sandwich structure. This could be evaluated by the ERR, if the failure becomes critical.

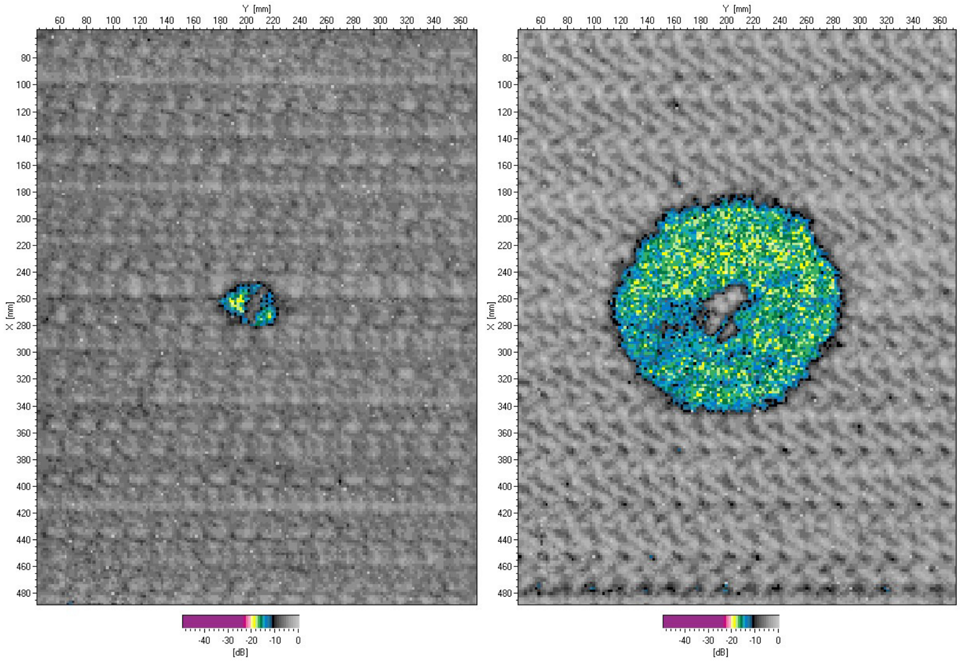

Figure 2: Representative defects caused by a low-velocity impact damage of 50 J (left) and 70 J (right) with an impact diameter of 25.4 mm, c-scan by air coupled ultrasonic image, transmission in dB

4 SINGLE CANTILEVER BEAM TEST

Based on experimental experience, the SCB-test is modified to determine the ERR of cracks in sandwich structures with a high percentage of Mode I load at the crack tip. The experimental setup, shown in Figure 3, is based on guidelines developed by Ratcliffe [4] and Adams [5] for a standardization of the SCB-test. Before testing, the specimen is fixed on a test plate and a hinge is adhered to its face sheet. The load application is realized by a long bar connected to the hinge to ensure that the load force is always normal the face sheet. This guarantees a high Mode I percentage during the hole test. The quasi-static SCB-tests are performed displacement-controlled at a universal testing machine. In each case, the displacement and the test load is recorded over the test time and displayed in a path-time diagram. The displacement is not continuously increased during the test procedure but in so-called loops. That means the displacement is controlled in loops, similar to a hysteresis, and therefore again reduced to zero after a predefined test time. Hence the critical areas, in which crack growth can occur, are approached several times, causing more evaluable data.

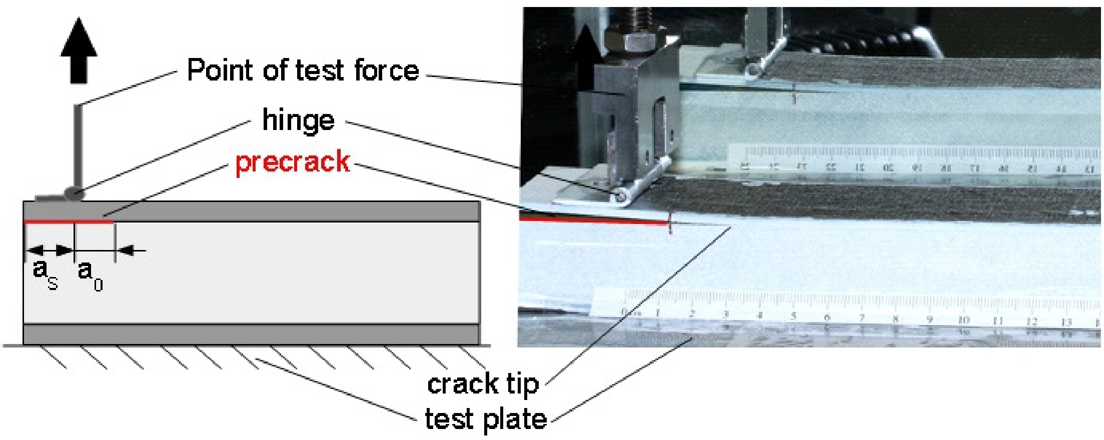

Figure 3: Experimental setup of SCB-test

Two different CFRP-pin configurations with different pin interval and same pin angle of 50° are tested and compared to a configuration without pin-reinforcement. The used pin configurations are illustrated in Figure 4. As there should be three basic cells with four pins along the width, the widths of the specimen vary from 50 mm to 140 mm. To quantify the grade of reinforcement the volume of pins per volume of foam is calculated. This calculation shows that type E01-5010 has a 64% higher grade of reinforcement than type E01-5020.

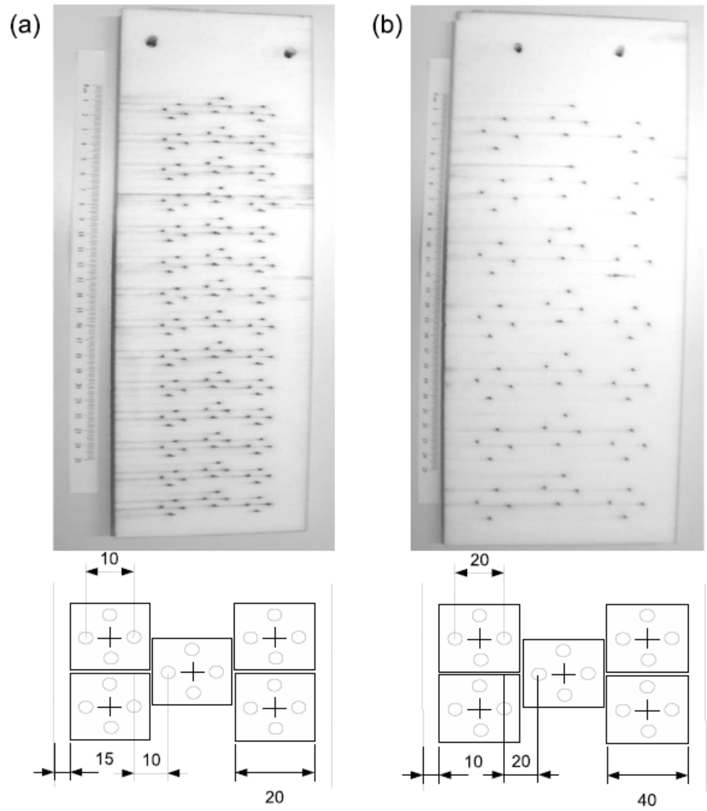

Figure 4: Pin pattern of 50°/10 mm (a) and50°/20 mm (b), top view to foam core midplane area

The evaluation of the SCB experiments is performed in three steps. First, the measured values from the recorded load-displacement curves are illustrated. The crack growth is identified with the help of pictures taken during the SCB-test. In this process then the crack lengths are determined by the Crack Opening Displacement Program CODA. CODA is a semi-automatic routine to determine the crack length out of image sequences of the crack opening made by a consumer camera. Finally, the energy release rate is calculated by different methods and the investigated pin configurations are compared.

This used two methods of evaluating the Energy Release Rate (ERR) from the load-displacement and crack length data are the Compliance Calibration Method (CCM) and the Area Method (AM). The CCM is based on the assumptions of the Linear Elastic Fracture Mechanics (LEFM). The ERR can be calculated, depending on the specimen width b, the maximum force F, and the Compliance C as a function of the crack length a, by Irwin's [6] equation:

$$G_{Ic} = \frac{F^2}{2 \cdot b} \cdot \frac{\partial C(a)}{\partial a} \tag{1}$$

The compliance C of the structure results from the experimental parameters force F and path δ:

$$C = \frac{F}{\delta} \tag{2}$$

For the AM the crack propagation energy E is required, which is determined by integrating the area of the force-displacement diagram. For this purpose the entire area within a desired range or the sum of all sub-areas has to be considered. In order that the ERR can be calculated by the Energy E, the specimen width b and the crack growth Δa:

$$G_c = \frac{E}{b \cdot \Delta a}. \tag{3}$$

5 RESULTS

In the performed experimental studies the crack growth could be observed very well under static load. The noticed load-displacement curves are very similar within a type of specimen and have only a small scatter of values. In Figure 5, some representative load-displacement curves of the three types of specimens are shown. For a clear presentation in each case only one curve per specimen type is illustrated. Based on these curves it can be seen that the deformation behavior of the specimen is linearly until reaching the maximum load F_{max}. The maximum load increases within the width of the specimen, shown in Table 1.

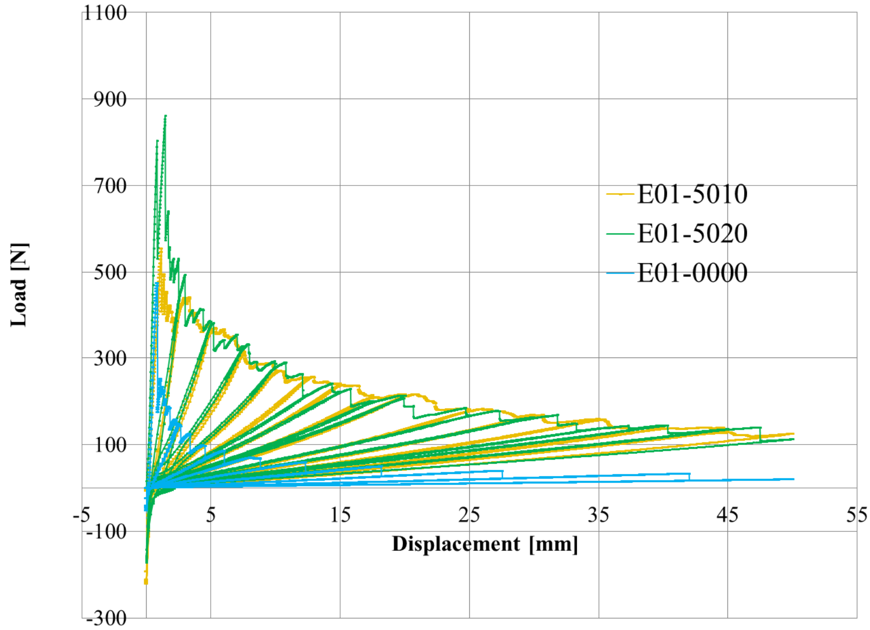

Figure 5: Representative load-displacement-curves of the investigated sandwich structures

In the case of the pin-reinforced specimen types E01-5010 and E01-5020 it has to be found that it sometimes takes a load drop before reaching the maximum load. So it appears that a crack progress occurs before the load maximum is reached. In addition it also can be determined that some specimens have no visible crack growth at a displacement of 2.5 mm. In the further progress of the load-displacement curve it can be observed that after a loop the obtained force is not as high as before. Accordingly, the loops may affect the crack growth in pin-reinforced foam sandwich specimen. With further deformation of the covering layer a stable crack growth enters along the interface between the covering layer and the foam core. The crack does not propagate exactly in this interface, but rather in the first foam cells underneath. This is clearly visible if the face sheet is separated at the end of the experiment from foam core. At the pin-reinforced specimen it can be shown that not the pins but their connections to the top layer fail. Figure 6 shows a sample with a completely detached top layer.

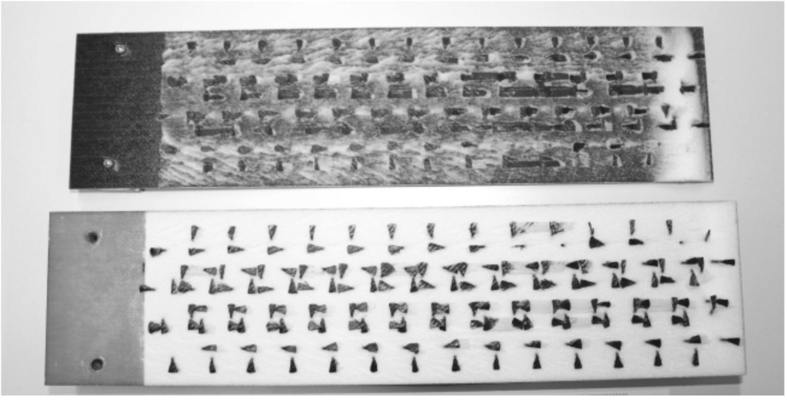

Figure 6: Total Delamination, view to area of pin-reinforced foam with 50° pins and 10 mm distance

The crack starts to grow after exceeding the critical ERR, until the crack tip is sufficiently relieved again. Thus the crack stops and rests until the critical ERR is exceeded again. This leads to the characteristic stepped profile of the load-displacement curves, which also can be seen in Figure 5. Noticeable is that the stepping of the curves is reduced by the pin-reinforcement of the foam cores. It creates several smaller spikes that lead with increasing degree of reinforcement to an almost uniform shape of the curve. This suggests that the crack growth in pin-reinforced specimens is much more continuous than the characteristically erratic progress.

The maximum attainable total crack length varies among the different types of specimens. As shown in Table 1, the non-reinforced specimens reach the largest crack lengths. The specimens with a higher grade of pin-reinforcement have shorter attainable crack lengths. Accordingly to this the grade of reinforcement is the main influencing factor regarding the crack growth. The crack is not entirely stopped by the capacity of pins as crack stoppers, but the crack growth will be significantly inhibited.

Specimen	Reinforcement	Width b [mm]	Maximum force F_{max} [N]	Crack length a_{sum} [mm]
E01-0000	Non	50	505.8 ± 20.6	264.1 ± 17.4
E01-5010	Pin-reinforced 50°/10 mm	90	530.7 ± 21.7	192.9 ± 1.1
E01-5020	Pin-reinforced 50°/20 mm	140	800.8 ± 31.9	229.7 ± 2.3

Table 1: Parameter and values of tested SCB-specimen

9 CONCLUSIONS

The SCB-test is used to determine the Energy Release Rate (ERR) as a characteristic value of the Damage Tolerance behavior of unreinforced and pin-reinforced sandwich structures. Two different methods of calculation are examined. Comparing the G_{IC} results from the two methods, shown in Table 2, several advantages and disadvantages can be detected.

Specimen	Compliance Calibration Method G_{IC} [N/m]	Are Method *whole area* G_{IC} [N/m]
E01-0000	144.7 ± 4.3	122.3 ± 4.1
E01-5010	417.2 ± 26.2	446.4 ± 2.6
E01-5020	214.4 ± 15.9	240.8 ± 10.3

Table 2: G_{IC} results of CCM and AM evaluation

It is noticeable that the deviation between the two evaluation methods is relative small and approximately constant. Hence the choice of methods should not only depend on the type of sample. Concerning the reinforced specimens the results from the AM are higher than the analyses with CCM. But it has to be considered, that ERR calculated with the AM contains every energy that occurs during the test, even those which are not associated to the crack growth.

It also can be recognized that the accuracy of the ERR calculation decreases with an increasing grade of pin-reinforcement in both methods. Also to mention is that the results of ERR may be affected by the grade of pin-reinforcement because the moment of real crack growth cannot be determined exactly enough. But compared to the unreinforced specimens (E01-0000) it is shown that the ERR can be triple increased by special CFRP-pin configuration of 50° pin angle and 10 mm distance (E01-5020).

All in all: the SCB-test itself is very suitable for an assessment of the Damage Tolerance. Before opting for a specific evaluation method the testable specimens should be taken into consideration. Even a more important role on the result of the ERR plays the face sheet stiffness and the foam core elasticity. Their influence has to be discovered in further investigations.

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