IMPACT RESISTANCE, DAMAGE TOLERANCE AND NON-DESTRUCTIVE DAMAGE DETECTION FOR SANDWICH STRUCTURES: ANALYSIS AND TESTING

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Abstract

Sandwich structures are of great importance for aircraft structures due to their high specific bending stiffness, bending strength and functional integrability.
However, impact damage can provoke a significant strength and stability reduction.
Computational methods for rapid and reliable design are presented together with advanced non destructive testing methods.

1 Introduction

Aircraft industry strives for safer and more efficient products, with even lower maintenance costs. The increasing use of composites (laminates & sandwiches) addresses all of these goals, since high performance composite materials hold a greater potential for cost and weight savings than metal technologies. The advantages of composites (high strength and stiffness at low weight) are however accompanied by their complex damage behavior. Tool drop or runway debris can lead to impact damage, which may be just barely visible, but nevertheless reduces the residual strength of the composite structure substantially. Due to missing analytical and numerical tools, time and cost intensive experiments are conducted to assess the damage resistance and tolerance of composite materials and structures.

Typical problems arise for the designing engineer who is not always aware of special behavior of composites. Structural phenomena like anisotropic strength, buckling, impact damage & degradation and residual strength need to be accurately addressed as well as the feasibility of non destructive testing (NDT).

With the development of CODAC (Composite Damage Tolerance Analysis Code) a set of important fast design methods is provided which account for

- more accurate deformation and stress states instead of using standard shell elements (FSDT theory),
- prediction of different typical failure modes,
- delamination growth during compression after impact.

For laminates these methods reach already high accuracy [1, 3]. However, for sandwich structures some additional problems arise through the material system inhomogeneity.

Therefore, this paper addresses specific innovative methods for

- impact behavior of sandwich structures, accounting for core and face sheet damage,
- efficient computation of impacted sandwich residual strength,
- reliable NDT methods for laminates with high and variable thickness, important to sandwich.

2 Impact

The considered sandwich shell structures (Fig. 1) consist of two thin composite face sheets separated by a lightweight core. Due to their high mass specific stiffness and strength, a very weight efficient design is achievable. Moreover, the core can provide damping and insulation, while the outer face sheet can act as an impact detector. However, impact damage in sandwich structures can provoke a significant strength and stability reduction.

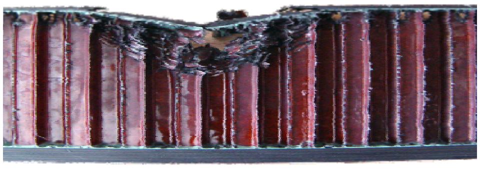

Fig. 1. Sandwich structure with impact

To achieve a rapid and accurate deformation and stress analysis, two suitable three-layered finite shell elements have been developed. Both account for shear deformation. However, one formulation bases on a plane stress approach while the other one additionally accounts for transverse compressibility. Since an accurate approximation of the transverse stresses is an important requirement for detecting impact damage, transverse stresses are improved by the so-called Extended 2D-Method, which is an equilibrium approach that has been applied to the three-layered shell formulations [4-6].

In the following, the major components of an efficient prediction of impact failure are described which mainly base on the work of Kärger [2,7].

2.1 Core failure

The core fails due to combined shear and compression. Consequently, for detecting failure initiation, the stress based failure criterion by Besant et al. is used, which includes both, transverse normal and transverse shear stresses. To model the behaviour of the damaged core, the stress–strain-path of the core material is accounted for. Therefore, the failure behavior of core compression, which arises by taking both, the residual strength and residual stiffness into account, is computed in a step-wise linear manner [1].

2.2 Skin failure

In CODAC several approved stress-based failure criteria and stiffness degradation models for fibre breakage, matrix cracking and delamination are available. Parametric studies were carried out to analyse the influence of skin failure criteria and skin degradation models on the impact response of the sandwich panels. The studies showed that fibre breakage is the most relevant failure mode, while degradation due to matrix cracking and delamination has little influence on force–time histories. Even though there might actually occur some matrix cracking or delamination before the skin starts to tear, these minor damages are not responsible for a remarkable stiffness reduction during impact. Consequently, for detecting the onset of clearly visible skin damage, stress-based failure criteria for fibre-breakage were more intensively analysed. Since the stress state of impacted, thin sandwich skins is dominated by membrane stresses, the maximum stress criterion was found to be sufficient for predicting fibre failure.

For a macro-mechanical, step-wise linear modelling of the material behaviour of the impacted skin, the behaviour is subdivided into three phases:

- Phase I: All laminas of the impacted skin are intact and behave linear elastically.
- Phase II: A few laminas are damaged and behave according to a degraded, linear-elastic material model.
- Phase III: All laminas are damaged, the skin tears.

2.3 Transient analysis

The impacted area is meshed a lot finer than the outer parts of the panel to be able to correctly predict incremental damage growth at the location of high stress concentration while keeping the computational effort as low as possible.

If the lay-up of the laminate is symmetric, it is sufficient to apply the symmetric boundary conditions and to model just a quarter of the panel.

The impactor is modelled by a point mass. The contact force between impactor and plate is distributed parabolically. The magnitude of the impact load as well as the expanse of the loaded area is calculated via the Hertzian contact law. For simulating the dynamic process, CODAC uses the implicit Newmark time integration scheme, which was found to most efficient and stable.

2.4 Method application and validation

Impact tests were conducted at the department ILR at Dresden University of Technology. Test results in the form of force–time histories, damage photographs and ultrasonic scans were provided by courtesy of ILR Dresden.

The sandwich panels were completely supported and impacted with a steel hemisphere (d=25.4 mm, 1.10 kg) and energies between 1 J and 15 J. The panels consisted of NOMEX honeycomb 4.8–48 core of 28 mm thickness and Cytec 977-2/HTA face sheets. In regard to the face sheets the sandwich is asymmetric: the impacted face sheet shall act as an impact detector and is, therefore, very thin with only three plies and a nominal thickness of 0.633 mm. The bottom face sheet carries the main in-plane loads and is with 2.7 mm much thicker.

Force–time and displacement–time histories (Fig. 2) are important experimental results for the validation of impact simulation.

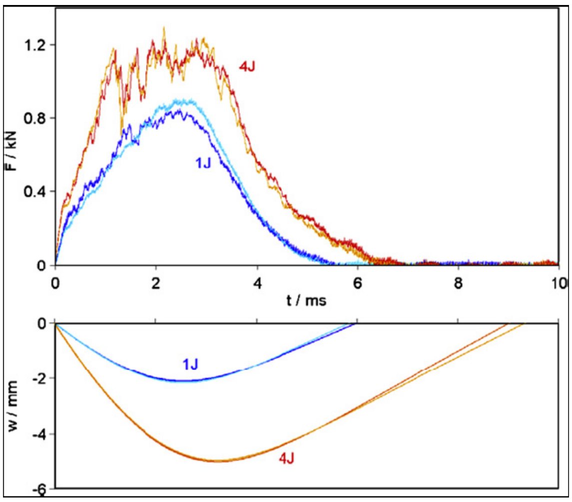

Fig. 2. Force-time and displacement-time histories from impact tests at ILR Dresden

Whereas the force–time curve of the 1 J impacts is almost sine-like, 4 J impacts lead to a sharp bend at about 1 kN, which coincides with an indentation of about 3 mm. This sharp bend indicates a massive damage, which can be identified as the begin of face sheet cracking.

Another but slight bend can be seen in all force–time curves at a very low energy-level. This indicates a stiffness reduction, which is caused by core crushing.

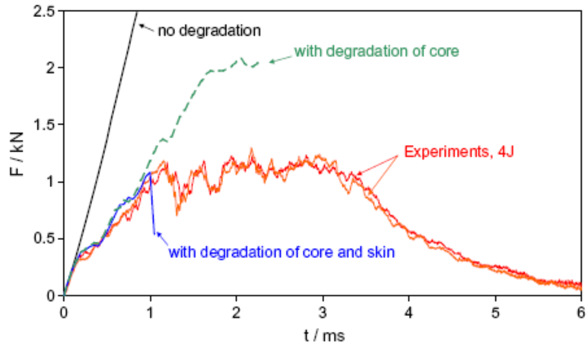

Fig. 3. Force–time histories of a 4 J impact for different stages of degradation

Three simulation results are compared to the experimental results (Fig. 3): If degradation is not regarded, too large contact forces are computed (top curve). By applying the proposed core degradation model, the slope of the force–time curve decreases as soon as core damage is detected (dashed curve in Fig. 3). Now, there is a good agreement with the experimental results up to a contact force of about 1 kN. To simulate the force drop at that point, the skin degradation model needs to be applied. Up to 1 kN, the skin degradation causes almost no changes in the force–time curve, since only the two outermost laminas are slightly affected and the skin is still capable of bearing loads. The face sheet tears only after the strengths of all laminas are exceeded, and subsequently, the contact force drops down. In the simulation this skin tearing occurs a little earlier than in the test. However, the difference is very small (1.09 kN compared to 1.17 kN) and gives a conservative result in this case. The simulation is stopped at the point of first skin cracking, as this gives the most important information to the designer.

An important advantage of the presented models and methodologies is their efficiency, which allows an application of the impact simulation in the design process. On one hand, the low number of empirical parameters and the applicability of coarse meshes are very convenient for a quick FE-modelling. On the other hand, the low numerical effort does not call for a high-performance processor and it keeps the computing time low, if, e.g. material and lay-up parameters have to be extensively varied in the design process. Depending on the extent of degradation, the here presented CODAC simulations took between 30 s and 1:40 min on a personal computer with 2.3 GHz.

3 Residual strength

Concerning the residual strength, uniaxial in-plane compression test data of impact damaged sandwich coupons were analyzed. The honeycomb core material of these sandwich structures was enclosed between face sheets of different thickness. Details of the CAI test program have been published by Wetzel et Baaran [10].

Besides face sheet and core damage, which are detected and characterized by ultrasonic scanning, the impact also caused a dent in the impacted face sheet. While increasing the in-plane compression the dent grew in depth and transverse to the loading direction until final failure of the impacted face sheet occurred. These phenomenological observations are reproduced in computational simulations in order to estimate the residual strength of the sandwich structures.

3.1 Simulation Methodology

Both the ABAQUS FE model and the semi-analytical model are based on the following assumptions:

- The in-plane stiffness of the core is neglected. The honeycombs of the core are not modelled in detail. Homogenized material properties are used.
- The core is represented by an elastic foundation of the Winkler type with only one parameter describing the out-of-plane stiffness of the core, which increases the out-of-plane normal stiffness of the core. In order to compensate the increased out-of-plane normal stiffness, the out-of-plane shear stiffness is neglected. The out-of plane normal stiffness is defined by the stabilized compression modulus provided by the manufacturer of the honeycomb core material and the core height.
- The strain gauges on the inner, undamaged face sheet measured similar in-plane strains on the clamped panel side and in the center of the panel. This supports the assumption that the inner face sheet undergoes only in-plane deformations. Therefore, the inner face sheet is not included in the model.
- Progressive damage growth is considered only for the core damage but not for the face sheet damage during the CAI failure process. However, the initial impact damage of the impacted face sheet is taken into account. The progressive damage growth is described by the elasto-plastic core material model of Olsson, see Ref. 11. The material parameters for the undamaged and the damaged core are derived from combined transverse shear-compression tests, see Kintscher et al. [8]. The elliptical impact dent in the impacted face sheet is described by a double-cosine function using the measured dent depth and the indentation radii along the in-plane half axes.

3.1.1 ABAQUS FE model

The impacted CFRP face sheet is modeled by 4-node shell elements based on the first order shear deformation theory. The core is represented by 1D elements with fixed nodes on the side of the inner, undamaged face sheet. The face sheet stiffness is obtained by the laminate theory, assuming transversely isotropic material behavoir of tape and fabric layers. The initial impact damage of the impacted face sheet is included by stiffness reduction in the damage area using a degradation factor d according to the following equation. The size of the degradation factor d depends on the severity of the face sheet damage.

$$\begin{bmatrix} \sigma \\ \tau \end{bmatrix} = d \cdot \mathbf{C} \cdot \begin{bmatrix} \varepsilon \\ \gamma \end{bmatrix}$$

A stepwise increase of the prescribed displacement Δu at one of the clamped panel sides introduces the compression loading. In order to account for the anti-buckling guides used in the tests, the out-of-plane displacement at the unloaded edges is set to zero.

3.1.2 Semi-analytical model

The out-of-plane displacement of the impacted face sheet is descriped by double sinus functions though the whole panel area. Von-Karman strain-displacement relations account for the geometrical non-linearity. The impact dent is modelled by prescribing a local, stress free initial out-of-plane deformation at the impact location.

The compression is applied by a far-field stress at one of the clamped panel sides. Stationary values of the potential energy are sought for each load step. The non-linear set of equations is solved using Newton's method or a modified arc-length method.

3.1.3 Simulation results and validation

All simulations show the impact dent growing transverse to the loading direction as observed in the experiments. This is displayed in Fig. 4, which shows the transverse displacements of the impacted face sheet for the specimen P04 with the 4 J impact damage and the ABAQUS model.

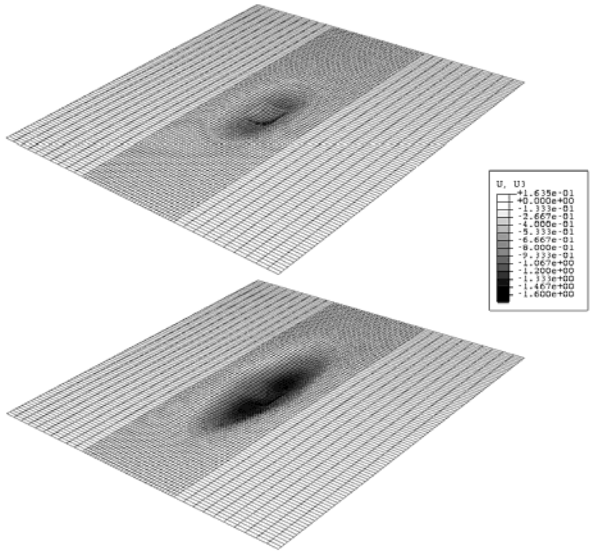

Fig. 4. Transverse displacement of the impacted face sheet under in-plane compression for the ABAQUS model (upper figure: Δu = 0.251 mm, lower figure: Δu = 0.411 mm)

Table 1 shows the simulated and measured residual strengths which are the maximum compressive loads of the whole sandwich structure before the impacted face sheet fails. For the ABAQUS model and impacts of up to 6 J a good agreement of the calculated and the measures residual strength is achieved. However, the simulation overestimates the residual strength for the 15 J impact. It is very likely that an impact damage with a penetrated face sheet shows a different failure mechanism that is not included in the model. The semi-analytical model gives very good results for impacts with less severe face sheet damages (impacts of 1 J and 2 J). Including the face sheet damage in the model raises the computational time enormously. Therefore, only one simulation including the face sheet damage is performed (see at Table 1, specimen P04 and degradation factor of 0.7). The calculated residual strength of 53.0 kN is very close to the experimental result of 53.2 kN.

Table 1: Residual strengths determined in simulations and experiments

Specimen No	Impact energy	Face sheet degradation factor	Residual strength ABAQUS Model	Residual strength Semi-analytical Model	Residual strength Experiment
	J		kN	kN	kN
P01	1.0	1.00	64.9	64.5	65.1
P02	2.0	1.00	62.1	62.3	62.4
P04	4.0	1.00	56.3	56.5	53.2
		0.70	55.2	53.0	
		0.30	53.0	-	
P06	6.0	0.01	41.2	-	39.3
P15	15.0	0.01	42.7	-	35.0

Fig. 5 shows that strain gauge measurements outside of the damage area (strain gauges 10 and 11) correspond well with the ABAQUS simulation results. Also inside the damage area (strain gauge 13) the strains are predicted quite accurately up to a compressive load of about 40 kN. The constant stiffness reduction factor of 0.3 for the face sheet damage seems to capture its softening effect towards the center of the face sheet damage quite well. Close to the border of the damage the stiffness reduction is less severe than in the centre of the damage area, where a larger amount of fibre and matrix fracture is expected. This might be the reason, why the ABAQUS model overestimates compressive strains at strain gauge 12, which is located on the border of face sheet and core damage due to the 4 J impact.

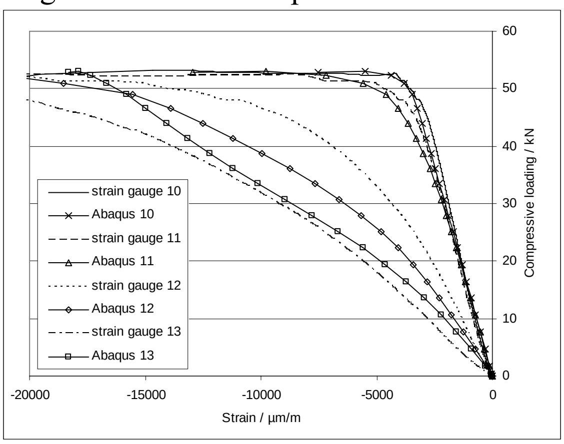

Fig. 5. Strains in loading direction in the vicinity of the 4J impact vs. compressive loading for the ABAQUS model with degradation factor of 0.3

3.2 Conclusion

The results of both the FE ABAQUS model and the semi-analytical model have shown that the 1D core model provides good results for the structures under investigation. To keep the computational time low the semi-analytical model should be only used for impacts with negligible face sheet damage. The ABAQUS model holds a high potential for further research.

4 NDT

For non-destructive testing of sandwich composites, ultrasonic testing methods are widely used. However, both in the monolithic CFRP skins and in the low-density core, the sound propagation is severely restricted. Hence the sound characteristics need to be adapted accurately to the specimen to test. Generally, high frequencies are desirable for good spatial resolution, and sufficient detection probability of small defects. On the other hand, the highly sound-attenuating composite material requires low frequencies for good penetration.

For the inspection of the entire sandwich including the core, air-coupled ultrasonic imaging as well as low-frequency water-coupled techniques are used (see Fig. 6). The combination of different methods provides reliable detection of typical damages in sandwiches together with differentiated damage characterization capability.

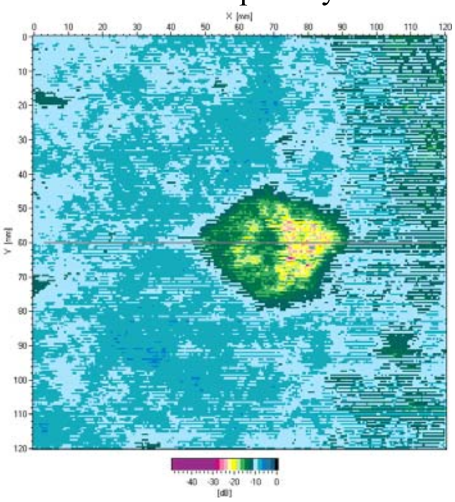

Fig. 6. US-scan of impacted sandwich

In monolithic parts as face sheets or reinforced areas, typical defects like delaminations, porosities or fibre/matrix breakages require short ultrasonic wave lengths to be detected. The required high spatial resolution on the one hand and the inhomogeneous structure with large grain size on the other hand result in a narrow range of optimal transducer spectra for a certain specimen. The loss due to scattering and absorption at the microstructure leads to a deviation of this optimal spectrum at deep positions, because Conventional Distance Amplitude Correction (DAC) compensates only for the general loss of sound pressure by additional variable amplification in the order of 1 dB/mm.

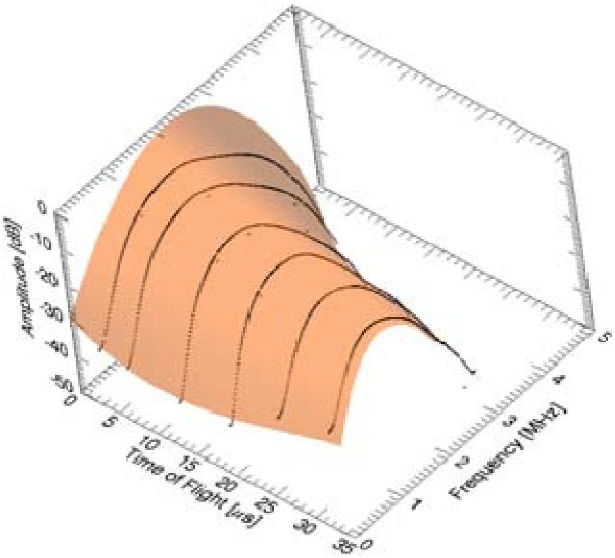

Fig. 7. Spectral loss over thickness (time of flight). Data had been recorded by using conventional DAC already

This generally leads to spectral shift towards low frequencies after long sound paths, as seen in Fig. 7. Thus, detection of small flaws is limited, because they require high frequency ultrasonic signal. Consequently, small and deep defects are underestimated in conventional ultrasonic testing, compared to flaws close to the upper skin.

To compensate for this effect, a method called SDAC (Spectral Distance Amplitude Correction) is applied, accounting for the disproportionately strong attenuation at high frequencies along the sound path [9]. The approach of SDAC is to adjust the signal shape of deep echoes to a reference echo from a shallow reflector.

SDAC is based on digital signal processing algorithms and consists of a signal analysis module and a signal processing module. Analysis provides the typical sound attenuation characteristics of a specific material in relation to frequency and time of flight. This provides the correction coefficient matrix $\Gamma(d,f)$ (see Fig. 8). Based on the correction matrix Γ, the compensation algorithm in the signal processing module recovers the lost spectral signal components in each A-scan. This is done in the time-frequency domain. From each pulse-echo A-scan (see Fig. 9), a spectrogram is calculated by using Short Term Fourier Transformation (STFT). Spectral amplitude correction is achieved by multiplying the STFT spectrogram of each single A-Scan with the correction matrix Γ. This results in a corrected spectrogram where the lost spectral components are recovered as far as possible. From there, we gather the corrected A-scan by inverse Short Term Fourier Transformation.

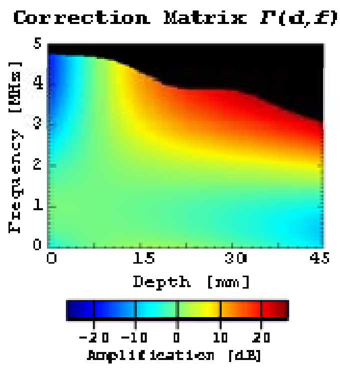

Fig. 8.

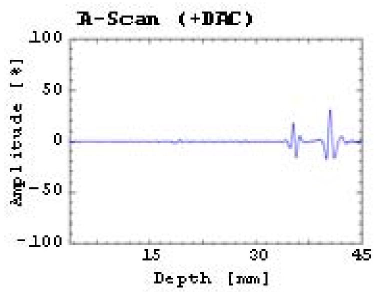

Fig. 9.

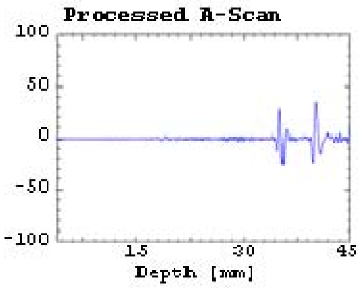

Fig. 10.

Processed A-scans look like if there was no sound attenuation (see Fig. 10). Then flaw echoes can be directly compared with each other, widely independent of the flaw's depth and size. The back wall echo is similar in amplitude, but narrower in shape; the flaw echo is both larger in amplitude and narrower in shape. Flaw echoes now can be directly compared with each other, independent of the flaw's depth and widely independent of its size. Only the geometrical laws of amplitude decrease due to beam divergence affect the reflectors echo amplitude, but this can be taken into account easily by the well known amplitude-distance laws.

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