Chapter 13
Impact and Residual Strength Assessment Methodologies

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Abstract In this chapter, efficient methodologies to evaluate impact resistance and damage tolerance of composite structures are introduced. Internal non-visible or barely visible impact damage (NVID, BVID) can provoke a significant strength and stability reduction in monolithic composite structures as well as in composite sandwich structures. Therefore, methodologies have been developed to reliably simulate the dynamic response and to predict the impact damage size that develops during low-velocity impact (LVI) events. Additionally, methods for the prediction of the compression-after-impact (CAI) strength are presented. Special attention is given to the impact assessment methodologies, which have been implemented in the DLR in-house tool CODAC. Simulation results of CODAC are presented and compared to experimental results.

13.1 Failure Analysis with Damage Initiation and Degradation

Adequately modelling the failure behaviour of composite materials is essential for an effective impact assessment. Firstly, the amount of damage indicates the residual strength of an impacted structure and is, therefore, the most important result of an impact analysis. Secondly, failure progression during an impact event can considerably influence the impact behaviour of the specimen. Consequently, material degradation needs to be taken into account. A comprehensive review of damage and failure models is given in Sect. 10.5. Specific failure assessment methodologies on a

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local scale are presented in Chaps. 11 and 12. The present section focuses on damage models, which are suitable for impact and CAI analysis.

13.1.1 Damage Models for Monolithic Composites

The three failure modes that typically occur during impact are fiber breakage, matrix cracking and delamination. They greatly differ in their behaviour and need to be treated separately in simulation. Thus, mode specific stress based failure criteria are usually applied. Damage evolution is accounted for by reducing specific stiffness components to specific values, depending on the failure mode.

An insight into the diversity of available composite failure criteria is given in Sect. 10.5.1. Many such criteria are available for application to static problems. However, their application for impact analysis is contentious. For instance Hashin [1] as well as Puck and Schürmann [2] recommend not to use their physically-based failure criteria for impact analysis. On the other hand, Choi and Chang [3] as well as Chai [4] developed delamination criteria particularly for the modelling of low-velocity impacts. Regarding fiber breakage, the maximum stress criterion is sufficient in most practical cases. However, criteria for impact induced matrix failure are difficult to validate due to a lack of experimental results.

An overview of modelling strategies of degradation and damage progression can be found in Sect. 10.5.2. The softening effect due to failure can be critical for both, impact and CAI. The reduction of the stiffness Q_{ij} of the damaged region via degradation factors D_{ij} as in

$$\begin{bmatrix} \sigma_{xx} \\ \sigma_{yy} \\ \tau_{xy} \end{bmatrix} = \begin{bmatrix} D_{11}Q_{11} & D_{12}Q_{12} & \\ D_{12}Q_{12} & D_{22}Q_{22} & \\ & & D_{66}Q_{66} \end{bmatrix} \begin{bmatrix} \varepsilon_{xx} \\ \varepsilon_{yy} \\ \gamma_{xy} \end{bmatrix}, \tag{13.1}$$

is a straight forward damage mechanics approach. The reduction depends on the combination of damage modes, cf. Kärger et al. [5]. Fiber failure is important for any type of loading and has a strong influence on in-plane stiffness and strength. Delamination strongly affects the CAI strength, cf Sect. 13.3.1, but does not have much influence on the impact behaviour. Matrix cracks have little direct influence on the stiffness, but can extend to interfaces between layers and, thus, lead to delaminations or even fiber cracks.

13.1.2 Core and Skin Damage in Sandwich Structures

Composite sandwich structures consist of two thin, stiff composite skins and an intermediate lightweight core. Nevertheless, impact damage in sandwich structures (Fig. 13.1) can provoke a significant strength and stability reduction.

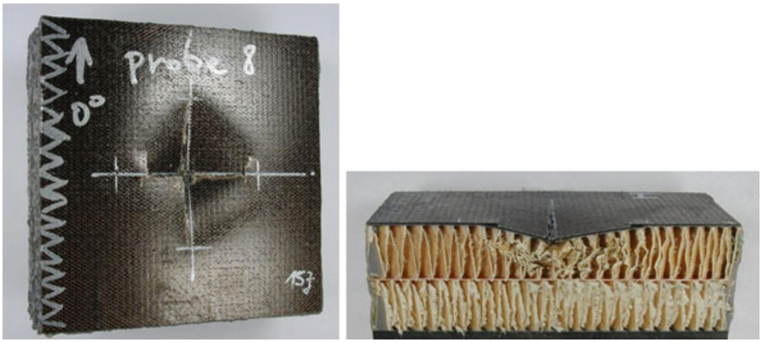

Fig. 13.1 Impact damage in a sandwich with composite skin and folded core

While skin damage, such as large cracks and indentations, may be visible, the amount of core damage can only be detected by expensive Non Destructive Testing (NDT) methods. The core fails due to combined shear and compression. Consequently, a failure criterion, which includes both, transverse normal and transverse shear stresses, such as Besant et al. [6], is recommended. To model the damage progression of the core, the stress–strain-path of the core material was investigated exemplarily [7]. After reaching ultimate strength, the core crushes at a certain stress level. The remaining crush strength plus a residual crush stiffness are taken into account by a step-wise linear failure function [8].

Damage models of monolithic laminates (Sect. 13.1.1) are available for the prediction of skin failure. Impacted, thin sandwich skins are dominated by membrane stresses. Since fiber breakage is the dominant failure mode, the maximum stress criterion is sufficient to predict impact failure. To describe skin failure progression during impact, a macro-mechanical, step-wise linear function was proposed by Kärger et al. [9]. For an efficient CAI analysis, Wetzel [10] considered initial damage (indentation, stiffness degradation) and core damage progression, but neglected skin damage progression.

13.2 Impact Analysis

For low-velocity impacts, the amount of damage can be analysed using iterative static analysis combined with the energy theorem of the contact problem [11]. Alternatively, a dynamic analysis can be chosen. The advantage of the latter is that the numerically obtained transient impact response can be validated by comparing it to respective experimental results. The impactor is usually coupled to the composite plate using the Hertzian contact law.

The DLR in-house tool CODAC, which aims for an efficient impact analysis, applies the implicit Newmark time integration scheme in order to reproduce the transient impact event. Further information on the impact analysis in CODAC can be found in [8, 9, 12].

13.2.1 Impact on a Monolithic Composite Panel

In the past, a great amount of research has be done to enable the prediction of impact damage in composite structures. Abrate [11] gives a good overview of impact studies on composite materials. The effects of local damage on the impact behaviour and on the load bearing capacity have been studied by several authors with differing focus. A short literature review can be found in [5].

Impacted composite panels are usually modelled with shell elements based on the first order shear deformation theory. However, transverse stiffness and stresses are important for the damage progression during impact. Thus, the Extended 2D Method by Rolfes and Rohwer [13] has been implemented in CODAC to improve the transverse properties.

Impact simulation results in the shape of damage areas are illustrated in Fig. 13.2. To model the complex damage state that develops during impact, a damage mechanics methodology according to Sect. 13.1.1 is applied in CODAC. For each Gauss point and each ply, the damage states are stored in a database and updated in real-time during the analysis [12]. In the presented example [14] a 5 mm thick composite plate was impacted with 30 J. Two different failure criteria have been applied and compared to test results. Due to a lack of experimental data, unfortunately, fiber and matrix cracking often cannot be properly assessed. In terms of delamination areas, the Chai failure criterion [4] provided better results than the Choi/Chang criterion [3].

In addition to the computed damage state, the force–time history is another important result of an impact analysis. Through maximum contact force and sudden curve drops or kinks, it provides information on the overall impact behaviour and on the damage progression. For the above presented impact test program, unfortunately, force–time histories were not available. A further impact test program is discussed in [12], where force–time histories are compared to experimental results, cf. Fig. 13.3.

13.2.2 Impact on a Composite Sandwich Panel

Since impact damage in sandwich structures can provoke a significant reduction in strength and stability, the number of publications has greatly increased in the last 10 years. Numerous experimental studies were conducted to observe the impact damage progression. Several methodologies have been developed to predict the impact response and the amount of impact damage. While simple analytical approaches require less computational effort, FE-based approaches generally attain a more accurate description of the impact response. Literature reviews can be found in [8, 9].

An important requirement for suitably simulating impact damage is the accurate approximation of in-plane and transverse stresses. For that reason, two new three-layered shell elements have been developed and implemented into CODAC.

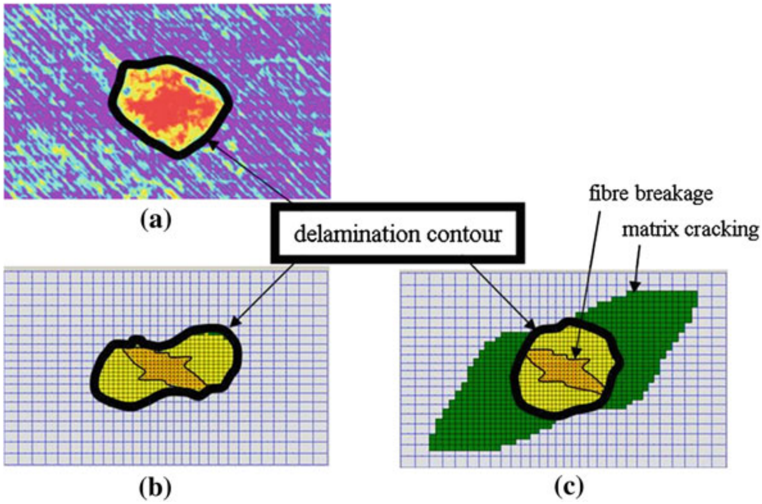

Fig. 13.2 Test result versus damage areas of two damage models [14]. **a** Test result. **b** Choi/Chang with degradation. **c** Chai with degradation

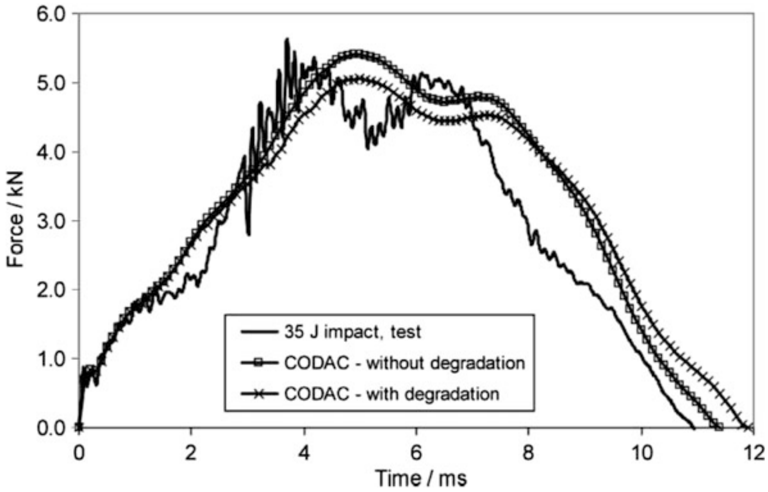

Fig. 13.3 Force–time history for a mid-bay impact on a two-stringer panel [12]

The first element, proposed by Kärger et al. [15], is based on a plane stress assumption and applies improved transverse stiffness and stresses by means of an enhanced Extended 2D Method. The second sandwich element, proposed by Wetzel et al. [16], accounts for the full 3D stress state and, thus, provides a higher accuracy for concentrated out-of-plane loads. Moreover, the strain–displacement relation is enhanced by nonlinear terms to take into account the membrane effect

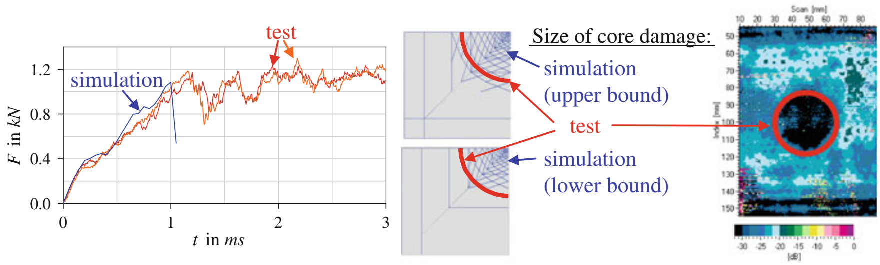

Fig. 13.4 Simulation results: Force-time history and core damage compared with test results

of large deflections in the impacted skin. Although it is computationally more expensive, it is recommended for the impact simulation in CODAC.

The complex impact damage behaviour of composite sandwich structures is modelled using the damage mechanics approach described in Sect. 13.1.2. Similar to the impact analysis of monolithic structures, the damage states of each Gauss point and each ply are stored in a database and updated in real-time during the analysis.

Impact simulation results, such as force–time histories and core damage areas, are illustrated in Fig. 13.4. In this study [9], a sandwich plate, with a 28 mm thick honeycomb core and a 0.63 mm thin CFRP skin, was impacted by energies between 1 and 15 J. Up to the onset of skin tearing at contact forces larger than 1 kN, it could be experimentally validated that force–time histories as well as core damage areas are well predicted by simulation. For higher energies, the core damage is properly limited by a lower and an upper bound. Furthermore, the presence of clearly visible skin damage is properly predicted. The lower bound represents the core damage at the moment when the skin starts to tear. The upper bound of the core damage is computed assuming an intact skin during the whole impact simulation.

13.3 Residual Strength Analysis

NVID/BVID can have a substantial effect on the load bearing capability of the composite laminate. This is particularly pronounced when delaminations locally split a monolithic laminate into several sublaminates, or if the core material of a sandwich structure loses its out-of-plane stiffness. Such damage not only reduces bending stiffness and strength, but also causes local instability. Compressive loading may cause these local instability effects, requiring an assessment of the residual, compression-after-impact (CAI) strength.

13.3.1 CAI Analysis for Monolithic Composites

Impact induced delaminations split a monolithic laminate into several sublaminates and, thus, cause a considerable local stiffness reduction. During postbuckling of the

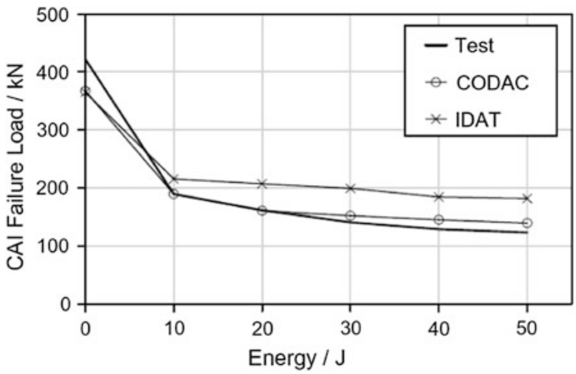

Fig. 13.5 Reduction of residual strength for increasing impact energy. Present methodology (CODAC) and alternative approach (IDAT) compared to test results [14]

sublaminates, the delamination region will behave like a soft inclusion. This leads to stress concentrations at the crack tips of the delamination. These stress concentrations may cause further delamination and damage growth and, in the worst case, lead to failure of a complete structure before the compressive strength of the undamaged laminate is reached.

Assuming a composite laminate of negligible curvature under plane stress, the stiffness loss of the delaminated region can be modeled using a Ritz approach to analyze sublaminate buckling [17]. This Ritz approach can be repeatedly applied to damaged regions with multiple stacked delaminations. It accounts for the fact that buckling of inner sublaminates is prevented by yet unbuckled adjacent sublaminates. Subsequently, stiffness reduction factors can be derived from these buckling loads [18]. Additional stiffness reduction caused by matrix cracking and fiber breakage should also be considered (Sect. 13.1.1), since the presence of these damage modes can further reduce the CAI strength.

A standard FE evaluation of the composite structure that accounts for reduction of stiffness can predict the stress concentration. A point-stress or average-stress fracture criterion can be used to predict damage growth. Tang et al. [18] proposed a semi-empirical point-stress fracture criterion, the so-called Damage Influence Criterion (DIC), for application to NVID/BVID. The DIC assumes failure in the cross section through the center of the damage, perpendicular to the uniaxial loading of the laminate.

Figure 13.5 shows a typical development of the uniaxial residual compressive strength for 4.5 mm thick specimens that were impacted with increasing impact energies. In this case, an impact energy of 10 J reduces the compressive strength already by about 50%. For higher energies, the residual strength is further reduced, but to a much smaller extent.

The present simulation approach, which applies the DIC (CODAC), reproduces this behavior quite well. The CODAC approach is compared to another approach (IDAT), where the CAI analysis is performed by an implicit, non-linear static FE solution using ABAQUS/Standard. Further details about the CAI analysis and validation results can be found in [5, 14].

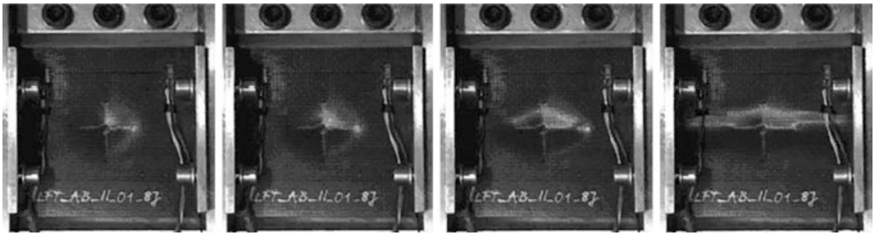

Fig. 13.6 Growth of impact indentation for compressive loading in vertical direction (increasing from left to right) [10]. *Source* ILR, TU Dresden

13.3.2 CAI Analysis for Composite Sandwich Structures

Low-velocity impact on composite sandwich structures typically causes a barely visible permanent indentation accompanied by invisible core damage below the indented face sheet. Compressive failure of impact damaged composite sandwich structures is often initiated by the growth of the initial permanent indentation in the direction perpendicular to the applied loading, cf. Fig. 13.6. This is accompanied by further core damage [19].

For the analysis of unsymmetrical honeycomb sandwich structures, a 3D FE model was used. The relatively thick core was modelled with volume elements and the thin face sheets with composite shell elements. In order to obtain accurate results, a careful evaluation of transverse stiffness and strength properties is essential. According to experiments (cf. Sect. 13.1.2), the post-failure reduction of transverse normal and transverse shear stiffness of the sandwich core was modelled using degradation factors of 0.2 and 0.01, respectively, cf. Eq. (13.1). This simple approach has been found to model the crushing behaviour of the core in an acceptable manner [10, 20]. The example in Fig. 13.7 shows that strain gauge measurements outside of the damage area (strain gauges 10 and 11) correspond well with the 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. 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 fiber and matrix fracture is expected. This might be the reason, why the simulation overestimates compressive strains at strain gauge 12, which is located on the border of the face sheet and the core damage resulting from the 4 J impact.

In order to improve computational efficiency, a non-linear semi-analytical Ritz method has been developed, which uses a 1-parameter stiffness model of the Winkler type for the core material. Instead of the core degradation model used for the 3D approach, a simplified model by Olsson [21] is applied here.

Unless face sheet damage substantially influences the compressive failure of the sandwich structure, the semi-analytical Ritz approach provides a very efficient

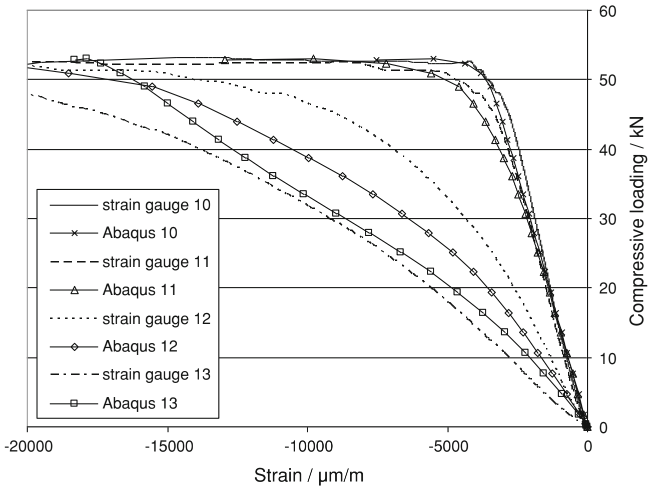

Fig. 13.7 Comparison between simulation results and test results: strains in loading direction in the vicinity of the 4 J impact versus compressive loading of the panel. Strain gauges are located abreast the impact damage with a distance between 7.5 mm (strain gauge 13) and 31.5 mm (strain gauge 10) from the damage centre [20]

means for the assessment of the CAI strength of sandwich structures. While accounting for face sheet damage is possible in principle, the Ritz approach loses its advantage in computational efficiency over a FE approach [10, 20].

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