EFFICIENT PREDICTION OF COMPOSITE DAMAGE TOLERANCE

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Abstract

The finite element (FE) tool CODAC (Composite Damage Tolerance Analysis Code) is presented, which can evaluate low-velocity impact behaviour and residual strength of composite structures. CODAC is a fast tool for use in the design process and allows for a quick evaluation of damage resistance and damage tolerance of wing and fuselage structures of today's and future aircraft. A methodology for the simulation of low-velocity impact of stringer-stiffened panels as well as methods for the prediction of the compression after impact (CAI) strength of composite laminates are described. Currently CODAC is being extended for application to sandwich structures. Special FE formulations were developed, permitting an accurate and efficient calculation of deformations and stresses in sandwich structures. These are necessary for the prediction of damage in the relatively soft core material due to combined transverse compressive and shear loading during an impact event. A comparison of CODAC's predictions to experimental data is presented, the first example being an impact on a two-stringer monolithic panel, the second being an impact on a honeycomb sandwich plate.

1 Introduction

Aircraft manufacturers are competing in making their products safer and more efficient, reducing the impact of air traffic on the environment and lowering the maintenance cost. The increasing use of composites is a means to address all of the above mentioned 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 behaviour. Tool drop or runway debris can lead to impact damage, which may be just barely visible, but can nevertheless reduce the residual strength of the composite structure substantially. Owing to missing analytical and numerical tools time and cost intensive experiments are conducted, to assess the damage resistance and damage tolerance of composite materials and structures. With such an experimental approach a design for damage tolerance is too expensive.

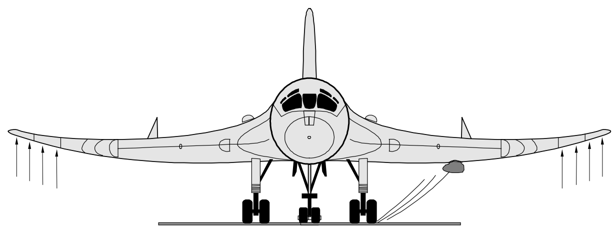

Fig. 1 Impact by runway debris can cause non- or barely visible impact damage (NVID, BVID) in composite structures.

To improve this situation, the program CODAC (Composite Damage Tolerance Analysis Code, DLR in-house tool) is developed. CODAC can quickly evaluate low-velocity impact behaviour and residual strength and is intended for the use in the design phase of composite structures. While originally being developed for the analysis of monolithic structures (stringer-stiffened panels), it is presently being extended for application to sandwich structures.

2 Stringer-stiffened composite panels

2.1 Impact

In CODAC finite eight-node shell elements with five degrees of freedom per node are used to model stringer stiffened composite structures, see Figure 2. The stringer is attached to the skin by either co-curing or adhesive bonding. Contact between impactor and structure is modelled by the Hertzian contact law, which relates the concentrated contact force F_c to the indentation α

$$F_\mathrm{c} = \frac{4}{3}\left(\frac{(1-\nu_i^2)}{E_i} + \frac{(1-\nu_s^2)}{E_s}\right)^{-1} r^{1/2}\alpha^{3/2},$$

with the radius of the impactor r and the elastic properties ν_i, E_i and ν_s, E_s of impactor and structure, respectively. For the formulation of the transient impact response an implicit Newmark time stepping scheme is employed.

While the determination of the in-plane stress components σ_{xx}, σ_{yy} and σ_{xy} makes no complications for 2-D shell elements, the determination of the transverse shear stresses σ_{yz} and σ_{zx} requires close attention. Because these stress components play an important role for matrix and delamination failure, it is essential to assess them as accurately as possible. In CODAC the so-called 'Extended 2-D Method' is implemented, which improves accuracy by using equilibrium conditions instead of the material law for the determination of the transverse stress components [7].

For the different failure modes of fibre breakage, matrix cracking and delamination separate stress based failure criteria are used for the assessment of damage during the transient impact process. For fibre failure the maximum stress criterion is used, while for inter-fibre failure the physically based criterion from Hashin is recommended. For delamination failure due to low-velocity impact physically based criteria from Puck and Hashin have yielded unsatisfactory results. For this failure mode a special semi-empirical criterion from Choi/Chang has lead to better results [3]. A serious limitation of the modelling approach in CODAC using 2-D shell elements is it's inability to properly model delaminations, which split the laminate into two or more sub-laminates. This failure mode leads to a reduction in bending stiffness and strongly influences the transverse shear distribution. A proper model of a delaminated structure would require e.g. a model of stacked shells and a method to deal with the contact problem between the different sub-laminates. However, it will be shown here that it is possible to quickly achieve acceptable results with the presented simplified methodology.

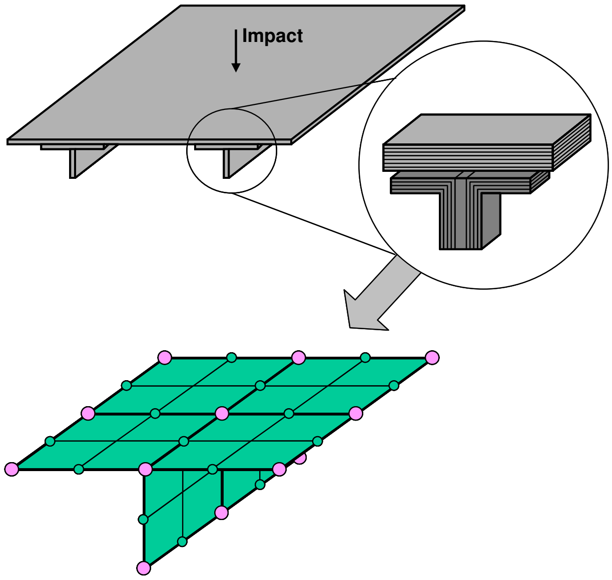

Fig. 2 Modelling of stringer-stiffened structures using 8-node finite shell elements.

A damage mechanics methodology is applied to be able to deal with the complex damage state that develops during an impact. Stress and damage are evaluated in the four Gauss points of the elements in each ply of the composite laminate. During the transient impact analysis the 3D damage state is stored in the so-called Damage Data Structure (DDS) and updated in every time step. The softening effect of damage (degradation) is modelled by reducing the stiffness of the damaged region. Combination and interaction of damage modes can be accounted for.

2.2 Sub-laminate buckling and delamination growth

For the evaluation of the damage tolerance of composite structures it is not sufficient to know the impact damage, it is also necessary to be able to predict the residual strength of the damaged structure. Impact damage typically consists of nearly elliptical delaminations with increasing size from the top (impacted side) to the bottom of the laminate. This delamination damage is often accompanied by fibre breakage and matrix cracks.

While often not being visible to the naked eye, delamination damage can be dangerous, because delaminated sub-laminates can buckle locally due to compressive loading. Sub-laminate buckling contributes to the softening effect of the impact damage. It can also lead to delamination growth.

Critical for sub-laminate buckling and delamination growth is usually a large delamination separating a thin sub-laminate from a much thicker base laminate, see Fig. 3.

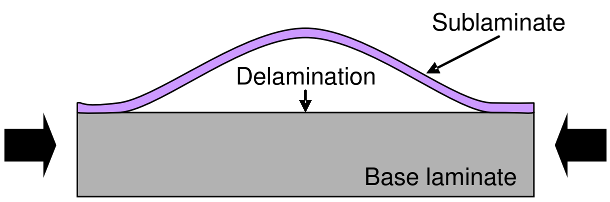

Fig. 3 Buckled sublaminate under post-impact compressive loading.

In CODAC sub-laminate buckling as well as stable and instable delamination growth are modelled using a non-linear Rayleigh-Ritz approach [2]. Four degrees of freedom (DOF) for the out-of-plane displacement of the sub-laminate and two DOF for each of the in-plane deformations make a total of eight DOF for an elliptical sub-laminate. On the border of the delamination a clamped boundary condition is assumed. The von-Karman stress-strain relationship is used to be able to simulate the post-buckling behaviour of the sub-laminate. For the solution of the non-linear system of equations the Newton-Raphson method is employed.

Possibly contact occurs between sub- and base-laminate. For this case, a numerical integration over the contact region is performed. A linear elastic behaviour with the contact modulus as a parameter is assumed to govern the relationship between contact force and deformation of the sub-laminate in the contact region.

Delamination growth is assumed to occur in the post-buckling regime of the delaminated sub-laminate. In a strain increment loop the in-plane strains are increased. In each increment the strain energy release rate G is computed for an increase of both half-axes of the elliptical sub-laminate and compared to the critical strain energy release rate G_c. If $G \geq G_c$, the delamination is assumed to grow along the respective half axis until G becomes smaller than G_c.

2.3 Strength based failure

Another typical failure mode of an impacted composite under compressive loading is strength based failure at the stress concentration near the soft inclusion at the impact location. A special point-stress criterion, the so-called Damage Influence Criterion (DIC) is used to predict this type of failure [8].

The first step is to determine the reduction of stiffness in the damage area. For delamination damage buckling loads per unit width N_n are determined for all possible outer (i.e. next to a laminate surface) sub-laminates n. For each delamination in the laminate there are two such sub-laminates. The smallest of these buckling loads is selected, the corresponding sub-laminate is removed from the laminate and the buckling analysis is repeated for the remaining laminate until all sublaminates have been assigned a buckling load.

For all buckling loads a stiffness reduction factor R_n is calculated, which is then assigned to all plies belonging to the corresponding sub-laminate. The stiffness reduction factor R_n for each sub-laminate n can be expressed as

$$R_n = \min\left(\frac{N_n}{t_n \sigma_0}, 1\right) = \min\left(\frac{\sigma_n}{\sigma_0}, 1\right)$$

with the critical buckling load for the sub-laminate N_n, the sub-laminate thickness t_n and the compressive strength of the undamaged laminate σ_0.

The stiffness reduction factor for delamination damage is applied to all components of the stiffness matrix **C**. In case of additional fibre and/or matrix damage further stiffness reduction of affected components of the stiffness matrix **C** is performed.

Subsequently a FE analysis of the structure with the soft inclusion under compressive loading is performed. Application of the DIC on the resulting stress distribution around the soft inclusion leads to the compressive strength of the damaged structure [8].

3 Sandwich structures

Presently CODAC is being extended for application to sandwich structures. Since double shell structures are capable of carrying high bending loads and allow a high level of structural integration, they are very attractive for aerospace applications. Composite sandwich structures are characterized by a core of comparatively small stiffness and thin face sheets of a very high stiffness.

3.1 Deformation and stress analysis

An accurate approximation of in-plane as well as transverse stresses is an important prerequisite for suitably simulating impact damage and computing residual strength. For that reason a three-layered finite element formulation is proposed, which efficiently analyzes deformation and the 3D stress state of sandwich structures [6]. The kinematics of layer L are described by

$$\begin{bmatrix} u_L \\ v_L \\ w_L \end{bmatrix} = \begin{bmatrix} u_L^0 \\ v_L^0 \\ w_L^0 \end{bmatrix} + z_L \begin{bmatrix} \psi_{xL} \\ \psi_{yL} \\ \psi_{zL} \end{bmatrix} + z_L^2 \begin{bmatrix} 0 \\ 0 \\ \varphi_{zL} \end{bmatrix}$$

where u_L^0, v_L^0, w_L^0 are the displacements at the layer reference planes $z_L = 0$. By satisfying the compatibility conditions at the layer interfaces, 15 degrees of freedom arise in total: three translations u_0, v_0, w_0, six rotations ψ_{xL}, ψ_{yL} and six degrees of freedom ψ_{zL}, φ_{zL} for the displacements in thickness direction. The approach of the out-of-plane displacements is chosen parabolically, in order to avoid Poisson thickness locking. The isoparametric quadrilateral eight-node shell element of the serendipity family only requires C^0-continuity conditions, which simplifies its integration into FE codes. While in-plane stresses are computed via the material law, out-of-plane stresses have to be improved with the above mentioned 'Extended 2D-Method', which has been adapted to a three-layered shell model [5].

3.2 Failure analysis during impact

As for monolithic composites CODAC's impact simulation for sandwich structures applies the Newmark time stepping scheme and the Hertzian contact law [4]. During impact the core is loaded by combined shear and compression. Therefore a suitable failure criterion should include both, transverse normal and transverse shear stresses. Besant et al. [1] carried out combined shear-compression tests on aluminium honeycombs and proposed the yield criterion

$$\left(\frac{\sigma_{zz}}{\sigma_{cu}}\right)^n + \left(\frac{\tau_{xz}}{\tau_{lu}}\right)^n + \left(\frac{\tau_{yz}}{\tau_{tu}}\right)^n = e_{\text{core}},$$

where a value of $n = 1.5$ produced the best fit with experimental results.

Stresses and damage are evaluated at the four Gauss points of the element. Therefore each finite element is divided into four 'element units', and each element unit is degraded separately if $e_{\text{core}} > 1$. Degradation of the core material is realized by reducing the stiffness components C_{ij} with degradation factors D_{ij} resulting in a degraded stiffness matrix $\mathbf{C}^*$. Whereas degradation of the in-plane stiffness components of the core is insignificant, the impact response is very sensitive to degradation of the out-of-plane stiffness components. Stiffness reduction alone is not sufficient to describe the stress-strain behaviour of the core. In fact, the honeycomb core behaves elasto-plastically as schematically shown in Fig. 4. Thus, the core crushes at a non-zero stress level and therefore absorbes energy, which has to be included in the principal of virtual work. Representing the absorbed energy by finite elements

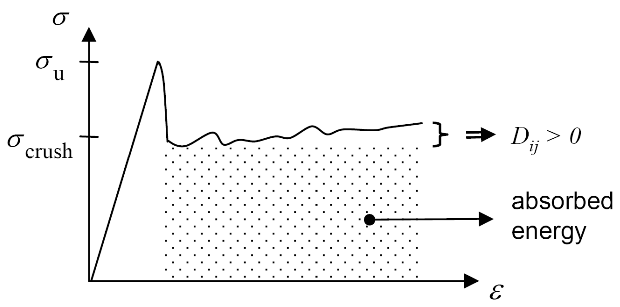

Fig. 4 Schematic stress-strain path for core compression.

and varying it against the nodal displacements $\mathbf{u}_e$, the inner force

$$F_{i,pl} = \frac{\partial W_{i,pl}}{\partial \mathbf{u}_e} = \int_A \left(\int_h \sigma_{\text{crush}} \mathbf{B} dz \right) \mathbf{N} dA$$

has to be taken into account, where $\mathbf{B}$ is the operator matrix of the strain-displacement relation and $\mathbf{N}$ is the matrix of the finite element shape functions.

For modeling face sheet damage several approved failure criteria for fibre breakage, matrix cracking and delamination are available. However, matrix cracking and delamination of thin sandwich skins have no considerable effect on the impact response. Furthermore, the amount of fibre breakage for barely visible impact damages (BVID) is negligible. Therefore, degradation of face sheets is not needed for modeling BVID and for simulating the corresponding impact events. At higher impact energies substantial, clearly visible fibre breaks occur in the impacted face sheet and lead to a different impact behavior. Simulating such impacts with clearly visible damage requires a damage model also for the impacted face sheet.

4 Examples

A comparison of CODAC's predictions with experimental data is presented, the first example being an impact on a two-stringer monolithic panel, the second one being an impact on a honeycomb sandwich plate.

4.1 Two-stringer CFRP panel

The contact force history for a 35 Joule mid-bay impact on a two-stringer panel is shown in Fig. 6. Impact duration and maximum contact force are predicted quite accurately by CODAC.

The delamination area was predicted using the Choi/Chang criterion with a scaling parameter of $D_a = 1.0$. Delaminations are predicted to increase from the impacted side towards the bottom of the laminate, which is confirmed by the experiment. The overlapped delamination size is shown in Fig. 7. While the absolute size of the overlapped delamination area agrees well, angle and shape of the large bottom delamination differs slightly between simulation and experiment.

As expected, taking degradation into account during the impact simulation slightly reduces the maximum contact force and the overlapped damage size.

For the residual strength of the impacted panel there is no experimental data available. CODAC predicts that the large delamination at the bottom interface does not grow for far field strains smaller than 8.0‰.

Assuming an undamaged compressive strength of the skin laminate of 400 MPa, corresponding to a compressive strain of 7.2‰ of the undamaged laminate, the soft inclusion approach implemented in CODAC predicts a maximum CAI strain of 4.6 ‰ for the damaged skin laminate. This prediction does not account for stability effects. The load-bearing capability of the damaged two-stringer panel will be substantially lower.

4.2 Honeycomb sandwich structure

In accordance with the introduced core failure criterion and degradation model, a multitude of numerical simulations was conducted and compared to impact tests carried out at ILR, TU Dresden. For one of these (Fig. 8) the force-time history and the core damage area are shown in Fig. 9 and 10, demonstrating the effects of different degradation models on the impact response and on the damage size. For reference the results rep-

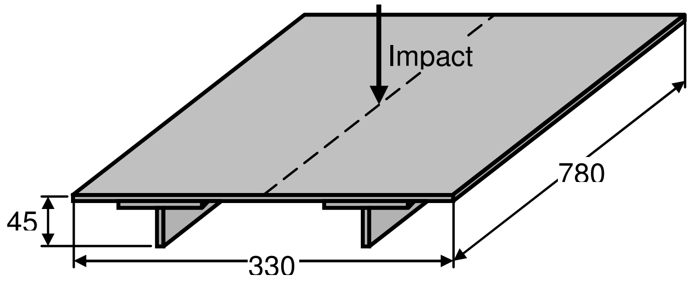

Fig. 5 Two-stringer panel with impact loading.

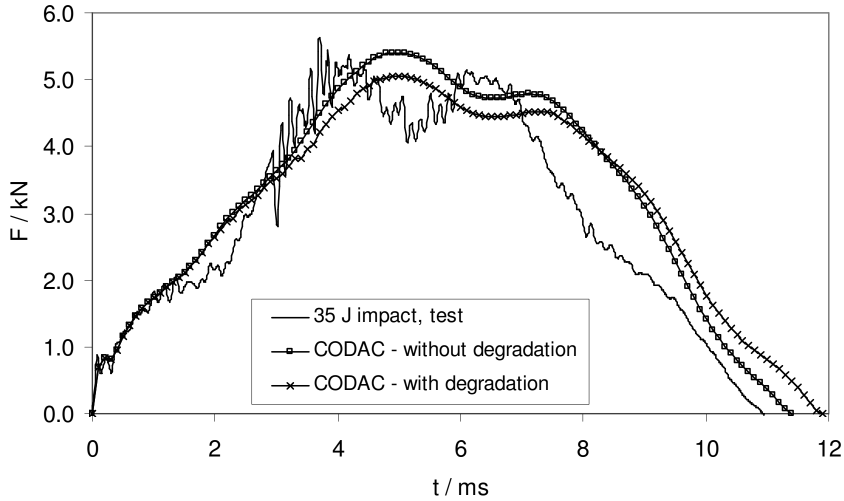

Fig. 6 Force-time history for a 40 Joule mid-bay impact on a two-stringer panel.

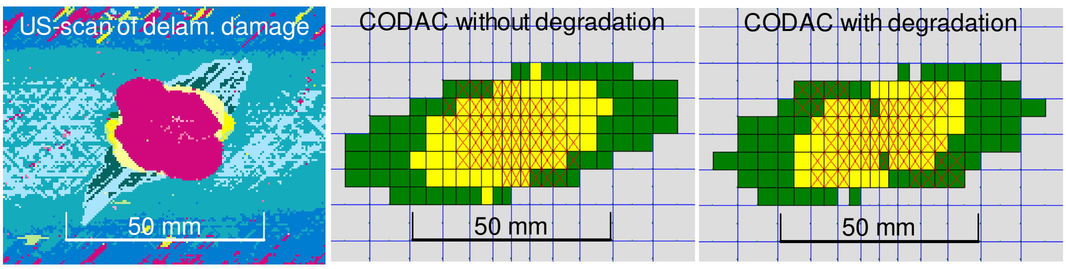

Fig. 7 Overlapped damage size for a 35 Joule mid-bay impact on a two-stringer panel. Yellow areas in the CODAC simulation indicate combined matrix cracking and delamination damage, green areas indicate matrix cracking, red crosses indicate fibre failure.

resenting the 'no degradation' approach are included.

Onset of core damage was computed at a contact force of 0.23kN, which agrees very well with the experimental results. As expected, a total core degradation ($Dij = 0, \sigma_{i,crush} = 0$) results in an underestimation of the contact force and an overestimation of the damage area. The outer border of the experimental damage area, which was taken from ultrasonic scans and is used for comparison, is displayed by circular lines in Fig. 10. By taking the remaining core resistance into account and applying the proposed core degradation model, the experimental results are approximated much better. Since the unloading stress-strain-path of the plastically deforming core is

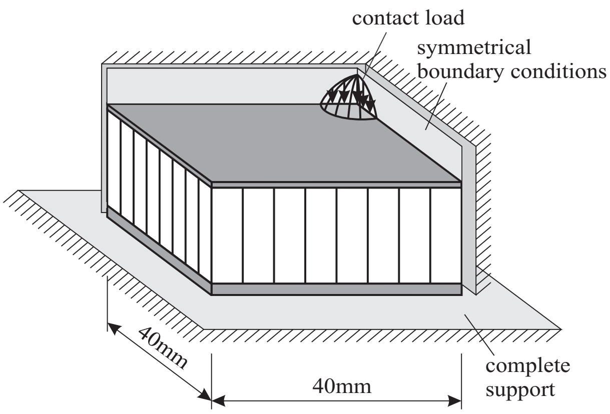

Fig. 8 Sandwich structure with impact loading.

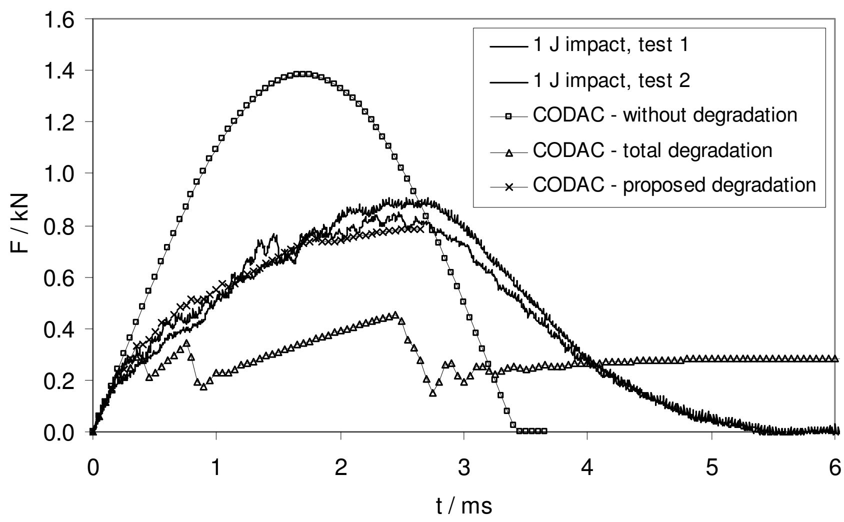

Fig. 9 Force-time histories for different core degradation models, 1J impact.

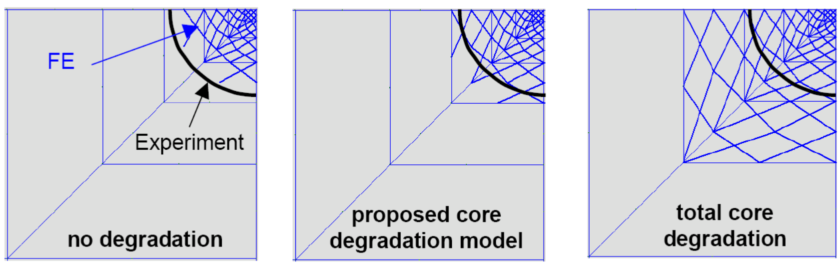

Fig. 10 Core damage areas for different core degradation models, 1J impact.

not implemented yet, the force-time curve, which accounts for absorbed energy, is displayed only up to maximum deflection.

Concluding the numerical investigations, the force-time curve and the core damage area are very well approximated by the presented methodology for impacts leading to barely visible damage. Impacts of larger energy resulting in clearly visible damage up to complete tearing of the impacted face sheet require an improved degradation model for the face sheets. Additionally geometrical non-linearity has to be taken into account because of large deflections in the vicinity of the impact location. These are fields of current investigations.

5 Conclusion

An efficient methodology is presented for the prediction of the low-velocity impact behaviour of composite stringer-stiffened panels, including the generation of impact damage. Models for the simulation of strength based failure at the stress concentration near the impact location and for delamination growth due to sub-laminate buckling are described. These enable the assessment of the compressive strength of composite laminates containing non or barely visible impact damage.

Recently developed three-layered finite shell elements are used to model sandwich structures. It is shown that the transient response of such structures during a low-velocity impact is strongly influenced by failure and degradation of the core material. For an accurate prediction of contact force and core damage a non-zero crush strength of the core material has to be taken into account.

Experimental results are used for validation of the presented methodologies. It is shown that these are able to quickly produce acceptable results for impact behaviour and residual strength of composite structures.

Currently ongoing investigations concentrate on the effects of geometrical non-linearity on the impact behaviour, improved degradation models for sandwich face sheet damage and on the prediction of the residual strength of impacted composite sandwich structures.

6 Acknowledgement

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