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MODELLING IMPACT DAMAGE IN DOUBLE-WALLED COMPOSITE STRUCTURES

Alastair F. Johnson and Nathalie Pentecôte

German Aerospace Center (DLR)
Institute of Structures and Design
Pfaffenwaldring 38-40
70569 Stuttgart (Germany)
Email: alastair.johnson@dlr.de, nathalie.pentecote@dlr.de, web page: http://www.st.dlr.de/BK

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Summary. *The paper describes recent progress on materials modelling and numerical simulation of foreign object impact damage in fibre reinforced composite aircraft structures. The work is based on the application of finite element (FE) analysis codes to simulate damage in composite shell structures under impact loads. Composites ply damage models and interply delamination models have been developed and implemented in commercial explicit FE codes. The failure models and code developments are validated in the paper by predicting transverse impact damage in composite aircraft sandwich structures and comparing numerical simulations with high velocity gas gun impact test data.*

1 INTRODUCTION

To reduce development and certification costs for composite aircraft structures, efficient computational methods are required by the industry to predict structural integrity and failure under dynamic loads, such as crash and impact. By using meso-scale models based on continuum damage mechanics (CDM)[1,2], it is possible to define materials models for FE codes at the structural macro level which include damage induced at the micromechanics level. CDM provides a framework within which in-ply and delamination failures may be modelled. In previous work[3] a delamination model was obtained by applying the CDM framework to the ply interface[2] with fracture mechanics concepts introduced to relate the total energy absorbed in the damaging process to the interfacial fracture energy. The delamination model has been implemented into a commercial explicit FE crash and impact code PAM-CRASH™ [4] using stacked shell elements and contact interfaces, which may separate when the interface fracture energy condition is reached, to model delamination failure.

The paper describes the application of these simulation methods to design studies on a novel form of double-walled composite panels with energy absorbing cores currently being assessed for use in aircraft structures. These are non-standard sandwich structures, in which a main load-bearing composite laminate is protected from impact damage by an energy absorbing core and a second cover laminate. Core materials being considered include folded composite plate structures, polymer foams and Nomex honeycomb. Impact load cases of interest include high velocity impacts from steel impactors and deformable, soft body impactors such as ice and rubber. Representative structures are modelled and FE simulation results are presented, which simulate numerically the observed impact failure modes and failure progression under medium to high impact velocities representative of civil aircraft applications. Of particular interest is to determine the impact damage threshold in the inner load-bearing laminate for impacts on the cover laminate, as impactor type and impact energy is varied. Effective delamination models are required in this inner laminate to determine damage levels for the cases when the projectile penetrates the cover laminate and core. FE simulation results are compared with gas gun impact test data on idealised double-wall panel structures at impact velocities in the range 60 – 250 m/s.

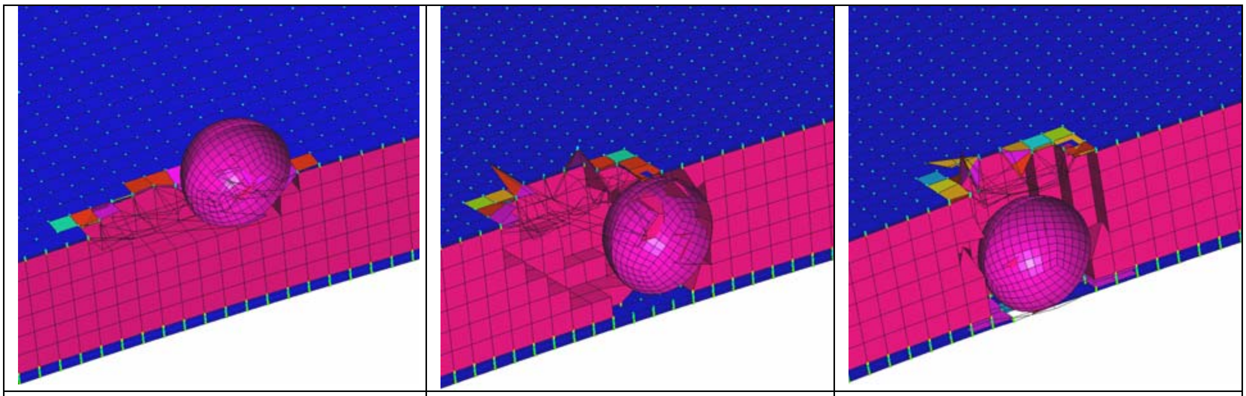
2 FE MODELLING OF IMPACT IN SANDWICH PANELS

Composite sandwich panels are of considerable interest in aircraft structures such as impact resistant fuselage panels and as low weight panels in wing leading edges and flaps. They are susceptible to impact damage due to their thin composite skins, but with suitable core materials may be designed to absorb impact energy. As part of a design concept study for impact resistant aircraft sandwich structures a number of sandwich panel variants have been designed and fabricated by the aircraft industry[5], and in-house at the DLR[6]. High velocity impact tests on these structures provide a database for validation of the impact simulation methodology described in this paper. The sandwich panels of interest consist of carbon fibre/epoxy skins with both UD and fabric reinforcements with several core variants are being considered, including polymer foam, Nomex® aramid paper honeycomb, and cellular composite cores of folded aramid/epoxy paper. Typical high velocity impact tests on composite sandwich panels show that impact damage and failure, particularly with hard projectiles, is very localised consists of penetration of the outer composite skin, damage to the core and, if impact energy is high enough, core penetration followed by inner skin damage or fracture. In order to simulate this local damage and failure detailed FE models are required representing small sandwich structural elements in the impacted region.

The composite laminate is modelled by layered shell elements or stacked shells with a contact interface which may fail by delamination. The shells are composed of composite plies which are modelled as a homogeneous orthotropic elastic damaging material whose properties may be degraded on loading by microcracking prior to ultimate failure. This paper uses the PAM-CRASH$^{\text{TM}}$ [4] FE code which contains bilinear 4-node quadrilateral isoparametric shell elements with uniform reduced integration in bending and shear. A Mindlin-Reissner shell formulation is used with a layered shell description to model a composite ply, a sublaminate or the complete laminate. The simulation results presented here are based on the ‘bi-phase’ ply model for UD and fabric plies in which it is supposed that damage evolution is dependent on strain invariants. The simplifying assumption is made that the composite ply has a single damage function d acting on the stiffness constants which is assumed to be a function of the second strain invariant ε_{II}, or the effective shear strain. Because of this shear strain dependence the damage parameter degrades the matrix dominated shear properties more strongly than the fibre properties. In the layered shell element the stiffness properties of the plies are degraded as the shear strain invariant increases until eventually a damaged shell element is eliminated from the computation when the shear strain invariant reaches a pre-defined critical value.

The delamination model[3] is implemented in the PAM-CRASH^{TM} code, with the laminate modelled as a stack of shell elements. Each ply or sublaminate ply group is represented by a set of layered shell elements and the individual sublaminate shells are connected together using a contact interface with an interface traction-displacement law. Contact may be broken when the interface energy dissipated reaches the mixed mode delamination energy criteria. This ‘stacked shell’ approach is an efficient way of modelling delamination, with the advantage that the critical integration timestep is relatively large since it depends on the area size of the shell elements not on the interply thickness.

In the simulation results presented here the skin laminates are each modelled as 3 stacked shell elements with 2 delamination interfaces. Each shell in the stack represents a sub-laminate modelled as a layered shell element. There are several modelling methods available for honeycomb cores. Here it is assumed to be an orthotropic bi-phase solid, with 1-axis in the honeycomb cell direction, modelled by a user-defined elastic/plastic materials law. Suitable parameters for the model have been derived at the DLR, based on through-thickness crush tests on Nomex core sandwich beam elements[6]. Contact interfaces model the adhesive bond between core and skins based on a through-thickness tension/shear fracture condition.



30° impact t = 1.08 ms

60° impact t = 2.12 ms

90° impact t = 2.0 ms

Fig. 1: Simulated damage in the double-skin structure (M = 22 gram, V_0 = 60 m/s)

Impact scenarios of interest for lower fuselage structures and wing panels are impact by tyre fragments and runway debris during start and landing. Because of the short time of the impact event, the structural restraint and boundary conditions outside the impacted region have little influence on local damage. A refined FE model for a sandwich plate segment typically has plate dimensions 250 x 250 mm, core thickness ca. 30 mm and 0.8 - 3 mm thick carbon/epoxy skin laminates with UD and /or fabric reinforcement. Simulated impact damage from such a model is shown in Fig. 1, which represents a 25 mm diameter stone projectile with mass 22 gram and impact velocity 60 m/s impacting the sandwich plate element at 90°, 60° and 30° impact angle. In the examples shown the outer sandwich skin is 0.8 mm carbon fabric/epoxy for impact protection and impact damage detection, with the inner skin load bearing and ca. 2.5 mm quasi-isotropic UD carbon/epoxy laminate, with a Nomex core. The stone is modelled as a rigid sphere in this case. Results in Fig. 1 show that the stone fractures the thin CF/epoxy outer skin, then penetrates and crushes the core. In Fig. 2 the normal velocity of the projectile is shown as it is slowed down during penetration of the sandwich. At 30° impact to the plate surface the projectile bounces off with limited damage to the Nomex core. At 60° impact angle there is extensive core damage, with the projectile rebounding onto the outer skin, but no damage to the inner skin laminate. Under normal impact at 90° the projectile penetrates through the core and is stopped by the inner skin, which has both delamination and ply damage. The detailed curves in Fig. 2 show that the composite skins have a more significant effect in absorbing impact energy and slowing the projectile than the Nomex core. These simulation results agreed well with DLR gas gun tests with concrete and glass projectiles on similar sandwich panels which showed extensive core damage and penetration at about 60 m/s normal impact. Thus the methodology developed here may be used further to evaluate monolithic, double shell and sandwich design concepts for aircraft fuselage and wing structures subjected to high velocity impact loads.

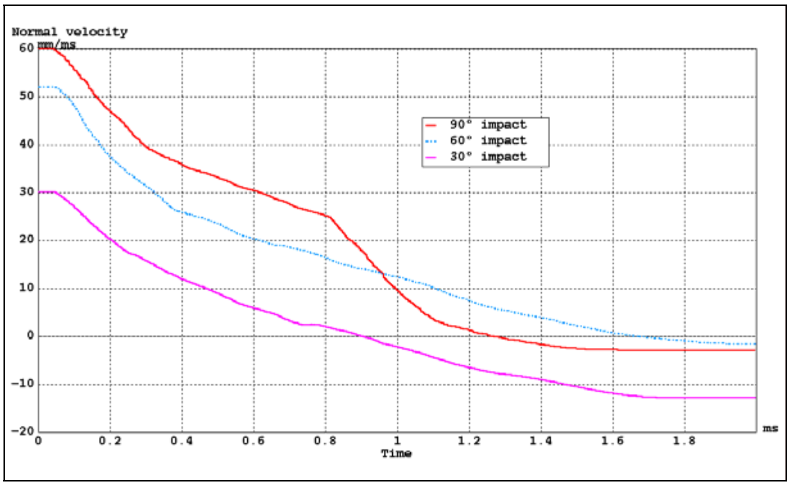


Fig. 2: Predicted normal velocity of projectile during impact (M = 22 gram, V_0 = 60 m/s)

REFERENCES

[1] P. Ladevèze, Inelastic strains and damage, Chapt. 4 in “Damage Mechanics of Composite Materials”, R. Talreja (ed), *Composite Materials Series*, Vol 9, Elsevier,1994.

[2] O. Allix, P. Ladevèze, Interlaminar interface modelling for the prediction of delamination, *Composites Structures*, **22**, 235-242,1992.

[3] A.F. Johnson, A.K. Pickett, P. Rozycki, Computational methods for predicting impact damage in composite structures, *Composites Sci. and Technol.*, **61**, 2183 – 2192, 2001.

[4] PAM-CRASH™ FE Code, Engineering Systems International, F-94578 Rungis, France.

[5] M. Kupke, C. Rückert, W.-D. Dolzinski, M. Kolax, Der CFK-Rumpf - Ergebnisse aus Bauweisenkonzeption und Wissenserwerb, Deutscher Luft- und Raumfahrtkongress 2002, DGLR-JT2002-062,2002.

[6] L. Aktay, A.F. Johnson, M. Holzapfel, Prediction of impact damage on sandwich composite panels. *Computational Materials Science*, **32**, 252-260, 2005.