MODELLING IMPACT DAMAGE IN SANDWICH CONCEPT STRUCTURES

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ABSTRACT

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 sandwich 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 applied in the paper to composite aircraft sandwich structures to predict high velocity impact damage from hard body impactors. The role of composite skin and core in the failure process and impact energy absorption are studied for different core concepts such as polymer foam and Nomex honeycomb.

Introduction

Composite sandwich panels are of considerable interest in aircraft structures, currently being used in transport aircraft as low weight panels in wing leading edges and flaps, and as primary fuselage structures in helicopters and light aircraft. Sandwich structure are being considered for future transport aircraft fuselage panels since their high bending stiffness compared with monolithic composite shells permits significant cost and weight reductions due to larger frame spacing and reduction of stringers. Impact performance is critical in these applications since sandwich materials are susceptible to impact damage in the thin composite skins, but with suitable core materials may be designed to absorb impact energy. The paper describes the development and application of FE simulation methods for predicting impact damage in composite structures and their application to design concept studies on sandwich composite panels with energy absorbing cores. These include 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.

Damage modelling in composites

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), proposed by Ladevèze and co-workers [1], [2], it is possible to define materials models for FE codes at the structural macro level which embody the salient micromechanics failure behaviour. CDM provides a framework within which in-ply and delamination failures may be modelled. In previous work [1], [3] ply failure models were developed for unidirectional (UD) fibre and fabric reinforced plies with three scalar damage parameters representing in ply microdamage and damage evolution equations introduced relating the damage parameters to strain energy release rates in the ply. Delamination models for interply failure were obtained by applying the CDM framework to the ply interface, as described in [2]. Failure at the interface is modelled by degrading stresses using two interface damage parameters corresponding to interfacial tension and shear failures, whilst fracture mechanics concepts are introduced by relating the total energy absorbed in the damaging process to the interfacial fracture energy. The ply CDM and delamination models have been implemented into a commercial explicit FE crash and impact code [4], which uses a numerical approach for delamination modelling based on stacked shell elements with contact interface conditions, which may separate when the interface failure condition is reached. The validation of these composites damage models and FE code developments to predict impact damage due to hard and soft body impact in monolithic composite plate and shell structures has been discussed in some detail by the authors in [5], [6], [7].

In this paper the damage models and code developments are applied to composite sandwich panels. The sandwich composite skin laminates are 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^{TM} 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 stack of layered shell elements and the individual sublaminate shells are connected together using a contact interface with an interface traction-displacement law. The interface is a contact constraint not an interface element in which a penalty force procedure is used to compute contact forces between adjacent shells. Contact may be broken when the interface energy dissipated exceeds the mixed mode delamination energy failure criterion:

$$\left(\frac{G_I}{G_{IC}}\right)^n + \left(\frac{G_{II}}{G_{IIC}}\right)^n = e_D < 1 \qquad (1)$$

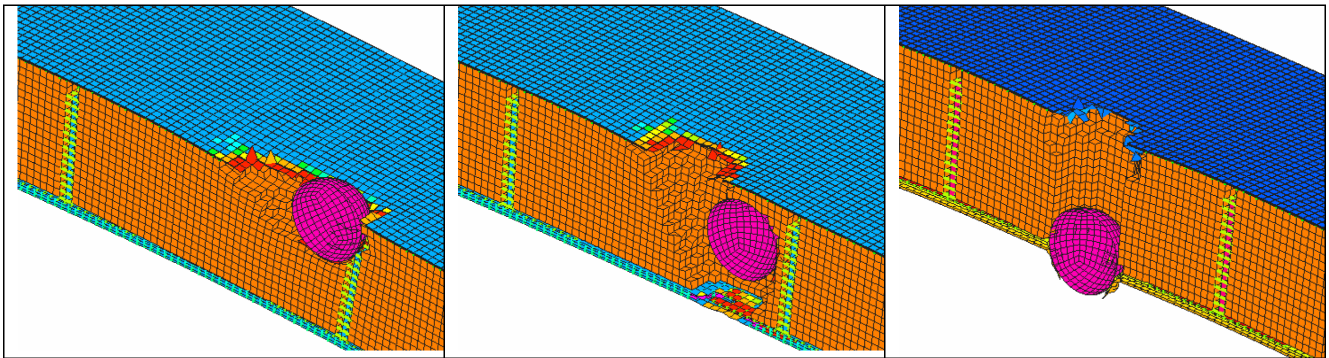
where G_I and G_{II} are the monitored interfacial energies in modes 1 and 2 respectively, G_{IC} and G_{IIC} are the corresponding critical fracture energies and the constant n is chosen to fit the mixed mode fracture test data. Typically n is found to be between 1 and 2. Failure at the interface is imposed by degrading stresses when $e_D < 1$. When $e_D \geq 1$ there is delamination and the interface separates. 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. Contact may be broken when the interface energy dissipated reaches the mixed mode delamination energy criteria. Further details of the delamination model and its application to improved impact damage predictions in composite laminates is discussed further in [6], [7].

In this paper attention is focussed on polymer foam and Nomex aramid paper honeycomb core materials, which are represented by 8-node solid elements. The polymer foam is modelled as an isotropic elastic-plastic material with failure, using DLR compression test data to determine the appropriate foam parameters as discussed in [8]. The aramid paper honeycomb core materials may be modelled with detailed shell models based on a hexagonal unit cells, or homogenised properties may be determined from a materials test programme on honeycomb blocks and used directly in solid elements. The latter approach is used here. The mechanical properties of honeycomb cellular materials are orthotropic. In sandwich structures the high stiffness direction orthogonal to the hexagonal cells is usually the through-thickness direction in the sandwich panel. Homogenised stiffnesses in the plane of the hexagonal cells are very low. For the homogenised model for Nomex^{TM} honeycomb material a nonlinear orthotropic bi-phase solid was available in PAM-CRASH to simulate the material response. This material model corresponds to an orthotropic solid in which the in-plane properties are nonlinear elastic and through-thickness compression properties are modelled as elastic-plastic. The compression behaviour is described by a buckling stress, a steady crush strength and a densification strain at which the honeycomb cells compact together. The material parameters are estimated by curve fitting the experimental compression stress-strain data to the standard model curves, as described in [8]. When impactors penetrate the composite skins the core elements are subjected to high compression and shear strains. For stable computations highly distorted elements require elimination, for which an effective shear strain elimination criterion is applied. In the foam and Nomex core models an element elimination strain was applied when the densification strain is reached at typically 80% compression strain.

FE modelling of impact in sandwich panels

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 [9], [10], and in-house at the DLR. High velocity impact tests on these structures provide a database for validation of the impact simulation methodology described in the paper. The sandwich panels of interest consist of carbon fibre/epoxy skins with both UD and fabric reinforcements and several core variants, including PMI 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 and 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. 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 composed of bi-phase composite plies as discussed above. The core foam or honeycomb materials use the homogenised materials models with solid elements. Contact interfaces model the adhesive bond between solid core elements and the layered shell skin elements. Where skin-core debonding is considered important, the contact interface may include a through-thickness tension/shear fracture condition which leads to skin-core separation when the adhesive bond strength is reached.

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, sandwich thickness ca. 30 - 40 mm thick and carbon/epoxy skin laminates with UD and /or fabric reinforcement. In order to investigate the structural integrity of sandwich design concepts the FE modelling techniques have been used to predict local impact damage and to compare different sandwich designs. Concept 1 is an unsymmetric sandwich design with a thin outer skin of carbon fabric/epoxy and inner skin approximately 4 times thicker composed of UD/epoxy laminate with approximate quasi-isotropic layup. The core is ~ 40 mm PMI foam core which is reinforced in one direction by composite T-ribs with spacing ~ 100 mm. In this concept the outer composite skin with the PMI foam provide thermal insulation and impact protection to the load bearing inner shell and reinforcing stringers. Concept 2 is a more conventional aircraft sandwich material, with similar unsymmetric inner and outer composite skin layups and ~ 30 mm thick Nomex honeycomb core. Variations of Concept 2 include the replacement of the honeycomb core structure by ventible folded aramid paper cores with similar mechanical properties.



30° impact t = 2.1 ms	60° impact t = 2.0 ms	90° impact t = 1.8 ms

Figure 1: Simulated impact damage in the Concept 1 sandwich structure with PMI foam core
(M = 22 gram, V_0 = 60 m/s, impact angles 30°, 60°, 90°)

The impact cases studied represent a 25 mm diameter stone projectile with mass 22 gram and impact velocity 60 m/s impacting the sandwich plate element at 30°, 60° and 90° impact angle to the panel surface. The 60 m/s impact velocity is typical of aircraft start and landing speeds when stone debris from the runway could be a potential threat to the lower fuselage panels and landing bay. The stone is modelled as a rigid sphere in this case. Results are shown in Fig. 1 for impact on the Concept 1 sandwich at the midpoint between the inner ribs. Depending on the impact angle the stone may bounce off or fracture the thin CF/epoxy outer skin and penetrate the foam core. At 30° impact to the plate surface the projectile damages the outer skin and upper layer of the foam core, and is stopped in its sliding motion by contact with the top of the rib. At 60° impact angle there is skin penetration and extensive core damage, with the projectile rebounding from the inner skin and being trapped by the rib. Under normal impact at 90° the projectile penetrates through the core and is stopped by the inner skin, which has both delamination and significant ply damage.

A better understanding of the penetration behaviour is seen in Fig. 2 which shows the normal (y-component) of the sphere velocity during the impact event. This shows that in the 30° impact the projectile gouges the panel surface and is stopped at about 1.2 ms by contact with the rib. At 60° it is stopped at 1.4 ms when it rebounds from the inner skin and then is trapped in the core at about 1.7 ms, with similar response at 90° impact angle but it is stopped at a later time of 1.7 ms. Fig. 2 also shows how the skins and core contribute to slowing down the impactor and thus absorbing the impactor kinetic energy. The initially steep inclined velocity-time curves at up to 0.3 ms represent the penetration of the impactor through the outer composite skin. The flatter region from 0.3 – 1.0 ms corresponds to the impactor penetrating through the softer foam core, whilst in the final steep part of the curves for the 60° and 90° impact the impactor is in contact with the very stiff inner shell which offers high resistance to penetration. In the case of the 60° impact this shell is not significantly damaged so that the slope is fairly constant up to rebound of the impactor from the inner skin. In the case of the 90° impact the sharp reduction in slope at about 1.3 ms corresponds to the inner shell being damaged and thus having much lower resistance. Thus the simulation results show the role of skins and core in impact energy absorption. Considering that the foam core has thickness of ~ 40 mm, whilst the total composite skin thickness is approximately 3 – 4 mm, it is apparent that the skins contribute most to stopping the complete penetration of the impactor. For example in the 60° impact case, the normal velocity is only reduced from about 38 m/s to 33 m/s as the impactor penetrates through the very thick core. Thus most of the absorbed impact energy in stopping the impactor is due to damage in the composite skins. Incidentally this shows that the concept here of a thin outer composite skin, with thick polymer foam core is not particularly effective as an impact protection concept. A thicker outer composite skin with stiffer core would be much more effective at preventing impactor penetration.

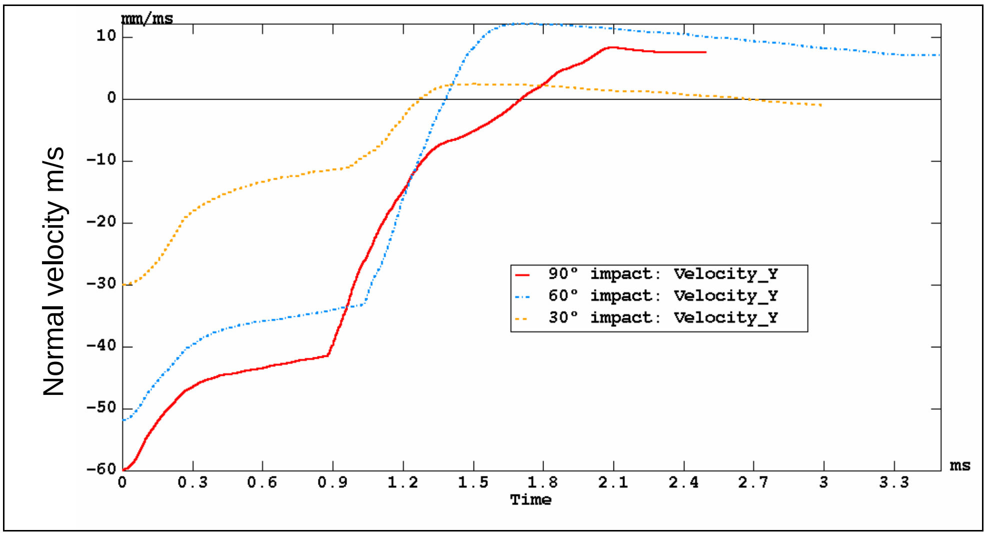
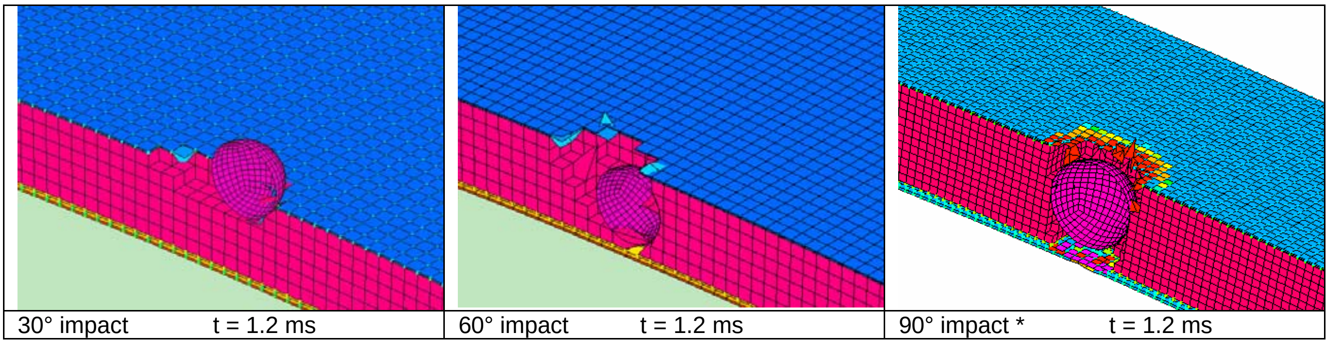


Figure 2: Comparison of the impactor normal velocities for Concept 1 at 30°, 60°, 90° impact angles

Fig. 3 shows the corresponding simulation results for stone impact under the same impact conditions on the Concept 2 sandwich with 30 mm Nomex core. The main features of the damage and penetration are very similar to those seen in Fig. 1. At 30° impact angle to the plate surface the projectile gouges into the outer skin with some surface core damage. At 60° impact angle there is skin penetration and extensive core damage, with the projectile rebounding from the inner skin and being trapped in the core. Under normal impact at 90° the projectile penetrates through the core and is stopped by the inner skin, which has both delamination and significant ply damage, but prevents penetration of the sandwich panel. This behaviour is confirmed by study of the normal velocity-time curve for Concept 2 in Fig. 4 for the 90° impact case, which shows that the impactor is stopped at 1 ms and rebounds from the stiffer inner skin without fracture. Note that the 90° impact simulation results shown in Fig. 3 were carried out with a refined mesh as part of the model validation studies, which gave an improved representation of the lower skin damage.



30° impact t = 1.2 ms	60° impact t = 1.2 ms	90° impact * t = 1.2 ms

Figure 3: Simulated impact damage in the Concept 2 sandwich structure with Nomex honeycomb core
(M = 22 gram, V_0 = 60 m/s, impact angles 30°, 60°, 90°) (* with refined mesh)

Fig. 4 also compares the normal velocities during impact of the Concept 1 and Concept 2 sandwich structures. The Concept 2 sandwich had a slightly thicker outer skin than Concept 1, which is apparent in Fig. 4 by the steeper initial slope of the curve for Concept 1. Then from about 0.3 – 0.9 ms the simulations show that the slope corresponding to penetration in the Nomex core is much steeper than in the PMI foam core, which indicates that the Nomex core is more effective at absorbing impactor energy and slowing down the impactor than polymer foam, particularly as the Nomex core is 25% thinner than the foam core. The consequence of this is that the damage to the load bearing inner composite laminate is considerably less for the Concept 2 sandwich than the Concept 1 sandwich for the same impact conditions. In fact the impactor normal velocity reduction in the Nomex core sandwich due to the core is from 40 m/s to about 20 m/s, compared with 48 m/s to 42 m/s in the foam core case.

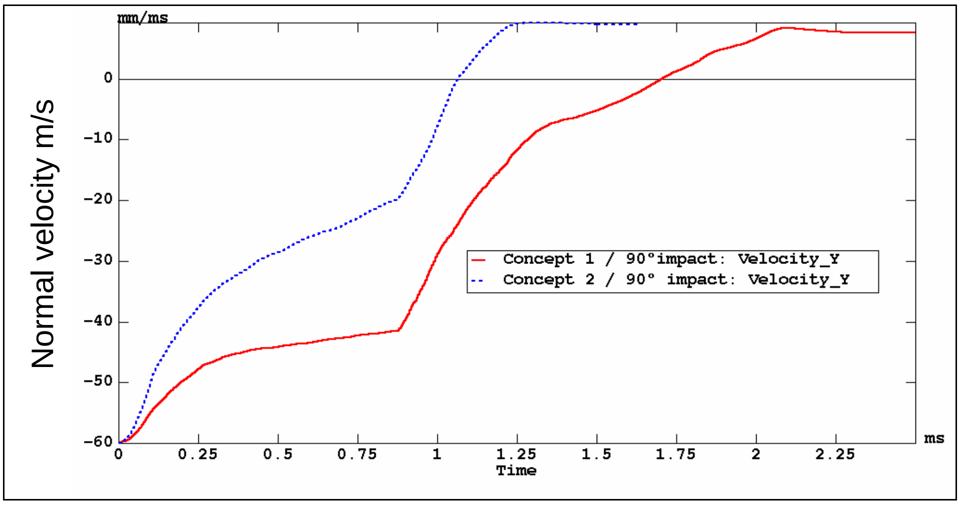


Figure 4: Comparison of the impactor normal velocities between Concepts 1 and 2 at 90° impact

For aircraft fuselage sandwich structures the inner composite skin would probably be load bearing, hence subjected to inner pressure during flight. In this case it is important that the inner skins are not significantly damaged by the type of stone impact being considered here. Some quantitative information on the inner skin damage is obtained by studying delamination damage in the laminates. As discussed above the inner skin is modeled as 3 stacked layered shells with 2 delamination interfaces. Contour plots of delamination damage may be computed to assess its importance. These are shown in Fig. 5 for the inner and outer skin laminates at 90° impact on the two sandwich concepts. They show fracture and penetration of the outer skin in both structures, with little delamination, and delamination damage on the inner skin. The Concept 1 panel has some delamination around the impact hole and along the stringer ribs, due to shock wave effects in the lower skin, whilst in the Concept 2 panel which was not penetrated there is a larger delaminated zone at the impact position. This demonstrates how the advanced damage models for composites being used here provide detailed design information for evaluating structural concepts under impact.

Concluding remarks

This paper has presented a materials failure model for composites with fibre fabric reinforcement which includes both intraply damage and interply delamination. This is implemented in the dynamic FE code PAM-CRASH and applied here for validation studies to predict impact damage in idealised sandwich composite panels. An important feature of the model is that it distinguishes clearly between intraply and interply delamination failure modes in the structure making it possible to simulate both the impact failure modes and failure progression during impact loading in sandwich structures. The simulation methods were then applied to evaluate local impact damage in two concept composite sandwich structures. Penetration of the outer carbon/epoxy skins by hard projectiles representative of runway stone impacts was predicted at typical impact speeds of 60 m/s, with core penetration and inner skin damage being dependent on type of core and impact angles. 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. Simulation results allowed a better understanding of the influence of core and skin properties on impact energy absorption. Results showed that the composite skins have a more significant effect in absorbing impact energy and slowing the projectile than the standard polymer foam and Nomex honeycomb cores currently being used in aircraft sandwich structures. It shows that there is considerable potential for sandwich design improvements based on new types of core structures. These should be both light, and in general stiffer in compression and shear than the core materials studied. In current work the DLR with other partners is studying core concepts made of folded aramid composite paper (foldcore), with a complex periodic folded geometry [10]. Preliminary design studies and gas gun tests on these core materials are encouraging and show they have potential for future lightweight energy absorbing structures. Thus the methodology described here will be used to evaluate damage due to impact loads on these more complex double shell and sandwich design concepts for aircraft fuselage and wing structures.

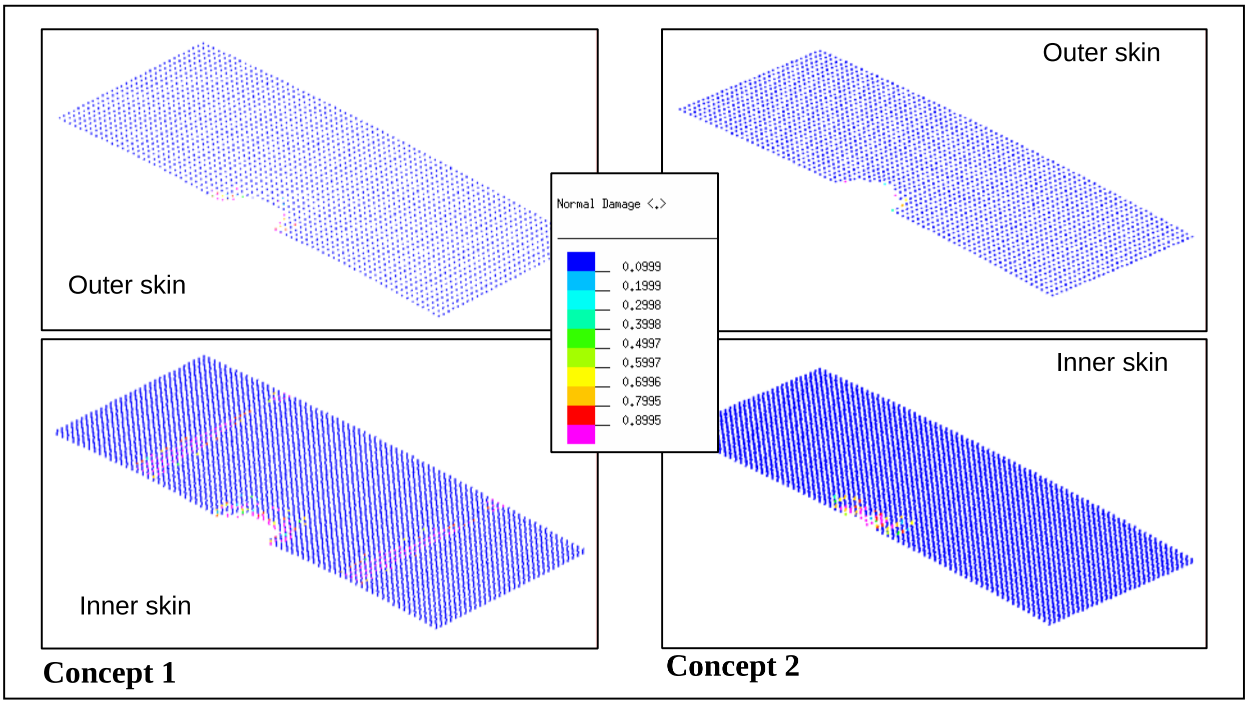


Figure 5: Delamination damage contours for Concepts 1 and 2 under 90° impact

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