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IMPACT DAMAGE ANALYSIS OF LAYERED COMPOSITE PLATES

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1. Introduction

The process of designing with composite materials exhibits significant differences compared to usual isotropic metallic ones, due to the intrinsic properties of composites. Unhomogenities in layered composites at micro, macro and meso level are source of difficulties in manufacturing and application. As composites are usually applied in aerospace and naval structures, where dynamic interactions between structure and surrounding mediums are significant, it is clear that these interactions will be the source of vast number of failure modes that are to be taken into account in the design process. As a structural response during exploitation, damage might appear at micro, macro or meso level, leading to significantly different approaches in their numerical prediction. The parameters playing significant role in the process are mechanical properties and type of matrix and fibre, the source of impact loading, the kinetic energy and geometry of impactor. The interaction of these parameters presents the main concern of researchers dealing with the problem of impact induced damage. The paper is to address some of these significant problems.

2. Modes of damage and influential parameters

Design considerations will mostly deal with aircraft structures, as they are classical examples of impact loaded structures where influence of exploitation parameters is critical. Here, impact damage is the result of dropped tooling during maintenance, hailstones or bird strikes during flight, stones ingested on the runway, or high velocity impact penetrations as the result of battle damage. For instance, recorded hail strike damaged airplane structural components include: elevator, inner and outer flaps, ailerons (airplane on the ground); Kevlar radome (airplane in flight) [Middleton 1990].

Impact induced damage in composites is mostly observed in the form of matrix cracking, fibre failure, delaminations and penetrations. The modes of failure are considerably dependent on the following parameters of layered composite:

- mechanical properties and type of matrix
- mechanical properties and type of fiber
- stacking sequence
- production technology

In addition, the following properties of the impactor are instrumental in the appearance of damage:

- mass
- velocity
- geometry of impact source

Material selection is one of the critical steps in the component design process. Fiber properties vary form excellent impact damage resistance as exhibited by glass fibre composites, good penetration resistance of Kevlar composites (aramid fibres) to the low damage resistance of carbon fibres. The favorable properties of glass fibres in impact loaded aircraft structures are the result of their high toughness that leads to dispersal of deformation energy to large portions of the structure. Quite opposite, despite their high elasticity modulus, intrinsic brittleness of carbon fibres makes them highly sensitive even to the small amount of impact energy. Their behaviour is especially infamous in the case of low velocity/low mass impacts where significant damage appears in the interior of the structure without noticeable external damage (barely visible impact damage – BVID). As BVID can very often happen unnoticed in the exploitation, its potential presence has to be taken into account when designing aircraft structures. If the structure is to be optimized for high velocity impact loading when visible penetration damage is expected, the composite structure is to be robust – very frequently in the form of monolithic panels with 100+ layers. Certain applications require strain rate to be taken into account, especially in high-speed impact of glass fibre composite. However, in the case of carbon or aramid fibres, strain rate is not that influential.

As stated before, the response of impact loaded structures does not depend solely on the material properties of laminate and impactor energy, but also on their geometric properties. The flexural response of the laminate is essential in determination whether delamination, matrix cracks or penetration is to occur. If the laminate is thin, and the impact velocity is low, the response of laminate is predominantly flexural. On the other hand, if laminate is of greater thickness and greater rigidity, local behaviour of structure such as penetration is of larger significance, and especially in the case of high velocity /low mass impact, complete penetration might occur (ballistic impact).

As example of impact damage criteria applied in the design of Airbus airplanes, it is defined that critical components have to withstand damage induced with energy of 35 Joules, what would correspond to free fall energy of stone with 5 cm in diameter, leading to minimum skin thickness of 0.8 mm [Middleton 1990]

3. Numerical model

This model has been devised for the prediction of damage in layered composite panels in case of low velocity impact. No penetration or large-scale visible damage is supposed to appear. Numerical algorithms applied in this research have been described in detail in [Smojver&Alfirevic 2000] and [Smojver et al. 2001]. Therefore, only the basic principles will be stated.

The model takes into account matrix cracks and delaminations as it is experimentally proven that their appearance is clearly connected in the case of low velocity impact [Collombet et al. 1996]. Transient dynamic finite element analysis using volume elements in the laminate was applied in the calculation of stress field in the laminate. All these tasks have been performed within the frame of ABAQUS finite element software [Hibbitt et al. 1998] by implementation of appropriate FORTRAN written user subroutines UMAT, URDFIL and MPC (see Figure 1). Impact loading is modeled through initial conditions taking into account velocity and mass of the analytically defined rigid impactor. Eshelby's tensor has been employed, using subroutine UMAT, in the calculation of the effective material properties of composite consisting of transversally isotropic fibre and isotropic matrix [Gavazzi&Lagoudas 1990]. By means of appropriate kinematic conditions applied at the coincident nodes on boundaries of layers supposed to delaminate (subroutine MPC), it is possible to model their separation. Degradation of laminate mechanical properties due to the appearance of matrix tensile cracks has been performed by applying model of Tsai [Tsai 1984] in subroutines KCALCUL and URDFIL.

As the illustration of numerical effectiveness of the method, the impact of rigid impactor on the carbon/epoxy square plate $[0_4 / 90_8 / 0_4]$ of 2 mm thickness has been performed [Razi&Kobayashi 1993]. The plate has dimensions 76.2×76.2 mm and is simply supported at edges. The impactor has hemispherical tip with radius of 3.175 mm. Mass of the impactor has been varied as $M = 0.59$ kg, 0.25 M, 0.5 M, 1.5 M and 2.0 M . The velocity of impactor has been held constant at 1.931 m/s. More detailed description of the model can be found in [Smojver et al. 2001]. Material and strength properties of the composite are defined in Tables 1 and 2.

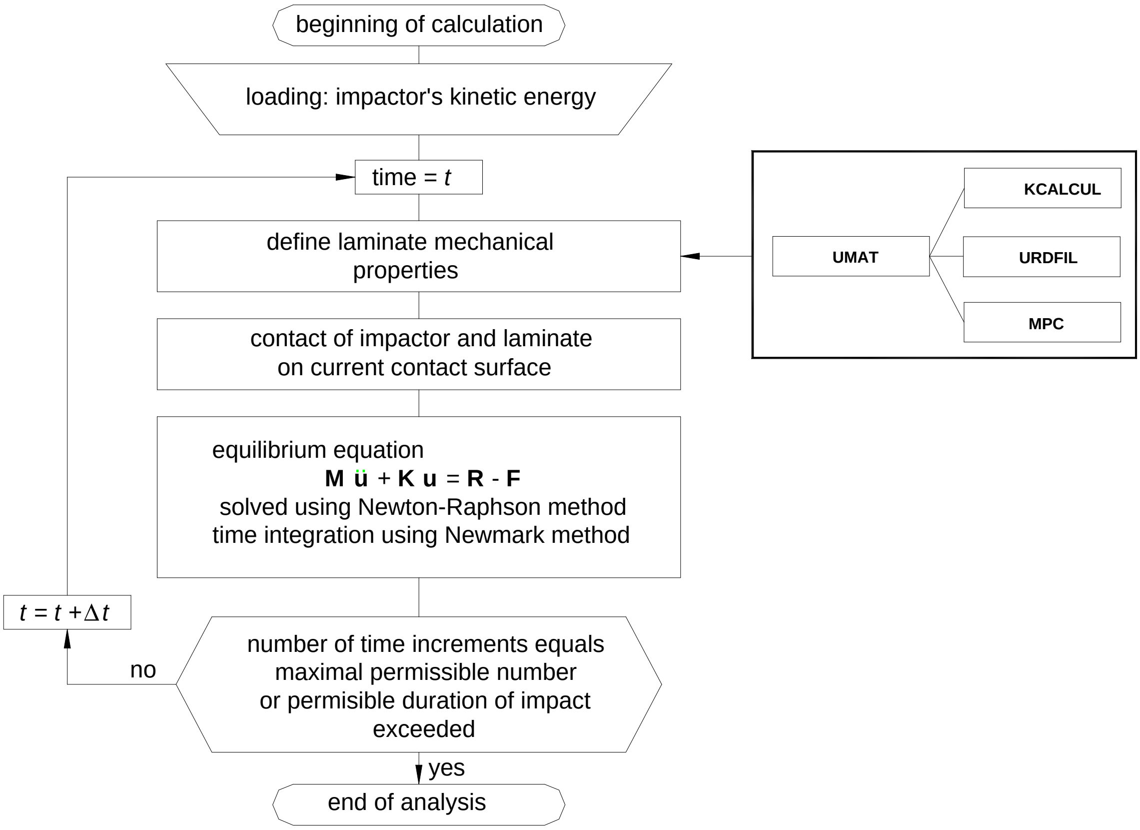

Figure 1. General algorithm of numerical model

Table 1. Material properties of carbon fibre and epoxy matrix

E_A [GPa]	E_T [GPa]	n_A	G_A [GPa]	G_T [GPa]	E_m [GPa]	n_m	c_f
227	15.5	0.41	23.2	5.4	3.46	0.35	0.6

Table 2. Strength properties of carbon/epoxy composite

X_t [GPa]	X_c [GPa]	Y_t [MPa]	Y_c [MPa]	S_{12} [MPa]	S_{23} [MPa]	S_{13} [MPa]
1.5	1.5	40	246	68	68	68

Figure 2 shows final delamination areas for various impactor masses *m*. Only one quarter of the laminate has been modeled in order to decrease numerical cost. Two interfaces have been under scrutiny: 0_4 / 90_8 (closer to the impactor) and 90_8 /0_4. It is clearly shown that significantly larger delamination area appears at the interface 90_8 / 0_4 . Difference between delamination areas at 0_4 / 90_8 and 90_8 / 0_4 interfaces increases with the increase of impactor mass. This is due to the fact that with the increase of a mass, flexural behaviour of the laminate becomes predominant, contact duration is prolonged and delaminations have more time to develop. At $m = 0.25\ M$ the difference between two interface delamination areas diminishes due to the small flexing of the laminate and higher influence of local effects.

Figure 3 depicts indentation of laminate defined as difference between displacements of impactor and central point at the bottom of the plate. It is clear that indentation increases with the increase of impactor mass. However, the dependence of indentation on mass of the impactor is not linear, because at increased mass of the impactor, flexing of the laminate decreases the indentation. Furthermore, it is noticeable that the plate, due to its elasticity, continues to vibrate after separation from the impactor (for instance curve 2, values between 1.6 ms and 2.5 ms). In addition, bouncing of the impactor is noticeable.

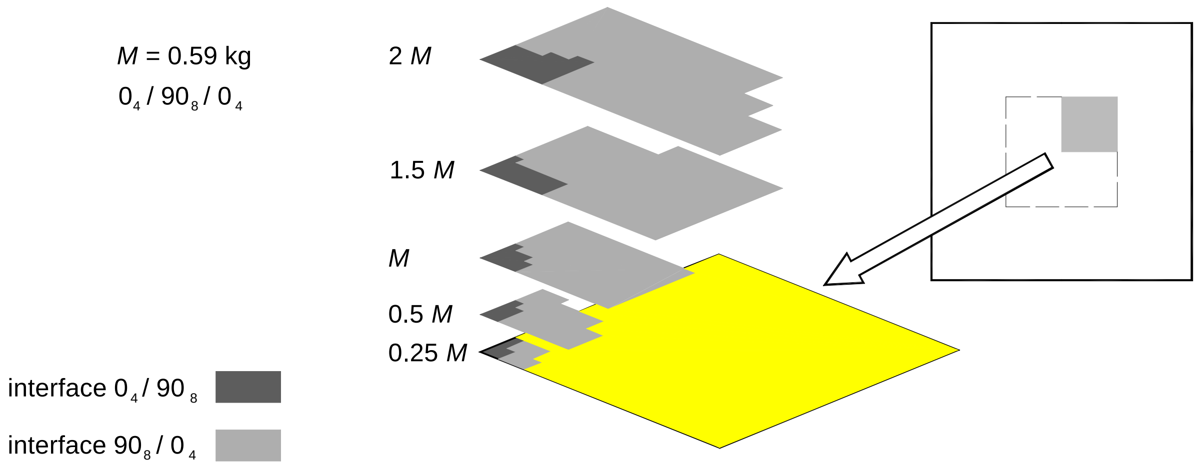

Figure 2. Final delamination areas at various masses of impactors

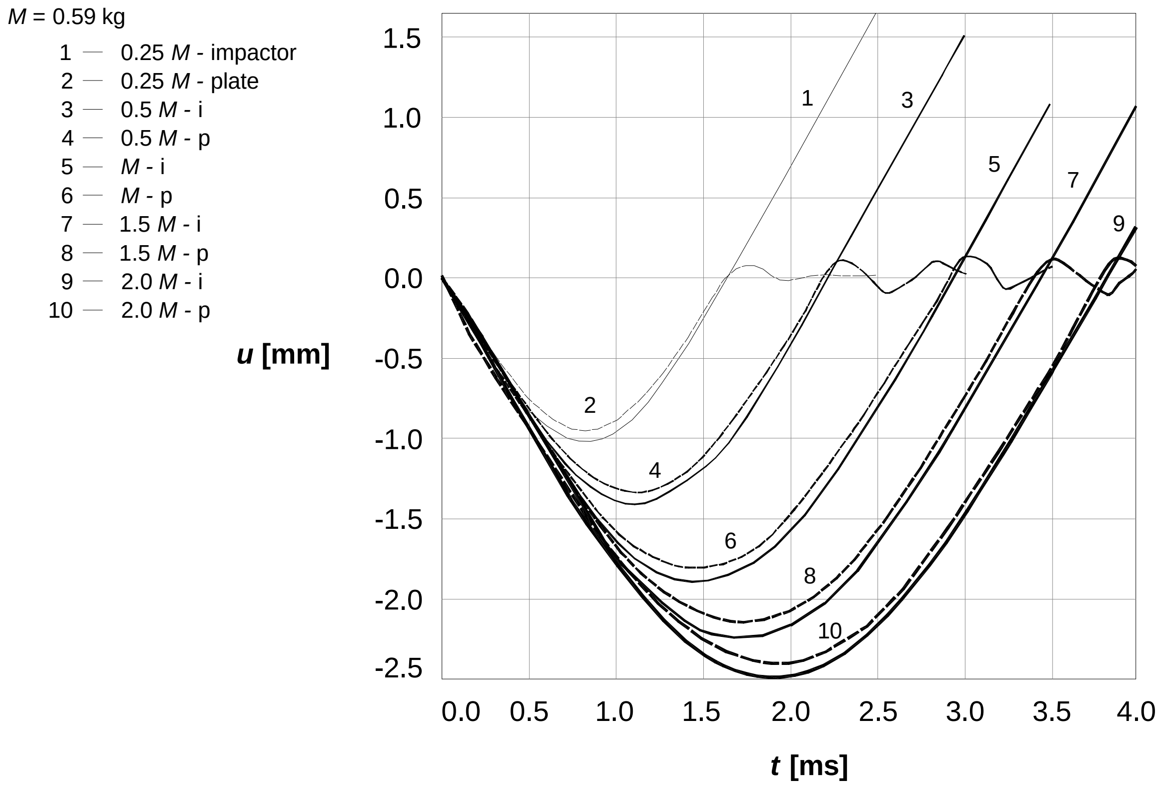

Figure 3. Indentation of laminate plate at various impactor masses

Contact force values have been illustrated at Figure 4. These are calculated at the point of contact between impactor and upper surface of the laminate. At the smallest mass of the impactor, there is significant wavering noticeable in the contact force curve. The stiffness of the laminate is predominant and local disturbances in the displacement of the impactor are reflected as the variation of the contact force. Differing from that, at $m = 2M$, this curve is relatively smooth, except at the beginning of the event. The time up to the appearance of maximum contact force is longer as impactor mass increases what can be explained by the fact that impactor and the plate remain in contact longer, and deformation of the plate is larger. However, the duration of the contact does not depend linearly on the increase of the mass of impactor.

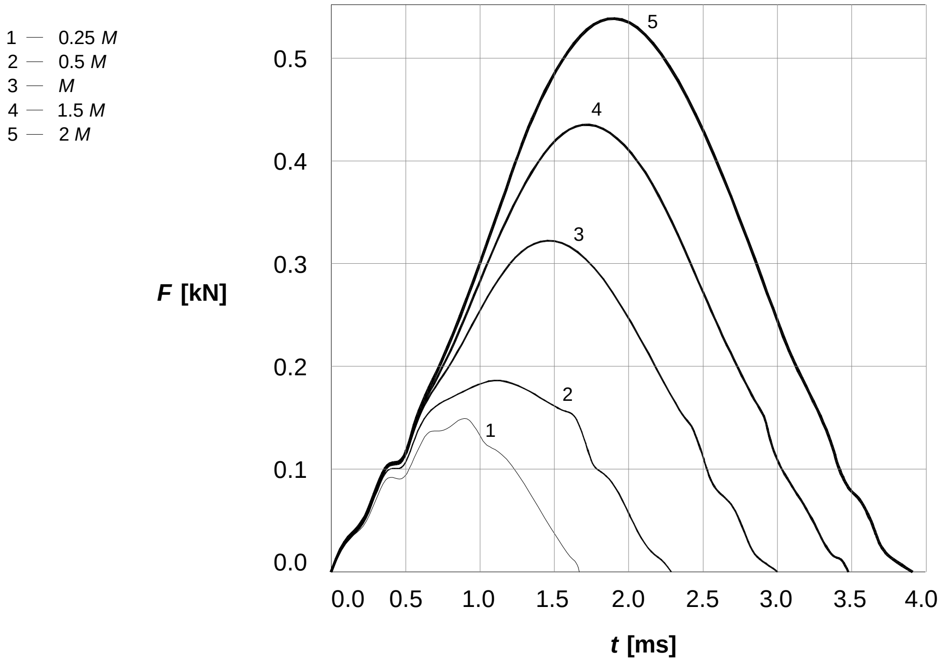

Figure 4. Variation of contact force between impactor and laminate plate

4. Conclusion

The paper presents the continuation of work in the field of damage assessment in layered composites. Results for contact force, delamination and indentation of laminate have been presented and show highly nonlinear behaviour under impact loading, as expected. Furthermore, under low velocity impact, the mechanical behaviour of laminate as well as properties of the impactor have to be taken into account. Estimation whether local of global behaviour dominates the structural response is dependent on correlation of all aforementioned factors. It is clearly demonstrated that in the design process of impact loaded composite structures, damage must be taken into consideration. The devised numerical procedure, in numerically efficient way estimates the appearance of critical failure modes and contributes to the quality of preliminary design.

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