MODELLING OF DAMAGE DEVELOPMENT IN BLAST LOADED COMPOSITE PANELS

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Abstract

This paper presents a robust framework for computational modelling of the response of composite laminates to blast loads. The numerical test-bed for the simulations is the explicit finite element code, LS-DYNA. Delaminations are modelled using a cohesive type tie-break interface introduced between sublaminates while intra-laminar damage mechanisms are captured using a continuum damage mechanics approach. In the latter case, a non-local regularization scheme is proposed in order to address the spurious mesh dependency and mesh orientation problems that occur with all smeared crack based constitutive models. The preliminary results for the predicted damage patterns are encouraging and qualitatively agree with the measurements obtained from sectioned post-mortem panels.

1 Introduction

This work supports the ongoing research at the Canadian Department of National Defence (DRDC – Valcartier) to provide lightweight mine blast protection for Light Armoured Vehicles (LAVs) and other military vehicles. Currently, most LAVs have either no underbody protection against buried mine threats or rely on deflecting the blast or using heavy metal plates to defeat the threat. Since it is critical for military vehicles to maintain their mobility, the lighter-weight alternative offered by composite materials is promising.

Fibre-reinforced polymer (FRP) composites are capable of absorbing significant amounts of energy through development of various damage mechanisms. However, numerical prediction of the sequence and extent of such mechanisms poses considerable challenges to the analyst.

The objective of this work is to characterize damage in blast-loaded FRP plates experimentally and develop a reliable numerical method for their prediction. Quantitative assessment of blast load induced damage mechanisms in laminated FRP plates will provide a foundation for better predictive models that can be used for optimum material selection [1].

2 Experiments

Explosive loading trials were conducted at DRDC-Valcartier on IM7/8552 carbon fibre/expoxy laminated composite panels. The panels had a quasi-isotropic $[90/45/-45/0/0/-45/45/90]_{12s}$ lay-up, resulting in a total stack of 96 layers. The dimensions of the panels were approximately 610×305×18 mm.

The test set-up is shown schematically in Fig. 1. The top cylinder height is adjustable to accommodate different test plate thicknesses.

The composite test plate was held loosely between removable steel cylinders, allowing it to slide freely as the plate bends due to the blast impulse. The trials consisted of explosively loading the plates with a 50 g C4 explosive at a stand-off distance of 14 cm.

A small aluminum cylinder with a diameter of 1” (25.4 mm) was placed on top of the composite panel at the center, and a high-speed camera was used to track the movement of this cylinder upwards due to the blast load underneath.

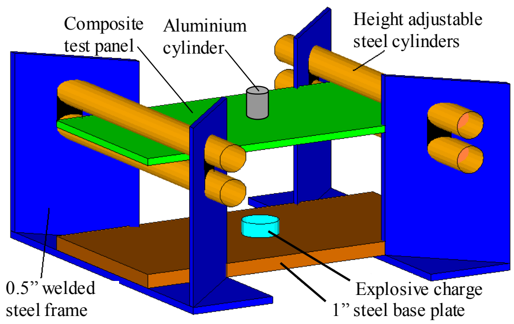

Fig. 1. Schematic of the test set-up

2.1 Damage Analysis

Surface damage from the blast was observed in all of the panels. None of the plates ruptured due to the blast load and little residual deformation was observed. The plates were sectioned to investigate the mechanisms of failure and energy absorption in the plates.

2.1.1 Delamination

One of the plates was sectioned to investigate the occurrence of delamination. A cross-section taken across the width of the specimen at the location of the blast load was polished and a stereomicroscope was used to observe and photograph the damage (Fig. 2). Two main delaminations were detected, one that runs through the width of the specimen jumping a few plies, and another that runs only half the width. Most of the delaminations were observed between +45° and -45° layers.

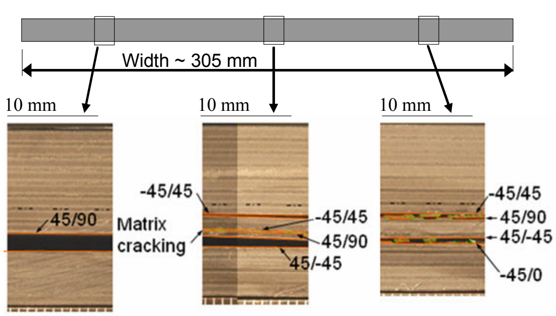

Fig. 2. Dominant damage mechanisms (delamination and matrix cracking) in the IM7/8552 CFRP quasi-isotropic laminate. Blasted surface is up.

2.1.2 Matrix Cracking

In terms of matrix damage, there was very little observed on the left side (which is dominated by severe opening of a single delamination), and a moderate amount was detected near the centre of the blast load and the right side. The majority of cracking was confined to the +45° and –45° layers that border a delamination.

No fibre breakage was observed in the specimen.

3 Numerical Model

In the finite element model, the plate is divided into a number of layers, modeled by shell elements and appropriately tied to each other (Fig. 3). Since it is not practical to model all the physical layers (96 in total), each layer in the numerical model represents a sub-laminate. An interface model is used to model the inter-laminar damage (delamination) and a continuum damage mechanics approach is used to model the intra-laminar damage (matrix cracking or fibre breakage).

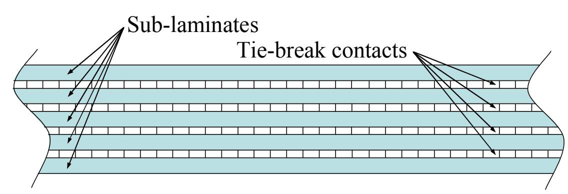

Fig. 3. Schematic showing a stack of shell elements each representing a sub-laminate of the composite panel and connected together using tie-break contact interfaces

A numerical tool suitable for modelling the response of composite panels under severe dynamic loads needs to be capable of simulating: (1) the dynamic structural behaviour of a laminated media, (2) the onset and growth of delamination and (3) the initiation and evolution of intralaminar damage modes consisting of matrix cracking and fibre breakage.

In simulating the elastic (pre-damage) dynamic structural bending response, the interface model used to connect the layers should be such that the layers are prevented from opening or slipping relative to each other. This would ensure that the elastic response of the plate is independent of the number of layers or sub-laminates into which it is divided.

Delamination is an important damage mode that influences the overall structural stiffness of the composite laminate. The finite element model should predict the initiation and growth of delamination appropriately. In so doing, the energy release rate for the growth of inter-laminar crack in the numerical model should be consistent with the experimental data such as those obtained from a double cantilever beam (DCB) test.

Delamination is modeled by removing the connection between the neighbouring sub-laminates. Therefore, the number of sub-laminates depends on the nature of the delamination and can be chosen based on relevant experimental observations, simple static analyses and engineering judgment.

Finally, matrix cracking and fibre breakage are intra-laminar damage modes that are often simulated using continuum damage mechanics models. Dependency of the numerical solution on the mesh size and orientation are common problems associated with classical smeared crack approaches based on damage mechanics. These issues need to be addressed in a robust finite element analysis of such problems.

The computational tool selected for the current study is the explicit nonlinear finite element code, LS-DYNA.

3.1 Cohesive Crack Model

The tie-break interface is one of the built-in contact options available in LS-DYNA. It is designed for modeling initially joined surfaces that will be disjointed or released after satisfying a certain stress/force criterion. The post-peak opening behaviour is based on a cohesive crack model where the traction transferred between the two crack surfaces decreases as a function of the crack opening. The algorithm used for the tie-break contact is based on the penalty method [2].

Various types of tie-break interfaces are available. The option 8 (available in version ls971 of the code), and referred to as CONTACT_AUTOMATIC_SURFACE_TO_SURFACE_TIEBREAK is suitable for modeling cohesive cracks. The failure criterion is based on the following parabolic normal-shear stress interaction relation:

$$\left(\frac{\sigma_n}{\sigma_{fn}}\right)^2 + \left(\frac{\sigma_s}{\sigma_{fs}}\right)^2 \geq 1 \qquad (1)$$

in which σ_{fn} and σ_{fs} are the normal and shear failure stresses and are supplied to the code as input parameters. A linear traction-opening displacement cohesive law governs the post-failure behaviour of the contact model, as shown in Fig. 4. The maximum opening displacement, δ_c, at which the surfaces are completely separated is a user defined input parameter.

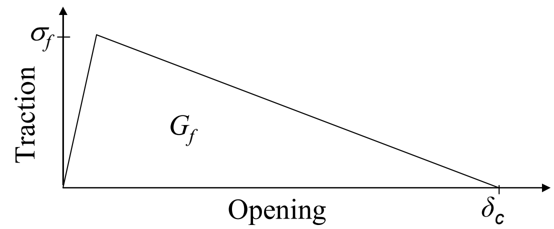

Fig. 4. Typical traction-separation law with linear softening for the cohesive crack model.

3.2 Validation of the Cohesive Crack Model

The Double Cantilever Beam (DCB) test as shown in Fig. 5 is used to validate the behaviour of the tie-break interface as a cohesive crack model. The DCB simulation is a numerical benchmark problem that has been studied by other researchers, e.g. Alfano and Crisfield [3]. The structural model consists of two layers of shell elements which act as two cantilever beams (100×20×1.5mm) that are tied together using the tie-break interface. The initial notch is 30mm long and a constant velocity is applied to the tips of the two cantilever beams resulting in a mode I quasi-static loading.

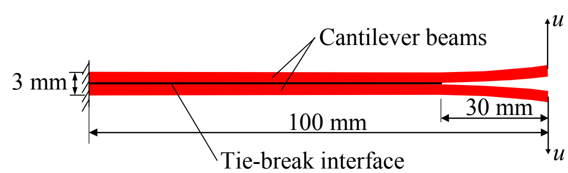

Fig. 5. Schematic configuration and dimensions of the simulated DCB test

The cantilever beams are modelled as linear elastic materials with a modulus (E) equal to 135 GPa and a Poisson's ratio of 0.24. The critical energy release rate (G_f) of the cohesive crack is equal to 0.28 kJ/m^2. The analysis is performed using different values of the peak stress and critical opening displacement while keeping the energy release rate constant. Fig. 6 shows the predicted load-displacement curves compared to the results presented in [3]. It can be seen that the response of the FE models using the tie-break interface generally agrees with the results reported in [3]. It can also be seen that the global response of the system mainly depends on the energy release rate (G_f), however, the models with lower peak stresses (σ_f) lead to results that are somewhat less oscillating.

The above analysis serves to verify the performance of the tie-break interface in modeling cohesive cracks in a quasi-static analysis.

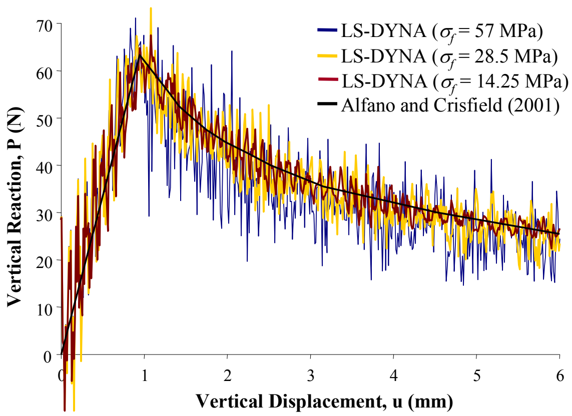

Fig. 6. Comparison of the predicted DCB results with results reported in [3]

3.3 Effect of contact characteristics on the dynamic response of the structure

The tie-break interface uses the penalty stiffness method which introduces an inherent finite stiffness between the layers that are tied together. The contact stiffness is calculated by LS-DYNA based on structural characteristics of the system and can be scaled by the user.

The contact stiffness has a significant effect on the response of a laminated media. Our goal is to introduce a model with a global response that is independent of the number of sub-laminates and position of the tie-break contacts. To study the effect of the tie-break contact, the IM7/8552 carbon fibre/expoxy laminated composite plate tested at DRDC-Valcartier is analyzed under blast loading.

In the FE analysis, the pressure-time pulse generated by the blast load is simulated using the CONWEP model [4] with 50 grams of C4 charge and stand-off of 140mm (Fig. 7). The plate is modeled using one, four and eight layers of shell elements tied together with tie-break interfaces. To conform to the experiments, an aluminum cylinder is placed on the distal face to measure the back-face velocity of the plate.

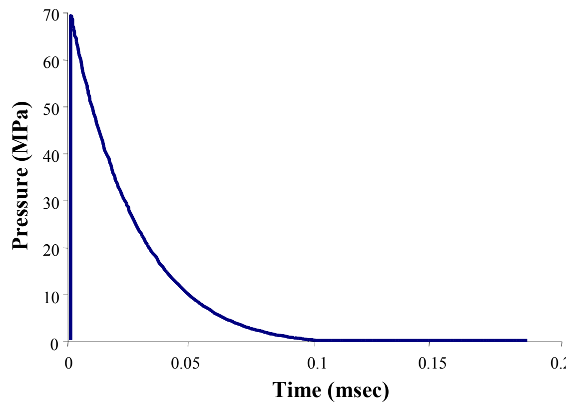

Fig. 7. The pressure-time history at the mid-point of the plate generated by the CONWEP model corresponding to a charge of 50g C4 at a stand-off distance of 140 mm

In the first set of analyses, the default values of LS-DYNA were used in the calculation of the contact stiffness. In order to investigate the effect of contact parameters solely, the material is assumed to be linear elastic. The resulting back-face velocity (v_b) and velocity of aluminum cylinder (v_a) are listed in Table 1.

It can be seen from Table 1 that the simulation results are not objective in the sense that the back-face velocity and velocity of the aluminum cylinder both depend on the number of sub-laminates. This is due to the fact that the interfacial tie is not stiff enough to ensure that the layers move together as a unit. Thus, the momentum transferred from the blast load is not carried by the whole laminate; rather it is carried by one or some of the layers at any given time. Given that each layer or sub-laminate is thinner (and hence lighter) than the entire laminate, the back-face velocities are generally over-predicted and strongly depend on the number of layers (sub-laminates).

The above can be addressed by appropriate scaling the of the initial contact stiffness. Table 2 shows the results of analyses when the default stiffness is scaled up by a factor of 10.

It can be seen that with the above modification the results have improved significantly and the velocities are almost invariant with the number of layers. Also it can be seen from both tables that the maximum back-face velocity and velocity of the aluminum cylinder are independent of the strength of the cohesive model (in terms of energy release rate). This is because the maximum velocity occurs during the first phase of the response when none of the interfacial ties are loaded in tension.

Table 1. Analysis of laminated composite plate under blast load using default options for the stiffness of the contact model

No. of layers	Contact Model			v_b (m/s)	v_a (m/s)
	σ_f (MPa)	δ_c (mm)	G_f (kJ/m^2)		
1	--------	-------	-------	45	45
4	50	0.1	2.5	65	60
4	50	0.01	0.25	65	60
8	50	0.1	2.5	90	72
8	50	0.01	0.25	92	72

Table 2. Analysis of laminated composite plate under blast load using modified stiffness values for the contact model

No. of layers	Contact Model			v_b (m/sec)	v_a (m/sec)
	σ_f (MPa)	δ_c (mm)	G_f (kJ/m^2)		
1	--------	-------	-------	45	45
4	50	0.1	2.5	50	46
4	50	0.01	0.25	49	46
8	50	0.1	2.5	52	47
8	50	0.01	0.25	52	47

3.4 Modeling intra-laminar damage

Numerical modeling of intra-laminar damage is based on the continuum damage mechanics theory. The constitutive stress-strain relation is devised such that it results in a global softening response of the system. This method, which was first developed for isotropic materials as a scalar damage model, has been extended to other materials such as composites [5]. It is commonly accepted that the finite element analysis of strain-softening materials suffers from mesh size and orientation dependency. The simplest and widely used remedy to this problem is to adopt the Bazant's crack-band method [6]. According to this method, the descending portion of the softening curve is modified based on the height of the damaging element. This results in a constant energy per unit area of damage and global system response in terms of absorbed energy that is independent of the mesh size. It should be noted that the crack band method is applicable to cases where there is a distinct localization of damage/crack into one row of elements. In very fast dynamic events such as blast and impact, due to the effect of inertia forces, damage does not localize and instead takes a more spatially distributed form. Consequently, the crack band method cannot be applied in such cases. Non-local methods have a much wider range of application [7]. In this method, in contrast to the local approaches, the state of stress at a point depends on the state of strain in a finite neighbourhood of that point. Non-local methods can also improve the unrealistic dependency of damage/crack pattern on mesh orientation, a problem that occurs in FE simulations based on local strain-softening models [8].

The LS-DYNA software has the capability of non-local integration for a selected number of its built-in material models. The material type, MAT_PLASTICITY_WITH_DAMAGE, is one that is suitable for comparing the results of classical smeared crack methods and non-local regularization. The current non-local tool in LS-DYNA practically supports scalar damage models and therefore cannot be used for general anisotropic damage models.

Fig. 8 and Fig. 9 show the damage/crack pattern in the analysis of a one layer plate under similar conditions using classical (local) and non-local analysis, respectively. It can be seen that the damage pattern and crack path in the classical smeared crack method are biased with respect to orientation of the mesh whereas the non-local regularization results in much more realistic damage patterns.

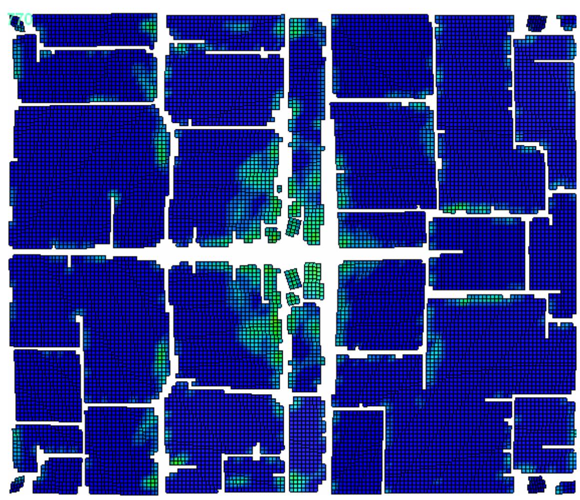

Fig. 8. Predicted intra-laminar damage/crack pattern using the classical (local) smeared crack model

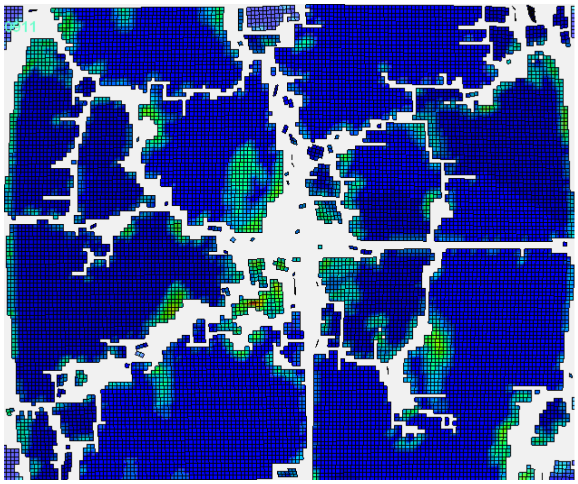

Fig. 9. Predicted intra-laminar damage/crack pattern using the non-local damage model

3.5 Evaluation of the response of composite plates to blast load

The structural model discussed in this section consists of 12 sub-laminates. Material properties of the IM7/8552 prepreg are listed in Table 3 [9]. Each sub-laminate is quasi-isotropic with a lay-up of [90/45/-45/0/0/-45/45/90] and in-plane properties listed in Table 4. The tie-break interface model with modified initial penalty stiffness is used as contact model. The failure stress (σ_f) is equal to 50 MPa and the critical opening displacement (δ_c) is equal to 0.012 mm which leads to an energy release rate (G_f) of 0.3 kJ/m^2. The MAT_PLASTICITY_WITH_DAMAGE is used as the material model and enhanced with non-local regularization. This material model employs a scalar damage parameter and a linear post peak softening behaviour as shown schematically in Fig. 11. The peak stress (σ_c) is chosen to be 550 MPa. The non-local regularization feature is employed. The non-local length parameter or integration radius (l) is 7.625mm and the strain to failure (ε_f) is chosen to be equal to 0.012 which leads to an energy release rate (G_c) of about 50 kJ/m^2. The blast load is once again simulated using CONWEP with 50 grams of C4 charge and a stand-off of 140mm (Fig. 7).

Table 3. Properties of IM7/8552 unidirectional CFRP Prepreg

E_{11}=161.0 GPa	E_{22}=11.38 GPa	E_{33}=11.38 GPa
ν_{12}=0.32	ν_{13}=0.32	ν_{23}=0.45
G_{12}=5.17 GPa	G_{13}=5.17 GPa	G_{23}=3.92 GPa

Table 4. In-plane properties of [90/45/-45/0/0/-45/45/90] quasi-isotropic lay-up of IM7/8552 CFRP

E_{xx}=61.6 GPa	E_{yy}=61.6 GPa	G_{xy}=23.3 GPa
ν_{xy}=0.32		

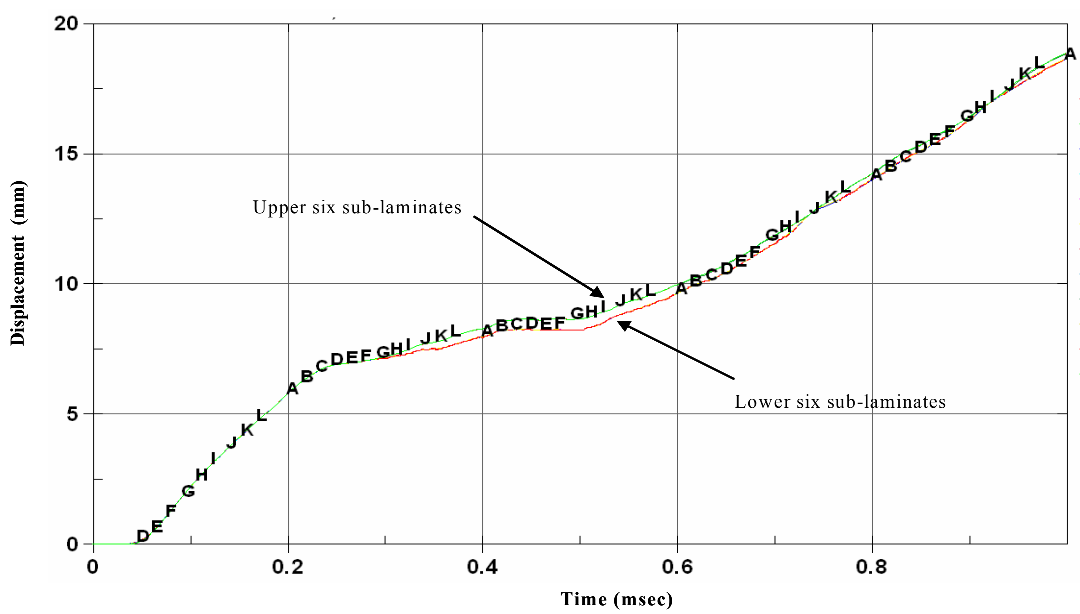

Fig. 10. Predicted time history of the transverse displacement of the various layers of the blast loaded CFRP laminate at the mid-point of the plate

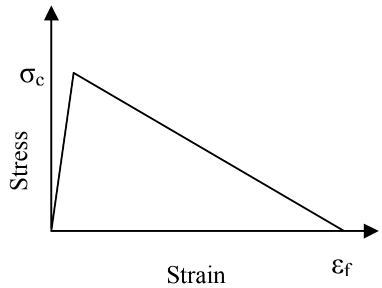

Fig. 11. Typical stress-strain law governing the post-peak behaviour in MAT_DAMAGE_WITH_PLASTICITY

Fig. 10 shows the time history of the displacement at the center of each layer (sublaminate) underneath the aluminum cylinder. Layer A is the first sub-laminate located at the bottom of the plate (impact face) and layer L is the last sub-laminate at the top of the plate (distal face). The lack of overlap between the displacements of the sublaminates above and below the mid-plane is indicative of a major delamination occuring at the mid-plane of the plate. This agrees well with the experimental observations (Fig. 2).

The structural response can be decomposed into three phases, as shown in Fig. 12. The first phase starts when the blast load strikes the plate and lasts about 40 microseconds. In this phase, the response of the structure is governed by the balance of momentum induced by the blast load. Therefore, the velocity of the system depends mainly on the blast impulse as well as the thickness and density of the plate. As shown in Fig. 12, at the end of this phase the aluminum cylinder detaches from the back-face of the plate. Thus, the velocity of the aluminum cylinder and maximum back-face velocity of the plate are mainly driven by the impulse content of the blast load and thickness and density of the plate.

The second phase starts about 50 microseconds after the blast hits the plate. In this phase, due to the deformation of the plate, strains and consequently stresses have developed in the plate and the structure starts to resist the load. According to Fig. 12, the velocity reduces and therefore during this phase the acceleration at the centre of the plate is negative. To resist the blast load, a significant punching shear develops, which leads to delamination of the layers. Since the maximum transverse shear stress occurs at

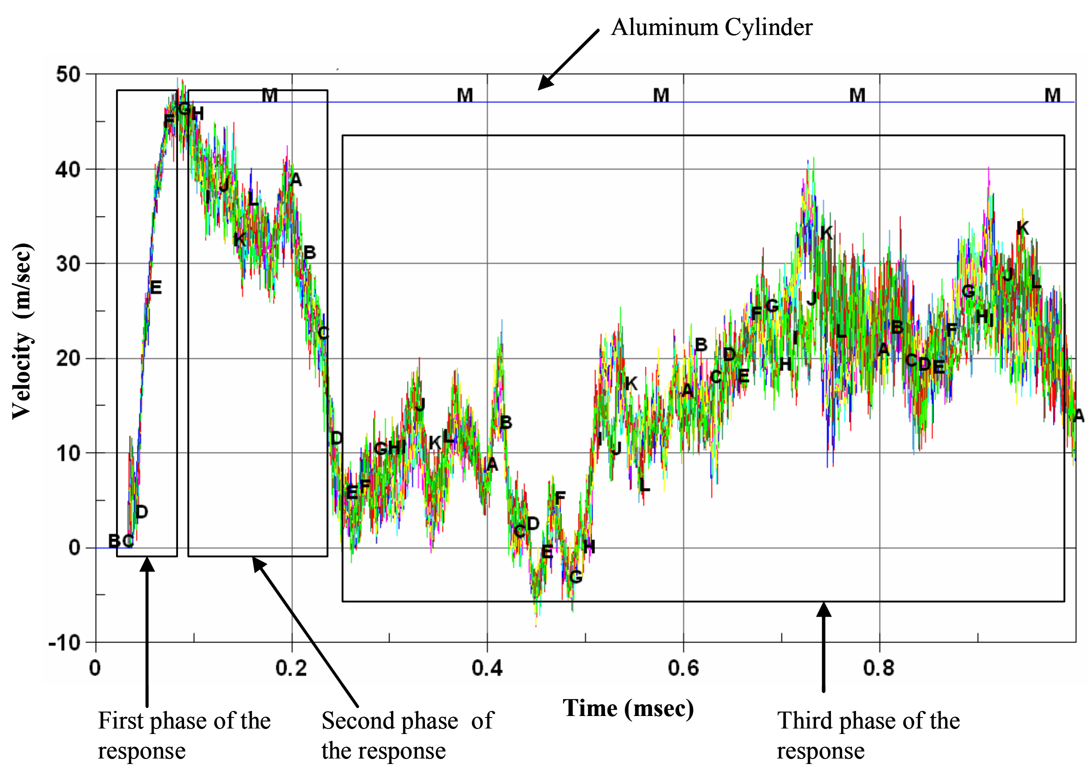

Fig. 12. Predicted time histories of the transverse velocity at the mid-point of the various layers of the thick CFRP plate. The response is divided into three distinct phases.

the mid-plane of the plate, a major delamination develops there.

The third phase starts about 300 microseconds after the blast. At this time the blast load has terminated and the structure responds in a steady state manner. Due to the delamination that developed earlier, the layers are not fully constrained by their neighbours and the response is generally more compliant with lower frequencies than the intact plate. In this phase, delamination may grow due to local tension or shear tractions between the layers.

3.6 Comparison of the numerical results with experimental observations

The only parameter that was measured during the experiments was the velocity of the aluminum cylinder. The average measured velocity was about 62 m/s. The predicted velocity of aluminum cylinder according to the numerical analysis is about 47 m/s as shown in Fig. 12. Therefore, the numerical simulation underestimates the back-face velocity. The accuracy of the CONWEP blast model in this case where the stand-off distance is only 14 cm is questionable and this underestimation of the blast load may be the main reason for the predicted velocities being smaller than the measured data.

In terms of delamination locations, as shown in Fig. 10, the FE analysis predicts a major delamination at the center of the plate. This generally agrees with the experimental observation which is shown in Fig. 2.

No major intra-laminar damage was predicted in the numerical simulation. The post-mortem examination of the blast loaded panels revealed some matrix cracking but no major fibre breakage (see Fig. 2). Underestimation of the predicted damage is expected because of the current inaccuracies in the characterization of the blast load.

4 Conclusions

A numerical model was proposed to model the damage in composite panels subjected to blast loading. The cohesive crack approach was used in modeling the delamination. It was shown that the tie-break interface option in LS-DYNA can be used successfully in simulating cohesive cracks. The effect of contact parameters on the structural response was discussed. The smeared crack model enhanced by non-local regularization was proposed for the intra-laminar damage and it was shown that the non-local approach can be used to address the spurious mesh dependency and mesh orientation problems.

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