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Damage Prediction of Graphite/Epoxy Composite Laminates Subjected to Low Velocity Impact

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ABSTRACT

This study investigates the damage prediction graphite/epoxy composite laminates during low-velocity impact scenario. The energy absorption process is examined using a numerical model, which accurately captures the transition of impactor kinetic energy into laminate damage mechanisms such as intralaminar and interlaminar damage, delamination, and friction. Analytical and numerical results show close agreement, with slight variations in energy absorption and rebound velocity due to damage dissipation. The ricochet phase highlights energy transfer back to the impactor, with partial dissipation due to damage mechanisms reducing rebound velocity. The force-time history demonstrates oscillatory behaviour linked to delamination onset and fibre fractures, with good numerical-analytical agreement for the progression of intralaminar damage. Deviations during the ricochet phase arise from dynamic forces due to delaminated ply interactions. The result conclusively indicates that laminate stacking sequence and thickness influence both matrix cracking and the resultant delamination damages. This comprehensive analysis validates the predictive capability of numerical models in simulating composite impact behaviour.

1. INTRODUCTION

Composite materials are extensively employed in aerospace structures primarily owing to their exceptional specific strength and stiffness, augmented by enhanced durability and diminished maintenance expenses, thereby facilitating a smaller environmental impact. The majority of fundamental composite aero-structures continue to rely on a stiffened skin methodology, rendering them susceptible to impact-induced damage. For example, lower fuselage panels are vulnerable to in-service damage stemming from runway debris or maintenance errors. Apprehensions regarding the implications of impact on the operational efficacy of composite structures have culminated in excessively conservative design approaches.

Laminated composite structures exhibit a heightened susceptibility to impact damage compared to analogous metallic structures, with impacts potentially inducing internal damage that frequently eludes detection through visual inspection. This internal damage may precipitate a reduction in strength by propagating under load conditions [1].

The damage incurred by composite structures as a result of low-velocity impact represents a critical factor that hampers their broader adoption within the industrial sector. These materials delineate elevated strength-to-weight and stiffness-to-weight ratios. Nonetheless, they are vulnerable to impact loading due to their laminar configuration characterized by weak interfacial bonds. Matrix cracking and delamination constitute the predominant damage mechanisms associated with low-velocity impact and are interdependent. Specifically, delamination arises from matrix cracks, which represent the initial form of damage. In the presence of delamination, the stiffness of the material, and consequently the stiffness of the associated structure, may experience substantial reduction, potentially culminating in catastrophic structural failure. Therefore, it is of paramount importance to accurately assess delamination in composite materials subjected to impact loading. Delamination represents a conventional interlaminar failure mode of laminated composite materials that may occur due to the low resistance of the thin resin-rich interface situated between adjacent layers, under the influence of impacts, transverse loads, or free-edge stresses. This type of damage is especially alarming in primary compression-loaded structures, as internal delamination can lead to significant reductions in compressive strength, even when such damage remains undetectable through visual inspection of the laminate surface.

Physical testing of components is characterized by being both labour-intensive and costly, thereby necessitating the advancement of robust numerical modeling tools within the aerospace sector. When examining the impact on composite structures, it is crucial to develop analytical and numerical tools capable of accurately capturing the impact event and the subsequent damage. The impact on composite structures can be classified as high-velocity and low-velocity. In the case of high-velocity impact, the impact event is remarkably brief, and the structure lacks the temporal capacity to absorb significant quantities of the impact energy, frequently resulting in the impactor penetrating the structure. Conversely, low-velocity impact pertains to an impact event that lasts sufficiently long for the entire structure to react to the impactor by absorbing energy elastically and potentially through the formation of localized damage. Numerous authors have investigated analytical solutions to model the impact event [2-9]. However, the physical phenomena associated with an impact event exhibit considerable complexity, thereby constraining the applicability of analytical solutions through the imposition of numerous simplifying assumptions. The finite element method (FEM) facilitates the formulation of intricate numerical models, enabling the simulation of impacts on composite structures within realistic boundary conditions and load scenarios. Furthermore, numerical damage models addressing both intralaminar and interlaminar failure can be developed and integrated into finite element code to accurately represent these damage mechanisms, thereby facilitating the prediction of both the initiation and propagation of damage in impacted composite structures. Continuum damage mechanics (CDM) has increasingly been employed in the creation of numerical damage models pertinent to composite materials. This methodological approach can be traced back to foundational work by Kachanov as referenced in [10] and subsequently advanced by [11,12]. Following the initiation of damage within the intact material, CDM systematically reduces the material stiffness to replicate the propagation of damage. As damage accumulates, the material properties are progressively degraded until sufficient energy is absorbed, culminating in the complete failure of the material. Damage initiation can be anticipated through either stress or strain damage initiation criteria, while the progression of failure can be modeled through a fracture mechanics framework by correlating internal damage variables, which represent distinct forms of damage, with their corresponding fracture energies. Initially, damage models were conceived for two-dimensional problems, exclusively considering in-plane stress effects. Ladeveze and Le Dantec as documented in [13,14], proposed a damage model for an elementary ply that delineated matrix micro-cracking and fiber/matrix debonding phenomena. Additionally, damage models for woven composites have been formulated to represent matrix cracks and fiber fractures occurring in both the warp and weft orientations [15-17]. Not confined to woven composites, numerous researchers [18-20] have developed an energy-based composite damage model, which is applicable to both woven and unidirectional composites, and subsequently implemented it within the explicit finite element package LS-DYNA [21]. More recently, failure criteria pertinent to composite materials have been extended and operationalized within comprehensive three-dimensional finite element models. Faggiani and Falzon [20] used Pinho et al [22] proposal to study a three-dimensional failure criteria, denoted LaRC04, for laminated fibre-reinforced composites. Implementation of such criteria was shown in LS-DYNA for a variety of problems exhibiting different failure mechanisms [23-25]. Also, Donadon [26] devised a fully three-dimensional progressive failure model based on CDM, which takes into account the various intralaminar damage mechanisms that may occur in composite materials. This model was also executed in the explicit finite element code LS-DYNA. A comparable damage model was incorporated in ABAQUS/Standard [27] by [28].

More recently, numerous investigations have been conducted regarding the behavior of composite structures subjected to low-velocity impact through both experimental and numerical methodologies recently, many studies have been done on the behaviour of composite structures subjected to low velocity impact using experimental and numerical models [29-36]. The aim of this paper is to analyze the behavior of quasi-isotropic graphite/epoxy composite laminates when subjected to low-velocity impact. The study employed ABAQUS/Explicit software (2020 version) to simulate intralaminar cracking as a result of the impact event, while interface elements in between plies are used to simulate interlaminar failure in the form of delamination.

2. ANALYTICAL MODELLING

Computational analysis was employed to substantiate the outcomes anticipated through the numerical method. The failure mechanisms induced by impact are inherently intricate, and efforts to predict and correlate the magnitude of damage with the relevant problem parameters have been undertaken through the finite element procedure, particularly by the researchers Choi and Chang [37, 38]. The authors established two distinct failure criteria, one pertaining to matrix cracking and the other to delamination failure. Furthermore, they proposed empirical constants, derived from impact experiments conducted on composite plates, to refine these failure criteria. The subsequent criteria are adopted to facilitate the examination of failure thresholds:

Matrix cracking criterion:

$$\left(\frac{\sigma_{22}}{Y_t}\right)^2 + \left(\frac{\sigma_{23}}{S_i}\right)^2 = e_M^2 \qquad (1)$$

$$e_M \geq 1 \rightarrow \text{failure occur;}$$

$$e_M < 1 \rightarrow \text{no failure occur}$$

$$Y = Y_t, \quad \text{if } \sigma_{22} \geq 0$$

$$Y = Y_c, \quad \text{if } \sigma_{22} < 0$$

Delamination criterion:

$$\left(\frac{\sigma_{23}}{S_i}\right)^2 + \left(\frac{\sigma_{13}}{S_i}\right)^2 + \left(\frac{\sigma_{22}}{Y}\right)^2 = e_D^2 \qquad (2)$$

$$e_D \geq 1 \rightarrow \text{failure occur;}$$

$$e_D < 1 \rightarrow \text{no failure occur}$$

$$Y = Y_t, \text{if } \sigma_{22} \geq 0$$

$$Y = Y_c, \text{if } \sigma_{22} < 0$$

The two failure criteria are implemented at all locations where stresses have been calculated at each time increment. When the average stresses in any of the plies within a laminate first fulfill the criterion (eM > 1) during the impact event, it is anticipated that impact damage (matrix cracking) will ensue. With the application of the first criterion at all points within a specific time increment, the second criterion is subsequently applied at all locations where the first criterion has been satisfied to evaluate the potential for delamination. It is posited that the crack propagates throughout the thickness of the ply group containing the cracked ply, thereby initiating delamination at the interfaces with the neighboring ply groups. To accommodate the reduction in load-carrying capacity of the compromised laminas, the stiffness of such laminas is diminished through the utilization of a compliance matrix, such as the one proposed by [37], which has been modified by exclusion of the third row and third column to render it suitable for the five degree-of-freedom shell elements currently employed as in Eq. (3).

$$|C| = \begin{vmatrix} E_x & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & E_{12} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & G_{xz} & 0 \\ 0 & 0 & 0 & 0 & 0 & G_{xy} \end{vmatrix} \quad (3)$$

3. NUMERICAL MODELING

To replicate the damage of quasi-isotropic graphite/epoxy composite laminate subjected to impact loading, a progressive damage model that integrates stress analysis, failure analysis, and material property degradation has been implemented in the ABAQUS/Explicit finite element software (2020 version). The quasi-isotropic graphite/epoxy composite laminate [±45/0]s is modeled as a circular plate and is clamped at the circumferential edge to emulate the clamped condition experienced in the testing apparatus. A circular plate with a radius of 250 mm, corresponding to the impact zone, was locally modeled with a thickness of 50 mm. Distinct parts were generated for each ply and each ply interface, and the impact region was embedded within the laminate utilizing appropriate tie constraints; additionally, plies were interconnected with their corresponding interfaces. Local coordinate systems and composite sections were employed to accurately depict the orientations of the plies. The impactor was modeled as a spherically shaped rigid surface with a radius of 50 mm, featuring a reference lumped mass of 2.55 kg. To conserve computational resources, only half of the structure was modeled for the simulation (Fig. 1). The boundary conditions established were: (i) symmetry for model division, and (ii) the composite laminate plate was assumed to be clamped. The elements utilized included: C3D8R, a hexahedral element for the standard model plate with each ply in the laminate represented by a solid element in the through-thickness direction, and C3D4, a tetrahedron element code for the semi-spherical steel indentor. The dimensions of the ball elements evidently do not influence the computational duration, as they do not participate in the formulation of the stiffness matrix. This particular mesh is exclusively employed for the delineation of the geometric configuration of the ball. The boundary conditions pertaining to displacement are implemented to facilitate the movement of the ball, via a reference node that encompasses a sizing zone length of 20mm. The extremities of the plate are constrained to radial motion exclusively, while all other degrees of freedom are constrained. Symmetrical boundary conditions are enforced on the planar surface of the semi-circle. The interaction between the ball and the plate is classified as kinematic contact, with a sliding-sticking friction model employed that incorporates a maximum shear stress. The constants utilized in the simulation are delineated in Table 1 [38,39].

Table 1. Material properties applied in the modeling.

Material properties of laminate	ρ = 1309 kg/m^3 E_1 = 140 GPa E_2 = 8.9 GPa E_3 = 8.9 GPa Nu_{12} = 0.263 Nu_{13} = 0.263 Nu_{23} = 0.452 G_{12} = 4430 MPa G_{13} = 4430 MPa G_{23} = 3260 MPa ρ = 1100 kg/m^3
Other parameter	Xt = 1200 MPa Xc = 1150 MPa Yt = 65.5 MPa Yc = 130 MPa S_i = 51.2 Mpa
Material properties of steel impactor	E = 200 GPa μ = 0.33 ρ = 7971 kg/m^3

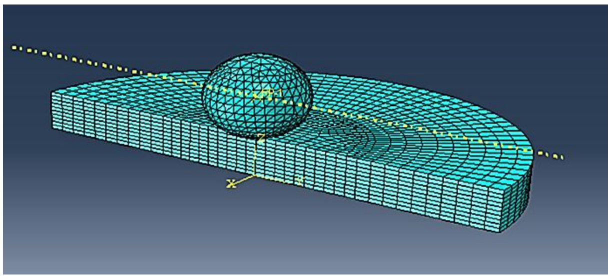

Fig. 1. Finite element model of the composite plate and ball.

4. RESULTS AND DISCUSSION

The numerical results obtained by the FE simulation were compared to those obtained through analytically formulations, specifically Eqs. (1) and (2) [37,38]. Analytical analysis results in reference are used to validate the numerical results. Time histories pertaining to the impact force and energy absorption throughout the propagation were scrutinized, alongside the predicted extent of damage surrounding the impact zone. The phenomena of matrix cracking and delamination damage, as projected by the interface elements within the model, were also examined.

4.1 Energy absorption analysis

The graph presented in Fig. 2 offers a comprehensive comparison of absorbed energy in relation to time, accentuating the complex dynamics of energy transfer during an impact event characterized by a velocity of 50 m/s. Initially, as evidenced, both the analytical and numerical results display a pronounced surge in absorbed energy concomitant with the impactor's interaction with the composite laminate. This swift phase of energy absorption correlates with the deceleration of the impactor and the initiation of damage mechanisms within the laminate. The numerical model, which closely parallels the analytical results, effectively captures this phase with a high degree of accuracy. The plot illustrates a marginal delay in the numerical curve in comparison to the analytical curve, a discrepancy attributed to the numerical model's meticulous consideration of energy dissipation mechanisms. As energy is absorbed, it undergoes transformation into intralaminar damage, interlaminar delamination, and frictional forces at the interfaces of the impactor-panel and ply-ply. These mechanisms, which are modeled numerically, account for the minor delay observed in the progression of absorbed energy towards its plateau. As depicted in Fig. 2, at approximately 3.15 ms, the numerical curve reaches stabilization, signifying that the impactor has completely transferred its kinetic energy to the laminate, achieving a velocity of zero. In contrast, the analytical result forecasts this stabilization slightly earlier, at 3.05 ms. The temporal difference of 0.1 ms falls within acceptable parameters and reflects the intrinsic assumptions inherent in analytical methodologies, such as the omission of certain intricate interactions like localized friction or ply slippage. The plateau region, wherein absorbed energy remains constant at 100 J, signifies the transition into the ricochet phase. During this phase, the absorption of energy ceases to augment as the laminate dissipates the retained energy through mechanisms of permanent damage and dynamic recovery processes. This diagram underscores the numerical model's proficiency in replicating these processes with high fidelity, thereby demonstrating its potential for precisely forecasting the behavior of composite laminates under low-velocity impact scenarios.

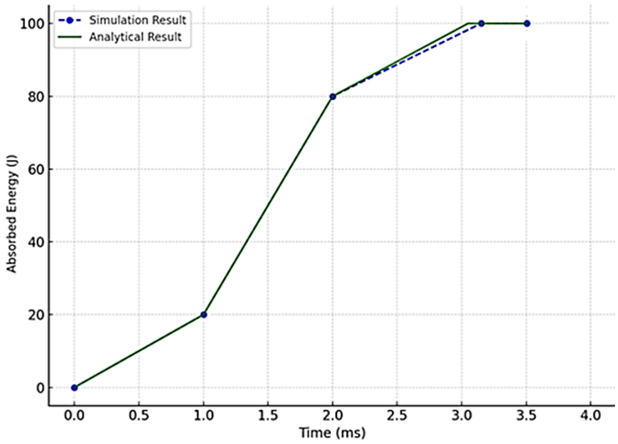

Fig. 2. Numerical evolutions of the absorbed energy versus time.

4.2 Impact force history

The graphical representation depicted in Fig. 3 elucidates the dynamic interplay between the impactor and the composite laminate during an impact event characterized by a velocity of 50 m/s. It is evident that the reductions in force observed in both curves (Fig. 1) are reflective of progressive damage mechanisms. The earlier manifestation of the initial load reduction in the numerical curve implies that the simulation effectively captures the initiation of micro-level damage at an earlier stage than the analytical method, which is predicated on homogenized material properties. The ensuing load reductions, particularly the more substantial decrease observed at 1.8 ms in the numerical results, signify a series of cascading damage phenomena, including the advancement of delamination and the onset of fibre fracture. These phenomena contribute to energy dissipation and are paramount in comprehending the structural integrity of the laminate under impact conditions. In the ricochet phase (post 3 ms), the force exhibits a gradual decline as the impactor rebounds. The numerical model successfully encapsulates the fluctuations occurring during this phase, attributable to ply realignment and residual elastic forces, which are not explicitly represented in the analytical framework. These fluctuations underscore the complex interplay between damage-induced energy dissipation and elastic recovery, thereby yielding profound insights into the behaviour of the laminate during rebound. The more pronounced oscillatory characteristics of the numerical curve demonstrate the sensitivity of the finite element (FE) model to real-world dynamics, wherein ply separations and recontacts significantly influence the force-time response. This particular behaviour is especially notable during the ricochet phase, when energy is transferred back to the impactor and the laminate initiates its recovery process. In contrast, the analytical model presumes smoother transitions, likely attributable to its dependence on simplified constitutive equations that inadequately account for frictional and dynamic interlaminar forces.

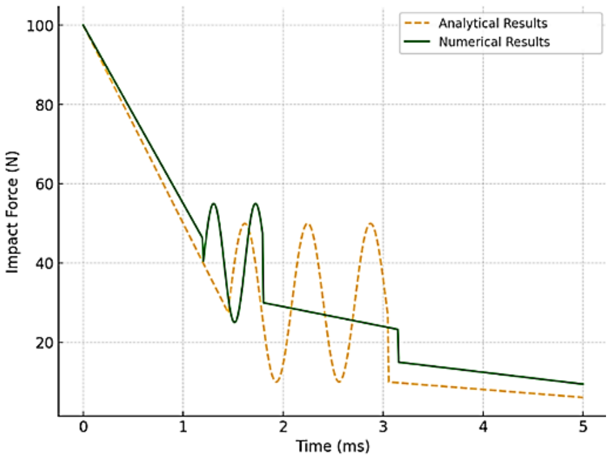

Fig. 3. Numerical condition of impact force versustime.

4.3 Numerical predicted matrix cracking and delamination

The intralaminar damage model facilitated the examination of various forms of intralaminar failure as the impact event unfolded. The predominant mode of intralaminar failure, consistent with analytical findings, was identified as matrix cracking resulting from matrix tensile failure. Fig. 4 illustrates the deformed configuration of the laminate alongside matrix cracking at 40μs subsequent to the impactor's ricochet. It is observable that matrix cracking commenced at a location directly beneath the impact zone within the +45 ply at the indentation face, extending to the corresponding back orientation of the +45 ply. The delamination is correlated with the maximum penetration of the impactor in the numerical impact simulation. Extensive matrix cracking was documented, radiating outward from beneath the impact zone and exhibiting variability in length contingent upon ply locations and orientations. Delamination exhibited a propensity to close as the surfaces of the delaminated plies made contact with one another. The directional characteristics of matrix cracks are most effectively visualized in Fig. 5, which depicts the positions of matrix cracking as predicted by the intralaminar damage model for each ply orientation. It is apparent that the shaped damage contours in the transverse direction are generally aligned parallel to the respective ply orientations.

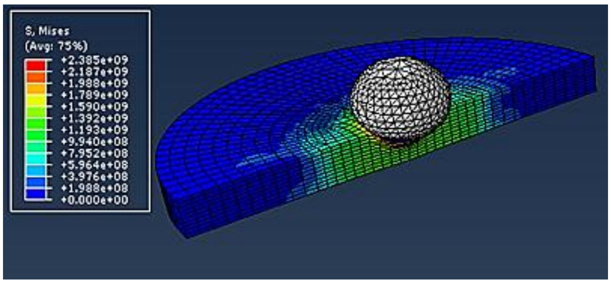

Fig. 4. Numerical predicted damage mode.

Furthermore, fiber failure was anticipated by the numerical damage model as a consequence of the impact phenomenon. This failure transpired at a site directly beneath the point of impact, and the model projected the fiber fracture damage contours, delineated by the damage in the longitudinal direction, to be orthogonal to the fiber orientation as depicted in Fig. 6, which illustrates the position of fiber rupture for plies exhibiting identical orientations. The numerical model did not forecast any debonding at the laminate interface; however, substantial interply delamination was observed in the impact zone. Delamination, which constitutes a pivotal component of impact damage, proliferates due to elevated interlaminar shear stresses in proximity to the impactor [1].

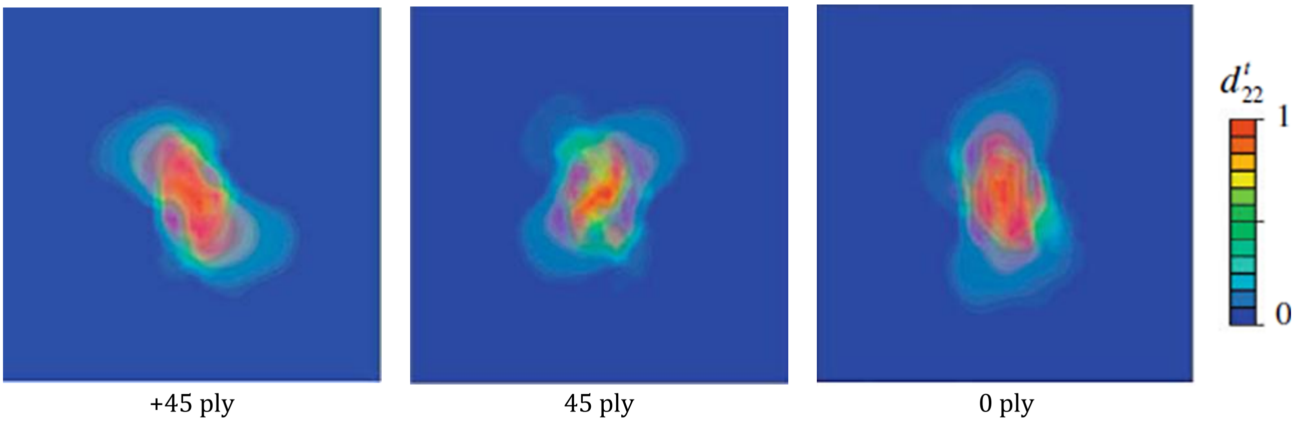

Fig. 5. Numerical predicted matrix cracking contours for different ply orientations.

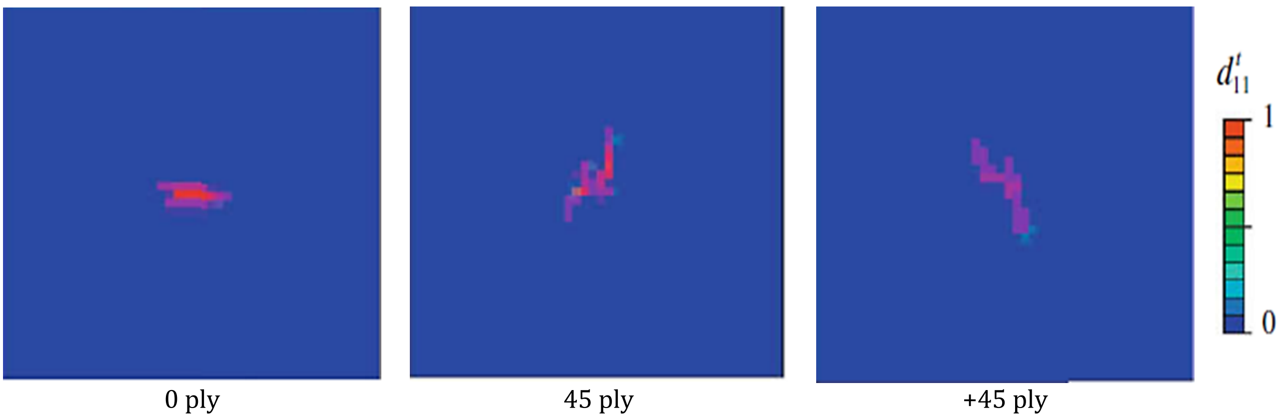

Fig. 6. Numerical predicted fibre breakage for different ply orientations.

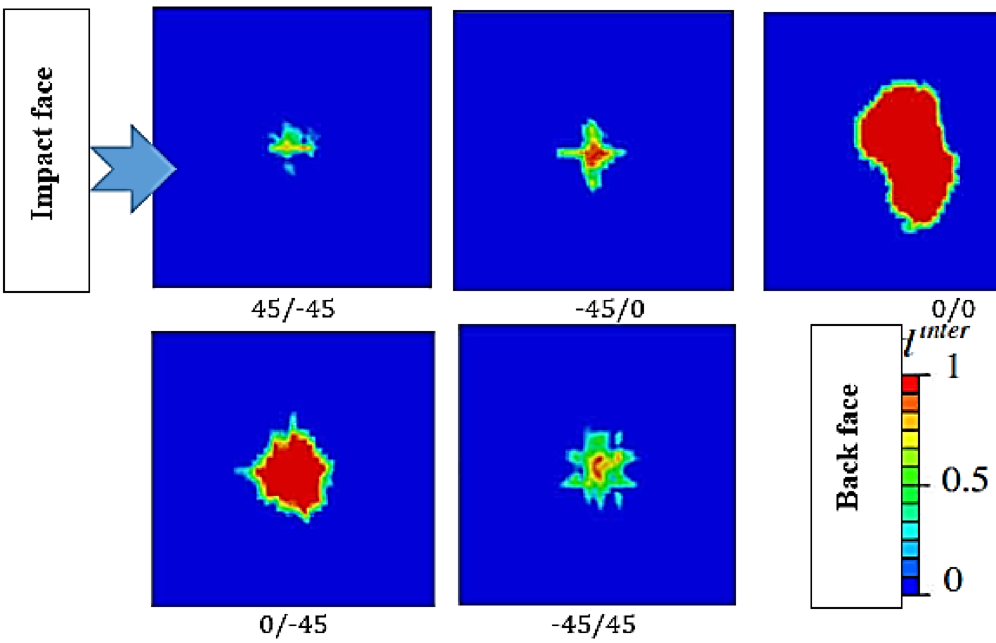

Fig. 7. Numerical interply delamination at zero thickness interface elements.

Figure 7 illustrates the delamination at each interface directly situated beneath the impactor, as quantified by the zero thickness interface elements positioned at each respective interface. It is observable that certain delamination propagated away from a site directly under the point of impact more significantly than others. The most critical delamination was predicted in the 0/0 interface at the laminate's mid-plane, succeeded by the 0/-45 and -45/45 interfaces, which are closest to the rear face, while the least affected interface was -45/45 adjacent to the impactor face. The predicted delamination are in substantial correlation with references [37, 38].

5. CONCLUSION

The study demonstrated the employment of both intralaminar and interlaminar damage within an Abaqus/Explicit finite element model to forecast the low-velocity impact behavior of a quasi-isotropic composite laminate. A commendable correlation was established between the analytical and numerical outcomes concerning energy and force time histories of the impact event, as well as the extent of damage predicted surrounding the impact location. The findings also suggest that the laminate stacking sequence and thickness significantly influence both matrix cracking and the subsequent delamination damages. In conclusion, while the analytical model offers a more generalized depiction, it lacks the resolution necessary to capture oscillatory dynamics during ricochet. Conversely, the numerical model adeptly captures the transient, nonlinear effects associated with the onset of delamination, fiber fracture, and ply interactions. These outcomes underscore the significance of numerical simulations in comprehending composite impact behavior while accentuating the necessity for analytical models to integrate dynamic interactions for enhanced accuracy.

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