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PRELIMINARY ANALYSIS METHOD FOR FRP LAMINATE IMPACT DAMAGE SIZE PREDICTION

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Abstract. *Low velocity impact damage on carbon reinforced polymer laminate composites has been identified as a key threat to airframe structural integrity since it reduces the strength under compressive loading. Airworthiness certification specifications dictate that the airframe structural components up to the full scale subassemblies have to adhere to the strength and fatigue airworthiness requirements imposed whilst being damaged. The study presented herein combines a set of numerical tools for generating an approach to numerically quantify the damage size after low velocity impact on FRP laminates.*

1 INTRODUCTION

Aircraft structures are exposed to damage threats from foreign object impacts in a wide range of conditions. A lot of experimental and numerical analysis research and some analytical works have been devoted to investigating the impact damage on Fiber Reinforced Polymer (FRP) laminates due to the severe consequences it entails on the airframe structural integrity.

Impact damage is categorized in terms of the energy and the subsequent damage size obtained from the event, although impact velocity is also an important factor [1]. The study herein focused on impacts with energies up to 50J, as it is the case when Barely Visible Damage (BVID) is most likely to form. This category encompasses low-velocity impacts such as dropped tools (4-10m/s) as well as intermediate velocity impacts with impactors of relatively small mass, like runway debris (100-150m/s). Metallic airframe structures are subjected to such impacts as well but they tend to absorb the impact kinetic energy by plastic deformation, unlike the mainly elastic behaving until failure CFRP structures, which respond to failure in a subtle manner, hiding the damage extends within the laminated structure from visual inspection on many occasions.

The classic preliminary stage airframe component design procedure mainly addresses and fulfills a number of quasi-static and dynamic loading scenarios in terms of strength and deformation criteria. Not so much attention is payed at this stage to the structural performance degrading environment the structure is to be immersed into. Certain acceptable strength and deformation levels are sought and on some occasions even material fatigue considerations are taken into account during early design. This approach has spawned through the usage of mostly metallic materials for airframes. The performance of structures made of CFRP materials is directly affected by the environment imposing its performance degradation effects by reducing the allowable load carrying levels.

Airworthiness certification specifications require the damaged CFRP structures to attain the acceptable performance levels [2] and this condition has to be proven by test. The airworthiness structural verification testing pyramid [3] commences with tests at the specimen level and proceeds to subcomponent testing until the full scale structure clearance tests. Testing at the specimen level for material characterization is easy and relatively cheap. A great deal of research on impact on composites has been performed based on square, circular or rectangular plates with standardized dimensions aiming at understanding the damage formation and the residual strength decrease especially when under a follow on compression loading. As pointed out by Abrate [4], the results of tests done on samples cannot directly represent the response of the full scale structure. Relevant work has been presented by the U.S. Federal Aviation Administration (FAA) [5] mainly describing the phenomena by parametric formulae curve fitting procedures as resulted from elementary specimen type testing. It can be stated for the impact damage on CFRP structures, there is a lack of information available on transforming simple plate specimen results into meaningful full scale structural design guidelines.

Numerical simulations with progressive damage modelling capturing the degrading material response onto a complete structural detail can provide with adequate information and level of fidelity. On the other hand they can be quite costly in terms of the resources needed. They are generally employed at a later design phase than the preliminary design stage, mainly for complementary design verification rather than design exploration. An alternative resource of information can come from previously tested similar structural components if access to such data is an option but even if so, these cannot account for a new material or for radically new design details.

The approach suggested within this work, provides with a method to quantify the damage size influencing the structural residual strength from low velocity impacts on FRP structural details, in an effort to optimize a component prior to actually manufacturing and testing. A scaled down numerical analysis methodology is proposed, verified by plate specimen tests, that can be further on used to generating more complicated design details which are practically more difficult to manufacture and test. Results from experimental research on plate specimen along with numerical model results of various design details were used to validate the proposed method presented in this work.

2 EXPERIMENTAL DATA

Experimental data used for validation were obtained from [6], where the damage resistance and CAI strength of IM7/977-3 toughened carbon-epoxy laminates were examined. The data have been used to calibrate and validate the generated numerical models and were employed in the benchmarking against the developed analytical procedure. Samples comprising of 17 lamina layers of 100mm x 150mm dimension were impacted by a 5.81kg impactor according to ASTM D7136 [7], with energies ranging from 8J to 20J. The specimen layup sequence was [±45,0,90,0,±45,0,90,0,±45,0,90,±45]s. The lamina properties of the composite used in the experiments are shown in Table 1. Impacted laminates were inspected by nondestructive and destructive inspection techniques and the size of the resulting damage imprints was documented. Some of the analyzed samples (impacted and pristine) underwent quasi-static compression after impact test for determining the CAI strength according to ASTM D7137 [8].

Laminate property	**Symbol**	**Value**	**Unit**
Longitudinal tensile modulus	E_{11}	162	GPa
Transverse tensile modulus	E_{22}	8.19	GPa
In-plane shear modulus	G_{12}	4.96	GPa
In-plane Poisson’s ratio	ν_{12}	0.12	--
Mode I critical strain energy release rate	G_{IC}	170	J/m2
Mode II critical strain energy release rate	G_{IIC}	580	J/m2
Longitudinal tensile strength	X_T	2110	MPa
Transverse tensile strength	Y_T	64	MPa
Longitudinal compressive strength	X_C	1680	MPa
Transverse compressive strength	Y_C	100	MPa
Shear strength	S	121	MPa
Nominal ply thickness	t_{ply}	0.115	mm
Nominal laminate density		1506	kg/m3

Table 1 Laminate material properties [6]

3 NUMERICAL MODELLING OF IMPACT

For the numerical simulation of the impact and CAI on FRP laminates, commercial software code LS-DYNA© was used [9, 10]. The aim of the numerical simulations was to generate data on the impact and CAI response of simple plates as well more complex geometries, like slightly curved plates and/or stiffened panel bays. The numerical results from plate specimen tests have been validated against the results from the experimental study [6] described in the previous section.

3.1 Material modelling

There are many material modelling options available for modeling FRP materials with failure and degradation. In this study, MAT_054/055 was used.

3.2 Laminate modelling

Amongst the various modeling techniques for a composite laminate, the use of solid or shell elements can be chosen depending on the desired simulation fidelity. Factors influencing the final choice are the scale of modelled phenomena, the structure of interest, the desired accuracy and the available computational resources.

Solid elements were used in many previous studies [11, 12] to model composite targets impacted at various velocities where a single element across the thickness was used for each layer. This approach proved to give a very good correlation with experimental results. Moreover, unlike shell elements, that are assumed to be in a plane stress state, solid elements do not neglect the through-the-thickness normal and shear stress tensor components. The main challenges associated with three-dimensional composite models are their very high computational cost as well as laborious FE mesh generation for thin and complex aerospace structures [13]. Composites can be also modelled with the use of shell elements provided that the thickness of the laminate is significantly lower than the remaining dimensions of the structure [14]. Separate plies are then represented by multiple integration points across the shell layer thickness. However, this way of composite modelling does not enable to predict delamination failure since one element accounts for the complete layup across the thickness. Another approach has been described in reference [13] that made it possible to capture the interface failure using 2D elements. The plies forming the laminate are grouped into sub-laminates separated by a cohesive layer or with an appropriate contact definition. This approach has been used in this study as shown in figure 3.

An alternative combining the two aforementioned methods is a thick shell modelling technique. Thick shells have been developed in order to achieve the computational efficiency of 2D shell elements while maintaining the 3D nature of solid elements. A study revealed that this method may bring challenges in terms of solution instability during delamination propagation and the occurrence of severe hour-glassing [14].

A significant amount of comparative analysis and discussion on the subject has been presented in the last decade [13,14,15]. It has been shown that all models are capable of providing a valuable insight into the response of a composite material subjected to low-velocity impact, however, with different levels of accuracy. A very good correlation with the experimental data was obtained with the use of solid and thin shell elements [14]. The latter method was also indicated as giving the most realistic prediction of internal energy and contact force [15]. All researchers agreed, however, that the accuracy of numerical solutions for all methods is strongly dependent on the simulation parameters, such as the element size, contact parameters as well as the number of interfaces.

3.3 Inter-laminar modelling

Since delamination is believed to play the key role in the impact damage size creation and the post-impact behavior of composites under compressive loading, there is a need for a reliable finite element procedure of modelling this phenomenon.

In this study, inter-laminar modelling used the **CONTACT_[...]_TIEBREAK* keyword. When the bonding layer is sufficiently thin to neglect the influence of its mass a contact definition between the bonded layers that has the traction separation laws built in can be used. When the failure criterion is reached the bonding is released and the contact behaves like a normal surface to surface contact.

According to Heimbs et al. [11], tiebreak contacts give less accurate results than the equivalent cohesive layer, due to the change in bending stiffness of the model with increasing number of interfaces and the inability to represent the delamination of each ply constituting the laminate. It is, therefore, suggested that this method should be used for first approximation. However, the results of comparative studies carried out [14, 15] lead to the opposite conclusions. Good accuracy and agreement with experimental results were recorded, proving that 2D shell elements combined with tiebreak contacts are capable of delivering satisfactory levels of accuracy.

3.4 The drop weight impact numerical model set-up

The laminate model has been created with four separate fully integrated shell elements layers comprising eight plies each, shown in figure 1. Shell layers were bonded together with the use of *surface to surface contact* definition, which is the preferred choice in case of limited input data availability and results in reasonable accuracy [12, 13]. The boundary conditions were according to ASTM D7136 [7] experimental set up procedure as shown in figure 2. Initial velocity applied to the ball impacting the plate varied for different simulation cases to meet the predefined impact energy condition. The mass of the impactor was 5.81kg, which is in agreement with the experimental study performed in [6].

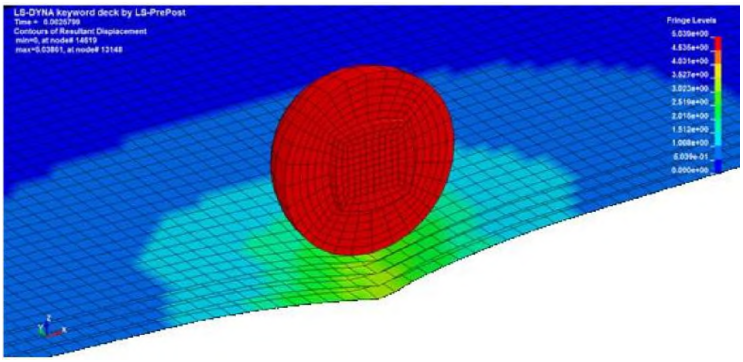

Figure 1 Drop weight impact simulation on a composite laminate modelled by 4 shell element layers representing 17 laminate plies

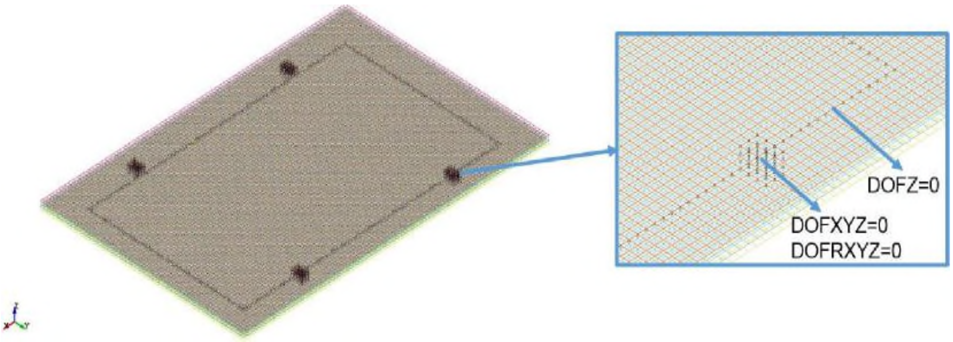

Figure 2 Boundary conditions assumed for the drop weight simulation

3.5 The CAI numerical model set-up

The laminate models used for CAI test simulation was identical to the ones used for the drop weight scenarios but with an artificial damage implemented in the structure. Following the methodology used in experimental studies [12], the impact damage has been represented by releasing contact between two top shell layers in the damage zone as shown in figure 3. Boundary conditions imposed on the model used for simulating the quasi-static compression test as per ASTM D7137 [8] are shown in Figure 4.

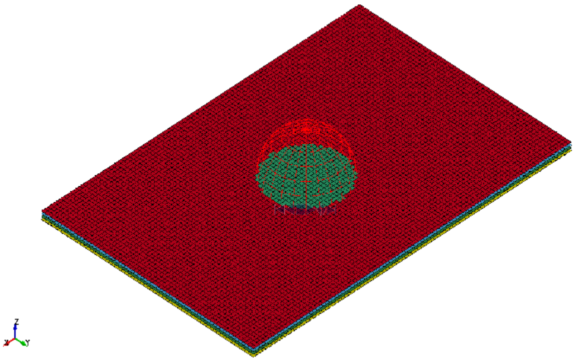

Figure 3 CAI simulations on a composite laminate having removed the inter-laminar bond between the outermost sub-laminate and the rest of the plate

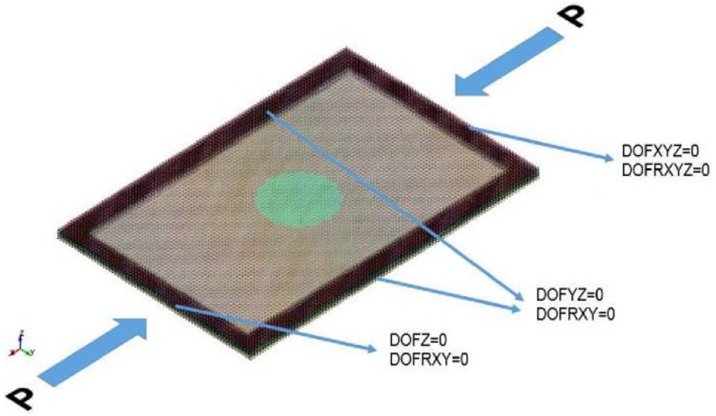

Figure 4 Boundary conditions in CAI test simulation

A simulation of the post-impact residual compressive strength test has been also performed. A sample impacted with the energy of 11.5J and subsequently tested in compression by has been chosen for comparison. The simulation resulted in the CAI strength of 210.6 MPa, which is 12.3% more than the experimental value of 171 MPa. Moreover, the damage pattern observed in the numerical simulation shows an excellent agreement with ASTM D7137 standard [8], as shown in figure 5.

Figure 5 CAI failure mode of the numerical model

3.6 Validation of the numerical models

The numerical model results of impact and CAI strength have been correlated with the results form experimental impact simulations for five representative energy levels [6]. Quantities compared with the experimental data for the impact modelling were the delamination size in terms of width as shown in figure 6 as well as energy absorbed during impact, measured as a difference between the initial and final impactor kinetic energy.

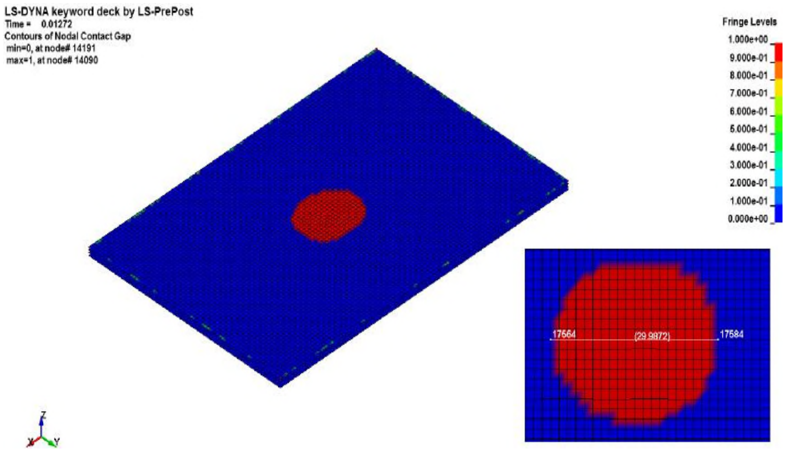

Figure 6 Delamination envelope size on the impacted laminate

In figures 8 and 9 the comparison between the impact and absorbed energy from the experimental survey and the numerical simulations is shown. An interesting observation can be made, suggesting that the numerical model absorbed more energy from the actual experiment under the same impact energy but for the same absorbed energy levels, the delamination sizes are comparable. From the numerical study, a good correlation between the absorbed energy and the peak impact force was found, observation which meant that there was a good correlation between the impact force and the delamination size.

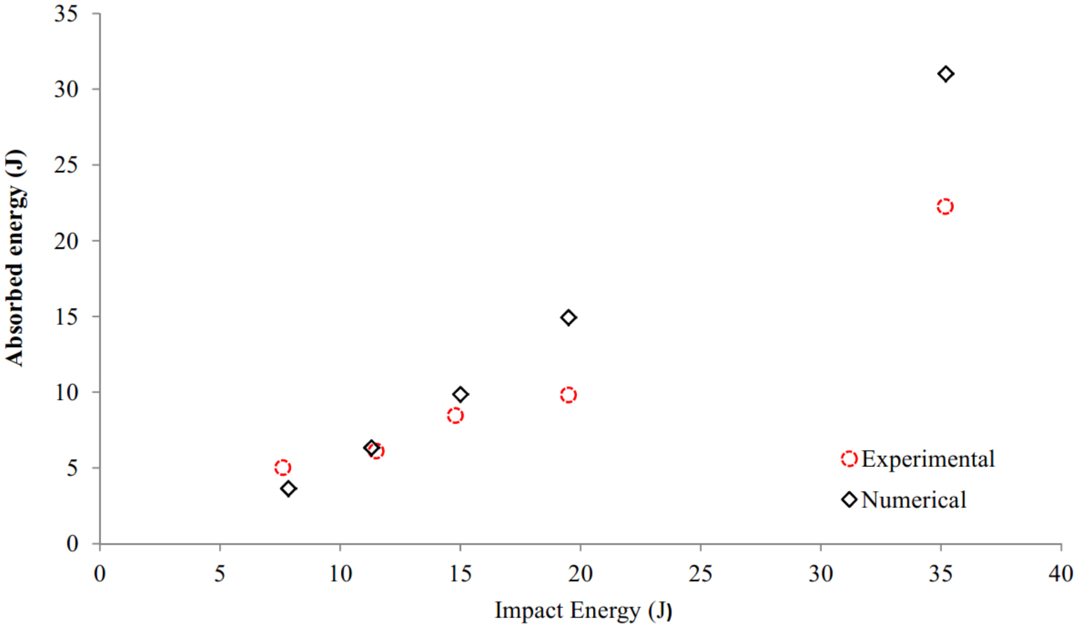

Figure 8: Impact energy versus absorbed energy from the impact

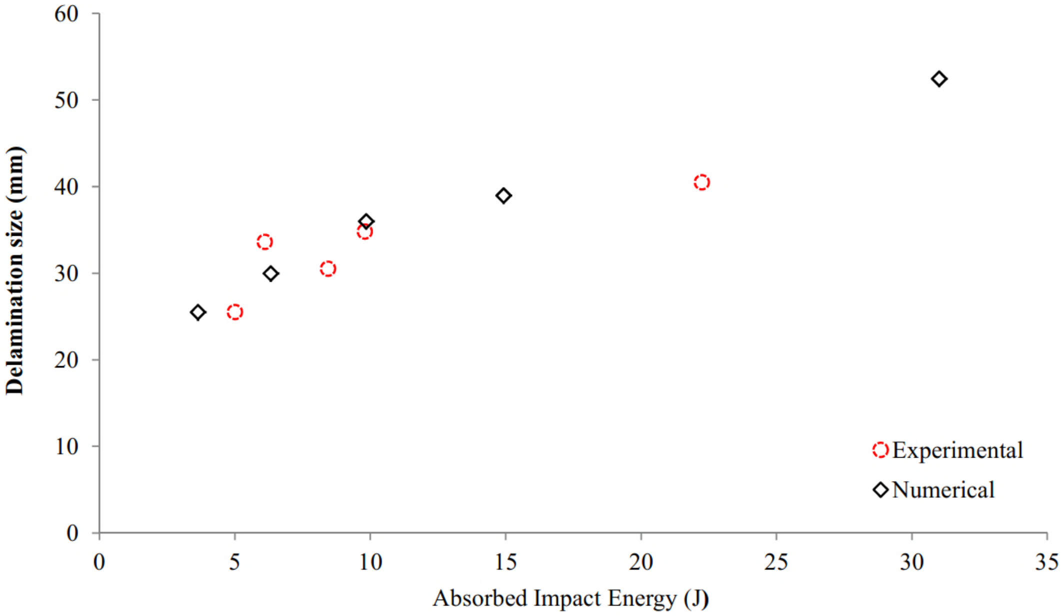

Figure 9: Absorbed energy from the impact versus maximum delamination width

4 ANALYTICAL PREDICTION OF DAMAGE SIZE

A significant amount of work on impact dynamics modeling exists in the literature, the majority of which require numerical tools to be solved [4, 7]. Olsson has provided with closed form analytic solutions based on theoretical models of impact on composite laminates [16].

A research review on composites impact resistance [9, 17, 18] suggested the existence of a direct correlation between the laminate fracture toughness G_{IIC} and the damage extent after impact. Studies carried out [19, 20] led to the conclusion that there is a threshold impact force, below which delamination does not occur. A simple model has been proposed based on quasi-isotropic layups [7].

$$F_{cr} = \pi \sqrt{\frac{8\, E_{flex}\, t^3\, G_{IIc}}{9\,(1-\nu^2)}} \tag{1}$$

Where

F_{cr} Threshold impact force below which delamination does not occur (N),

E_{flex} Equivalent flexural modulus of the laminate (MPa),

t Laminate thickness (mm),

G_{IIC} Fracture toughness under mode II (J/m^2),

v Laminate in-plane Poisson’s ratio

On the other hand, delamination size can be directly related to the impact and plate parameters according to equation (2) [1], where the nominator in this expression is the Peak Impact Force:

$$D = \frac{V_o \sqrt{M\, k_b}}{\pi\, t\, \bar{\tau}} \tag{2}$$

Where

D Delamination width of an assumed circular delamination (mm),

V_o Impactor velocity (mm/s^2),

M impactor mass (kg),

k_b Equivalent plate stiffness at the impact location if assumed a linear spring (N/mm)

t Laminate thickness (mm),

τ Average shear strength (MPa)

Overall, equations (1) and (2) combine in the following expression (3):

$$D = \begin{cases} 0 & if\ F_{peak} < \pi \sqrt{\dfrac{8\, E_{flex}\, t^3\, G_{IIc}}{9\,(1-\nu^2)}} \\[2ex] \dfrac{V_o \sqrt{M\, k_b}}{\pi\, t\, \bar{\tau}} & if\ F_{peak} > \pi \sqrt{\dfrac{8\, E_{flex}\, t^3\, G_{IIc}}{9\,(1-\nu^2)}} \end{cases} \tag{3}$$

On figure 10, the correlation between the experimental, numerical and analytical results is shown.

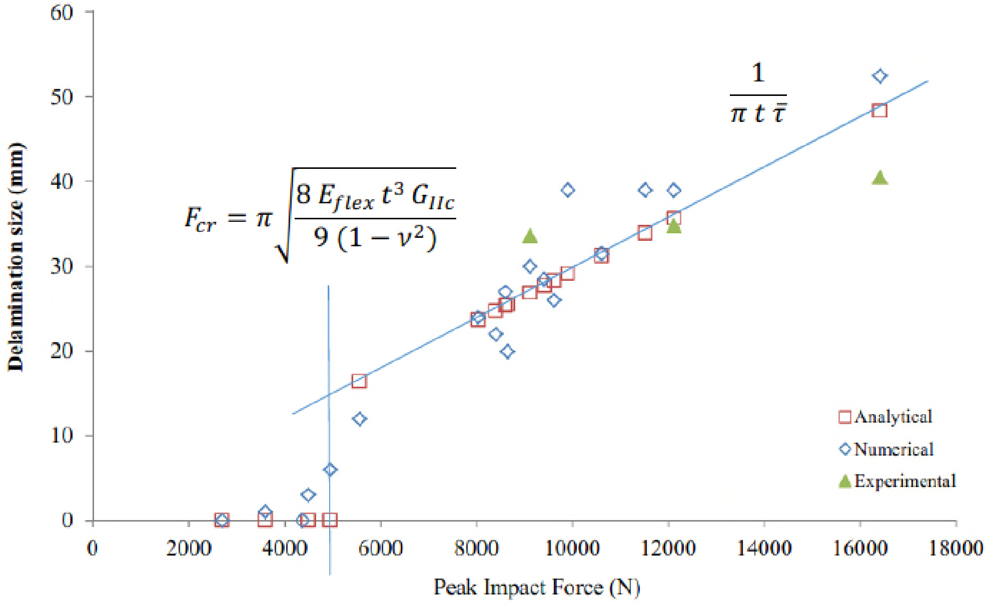

Figure 10: Experimental and numerical results relative to the proposed peak force delamination relation

Equation (3) in essence, relates the impactor velocity and mass with the material properties of the target structure, amongst them being the equivalent plate stiffness of the target at the impact location. The proposition in this work is that in the case the target structure is different than the plate specimens per ASTM D7136, this can be reflected onto the equivalent plate stiffness and hence result on a different damage size according to equation (3). The numerical results on figure 10 are drawn from simple plates, curved plates and bays within stiffened panels.

5 CONCLUSIONS

A semi-analytical methodology was proposed for quantifying the damage size from low velocity impact on FRP laminate airframe design details other than simple plate specimen. The method is suggested for preliminary design analysis prior to component testing. The method has been partially validated via flat plate impact specimen testing and partially through LSDYNA numerical analysis of some more complicated design details. The numerical modeling strategy proposed was in good agreement with the experimental survey.

A proper evaluation of the effects from impact damage can result only after testing the full scale component which would exclude major re-design improvements at that stage. The method can provide with very useful insights to designs benchmarking, design envelope exploration and design optimization.

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