The effect of preloaded on delamination of composite laminate subjected to low energy impact

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Abstract. The CFRP laminate composite is used widely especially in aerospace industry. The design concern of this type of structure is on its strength under impact loading even under low energy impact. Under low impact loading, delamination occurs and reduce the residual strength of laminate, therefore the necessity to predict this phenomena prior to its utilization. In practice the aircraft structure is subjected to pre-stress loading such as due to aerodynamics loading while in the same time loaded under impact loading due to, for example, birds impact. This paper deals with the investigation on the delamination trend of pre-stressed CFRP composite laminate subjected to low energy and low speed impact. A FE model is proposed and validated using published data. After validation confirmation, 2 types of pre-stressed; compression and tension are used to vary the pre-stress parameter. The pre-stress is modelled by prescribe displacement at both edge of the laminate with 5 different values of -0.01, -0.05, -0.1, -0.15, -0.2 mm for compression and 0.01, 0.05, 0.1, 0.3, 0.5 mm for tension. The FE shows that maximum force during impact increases with pre-stress in compression and decreases in tension. The contact time between impactor and laminate remains constant for pre-stress in tension and increases in compression. The impactor displacement during impact is lower for tension and higher for compression. Delamination area increases regardless whether in pre-stress tension or compression. The same trend of delamination shape evolution during impact is observed both for compression and tension; ellipse evolution in transverse or perpendicular direction to the pre-stress direction.

Keywords: FEA, CFRP laminate, impact, delamination, pre-stress.

1. Introduction

In 1961, the first ever composite material was patented, but it was several years before it was made available commercially. This composite improves the strength to weight ratio of structure, thus enable more applications in various industries such as aerospace, automotive, sporting goods and even consumer goods. Due to the development of the material science, various study has been done to learn exactly how the materials behave in different conditions especially during an impact. During an impact, metallic components can yield and dissipate energy through plasticity. As for laminate composites can only dissipate energy by a variety of damage modes, which usually degrades the strength of the structural
component. Low velocity impact such as tool falling down onto the composite laminate structures can affect the structure on the macroscopic level before its affect can be seen. The damage produces by the low velocity impact involved a complex failure mechanism: matrix crack, delamination and fiber break where matrix crack and delamination occur invisible on the surface of the structure. There were a quite significant number of researches and approaches have been done to study the effect of delamination but the prediction of the damage propagation is still up to date for investigation.

The traditional approaches to study the failure of the composite laminate is through experiments. The experiments should be tested from material, specimen and structure itself as recommended for certain application such as for aircraft structures through pyramid process testing for its certification. The number of tests is significant and costly. That is the reason, finite element analysis (FEA) has been developed to replace the testing. Furthermore, FEA can observe the effect on the macrostructure of the composite laminate plate due to the low velocity impact.

The damage caused by low velocity impact (LVI) in laminated composite plate is an important problem faced by designers using composite [1-10]. Not only the in-plane stresses, but the interlaminar normal and shear stresses also play a role in estimating the damage caused by the LVI. LVI is considered dangerous for a composite structure because the damage caused is difficult to be detected and tends to be created on the back face or within the laminate.

In the other hand, the published study relates to the laminate delamination due to impact loading alone [1-5,8-9]. In practice, the laminate structures used for all application especially aerospace ones are pre-stressed before impacted due to expected loading during its service. In this case, the matrix is over-stressed and local sub-critical cracking is produced. These micro-cracks are the main sources of stress concentration at the inter-ply regions and will lead to crack propagation, delamination and fracture of the structure [3,6-7].

Therefore, this paper proposes to observe the effect of pre-stressed on laminate composite subjected to low energy impact. The trend of peak contact force and delamination area trend during impact. The laminate properties used for the simulation is shown in Table I below which are taken from [10].

| Table 1. Mechanical Properties of Composite Plate |
|-----------------------------------------------|
| Dimension (mm)                                  |
| Laminate Thickness (mm)                        |
| Density (kg/m3)                                |
| Young’s Modulus, E_{11} (GPa)                  |
| Young’s Modulus, E_{22} (GPa)                  |
| Young’s Modulus, E_{33} (GPa)                  |
| In-Plane Shear Strength, \( \sigma_{12} \) (GPa) |
| Tensile Strength, \( \sigma_{11} \) (GPa)      |
| Tensile Strength, \( \sigma_{22} \) (GPa)      |
| Poisson’s Ratio                                |
| Shear Modulus, G_{12} (GPa)                   |
| Shear Modulus, G_{13} (GPa)                   |
| Shear Modulus, G_{23} (GPa)                   |
| Shear Strength, \( \sigma_{13} \) (GPa)       |
| Shear Strength, \( \sigma_{23} \) (GPa)       |
| Compressive Strength, \( \sigma_{11} \) (GPa)  |
| Compressive Strength, \( \sigma_{22} \) (GPa)  |
| 100 x 75                                       |
| 1                                             |
| 1600                                          |
| 140                                          |
| 9.5                                          |
| 9.5                                           |
| 0.105                                         |
| 2.000                                         |
| 0.070                                         |
| 5.8                                           |
| 5.53                                          |
| 3.7                                           |
| 0.085                                         |
| 0.105                                         |
| 1.650                                         |
| 0.240                                         |

The solid spherical impactor is modelled using rigid body with the properties listed in the Table 2 below.
| Table 2. Mechanical Properties of Composite Plate |
|-----------------------------------------------|
| Impact Energy (J)                              | 0.67 |
| Impactor Mass (kg)                             | 0.412|
| Density (kg/m$^3$)                             | 381438|
| Velocity (m/s)                                 | 1.8  |
| Diameter (mm)                                  | 12.7 |
| Poisson’s Ratio                                 | 0.3  |

The laminate is modelled using Shell elements with dimension 100mm length, 75mm width, and total thickness of 1mm. 2D modelling approach with shell elements is appropriate when the ratio of length and width dimension is very large compared to the thickness of the plate. As for the material, MAT 22 MAT_COMPOSITE_DAMAGE is used with Chang-Chang failure criteria.

The layup of the laminate of 8 plies [45/-45/90/0/0/90/-45/45] is used for the simulation and to be similar with L.Iannucci [10] work for the purpose of validation and further investigation. The delamination is modelled, at this stage of investigation, using tie-break contact, CONTACT_AUTOMATIC_SURFACE_TO_SURFACE_TIEBREAK. Using this type of contact, it allows for the simulation of delamination based on the cohesive zone model (CZM). After defined the normal and shear failure stresses (NFLS, SFLS), damage is a linear function of the distance of two nodes initially in contact.

The delamination is modelled only at mid-plan of the laminate. Therefore, the 8 plies of laminate will be modelled by two plates of shell with 4 plies each; [+45/-45/90/0] at upper part and [0/90/-45/+45] at lower part. Globally the proposed finite element model is shown in Figure 1 below.

![Figure 1. Finite Element model with delamination at mid-plan of the laminate](image)

3. Validation

For validation, 2 cases will be computed; without delamination and with delamination element. The result of finite element will be compared to the experimental and simulation result of L. Iannucci works [10]. It should be noted that the boundary conditions used for the experiments are clamped at all edges of the laminate, as for the laminate properties and impactor specification, the simulation used the data shown at Table 1 and 2.
Figure 2 shows the comparison between Finite Element and experiment results. The Finite element results correlate the experimental one. Figure 2 shows as well that the delamination model using tie break elements indicates a good approach at the early stage of investigation on the delamination due to low energy impact loading. The tie-break element simulates well the effect of delamination by giving a different force history compared to without delamination (single laminate).

![Figure 2. FEA-Experiments Comparison for validation](image)

4. Pre-Stress Investigation
Once validated, the same laminate is investigated for the effect of pre-stress before subjected to low energy impact. The boundary conditions are changed to allow the pre-stress conditions to be applied; free displacement in longitudinal direction at 4 edges of laminates (Figure 3).

![Figure 3. FE model with pre-stress](image)

The pre-stress parameters used is in compression and tension. For stability of the computation, a prescribed displacement is employed instead of direct force. The magnitudes of prescribes displacement are shown in Table 3 where negative values represent compression and positive values for tension. The
FE computation integrating pre-stress is arranged in such that the pre-stress displacement occurs first and reaches the intended magnitude followed by the impact.

**Table 3. Prescribed Displacement Simulating the Pre-Stress Conditions**

| Time of displacement (ms) | 15 |
|--------------------------|----|
| Displacement (tension) (mm) | 0.01, 0.05, 0.1, 0.3, 0.5 |
| Displacement (compression) (mm) | -0.01, -0.05, -0.1, -0.15, -0.2 |

In order to analyse the effect of pre-stress in compression and tension, the FE outputs such as; Maximum / peak force, contact time, impactor displacement and area of delamination is compared. From Figure 4, maximum force obtained by FE computation increases linearly with the magnitude of pre-stress in compression while in tension the force decreases insignificantly compared to compression. As for contact time of the impactor with the laminate during impact, it remains constant at 5.5ms (Figure 5) for pre-stress in tension case and increases linearly for compression case. It has been observed as well that local buckling occurs during the high value of pre-stress in compression. As for Impactor displacement (Figure 6), it varies insignificantly during tension and increases during compression.

Figure 4, 5 and 6 shows that pre-stress in compression effects significantly the behaviour of laminate subjected to impact loading by producing higher maximum impact force, longer impact contact and therefore higher deflection of laminate (higher impactor displacement) to absorb the impact energy. As for pre-stress in tension, the effect is not as significantly as for compression even though the pre-stress gives an additional stiffness to the laminate before impact.

**Figure 4.** Maximum force in function of pre-stress displacement

**Figure 5.** Contact time in function of pre-stress displacement
Figure 6. Impactor displacement in function of pre-stress displacement

Figure 7 shows that delamination area increases linearly with the magnitude of pre-stress displacement regardless of in tension or compression. The increment is significant for pre-stress in tension compared to compression. However, upon closer observation, under pre-stress in tension (Figure 8), the shape of delamination changes from circular (without pre-stress) to elliptical shape. The elliptical radius of delamination area in the direction of pre-stress increases with the magnitude of pre-stress. As for compression (Figure 9), it is observed that the evolution is not as regular compared to tension one. For both cases, in general the delamination shape becomes ellipse from circular without pre-stress after impact and under pre-stress loading.

From Figure 7-9, it can be concluded that pre-stress in compression has an effect more on the global behaviour of laminate during impact by having higher global deflection, contact time and maximum force during impact. As for pre-stress in tension, it produces the effects on the delamination area rather than the global behaviour of laminate during impact.

Figure 7. Delamination area in function of pre-stress displacement
5. Conclusion
This research work investigates the effect of pre-stressed in tension and compression on the delamination of laminate composite subjected to low energy impact. A finite elements model has been proposed and validated with published experiments data. The validated FE model was then used to compute the same laminate with different magnitude of pre-stress loading before impact. The pre-stress was model by prescribed displacement at the edges of the laminate. The Finite elements computation results shows that pre-stress in compression has an effect more on the global behaviour of laminate during impact by having higher deflection, contact time and maximum force during impact. As for pre-stress in tension, it produces the effects on the delamination area rather than the global behaviour of laminate during impact. The proposed FEA can be developed further for investigation on the prediction of delamination area at all interfaces of the proposed laminate.
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