Effect of Impactor velocity and boundary condition on low velocity impact finite element modelling of CFRP composite laminates

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Abstract: The demand for Composite structures is increasing in different engineering fields such as automobile, aircraft, civil because of its higher specific mechanical properties. It’s very important to consider failure modes like fiber breakage, delamination, matrix cracking, etc. when it is impacted by a foreign object such as dropping of tool (impact type events). Susceptibility of damage due to low velocity impact is more in the laminated composite structures than metal. It is important to study the response of composite for varying velocities with different boundary conditions in case of low velocity impact analysis. Thus, this paper presents the combined effect of different boundary conditions with varying velocities of impacter on low velocity impact modelling of CFRP composite laminates. Numerical analysis is performed on T700GC/M21 material with layup [0/-45/90/-45/2]s to study the force-time/displacement curve. Numerical analysis is performed using ABAQUS 6.14. First, Numerical analysis is carried out for impacter velocities varying from 2.5 m/s to 10 m/s. In ABAQUS/Explicit, two boundary conditions i.e. simply supported edges boundary condition SSSS and Clamped supported edges, CCCC are used to study the force-time/displacement curve. Out of that numerical results of impacter velocity 5 m/s with boundary condition SSSS is validated with results of literature by studying force-time/displacement curves. The numerical findings revealed that; as impacter velocity increases, the force and displacement also increases. Also, current simulation results are closely matching with the existing numerical and experimental data.

Keywords: Impacter velocity, low velocity impact, boundary condition, force-time/displacement, finite element.

1. Introduction:

The demand for Composite structures is increasing in different engineering fields such as automobiles and aircraft due to their inherently higher specific mechanical properties. The most important features of composites are higher strength, high stiffness, low density, and shear properties, etc. These composite laminates or structures are often subjected to dynamic impact loads during their use. Plastic deformations, matrix cracking, delaminations, Fiber breakage are some effects that should be taken care of when there is a low velocity impact (tool drop while maintenance, bird strike, etc.) on composite structures.

Low velocity impact and high velocity impact are the two main classifications of the impact problem of the composite while studying the damage mechanisms. To study damage mechanism, usually low velocity impact analysis is done due to its lightweight design. The damage due to low velocity impact is not clearly visible to naked eyes when the composite laminate is impacted by some foreign object.
For composite structures under the impact, the primary failure mechanism includes transverse matrix cracking, longitudinal fibre breakage, delamination also interactions.

Finite element method (FEM) is an essential tool available for the numerical analysis of composite structures. It is beneficial to study failure properties while designing the composite. Numerical analysis in ABAQUS includes a series of complicated numerical issues like geometry, material properties, boundary conditions, frictional contact, failure law, and time-stepping, which are essential while modelling low velocity impact.

Zuleyha Aslan et al. [2] studied the effect of low velocity impact loading on laminated composite. The in-plane dimensional effect of CFRP laminated composite evaluated for impact loading. Numerical simulation is done using 3D IMPACT for calculating contact forces & stresses during impact. Volnei Tita et al. [3] presented a study on thin disks of carbon fiber composite with epoxy resin for low velocity impact. An investigation is done to see the effect of energy impact and stacking sequence using force-time/displacement curves by the NDE technique.

D. Fang and E. Aymerich [4] presented a damage model that is based on continuum damage mechanics. The study carried out for the prediction of different failure mechanisms and structural response of composite laminates low velocity impact loading. Shi-Xu Wang et al. [11] investigated low velocity impact characteristics and residual tensile strength of CFRP laminates numerically (using ABAQUS/Explicit) and experimentally.

Jikui Zhang and xiang zhang [5] presented an approach to predict the damage mode and impact force in laminated composite under low velocity impact. N. Hongkarnjanakul et al. [6], Y. Shi et al.[7], Wei Tan et al. [8] used ABAQUS for low velocity impact finite element modelling and analysis of CFRP composite laminates.

In the above literature, the impact response of the composite structure is found out by different EF software but the combination of velocity with boundary conditions is less evolved. So, This paper presents the combined effect of different boundary conditions with varying impactor velocities on low velocity impact modelling of CFRP composite laminates. The stacking sequence considered for analysis is [0°/45°/90°/-45°], having 8-double ply, quasi-isotropic, and mirror-symmetric laminated plate of material T700GC/M21 (Carbon/Epoxy). The studies carried out on plate dimension 100mm×150mm with 4mm thickness on laminate. Impactor is of 16 mm diameter and having mass 2 Kg. First, Numerical analysis is carried out for impactor velocities varying from 2.5 to 10 m/s with the step of 2.5 for two boundary condition i.e., simply supported edges boundary condition SSSS and Clamped supported edges, CCCC to study the force-time/displacement curve. Out of that numerical results of impactor velocity 5 m/s with boundary condition, SSSS is validated with the results of P. F. Liu et al. [1] by studying force-time/displacement curves.

**Properties for T700GC/M21 composite laminates**

**Layer Properties:**

- $E_1 = 130$ GPa, $E_2 = E_3 = 7.7$ GPa, $G_{23} = 3.8$ GPa, $G_{12} = G_{13} = 4.8$ GPa, $v_{12} = v_{13} = 0.33$, $v_{23} = 0.35$,
- $X^T = 2080$ MPa, $X^C = 1250$MPa, $Y^T = 60$MPa,
- $Y^C = 110$ MPa, $Z^T = Z^C = 290$ MPa,
- $S_{12} = S_{23} = S_{13} = 110$ MPa, $\Gamma_{11}^T=133$ N/mm, $\Gamma_{11}^C=40$ N/mm, $\Gamma_{22}^T=0.6$ N/mm, $\Gamma_{22}^C=2.1$ N/mm.

**Interface properties:**

- $G_1^C=0.6$ N/mm, $G_2^C=G_3^C=2.1$ N/mm, $\eta=1.45$, $T_1^0=T_2^0=T_3^0=30$MPa

2. Finite element modeling of impact problems of composites

ABAQUS 6.14 is used for Low velocity impact Finite element modelling problem. Layup parameters, material properties, interactions between lamina to lamina, and laminate to impactor, impact velocity, the meshing of laminate and impactor, different boundary conditions are provided using ABAQUS. The reduced integration with hourglass control element SC8R used for the laminate. The 0.3 friction contact coefficient is considered. Material T700GC/M21 is used for layup [0°/45°/90°/-45°], and material parameters are given in Table. The geometry size for laminate is 100mm×150mm×4mm and ply thickness is 0.25mm. The mass & diameter of the impactor are 2kg and 16mm respectively.
In the following, the effect of different impact velocities with boundary conditions are discussed. Also, validation of existing results is done.

![FE impact analysis model](image)

**Figure 1: FE impact analysis model**

### 2.1 Effect of Impactor velocity for two boundary conditions

In this section, the impact analysis responses for velocities varying from 2.5 to 10 m/s with two boundary conditions are presented.

#### 2.1.1 Impactor Velocity 2.5 m/s

![Impact force vs time for 2.5 m/s vel. with clamped supported edges, CCCC](image)

![Impact force vs displacement for 2.5 m/s vel. with clamped supported edges, CCCC](image)

#### 2.1.2 Impactor Velocity 5 m/s

![Impact force vs time for 2.5 m/s vel. with simply supported edges, SSSS](image)

![Impact force vs displacement for 2.5 m/s vel. with simply supported edges, SSSS](image)
2.1.3 Impactor Velocity 7.5 m/s

Figure 6: Impact force vs time for 5 m/s vel. with clamped supported edges, CCCC

Figure 7: Impact force vs displacement for 5 m/s vel. with clamped supported edges, CCCC

Figure 8: Impact force vs time curve for 7.5 m/s vel. with clamped supported edges, CCCC

Figure 9: Impact force vs disp. curve for 7.5 m/s vel. with clamped supported edges, CCCC

Figure 10: Impact force vs time curve for 7.5 m/s vel. with simply supported edges, SSSS

Figure 11: Impact force vs disp. curve for 7.5 m/s vel. with simply supported edges, SSSS

2.1.4 Impactor Velocity 10 m/s
Figure 12: Impact force vs time for 10 m/s vel. with clamped supported edges, CCCC

Figure 13: Impact force vs displacement for 10 m/s vel. with clamped supported edges, CCCC

Figure 14: Impact force vs time curve for 10 m/s vel. with simply supported edges, SSSS

Figure 15: Impact force vs displacement curve for 10 m/s vel. with[1]simply supported edges, SSSS

Table 1: Max. force and max. displacement for 2.5 to 10 m/s velocities.

| BC                  | Impactor velocity 2.5 | Impactor velocity 5 m/s | Impactor velocity 7.5 | Impactor velocity 10 |
|---------------------|-----------------------|--------------------------|------------------------|----------------------|
|                     | Force (N)             | Force (N)                | Force (N)              | Force (N)           |
| Clamped supported   | 4841.15               | 10661.7                  | 17014.01               | 23067.86            |
| edges, CCCC         | 4464.47               | 8714.63                  | 15131.01               | 18553.82            |
| Simply supported    | 2.52062               | 4.83095                  | 6.89633                | 8.84218             |
| edges, SSSS         | 2.69725               | 5.4                      | 7.87083                | 10.70158            |

From the results following observation are seen

1. It is found that as impactor velocity increases the force and displacement also increases.
2. In CCCC boundary condition force is higher than SSSS boundary condition and displacement is lesser in CCCC.
3. The fluctuation in force time/displacement curve is more in Simply supported edges SSSS may be due to fiber failure, matrix failure or other failure modes.
4. Failure is higher in impactor velocity 10 m/s.

3. Validation of Numerical results with the experimental and numerical results from Liu et al. [1]

Drop weight impact is used in ABAQUS. Geometrical Modelling, meshing, material properties, boundary condition, interaction between impactor and laminates, between lamina to lamina properties, other parameters are established using ABAQUS/Explicit. The 25J impact energy is used for as specified in [1]. Dynamic penalty method is used between impactor and laminates. The friction contact coefficient is 0.3. Material T700GC/M21 is used for layup [0°/45°/-45°/90°]. The geometry size for laminate is 100mm×150mm×4mm and ply thickness is 0.25mm. The number of all elements is 60352. Hongkarnjanakul et al. [6] and Liu et al. [1] got 3.5ms impact contact time by experiments, and thus we considered 4.0ms impact time per period for simulation. Numerical and experimental data taken from Liu et al. [1] using X-Y plotter software for comparison.

![Impact force vs time curve](image1)

![Impact force vs displacement curve](image2)

Table 2: Comparison of current numerical result with reference paper [1] data.

|                  | Numerical data from [1] | Experimental data from [1] | Current results  |
|------------------|-------------------------|----------------------------|------------------|
| Force            | 8318.04 N at 0.0017 sec | 8426.84 N at 0.0015 sec    | 8714.63 N at 0.0015 sec |
| Displacement     | 5.1 mm                  | 5.5 mm                     | 5.4 mm           |

Fig 16 and 17 shows the validation of current numerical results with the numerical and experimental results of P. F. Liu et al. [1]. The peak impact force for numerical and experimental taken from Liu et al. [1] are found to be 8318.04 N at 0.0017 sec and 8426.84 N at 0.0015 sec respectively. The impact for of current numerical simulation is 8714.63 N at 0.00156 sec which is acceptable. The max. displacement for numerical and experimental taken from Liu et al. [1] are found to be 5.1 mm and 5.5 mm respectively. The displacement for current numerical simulation is 5.4 mm which very close to the existing results. The variation of results may be due to numerical filters which is used by [1]. Some numerical oscillations appear in the curve that may be because of numerical effects and dynamic
responses. The impactor starts rebound at time 0.0017 sec approx, after the peak force. In the numerical simulation, Hasin’s criterion is used, which is already inbuilt in ABAQUS package.

4. Conclusion:
This paper aims to discuss the effects of Impactor velocity and different boundary conditions on the force-time and displacement histories of CFRP laminates under low velocity impact. The impact responses are classified and discussed according to impactor velocity and boundary condition. Hashin failure criteria which is inbuilt in ABAQUS is very useful for developing solution. In numerical analysis, we can easily determine different failure like fiber failure, matrix failure etc. with help of force time/Displacement curve. There are other failure criteria like Chang-Chang and Puck criteria, which can be used for analysis.

The research can further be extended for this model like other validations such as the effect of different layup, stacking sequence, the effect of boundary condition. The effect of different friction coefficient on numerical results can be explored. Selection of different parameters are important for enhancing the impact strength.

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