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Prediction of Low Velocity Impact Damage Resistance in Fibre-Reinforced Laminated Composites

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ABSTRACT

A composite material is a material, which is produced from two or more constituent materials. These constituent materials have notably dissimilar chemical or physical properties and are merged to create a material with properties unlike the individual elements. Laminated composite structures are always exposed to different kinds of impact loads, and because of the heterogeneous, anisotropic and brittle behaviour of the material, impact damage is considered to be a threat to them. A constant concern for laminates – much more than for similar metallic structures – are impact loads of foreign objects, which can cause internal material damage and impact on composite laminates typically results in concentrated contact loads, which cause local indentation in addition to any deflection of the laminate. There are three types of impact, namely low-velocity impact (4-8m/s), intermediate velocity (70m/s) and high-velocity impact (300 to 2,500m/s). Low-velocity impact may cause different damage mechanisms and in particular barely visible ones that severely reduce the structural integrity. The investigation of low velocity impact damage resistance in fiber reinforced composite laminates is done in the paper using finite element software Abaqus. The main objectives of this study is to identify a benchmark problem with suitable experimental results and simulate the same using abaqus and validation of simulated results with experimental data. Further iterations are performed to predict the damage resistance for various reinforcements, laminate thickness and Ply Orientations and also the comparison of contact force, impacted energy, displacement and damage area. The validation of the simulated results with the experimental benchmark results is completed and it is observed that the results coincide with each other.

Keywords: *Low-Velocity impact, Composite material, reinforcement, Ply Orientation, Finite Element Analysis.*

1. Introduction

These days, composite materials are widely used in automobile and aerospace industries, and they are replacing many traditional metals. These Fibre-reinforced composite materials are known for their high weight-specific mechanical properties and therefore are used in numerous lightweight engineering applications. Due to their low weight and high strength these are preferred in applications where weight plays an important role. However, a constant concern for such laminates much more than for similar metallic structure are impact loads of foreign bodies. The problem of impact damage in laminate composite structures is the reduction in residual strength [4]. Impact performance is a particularly important consideration in designing laminated composites. Especially, low-energy impacts or minor object drops, like tools dropping during assembly or maintenance can cause significant damage in terms of matrix cracking, delamination or fibre breakage, which maybe barely visible from the surface by visual inspection [6]. Typical impact scenarios in aircraft design are high mass-low velocity impacts (tools dropping) ranging 4-8 m/s with energies up to 50J, low mass-high velocity impacts (runway debris hitting the aircraft body) ranging up to 70 m/s with energies upto 50J and high mass-high velocity impacts (bird impact on the aircraft wings) ranging 300-2500 m/s with energies up to 20kJ [4].

The impact behavior of composite laminates has been treated extensively in this study [12]. Composite laminates are likely to experience low velocity impacts which may cause different damage mechanisms and in particular barely visible ones that severely reduces the structural integrity. Identification of the behavior of the composite laminates due to these low velocity impacts is the main objective of the study. Also, prediction of damage resistance for various reinforcements, geometry and ply orientations and comparing the contact force impact energy and displacement is covered in this study.

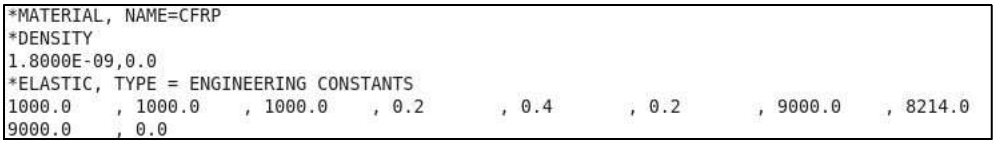
In order to predict damage resistant behavior of the fibre-reinforced composite laminates under low velocity impact loads, a benchmark problem is identified with suitable experimental results a model of the composite plate with the impactor is developed using finite element software, Abaqus and the obtained results are validated with the benchmark results. Further iterations are carried for various reinforcements and ply orientations and the results are compared with the validated results.

2. Method and Methodology

The first step is to identify a benchmark problem with the necessary experimental test results and then modelling the same test case scenario using finite element software. The current study leverages Abaqus 6.14 software for the undertaken analyses.

Composite plate is modelled with shell elements (S4) with 24 plies and the impactor is modelled as a rigid body (R3D4 elements). The composite plate is modelled with dimensions, 400mm×150mm×2mm [12]. The impactor is modelled as a sphere with diameter 25.4mm and weight of 1.85kgs [12].The impactor is made to fall with a velocity of 6.5m/s which makes an impact energy of 40J [12].

The material property of the Carbon Fiber Reinforced Plastic(CFRP) and the impactor used for the simulation is shown in figure 1 and 2 respectively.



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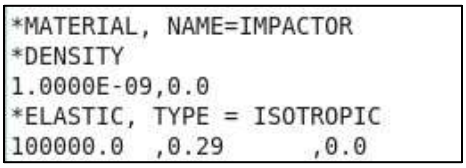
9000.0    , 0.0
```

Fig. 1 - CFRP material properties



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*ELASTIC, TYPE = ISOTROPIC
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Fig. 2 - Impactor material properties

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3.2       ,          3,CFRP,0.,PLY-2
3.2       ,          3,CFRP,45.,PLY-3
3.2       ,          3,CFRP,90.,PLY-4
3.2       ,          3,CFRP,-45.,PLY-5
3.2       ,          3,CFRP,0.,PLY-6
3.2       ,          3,CFRP,45.,PLY-7
3.2       ,          3,CFRP,90.,PLY-8
3.2       ,          3,CFRP,-45.,PLY-9
3.2       ,          3,CFRP,0.,PLY-10
3.2       ,          3,CFRP,45.,PLY-11
3.2       ,          3,CFRP,90.,PLY-12
3.2       ,          3,CFRP,90.,PLY-13
3.2       ,          3,CFRP,45.,PLY-14
3.2       ,          3,CFRP,0.,PLY-15
3.2       ,          3,CFRP,-45.,PLY-16
3.2       ,          3,CFRP,90.,PLY-17
3.2       ,          3,CFRP,45.,PLY-18
3.2       ,          3,CFRP,0.,PLY-19
3.2       ,          3,CFRP,-45.,PLY-20
3.2       ,          3,CFRP,90.,PLY-21
3.2       ,          3,CFRP,45.,PLY-22
3.2       ,          3,CFRP,0.,PLY-23
3.2       ,          3,CFRP,-45.,PLY-24
```

Fig. 3 - Ply orientation of composite plate

The carbon fiber reinforced plastic has 24 plies with orientation [-45/0/45/90]3S [12] as shown in Figure 3.

Since the impact energy and mass of the impactor is known from [12], the height of the drop is calculated as:

$P_e = mgh$

$P_e = 40$ J

m = 1.85 Kgs

$g = 9.81\ m/s^2$

Therefore, h = 2.2 m

2.1 ABAQUS

Abaqus Explicit is used in solving the impact scenario with Hypermesh as the pre-processor. The modelling of composite plate is done in Hypermesh as continuum shell elements. Composite shell section is created by specifying the ply orientation, material property and ply thickness as shown in figure 4.

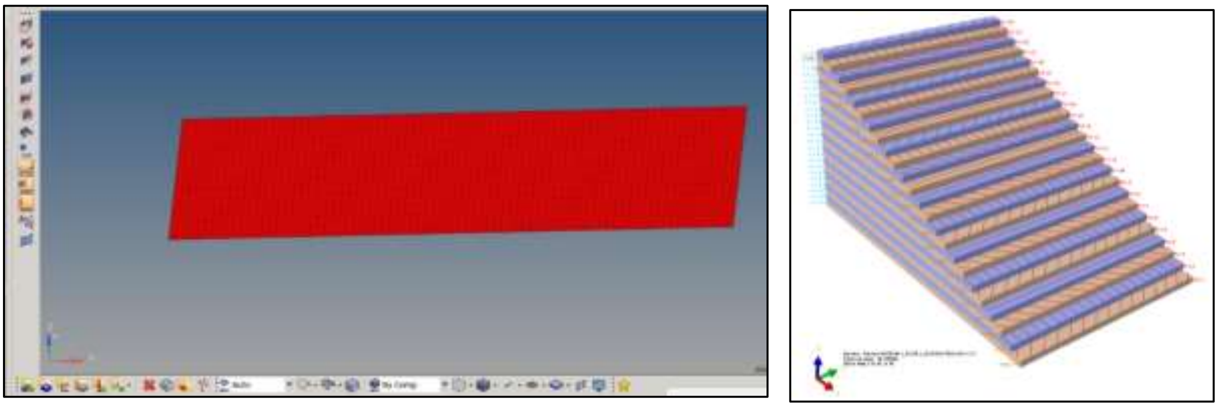
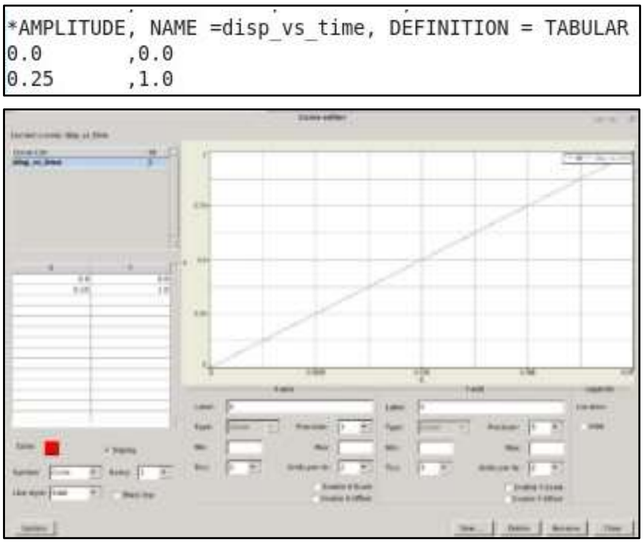


Fig. 4 - Composite plate with 24 Ply's



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0.25      ,1.0
```

Fig. 5 - Amplitude curve defining the displacement of the ball

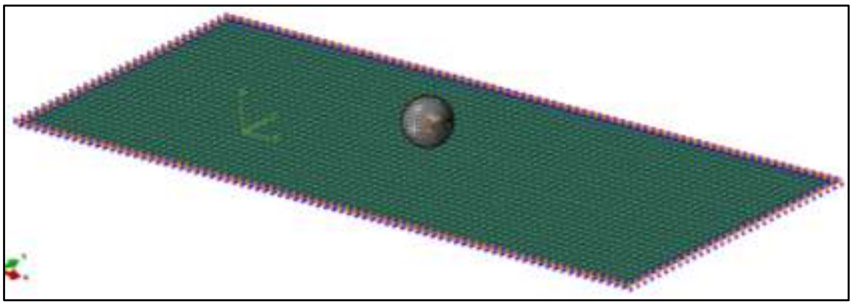


Fig. 6 - Boundary conditions for the plate and the impactor

The ball is made to drop from the height of 2.2m by specifying a linear amplitude curve for the displacement of the ball as shown in the figure 5. The plate is pinned at two edges of the plate and fixed at the other two edges and the impactor is left free for falling and is constrained for rotational degrees of freedom as shown in the figure 6.

3. Benchmark Problem

The impact case for the mentioned inputs is simulated and the results obtained from the simulations are compared with the benchmark results obtained from the hardware test results. The results are compared for displacement and contact stresses on the composite plate due to impact.

The simulation for low velocity impact on the composite plate is carried out for CFRP material and the results obtained is compared with the benchmark results.

3.1 Case study 1 – Validation of the Model

For the validation, CFRP material properties shown in figure1 is used for the flat plate with orientation [-45/0/45/90]3S. [12] The impactor is made to fall from the calculated height of 2.2m.

Figure 7 shows the impact scenario where a ball impactor hits the composite plate and there is a dent in the plate observed.

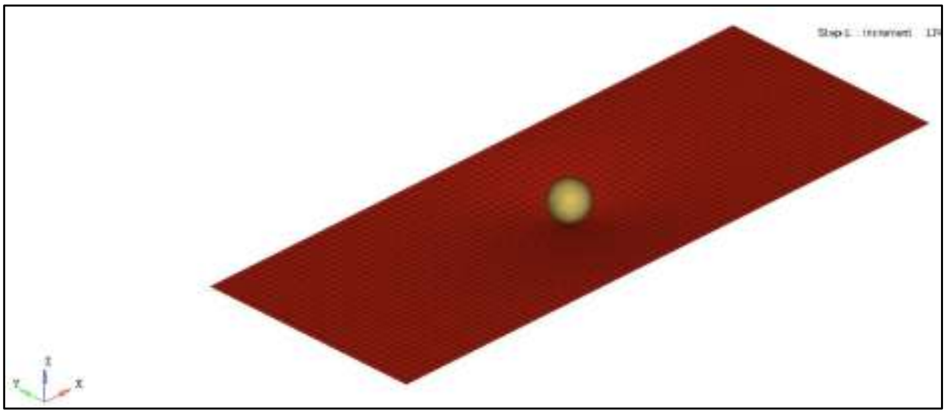


Fig. 7 - Impact scenario of ball impactor with the CFRP plate

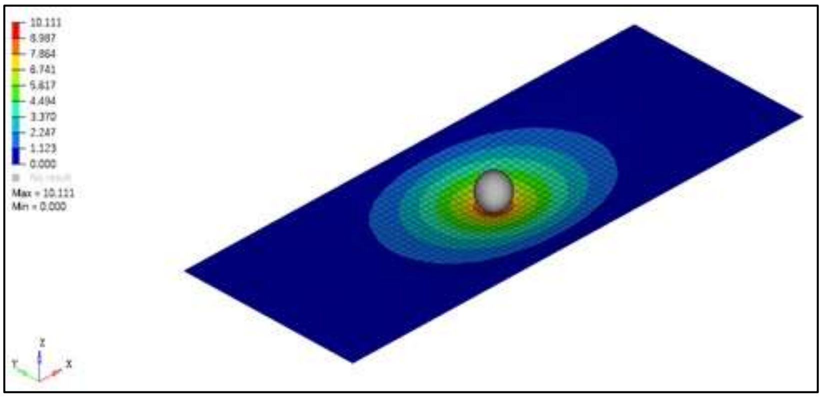


Fig. 8 - Displacement of the CFRP plate due to the impact

The displacement of the composite plate is shown in figure 8. The figure also indicates the behavior at the area of impact, where a small dent is observed at the time of impact.

The displacement vs time are extracted as shown in figure 9(a&b) and the curves are compared with the benchmark results.

The dashed curve indicates values for displacement v/s time as shown in figure 8a. Figure 8b indicates the same for the obtained results. We can observe that the obtained results for displacement is more or less the same as that of the benchmark value.

The stress values in the CFRP plate during the impact is as shown in the figure 10.

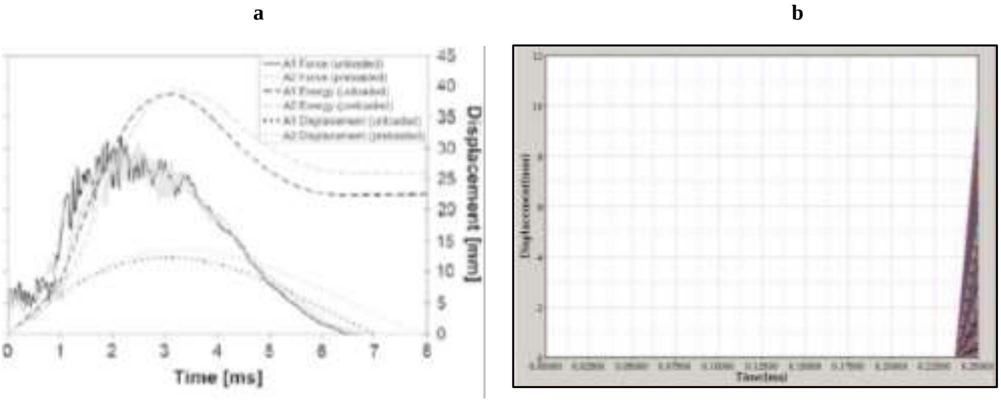

a **b**

Fig. 9 - (a) Displacement values from benchmark problem, (b) Obtained graph for displacement vs time.

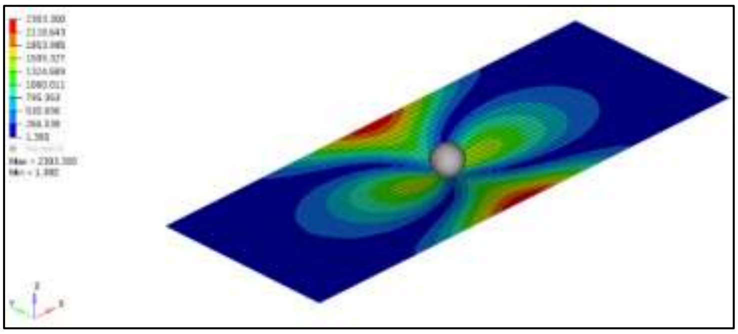


Fig. 10 - Stress values in the composite plate due to impact

a

b

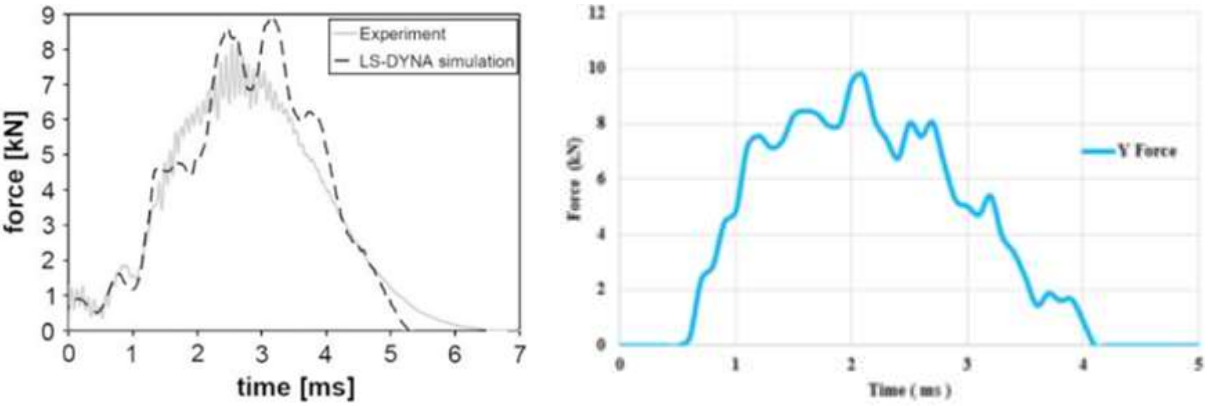


Fig. 11 - Contact forces in the composite plate due to impact, (a) Benchmark results, (b) Obtained results

3.2 Case study 2 – Curved Plate analysis

For the same CFRP material used in the above validation, the shape of the plate is changed and instead of a flat plate, a curved plate is considered with same material properties and orientation as of the benchmark values and the behavior of the plate for the impact is observed [21].

Figure 12 shows the curved composite plate modelled for the simulation. The force and displacement of the composite due to the impact is observed. The obtained results are compared with the results of flat plate.

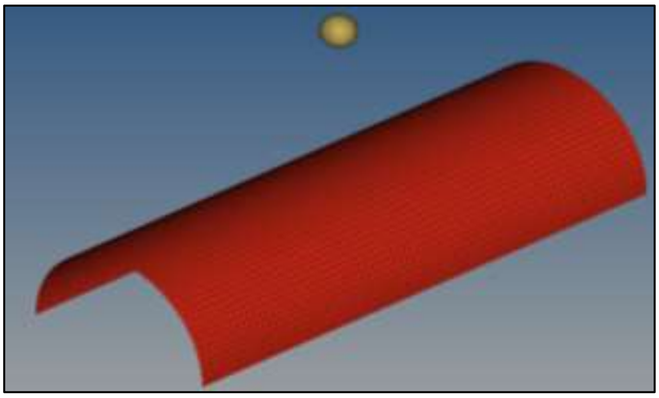


Fig. 12 - Curved composite sheet

The stresses on the composite sheet as shown in figure 13, due to the curvature of the plate is observed and the behavior of the plate is noticed. Also the deformation of the curved plate shown in figure 14, due to the impact and the effect of the curvature to the deformation is observed.

The corresponding graphs for displacement vs time and stresses vs time is plotted as shown in figure15 and 16 respectively.

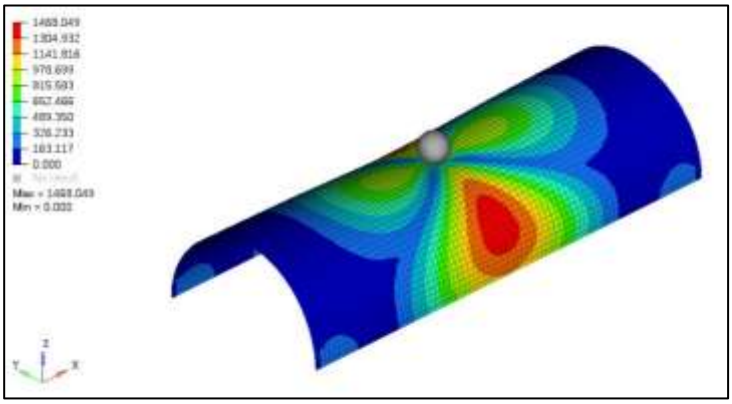


Fig. 13 - Stresses on curved composite sheet

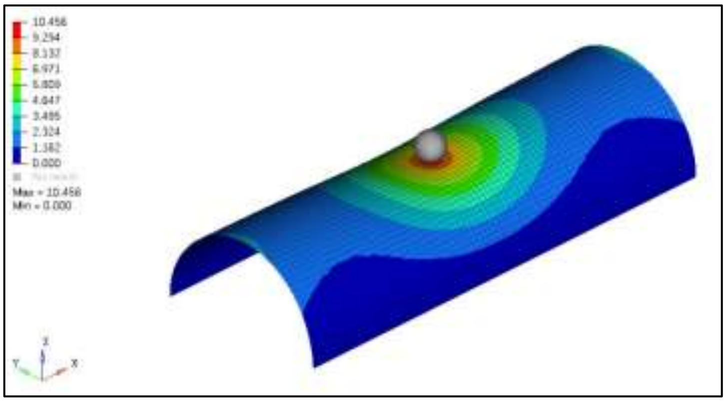


Fig. 14 - Deformation of curved composite sheet due to impact

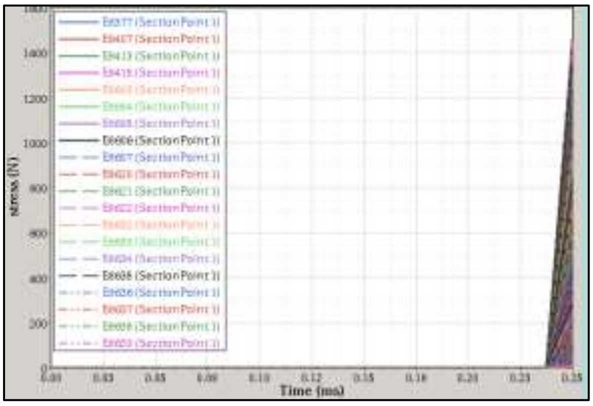


Fig. 15 - Stesses vs time

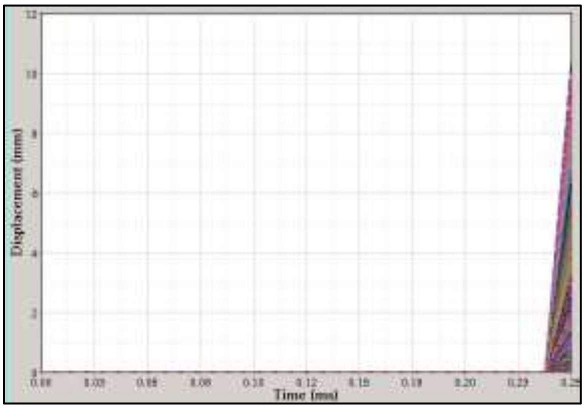
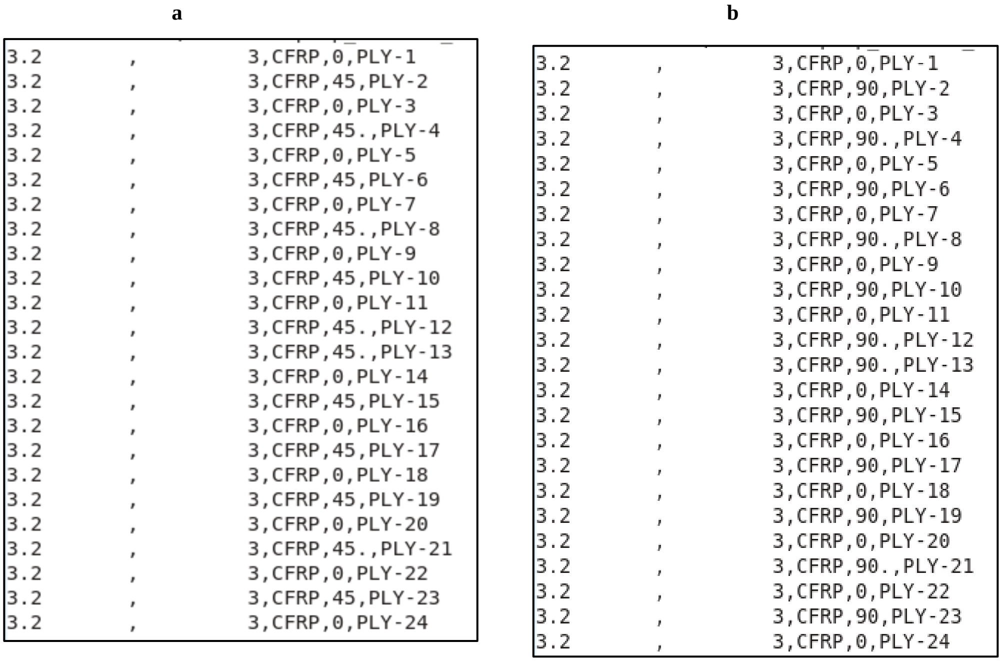


Fig. 16 - Displacement vs time

3.3 Case study 3 – Analysis for various ply-orientation

This iteration assesses the effect of ply orientation on the composite plates (both flat and round) keeping the material properties same. The composite material is modelled with two different ply orientation, [0/45] 12s and [0/90]12s [11] as shown in figure 17.



a

```
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3.2        ,        3,CFRP,45,PLY-2
3.2        ,        3,CFRP,0,PLY-3
3.2        ,        3,CFRP,45.,PLY-4
3.2        ,        3,CFRP,0,PLY-5
3.2        ,        3,CFRP,45,PLY-6
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3.2        ,        3,CFRP,45.,PLY-8
3.2        ,        3,CFRP,0,PLY-9
3.2        ,        3,CFRP,45,PLY-10
3.2        ,        3,CFRP,0,PLY-11
3.2        ,        3,CFRP,45.,PLY-12
3.2        ,        3,CFRP,45.,PLY-13
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3.2        ,        3,CFRP,0,PLY-20
3.2        ,        3,CFRP,45.,PLY-21
3.2        ,        3,CFRP,0,PLY-22
3.2        ,        3,CFRP,45,PLY-23
3.2        ,        3,CFRP,0,PLY-24
```

b

```
3.2        ,        3,CFRP,0,PLY-1
3.2        ,        3,CFRP,90,PLY-2
3.2        ,        3,CFRP,0,PLY-3
3.2        ,        3,CFRP,90.,PLY-4
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3.2        ,        3,CFRP,0,PLY-22
3.2        ,        3,CFRP,90,PLY-23
3.2        ,        3,CFRP,0,PLY-24
```

Fig. 17 - (a) Composite lay-up for[0/45]orientation, (b) Composite lay-up for[0/90]orientation

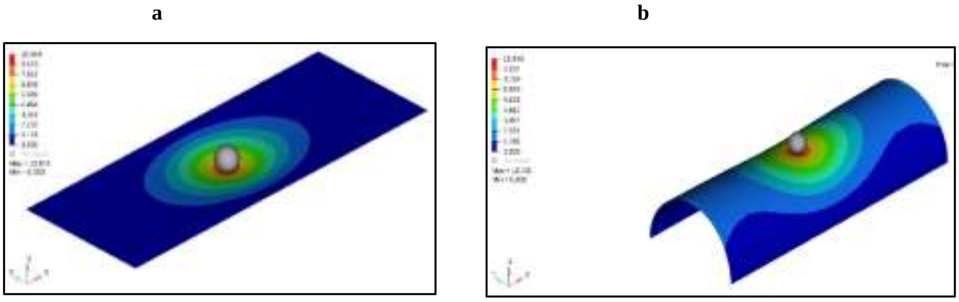


Fig. 18 - (a) Displacement for flat plate with orientation [0/45], (b) Displacement for curved plate with orientation [0/45]

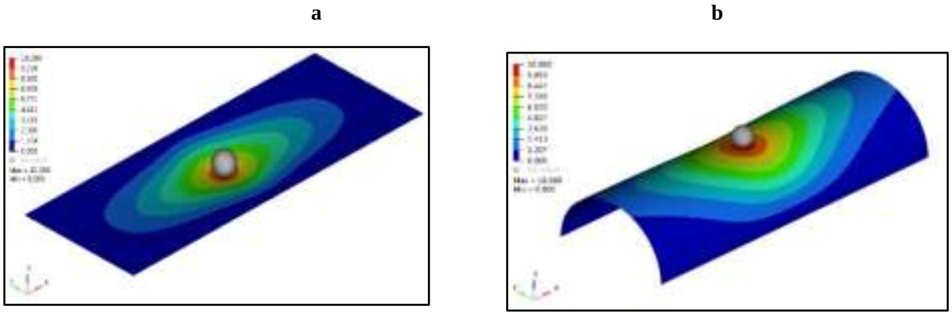


Fig. 19 - (a) Displacement for flat plate with orientation [0/90], (b) Displacement for curved plate with orientation [0/90]

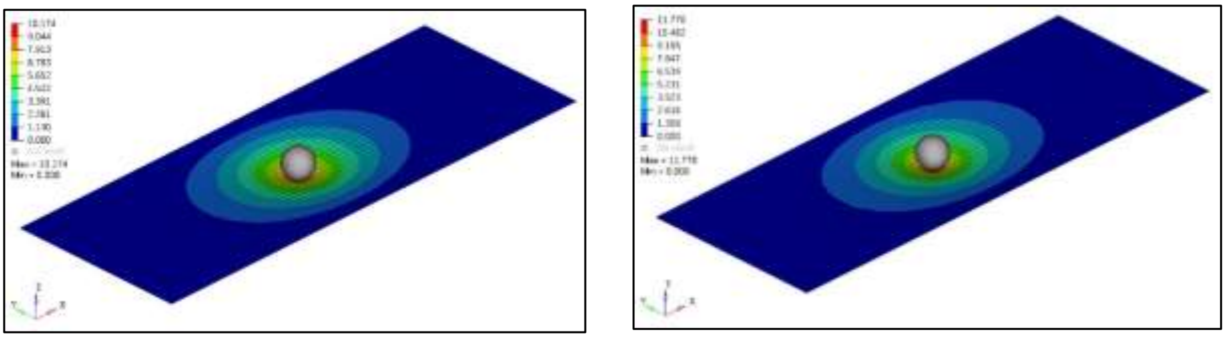
The stresses variation along with the deformation as shown in figures 18 and 19, for the different orientations for both flat and curved plates are observed and compared.

3.4 Case study 4 – Simulation for different Materials

This iteration is performed by changing the material of the composite plate to observe their behavior for the impact scenario and compare the resistance of the materials for the same.

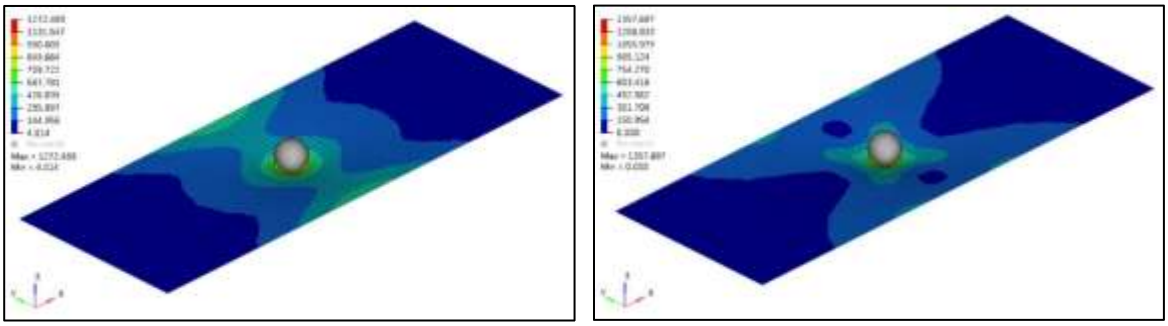
The different materials used for the comparison are, Glass Fiber Reinforced Plastic (GFRP) and Kevlar with the validated CFRP material [21].

Figure 20 shows the maximum deformation of the composite plate for GFRP and Kevlar materials and figure 21 indicates the maximum stresses in the plates for GFRP and Kevlar materials.



a **b**

Fig. 20 - (a) Max. deflection for GFRP material (b) Max. deflection for Kevlar material



a **b**

Fig. 21 - (a) Max. stress values for GFRP material (b) Max. stress values for Kevlar material

Table 1 - Comparison table for validation of the simulated results with benchmark results.

Orientation	Benchmark Results		Obtained Results (Abaqus)	
	Max. Deflection (mm)	Contact Force (kN)	Max. Deflection (mm)	Contact Force (kN)
[-45/0/45/90]$_{3s}$	12.2	9	10.11	9.1

Table 2 - Table comparing max. deformation and stresses generated in composite plate.

Orientation	Flate Plate		Curved Plate	
	Max. Deflection (mm)	Max. Stress MPa	Max. Deflection (mm)	Max. Stress MPa
[-45/0/45/90]$_{3s}$	10.11	2383.30	10.46	1468.05
[0/45]$_{12s}$	10.04	1241.19	10.49	827.36
[0/90]$_{12s}$	10.39	768.14	10.86	333.04

Table 3 - Comparison for max. deformation and stresses for different materials.

Orientation	CFRP		GFRP		Kevlar	
	Max. Deflection (mm)	Max. Stress MPa	Max. Deflection (mm)	Max. Stress MPa	Max. Deflection (mm)	Max. Stress MPa
Flat Plate	10.11	2383.30	10.174	1272.49	11.77	1357.69

[-45/0/45/90]$_{3s}$						

The tables above indicates the comparison between all the iterations performed by changing the shape of the impactor, ply orientation and material of the composite plate.

Table 1 indicates the validation of the results obtained by simulating the impact scenario with the benchmark results comparing the maximum deformation of the composite. By this table we can observe that the obtained results are more or less the same as that of the benchmark results and hence we can validate that the procedure followed to model the load case is correct and the results are matching with the experimental results.

Table 2 compares the results obtained for different shapes of the composite plate for different ply orientation. How the shape and the ply orientation of the composite effects the strength and deformation of the part. From the table it can be observed that the flat plate offers more resistance to deformation than that of the curved plate. Also the strength of the flat plate is greater than the curved plate.

Table 3 shows us the behavior of the plate for different materials. For a flat plate with a fixed ply orientation for three different materials, the behavior of the plates for the impact is compared.

4. Conclusion

In this study, the prediction of low velocity impact resistance is carried out by performing certain iterations and comparing the results of the same. The simulation of low velocity impact case for a composite material is carried in Abaqus and the obtained results are validated with the benchmark results and from that further iterations are performed on the composite plate are carried out. From the comparison tables we can see that the resistance for low velocity impact damage varies with small changes. It can be seen that the resistance to the damage is more for flat plate with [0/45]12s orientation and is least for curved plate with [0/90] 12s orientation. The study helps to identify the damage resistance and the strength of the composite for various low velocity applications and helps to choose the composite for the required application.

5. Scope for Future Work

- More research can be done to comprehend how composite laminates behave under various load cases and fibre orientations.
- Altering the impactor's shape, size, and height of impact allows for the study of varied damage patterns for different impactors.
- Impact energy can be adjusted, and a table of the composite's behaviour for different impact energies can be produced.

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