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Analyzing the effect of carbon fiber reinforced polymer on the crashworthiness of aluminum square hollow beam for crash box application

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Abstract: Crashworthiness of a material is a measure of its ability to absorb energy during a crash. A well-designed crash box is instrumental in protecting the costly vehicle components. A square, hollow, hybrid beam of aluminum/CFRP was subjected to dynamic axial load to analyze the effect of five different lay-up sequences on its crashworthiness. The beam was placed between two plates. Boundary conditions were imposed on them to simulate a frontal body crash test model. Modeling and dynamic analysis of composite structures was done on ABAQUS. Different orientation of carbon fibers varies the crashworthiness of the hybrid beam. Addition of CFRP layer showed clear improvement in specific energy absorption and crush force efficiency compared to pure aluminum beam. Two layers of CFRP oriented at 90° on Aluminum showed 52% increase in CFE.

1.**Introduction**

A crash box is a vital component located between the side-rails and the bumper protecting passengers as well as the parts that are expensive to repair like fender hood and radiator from serious damage during a frontal crash [1]. They are designed to meet the low speed impact regulations listed by the Research Council for Automotive Repair (RCAR) [2].Aluminum is a lightweight replacement that delivers excellent energy absorption compared to traditional materials like steel. Much research has been done to prove the crashworthiness of Aluminum [3]. Fiber reinforced polymers though expensive are used for light weight vehicles to improve its strength and crashworthiness with minimal increase in weight. Due to the presence of differently oriented fibers composites have better energy absorption characteristics than metals [4]. But metals are ductile while composites are brittle thus composites cannot be used as collapsible crash boxes to absorb energy despite its merits.

A hybrid beam is a metal tube coated with a particular polymer composite thus retaining the ductility of metal and energy absorption of composites while increasing the overall strength, stiffness and crashworthiness [5]. Numerous researchers conducted axial crushing experiments on hybrid beams. Crashworthiness of these was investigated while considering different cross sections, materials and different orientation of the fibers and ply [5-17]. An experimental analysis though necessary is expensive not to mention time consuming with a lot of uncertainty. A modeling and analysis software is a perfect utility to narrow down the total number of cases so that experimental validation can be done for the most important and positive cases. ABAQUS CAE by Dassault Systems is one of the best software that allows modeling and dynamic analysis of composite structures.

IOP Conf. Series: Materials Science and Engineering **263** (2017) 062068 doi:10.1088/1757-899X/263/6/062068

2. Methodology

2.1 Set-up

Five cases were considered pure Al, and four CFRP layup sequences [0°]2, [90°]2, [0°/90°], and [45°/-45°]. The outer dimensions of the SHS beam is given in table 1

Table 1. Dimension of pure and hybrid specimen

Dimension	Pure Al (mm)	Hybrid Al beam (mm)	Hybrid CFRP layer (mm)
Length	250	250	250
Side	65	64	65
Thickness	2.5	2	0.5

Modelling was done in ABAQUS based on the above dimensions. Material properties of Aluminum and CFRP are listed in table 2

Table 2. Material properties [18]

Materials	Young's Modulus (GPa)	Density (kg/m^3)
Aluminum	57.1	2700
CFRP 0°	142.9	1600
CFRP 90°	7.8	1600
CFRP 0°,90°	78.7	1600
CFRP 45°,-45°	17.1	1600

The Johnson-Cook equation describes the flow stress as a product of the equivalent strain, strain rate, temperature dependent terms and several parameters to adequate the real behavior of the materials.

$$\sigma_y = \left[A + B\left(\varepsilon_p\right)^n\right]\left[1 + C\left(\frac{\varepsilon_p}{\varepsilon_o}\right)\right]\left[1 - \left(\frac{T - T_{room}}{T_{melt} - T_{room}}\right)^m\right]$$

These parameters for Aluminum and CFRP are given in Table 3

IOP Conf. Series: Materials Science and Engineering **263** (2017) 062068 doi:10.1088/1757-899X/263/6/062068

Table 3. Johnson-Cook parameters [19,20]

Parameters	Aluminum	CFRP
A (MPa)	369	200
B (MPa)	684	450
N	0.73	0.2
C	0.0083	5
M	1.7	1

After part modeling and assigning the properties the end plates were designed. The dimension of plate was larger than the tube. Two reference points were created on the plates. Lower plate was fixed to prevent it from translation and rotation. The top plate was restricted to move only in the axial direction.

The various process parameters are tabulated in Table 4.

Table 4. Process Parameters

Description	Value
No. of Instances	100
Friction coefficient	0.2
Time of crash	0.028 sec
Mass of top plate	250 kg
Velocity of top plate	15.6 m/s

Mesh was designed and rendered to obtain the distribution of stress and displacement during the dynamic analysis as shown in Figure 1.

A dynamic explicit job was defined based on the above process parameters and analysis was done. The resultant force and axial displacement was tabulated and compared for the various cases.

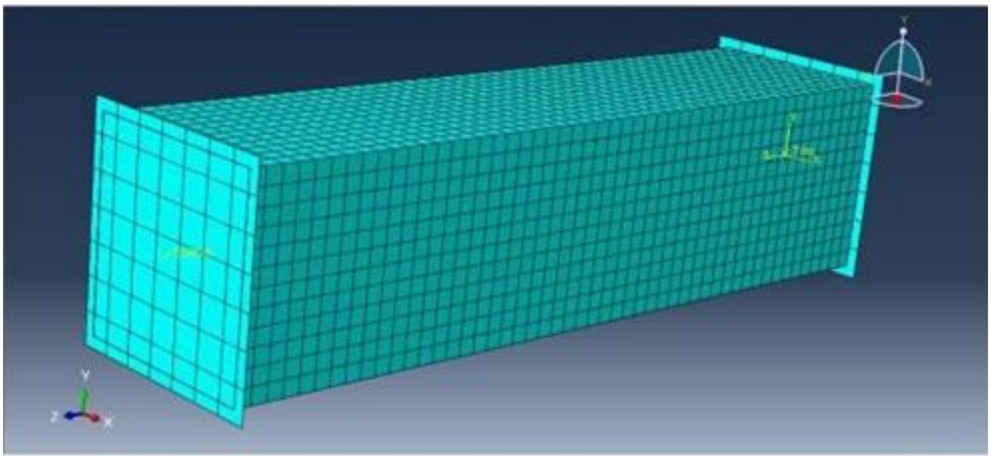

Figure 1. Meshed Hybrid beam in ABAQUS CAE

2.2 Crashworthiness Parameters

Crashworthiness of a material is expressed by two major parameters.

Specific Energy Absorption (SEA)
Crush Force Efficiency (CFE)

$$\mathrm{SEA}(E_s) = \frac{E}{\mu \Delta L} = \frac{P_{mean}}{\mu}$$

$$\mathrm{CFE}(\eta) = \frac{P_{mean}}{P_{\max}}$$

Where,E is the Total Energy Absorbed during the impact. μ, mass/unit length of the specimen is given in table 5. Crushed length ΔL is defined by the difference in the specimen length between before and after the dynamic axial crash test. Short crushed length means that damage to the vehicle body structure is small and a sufficient safety zone for passengers can be secured. Mean crushing load Pmean is defined by the ratio of absorbed energy and crushed length.

The hybrid specimen with high mean crushing load can absorb energy with less deformation of structural members. Peak crushing load is defined as the initial maximum crushing load in the load displacement curves and is denoted by Pmax. High peak crushing load causes damage to connected members and the injury of passengers.

3. ABAQUS Results

Crashworthiness characterization is given in table 5 and6.

Table 5. Direct results obtained from analysis.

Material / Parameter	Mass/Length μ (g/mm)	Crushed Length ΔL (mm)	Mean Load Pmean (N)	Peak Load Ppeak (N)
Al	1.22	219	126136.6845	196380.5

IOP Conf. Series: Materials Science and Engineering **263** (2017) 062068 doi:10.1088/1757-899X/263/6/062068

Al/CFRP [0°]2	1.39	223	147415.459	193025.6
Al/CFRP [90°]2	1.39	227	144857.36	148723.8
Al/CFRP [0°/90°]	1.37	224	146840.3876	193421.6
Al/CFRP [45°/-45°]	1.39	226	145837.993	176944.6

Table 6. SEA and CFE of all specimens

Material / Parameter	Energy absorbed kJ	Specific Energy Absorption (J/g)	Crush Force Efficiency (-)
Al	27.6239	103.39	0.6423
Al/CFRP [0°]2	32.873	106.054	0.764
Al/CFRP [90°]2	32.88	104.213	0.974
Al/CFRP [0°/90°]	32.892	107.183	0.7592
Al/CFRP [45°/-45°]	32.959	104.91	0.8242

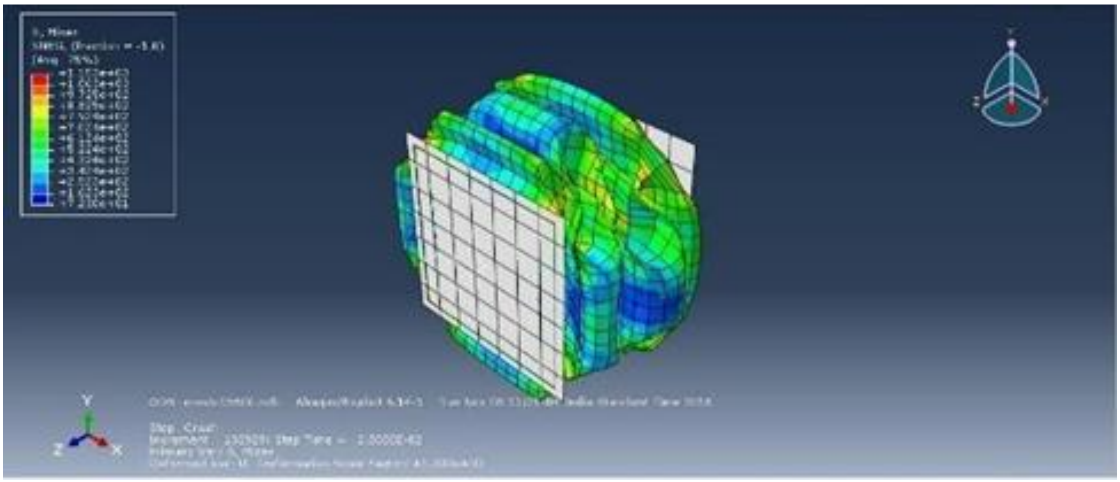

Figure 2. Crushed Aluminium beam

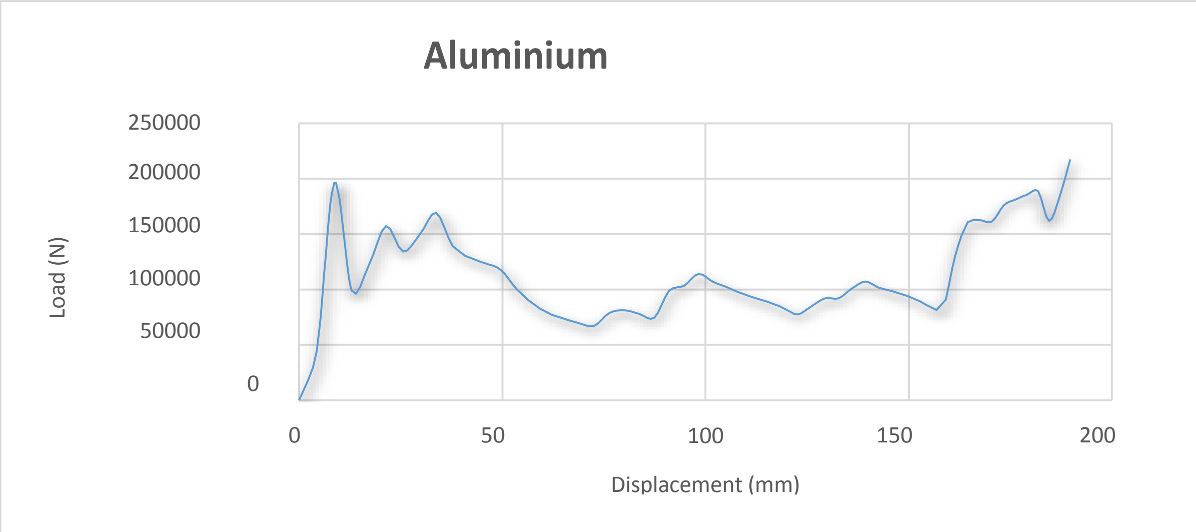

Figure 3. Load Displacement curve for Aluminium

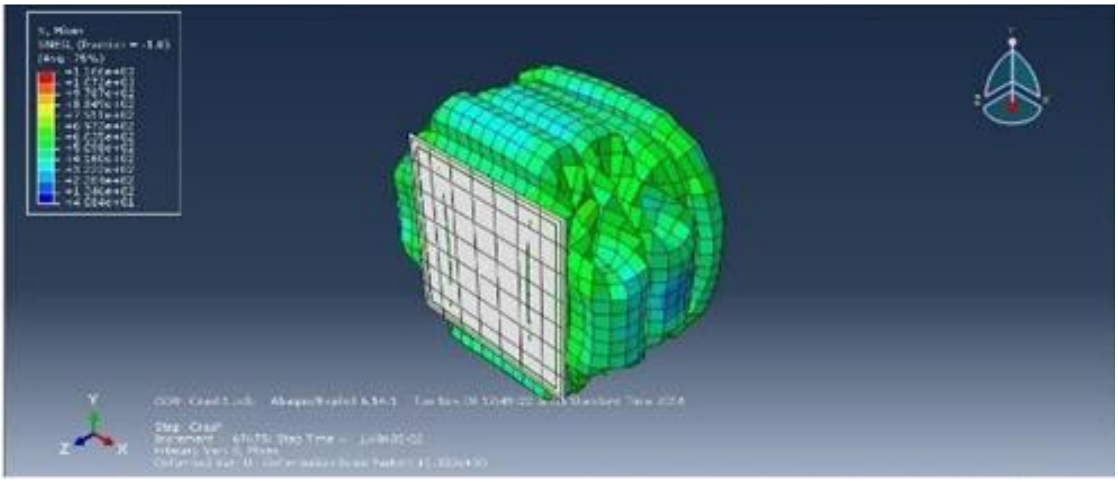

Figure 4. Crushed Al/CFRP [0°]2

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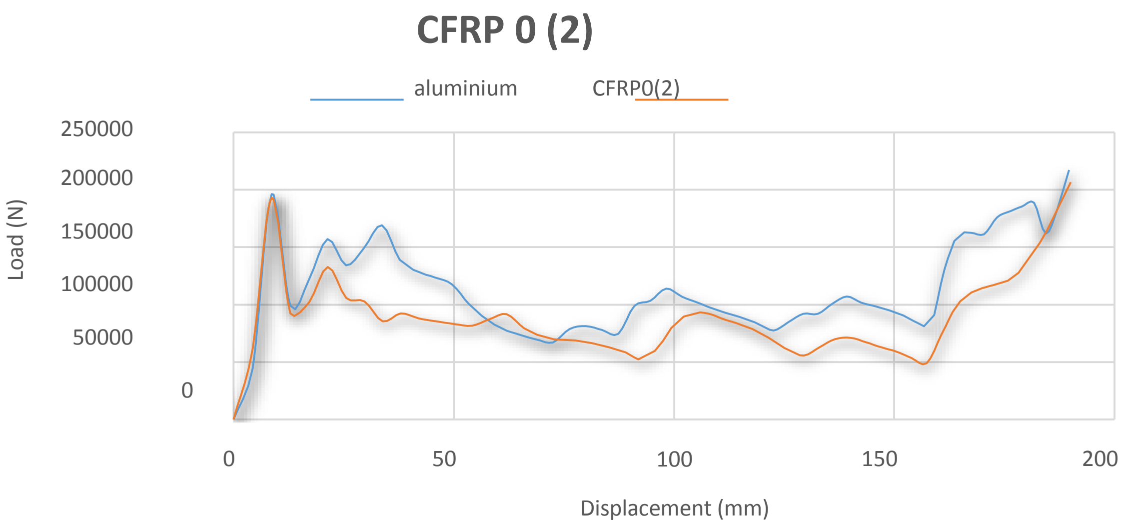

Figure 5. Load Displacement curve for [0°]2

In the Al/CFRP$[0^\circ]_2$ specimen, even though the SEA was highly improved, the CFE was relatively low, because the high strength of carbon fibers in the axial direction reduced the crushed length and increased the peak crushing load at the same time.

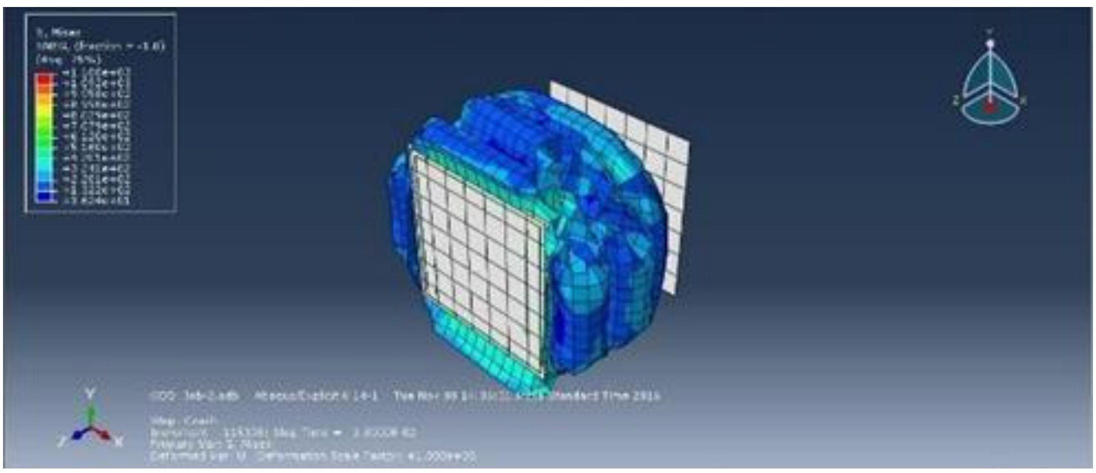

Figure 6. Crushed Al/CFRP [90°]2

IOP Conf. Series: Materials Science and Engineering **263** (2017) 062068 doi:10.1088/1757-899X/263/6/062068

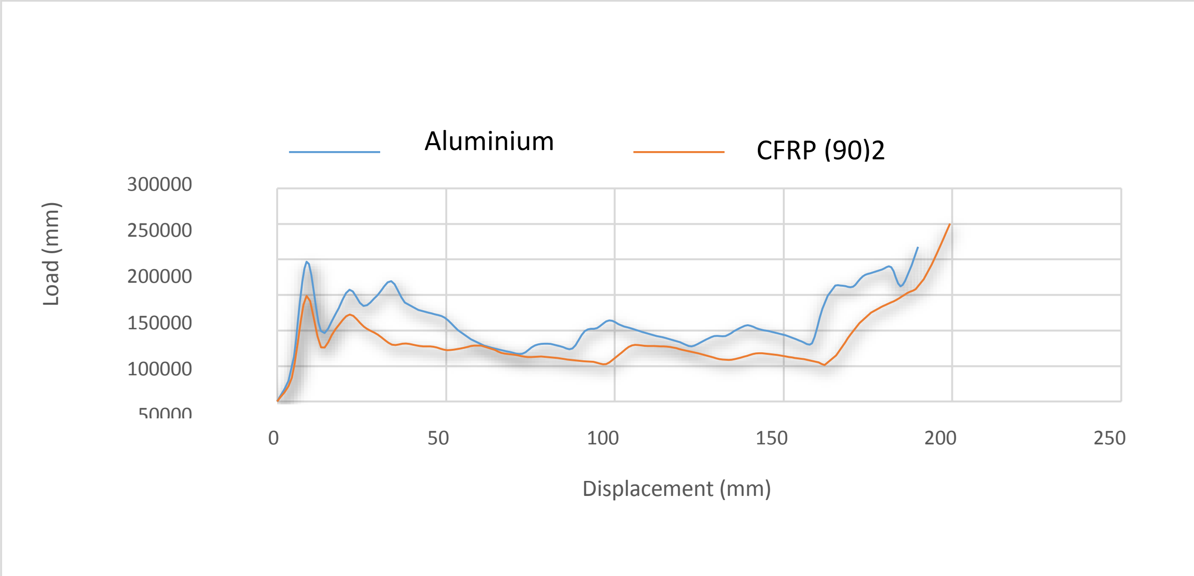

Figure 7. Load Displacement curve for [90°]2

In the Al/CFRP[90°]2specimen, the CFE was highly improved, but the SEA was relatively low. This trend was opposite to that of the Al/CFRP [0°]2specimen.

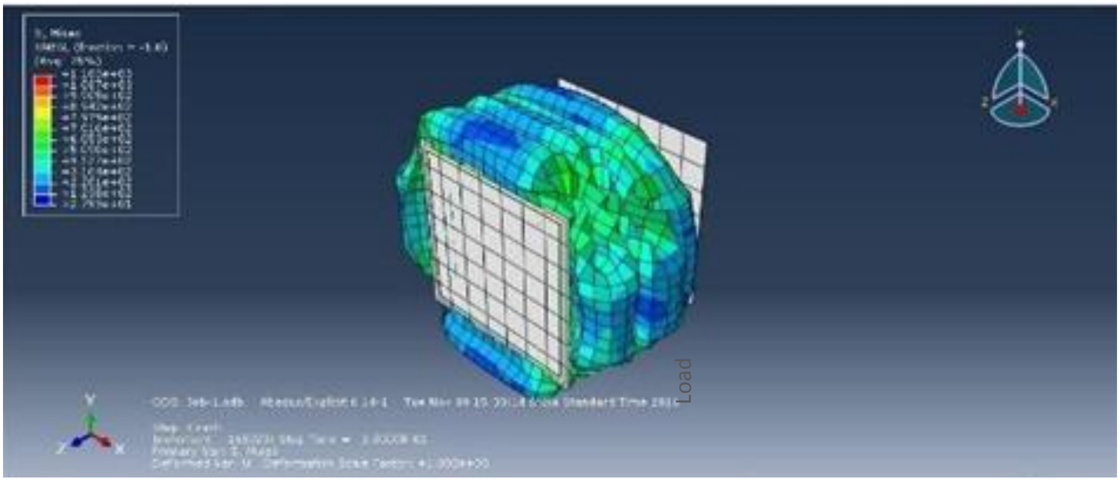

Figure 8. Crushed Al/CFRP [0°/90°]

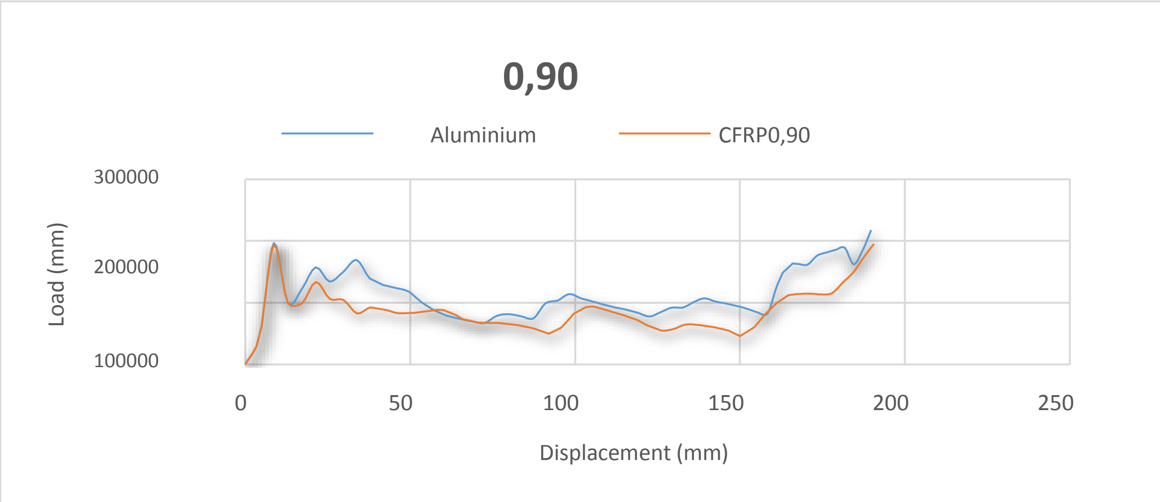

Figure 9. Load Displacement curve for [0°/90°]

In the Al/CFRP [0°/90°]n specimen, the SEA and CFE were improved simultaneously, because the carbon fibers reinforced the Al SHS beam in both the axial and hoop directions.

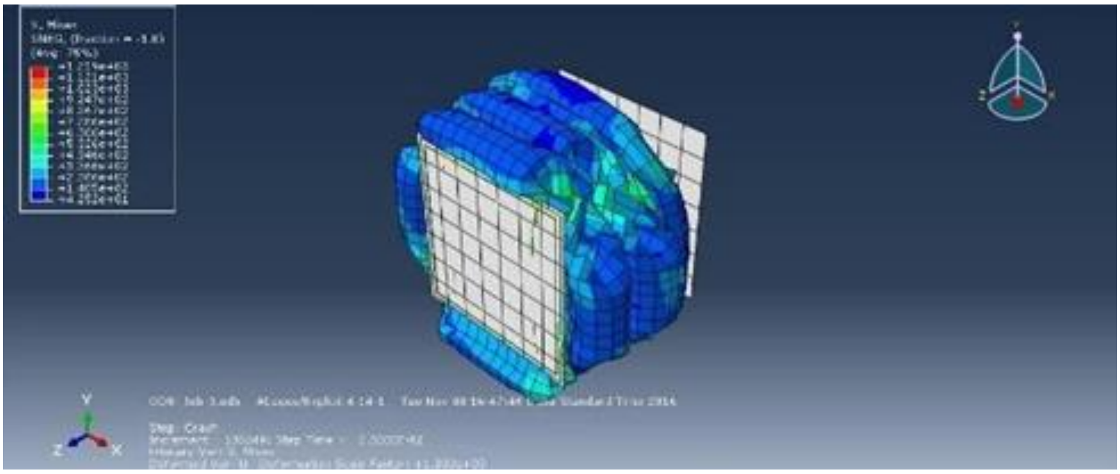

Figure 10. Crushed Al/CFRP [45°/-45°]

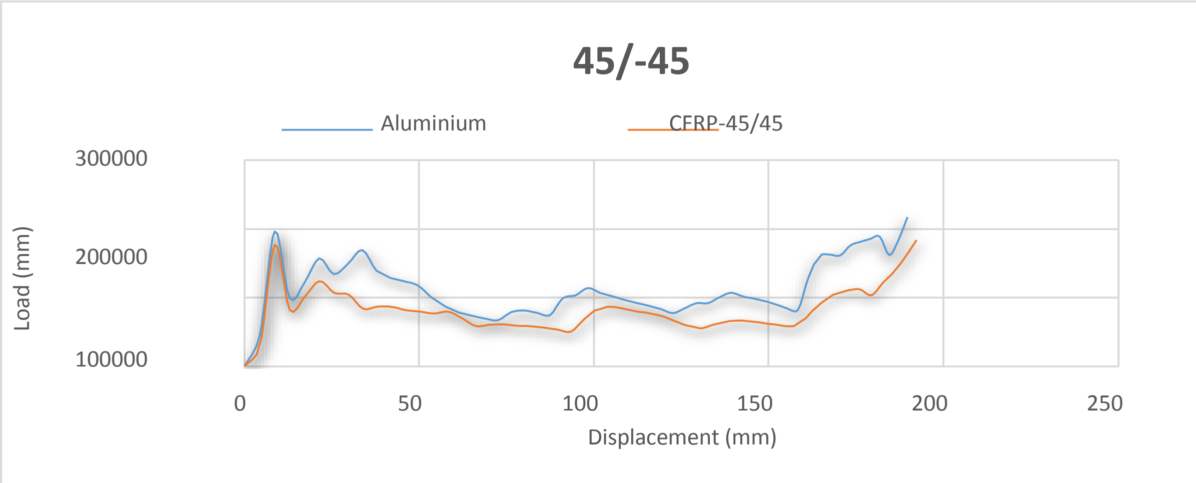

Figure 11. Load Displacement curve for [45°/-45°]

In the Al/CFRP [45°/-45°]n specimen, both the SEA and CFE improved a little. The peak crushing load was increased by the scissoring effect of ±45° carbon fibers, and the crushed length was not reduced

4. Conclusion

Addition of CFRP layers increased the Specific Energy absorption and Crush Force Energy of a pure Aluminum beam. It is observed that Al/CFRP [0°/90°] in hybrid beam offers the most optimum conditions to maximize both SEA and CFE.ABAQUS analysis results agree with experimental results obtained by other researchers thus ABAQUS is an accurate and fast tool to analyze the crashworthiness of materials even composites.

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