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RESEARCH ARTICLE

IMPLEMENTATION OF CIRCULAR DISCONTINUITIES IN CFRP BUMPER BEAM FOR MATERIAL SAVING: A CASE STUDY

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Abstract

An automotive bumper system consists of an energy absorber, fascia and bumper beam. Among them, the bumper beam is the main component contributing to the overall weight of the vehicle. The bumper beam absorbs the kinetic energy during an accidental collision by deflection in low speed impact and by deformation in high speed impact. Carbon Fibre Reinforced Plastic (CFRP), being an extremely strong and lightweight composite, is a good candidate for bumper beam material. Earlier used in high performance cars CFRP is nowadays being promoted to be used in passenger cars also. The reinforcement beam is the vital part which ensures safety and needs to be validated through Finite Element Analysis (FEA). Therefore, the double hat bumper beam is impacted with a cylindrical impactor and analyzed in Abaqus. In this paper the bumper beam is analyzed after weight reduction by putting circular holes for material saving. Further the effect on cost of production is calculated. Above all, material saving reduces carbon footprint.

Introduction:-

The bumper system of an automobile consists of three main parts which are the bumper beam, the absorber and the fascia. The fascia and the absorber absorb low impact and the bumper beam either deflects normal impacts or absorbs high impacts by deformation, or a combination of these two. Thus, bumper beam plays an important role in the safety of vehicle and its passengers. Structural crashworthiness is a necessary requirement for designing parts of an automobile as it shows the response of the vehicle to an impact or collision. Some of the most commonly used cross-sections of bumper beam are C or channel, hat box section, hat section and double hat section. This is significant because the cross section of the bumper beam comes in direct contact with the impactor and is therefore responsible for the amount of energy which gets absorbed by the bumper beam.

The bumper beams were commonly made of steel. But steel contributes highly to the overall weight of the automobile. So, aluminium came as a replacement to steel for manufacturing bumper beams. But this heavily increased the production cost even though there was a significant weight reduction of the bumper beam. So, this pushed the research community to develop new materials like composites. This is where Carbon Fibre Reinforced Plastics (CFRP) with a high strength to weight ratio came to be used as the raw material for bumper beam manufacturing. This is especially because of the strength CFRP offers at a low weight and affordable cost. It is also easy to fabricate complex shapes and absorbs high impact energy.

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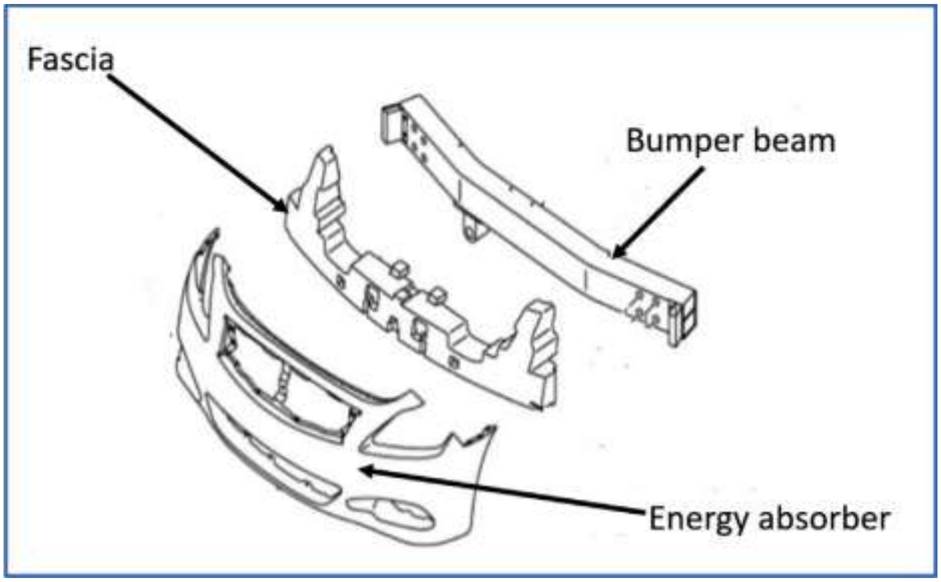

Figure 1:- A simple bumper system. Courtesy S. M. Nasiruddin et al.

Furthermore, introducing reinforcement of about 30% can help in yielding the composite with superior tensile strength and significant weight reduction. Epoxy resin is a thermosetting resin which has high adhesion strength and mechanical properties making them excellent for structural composite applications. In the case of CFRP, the epoxy resin is interwoven with carbon fibres and this gives the composite features like high stiffness, long fatigue life, high corrosion resistance, environmental stability and wear resistance in addition to the specialities mentioned earlier. Stricter legislation is being constantly updated to make bumper beam design more and more environment friendly, recyclable, fuel efficient and pedestrian and passenger safe.

The objective of this case study is to analyze a double hat CFRP automobile bumper beam for material saving. Circular discontinuities are introduced to investigate the structural strength, deformation and strain energy absorption of the bumper beam. Furthermore, reinforcements are given to analyze the crashworthiness of the bumper beam during high impact collision with low mass. Finally, the annual cost reduction is to be calculated.

In most of the studies the crack of the CFRP is analyzed. Most computational methods are focused on the energy absorption efficiency (EAE) of conventional CFRP bumper beams under impact. With stiffer IIHS rules being imposed every year there is a need to study and analyze CFRP bumper beams with even lesser weights. This can potentially reduce fuel consumption.

Impact theory:-

The first law of thermodynamics, which is the conservation of energy states that energy can neither be created nor be destroyed. Energy can be transferred from one form to another. In the case of high-speed impact, the kinetic energy of the impactor is transferred to and absorbed by the bumper beam in the form of strain energy, which is the internal energy. It can be calculated using the theory of impact.

The impact theory says that there are two types of impacts namely elastic and inelastic or plastic impact. During an elastic collision the total kinetic energy before collision is equal to the energy after collision ie, the kinetic energy is conserved throughout the process. The momentum (total) is same before and after the collision or impact as in this case. The expressions for the same is:

$$\frac{1}{2}M_A V_A^2 = \frac{1}{2}M_A V_{A2}^2 + \frac{1}{2}M_B V_{B2}^2 \quad (1)$$

$$M_A V_A = (M_A + M_B)V_0 \quad (2)$$

where MA and MB are the impactor and bumper beam masses respectively, and VA, VB and V0 are impactor, bumper beam and after collision impactor and bumper beam combined velocities. Using the coefficient of restitution (e), the velocities after impact can be calculated. The strain energy on bumper beam is calculated by Abaqus by finding the difference between KEs before & after impact. The expression for e is:

$$e = \frac{V_{B2} - V_{A2}}{V_A - V_B} \quad (3)$$

Finite Element Analysis:-

FEA is being used from as early as 1941, when A. Hrennikoff solved an elastic mechanics problem by framework method known as the discrete element method. With the birth of computer and further rapid developments to date, FEA has been applied to almost all walks of life including aerospace, automobile, machinery manufacturing, electronics and so on. It can be applied on 2D as well as 3D complex problems, from static to dynamic analysis and from linear to nonlinear problems. Using traditional methods to impact test is costly, time consuming, involves a lot of variables in real life situation and prone to error. Hence industries mainly use FEA softwares for designing and testing products under development. It is relatively easier with sufficient computational facilities to conduct impact response test by changing variables and to observe different parameters' effect on appropriate functionality of a component.

FEA is a good method to analyze the stresses developed in a model and the stiffness of a material under study. It is a suitable method to analyze the impact energy absorbed and the deflection response of, say, a bumper beam during a collision. So, a real physical test is conducted only after several simulated analyses of prototype which tremendously saves time and cost.

FEA model:-

The model of the rigid impactor and double hat cross sectioned bumper beam was modelled and simulated in Abaqus CAE. Figure 2 and 3 shows the impactor and beam assembly and the meshed model respectively.

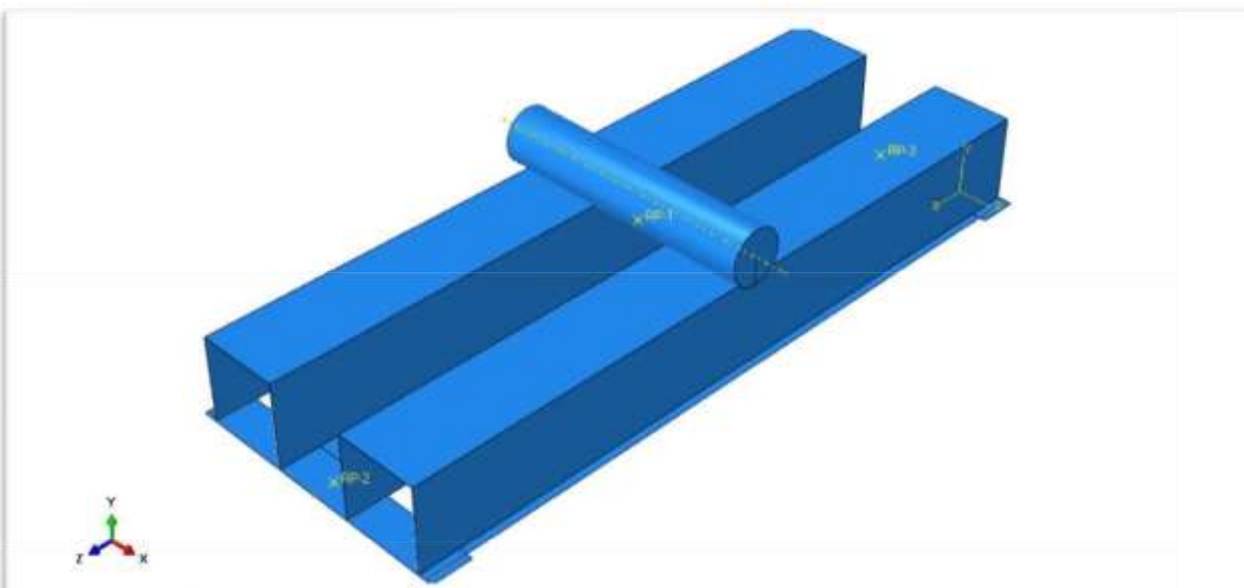

Figure 2:- Assembled model of bumper beam and impactor.

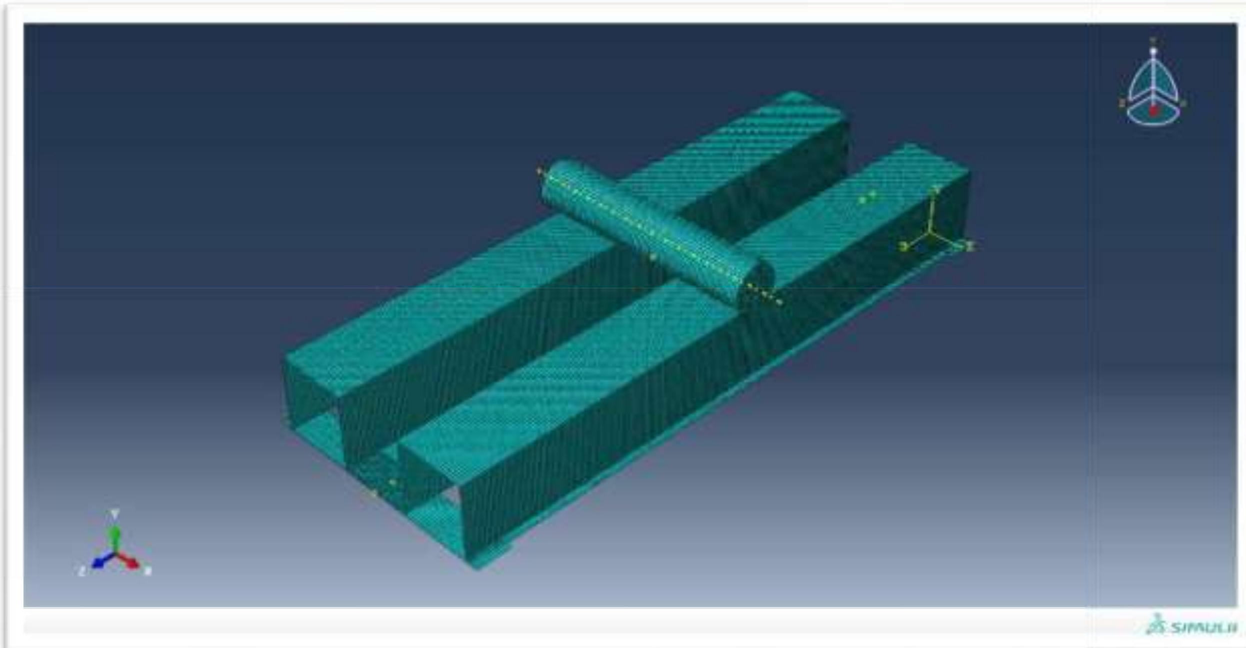

Figure 3:- Meshed assembly model of bumper beam and impactor.

Table 4.1 tabulates the mechanical properties of Carbon fibre reinforced plastic. The dimensions regarding the modelled parts ie, bumper beam and rigid impactor are shown in table 4.2. The whole assembly was meshed with an approximate global size 10.

Table 1:- Mechanical properties of CFRP.

Material	Carbon Fibre Reinforced Plastic (CFRP)
Modulus of elasticity (GPa)	150
Poisson's ratio	0.30
Density (kg/m^3)	1700
Yield strength (MPa)	276

Table 2:- Dimensions of bumper beam (m).

Length	1.070
Thickness	0.002
Distance between supports	0.95
Height	0.125

The entire model was assembled after making 3D deformable shell type part for double hat bumper beam and 3D discrete rigid shell type part for the rigid cylindrical impactor. For the bumper beam the cross section was sketched first and then extruded to the required width of beam. The impactor was sketched and then revolved to get the required cylindrical shape. The material properties were assigned to appropriate section after its creation.

Under the mesh module the assembly was assigned appropriate element type and a number of nodes were created. For the impactor linear quadrilateral element type of R3D4 were assigned to 1152 nodes. The double hat bumper beam was meshed with linear quadrilateral element type of S4R was used with 9951 nodes. Total number of nodes of the assembly are 11576. Figure 4.3 shows the various element types used in Abaqus. S4R is a general purpose, robust element type used in abaqus that is applicable to a wide range of applications. With R3D4 element type it is possible to give thickness to the meshed body. In abaqus explicit thickness is required. Both R3D4 and S4R have 4 nodes. The Hashin damage model is used to predict anisotropic damage in elastic-brittle composite models. It is intended to be used for analyzing lamina damage in fibre reinforced composites. The main failure modes considered are: fibre tension, fibre compression, matrix tension and matrix compression.

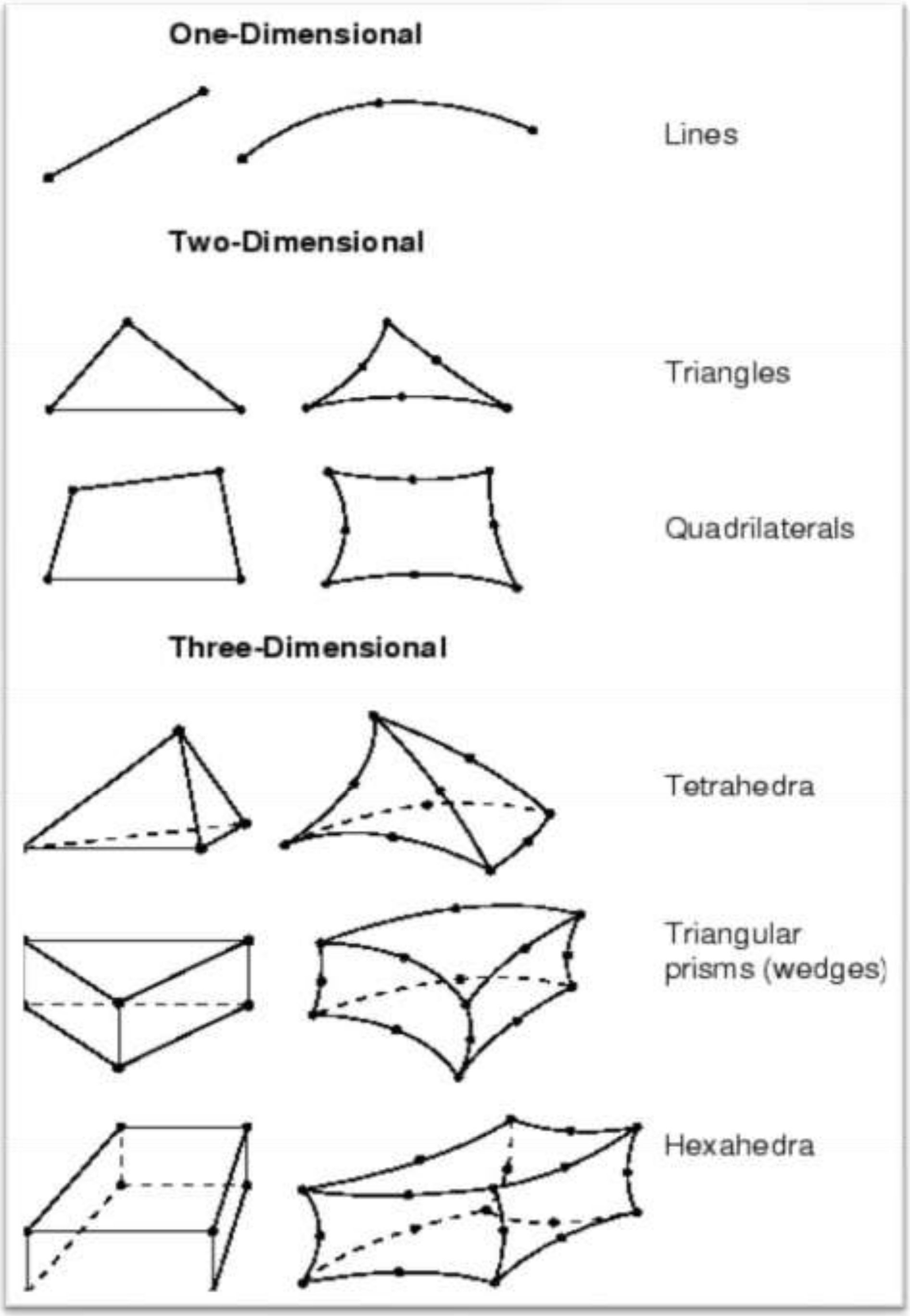

Figure 4:- Element types used in FEA.

The model was developed in such a way that the rigid impactor collides with the double hat bumper beam at a velocity of 50m/s in a time step of 2ms. The mass of the impactor is 2kg. The velocity of collision represents the longitudinal condition of impact while the step time accounts for the total duration of the analysis (from time of impact till final separation). After analyzing the first model 2 other models were created for material saving. In that, the second model was created by implementing circular discontinuity in the double hat bumper beam. Total

63 circular discontinuities of radius 18mm wese implemented successfully in a uniform manner across the surface area of the double hat bumper beam. Considering the possibility of stress concentration around the discontinuities during a high speed impact, a third model was created and analyzed. In that the circular discontinuities were reinforced with a circular ring of the same material that is, CFRP. Figure 4.4 and 4.5 shows the second and third model mentioned above.

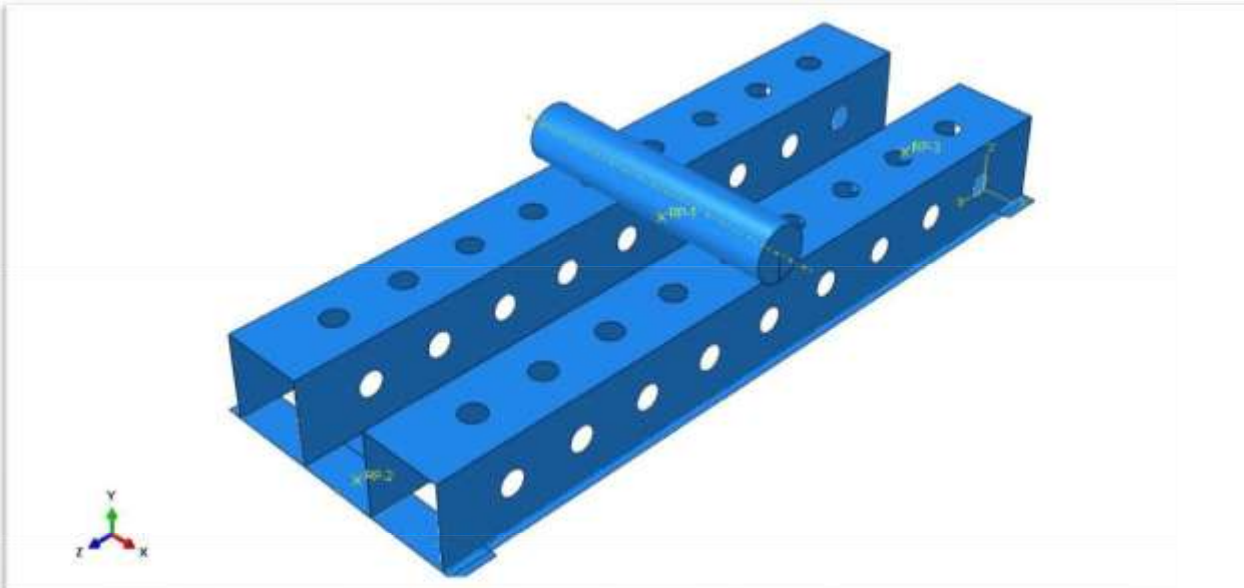

Figure 5:- Double hat bumper beam with 18mm circular discontinuities.

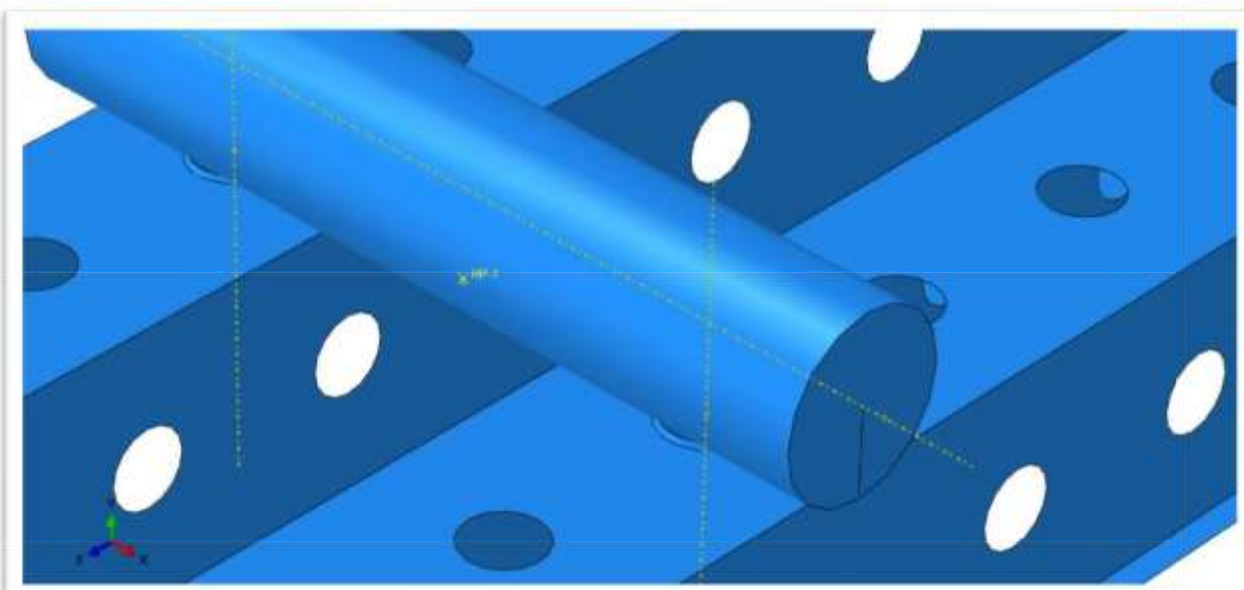

Figure 6:- Double hat bumper beam with circular reinforcements.

Results and Discussions:-

The stress developed in CFRP double hat bumper beam is shown in figure 5.1. It is lower than CFRP double hat bumper beam with circular discontinuities shown in figure 5.5. The stress developed is the highest in CFRP double hat bumper beam with reinforcement as shown in figure 5.9. But this higher stress is prevalent only in the reinforcement. Hence reinforcement is shown to serve its purpose.

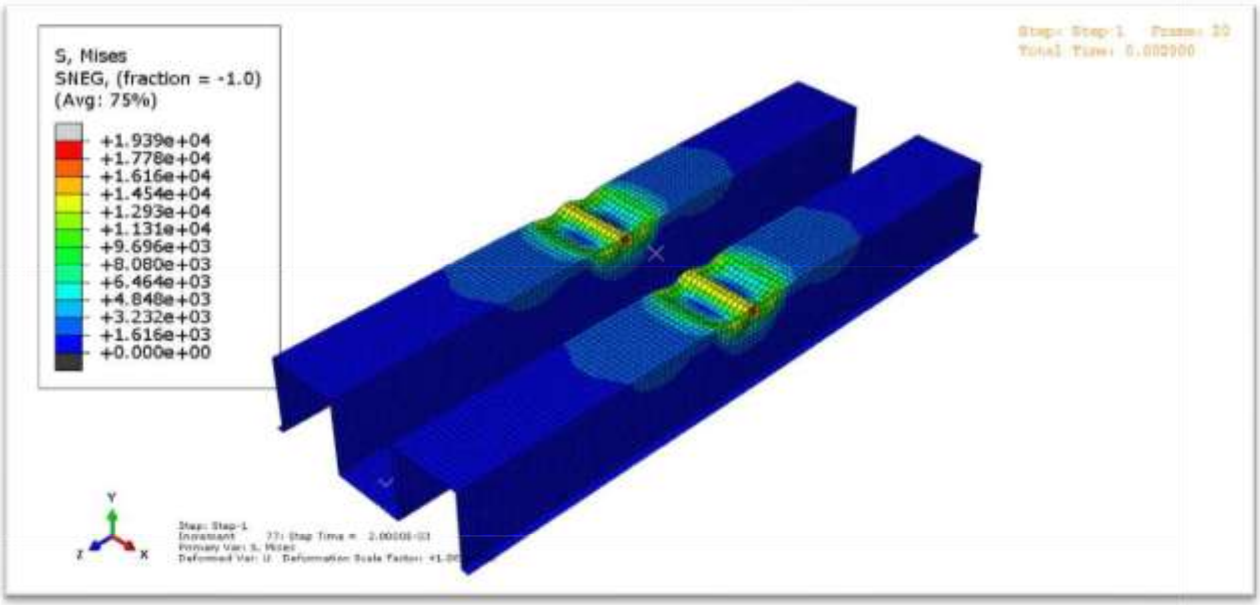

Figure 7:- Stress developed in CFRP double hat bumper beam.

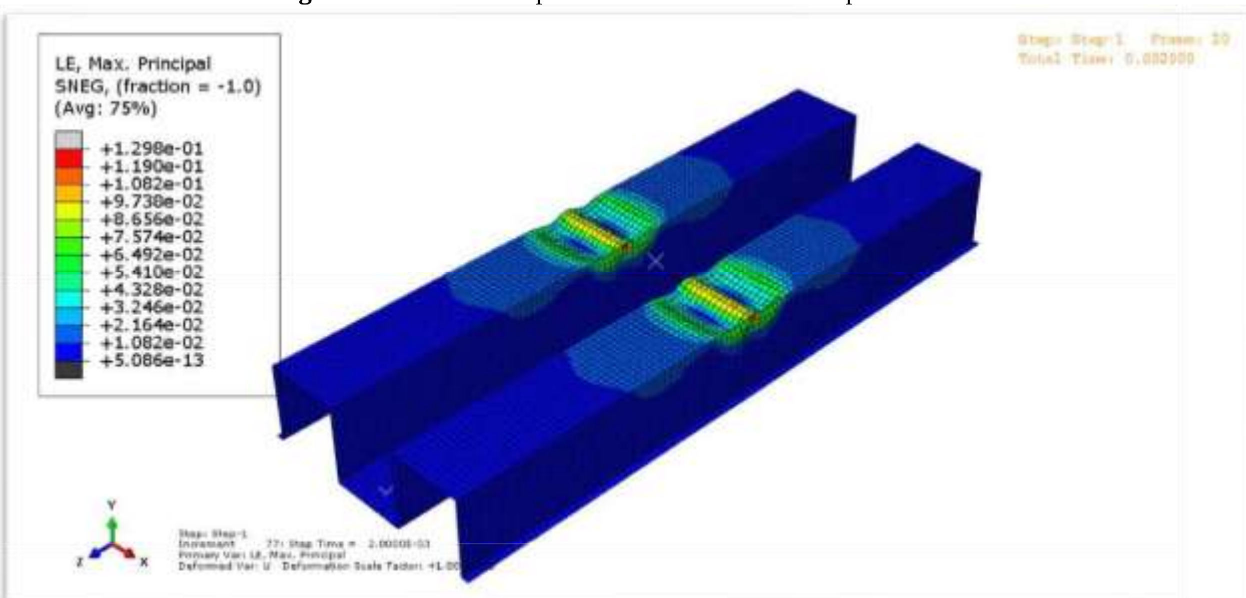

Figure 8:- Strain developed in CFRP double hat bumper beam after impact.

The developed strain in CFRP double hat bumper beam, CFRP double hat bumper beam with circular discontinuities and CFRP double hat bumper beam with reinforcement is shown in figure 5.2, 5.6 and 5.10 respectively. The strain increases with the implementation of circular discontinuities on the bumper beam but shows a drastic decrease when those discontinuities are reinforced. This signifies that CFRP bumper beam with circular discontinuities when reinforced, can withstand more strain before failure.

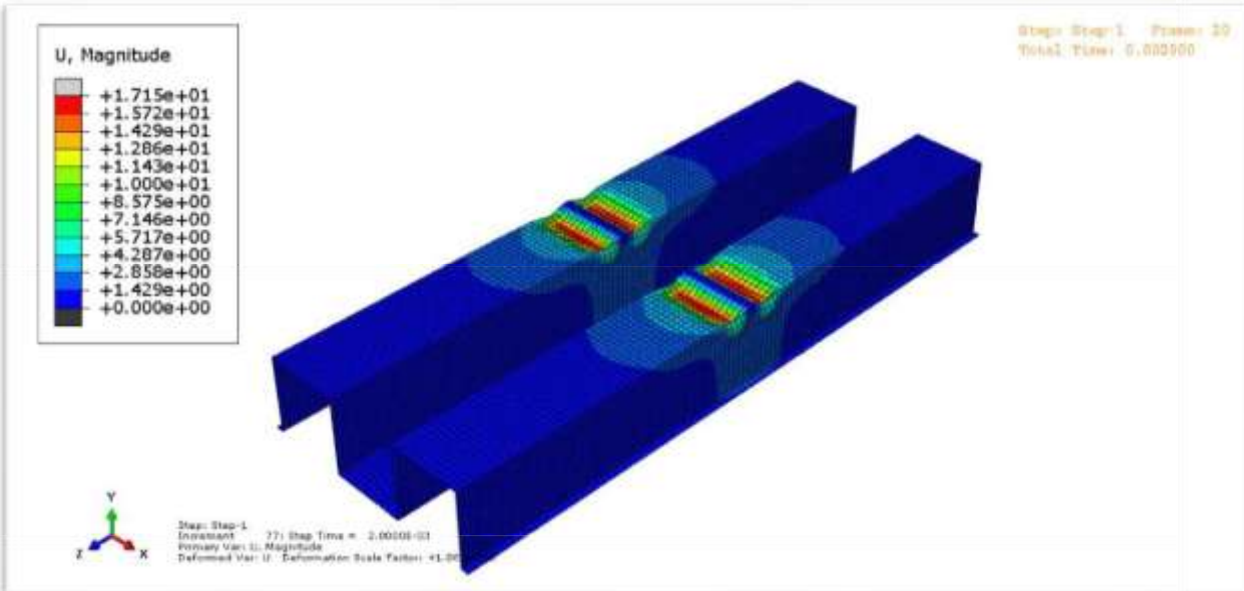

Figure 9:- Displacement of CFRP double hat bumper beam after impact.

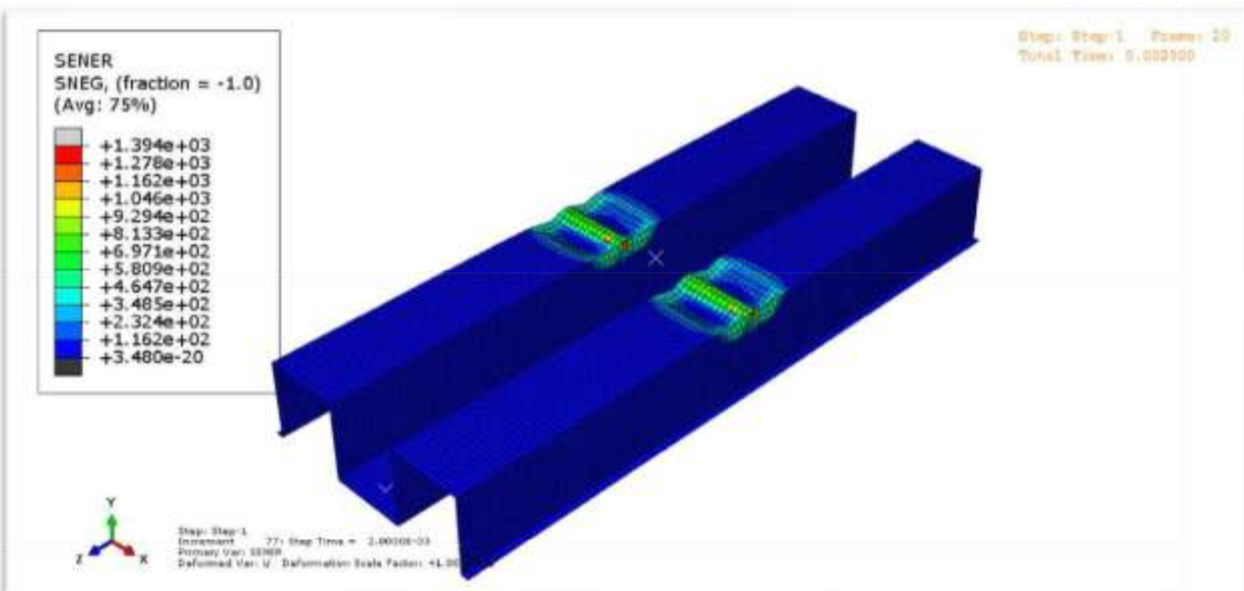

Figure 10:- Strain energy developed in CFRP double hat bumper beam after impact.

Furthermore, CFRP double hat bumper beam, CFRP double hat bumper beam with circular discontinuities and CFRP double hat bumper beam with reinforcement as shown in figure 5.3, 5.7 and 5.11 is decreasing from model 1 to 3. But in the case of reinforced bumper beam displacement of the beam itself is lower and only the reinforcement is getting displaced or deformed. This can be attributed to the higher tendency of CFRP double hat bumper beam with reinforcement to remain intact during a low velocity impact than a CFRP double hat bumper beam or a CFRP double hat bumper beam with circular discontinuities.

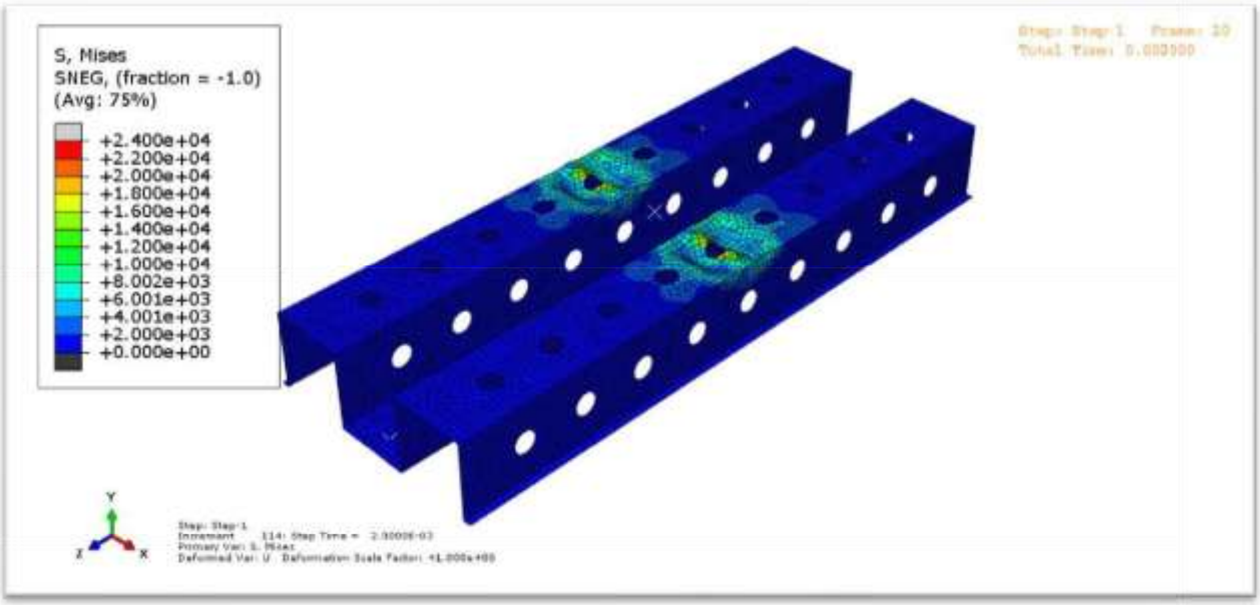

Figure 11:- Stress developed in CFRP double hat bumper beam with circular discontinuities.

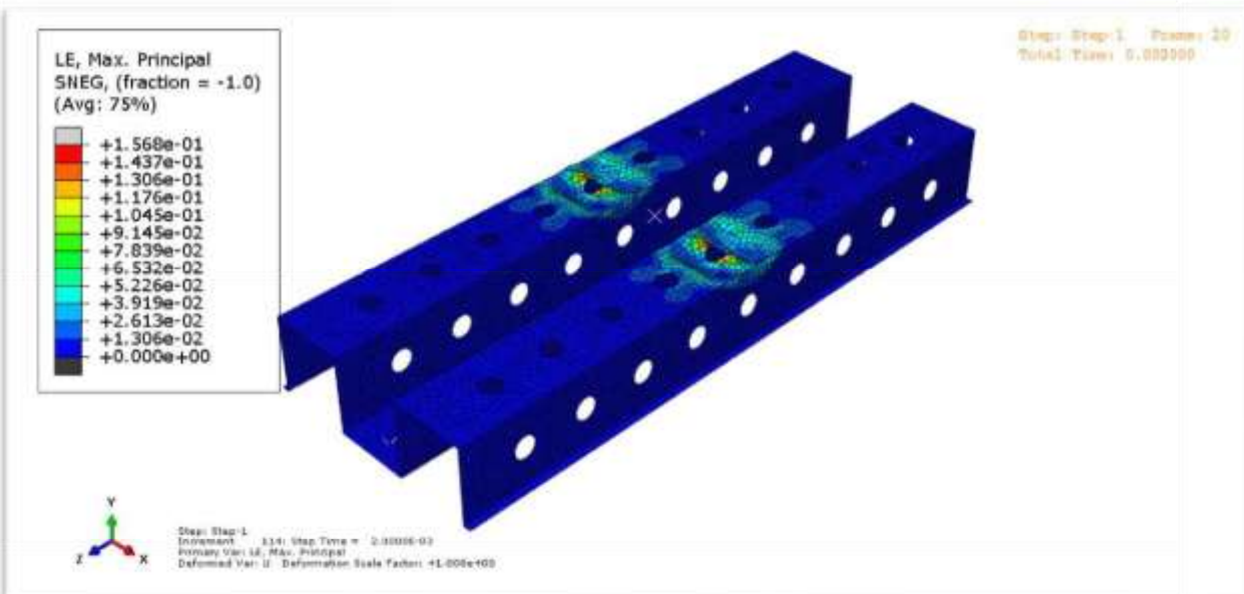

Figure 12:- Strain developed in CFRP double hat bumper beam with circular discontinuities after impact.

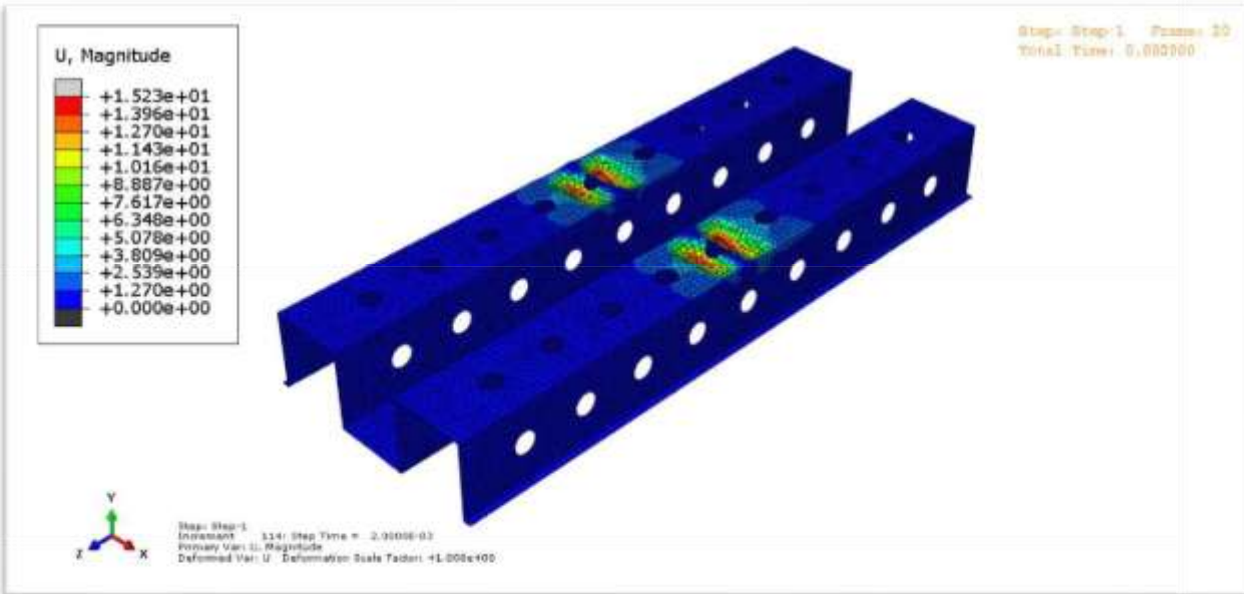

Figure 13:- Displacement of CFRP double hat bumper beam with circular discontinuities after impact.

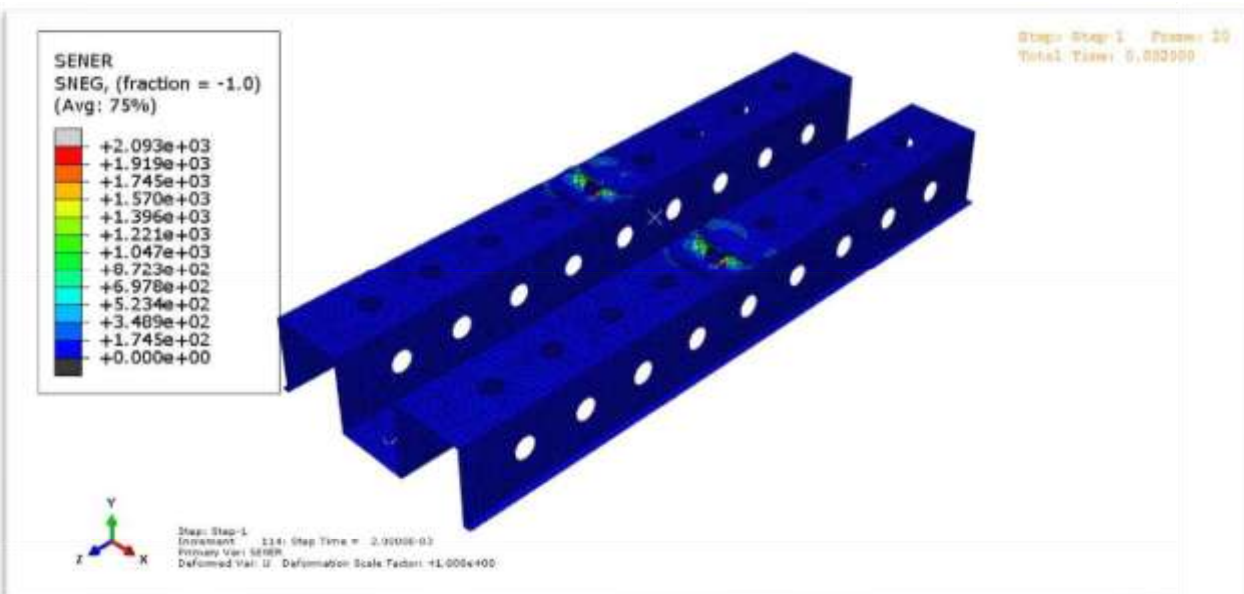

Figure 14:- Strain energy developed in CFRP double hat bumper beam with circular discontinuities after impact.

Using the strain energy equation shown in equation 3.4, Abaqus computes the total strain energy absorbed by the bumper beams considered here, during the impact. It is observed that the strain energy absorbed by CFRP double hat bumper beam is less than that with discontinuities.

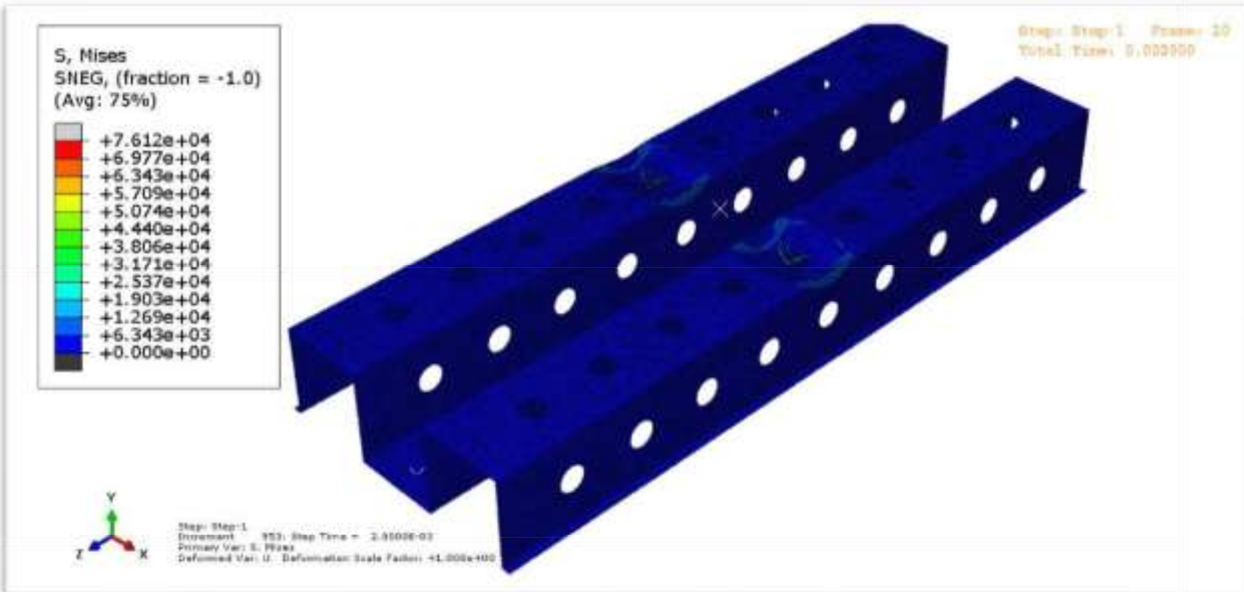

Figure 15:- Stress developed in CFRP double hat bumper beam with reinforcement.

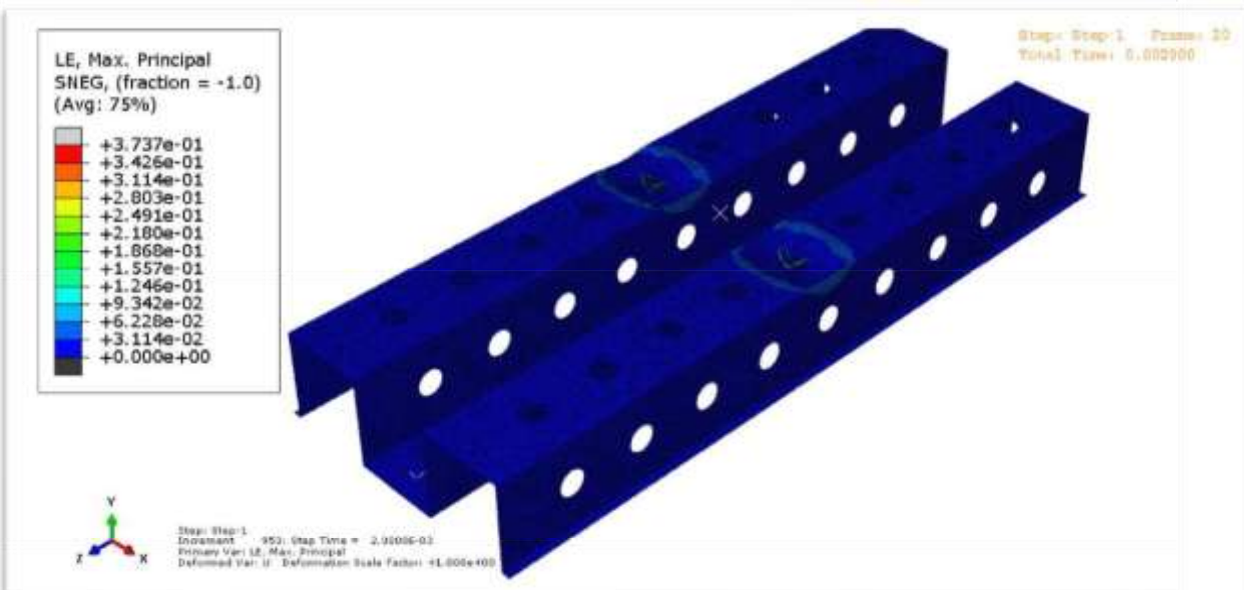

Figure 16:- Strain developed in CFRP double hat bumper beam with reinforcement after impact.

Again, the third model which is the CFRP double hat bumper beam with reinforcement is showing the highest strain energy absorbed. This means reinforcing the discontinuities not only saves material and retains the required strength, but also absorbs the impact energy effectively to ensure safety to passengers.

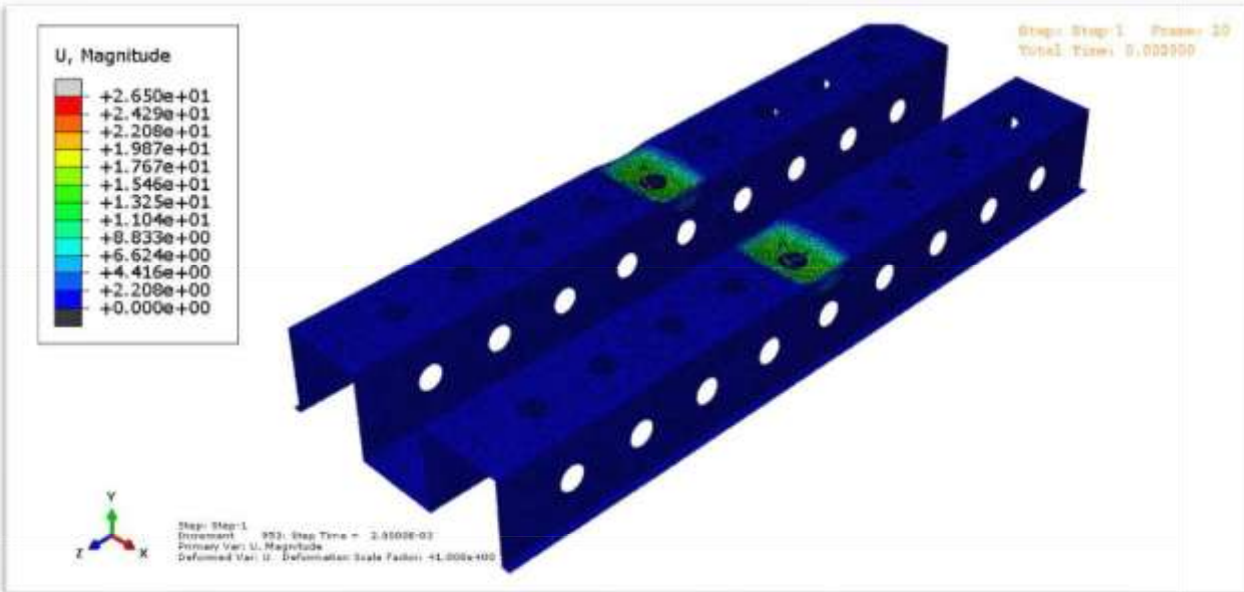

Figure 17:- Displacement of CFRP double hat bumper beam with reinforcement after impact.

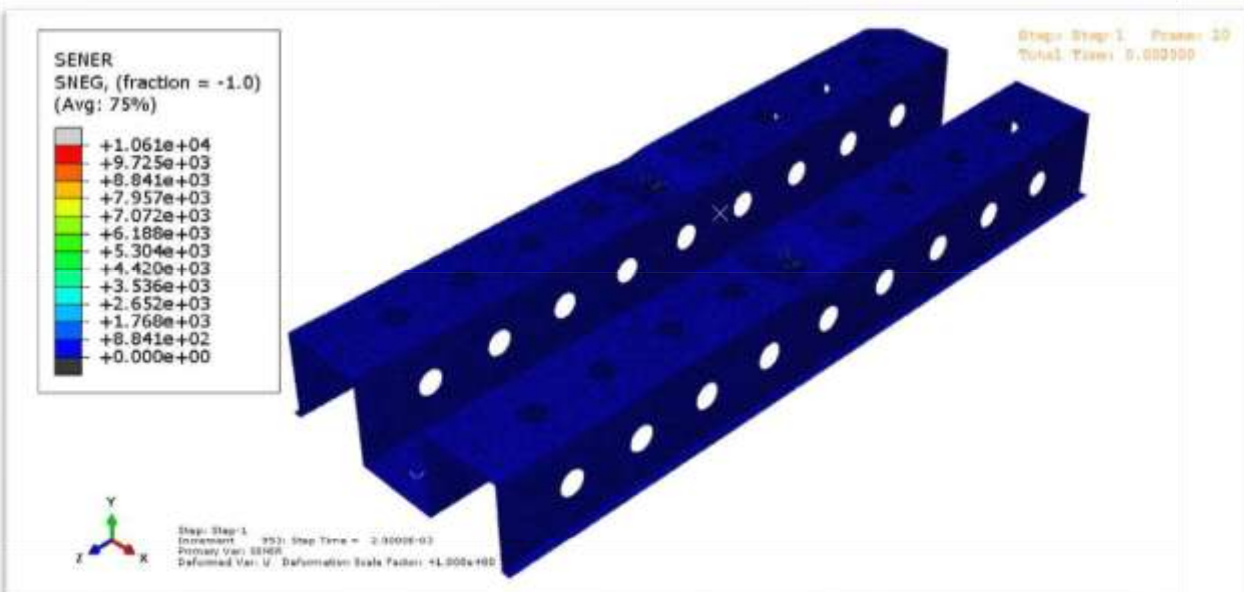

Figure 18:- Strain energy developed in CFRP double hat bumper beam with reinforcement after impact.

Conclusions:-

In this case study, high velocity impact of carbon fibre reinforced plastic double hat bumper beam without discontinuity, with implementation of circular discontinuities and with reinforcement of the circular discontinuities were simulated using finite element analysis software, Abaqus CAE and their results were compared. Although the stress developed in CFRP double hat bumper beam is higher after implementation of circular discontinuities and then reinforcing them, the beam's strain, displacement and strain energy after impact are on decreasing trend. The lower strain value and displacement of reinforced CFRP double hat bumper beam can be attributed to the effect of reinforcement on the bumper beam after implementation of circular discontinuities. More strain energy can be absorbed by CFRP beam with discontinuities at the expense of its strength. Hence reinforcement was needed to absorb the kinetic energy of high velocity impact on CFRP double hat bumper beam with discontinuities to keep the passengers safe.

Simultaneously material is being saved. The cost reduction per annual production of an automobile, say, Alto 800 was calculated to go upto 6% which corresponds to around Rs. 50 lakhs.

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