Comparative Study on Damage Behaviour of Synthetic and Natural Fiber Reinforced Brittle Composite and Natural Fiber Reinforced Flexible Composite Subjected to Low Velocity Impact

Vishwas Mahesh*, Sharnappa Joladarashi* and S M Kulkarni*

*Department of Mechanical Engineering, National Institute of Technology Karnataka, Surathkal, Mangaluru 575025, India.

*Corresponding Author: vishwasmahesh@gmail.com
Mobile Number: +91-9986644944

Abstract.
In the present study, comparative study on the damage behaviour of Glass-Epoxy (GE), Jute-Epoxy (JE) laminates with [0/90]s orientation and Jute-Rubber-Jute (JRJ) sandwich is carried out using ABAQUS/CAE finite element software. The GE, JE laminate and JRJ sandwich with thickness of 2 mm is impacted by a hemispherical shaped impactor at a velocity of 2.5 m/s. The mechanisms in which the brittle laminate gets damaged are analyzed using Hashin’s 2D failure criteria and flexible composites are analysed by ductile damage mechanism. The energy absorbed and the incipient point of each laminate was compared. It was observed from the results that there is no evidence of delamination in JRJ as opposed to GE and JE. The compliant nature of rubber contributes in absorbing more energy and it is slightly higher than GE. Also it was observed that there is no incipient point in JRJ sandwich which means there is no cracking of matrix since rubber is elastic material. Thus the JRJ material can be a better substitute for GE laminate in low velocity applications. The procedure proposed for the analysis in the present study can serve as benchmark method in modelling the impact behaviour of composite structures in further investigations.

Keywords: Rubber; Damage; Energy absorbed; Glass fiber; Jute fiber; Low velocity impact; Stiff and Flexible Composites

1. Introduction
In the field of automobiles, most of the fuel consumption is directly dependant of weight of the vehicle. Thus from environment and economy point of view, reducing the weight of the vehicle is of greater interest as pointed out by Friedrich and Almajid [1]. Out of the various alternatives available in reducing the weight of vehicle, the most popular method is using fiber reinforced plastic (FRP) composites in place of metals and alloys. The specific stiffness and strength of FRP’s are superior compared to metals making them a potential candidates for structural applications in automotive. However, according to Dorgan and Arikan [2], there is a matter of concern in using FRPs as they are highly prone to internal damage due to external dynamic loads such as low velocity impact (LVI: defined as events in the velocity range 1–10 m/s)

According to Richardson and Wisheart [3], before deciding upon using the FRPs in structural components, predicting the damage under impact load is a critical issue as the structural integrity of the component can be
reduced due to impact loading. Damages such as matrix cracking and delamination are expected in the FRPs subjected to LVI which are barely visible through visual inspection and it seems that the component is undamaged [4-6]. Hence, to prevent the catastrophic failure of the components made by FRP’s, study of the behavior of FRP’s subjected to LVI has received considerable attention [2, 7-10].

Engineers in almost all industries are using synthetic fibers like Glass-Epoxy (GE) and Carbon-Epoxy (CE) to reduce the weight of the component [11-12]. However, brittleness is the drawback of such fibers making them low impact damage resistant material pulling it’s candidature back in impact dynamics [13-17]. Owing to environmental and energy concerns, researchers are losing interest in synthetic fibers [18-19]. The natural fibers are slowly taking over the synthetic fibers in almost all industries. The automotive industry has already started using the components made by natural fibers, especially in their interior parts [20-21]. Apart from benefits such as low cost and environmental concerns, naturally available fibers also possess some technical benefits. Compared to brittle glass fibers, the resistance to impact of brittle fibers is an important advantage.

Of all the various natural fibers available for usage in composites, the most investigated natural fiber is jute, which is extracted from *Corchorus capsularis* plant. According to the study carried out by Satyanarayana et al. [22], it consists of 60% of cellulose, 22% of hemi-cellulose and 16% of lignin. Though jute provides useful mechanical properties to become a potential reinforcement material in composite, some properties needs further evaluation before finalizing its application.

Ariatapeh et al. [23] argued that, high cost and time involved in sample preparation, manufacturing and testing makes the usage of numerical method inevitable as a preliminary step. Since the present study is a preliminary step aimed at exploring the usage of new material for energy absorption application under low velocity impact, analysis is performed using finite element method (FEM). In the present study, the numerical analysis of GE and JE laminates are carried out with stacking sequence [0/90], and compared with JRJ sandwich to determine the suitability of the fiber for low velocity impact applications. It was established from the study carried out by Vishwas et al. [24] that using rubber in the composite will enhance the energy absorption ability of the composite. The nature of damages in GE, JE and JRJ are analysed

2. **Mesh convergence and verification of FE model**

The present section deals with the mesh convergence study and verifying the FE model. The FE tool is used in the present study to validate the results obtained by Karas [25]. The work carried out by Hyunbum [26] has made use of the same reference to validate his study on graphite-epoxy composite. To this end, the example considered by Karas [25] is reproduced with the aid of present methodology.
Karas [25] in his study considered a steel plate of dimension 0.2 m x 0.2 m x 0.008 m with fixed edges being impacted by steel ball of 0.01 m diameter with a velocity of 1 m/s.

Fig. 1 shows the plate and the impactor reproduced as per the Karas [25] reference. Quadratic element S4R (A 4-node doubly curved thin or thick shell, reduced integration, hourglass control, finite membrane strains) and R3D4 (A 4-node 3-D bilinear rigid quadrilateral) are used for meshing the plate and ball respectively. In the present study, the total number of elements and nodes used are 1982 and 2064 respectively. In order to select a better mesh size keeping in mind the convergence and computational efficiency, a mesh convergence study has been carried out with a series of mesh sizes ranging from 0.5 mm to 2.5 mm with increment of 0.5 mm.

The results obtained by the FE method are compared with the analytical results obtained by Karas [25] as shown in Fig. 2. Observing the variation of contact force and deformation against time, it can be conclude that the results of present method adopted through FE simulation closely matches with the results of Karas [25] when the mesh size chosen in 1 mm. Hence it is concluded that the finite element method applied in this study has validity with a mesh size of 1 mm.

3. Material Properties and Numerical Modelling

3.1 Material Properties

GE, JE laminates along with JRJ sandwich composite plates are considered for the present study. The properties of GE, JE and JRJ are taken from study carried out by [27-32]. Table 1 gives the material properties of GE and JE and table 2 gives the properties of Jute and rubber.

3.2 Modeling of Laminate Failure

The present study makes use of Hashin failure criteria to anticipate the failure of composite laminate used in the present study. Hashin 2D criteria is inbuilt in ABAQUS and works only with shell elements (SC8R). Eqs. (1) - (4) gives the four failure modes considered during the analysis.

\[
F^t_f = \left(\frac{\sigma^t_{11}}{X^t}\right)^2 + \alpha \left(\frac{\sigma^t_{12}}{S^t}\right)^2
\]

(1)

\[
C_d F^c_f = \left(\frac{\sigma^c_{11}}{X^c}\right)^2
\]

(2)

\[
\begin{align*}
\text{Fiber Tension} & \quad \left(\sigma^t_{11} \geq 0\right) \\
\text{Fiber Compression} & \quad \left(\sigma^t_{11} \leq 0\right)
\end{align*}
\]

Where, \( \sigma^t_{11} \) and \( \sigma^c_{11} \) are the principal stress in tension and compression, respectively, \( X^t \) and \( X^c \) are the principal stress and \( S^t \) is the upper bound stress.\( C_d \) is a material property.
Matrix Tension \( \sigma_{22} \geq 0 \)

\[
F_m = \left( \frac{\sigma_{22}}{Y} \right)^2 + \left( \frac{\sigma_{12}}{S_L} \right)^2
\]  

(3)

Matrix Compression \( \sigma_{22} \leq 0 \)

\[
F_m = \left( \frac{\sigma_{22}}{2S^T} \right)^2 + \left[ \frac{Y_C}{2S^T} \right]^2 - \left( \frac{\sigma_{22}}{Y_C} \right) + \left( \frac{\sigma_{12}}{S_L} \right)^2
\]  

(4)

In Eq. (1-4), \( \sigma_{ij} \) \((i, j = 1, 2)\) represents the effective stress tensor components. The tensile and compressive strength of the laminate are represented by \( X^t \), \( Y^t \) in longitudinal direction and \( X^c \), \( Y^c \) in transverse direction. The in plane and out of plane shear strength of the laminate are represented by \( S^i \) \((j = L, T)\). The material, before initiation of damage will behave linear elastic during which the stress-strain can be related as \( \{\sigma\} = [C]\{\varepsilon\} \) where \([C]\) is the elasticity matrix which changes to damage elasticity matrix \([C_d]\) once the damage is initiated. The damage elasticity matrix is defined as in Eq. (5) below

\[
[C_d] = \begin{bmatrix}
(1-d_f)E_i & \left(1-d_f\right)\left(1-d_m\right)\gamma_{21}E_i & 0 \\
(1-d_f)(1-d_m)\gamma_{12}E_2 & (1-d_m)E_2 & 0 \\
0 & 0 & (1-d_s)G_{12}D
\end{bmatrix}
\]  

(5)

Where,

\[ D = 1 - \left(1-d_f\right)\left(1-d_m\right)\gamma_{12}\gamma_{21} \]

and \( d_f, d_m \) and \( d_s \) are current states of fiber damage, matrix damage and shear damage respectively. The stacking sequence used for the purpose of analysis is \([0/90]\), for GE and JE laminate.

3.3 Details of FE Model

The damage phenomenon that occurs in the present study is highly non linear and for such situations ABAQUS/CAE (explicit) is a highly robust software. Thus FE analysis using ABAQUS/CAE FE software is carried out to study the behavior of GE and JE laminate along with JRJ sandwich subjected to low velocity impact. Eight node continuum shell elements (SC8R) with Hashin 2D criterion are used to model the laminates. The laminate is modeled as per the ASTM D7136/ D7136M standard with a dimension of 0.1 m x 0.15 m as shown in Fig. 3. In order to reduce the computational time and effort, only quarter plate and impactor is modeled due to symmetry in nature.

Stiffness hourglass option was used for continuum shell elements. The total thickness of laminate is 0.002 m (2mm) with each ply measuring 0.0005 m (0.5 mm) for GE and JE laminates and for JRJ sandwich, the rubber
core thickness is maintained as 0.001 m and each facesheet of jute as 0.0005 m. The impact zone was meshed finer (1x1 mm$^3$) and the remaining regions coarser (1.5x1.5 mm$^3$) for GE and JE.

The impactor was modeled with rigid shell elements (R3D4) with the reference point at its center of mass where the initial velocity of 2.5 m/s was prescribed. As a part of interaction property general contact (Explicit) is assigned for the purpose of analysis where frictionless contact and separation after contact were defined. The boundary condition of fixed support on four side of finer mesh region of composite plate are considered and for the two side edges of the laminate PINNED boundary condition was considered. For the impactor, displacement/ rotation boundary condition is defined with its movement restricted in U1, U2, UR1, UR2 and UR3 direction and allowing movement only in U3 direction which is Z direction. The assembled view of laminate and impactor along with their meshing is as shown in Fig. 4 and for JRJ sandwich it is shown in Fig. 5. The number of elements used in the analysis are as shown in Table 3.

Penalty contact method was used to model the contact between the impactor and top surface of the laminate and general contact method was used for defining contact between the plies in order to bring them under general contact domain. A hard contact with pressure over closure and friction coefficient of 0.3 were used between the impactor and top laminate while a friction coefficient of 0.7 was used between the different plies, based on reported studies [33-34].

4. Results and Discussion

4.1 Cohesive Surface Quadratic Stress Criterion (CSQUADSCRT) in GE and JE Laminate

The cohesive based surface is used to connect the surfaces of plies in the present work. The cohesive surface quadratic stress criterion (CSQUADSCRT) indicates whether the contact stress damage initiation criterion has been satisfied at the contact point. Whenever CSQUADSCRT =1, at that point of contact, damage initiation criterion has been satisfied. Fig. 6 shows damage initiation for GE and JE where we can clearly identify the delamination happening in case of GE and JE laminates.

4.2 Hashin Damage Parameters for GE and JE Laminates

For fiber reinforced composites, the material damage initiation capability is based on Hashin’s theory and the various Hashin damage initiation criterion used are shown in Fig. 7. From the Fiber compressive initiation criterion (HSNFCCCRT) for GE and JE laminate it can be observed that delamination happening in GE and JE laminate with extent of delamination being larger in JE compared to GE. Also the fibers getting failed due to compression is more in GE compared to JE laminate. In case of JE, jute fibers are damaged more at the point
of contact of impactor and gradually reduces towards the tip of laminate, whereas in case of GE laminate, the fiber damage area remains even throughout. From fiber tensile initiation criterion (HSNFTCRT), it can be observed that, the amount of fibers failing in tension is more in GE compared to JE.

Looking into the matrix compressive initiation criterion (HSNMCRT) and matrix tensile initiation criterion (HSNMTTCRT), it can be concluded that the failure of matrix by compression and tension is more in GE and JE laminates which can be due to the brittle nature of the laminate and is more evident at the impact zone compared to other zones of laminate. The matrix failure due to tension is almost similar both in GE and JE except that the matrix failure extends to other regions of JE laminate but confined to impact zone in case of GE laminate. It can be concluded that the main reason for failure in GE and JE laminate is delamination which is very much evident from the Fig. 6.

4.3 Damage Behavior of JRJ Sandwich

Figure 8 shows the damage behavior of JRJ sandwich. It can be clearly observed that the nature of damage is ductile as opposed to GE and JE laminates where the nature of damage is brittle. The JRJ sandwich deforms more compared to GE and JE there by absorbing more energy. The reason behind such a behavior of the JRJ sandwich may be the presence of rubber which is compliant in nature and thus enabled the JRJ sandwich is higher energy absorption. Thus the flexible composites can absorb more energy compared to conventional brittle composites.

4.4 Force

Fig. 9 shows the Comparison of incipient point (IP) and peak load (PL) for GE, JE and JRJ laminates. The incipient point for GE, JE and JRJ is at a force of 480 N, 310 N and 0 N respectively which means that the matrix in case of JRJ which is rubber has not failed as opposed to GE and JE where the matrix is epoxy. This is due to the ductile and compliant nature of rubber and matrix in JE laminate fails earlier followed by GE. This statement is supported by the Hashin’s failure criteria discussed earlier where it was evident that matrix cracking plays a vital role in failure of JE laminate. The peak load for GE, JE and JRJ are 580 N, 480 N and 668 N respectively.

4.5 Energy

The energy history for GE, JE and JRJ laminate is compared in Fig.10. The impactor transfers all its energy to the laminate and then due to elastic recovery of plate, it rebounds. Because of various damage dissipation phenomenon that occurs during an impact event, energy used for recovery was less compared to impact energy. The energy is dissipated in different failure modes. At the end of the rebound stage, the energy absorbed
stabilizes to a particular value. The energy absorbed in case of GE, JRJ and JE laminates are 6.3 J, 6.68 J and 4.2 J respectively. The energy absorbed by JRJ is superior to that of GE composite.

5. Conclusions

In the present work, drop weight impact response of GE, JE and JRJ laminate is investigated through FE analysis. Cohesive based surface is used to connect the surfaces of plies. Hashin’s damage criterion (2D) for fiber reinforced composites readily available in ABAQUS/CAE is made use of to study the damage behavior of the GE and JE laminates. It is found that delamination happening in case of GE and JE laminates with highest amount of delamination in JE, whereas there is no delamination in case of JRJ laminate. The failure of matrix by compression and tension is more in GE and JE laminates which can be due to the brittle nature of the laminate and is more evident at the impact zone compared to other zones of laminate, whereas for JRJ laminate, the evident of matrix failure is minimal. This can be due to the compliant nature of rubber which can expand thereby absorbing more energy during low velocity impact loading. The incipient point for JRJ is absent which means that the matrix in case of JRJ which is rubber has not failed as opposed to GE and JE where the matrix is epoxy. This is due to the ductile and compliant nature of rubber and matrix in JE laminate fails earlier followed by GE. The peak load for JRJ is 1.15 times more than GE and 1.4 times more than JE and the energy absorbed by JRJ is 1.06 times more than GE and 1.6 times more than JE. JRJ Flexible composites are less prone to damage compared to brittle composites like JE and GE and thus suitable for low velocity impact applications. The natural fiber in combination with rubber yields a flexible composite which is a better energy absorbing material compared to brittle composites

References


**Biography**

**Vishwas Mahesh** received his Bachelor of Engineering degree in Mechanical Engineering and Master of Technology degree in Product Design and Manufacturing in 2007 and 2011 respectively from Visvesvaraya Technological University, Belagavi, Karnataka, India. He is currently working as Research Scholar in the Department of Mechanical Engineering, National Institute of Technology Karnataka, Surathkal, Mangalore, India. His research interests include composite materials and impact dynamics. He has published and presented many papers in international journals and conferences.

**Sharnappa Joladarashi** received his Bachelor of Engineering degree in Mechanical Engineering and Master of Engineering degree in Advanced Manufacturing Engineering in 2000 and 2003 respectively from Gulbarga University, Karnataka, India and National Institute of Technology Karnataka, Surathkal. He has also received his Ph.D. degree from Indian Institute of Technology Madras (IIT-M) in 2008. He is currently working as Assistant Professor in the Department of Mechanical Engineering, National Institute of Technology Karnataka, Surathkal, Mangalore, India. His research interests include composite materials. He has published and presented many papers in international journals and conferences.

**S M Kulkarni** received his Bachelor of Engineering degree in Mechanical Engineering and Master of Engineering degree in Mechanical Engineering in 1985 and 1989 respectively from Mysore University, Karnataka, India and Bharthiar University, Tamilnadu, India. He has also received his Ph.D. degree from Indian Institute of Science Bangalore (IISc) in 2002. He is currently working as Professor in the Department of Mechanical Engineering, National Institute of Technology Karnataka, Surathkal, Mangalore, India. His research interests include composite materials, MEMS. He has published and presented many papers in international journals and conferences and also authored many book chapters.

**List of Figures Caption**

**Figure 1.** (a) Modeling and (b) meshing of the plate and spherical ball
Figure 2. Variation of (a) contact force and (b) deformation of the plate as a function of time (Intended for colour reproduction)

Figure 3. Schematic representation of (a) GE and JE laminate and (b) JRJ sandwich

Figure 4. Assembled view of laminate and impactor, meshing for (a) GE and JE laminate (b) JRJ sandwich

Figure 5. Boundary condition applied to (a) GE and JE laminate and (b) JRJ sandwich

Figure 6. Damage initiation for (a) GE (b) JE and (c) JRJ laminate (Intended for colour reproduction)

Figure 7. Hashin damage initiation criteria for (a) GE (b) JE (Intended for colour reproduction)

Figure 8. Damage behavior of JRJ sandwich (Intended for colour reproduction)

Figure 9. Comparison of incipient point and peak load for GE, JE and JRJ (Intended for colour reproduction)

Figure 10. Energy v/s Time plot for GE,JE and JRJ (Intended for colour reproduction)

List of Tables Captions

Table 1: Material Properties of GE and JE

Table 2: Material properties of Jute and Rubber

Table 3: Number of Elements used for Various Parts

List of Figures

Figure 1. (a) Modeling and (b) meshing of the plate and spherical ball
Figure 2. Variation of (a) contact force and (b) deformation of the plate as a function of time (Intended for colour reproduction)

Figure 3. Schematic representation of (a) GE and JE laminate and (b) JRJ sandwich
Figure 4. Assembled view of laminate and impactor, meshing for (a) GE and JE laminate (b) JRJ sandwich

Figure 5. Boundary condition applied to (a) GE and JE laminate and (b) JRJ sandwich

Figure 6. Damage initiation for (a) GE (b) JE and (c) JRJ laminate (Intended for colour reproduction)
Figure 7. Hashin damage initiation criteria for (a) GE (b) JE (Intended for colour reproduction)
Figure 8. Damage behavior of JRJ sandwich (Intended for colour reproduction)

Figure 9. Comparison of incipient point and peak load for GE, JE and JRJ (Intended for colour reproduction)

Figure 10. Energy v/s Time plot for GE,JE and JRJ (Intended for colour reproduction)

List of Tables

Table 1: Material Properties of GE and JE
<table>
<thead>
<tr>
<th>Material</th>
<th>Density $\rho$ (Kg/m$^3$)</th>
<th>$E_1$ (GPa)</th>
<th>$E_2 = E_3$ (Gpa)</th>
<th>$G_{12} = G_{13}$ (Gpa)</th>
<th>$G_{23}$ (Gpa)</th>
<th>$X_t$ (Gpa)</th>
<th>$X_c$ (Gpa)</th>
<th>$Y_t$ (Gpa)</th>
<th>$Y_c$ (Gpa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GE</td>
<td>1635</td>
<td>30.5</td>
<td>4.02</td>
<td>2.08</td>
<td>1.44</td>
<td>0.686</td>
<td>0.270</td>
<td>0.035</td>
<td>0.088</td>
</tr>
<tr>
<td>JE</td>
<td>1337.5</td>
<td>4.5</td>
<td>3.2</td>
<td>1.45</td>
<td>1.63</td>
<td>0.104</td>
<td>0.102</td>
<td>0.011</td>
<td>0.095</td>
</tr>
</tbody>
</table>

Table 2: Material properties of Jute and Rubber

<table>
<thead>
<tr>
<th>Density $\rho$ (Kg/m$^3$)</th>
<th>Youngs Modulus $E$ (GPa)</th>
<th>Poissons Ratio $\nu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jute</td>
<td>1450</td>
<td>20</td>
</tr>
<tr>
<td>Rubber</td>
<td>1060</td>
<td>Neo Hookean parameters:</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$C_{10}$: 16.77E9 Pa, $D_1$ : 1.2 E-9 Pa$^{-1}$</td>
</tr>
</tbody>
</table>

Table 3: Number of Elements used for Various Parts

<table>
<thead>
<tr>
<th>Part</th>
<th>Number of Elements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laminate: Impact Zone (Finer Mesh Region)</td>
<td>5,184</td>
</tr>
<tr>
<td>Laminate (Coarser Mesh Region)</td>
<td>21,984</td>
</tr>
<tr>
<td>Impactor</td>
<td>661</td>
</tr>
<tr>
<td>Jute</td>
<td>788</td>
</tr>
<tr>
<td>Rubber</td>
<td>1489</td>
</tr>
</tbody>
</table>