Quasi-static puncture shear loading behaviour MWCNT/glass fibre epoxy laminates with various indenters

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Investigation was performed to evaluate the puncture resistance of multi-walled carbon nanotubes (MWCNTs)/glass fibre epoxy laminate composites using different indenters (conical, elliptical, flat, and hemispherical). For the puncture tests, MWCNT weight percentage and indenter type were varied. Furthermore, the impact of MWCNT on tensile, flexural, and interlaminar shear strength was evaluated. Ultrasonic C-scan provided insights into the damage evolution and failure mechanisms of the laminates under puncture. The results indicate that the flat indenter exhibits prolonged indentation time and enhanced energy absorption, resulting in a disc-shaped failure pattern. On the other hand, the conical indenter demonstrates rapid penetration due to its smaller contact surface area. The elliptical indenter generates higher frictional energy, leading to bulging damage. The hemispherical indenter showed an even distribution of force across the impacted surface, minimizing force concentration and reducing the extent of damage. These findings shed light on the puncture mechanisms of MWCNT/Glass fibre epoxy laminate composites, paving the way for more precise glass fibre laminate composite design and optimisation in practical applications such as aerospace, automotive, and sporting goods, where puncture loading is a critical consideration.

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- Puncture resistance
- Multi-walled carbon nanotubes
- Glass/epoxy composites

**ABSTRACT**

1. Introduction

Glass fibre reinforced composites (GFRP) have gained significant attention in various industries due to their unique properties such as superior strength-to-weight ratios and tailored properties such as strength, stiffness and durability. GFRP have proven their high mechanical performance in various industries, including aerospace, automotive, packaging, sporting goods, and construction [1]. In such applications, composites are prone to puncture failure. For instance, in aerospace and defence industries, composites are extensively employed in aircraft panels, helicopter rotor blades, and ballistic protection systems, where the likelihood of puncture damage caused by projectiles or bird strikes is notably high. Similarly, the automotive industry demands composites with exceptional puncture resistance, particularly in critical components such as fuel tanks, underbody panels, and bumper structures, which are prone to punctures resulting from road debris or accidents. Puncture resistance is critical in determining the mechanical integrity of materials when subjected to localised or dynamic loading and impacts, and hence, it determines their ability to withstand such forces without catastrophic failure. Therefore, it is critical to increase the puncture resistance of GFRP composites without compromising weight and strength.

Various methods have been used to improve the properties of GFRP, including modifying thermoset matrices, such as epoxy, and by adding dispersed secondary phases such as rubber or thermoplastic materials [2–4]. Furthermore, the use of thermoplastic matrices and the incorporation of interlayers between reinforcement laminae have yielded promising performance. For instance, Raja et al. [5] reported that the addition of nano-fly ash to GFRP composites increased tensile strength, compressive strength, flexural strength, and hardness. Flyash with
average size of 1000, 264, 198, 94, and 68 nm was used. Specifically, flyash with an average size of 68 nm demonstrated the highest tensile strength (172 MPa), compressive strength (98 MPa), and flexural strength (190 MPa). In another investigation, Ramesh et al. [6] modified GFRP composite through the addition of natural fibres such as sisal and jute fibre. The composite specimen had five layers, with glass fibre layers at the top, middle, and bottom. The second and fourth layers contained 30 mm of chopped natural fibre. The developed composites showed the tensile strength varying between ca.175 MPa to ca.230 MPa. Similarly, Naresh et al. [7] developed glass and carbon fibre-based epoxy hybrid composites with increased strength. The tensile strength of the glass/epoxy composites increased by ca [8]. 66% as the strain rate increased. In each approach, the composite was modified to improve mechanical properties or to facilitate energy absorption through plastic deformation. Although these methods can improve certain performance properties, they are, generally detrimental to toughness and thermal stability [3,9–11]. As a result, there is a need to preserve the overall thermo-mechanical properties of fibre reinforced polymer composites, which can be accomplished by deploying toughening agents [12,13]. The addition of carbon-based fillers has been shown to improve the fracture toughness of polymer matrices while maintaining their thermo-mechanical properties [14–16]. Extensive research has been performed on utilising carbon-based nanoparticles, such as graphene [17–19], carbon nanotubes (CNTs) [20,21], and other carbon materials [22], as toughening agents. These nanoparticles have demonstrated the ability to enhance the toughness of GFRP composites. CNTs (single, double, or multi-walled) are particularly popular for improving the performance of GFRP [23–25]. However, the effect of CNTs on puncture behaviour and the interaction with different shape indenters remains an area requiring further investigation. The shape of the indenter directly affects the stress distribution and deformation mechanisms during loading. Different indenter geometries can lead to variations in puncture strength, energy absorption, and failure modes, making it essential to investigate their influence on GFRP. The choice of indenter geometry in puncture tests could also provide a clear understanding of the puncture behaviour and failure mode in GFRP.

Therefore, this manuscript aims to explore the puncture behaviour of the MWCNT/glass fibre epoxy laminate composites using different shape indenters. The study investigates the influence of indenter geometry on the mechanical response, puncture strength, and failure modes of MWCNT/glass fibre epoxy laminate composites. By examining various shape indenters, a comprehensive understanding of the puncture behaviour can be obtained, aiding in the selection and optimisation of materials for applications requiring puncture resistance in GFRP. Moreover, the incorporation of MWCNTs as a reinforcement phase offers potential for developing advanced GFRP laminate composites with improved puncture resistance, broadening their range of engineering applications.

2. Materials and methods

2.1. Materials

In this study, glass fibre, MWCNTs, and epoxy were used. JD Techfab, India, provided 400 gsm woven roving e-glass fibre with a tensile strength of 1480 N/25 mm (Warp), 1380 N/25 mm (Weft), a thickness of 0.4 mm, and an area weight of 400 g/m². Intelligent Materials Private Limited, Punjab India supplied MWCNT with a size of 40 nm, length of 30–40 μm, specific surface area of 90–350 m²/g and bulk density of 0.05–0.17 g/cm³, and Huntsman, Pune, India supplied epoxy resin (LY 556) with hardener (HY 951). The viscosity of epoxy resin used is 10000–12000 mPa*s at 25 °C (ISO 12058-1) and density is 1.15–1.2 g/cm³ at 25 °C (ISO 1675).

2.2. Fabrication of composites

Composite laminates were made using compression moulding. The fibre-to-resin ratio was set at 1:1 by weight. A steel mould with 300 × 200 mm dimension was used. Glass fibres were laid over the mould during fabrication, and resin was applied layer by layer. The mould used was coated with wax for easy removal of composite. The sonication process was used to prepare the resin and MWCNTs solution, and the epoxy and MWCNTs were mixed for 4 h to ensure proper mixing. The hardener was then added (resin to hardener ratio - 10:1) and thoroughly mixed before being applied to the fibre layers. After that, the mould was closed, and a uniform load of 50 kg was applied. The mould was then left undisturbed for 24 h for curing.

2.3. Quasi-static punch shear (QS-PS) test

A quasi-static punch shear test (QS-PS) determines a material’s shear strength and deformation behaviour when subjected to a punching load. The QS-PS test was performed using Instron UTM at a loading rate of 2 mm/min, and the experimental set up is shown in Fig. 1(a and b). QS-PS tests were carried out using different indenter shapes such as hemispherical, cone, elliptical, and flat. The specifications of the indenters used are shown schematically in Fig. 1 c. All the four indenters used in this study are made of stainless steel. The indenter used had a diameter of 12.7 mm. The conical indenter’s nose half-angle was 45°. Using the test results, force-displacement curve was drawn. The surface area under the force-displacement curve represents the total energy (Eₜ) absorbed by the laminate during penetration. It is the sum of the energy absorbed by the laminate in three damage areas: elastic energy, damage energy, and friction energy. The total absorbed energy (Eₜ) was calculated using the trapezium integration method in the MatLab suite (R2017b version).

Fig. 1. (a and b) Experimental set of quasi-static punch shear test, (c) Schematic representation of different indenter configurations (i) Conical (ii) Elliptical (iii) Flat (iv) Hemispherical (All dimensions are in mm).
The puncture shear strength (PSS) was calculated according to Formula (1)

\[ \text{PSS} = \frac{P_{\text{max}}}{D_p H_c} \]  

where: \( P_{\text{max}} \) = maximum force, \( D_p \) = diameter of the punch, \( H_c \) = thickness of the laminate.

To assess the energy absorption efficiency, specific energy absorption (SEA) metric was employed, which represents the absorbed energy per unit mass of the specimen. The calculation of SEA was performed using equation (2).

\[ \text{SEA} = \frac{\text{TEA}}{M} \]  

Where TEA = total energy absorption and \( M = \) The mass of the specimen.

### 2.4. Immersion ultrasonic testing system

Following the puncture testing, the composite laminates were subjected to automated ultrasonic inspection using a water immersion ultrasonic testing system (SHRUTI®). The SHRUTI® (Scanning High-Resolution Ultrasonic Testing and Imaging) system, developed by DHVANI RESEARCH, is a customizable, automated, multi-axis robotic scanner. The system includes an advanced ultrasonic inspection instrument, specialized data analysis software (execut®), and an image analysis package (imagin®). The scanner performs interface scanning using a side-looking transducer with a frequency of 2.25 MHz in pulse-echo mode operated at a pulser voltage of 313 V and a gain of 20 dB. Measurement was performed in three orthogonal directions on rectangular MWCNT/glass fibre epoxy laminates, specifically along the thickness (T), width (W), and length (L) of the laminates, respectively. During the inspection process, a pulser probe was used to emit ultrasonic waves into the composite laminates. These waves travelled through the laminates, interacting with internal features such as defects, interfaces, and thickness variations. The transducer in the system detects and analyses the reflected waves. The data was converted into a visual representation known as a C-scan image. This image is a two-dimensional map of the reflected waves. The C-scan images were then analysed with imageJ software to find the total area of damage. Fig. 2 depicts the C-scan experimental setup.

### 2.5. Tensile and flexural test

Tensile and three-point bending (i.e., flexural) tests were conducted on the composites using Instron universal testing machine (UTM) and the testing was done according to ASTM D3039 and ASTM D790 protocol, respectively. The samples had a span-to-depth ratio of 16:1, and the crosshead speed of the flexural tests was set to 2 mm/min. Equation (3) was used to calculate flexural strength \( f_c \).

\[ f_c = \frac{3 PL}{2 BD^2} \]  

where \( f_c \) = flexural strength (MPa), \( P \) = load (N), \( L = \) length of span (mm), \( B = \) width of prism (mm), and \( D = \) depth of prism (mm).

The Flexural strain \( \epsilon_b \) was calculated using equation (4).

\[ \epsilon_b = \frac{6D\delta}{L^2} \]  

where \( \epsilon_b \) = flexural strain, \( \delta = \) displacement (mm), \( L = \) length of span (mm)

### 2.6. Inter laminar shear strength (ILSS)

The interlaminar shear strength (ILSS) of a laminate composite made up of multiple layers refers to the ability of the layers to resist slipping or sliding past each other when subjected to an applied load. The short beam shear (SBS) test method was used to determine the composite’s ILSS. The ILSS was tested using UTM according to ASTM D2344 protocol. The specimen was supported by two cylindrical supports, and a cylindrical head was moved down to apply a force at the centre of the specimen and generate an increasing transverse load until the failure was recorded. The load at failure was used to calculate the composite’s ILSS. Equation (5) was used to calculate the ILSS \( \tau \).

\[ \tau = \frac{3 P_b}{4BD} \]  

where \( \tau = \) ILSS, \( P_b = \) maximum load, \( B = \) width of sample (mm), and \( D = \) depth of sample (mm).

### 3. Results and discussion

#### 3.1. Quasi-static punch shear (QS-PS) properties

The study revealed that the extent of puncture damage on the composite laminate varied depending on the configuration of the puncture indenter and the specific composite laminate composition. Fig. 3(a)-(d) displays the puncture damage areas observed in the 2 wt% MWCNT/glass fibre epoxy laminates. Notably, the damage area was slightly larger than the diameter of the indenter. Comparative analysis of the different indenters demonstrated that the flat indenter (Fig. 3(d)) resulted in a greater damage area compared to the other indenters.

Fig. 4 illustrates the progressive stages of damage mechanisms observed during punch-shear loading. Initially, a drop in load (Point A) indicates the occurrence of matrix cracks and the initiation of delamination as the indenter penetrates specific layers. Subsequently, delamination propagates as compressive-shear, while fibres begin to fracture between Points B and C. At Point C, the peak load is reached, marking the formation of a plug. Following this, a sudden decrease in load occurs due to the development of compressive-shear near the lower surface of
Subsequently, the load enters a plateau region (from Point E to F), primarily matrix damage. At this point, the plate expels the plug (Point E). From the graph, it was understood that the flat and conical indenters produced higher force than the other indenters. A lower force was noticed for the elliptical indenter. The force vs. displacement curve produced by the flat indenter showed a relatively linear increase in force with displacement. The curve does not show a distinct plateau unlike the other indenters and exhibited a quick peak with lower compressive-shear, likely due to the absence of a sharp tip. This absence reduced the stress concentration, resulting in more evenly distributed and gradual deformation of the laminate. However, the force required to produce deformation was higher compared to the other indenters due to the larger contact area. When a conical indenter was used, the force vs. displacement curve showed an initial rapid increase in force with relatively low displacement. As the displacement progressed, the force continued to increase, but at a decreasing rate. Furthermore, the conical indenter exhibited higher deformation, which could be attributed to amplified stress concentration at the indenter tip. The force vs. displacement curve of the elliptical indenter had combined aspects of both the conical and flat indenters. Initially, there was a rapid increase in force, similar to the conical indenter. However, as the displacement progressed, the force increased more gradually, resembling the behaviour of the flat indenter. The curve exhibited a plateau, but it was less pronounced when compared to the conical indenter. With a hemispherical indenter, the force vs. displacement curve showed a gradual increase in force with increasing displacement. The curve showed a distinct plateau characteristic, indicating a more uniform distribution of forces across the composite laminate. The displacement was found to spread more evenly, potentially resulting in less localised damage compared to the conical and flat indenters.

From Fig. 5, it can be understood that the presence of MWCNTs in the composite material had a significant effect on its peak load capacity. The curves in the graph show higher peak load values for MWCNT/Glass fibre epoxy laminates, emphasising their superior load-bearing capacity over the Glass/Epoxy laminate. This improvement was attributed to MWCNTs’ exceptional mechanical properties, such as high stiffness, strength, and toughness, which are effectively expressed in the composite material. Flat and spherical indenters had the highest load capacity in 1 wt% MWCNT/Glass fibre epoxy laminates. When 0.5 wt% MWCNT/glass fibre epoxy laminates were tested, conical indenters showed the highest load capacities. Thus, it can be understood that there is a significant relationship between the material and indenter characteristics.

Fig. 6(a–d) depict the punch shear strength of Glass/Epoxy and MWCNT/glass fibre epoxy laminates subjected to different indenters. The results of tests with four different types of indenters revealed some interesting findings about the punch shear strength of glass/epoxy composites. 0.5 wt% MWCNT/glass fibre epoxy laminate demonstrated the highest punch shear strength in tests using a conical indenter and an elliptical indenter. For the composite with 1 wt% MWCNTs, the highest punch shear strength was noted when the hemispherical indenter and a flat indenter were used. When the conical indenter and the elliptical indenter were used, the glass/epoxy composite containing 0.5 wt% of MWCNTs had the highest punch shear strength, while the composite containing 1 wt% of MWCNTs had the highest punch shear strength with the hemispherical indenter and the flat indenter. The optimal weight percentage of MWCNTs in glass/epoxy composites, according to these findings, varies depending on the type of indenter used.

### 3.1.1. Energy absorption capacity

In a composite material, the calculation of absorbed energy provides valuable insights into the energy required for full penetration or material failure by an indenter. It is important to recognise that absorbed energy is not constant throughout the deformation process. The non-linearity of load-displacement behaviour and the presence of distinct failure mechanisms along the material’s thickness contribute to variations in absorbed energy at different deformation stages. These variations arise from diverse failure mechanisms, including delamination, matrix cracking, fibre breakage, and fibre pull-out. The occurrence of these mechanisms at different deformation stages leads to varying levels of energy absorption. Consequently, a comprehensive understanding of absorbed energy behaviour in composite materials plays a pivotal role in their design and optimisation for specific applications.

Table 1 shows the effect of MWCNT addition on the energy absorption capacity of glass/epoxy composites when subjected to different indenter geometries, such as conical, elliptical, flat, and hemispherical shapes. Notably, the energy absorption capacity increased with the addition of MWCNTs, up to 1.5 wt%. Beyond this point, the energy absorption capacity began to decline. Notably, compared to 1.5 wt%
MWCNT/glass fibre epoxy laminate, 2 wt% MWCNT/glass fibre epoxy laminate showed ca. 20%, ca. 4%, ca. 12%, ca. 8% reduction in specific energy absorption on conical, elliptical, hemispherical and flat indenters, respectively. It is worth noting that the shape of the indenter had a significant impact on the energy absorption capacity of the composite material. For instance, at 1.5 wt% MWCNT/glass fibre epoxy laminate, the flat-shaped indenter had ca. 22% higher energy absorption capacity than the elliptical counterpart. This is because the flat indenter typically has a larger contact area with the composite laminate than the elliptical indenter. The larger contact area allows for a greater distribution of the applied force, resulting in a more efficient transfer of energy. Furthermore, it was found that the energy absorption due to compression-shear was greater for all combinations, indicating that this mechanism contributes significantly to the composite material’s overall energy absorption capacity. These findings suggest that the geometry of the indenter nose shape has a significant impact on the energy absorption capacity of composite plates.

3.1.2. Damage Assessment through Ultrasonic C-Scan method

Fig. 7 depicts the C-scan results of MWCNT/glass fibre epoxy laminates subjected to conical, elliptical, hemisphere, and flat indenters. For ultrasonic C scan imaging, composite having higher SEA and TEA was used. The middle blue area represents the concentrated damage area that was in direct contact with the indenter geometry in the case of the conical indenter, while the surrounding blue area represents the distributed damage area that was not in direct contact with the indenter. The damage area was calculated using ImageJ software and shown in Table 2. The conical indenter’s impact area measured was 533.57 mm\(^2\) whereas for the elliptical indenter, it was ca. 8% higher than the damage produced by the conical indenter. The conical indenter, with its tapered shape and smaller contact area, concentrated the force onto a smaller region, resulting in a more localised damage area. The elliptical indenter, on the other hand, distributed force over a larger region upon impact due to its elongated shape and broader contact area, resulting in a larger impact area and potentially less localised damage than the conical. The hemispherical indenter had a lower impact area than the other three indenters, measuring 491.37 mm\(^2\). The hemispherical indenter has a rounded shape, which allowed the force to be distributed more evenly across the surface it impacts. The rounded shape reduced the concentration of force in a specific area, resulting in a smaller damage area. Furthermore, the hemispherical indenter has a larger contact area than the conical, flat, and elliptical indenters. The larger contact area allowed the force to spread out over a larger area, reducing localised damage. When tested with the flat indenter, the glass/epoxy laminate revealed a much larger impact area of 3546.99 mm\(^2\) than the other indenters. Damage assessment using ultrasonic C scan imaging reveals that the flat indenter caused more impact area damage than other indenters due to its large surface area. The impact damage caused by the elliptical indenter is quite low when compared to other indenters, owing to the indenter’s smaller contact area with the MWCNT/glass fibre epoxy laminates. Thus, it can be understood that the type of indenter and its geometry greatly influence the degrees of damage and impact area.

3.2. Tensile properties

The tensile stress-strain graph and tensile strength of MWCNT/glass fibre epoxy are shown in Fig. 8(a&b). For all the composites, the stress-strain response was linearly proportional until failure (Fig. 8a). The incorporation MWCNT in glass fibre epoxy laminate resulted in a significant enhancement in the ultimate tensile strength (Fig. 8b). The laminate composites exhibited an ultimate tensile strength ranging from 180 to 235 MPa, depending on the loading of MWCNTs. This represents a significant improvement over the glass fibre epoxy laminate, which had a tensile strength of ca. 171 MPa. Subsequent additions of MWCNTs, at different weight percentages, led to further increases in the tensile strength. The addition of 0.5 wt% MWCNTs resulted in ca. 6% increase in tensile strength. Furthermore, adding 1 wt%, 1.5 wt%, and 2 wt% MWCNTs resulted in ca. 9%, ca. 27%, and ca. 35% increase, respectively. These findings highlight the significant improvements in the
Fig. 6. Punch puncture shear strength of MWCNT/glass fibre epoxy laminates subjected to different indenters (a) Conical (b) Elliptical (c) Hemispherical (d) Flat.

Table 1
Energy absorption for MWCNT/glass fibre epoxy laminates.

<table>
<thead>
<tr>
<th>Indenter shape</th>
<th>MWCNT content (wt.%)</th>
<th>( P_{\text{max}} ) (kN)</th>
<th>Puncture Shear Strength (MPa)</th>
<th>Total Energy Absorption (J)</th>
<th>Specific Energy Absorption (J/g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conical</td>
<td>0</td>
<td>3986.42</td>
<td>42.93 ± 2.15</td>
<td>11.213 ± 0.56</td>
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<td>1</td>
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<tr>
<td></td>
<td>1.5</td>
<td>3823.61</td>
<td>45.745 ± 2.29</td>
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<tr>
<td>Elliptical</td>
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<td>1056.52</td>
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<td>Hemispherical</td>
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<td>24.43 ± 1.22</td>
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<td>12.636 ± 0.63</td>
<td>0.3855 ± 0.02</td>
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Fig. 7. Ultrasonic C scan image of 1.5 wt% MWCNT/glass fibre epoxy laminate subjected to conical indenter, elliptical indenter, hemisphere indenter and flat indenter.
mechanical properties of the MWCNT/glass fibre epoxy laminates achieved through the incorporation of MWCNT loadings. The addition of MWCNTs to the glass fibre epoxy laminate improved stress transfer and load-bearing capability, which contributed to the improved tensile strength. The strong interfacial bonding between MWCNTs and the epoxy matrix facilitated this, promoting effective load transfer and preventing crack propagation. Furthermore, MWCNTs’ inherent high stiffness and mechanical properties contributed to the overall stiffness and strength of the composite, as their rigid structure allows for efficient stress transfer and reinforces the composite, increasing its tensile strength. All of these beneficial properties of MWCNT were previously discussed in the literature [27–31].

3.3. Flexural strength

Fig. 9 shows the flexural properties of MWCNT/glass fibre epoxy laminates. Flexural strength increased as MWCNT loading increased from 0 to 2 wt%. The flexural strength of unfilled laminate was ca. 294 MPa, while the flexural strength of 2 wt% MWCNT/glass fibre epoxy laminate was ca. 361 MPa. The addition of 0.5 wt% MWCNTs resulted in ca. 11% increase in flexural strength. Similarly, the addition of 1 wt% MWCNTs increased flexural strength by ca. 16%. The addition of 1.5 wt % MWCNTs increased flexural strength by ca. 18%. The addition of 2 wt % MWCNTs increased flexural strength by ca.23% when compared to unfilled laminate. Within the composite laminate matrix, MWCNTs acted as secondary reinforcement agents and increased the bending resistance and overall flexural strength of the composite. The MWCNTs increased the material’s strength and stiffness, preventing crack propagation and improving load-bearing capacity. This was achieved through the increased interfacial adhesion between the matrix and the fibres in the laminate composite as a result of MWCNTs addition. This improved adhesion caused efficient load transfer between the matrix and the reinforcement, and reduced stress concentrations which developed because of the inhomogeneities or defects in the composite laminate, such as voids, delaminations, or fibre misalignments. Because of the stress concentration in GFRP composite laminates, local areas of weakness develop within the composite laminate, resulting in sudden failure and lower strength. However, in the MWCNT/glass fibre epoxy laminates, the MWCNTs in the matrix formed a strong network, assisting in distributing the applied load evenly throughout the laminate, reducing localized stress concentrations, and improving flexural strength.

3.4. Inter laminar shear strength (ILSS)

Fig. 10 shows the interlaminar shear strength variations for MWCNT/glass fibre epoxy laminates. The addition of MWCNTs improved the ILSS of the glass fibre epoxy laminate significantly. The ILSS of a glass fibre epoxy laminate was ca. 12 MPa, while the ILSS of a composite containing 2 wt% MWCNT was ca. 36 MPa, which was ca. 205% higher. When 0.5 wt% MWCNT was added, the ILSS increased by approximately 63%, while 1 wt% and 1.5% MWCNT addition increased the ILSS by ca. 113% and ca. 166%, respectively. The addition of MWCNTs improved the interfacial bonding between composite layers by adding contact points and increasing surface area for bonding. This improved interfacial bonding prevented interlaminar delamination and raised the composite’s ILSS. Furthermore, MWCNTs acted as crack arrestors within the composite structure, preventing crack propagation. MWCNTs connected the delamination interfaces and decreased crack deflection and branching, which helped to redistribute applied stresses

<table>
<thead>
<tr>
<th>Indenters</th>
<th>Damage Area (mm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conical</td>
<td>533.57 ± 26.68</td>
</tr>
<tr>
<td>Elliptical</td>
<td>577.56 ± 28.88</td>
</tr>
<tr>
<td>Hemisphere</td>
<td>491.37 ± 24.57</td>
</tr>
<tr>
<td>Flat</td>
<td>3546.99 ± 177.35</td>
</tr>
</tbody>
</table>

Table 2

Damage area of corresponding indenter.
4. Conclusion

This manuscript presented an analysis of puncture tests performed on MWCNT/glass epoxy laminate, with a focus on the influence of different indenter shapes on the quasi-static punch behaviour and failure characteristics. A significant increase in tensile strength of ca. 35% was observed on 2 wt% MWCNT/glass fibre epoxy laminate. The flexural strength of 2 wt% MWCNT/glass fibre epoxy laminate was ca. 360 MPa, exhibiting a substantial improvement of ca. 23% compared to glass fibre epoxy laminate. This increase in flexural strength highlights the effectiveness of MWCNT in enhancing the resistance to bending stresses. Furthermore, the ILSS of 2 wt% MWCNT/glass fibre epoxy laminate demonstrated a significant increase, reaching ca. 36 MPa, which corresponds to an impressive enhancement of ca. 205% compared to glass fibre epoxy laminate. This improvement in interlaminar shear strength was attributed to the enhanced interfacial bonding between composite layers facilitated by the presence of MWCNTs. The MWCNTs act as bridge-like structures, connecting the interfaces and inhibiting interlaminar delamination. The puncture test results revealed that the indenter characteristics significantly influence the puncture behaviour and failure modes of the composite materials. Different indenter shapes resulted in variations in the force-displacement response during the puncture loading. Additionally, the incorporation of MWCNTs into the epoxy matrix led to enhanced mechanical properties, such as increased tensile strength, flexural strength, interlaminar shear strength, puncture resistance, and improved energy absorption capabilities. The reported results can assist in the design of composite structures, enabling the development of advanced composites with improved puncture resistance for various engineering applications.

CRediT author statement


Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

References


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