Experimental Investigation of the Three-Point Bending Property of a Sandwich Panel with a Metal Rubber Core

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Abstract: Sandwich structures and porous materials have been applied widely in various fields due to their excellent mechanical performance, and multifunctional composites will have a significant engineering demand in the future. Studying damped composites' mechanical properties and failure forms has significant engineering value and significance. However, the current connecting processes for sandwich panels and porous materials must be improved. Therefore, to explore the ambiguity of the connection interface between the core material and panel in sandwich panels, as well as the mechanical properties of such structures, a sandwich panel with a metal rubber core material was prepared using vacuum brazing and cementing processes. Microscopic examinations using scanning electron microscopy and energy-dispersive spectroscopy were conducted to observe the physical bonding mechanism at the interface of the sandwich panel. The results indicate that the brazed sandwich panels exhibited a more uniform and continuous interface than the cemented sandwich panels. This work designs three-point bending compression experiments to investigate the effects of core material thickness, density, and preparation process on the bending mechanical properties of the sandwich panel. Failure modes of the sandwich panel during the experiments are analyzed. The experimental results show that the failures of the brazed sandwich panels are attributable to the bending deformation of the panel and the shear failure of the metal wire core material. The cemented sandwich panels exhibit separation failures in the area below the indenter and at both ends of the panel. The core material's thickness and density significantly influence the bending performance of the sandwich panels. An increase in the core material's thickness and density effectively enhances the sandwich panels' peak load and energy absorption capacity.

Keywords: metal rubber; sandwich panel; bending failure modes; mechanical property

1. Introduction

Composite materials typically consist of two or three distinct components, each with unique properties and structures. These composites combine the characteristics of their constituents and exhibit properties not present in the original materials, leading to broader applications than single metals. The raw material for metal rubber is a specific metal wire characterized by resistance to high or low temperatures, corrosion, and impact. The interior of metal rubber has a spatial structure where metal wires are interwoven and interlocked [1,2]. Metal rubber products inherit the inherent properties of metal wire and exhibit elasticity and damping properties similar to rubber-like polymer materials. They enhance reliability and environmental adaptability and have been successfully applied in various fields, such as aerospace and biomedicine [3–5].

Recent scholarly interest has focused on exploring metal rubber composite structures. Zheng et al. [6] investigated a composite of entangled metallic wire and polyurethane, utilizing metallic wire as the matrix and polyurethane for reinforcement. Their dynamic mechanical tests indicated superior mechanical performance in the composite compared...
to the pure material. Tan et al. [7] prepared aluminum-based reinforced metal rubber composites using casting. Their research results showed the reinforcing material has good adhesion with the interface of an aluminum-based matrix, and the composite structure effectively enhances the yield strength of metal rubber composites. Zhang et al. [8] analyzed the damping characteristics and electrical conductivity of the metal rubber materials of the copper–steel double-helix composite structure. The static experiment results found that a high weight ratio of copper wire to steel wire has a greater energy dissipation capacity and lower stiffness, and the electrical conductivity decreases with the increase of the weight ratio. Li et al. [9] prepared 304/Mg reinforced composite metal rubber using a percolation casting process. The compressive experiments indicated that the strength and elastic modulus of the composite material were 42.8% and 55.6%, which were higher than pure Mg.

Sandwich structures have been used in aerospace applications since the 1960s because of their light weight, high strength, and excellent stability. The mechanical properties of sandwich panels are closely related to the core material. Therefore, the use of metal rubber material with high damping and high reliability as the core material gives the sandwich structure broad prospects in the field of vibration damping. Sandwich structures are typically composed of two high-strength panels and a core. A variety of porous materials, such as pyramid cores [10], lightweight lattice cores [11], corrugated cores [12], foam cores [13–15], and honeycomb cores [16–18], are commonly used in the core layer. Xin et al. [19] successfully prepared foam aluminum sandwich panels using an epoxy resin adhesive. Huang et al. [20] fabricated foam sandwich structures through ultrasonic torsional brazing and experimentally demonstrated the feasibility of the brazing process. Zhang et al. [21] also used brazing to make foam aluminum sandwich structures, studying the microstructure, mechanical properties, and fracture behavior of the brazing interfaces. Currently, various experimental methodologies are available to assess the mechanical properties of sandwich structures, which can be categorized as bending experiments (including three-point and four-point bending), compression experiments, tension experiments, and dynamic impact and fatigue experiments [22]. Sandwich panel structures have multiple failure modes when subjected to bending load. Yang et al. [23] conducted three-point bending experiments to analyze the bending properties, bending failure modes, and stiffness degradation modes of a sandwich beam structure consisting of glass fiber-reinforced polymer planes. Wang et al. [24] adopted numerical analysis methods to explore the bending performance of a new type of ceramic sandwich panel structure. The results indicated that the bending performance of the sandwich panel dramatically depends on its geometric structure. Fang et al. [25] revealed the impact resistance of the graded and uniform sandwich beams subjected to high-velocity impacts. The experimental results showed that the impact resistance of graded sandwich beams is significantly better than that of uniformly sandwiched beams at low-speed impacts. Xia et al. [26] manufactured sandwich panels with corrugated pyramidal lattice cores using 3D printing, exploring their mechanical performance under compression and bending.

The current connection processes for metal panels and porous materials are mainly physical connection and metallurgy. Physical connection includes bolting, riveting, gluing, and other processes; metallurgical bonding includes vacuum brazing, electron beam welding, laser pulse welding, and other methods. Physical connection is simple to operate, and the product process precision is high, but it is easy to destroy the core structure under alternating load [14]. The welded connection has high energy density and high production efficiency but will have problems such as more joint cracks and low strength [21]. Therefore, it is significant for its engineering application to adopt a suitable joining process to obtain composite sandwich structures with excellent interfacial properties and accurately predict the failure behavior of sandwich structures under various complex loads. Currently there are few studies on sandwich structures with metal rubber cores, and there will be a large engineering demand for such multifunctional composites in the future. Therefore,
the study of the mechanical properties and failure mechanisms of sandwich panels with metal rubber cores possesses important engineering value and significance.

Based on the structural characteristics of metal rubber, this study introduces a novel sandwich panel with a metal rubber core. The proposed panel integrates the core’s cushioning, vibration reduction, high damping, and impact energy absorption qualities while maintaining the sandwich structure’s inherent strength and stiffness. In this paper, vacuum brazing and cement processes were used to prepare sandwich panels with metal rubber cores. The physical mechanisms of the interfacial bonding of the sandwich structure were investigated by using SEM and EDS. Through three-point bending experiments, the failure mode of the sandwich panels and the influence of structural parameters on their mechanical properties were investigated. It provides an experimental basis and scientific guidance for the structural design of metal rubber composite sandwich panels and improvement of the interface quality of the sandwich structure.

2. Preparation of Sandwich Panel with Metal Rubber Core

2.1. Preparation of the Core Material

The core material is made of 304 (06Cr19Ni10) stainless steel wire with a diameter of 0.3 mm. 304 stainless steel possesses excellent comprehensive mechanical properties, including corrosion resistance, oxidation resistance, and processability. Table 1 lists the performance parameters of the raw material, 304 stainless steel.

<table>
<thead>
<tr>
<th></th>
<th>Fe</th>
<th>Ni</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>S</th>
<th>P</th>
<th>Cr</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Spare</td>
<td>8.01%</td>
<td>≤0.08%</td>
<td>≤1.00%</td>
<td>≤2.00%</td>
<td>≤0.03%</td>
<td>≤0.035%</td>
<td>17.12%</td>
</tr>
</tbody>
</table>

The density and thickness of the metal rubber components influenced the mechanical properties of the core material, including the spring diameter and winding angle of the helical coils. The preparation process of the core material is shown in Figure 1.

Figure 1a shows the winding of the metal wire into a spiral coil using CNC coreless-axis spiral winding equipment. The diameter of the spiral coil, when maintained within a range of 5 to 15 times the diameter of the metal wire, ensures that the metal wire inside the metal rubber products forms a stable interlocking and biting state. Accordingly, the diameter of the spiral coil wound in this work was 3 mm [4]. The spiral coil underwent equal pitch stretching after winding, which ensured the pitch after stretching was approximately equal to the diameter of the spiral coil, effectively improving the uniformity of the quality of the blank. In this study, CNC automatic metal rubber blank winding equipment, as shown in Figure 1b, was used to wind the stretched spiral coil into a blank at a fixed angle on the core shaft of the equipment. Cold stamping involves placing the metal rubber blank into a pre-designed mold and forming it under a certain pressure. The structure of the designed mold and the cold stamping equipment are shown in Figure 1c. This study primarily focuses on the mechanical properties of sandwich panels with metal rubber cores, disregarding the influence of the working environment. Thus, no post-processing step was conducted after the cold stamping forming process.
2.2. Sandwich Panel/Core Connection Process

The quality of the connection between the panel and the core material directly affects the mechanical properties of the sandwich panel. To address the problem of unclear interface connection performance in sandwich panels with metal rubber cores, vacuum brazing and cementing processes were adopted for connecting the panel to the core material.

2.2.1. Vacuum Brazing Process

The core material and panel of the sandwich structure in this work were made of 304 stainless steel. BNi-2 was selected as the brazing material to ensure the stability of the brazed joints. Chromium (Cr) in the brazing material enhances its oxidation and corrosion resistance. Boron (B) and Silicon (Si) reduce the melting point, and the addition of iron (Fe) improves the strength of the brazing interface. The chemical composition of the brazing material is shown in Table 2.
An oxidation film commonly forms on metal surfaces, especially in high-temperature environments, affecting the mechanical properties of the brazing interface. Thus, it is necessary to remove the oxidation film from the metal surface before brazing. Ultrasonic cleaning technology was employed to remove the oxidation film from the metal surface and to prevent the deformation of the core material. Finally, the vacuum oven was used to dry the brazed material after cleaning. The vacuum high-temperature furnace was then used for brazing samples. The solidus temperature of the BNi-2 brazing material is 970 °C, and the liquidus temperature is 1000 °C. Hence, the brazing temperature in this work was set at 1050 °C, considering that the optimal brazing temperature should be between 1010–1170 °C [13]. The heating rate during the brazing process not only affects the melting temperature of the brazing material but also influences the size and thermal conductivity. Therefore, the brazing duration was set to 2 h. After the brazing process was completed, a holding duration was necessary for homogenizing the brazing and enhancing the strength of the brazing interface. The selected holding duration was 0.5 h. The sample was then cooled to 150 °C to improve the brazed structure and mechanical properties of the brazing.

2.2.2. Cementing Process

The process for preparing a cemented sandwich panel was similar to vacuum brazing. Three preprocesses were conducted before the cementing process:

(a) The surface of the panel was preprocessed by sequentially using abrasive paper of varying grits (600#, 800#, 1000#, 1500#, 2000#, 2500#);
(b) The adhesion between the panel and the core material was facilitated by using ultrasonic cleaning;
(c) The panel was cleaned with industrial ethanol to remove surface residues and oil stains.

Figure 2 illustrates the use of JL-101 high-temperature resisting metallic adhesive in the cementing process. This adhesive, mixed with components A and B in a ratio of 2:1 as per the manufacturer’s instructions, ensured uniform color and consistency. The parameters of JL-101 metallic adhesive are listed in Table 3.

![Figure 2. Cementing process: (a) JL-101 metallic adhesive; (b) WDW-T200 electronic universal testing machine; (c) process result.](image-url)
Following the completion of all pre-processes, the prepared metallic adhesive was first applied evenly to both the panel and the core material. This application facilitated a slow and even bonding between the panel and the core material. The metallic adhesive was then applied to the underside of the core material. Subsequently, the panel was placed on the WDW-T200 electronic universal testing machine (Jinan Tianchen Testing Machine Manufacturing Co., Ltd., Jinan, China), applying a compressive load of 1 kN for 6 h. The other side of the panel underwent the same bonding process.

### 3. Experimental Procedures

This study examined the bending properties and characteristics of sandwich panels with a metal rubber core through a three-point bending (TPB) experiment, with a focus on the impact of core material thickness, density, and preparation process on the bending properties. Additionally, the failure modes of the sandwich panels were analyzed. The parameters for the various specimens are presented in Table 4. Figure 3 shows the setup of the three-point bending experiment system. The dimensions of the panel are 130 mm in length and 45 mm in width. The upper loading head and the two supporting heads each have a diameter of 30 mm. The distance between the two supporting heads and the ends of the specimen is 30 mm.

### Table 3. Parameters of JL-101 metallic adhesive.

<table>
<thead>
<tr>
<th>Density (g/cm³)</th>
<th>Compressive Strength (MPa)</th>
<th>Tensile Strength (MPa)</th>
<th>Shear Strength (MPa)</th>
<th>Operating Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.64</td>
<td>87.6</td>
<td>26.8</td>
<td>19.8</td>
<td>–60–300</td>
</tr>
</tbody>
</table>

### Table 4. Parameters of specimens for the three-point bending experiment.

<table>
<thead>
<tr>
<th>Specimen No.</th>
<th>Length/mm</th>
<th>Width/mm</th>
<th>Core Density (kg/m³)</th>
<th>Core Thickness/mm</th>
<th>Preparation Process</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1-1</td>
<td>180</td>
<td>45</td>
<td>1.43</td>
<td>5</td>
<td>Brazing</td>
</tr>
<tr>
<td>B1-2</td>
<td>180</td>
<td>45</td>
<td>1.79</td>
<td>5</td>
<td>Brazing</td>
</tr>
<tr>
<td>B1-3</td>
<td>180</td>
<td>45</td>
<td>2.14</td>
<td>5</td>
<td>Brazing</td>
</tr>
<tr>
<td>B1-4</td>
<td>180</td>
<td>45</td>
<td>2.50</td>
<td>5</td>
<td>Brazing</td>
</tr>
<tr>
<td>B2-1</td>
<td>180</td>
<td>45</td>
<td>2.14</td>
<td>3</td>
<td>Brazing</td>
</tr>
<tr>
<td>B2-2</td>
<td>180</td>
<td>45</td>
<td>2.14</td>
<td>4</td>
<td>Brazing</td>
</tr>
<tr>
<td>B2-3</td>
<td>180</td>
<td>45</td>
<td>2.14</td>
<td>5</td>
<td>Brazing</td>
</tr>
<tr>
<td>B2-4</td>
<td>180</td>
<td>45</td>
<td>2.14</td>
<td>6</td>
<td>Brazing</td>
</tr>
<tr>
<td>B3-1</td>
<td>180</td>
<td>45</td>
<td>2.14</td>
<td>3</td>
<td>Cementing</td>
</tr>
<tr>
<td>B3-2</td>
<td>180</td>
<td>45</td>
<td>2.14</td>
<td>4</td>
<td>Cementing</td>
</tr>
<tr>
<td>B3-3</td>
<td>180</td>
<td>45</td>
<td>2.14</td>
<td>5</td>
<td>Cementing</td>
</tr>
<tr>
<td>B3-4</td>
<td>180</td>
<td>45</td>
<td>2.14</td>
<td>6</td>
<td>Cementing</td>
</tr>
</tbody>
</table>

Figure 3. Three-point bending experiment system.
4. Results and Discussion

To assess the connection quality before conducting experiments, the brazing (adhesive) rate and connection between the panel and core material were observed. Scanning electron microscopy (SEM) and energy-dispersive spectroscopy were adapted to analyze the sandwich structure prepared through brazing and cementing.

4.1. Panel/Core Material Connection Quality Inspection

4.1.1. Energy-Dispersive Spectroscopy

The steps of energy-dispersive spectroscopy are as follows:

(a) The sandwich structure was cut along the direction perpendicular to the brazing interface using laser cutting technology;

(b) Epoxy resin served as the inlay material for preparing EDS specimens of sandwich panels through cold inlay;

(c) The EDS specimens were polished with abrasive paper of varying grits (600#, 800#, 1000#, 1500#, 2000#, 2500#).

A polishing machine was used to remove the abrasive marks left after fine grinding and ultrasonic cleaning of the specimens. Figure 4 shows the metallographic organization of the brazed joints of the sandwich panel. The micro-morphology of the panel and metal wire as a whole at the brazing interface of the sandwich panel is shown in Figure 4a. The connection at the brazing interface between the panel and the metal rubber was smooth and continuous. The BNi-2 brazing material demonstrated the brazing material filled the brazed interface after melting at high temperatures. The use of BNI-2 brazing material for brazing the sandwich panel yielded excellent results. As depicted in Figure 4b, some air holes and trachomas were observed in the brazed line, possibly due to the incomplete removal of the oxide film on the metal surface during the pre-treatment of the material. Despite this, the brazed joints of the sandwich panels formed an effective metallurgical bond.

![Figure 4](image_url)

Figure 4. Brazed joint microstructure of sandwich panel: (a) brazing interface; (b) brazed line.

4.1.2. Scanning Electron Microscopy Analysis

The raw materials for both the panel and core material were SUS304, resulting in a significant difference in the atomic number compared to the adhesive JL-101. This contrast facilitated the observation of the interface morphology of the sandwich panel and the distribution of different components within the interface using scanning electron microscopy. The interface morphology of the sandwich panel, prepared by cementing, is depicted in Figure 5. An adhesive layer was present between the panel and the core material, with the adhesion between them achieved through the cohesive force of the adhesive. Figure 5a shows many metal wires connected to the panel through the adhesive layer. However, Figure 5b shows only a few metal wires connected in this manner. During preparation, the metallic adhesive was coated on the surfaces of the panel and core material. However, the adhesive filling between the panel and metal wires was incomplete, leading to a stratification phenomenon.
4.2. Failure Analysis of Three-Point Bending Experiment

4.2.1. Sandwich Panel with Metal Rubber Core Prepared by Vacuum Brazing Process

During three-point bending experiments, the failure process of the brazed specimen is shown in Figure 6. As the downward displacement of the upper load head continues to increase to contact the upper panel of the specimen, structural deformation initiates. The upper panel initially experiences force, followed by the core material, which also undergoes elastic deformation. Figure 6b shows that as load head displacement increases, the sandwich panel begins to bend, and the core material positioned between the upper and lower panels starts to experience shear forces. Subsequently, cracks develop in the core material below the load head on both sides, progressing upward as loading displacement intensifies, as shown in Figure 6c. Finally, the sandwich panel fails, as depicted in Figure 6d.

Throughout this process, the loads experienced by various structures of the brazed specimens are as follows:

(a) The upper panel primarily bears the compression load applied by the loading indenter and the lateral compression load generated by the bending deformation of the specimen;
(b) The lower panel mainly withstands the lateral tensile load resulting from the bending deformation of the specimen;
(c) The core material bears the shear load generated by the bending deformation of the specimen, as well as the compression load in the vicinity of the loading point.

Therefore, the failure mode of the brazed specimen involves the bending of panels and the shear failure of the metal wire within the core material.
4.2.2. Sandwich Panel with Metal Rubber Core Prepared by Cementing Process

Figure 7 illustrates the failure process of the sandwich panel, prepared using the cementing process, during a three-point bending experiment. Initially, the upper panel of the sandwich structure deforms, creating indents under the applied load, as shown in Figure 7b. With further displacement of the upper load head, the metal rubber materials at the extremities begin to detach from the upper panel due to shear forces, as depicted in Figure 7c. The detachment area of the core material from the upper panel expands with increasing loading displacement until the failure of the sandwich panel occurs.

![Figure 7. Failure process of the cemented sandwich panel: (a) non-deformation; (b) bending; (c) starting to separate; (d) full separation.](image)

Furthermore, Figure 8 illustrates four typical failure modes observed in the cemented specimens during this experiment: panel yielding, panel wrinkling, shear failure of the core material, and separation between the panel and the core material. The occurrence of a specific failure mode depends on various factors, including the ratio of panel thickness to core material thickness, the tensile strength of the core material, and the adhesive quantity. As demonstrated in Figure 8a,b, the core material experiences tensile and shear stresses, which progressively intensify the shear failure as the load head moves downward, eventually causing the panel wrinkling. In contrast, the specimen in Figure 8c fails at the loading point, where the panel yields but remains attached. Figure 8d displays a failure mode characterized by detachment at both ends, occurring when the plastic hinge forms near the support points.

![Figure 8. Typical failure modes of the cemented sandwich panel: (a) localized separation between the core material and the bottom panel; (b) panel wrinkling; (c) panel yield; (d) separation between the panel and the core material.](image)
4.3. Analysis of Experiment Results
4.3.1. Effect of Core Density on Three-Point Bending Performance

To investigate the effect of core material density on the bending resistance characteristics of sandwich panels while maintaining other structural parameters constant, three-point bending experiments were conducted on specimens with metal rubber core densities of 1.43 g/cm³, 1.79 g/cm³, 2.14 g/cm³, and 2.50 g/cm³, respectively. Figure 9 shows the force-displacement curve for specimens of four different densities. The curves for varying core densities show a similar trend. Initially, the load force increases nearly linearly. After reaching its peak, the load force stabilizes with minimal variation, and the sandwich panel predominantly exhibits a damping effect at this stage.

![Force-displacement curve](image)

Figure 9. Force-displacement curves of the brazed sandwich panels with metal rubber cores having different core material densities.

Figure 10 illustrates the bending peak load, total energy absorption, and specific energy absorption (energy absorbed per gram) for specimens with four different core material densities. The bending peak loads for the specimens with the four core densities are 1.456 kN, 1.524 kN, 1.670 kN, and 1.769 kN. The total energy absorptions are 41.572 J, 43.480 J, 49.190 J, and 49.590 J. The specific energy absorptions are 1.039 J/g, 0.869 J/g, 0.819 J/g, and 0.704 J/g, respectively. It is concluded that as the core material density increases, the peak load and the total energy absorption of the specimens rise, whereas the specific energy absorption decreases.

![Force and energy absorption](image)

Figure 10. Three-point bending experiment of brazed sandwich panels with different core densities: (a) bending peak load; (b) total energy absorption; (c) specific energy absorption.

Increasing the density of core material reduces the internal pores within the metal rubber core while maintaining a constant volume, thereby enhancing the stiffness of the core (peak load). As the density of the core material increases, the dry friction within the core material also increases, enhancing the core material’s ability to absorb energy. In thin-panel sandwich structures, the core material’s weight forms a considerable portion of the total weight. Consequently, as the density of the metal rubber increases, there is a significant rise in the overall weight of the sandwich panel, although the improvements in peak load and energy absorption are relatively small. As a result, the peak load and total
energy absorption of the sandwich panel increase with the density of the core material, but the specific energy absorption decreases accordingly.

4.3.2. Effect of Core Thickness on Three-Point Bending Performance

In this work, four core thicknesses (3 mm, 4 mm, 5 mm, and 6 mm) were selected for the three-point bending experiments, keeping all other structural parameters constant. Figure 11 illustrates the force-displacement curves for sandwich panels with different thicknesses. The trends across the four curves are generally consistent.

![Figure 11. Force-displacement curves of brazed specimens with different core material thicknesses.](image)

Figure 12 shows the peak load, total energy absorption, and specific energy absorption for specimens with the four different core thicknesses. The peak bending loads for the specimens with core thicknesses of 3 mm, 4 mm, 5 mm, and 6 mm were 1.219 kN, 1.387 kN, 1.670 kN, and 2.200 kN, respectively. The total energy absorptions were 34.78 J, 39.66 J, 49.19 J, and 58.91 J, while the specific energy absorptions were 0.791 J/g, 0.662 J/g, 0.657 J/g, and 0.655 J/g, respectively.

![Figure 12. Three-point bending experiment results for brazed specimens with different core thicknesses: (a) bending peak load; (b) total energy absorption; (c) specific energy absorption.](image)

Analysis of the graph reveals that as core thickness increases, both the peak load and total energy absorption of the specimens also increase, while the specific energy absorption decreases. This trend occurs because the size of the specimen cross-section affects the distribution of stress levels in the panel. Under identical loading conditions, sandwich panels with thinner cores exhibit a more concentrated stress level distribution compared to those with thicker cores. Therefore, sandwich panels with smaller metal rubber core heights demonstrate a lower load-bearing capacity and are more susceptible to failure.

4.3.3. Effect of Connection Process on Three-Point Bending Performance

Figure 13 illustrates a comparison of force-displacement curves for sandwich panels with four core thicknesses (3 mm, 4 mm, 5 mm, and 6 mm) produced using two different preparation processes. These curves depict distinct trends in the load-displacement relationship. For the brazed specimen, the load increases linearly at the initial stage of displacement loading. It then reaches a peak and maintains a relatively high level. In
contrast, the cemented specimen also experiences a linear increase in load during the initial loading stage. However, due to the presence of the adhesive layer, the cemented specimen exhibits a higher bending stiffness than the brazed specimen. The load then reaches a peak and maintains for a short period before plummeting, indicating that the cemented specimen has failed under compression. The maximum deformation ranged from 10 cm to 15 cm for cemented specimens, and the maximum deformation was more than 30 cm for vacuum brazing specimens.

![Figure 13](image)

Figure 13. Force-displacement curves of brazed and cemented sandwich panels: (a) thickness = 3 mm; (b) thickness = 4 mm; (c) thickness = 5 mm; (d) thickness = 6 mm.

Figure 14 presents a comparison of the peak load, total energy absorption, and specific energy absorption of sandwich panels prepared using both cementing and brazing processes. The graph shows that the trend of changes in core thickness is similar for specimens produced by both methods. The bending peak loads for specimens prepared with the two processes are relatively similar. However, the brazed specimen demonstrates significantly higher total and specific energy absorption compared to the cemented specimen. This difference can be attributed to variations in failure modes observed during three-point bending experiments. The brazed specimens mainly fail due to the yielding of the panel and shear failure of the core material, which is a progressive failure process, and the load remains stable with the increase in load. In contrast, the cemented specimens experience a separation between the panel and core material. Once the layers separate, the sandwich panel fails suddenly and completely, resulting in a sharp drop in load and a loss of load-bearing capacity for cemented specimens.

![Figure 14](image)

Figure 14. Three-point bending experiment results for brazed sandwich panel with different preparation processes: (a) bending peak load; (b) total energy absorption; (c) specific energy absorption.
5. Conclusions

In this study, sandwich panels containing metal rubber cores were prepared using vacuum brazing and cementing processes. The failure processes and modes of the sandwich panels under three-point bending experiments were analyzed. The influences of structural parameters (thickness and density of the core material) and preparation processes on mechanical properties were investigated. The main findings of this study are as follows:

1. EDS and SEM analyses showed that the connection interface in the brazed specimen is more uniform and continuous compared to that in the cemented specimen. There is a noticeable diffusion of Ni and Si elements in the brazing filler metal, as well as Fe and Cr elements in the core material and panel, resulting in a superior metallurgical bond;

2. The results of the three-point bending experiments indicate that the top panel of the sandwich panel primarily bore compressive loads applied by the load head, along with lateral compressive loads caused by structural deformation. The bottom panel mainly experiences lateral tensile loads due to structural deformation, while the metal rubber core material endures shear loads resulting from structural deformation. The failure of the brazed specimen is characterized by panel bending and the shear failure of internal metal wires within the core material, whereas the cemented specimen experiences separation failure at both ends;

3. The thickness and density of the core material significantly influence the three-point bending performance. Increasing the thickness and density of the core material effectively improves the peak load and energy absorption capacity of a sandwich panel with a metal rubber core. With the density of the metal rubber core increasing from 1.43 g/cm$^3$ to 2.50 g/cm$^3$, the bending peak load enhances from 1.456 kN to 1.769 kN, the total energy absorptions rise from 41.572 J to 49.590 J, while the specific energy absorptions decrease from 1.039 J/g to 0.704 J/g. As the thickness of the metal rubber core increases from 3 mm to 6 mm, the bending peak load enhances from 1.219 kN to 2.200 kN, the total energy absorptions rise from 34.78 J to 58.91 J, while the specific energy absorptions decrease from 0.791 J/g to 0.655 J/g. The brazed specimen demonstrates significantly higher total and specific energy absorption compared to the cemented specimen with the same structural parameters.

Author Contributions: Conceptualization, W.Z.; methodology, S.W.; formal analysis, W.Z.; writing—original draft preparation, W.Z.; writing—review and editing, X.Z. and X.X.; supervision, X.X.; project administration, X.X. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: The data presented in this study are available on request from the corresponding author. The data are not publicly available due to non-disclosure of data.

Conflicts of Interest: The authors declare no conflict of interest.

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