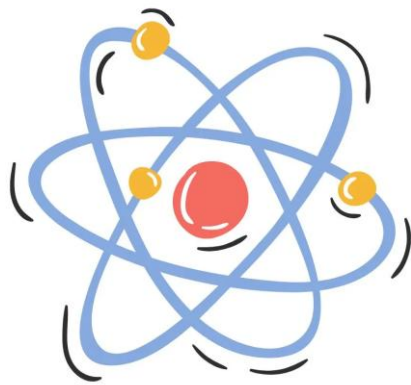




ISSN: 1672 - 6553

JOURNAL OF DYNAMICS AND CONTROL

VOLUME 10 ISSUE 08:P22-40

DEVELOPMENT AND MECHANICAL CHARACTERIZATION OF IRON OXIDE NANOFILLER REINFORCED POLYURETHANE FOAM-GLASS FIBER SANDWICH COMPOSITES

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Abstract: This study focuses on the development and mechanical characterization of Iron Oxide Nanofiller Reinforced Polyurethane Foam Glass Fiber (INPGF) sandwich panels. Two sets of panels-without and with varying iron oxide filler contents (1-5 wt. %) were fabricated using a hand lay-up process with Polyurethane (PU) foam cores and glass fiber face sheets. The influence of ferric oxide (Fe_2O_3) on the panels' mechanical performance was experimentally evaluated through three-point bending, flatwise compression, edgewise compression, and drop-weight impact tests. Results reveal that increasing iron oxide content enhances bending strength, compressive resistance, and impact energy absorption, with 3-5 wt% providing the best balance between stiffness and toughness. The incorporation of Fe_2O_3 nanoparticles improves stress transfer, interfacial bonding, and crack resistance within the foam core, significantly increasing load-bearing capacity and damage tolerance. These findings demonstrate the potential of INPGF sandwich composites for lightweight structural applications in the aerospace, automotive, and defense sectors, where enhanced impact resistance and mechanical strength are crucial.

Keywords: Iron Oxide (Fe_2O_3) Nanofiller, Polyurethane Foam Core, Impact Energy Absorption, Stress Transfer & Interfacial Bonding

1. Introduction

The development of high-performance lightweight materials is a growing focus in structural engineering, aerospace, automotive, and marine industries. In particular, polymer sandwich panels have garnered significant interest due to their excellent strength-to-weight ratio, energy absorption, wear resistant, absorb impacts and design flexibility [1]. These sandwich structures typically consist of two stiff face sheets and a lightweight core. While face sheets provide structural stiffness carrying in-plane and bending loads, the core contributes to impact absorption, insulation, withstand shear forces, overall stiffness and dimensional stability [2]. However, achieving the right balance of mechanical performance and weight reduction remains a critical challenge, especially when subjected to various static, dynamic, impact and fatigue loading [3].

Polyurethane (PU) foam is a widely used core material owing to its low density and ease of fabrication. Its mechanical limitations, such as low compressive and flexural strength, restrict its broader use in load-bearing or protective structural applications [4]. To overcome this, the incorporation of inorganic fillers has been shown to significantly enhance the mechanical behavior of polymer matrices [5]. Among these, ferric oxide (Fe_2O_3) stands out due to its hardness, thermal stability, biocompatibility, availability and cost-effectiveness [6].

Ferric oxide particles act as reinforcement agents that improve stress distribution, thermal stability and delay crack propagation when incorporated into polymer matrices [7]. When used in foam cores, Fe_2O_3 improves compressive strength, rigidity, and load-bearing capacity while maintaining foam characteristics like low density and energy absorption [8]. Several studies confirm that varying the particle size, dispersion technique, and filler loading significantly affects the mechanical response of these composites [9].

The microstructure of Fe_2O_3 -reinforced polymer composites plays a key role in determining their mechanical properties. A uniform dispersion of Fe_2O_3 particles leads to effective stress transfer, improved mechanical properties and thermal and electrical conductivity, resistance to localized deformation [10]. Conversely, agglomeration of particles leads to stress concentration zones, variation in density, lower impact resistance, increased brittleness, reducing mechanical performance [11]. Hence, optimized processing methods such as high-speed mechanical stirring, ultrasonication, and surface treatment of fillers are employed to improve dispersion [12].

Recent research emphasizes the importance of optimizing filler content. A lower concentration may not significantly influence mechanical strength, while an excessively high concentration may lead to poor processability and embrittlement [13]. Studies suggest that a ferric oxide content between 5–15 wt.% tends to yield the best compromise between mechanical enhancement and material workability [14].

Furthermore, when used in sandwich panel construction, ferric oxide-reinforced foams enhance not only the compressive and flexural strength, but also impact resistance and fatigue durability [15]. This makes them suitable for applications where resistance to repeated loading enhancing ability to resist crack initiation and propagation under cyclic loading and long-term durability are vital [16]. For example, in automotive crash panels or aerospace flooring, such composites offer enhanced safety marine applications and structural reliability without increasing overall mass [17].

Despite the promising progress, comprehensive studies focusing specifically on Fe_2O_3 -nanoparticles reinforced sandwich panels are still limited. Most existing works investigate isolated mechanical tests, often without exploring the synergistic effects of core and skin material combinations [18]. There is also a gap in understanding how foam density, filler-matrix bonding, and panel configuration influence overall panel performance under complex loading conditions [19].

The objective of this study is to develop ferric oxide-reinforced nanofiller reinforced polyurethane foam-glass fiber laminate sandwich panels and systematically analyze optimizing the Fe_2O_3 content, studying its influence on flexural, compressive and impact properties. The findings aim to contribute to the body of knowledge in advanced composite development and support the engineering of next-generation lightweight structures.

2. Experimental Studies

2. 1. 1. Material Selection

The materials selected for the fabrication of the composite sandwich panels were chosen based on their mechanical performance, compatibility, and availability. The face sheets of the sandwich structure were developed using glass fiber laminates, which provide excellent tensile strength and stiffness carrying in-plane and bending loads. For this purpose, glass fiber mats, epoxy resin (LY556), and hardener (HY951) were used. A Mylar sheet served as the surface separator, and mold release wax ensured easy demolding during the laminate curing process. The core of the sandwich panel was constructed using PU foam, selected for its low density, energy absorption properties with standing shear force, overall stiffness, insulation and dimensional stability. The PU foam was synthesized using commercially available polyol and isocyanate in a wooden mold, allowing free expansion. To enhance the mechanical properties of the foam, varying concentrations of ferric oxide (Fe_2O_3) as reinforcement were incorporated during the mixing stage. A magnetic stirrer was used to ensure uniform dispersion of the filler within the polymer matrix.

2. 1. 2. Fabrication of Glass laminates

The fabrication of glass laminates commenced by cutting glass fiber mats into square pieces of 210 mm × 210 mm. A Mylar sheet was placed on a flat surface and coated with mold-releasing wax to facilitate easy removal of the laminate after curing. The glass fiber to epoxy resin ratio

was maintained at 60:40 by weight. The epoxy resin (LY556) and hardener (HY951) were mixed thoroughly in a 10:1 weight ratio using a mechanical stirrer to ensure uniform blending. The resin mixture was then uniformly impregnated to each layer of glass fiber, a total of three layers were stacked by hand layup technique, then subjected to vacuum bagging, a process that removes trapped air and ensures better fiber wet-out and compaction. The entire assembly was left to cure at room temperature for 24-48 hours under vacuum pressure, resulting in high-quality, void-free glass fiber laminates. Post-curing at an elevated temperature may be necessary to further enhance the mechanical properties (at 60° for 20 mins).

2. 1. 3. Fabrication of polyurethane foam

To create the PU foam, start by setting the wooden dye, measuring 193x189x22 mm, on the table. Weigh 40 grams of polyol and 40 grams of isocyanate that is in a 1:1 ratio. Add the predetermined iron oxide amount to the polyol, stirring until it's well-mixed using a magnetic stirrer. Then, combine the isocyanate and continue stirring until the mixture starts to foam. Pour the solution into the dye, seal it tightly, and leave it for 30 minutes before removing it.

2. 1. 4. Fabrication of Sandwich structure

The foam and glass sheet laminates were both cut to their specified dimensions. The epoxy resin, previously prepared, served as the bonding agent between the glass laminates and the foam (bonding the foam core between two layers of the glass laminate). This assembly underwent a 12-hour pressurization at 10 bar using a hot press. Once the sandwich structure was cured, all sharp edges were ground to maintain standard dimensions for subsequent mechanical characterization.

2. 2. Mechanical Characterization

2. 2. 1. Flexural (three-point bending) test

The flexural test specimen, conforming to ASTM D7249 standards, was shaped to dimensions of 150 mm x 50 mm x 25 mm. Utilizing a Universal Testing Machine (UTM), three-point loading bending tests were performed. The load was gradually applied at a rate of 0.1 mm/s until the specimen fractured, and the resulting data was directly collected from the UTM and transferred to a desktop using TrapeziumX software.

2. 2. 2. Flatwise compression test

The flatwise compression strength test of sandwich structures was conducted ASTM C365/C365M and cubic specimen dimensions were 25mm X 25mm X 25 mm. The specimens were secured in the grip with proper alignment and uniform rate of 0.1 mm/s. conduct the test on three specimen and obtain an average value for the flatwise compression strength of the sandwich structure.

2. 2. 3. Edgewise compression test

The prepared sandwich structure subjected to Edgewise compression test as per ASTM standard C364/C364M and cubic specimen dimension of 25 mm x 25 mm x 25 mm. Position the sandwich structure between the fixture of UTM and loading direction aligned with sandwich panel's edge. Gradually apply compressive force at rate of 0.1 mm/s until the specimen buckled or fails.

2. 2. 4. Drop weight impact Test

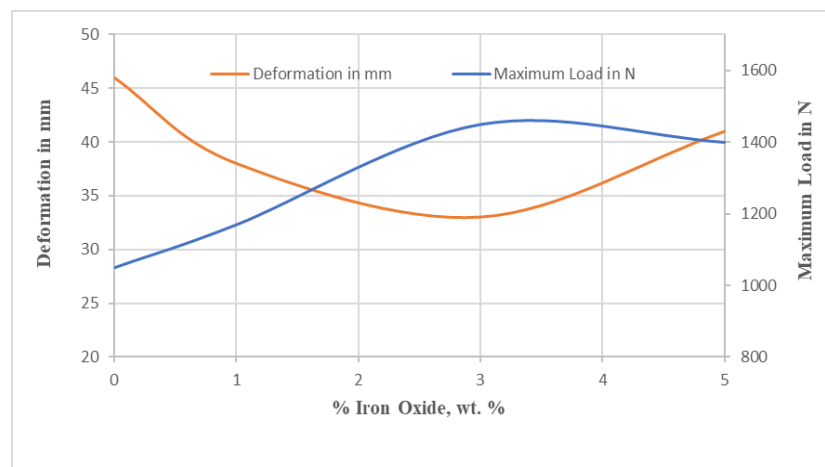
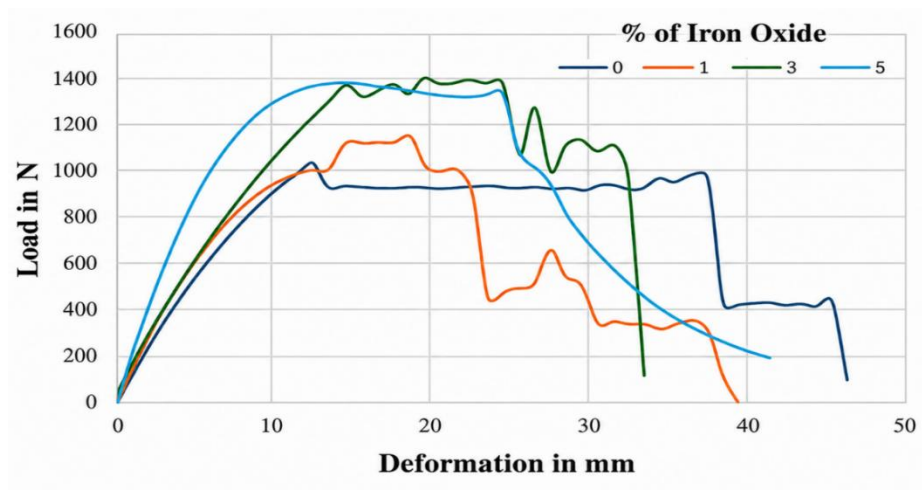
Prepare the sandwich panel specimens measuring 150 x 150 x 25 mm with diverse energy-absorbing materials such as skin, core and interfaces. Set up the instrumented drop weight impact testing machine adhering to the manufacturer's guidelines, verifying the instrumentation's precision for measuring the impact parameters. Conduct the impact test by positioning the specimen on the apparatus, aligning the 25 mm diameter, 3 kg hemispherical impactor at its center. Release the impactor from a 1-meter height consistently across tests to penetrate the specimen's center. Employ the instrumented apparatus to record and analyze absorbed energy, maximum impact load, and resultant damage mechanisms post-impact. Perform impact tests at varying energy levels by adjusting the drop height (height of the ball) while ensuring uniform alignment and testing conditions.

3. Result and Discussion

3. 1. Three point Bending



Fig. 1: a) Load-Deflection Curve and b) Effect of Iron Oxide Addition on Maximum Load and Deformation in INPGF Sandwich Structure under Bending



The effect of iron oxide filler content on the bending behavior of INPGF sandwich structures was investigated under quasi-static three-point bending. Fig. 1(a) presents the load-deflection curves for samples containing 0 wt.%, 1 wt.%, 3 wt.%, and 5 wt.% of iron oxide. The mechanical response, including maximum load and deformation capacity, varied significantly with the filler content.

The neat specimen (0 wt.% iron oxide) exhibited a maximum load of approximately 1050 N and the highest deformation of around 46 mm. This response indicates a relatively ductile behavior but with limited load-bearing capacity. The inclusion of 1% iron oxide led to a slight improvement in initial stiffness but resulted in slightly increase in peak load of approximately 1170 N and a deformation limit of about 38 mm.

A significant improvement in mechanical performance was observed with 3% iron oxide addition. This configuration demonstrated the highest peak load (~1450 N) and maintained a deformation capacity of approximately 33 mm. The improved load-bearing capacity is attributed to better stress distribution, increased matrix-filler interaction, and interfacial bond between of the foam core-face sheet interface. These factors contribute to enhanced energy absorption and delayed failure initiation.

The specimen with 5% iron oxide also exhibited a high maximum load (~1400 N); however, a notable increase in deformation capacity (~41 mm) was observed. The relatively abrupt load drops beyond peak load indicate the onset of premature failure mechanisms such as matrix cracking, due to the reduced stress transfer. The composite defect more compared to well-dispersed nanoparticles. Excess filler content may lead to inhomogeneity and localized stress concentration, thereby reducing the composite's stiffness, toughness and flexibility.

The increased strength/load bearing capacity is attributed to the combined effect of reinforcement on the sandwich structure. This is due to addition of iron oxide nanoparticles acting as fillers, bridging the polymer chains leading to hindering their movement under stress. The interfacial bond between polyurethane and glass laminate skin, allowing better load transfer.

As nanoparticles can act as obstacle to crack propagation, minimizes stress concentration leading to improved load bearing capacity. Overall, the results indicate that an optimal iron oxide content between 3 wt.% and 4 wt.% yields the best combination of strength and ductility.

Fig.1(b) illustrates the influence of iron oxide content on the maximum bending load and maximum deformation of INPGF sandwich structures under three-point bending. The graph highlights the trade-off between load-bearing capacity and flexibility as a function of iron oxide content ranging from 0 to 5 wt.%.

Conversely, the maximum deformation showed a decreasing trend with increasing iron oxide content. The highest deflection was recorded in the neat composite (~46 mm), 3 wt.% composite shows lowest deflection of (~33 mm), this reduction in deformation indicates increased stiffness and decreased ductility. While the 5 wt.% composite showed slight increase in deflection (~41 mm) likely due to filler-matrix interface weakening, nano particles agglomeration, resulting in stress concentration points, formation of voids promoting brittle failure.

The intersection point between the deformation and load curves, occurring near 2 wt.%, may represent a critical composition where moderate strength is achieved without severely compromising flexibility. However, the 3 wt.% composition provides the best balance between strength and acceptable deformation, making it the optimal filler loading for applications requiring both high bending resistance and structural resilience. These results affirm that the addition of iron oxide significantly influences the flexural behavior of INPGF sandwich panels. An appropriate filler content enhances the load-carrying capacity, and it must be optimized to get maximum flexural strength, stiffness to prevent agglomeration.

3. 2. Flatwise compression

Fig. 2 (a) illustrates the load-deflection behavior of INPGF sandwich structures subjected to flat compression, incorporating varying iron oxide contents (0%, 1%, 3%, and 5% by weight). The load deflection curve shows the deformation in linear region upto around 11 mm and 15 mm and then the final linear region approximately between 15 and 17 mm. The initial linear region is due to the elastic deformation of PU foam core and the glass laminate face sheets. The non linear region is due to the progressive collapse or densification of core material leads to change in load-deflection characteristics. The densification effect of the core and face sheets causes linear characteristics, but steeper slope.

From fig 2 (a) and 2 (b) the highest compressive strength for neat specimen (0 wt.% iron oxide) is 62000 N at the deformation of 17.2 mm. For 1 wt.% the deformation at the highest compressive strength of 70000 N is 17.3 mm, this increase in deformation compared to neat specimen is due to uneven disperse of nanoparticles forming weak bonds leading to higher overall deformation compared to neat composites. Further increase in wt.% of nanoparticles the compressive strength increases. The deformation for 3 wt.% of nanoparticles decreases, this decrease in deformation is attributed to the interaction of nanoparticles creating cross linking and forming more orderly reinforced polymer which resists deformation more

effectively under compressive loads. For 5 wt.% the nanoparticles tends to overcome the stabilizing forces within the polymer forming clusters or agglomeration which acts as the stress risers making the composite deform more.

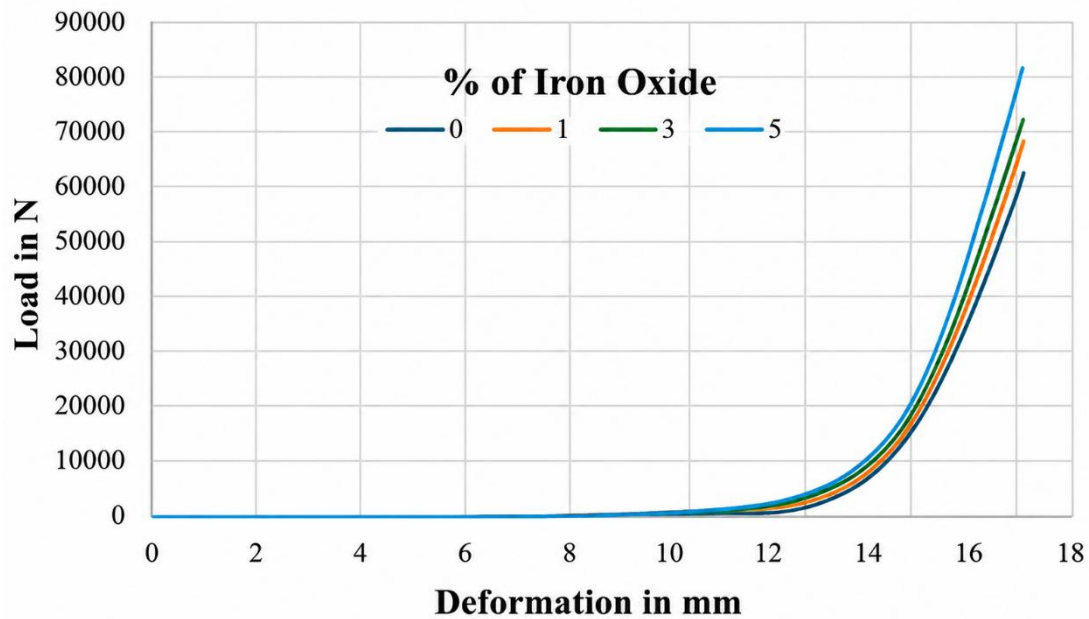


Fig. 2: a) Load-Deflection Curve of INPGF Sandwich Structure under flat compression.

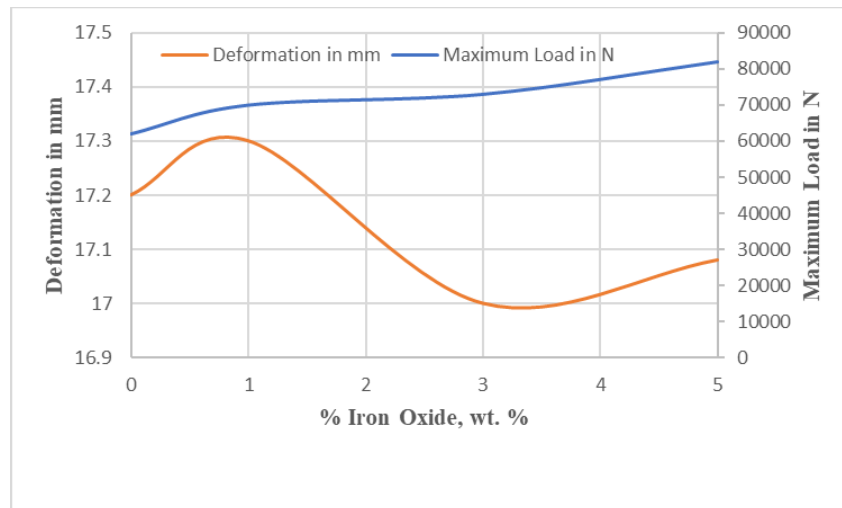


Fig. 2: b) Effect of Iron Oxide Addition on Maximum Load and Deformation in INPGF Sandwich Structure under flat compression.

Overall, the addition of iron oxide positively influences the compressive strength of the INPGF sandwich composites, with 5 wt.% iron oxide delivering the most significant improvement.

However, this comes at the expense of deformation capacity, implying a trade-off between strength and ductility. Therefore, for applications demanding high compressive strength with moderate deformation, 3-4 wt.% iron oxide offers an optimal range.

3. 3. Edgewise compression

Fig. 3 (a) and 3 (b) illustrates the edgewise compressive behavior of INPGF sandwich structures with varying iron oxide contents (0%, 1%, 3%, and 5% by weight). The load-deflection curves display the mechanical response under edgewise compression, where load is applied parallel to the plane of the face sheets. The analysis reveals a significant influence of filler content on both the peak load and the failure characteristics.

The composite containing 5 wt.% iron oxide exhibited the highest load-bearing capacity, with a peak load exceeding 11,100 N, followed by the 3 wt.% and 1 wt.% samples (9900 N & 9100 N). The neat specimen (0 wt.%) recorded the lowest peak load, approximately 7,200 N. These results confirm that the incorporation of iron oxide significantly enhances the compressive resistance of the sandwich structure by increasing the stiffness and delaying core-face sheet debonding or localized crushing. These increase in compressive strength is attributed to hard nanoparticles embedded in the polymer matrix improves resistance to compressive load and increase in the interfacial bonding between the glass laminates and polyurethane core, leads to increase in the energy needed for crack propagation between the layers.

In terms of deformation, the neat and 1 wt.% iron oxide specimens demonstrated larger deflection (4.6 mm & 4.2 mm) before complete load drop, indicating more progressive and ductile failure modes. In contrast, the 3 wt.% and 5 wt.% specimens showed sharper post-peak load drops (2.8 mm & 2.4 mm), the overall deformation of the composite decreases. The initial elastic energy absorption may increase, the total energy absorbed decreases before failure as the composite become more brittle, indicative of brittle or sudden failure. The stiffening effect imparted by higher filler content.

This phase is succeeded by a nonlinear stage leading to the load peak. Subsequently, the post-peak behavior is characterized by a substantial decline in the compressive strength of the sandwich panel, attributed to cracks propagating until the final failure of the specimen under buckling. The non linear behaviour attributed to layered structure of the composite, the properties of the individual materials and the interaction between the iron oxide nano particles and PU matrix. Following the post-peak phase, cracks densify on both the top and bottom of

the supports, compelling the eventual rupture of the specimens. This failure mechanism mirrors that observed in bending tests, involving phenomena such as decline in load bearing capacity, debonding between the core and face sheet and delamination between fibers occurring at the interface during buckling. In Fig. 3(b), it is evident that the edge compressive strength experiences an increase with the rising percentage of iron oxide, resulting in higher compressive strength. However, the specimen's brittleness becomes apparent as it fails at lower deformations despite the enhanced compressive strength.

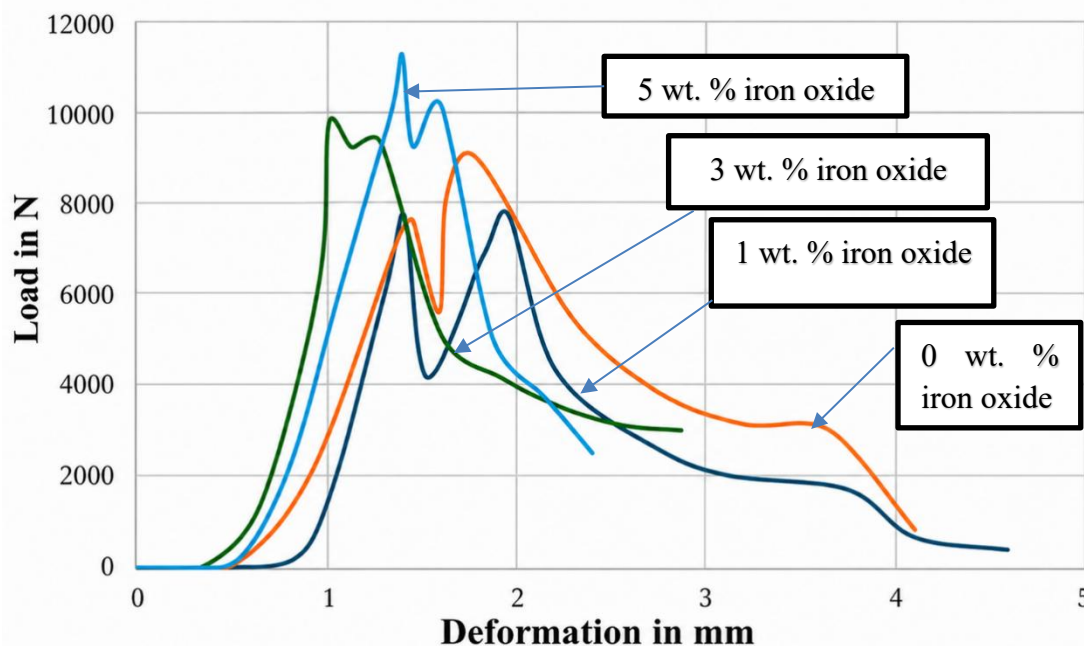


Fig. 3 a) Load-Deflection Curve of INPGF Sandwich Structure under Edgewise compression

The trends observed in Fig. 3 (a) reveal that each case exhibits an initial phase marked by a linear increase in load, indicative of small strain. This phase is succeeded by a nonlinear stage leading to the load peak. Subsequently, the post-peak behavior is characterized by a substantial decline in the compressive strength of the sandwich panel, attributed to cracks propagating until the final failure of the tested panels under buckling. The non linear behaviour attributed to layered structure of the composite, the properties of the individual materials and the interaction between the iron oxide nano particles and PU matrix. Following the post-peak phase, cracks densify on both the top and bottom of the supports, compelling the eventual rupture of the specimens. This failure mechanism mirrors that observed in bending tests, involving phenomena such as decline in load bearing capacity, debonding between the core and face sheet and delamination between fibers occurring at the interface during buckling. In

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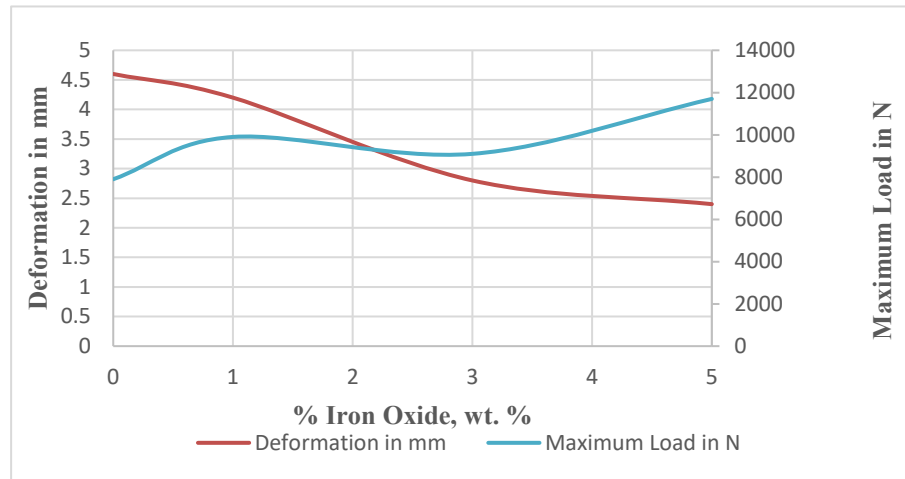


Fig. 3 b) Effect of Iron Oxide Addition on Maximum Load and Deformation in INPGF Sandwich Structure under Edgewise compression

The irregularity in the load-deflection patterns, particularly the multiple local peaks and drops in 3 wt.% and 5 wt.% specimens, may be attributed to progressive face-core debonding, complex interaction between the nanoparticles and polymer matrix, microcracking, or filler agglomeration leading to stress concentrations. The edgewise compressive performance of INPGF sandwich structures improves notably with iron oxide addition, reaching optimal strength at 5 wt.%. However, higher filler concentrations may reduce ductility and lead to brittle failure.

3. 4. Drop Weight Impact

Fig. 4 (a) presents the impact response of INPGF sandwich structures reinforced with various iron oxide contents (0%, 1%, 3%, and 5 wt.%) under drop weight impact loading condition. The impact force-impactor displacement curves provide insight into energy absorption capability, impact resistance, and failure behavior. The analysis focuses on three key parameters: maximum impact load, displacement at peak load, and damage progression.

Impact Load and Energy Absorption:

The specimen containing, the neat sample 0 wt.% (~40 N), followed by the 1 wt.% (~46 N), 3 wt.% (~50 N), and the 5 wt.% iron oxide demonstrated the highest peak impact load (~63

N). This progressive increase in impact force with filler content indicates a significant enhancement in impact resistance due to iron oxide addition. The presence of filler particles within the core matrix contributes to higher localized stiffness leading to improved energy absorption, higher strength-to-weight ratio and improved interfacial bonding, which aids in resisting impact-induced damage.

The energy absorption capacity, inferred from the area under the impact curves, was also highest for the 5 wt.% composite. The increase in energy absorption is due to increase interfacial adhesion, and disrupt the damage to travel. The 3 wt.% sample offered a comparable energy profile but with slightly less fluctuation, suggesting more stable energy dissipation behavior. The 0 wt.% and 1 wt.% composites exhibited lower energy absorption, at lower filler content, the vander Waal's force between nanoparticles can cause them to clump together forming weak regions leading to premature failure and lower energy absorption.

Deformation and Failure Behavior:

Addition of iron oxide nanoparticles improves impact resistance of structure hence the maximum impactor displacement reduced, because the composite absorbs and distributes the impact force. Hence the impactor's displacement varied inversely with the iron oxide content. The neat sample allowed the largest displacement (~8.3 mm), while the 5 wt.% composite resisted deformation effectively (~6.4 mm), revealing increased structural rigidity. While reduced displacement corresponds to greater impact stiffness, it may also suggest lower post-yield ductility in higher filler composites. An optimal concentration, the nanoparticles act as effective fillers and cross linking agents thus strengthening the material enabling it to resist deformation.

Impact Damage Characteristics

The post-impact observations revealed that 5 wt.% iron oxide specimens sustained the least surface damage, with localized dents and minimal core crushing. Conversely, the 0% and 1% samples exhibited more extensive face sheet wrinkling, core shear, and interfacial delamination. These trends further corroborate the superior impact damage resistance of iron oxide-reinforced structures, particularly at 3-5 wt.% filler content.

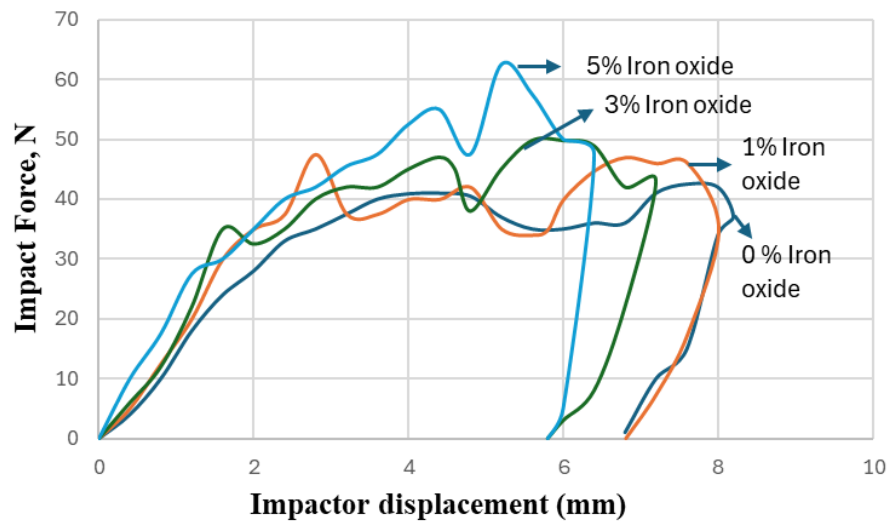


Fig. 4: a) Impact Load-impactor displacement Curve.

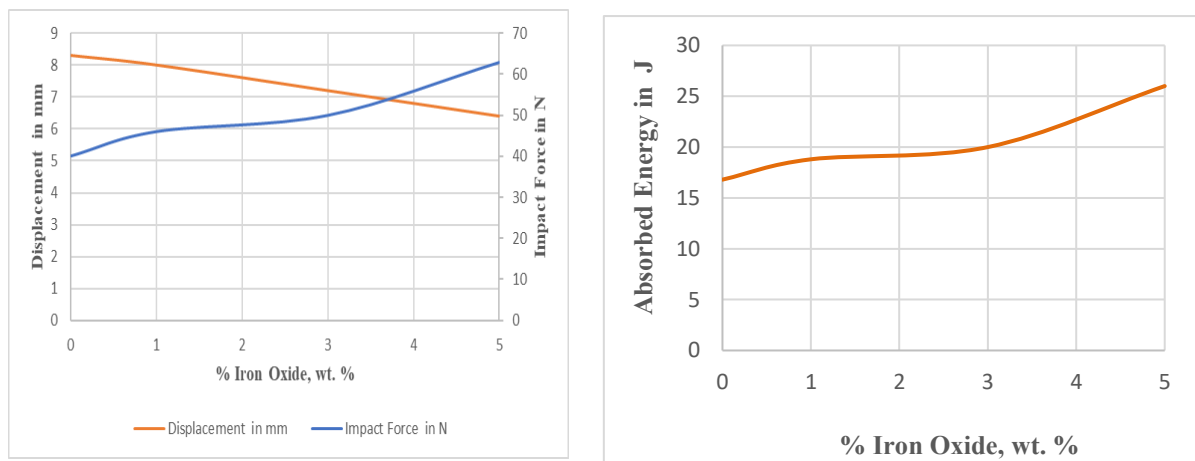


Fig. 4: b) Effect of Iron Oxide Addition on Maximum Impact Force, Displacement, Absorbed Energy in INPGF Sandwich Structure under Drop Weight Impact Load.



Fig. 4: c) Impact Damages after Failure of the Specimens in Different Loading Conditions.

Fig. 4 (b) illustrates the quantitative relationship between iron oxide filler content (0-5 wt.%) and three key impact parameters, maximum impact force (N), maximum displacement (mm) absorbed energy (mJ), for INPGF sandwich structures under drop weight impact condition.

The absorbed energy exhibited a significant upward trend with increasing iron oxide content. Starting from approximately 16.8 J for the neat sample (0 wt.%) , energy absorption increased steadily, reaching a peak of ~26 J at 5 wt.%. This improvement reflects the enhanced capacity of the sandwich structure to dissipate impact energy, attributable to stronger fiber matrix bond, crack deflection, micro buckling increasing local stiffness and fracture resistance of the foam core. The increasing energy profile also aligns with the rising peak impact loads observed in the previous load-displacement curves (Fig. 4 a).

The impact force bearing capacity improved progressively with increasing filler content. The force increased from ~40 N for the neat sample to ~63 N at 5 wt.% iron oxide. This indicates improved impact resistance, as the structure can withstand higher instantaneous loading without catastrophic failure. The slope of increase was steeper beyond 3 wt.%, suggesting a threshold beyond which the reinforcement effect of iron oxide becomes more dominant due to better dispersion and matrix interaction.

Maximum Displacement:

In contrast to energy and force, the maximum impactor displacement showed a gradual decrease with increasing iron oxide content. The neat sample showed the highest deformation (~8.3 mm), while the 5 wt.% sample demonstrated the lowest (~6.4 mm). This inverse correlation suggests that iron oxide reinforcement stiffens the structure, reducing its deformability under impact loading. Although lower displacement indicates enhanced stiffness and resistance to penetration, it also suggests a potential trade-off with post-yield ductility.

Specimens with 3-5 wt.% iron oxide likely sustained less face sheet wrinkling, core crushing, and delamination, due to improved energy dissipation, strong interfacial bonding, nanoparticles can deflect the crack path, progressive energy absorption and other mechanisms. On the other hand, lower filler content (0-1 wt.%) samples likely experienced more severe surface and core damage under similar impact energies, due to poor stress distribution, interfacial bonding, limited crack deflection and other mechanisms.

Fig. 4 (c) presents the post-impact damage images of INPGF sandwich specimens reinforced with varying iron oxide contents (0 wt.%, 1 wt.%, 3 wt.% and 5 wt.%) subjected to drop weight impact. The damage morphology offers visual insight into the failure behavior, correlating with mechanical responses observed in the corresponding force-displacement and energy plots (Fig. 4a and 4b).

The neat specimen (0 wt.% iron oxide) exhibited visible damage in the form of surface indentation and widespread matrix cracking. The absence of reinforcing particles resulted in insufficient impact resistance, causing core crushing and significant local delamination. This damage is consistent with the lowest impact energy absorption (~ 16.8 J) and high deformation (~ 8.3 mm). In 1 wt.% iron oxide slight improvements in structural integrity were observed. The indentation is more confined, and matrix cracking appears less extensive compared to the neat specimen. However, minor face sheet–core debonding is still evident. This matches the marginal gains in absorbed energy and peak load, as seen in previous results. In 3 wt.% iron oxide, the sample exhibited a relatively compact damage zone with minor visible delamination or fiber breakage. The damage is well-contained, suggesting effective dispersion of stress across the matrix. This is in agreement with its improved mechanical behavior, which showed high energy absorption (~ 20 J) and reduced displacement of 7.2 mm. The material at this concentration appears to strike a balance between strength and toughness. And 5 wt.% iron oxide, the most notable enhancement in impact resistance was observed here. The surface damage was minimal with only a shallow dent and no visible signs of core cracking or face sheet delamination. The structure remained largely intact, confirming superior reinforcement. This corresponds with the highest observed impact force (~ 63 N) and energy absorption (~ 26 J), validating that 5 wt.% filler effectively increases resistance to localized impact damage.

The progression of impact damage across increasing iron oxide concentrations reveals a clear trend of enhanced structural resilience and localized damage control. The 3-5 wt.% iron oxide compositions significantly improved impact resistance and reduced damage severity, while the 0-1 wt.% specimens showed more extensive and uncontrolled failure. This visual assessment confirms and complements the mechanical data, reinforcing the conclusion that iron oxide filler, particularly at 5 wt.%, effectively fortifies the INPGF sandwich structure against drop weight impact-induced damage.

Conclusion

The incorporation of iron oxide into INPGF sandwich structures has a pronounced effect on their mechanical and impact performance under bending, flatwise compression, edgewise compression, and impact loading conditions. Key findings across all tested properties are summarized below:

1. Bending Behavior:

- The maximum load under bending increased with increasing iron oxide content, peaking at 3-4 wt.%.
- The inclusion of iron oxide enhanced stiffness but reduce deflection, compared to neat composite
- 3 wt.% showed a balanced performance between strength and ductility.

2. Flatwise Compression:

- Peak compressive strength improved significantly with increasing filler content.
- Maximum deformation decreased, indicating greater stiffness and localized resistance.
- 5 wt.% iron oxide demonstrated the highest compressive strength.
- For application demanding high compressive strength with moderate deformation, 3-4 wt.% of iron oxide offers an optimal range.

3. Edgewise Compression:

- Enhanced load-bearing capacity and energy absorption were recorded with iron oxide addition.
- 5 wt.% offered the highest peak load but showed signs of brittle failure.
- Hard nano particles embedded in the polymer matrix, improves the resistance to compressive load.

4. Impact Performance:

- Impact force and absorbed energy increased consistently with iron oxide addition.
- Displacement decreased with higher filler levels, reflecting enhanced resistance to penetration and surface damage.
- Damage morphology confirmed that 5 wt.% resulted in the least visible impact damage, while 0-1 wt.% specimens showed severe matrix cracking and delamination.

- With 5 wt.% filler addition highest observed impact force (~ 26 J) attributed to well dispersed, optimal concentration of nanoparticles and more energy is dissipated through crack pinning and crack deflection.

Overall, the addition of iron oxide significantly enhances the structural integrity, load-carrying capacity, and impact resistance of foam INPGF sandwich composites. A filler concentration of 3-5 wt.% is optimal for achieving high mechanical strength, energy absorption, and reduced damage under multi-axial loading conditions. This suggests the potential suitability of these enhanced composites in automotive, aerospace, and defense applications where lightweight yet impact-resistant materials are critical.

References

1. R. Mehta and T. Agarwal, "Review of Polymer Sandwich Structures in Load-Bearing Applications," *Polym. Eng. Sci.*, vol. 65, no. 3, pp. 342–351, 2023.
2. P. Suresh et al., "Advances in Core Materials for Polymer Sandwich Composites," *Compos. Struct.*, vol. 312, pp. 117851, 2023.
3. D. Yadav and S. Roy, "Mechanical Behavior of Lightweight Sandwich Composites," *Mater. Today Proc.*, vol. 69, pp. 491–496, 2023.
4. A. K. Sharma et al., "PU Foam Composites: Recent Trends in Structural Performance," *J. Reinf. Plast. Compos.*, vol. 42, no. 2, pp. 150–162, 2024.
5. N. Bhatia and K. Thomas, "Ceramic Fillers for Improved Mechanical Properties of Polymer Matrices," *Compos. Part B: Eng.*, vol. 258, pp. 110694, 2024.
6. S. Gupta and M. Ali, "Nanostructured Fe_2O_3 for Reinforced Polymer Systems," *J. Mater. Sci.*, vol. 59, pp. 1123–1134, 2025.
7. V. Das et al., "Improving PU Foam Rigidity with Ferric Oxide Micro-Fillers," *Mater. Des.*, vol. 243, pp. 111759, 2024.
8. K. R. Iyer et al., "Impact Performance of Fe_2O_3 -Filled PU Sandwich Cores," *Polym. Test.*, vol. 124, pp. 108219, 2024.
9. T. K. Singh et al., "Microstructure and Strength Correlation in Ferric Oxide Composites," *J. Appl. Polym. Sci.*, vol. 140, no. 7, pp. 53519, 2023.
10. Y. Li and Z. Huang, "Interfacial Adhesion in Oxide-Filled Polymers," *Polym. Compos.*, vol. 44, no. 1, pp. 27–35, 2023.
11. M. K. Anand et al., "Optimization of Filler Dispersion in High-Strength Foams," *Mater. Chem. Phys.*, vol. 310, pp. 127075, 2024.
12. H. S. Park et al., "Effect of Sonication on Fe_2O_3 Filler Distribution," *J. Thermoplast. Compos. Mater.*, vol. 38, no. 5, pp. 915–930, 2025.
13. R. P. Verma and B. Singh, "Evaluating Optimal Oxide Filler Loading," *Polym. Eng. Sci.*, vol. 65, no. 1, pp. 102–110, 2024.

14. J. M. Thomas and L. R. Kohli, “Influence of Ferric Oxide Concentration on PU Foam Properties,” *J. Cell. Plast.*, vol. 61, no. 2, pp. 129–143, 2025.
15. F. Wang et al., “Structural Integrity of Foam-Core Sandwich Composites,” *Compos. Sci. Technol.*, vol. 245, pp. 110699, 2024.
16. N. P. Rajan et al., “Fatigue Behavior of Ceramic-Reinforced Sandwich Panels,” *Compos. Part A: Appl. Sci. Manuf.*, vol. 175, pp. 107624, 2023.
17. C. K. Jain and D. Murthy, “Crashworthiness of Ferric Oxide Sandwich Panels,” *Mater. Today Commun.*, vol. 36, p. 105045, 2023.
18. L. Sharma et al., “Holistic Testing of Polymeric Sandwich Structures,” *J. Sandw. Struct. Mater.*, vol. 27, no. 1, pp. 93–110, 2025.
19. S. Rao and M. Pillai, “Interfacial Effect in Oxide-Filled Core Panels,” *Compos. Interfaces*, vol. 32, no. 3, pp. 245–259, 2024.