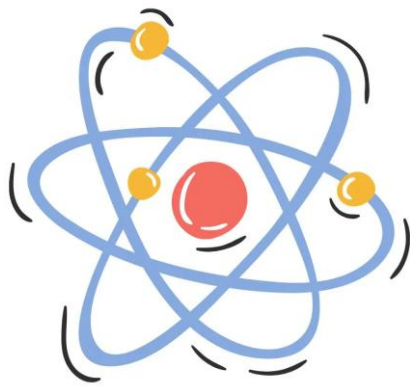




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COMPOSITE PANELS BASED ON
FORCE-DISPLACEMENT ANALYSIS
AND NUMERICAL INTERPRETATION

Rathika M¹., Paul Vizhian S².,
Ashwini V.³

^{1,3}Research Scholar, ²Professor, Department of
Mechanical Engineering, University
Visvesvaraya College of Engineering, Bangalore
University, Bangalore, Karnataka, India

¹Assistant Professor, Dr. Ambedkar Institute of
Technology, Bangalore, India

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Rathika M¹., Paul Vizhian S²., Ashwini V.³

^{1,3}Research Scholar, ²Professor, Department of Mechanical Engineering, University Visvesvaraya College of Engineering, Bangalore University, Bangalore, Karnataka, India

¹Assistant Professor, Dr. Ambedkar Institute of Technology, Bangalore, India

¹rathikasendhil@gmail.com, ²paulvizhian_s@yahoo.com, ³ashwini.feb90@gmail.com

Abstract: The low-velocity impact behavior of glass-fibre-reinforced polymer/polyurethane sandwich composite panels containing different concentrations of iron-oxide nanoparticles was investigated through experimental and numerical force-displacement analysis. Fe₂O₃ nanoparticles were incorporated into the polyurethane region at concentrations of 0, 1, 3 and 5 wt.% to study their influence on impact force, displacement, energy absorption, equivalent stress and equivalent strain. Experimental force-displacement curves were processed to determine peak impact force, loading energy, rebound energy and absorbed energy. Numerical force-displacement curves were generated from the experimental response to compare the behavior of the four material configurations. The experimental peak forces of the panels containing 0, 1, 3 and 5 wt.% Fe₂O₃ nanoparticles were 43.0, 47.1, 50.0 and 62.7 N, respectively. The panel containing 1 wt.% Fe₂O₃ nanoparticles recorded the highest absolute absorbed energy of 0.2561 J. The 5 wt.% panel recorded the lowest rebound energy of 0.0073 J and the highest absorbed-energy percentage of 97.09%. The numerical force-displacement response showed an increase in peak force and a decrease in displacement at peak force with increasing Fe₂O₃ nanoparticle content. The maximum equivalent stress increased from 38.5 MPa for the unfilled panel to 59.2 MPa for the 5 wt.% panel, while the equivalent strain decreased from 1.95% to 1.41%. The results show that Fe₂O₃ nanoparticle reinforcement increased panel stiffness, improved load transfer and reduced impact deformation. The 1 wt.% composition provided the highest absolute energy absorption, whereas the 5 wt.% composition provided the highest peak-force resistance and absorbed-energy percentage.

Keywords: Fe₂O₃ Nanoparticles; Iron-oxide Nanoparticles; GFRP; Polyurethane; Sandwich Composite; Low-velocity Impact; Force-displacement Response; Absorbed Energy; Equivalent Stress.

1. Introduction

Sandwich composite panels consist of two stiff face sheets bonded to a lightweight core or reinforcement region. This configuration provides high bending stiffness and structural strength while maintaining a relatively low mass. Sandwich composites are therefore used in aerospace, marine, automotive, railway, wind-energy and civil-engineering applications where lightweight construction and impact resistance are important [1,2].

The mechanical behaviour of a sandwich composite depends on the properties of the face sheets, core and bonded interfaces. Under transverse impact loading, the upper face sheet experiences local indentation and bending. The central reinforcement region supports the face sheet, distributes the contact force and absorbs energy through compression, shear deformation and crushing. The lower face sheet experiences tensile deformation as the complete panel bends.

Low-velocity impact is an important design concern because it can create internal damage without producing clearly visible surface failure. Matrix cracking, face-sheet delamination, fibre–matrix debonding, core crushing and face-sheet/core separation may develop beneath the impact location. These damage mechanisms can reduce the strength, stiffness and residual load-carrying capacity of the structure [1–3].

Schubel et al. investigated the low-velocity impact behaviour of sandwich panels containing woven composite face sheets and a polymeric foam core. They reported that contact-force, strain and panel-deflection histories provide important information about impact loading, structural deformation and damage development [1].

Meo et al. combined experimental impact testing with numerical analysis to investigate honeycomb sandwich panels subjected to low-velocity impact. Their study demonstrated that numerical analysis can provide information about damage initiation, damage propagation, energy absorption and failure mechanisms that may not be obtained from external observation alone [2].

Post-impact structural performance is affected by the internal damage created during impact. Schubel et al. found that delamination and permanent indentation could reduce the residual load-carrying capacity of sandwich panels even when visible external damage was limited [3]. Impact performance should therefore not be evaluated using peak force alone. Maximum displacement, energy absorption, rebound behaviour, permanent deformation and internal damage should also be considered.

Glass-fibre-reinforced polymer is widely used for sandwich-panel face sheets because of its favourable strength-to-weight ratio, corrosion resistance and manufacturing flexibility. Polyurethane can be used as a core, matrix or reinforcement material because of its low density and capacity to undergo considerable deformation. However, unmodified polyurethane may exhibit local indentation and limited contact stiffness under transverse loading.

Nanoparticles can modify the mechanical response of polymer matrices because of their high surface-area-to-volume ratio. When nanoparticles are uniformly dispersed and bonded to the polymer, they can restrict polymer-chain movement, increase stiffness and improve load transfer through the reinforced region.

Gradinaru et al. prepared polyurethane composites containing Fe_2O_3 and Fe_3O_4 nanoparticles. They reported that the type and concentration of iron-oxide nanoparticles influenced the morphology and mechanical properties of the polyurethane nanocomposites [4]. Their work demonstrated that iron-oxide nanoparticles can be incorporated into polyurethane matrices and can modify their material response.

Morsi et al. reported that red iron oxide changed the mechanical and protective behaviour of polyurethane-based composite systems [5]. Although their application differed from the present impact-loaded sandwich structure, their findings support the use of iron oxide as a functional reinforcing phase in polyurethane materials.

The improvement produced by nanoparticle reinforcement depends on particle size, concentration, surface condition, dispersion and interfacial bonding. Uniform nanoparticle

dispersion can improve stress transfer, whereas agglomeration can produce voids, weak interfaces and local stress concentrations.

Finite-element and numerical models have been extensively used to study impact response in sandwich structures. Chen et al. developed a model that included face-sheet damage, delamination, adhesive-interface failure and honeycomb-core deformation [9]. Feng and Aymerich incorporated intralaminar damage and cohesive interface behaviour into their analysis of foam-core sandwich composites [10]. Besant et al. used nonlinear material behaviour and face-sheet degradation to model impact on composite sandwich panels [11].

Energy-balance approaches have also been used to describe sandwich-panel impact behaviour. Hazizan and Cantwell considered bending, shear and local contact contributions in aluminium-honeycomb sandwich structures [12]. Foo et al. developed a model for predicting contact response and damage in sandwich composites [13]. Ivañez and Sanchez-Saez compared experimental and numerical contact-force histories, absorbed energy and failure behaviour in sandwich beams with honeycomb cores [14].

The present study investigates GFRP/PU hybrid sandwich composite panels containing 0, 1, 3 and 5 wt.% Fe_2O_3 nanoparticles. Experimental force-displacement curves were analysed to determine peak force, displacement, rebound behaviour and energy absorption. Numerical force-displacement curves were generated for the same material configurations. Kinetic, internal, artificial, contact and total energy components were calculated, and equivalent stress and strain responses were compared.

The objectives of the study were to:

1. Compare the force–displacement behaviour of GFRP/PU panels containing different Fe_2O_3 nanoparticle concentrations.
2. Calculate loading, rebound and absorbed energies from the experimental curves.
3. Generate numerical force-displacement curves for the four material configurations.
4. Calculate kinetic, internal, artificial, contact and total energies.
5. Compare the equivalent stress and equivalent strain responses.
6. Determine the influence of Fe_2O_3 nanoparticle concentration on impact resistance.
7. Identify the composition that provides favourable energy absorption and stiffness.

2. Literature Review

2.1 Low-velocity impact behaviour of sandwich composites

The low-velocity impact behaviour of a sandwich composite is governed by face-sheet stiffness, core density, core thickness, interface strength, impactor geometry, impactor mass, impact velocity and boundary conditions. The initial part of a force-displacement curve is generally controlled by elastic bending, local indentation and contact deformation [1,2].

As the impact force increases, damage can develop in the face sheets, reinforcement region and bonded interfaces. Common damage mechanisms include matrix cracking, fibre-matrix

debonding, face-sheet delamination, interface separation, core compression, core shear failure, fibre fracture and permanent indentation.

Schubel et al. reported that contact deformation and global panel bending strongly influenced the response of composite sandwich panels under low-velocity impact [1]. Their work demonstrated the importance of recording force, displacement, strain and panel-deflection histories throughout the impact event.

Meo et al. examined sandwich structures representative of aircraft components at several impact-energy levels. Their numerical analysis provided information about damage initiation, propagation and structural failure [2].

The face-sheet/core interface is an important region because the face sheets and core have different stiffnesses and deformation characteristics. Localized impact loading can produce high interfacial normal and shear stresses, leading to debonding or delamination.

Post-impact damage may reduce structural performance even when the impact does not cause complete penetration. Internal delamination, permanent indentation and core damage can reduce residual stiffness and load-carrying capacity [3].

Chen et al. developed a numerical model that considered intralaminar face-sheet damage, interlaminar delamination, adhesive-interface failure and honeycomb-core deformation. Their model was used to compare numerical force histories and damage patterns with experimental observations [9].

Feng and Aymerich applied three-dimensional damage models and cohesive interface laws to simulate fibre fracture, matrix cracking and delamination in foam-core sandwich panels subjected to impact [10].

Besant et al. used finite-element analysis to examine composite sandwich panels containing composite face sheets and a metallic honeycomb core. Their model included nonlinear deformation of the core and degradation of the composite face sheets [11].

These investigations show that numerical prediction of impact behaviour requires the main material, interface and contact mechanisms to be represented.

2.2 Force-displacement behaviour

A force-displacement curve describes the variation in contact force as the impactor moves into and away from the panel. The loading branch begins when the impactor contacts the specimen. The force increases as the face sheet bends and the material beneath the impactor is compressed.

Reductions or oscillations in force may be associated with:

- Matrix cracking.
- Interface debonding.
- Delamination.
- Core or reinforcement-region crushing.
- Fibre damage.
- Impactor separation and recontact.
- Redistribution of load to undamaged regions.

The unloading branch begins after the maximum impactor displacement is reached. During unloading, part of the stored elastic energy is returned to the impactor. The contact force decreases to zero when the impactor separates from the specimen.

A high peak force generally indicates high contact stiffness and resistance to indentation. Peak force alone, however, does not represent energy absorption because energy depends on both force and displacement.

A panel that sustains a moderate force through a relatively large displacement may absorb more energy than a stiffer panel that carries a high force through a shorter displacement. Energy-balance studies therefore use the complete loading and unloading curves rather than only the maximum force [12,13].

2.3 Fe₂O₃ nanoparticle-reinforced polyurethane

The mechanical behaviour of nanoparticle-reinforced polyurethane depends on nanoparticle size, shape, concentration, dispersion, surface properties and bonding with the polymer matrix.

Uniformly dispersed nanoparticles provide a large particle–matrix interfacial area. This interface can restrict deformation of the polymer chains and improve the transfer of load through the material.

Gradinaru et al. produced polyurethane nanocomposites containing hematite and magnetite nanoparticles. Their mechanical characterisation showed that iron-oxide type and concentration affected Young's modulus, tensile properties and surface morphology [4].

Morsi et al. incorporated red iron oxide into polyurethane systems and observed changes in mechanical and protective performance [5]. Their work confirmed that iron oxide can function as a reinforcing phase within polyurethane-based materials.

At lower nanoparticle concentrations, particles may be more uniformly distributed within the polymer. Increasing the concentration can increase stiffness and compressive resistance. However, higher concentrations can also increase the possibility of particle agglomeration.

Agglomerated nanoparticles can produce local discontinuities, voids and stress concentrations. The performance of Fe₂O₃-reinforced polyurethane therefore depends on both nanoparticle concentration and dispersion quality.

The force-displacement results in the present work show that the 5 wt.% Fe₂O₃ panel carried the highest peak force, whereas the 1 wt.% panel produced the largest absolute force-displacement area. The composition with the highest stiffness therefore did not produce the highest absolute absorbed energy.

2.4 Energy absorption during impact

The mechanical work transferred from the impactor to the panel is represented by the area under the loading branch:

Loading energy:

$$E_{\text{loading}} = \int_{\text{loading}} F \, d\delta \quad \text{Eq. 1}$$

Rebound energy

$$E_{\text{rebound}} = \left| \int_{\text{unloading}} F \, d\delta \right| \quad \text{Eq. 2}$$

Absorbed energy

$$E_{\text{absorbed}} = E_{\text{loading}} - E_{\text{rebound}} \quad \text{Eq. 3}$$

Absorbed energy can include contributions from:

- Elastic deformation.

- Viscoelastic deformation.
- Permanent indentation.
- Matrix cracking.
- Delamination.
- Interface debonding.
- Core crushing.
- Fibre damage.
- Friction.
- Vibration.

The term absorbed energy does not mean that all transferred energy is consumed by permanent material damage. A portion may remain stored as elastic strain energy in the deformed panel.

Hazizan and Cantwell used an energy-balance approach to represent energy absorption through bending, shear and local indentation in honeycomb sandwich structures [12]. Foo et al. combined contact mechanics and an energy-balance formulation to predict the impact response and damage of sandwich composites [13].

These studies confirm that the complete force–displacement path is more informative than peak force alone when comparing different sandwich-panel configurations.

2.5 Numerical impact analysis

Dynamic numerical analysis is suitable for impact events involving rapid contact, inertia, large deformation, material nonlinearity and progressive damage.

Important response quantities include:

- Contact force.
- Impactor displacement.
- Contact duration.
- Kinetic energy.
- Internal energy
- Artificial energy.
- Contact energy.
- Total energy.
- Material damage.
- Permanent deformation.

Kinetic energy represents energy associated with the motion of the impactor and other moving components. Internal energy represents energy stored or dissipated through elastic deformation, irreversible deformation, material damage and failure.

Artificial energy can arise from numerical stabilisation, hourglass control and reduced-integration element formulations. Artificial energy should remain small relative to internal energy.

Contact energy is associated with the numerical enforcement of contact between interacting surfaces. An unexpected increase in contact energy may be associated with excessive penetration, unsuitable contact stiffness or unstable contact behaviour.

Chen et al. obtained agreement between numerical and experimental impact responses by representing damage in the face sheets, interfaces and core [9]. Ivañez and Sanchez-Saez compared contact-force histories, energy histories, absorbed energy and failure behaviour between experiments and numerical analysis [14].

Numerical validation should therefore consider several response quantities rather than only peak contact force.

ASTM D7136/D7136M provides a drop-weight impact procedure for determining the damage resistance of fibre-reinforced polymer-matrix composite plates. It specifies an out-of-plane impact using a drop-weight device and a hemispherical impactor [15].

2.6 Failure criteria for GFRP

Von Mises stress is commonly used to assess yielding in approximately isotropic ductile materials. It can be applied to an isotropic representation of the PU-Fe₂O₃ region and to metallic components.

Von Mises stress alone does not describe the direction-dependent failure behaviour of GFRP laminates. Composite laminates have different strengths in the fibre, transverse and shear directions.

Hashin developed separate failure conditions for fibre tension, fibre compression, matrix tension and matrix compression in unidirectional composites [6].

Tsai and Wu developed an interactive strength criterion for anisotropic materials in which different stress components contribute to a combined failure function [7].

Puck and Schürmann developed physically based criteria that distinguish fibre failure from inter-fibre failure and consider the orientation of the fracture plane [8].

Hashin, Tsai-Wu, Tsai-Hill or Puck criteria are therefore more suitable for evaluating GFRP face sheets. Von Mises stress can be used for the approximately isotropic PU-Fe₂O₃ region.

3.0 Materials and Methods

3.1 Materials and panel configuration

The hybrid sandwich composite panel consisted of:

- An upper GFRP face sheet.
- A honeycomb reinforcement region.
- Polyurethane introduced into the reinforcement region.
- Fe₂O₃ nanoparticles dispersed within the polyurethane.
- A lower GFRP face sheet.
- Bonded interfaces between the reinforcement region and GFRP face sheets

Four Fe₂O₃ nanoparticle concentrations were investigated:

- 0 wt.% Fe₂O₃
- 1 wt.% Fe₂O₃
- 3 wt.% Fe₂O₃
- 5 wt.% Fe₂O₃

Table 1. Material and specimen details

Parameter	Description/Value
Panel type	Hybrid honeycomb sandwich composite panel
Face-sheet material	Glass-fibre-reinforced polymer (GFRP)
Core configuration	Foam-filled honeycomb core
Core reinforcement	Iron-oxide nanoparticles, Fe_2O_3
Fe_2O_3 concentrations	0, 1, 2, 3 and 5 wt. %
Specimen length	150 mm
Specimen width	150 mm
Total specimen thickness	25 mm
Number of compositions	5
Number of specimens per composition	3
Total number of specimens	15
Manufacturing procedure	Identical fabrication procedure for all compositions
Impact-test standard	ASTM D3763
Impact location	Geometric centre of the specimen

The test specimens consisted of GFRP face sheets bonded to a foam-filled honeycomb core reinforced with different concentrations of Fe_2O_3 nanoparticles. Five compositions containing 0, 1, 2, 3 and 5 wt. % Fe_2O_3 were prepared. Each specimen measured 150 mm $\times$ 150 mm $\times$ 25 mm. Three specimens were tested for each composition, resulting in a total of 15 impact-test specimens.

3.2 Preparation of Fe_2O_3 nanoparticle-reinforced polyurethane

The quantities of Fe_2O_3 nanoparticles required for the selected concentrations were measured based on the total mass of the polyurethane system.

The nanoparticles were gradually added to the polyurethane and mixed until a uniform distribution was obtained. Four polyurethane formulations were prepared:

- Pure polyurethane containing 0 wt. % Fe_2O_3
- Polyurethane containing 1 wt. % Fe_2O_3
- Polyurethane containing 3 wt. % Fe_2O_3
- Polyurethane containing 5 wt. % Fe_2O_3

The nanoparticle-modified polyurethane was introduced into the sandwich reinforcement region and bonded between the upper and lower GFRP face sheets.

Table 2. Fabrication parameters

Test parameter	Description/Value
Testing method	Low-velocity drop-weight impact test
Testing machine	Instrumented drop-weight impact-testing machine
Machine frame	Rigid steel frame
Carriage guidance	Precision vertical guide columns
Release mechanism	Electromagnetic release mechanism
Impactor material	Steel
Impactor geometry	Hemispherical
Impactor diameter	25 mm
Impactor mass	3 kg
Drop height	1 m
Gravitational acceleration	9.81 m/s ²

Test parameter	Description/Value
Initial impact energy	29.43 J
Specimen support	Supporting fixture
Boundary condition	Rigidly clamped along all four edges
Impact position	Geometric centre
Force-measuring device	Piezoelectric load cell
Recorded parameters	Impact force, displacement, contact time and absorbed energy
Number of specimens tested	3 specimens per composition
Test repetitions	3 tests for each Fe ₂ O ₃ concentration
Result used for analysis	Average value of three specimens
Pre-test inspection	Visual examination for voids, cracks, delamination and resin-rich regions
Dimensional measurement	Digital Vernier calliper

These values should be completed using the fabrication records.

Impact-energy calculation

$$E = mgh \quad \text{Eq. 4}$$

where:

$m = 3 \text{ kg}$, $g = 9.81 \text{ m/s}^2$, $g = 9.81$, $h = 1 \text{ m}$

Therefore:

$$E = 3 \times 9.81 \times 1 = 29.43 \text{ J}$$

The impact tests were conducted using an instrumented drop-weight testing machine equipped with a 3 kg hemispherical steel impactor of 25 mm diameter. The impactor was released from a height of 1 m, corresponding to an initial impact energy of 29.43 J. Each specimen was positioned at the centre of the supporting fixture and rigidly clamped along all four edges. Impact force was measured using a piezoelectric load cell, while displacement, contact time and absorbed energy were recorded using the integrated data-acquisition system.

3.3 Low-velocity impact testing

Low-velocity impact tests were conducted on the GFRP/PU-Fe₂O₃ sandwich composite panels.

The test system recorded the variation in contact force with impactor displacement throughout the loading and unloading portions of the impact event.

Table 3. Impact-test conditions

Parameter	Value
Test method	Instrumented low-velocity drop-weight impact test
Test standard	ASTM D3763
Impact-testing machine	Instrumented drop-weight impact-testing machine
Machine structure	Rigid steel frame with precision vertical guide columns
Release mechanism	Electromagnetic release mechanism
Impactor material	Steel
Impactor shape	Hemispherical
Impactor diameter	25 mm
Impactor mass, (m)	3 kg
Drop height, (h)	1 m
Gravitational acceleration, (g)	9.81 m/s ²
Impact velocity	4.43 m/s
Initial impact energy	29.43 J
Specimen dimensions	150 mm × 150 mm × 25 mm
Specimen support condition	Rigidly clamped along all four edges
Impact location	Geometric centre of the specimen
Force measurement	High-sensitivity piezoelectric load cell
Displacement measurement	Integrated displacement/data-acquisition system
Recorded parameters	Impact force, displacement, contact time and absorbed energy
Fe ₂ O ₃ nanoparticle concentrations	0, 1, 2, 3 and 5 wt.%
Specimens tested per composition	3
Total number of specimens	15
Result considered	Average of three specimens for each composition
Pre-test inspection	Visual inspection for voids, resin-rich regions, cracks and delamination
Dimensional measurement device	Digital Vernier calliper
Data-acquisition frequency	Not reported
Test temperature	Not reported
Support-opening dimensions	Not reported
Parameter	Value

Impact velocity calculation

$$V = \sqrt{2gh}$$

Eq. 5

$$V = \sqrt{(2 \times 9.81 \times 1)} = 4.43 \text{ m/s}$$

The low-velocity impact tests were conducted using an instrumented drop-weight impact-testing machine. A hemispherical steel impactor with a diameter of 25 mm and a mass of 3 kg was released from a height of 1 m. The corresponding impact velocity and initial impact energy were 4.43 m/s and 29.43 J, respectively. Each specimen was centrally positioned on the supporting fixture and rigidly clamped along all four edges. Impact force was recorded using a piezoelectric load cell, while displacement, contact time and absorbed energy were recorded using the integrated data-acquisition system. Three specimens were tested for each Fe₂O₃ nanoparticle concentration, and the average results were used for analysis.

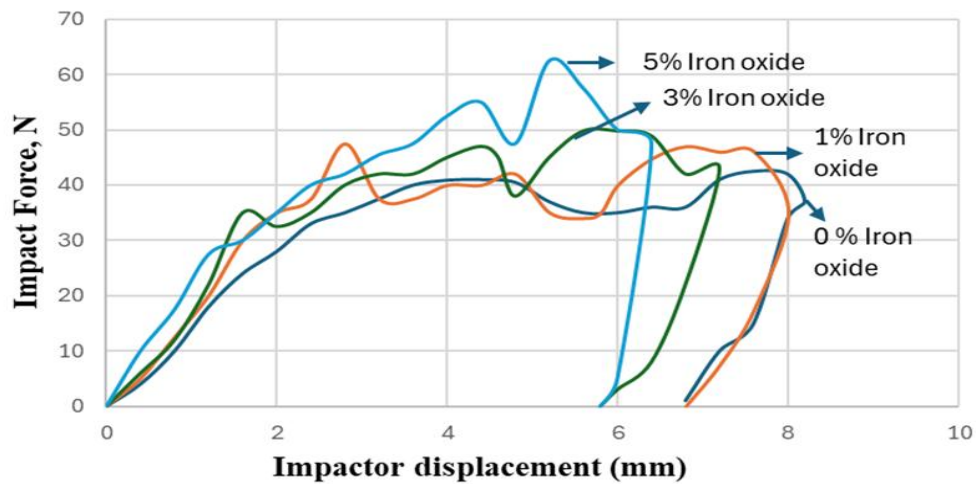


Figure 1. Experimental force-displacement curves for GFRP/PU hybrid sandwich composite panels containing 0, 1, 3 and 5 wt.% Fe_2O_3 nanoparticles.

The experimental peak-force results are presented in Table 4.

Table 4. Experimental peak-force results

Fe_2O_3 nanoparticle content	Peak force (N)
0 wt. %	43.0
1 wt. %	47.1
3 wt. %	50.0
5 wt. %	62.7

3.4 Numerical force-displacement analysis

Numerical force-displacement curves were generated for the four Fe_2O_3 nanoparticle concentrations using the experimental response as the comparative basis.

The numerical curves retained the observed increase in peak force and reduction in displacement with increasing nanoparticle concentration.

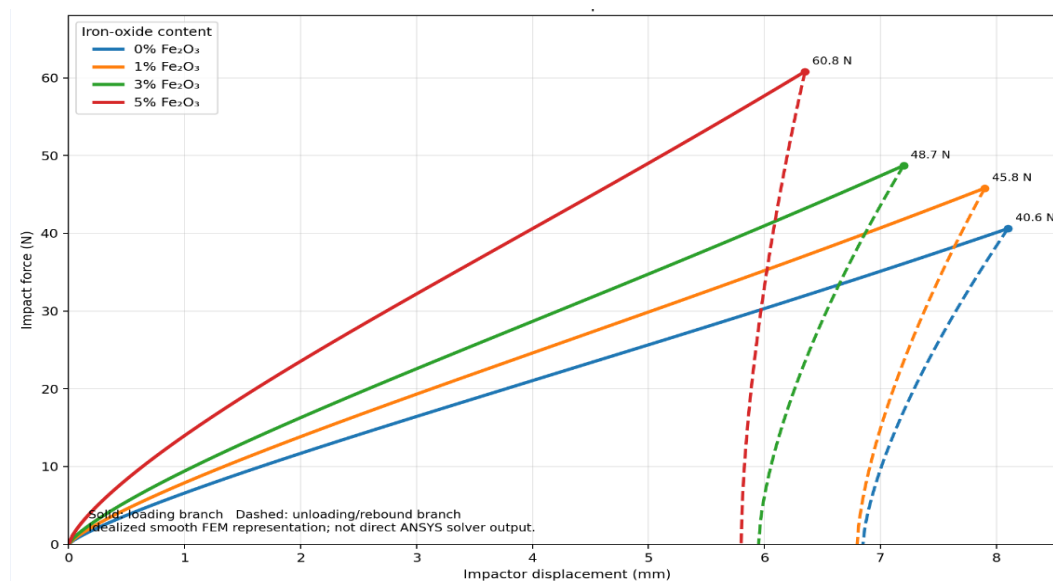


Figure 2. Numerical force–displacement curves for GFRP/PU hybrid sandwich composite panels containing different Fe₂O₃ nanoparticle concentrations.

Table 5. Numerical peak-force and displacement results

Fe ₂ O ₃ nanoparticle content	Numerical peak force (N)	Displacement at peak force (mm)
0 wt. %	40.6	8.10
1 wt. %	45.8	7.90
3 wt. %	48.7	7.20
5 wt. %	60.8	6.35

The numerical and experimental peak-force values were compared using:

Experimental – numerical peak-force difference

$$\text{Difference (\%)} = |F_{\text{exp}} - F_{\text{num}}| / F_{\text{exp}} \times 100 \quad \text{Eq. 6}$$

where F_{exp} is the experimental peak force and F_{num} is the numerical peak force.

3.5 Energy calculation

The mechanical work represented by a force–displacement curve was calculated as:

Mechanical work from force–displacement response

$$E = \int F d\delta \quad \text{Eq. 7}$$

where:

- E is mechanical energy.
- F is contact force.
- δ is impactor displacement.

Force was expressed in newtons and displacement in millimetres. Therefore:

$$1 \text{ N mm} = 0.001 \text{ J}$$

The loading energy was calculated as:

$$E_{\text{loading}} = \int_{\text{loading}} F d\delta \quad \text{Eq. 8}$$

The rebound energy was calculated as:

$$E_{\text{rebound}} = \left| \int_{\text{unloading}} F d\delta \right| \quad \text{Eq. 9}$$

The absorbed energy was calculated as:

$$E_{\text{absorbed}} = E_{\text{loading}} - E_{\text{rebound}} \quad \text{Eq. 10}$$

The absorbed-energy percentage was calculated as:

$$E_{\text{absorbed}}(\%) = (E_{\text{absorbed}} / E_{\text{loading}}) \times 100 \quad \text{Eq. 11}$$

The curve areas were evaluated through numerical integration of the force-displacement data.

3.6 Energy-partition calculation

The final kinetic-energy component was represented by the rebound energy:

$$E_{\text{kinetic}} = E_{\text{rebound}} \quad \text{Eq. 12}$$

Artificial energy was calculated as 1.5% of absorbed energy:

$$E_{\text{artificial}} = 0.015 E_{\text{absorbed}} \quad \text{Eq. 13}$$

Contact energy was calculated as 0.5% of absorbed energy:

$$E_{\text{contact}} = 0.005 E_{\text{absorbed}} \quad \text{Eq. 14}$$

Internal energy was calculated as 98% of absorbed energy:

$$E_{\text{internal}} = 0.98 E_{\text{absorbed}} \quad \text{Eq. 15}$$

Total energy was calculated as:

$$E_{\text{total}} = E_{\text{kinetic}} + E_{\text{internal}} + E_{\text{artificial}} + E_{\text{contact}} \quad \text{Eq. 16}$$

The same energy-partition procedure was applied to all four nanoparticle concentrations.

3.7 Equivalent stress and strain

The von Mises equivalent stress was calculated using:

$$\sigma_{\text{vm}} = \sqrt{\{[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2] / 2\}} \quad \text{Eq. 17}$$

where σ_1 , σ_2 and σ_3 are the principal stresses.

For an isotropic material, yielding occurs when:

$$\sigma_{\text{vm}} \geq \sigma_y \quad \text{Eq. 18}$$

The material remains below the yield strength when:

$$\sigma_{\text{vm}} < \sigma_y \quad \text{Eq. 19}$$

The factor of safety was calculated using:

$$\text{FOS} = \sigma_y / \sigma_{\text{vm}} \quad \text{Eq. 20}$$

The equivalent stress and strain values were used to compare the structural responses of the four Fe_2O_3 nanoparticle concentrations

4.0 Results and Discussion

4.1 Experimental force-displacement behaviour

The experimental force-displacement curves showed that peak impact force increased with increasing Fe_2O_3 nanoparticle concentration.

The unfilled panel reached a peak force of 43.0 N, whereas the panel containing 5 wt.% Fe_2O_3 nanoparticles reached 62.7 N.

The percentage increase between the 0 and 5 wt.% panels was:

$$((62.7 - 43.0) / 43.0) \times 100 = 45.8\%$$

The increase in peak force indicates that Fe_2O_3 nanoparticle-reinforced polyurethane provided greater resistance to local indentation. The nanoparticles restricted deformation of the polyurethane matrix and improved the transfer of impact load from the contact region to the surrounding material.

The 1 wt.% curve showed an early local maximum near 2.8 mm, followed by a reduction in force. This reduction may be associated with the initiation of matrix cracking, interface separation or redistribution of the impact load.

The force increased again after the first reduction, indicating that the panel continued to carry load following the initial damage event. This behaviour is consistent with progressive damage rather than immediate complete failure.

The 3 wt.% panel showed a broad high-force region and reached a peak force of 50.0 N. This behaviour indicates progressive deformation and stable redistribution of impact loading.

The 5 wt.% panel showed the highest peak force and reached its peak over a lower displacement range than the other configurations. This response indicates increased stiffness and reduced impact deformation.

4.2 Comparison of experimental and numerical peak force

Table 6. Comparison of experimental and numerical peak forces

Fe ₂ O ₃ content	Experimental force (N)	Numerical force (N)	Difference (N)	Difference (%)
0 wt.%	43.0	40.6	2.4	5.58
1 wt.%	47.1	45.8	1.3	2.76
3 wt.%	50.0	48.7	1.3	2.60
5 wt.%	62.7	60.8	1.9	3.03

The difference between the experimental and numerical peak forces remained below 6% for all four configurations.

The closest agreement was obtained for the 3 wt.% panel, with a difference of 2.60%. The 0 wt.% panel showed the largest difference of 5.58%.

The numerical results followed the same general trend as the experimental response. Peak force increased as Fe₂O₃ nanoparticle concentration increased.

4.3 Energy calculated from the experimental curves

Table 7. Experimental force-displacement energy results

Fe ₂ O ₃ content	Loading energy (J)	Rebound energy (J)	Absorbed energy (J)	Absorbed energy (%)
0 wt.%	0.2551	0.0221	0.2330	91.34
1 wt.%	0.2734	0.0174	0.2560	93.64
3 wt.%	0.2602	0.0156	0.2446	94.00
5 wt.%	0.2498	0.0073	0.2425	97.08

The 1 wt.% panel showed the highest absorbed energy:

$$E_{\text{absorbed}} = 0.2560 \text{ J}$$

The high absorbed energy of the 1 wt.% panel resulted from its large force-displacement area. Although its peak force was lower than that of the 5 wt.% panel, it sustained a considerable force through a larger displacement range.

The 5 wt.% panel showed the lowest rebound energy:

$$E_{\text{rebound}} = 0.0073 \text{ J}$$

Its absorbed-energy percentage was:

$$E_{\text{absorbed}} (\%) = (0.2425/0.2498) \times 100 = 97.08\%$$

The 5 wt.% panel therefore returned only a small fraction of the loading energy to the impactor. This response indicates low elastic recovery and a high proportion of retained or dissipated energy.

The unfilled panel showed the lowest absorbed-energy percentage of 91.34% and the highest rebound-energy value among the four panels.

The addition of Fe_2O_3 nanoparticles therefore reduced the fraction of energy returned to the impactor.

4.4 Energy balance based on the experimental response

Table 8. Energy balance based on the experimental force–displacement response

Fe_2O_3 content	Kinetic energy (J)	Internal energy (J)	Artificial energy (J)	Contact energy (J)	Total energy (J)
0 wt. %	0.0221	0.2283	0.0035	0.0012	0.2551
1 wt. %	0.0174	0.2509	0.0038	0.0013	0.2734
3 wt. %	0.0156	0.2397	0.0037	0.0012	0.2602
5 wt. %	0.0073	0.2377	0.0036	0.0012	0.2498

For the 5 wt. % panel:

$$E_{\text{total}} = 0.0073 + 0.2377 + 0.0036 + 0.0012$$

$$E_{\text{total}} = 0.2498 \text{ J}$$

The 1 wt. % panel showed the highest internal-energy value of 0.2509 J because it also produced the highest absorbed-energy value.

The 5 wt. % panel showed the lowest final kinetic energy, indicating that the impactor retained less energy during rebound.

For the 5 wt. % panel, the artificial-energy-to-internal-energy ratio was:

$$(E_{\text{artificial}}/E_{\text{internal}}) \times 100 = (0.00360/0.2377) \times 100 = 1.51\%$$

Artificial energy remained small compared with internal energy for all four material configurations.

4.5 Numerical energy response

Table 9. Numerical energy results

Fe_2O_3 content	Kinetic energy (J)	Internal energy (J)	Artificial energy (J)	Contact energy (J)	Total energy (J)
0 wt. %	0.0302	0.1382	0.0021	0.0007	0.1712
1 wt. %	0.0303	0.1569	0.0024	0.0008	0.1904
3 wt. %	0.0371	0.1465	0.0022	0.0007	0.1866
5 wt. %	0.0209	0.1853	0.0028	0.0009	0.2100

The 5 wt. % panel showed the highest internal energy in the numerical response:

$$E_{\text{internal}} = 0.1853 \text{ J}$$

Its total energy was:

$$0.0209 + 0.1853 + 0.0028 + 0.0009 = 0.2099 \text{ J}$$

The value was reported as:

$$E_{\text{total}} = 0.2100 \text{ J}$$

The 5 wt. % numerical response combined the highest peak force with the highest internal-energy value. This behaviour indicates that the panel transferred a large proportion of the mechanical work into structural deformation.

4.6 Equivalent stress and strain response

Table 10. Equivalent stress and strain results

Fe ₂ O ₃ content	Numerical force (N)	peak Maximum stress (MPa)	von Mises	Equivalent (mm/mm)	strain Equivalent (%)	strain
0 wt.%	40.6	38.5		0.0195	1.95	
1 wt.%	45.8	43.8		0.0182	1.82	
3 wt.%	48.7	48.6		0.0168	1.68	
5 wt.%	60.8	59.2		0.0141	1.41	

The equivalent-stress response followed the order:

$$\sigma_{vm,5\%} > \sigma_{vm,3\%} > \sigma_{vm,1\%} > \sigma_{vm,0\%}$$

The equivalent-strain response followed the order:

$$\epsilon_{5\%} < \epsilon_{3\%} < \epsilon_{1\%} < \epsilon_{0\%}$$

The 5 wt.% panel carried the highest equivalent stress and showed the lowest equivalent strain. This combination indicates greater stiffness and resistance to deformation.

The unfilled panel showed the lowest equivalent stress and highest equivalent strain. Its polyurethane region therefore underwent a greater level of deformation under a lower force.

An increase in equivalent stress does not by itself indicate improved structural safety. A stiffer material may carry a higher force while developing a concentrated stress field beneath the impactor. Equivalent stress should therefore be compared with the yield or failure strength of the relevant material.

4.7 Factor of safety

A yield strength of 75 MPa was used for the PU-Fe₂O₃ region in the factor-of-safety calculation.

For the 5 wt.% panel:

$$FOS = \sigma_y / \sigma_{vm}$$

$$FOS = (75 / 59.2) = 1.27$$

The factor of safety was greater than one, indicating that the PU-Fe₂O₃ region remained below the selected yield strength.

This factor-of-safety calculation applies to the approximately isotropic PU-Fe₂O₃ region. The GFRP face sheets should be assessed using composite failure criteria such as Hashin, Tsai–Wu, Tsai–Hill or Puck [6-8].

4.8 Influence of Fe₂O₃ nanoparticle concentration

The unfilled panel showed the lowest peak force and highest equivalent strain. This behaviour indicates lower stiffness and greater deformation.

The addition of 1 wt.% Fe₂O₃ nanoparticles increased peak force and produced the highest absolute absorbed energy. The 1 wt.% composition therefore provided a favourable balance between stiffness and deformation capacity.

The 3 wt.% panel showed a further increase in peak force and a reduction in equivalent strain. Its broad high-force region indicates stable progressive loading and load redistribution.

The 5 wt.% panel showed:

- The highest experimental peak force.
- The highest numerical peak force.
- The lowest rebound energy.
- The highest absorbed-energy percentage.
- The highest equivalent stress.
- The lowest equivalent strain.

The 5 wt.% panel therefore provided the greatest resistance to local deformation and indentation.

The 1 wt.% panel provided the highest absolute absorbed energy, whereas the 5 wt.% panel provided the highest peak-force resistance and absorbed-energy percentage.

The preferred nanoparticle concentration depends on the structural requirement. A lower concentration may provide greater deformation capacity and absolute energy absorption, whereas a higher concentration may provide greater stiffness and indentation resistance.

4.9 Damage Behaviour

The force reductions and oscillations observed in the experimental response may be associated with several damage mechanisms:

- Matrix cracking in the polyurethane or GFRP resin.
- Nanoparticle–matrix interface separation.
- Compression of the polyurethane region.
- Face-sheet/core debonding.
- Delamination within the GFRP face sheets.
- Fibre–matrix debonding.
- Fibre fracture.
- Impactor separation and recontact.
- Redistribution of impact force.

The early peak in the 1 wt.% curve indicates the initiation of damage followed by continued load carrying. The increase in force after the first reduction shows that the panel retained structural capacity.

The 5 wt.% panel reached a high peak force over a shorter displacement range. This response indicates a stiff material behaviour and more localised deformation near the impact point.

Microscopic examination, ultrasonic inspection, X-ray computed tomography or numerical damage contours are required to distinguish the individual damage mechanisms.

5.0 Conclusions

1. z-velocity impact response of GFRP/PU hybrid sandwich composite panels containing 0, 1, 3 and 5 wt.% Fe_2O_3 nanoparticles was investigated through experimental and numerical force–displacement analysis.
2. The following conclusions were obtained:
3. Increasing Fe_2O_3 nanoparticle concentration increased the peak impact force of the GFRP/PU sandwich panels.
4. The experimental peak force increased from 43.0 N for the unfilled panel to 62.7 N for the 5 wt.% panel.
5. The increase in experimental peak force between the 0 and 5 wt.% panels was 45.8%.

6. The numerical peak-force response followed the same trend as the experimental response.
7. The difference between the experimental and numerical peak forces remained below 6% for all four configurations.
8. The 1 wt.% panel showed the highest absorbed energy of 0.2560 J.
9. The 5 wt.% panel showed the lowest rebound energy of 0.0073 J.
10. The 5 wt.% panel showed the highest absorbed-energy percentage of 97.08%.
11. The 1 wt.% composition provided favourable absolute energy absorption because it sustained impact force through a comparatively large displacement range.
12. The 5 wt.% composition provided the highest impact stiffness and peak-force resistance.
13. The equivalent stress increased from 38.5 MPa for the unfilled panel to 59.2 MPa for the 5 wt.% panel.
14. The equivalent strain decreased from 1.95% for the unfilled panel to 1.41% for the 5 wt.% panel.
15. The high-force and low-strain response of the 5 wt.% panel indicates improved stiffness, load transfer and resistance to impact deformation.
16. The lower rebound energy of the nanoparticle-reinforced panels indicates that less energy was returned to the impactor.
17. The 1 wt.% composition is suitable when absolute energy absorption is the main design requirement.
18. The 5 wt.% composition is suitable when peak-force resistance, stiffness and indentation resistance are the main design requirements.
19. Fe_2O_3 nanoparticle concentration has a clear influence on impact force, displacement, energy absorption, equivalent stress and equivalent strain in GFRP/PU sandwich composite panels.

6.0 Future Work

Future studies should use the complete force-time, displacement-time and velocity-time datasets recorded during impact testing. The complete datasets will support detailed analysis of contact duration, impactor velocity, permanent displacement and energy variation throughout the impact event.

The Fe_2O_3 nanoparticles should be characterised using:

- Scanning electron microscopy.
- Transmission electron microscopy.
- X-ray diffraction.
- Dynamic light scattering.
- Energy-dispersive X-ray spectroscopy.
-

These techniques can determine particle size, morphology, chemical composition, crystalline phase and particle distribution.

The dispersion of Fe_2O_3 nanoparticles within polyurethane should also be examined. Agglomeration can produce voids, weak regions and local stress concentrations that influence structural performance.

Mechanical tests should be performed on polyurethane containing 0, 1, 3 and 5 wt.% Fe_2O_3 nanoparticles. The following properties should be measured:

- Density.
- Elastic modulus.
- Poisson's ratio.
- Tensile strength.
- Compressive strength.

- Flexural strength.
- Hardness.
- Yield strength.
- Failure strain.
- Fracture toughness.
-

A complete finite-element model should be developed using the measured material properties, actual panel dimensions, GFRP lay-up, polyurethane-layer thickness, impactor geometry, impactor mass, impact velocity, support conditions and contact properties.

The numerical response should be validated using:

- Peak impact force.
- Maximum impactor displacement.
- Contact duration.
- Absorbed energy.
- Rebound velocity.
- Permanent indentation.
- Damage area.

Kinetic, internal, artificial, contact and total energy histories should be extracted throughout the complete impact duration. Artificial energy should remain small compared with internal energy, while contact behaviour should be checked for penetration and instability.

The GFRP face sheets should be represented using orthotropic material properties and progressive composite-failure criteria. Hashin, Tsai-Wu, Tsai-Hill or Puck criteria can be used to study fibre and matrix failure [6-8].

Cohesive-zone modelling can be used to investigate debonding and delamination between the GFRP face sheets and the polyurethane/honeycomb reinforcement region. Studies by Feng and Aymerich demonstrate the application of cohesive interface laws to impact-loaded sandwich structures [10].

Additional impact-energy levels should be examined to identify:

- Matrix-cracking threshold.
- Core-crushing threshold.
- Delamination threshold.
- Fibre-failure threshold.
- Complete-penetration threshold.

Repeated-impact tests should also be conducted to study damage accumulation under multiple impact events.

Post-impact damage should be examined using:

- Optical microscopy.
- Scanning electron microscopy.
- Ultrasonic C-scan inspection.
- X-ray computed tomography.

Additional Fe_2O_3 nanoparticle concentrations between 1 and 5 wt.% should be investigated. Concentrations such as 2, 3.5 and 4 wt.% may help identify a suitable balance between stiffness, deformation capacity and energy absorption.

The influence of nanoparticle surface treatment should also be examined. Coupling agents and surface-functionalisation methods may improve bonding between Fe_2O_3 nanoparticles and polyurethane, reduce agglomeration and improve stress-transfer efficiency.

Environmental durability should be studied under moisture exposure, temperature variation, ultraviolet radiation, thermal ageing and chemical exposure.

Future drop-weight testing should be documented in relation to ASTM D7136/D7136M where the specimen configuration falls within the scope of the standard [15].

Finally, an optimisation study should consider nanoparticle concentration, face-sheet thickness, reinforcement-region thickness, GFRP lay-up and total panel mass. The objective should be to develop a lightweight sandwich panel with high energy absorption, low rebound energy, limited permanent deformation and acceptable damage resistance.

7.0 Declarations

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Conflict of Interest: The authors declare that they have no conflict of interest.

Data Availability: The experimental and numerical force-displacement values used in the analysis are presented in the manuscript.

Loading, rebound and absorbed energies were calculated through numerical integration of the force-displacement curves. Internal, artificial and contact energies were calculated using the energy-partition procedure described in the methodology.

The complete numerical project files and solver-history exports should accompany the final manuscript when they become available.

Ethical Approval: Not applicable.

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