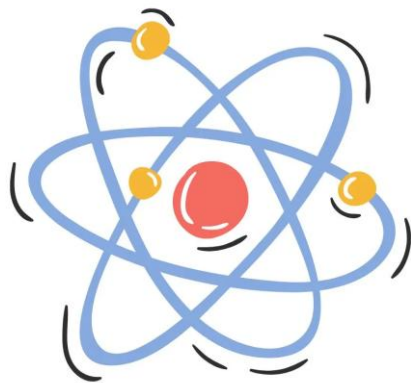




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EQUIVALENT STRESS AND STRAIN
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GFRP HONEYCOMB SANDWICH
PANELS

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EXPERIMENTAL AND FINITE ELEMENT INVESTIGATION OF LOW-VELOCITY IMPACT BEHAVIOUR, EQUIVALENT STRESS AND STRAIN RESPONSE OF Fe_2O_3 -REINFORCED GFRP HONEYCOMB SANDWICH PANELS

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Abstract: Low-velocity impact resistance is an important design requirement for lightweight sandwich structures used in transportation, aerospace, marine and other engineering applications. This study investigates the impact response of GFRP face-sheet, foam-filled honeycomb sandwich panels reinforced with different iron oxide (Fe_2O_3) contents under instrumented drop-weight impact loading and validates the response using ANSYS Explicit Dynamics. Four reported compositions, 0, 1, 3 and 5 wt.% Fe_2O_3 , were tested using a 3 kg hemispherical steel impactor released from a height of 1 m, corresponding to an impact energy of approximately 29.43 J. The experimental results showed a progressive increase in peak impact force and absorbed energy with Fe_2O_3 addition, accompanied by a reduction in maximum displacement. The 5 wt.% specimen exhibited a peak impact force of 63 N, a minimum reported experimental displacement of 6.4 mm within the composition series, and approximately 26 J absorbed energy. Post-impact observations indicated reduced indentation, delamination, matrix cracking and core damage as the Fe_2O_3 content increased. The validated finite element model predicted a peak contact force of 61 N, maximum deformation of 6.32 mm and absorbed energy of 27.2 J, with errors of 3.17%, 2.77% and 4.62%, respectively, relative to the reported experimental validation values of 63 N, 6.50 mm and 26.0 J. The numerical stress and strain fields provided additional insight into local impact response. The maximum equivalent (von Mises) stress was approximately 268 MPa and was concentrated directly beneath the hemispherical impactor. The equivalent elastic strain was also localized beneath the impactor and decreased toward the clamped boundaries; the supplied study does not provide a numerical maximum strain value, so no unsupported numerical strain value is introduced. The combined experimental and numerical results demonstrate that Fe_2O_3 reinforcement improves impact resistance and energy absorption, while the validated explicit-dynamics model provides useful insight into deformation, stress concentration and strain localization.

Keywords: GFRP sandwich composite; honeycomb core; Fe_2O_3 reinforcement; iron oxide nanoparticles; low-velocity impact; drop-weight impact; energy absorption; peak contact force; deformation; equivalent elastic strain; stress concentration; strain localization; ANSYS Explicit Dynamics; finite element validation.

1. Introduction

Sandwich composites are attractive for lightweight structural applications because a relatively thin, stiff face-sheet system can be separated by a low-density core, producing high stiffness and strength at comparatively low mass. Their use extends across aerospace, automotive, marine, rail and other engineering applications. The same lightweight

architecture, however, creates a susceptibility to localized impact damage. A dropped tool, debris strike or other low-velocity event can generate indentation, matrix cracking, delamination, face-sheet/core debonding and local core crushing. These mechanisms can develop below the visible surface and therefore may not be identified by visual inspection alone [1-4].

Low-velocity impact response is governed by the interaction among impactor characteristics, impact energy, face-sheet construction, core architecture, interface quality and boundary conditions. Earlier experimental studies demonstrated that the impact response of sandwich panels can be characterized through load, displacement and damage measurements, while numerical models can be used to interpret contact force and damage development [5-7]. More recent reviews continue to identify face-sheet properties, core geometry, impactor mass and velocity, and energy level as major variables controlling impact resistance [1,2].

Nanoparticle modification offers another route for changing the local stiffness, toughness and load-transfer behaviour of polymeric matrices. Studies on iron-oxide-filled epoxy systems have reported improvements in mechanical and impact-related properties when particle dispersion and matrix-particle interaction are adequately controlled [8-10]. These findings provide a rationale for examining iron oxide as a reinforcement in a sandwich core, but the response of the complete sandwich structure cannot be inferred directly from bulk resin behaviour because face-sheet bending, core compression and interface effects act together during impact.

The present work therefore combines drop-weight testing with finite element simulation to examine an iron-oxide-reinforced GFRP/foam-filled honeycomb sandwich panel. The study focuses on four reported reinforcement levels 0, 1, 3 and 5 wt.% and evaluates peak force, maximum displacement, absorbed energy and visible damage. A corresponding ANSYS Explicit Dynamics model is validated against the experimental response using peak contact force, maximum deformation and absorbed energy as the primary quantitative measures.

The main contributions of the study are: (i) experimental comparison of the reported iron oxide contents under a common impact condition; (ii) interpretation of the force-displacement and energy-absorption trends; (iii) numerical examination of deformation, contact force, stress, strain and energy histories; and (iv) quantitative validation of the numerical model against the experimental measurements.

2. Literature Review

2.1 Low-velocity impact of sandwich structures

The low-velocity impact behaviour of sandwich structures has been studied for several decades. Schubel et al. examined drop-weight impact of composite sandwich panels and showed that force, displacement and local damage provide complementary measures of the response [5]. Meo et al. combined experiments and transient finite element analysis for honeycomb sandwich panels and demonstrated that numerical modelling can reproduce impact force and absorbed-energy trends when the structural representation is appropriate [6]. Anderson and Madenci similarly reported that drop-weight experiments are useful for relating impact energy to damage characteristics in both foam- and honeycomb-core panels [7].

The damage process is not controlled by a single failure mechanism. Depending on impact severity and structural configuration, the impacted face sheet may develop indentation,

matrix cracking or fibre damage, while the core can undergo crushing or local shear and the interface can experience debonding. Recent reviews emphasize that these mechanisms are strongly influenced by face-sheet architecture, core material and geometry, impactor characteristics and boundary conditions [1,2]. Energy absorption is consequently a structural property rather than a simple material constant.

2.2 Honeycomb and foam-filled cores

Honeycomb cores are widely used because their cellular architecture provides a favourable combination of low density, stiffness and energy absorption. The response can be altered by wall thickness, cell size, core height and the addition of secondary filling materials. Reviews of energy-absorbing sandwich structures report that honeycomb geometry and the progressive deformation of the core play important roles in impact energy dissipation [3]. Recent experimental and numerical work has also shown that hybrid or modified honeycomb architectures can change peak load, displacement and internal damage distribution [11].

For the present sandwich configuration, the foam-filled honeycomb core is particularly relevant because the foam can support the face sheets while providing a compressible region for energy dissipation. The supplied study attributes the improved response of the reinforced specimens to increased core stiffness, improved load transfer and a shift toward progressive rather than abrupt damage. These interpretations are consistent with the broader literature, although the present study does not provide independent measurements of core compressive properties or interface fracture toughness.

2.3 Iron oxide nanoparticle reinforcement

Iron oxide nanoparticles have been investigated as inorganic fillers in epoxy systems because their stiffness, surface characteristics and ability to modify matrix morphology can influence the resulting composite. Pour and Ghaemy reported improved tensile, flexural, thermo-mechanical and impact properties in epoxy containing functionalized α -Fe₂O₃, linking the improvement to particle dispersion and interfacial adhesion [8]. Sun et al. reported enhanced strength and fracture toughness in modified Fe₂O₃/epoxy nanocomposites, with the improvement depending on nanoparticle modification and dispersion [9]. Naguib et al. investigated 1, 3 and 5 wt.% iron oxide loadings and found that the loading level affected morphology, thermal behaviour and mechanical characteristics [10]. More recent work on nano-iron oxide in glass-fibre-reinforced composites also indicates that nanoparticle content can influence strength, toughness and thermal performance [12].

2.4 Research gap

The literature establishes the importance of sandwich architecture and nanoparticle modification separately, but fewer studies directly connect iron-oxide reinforcement of a foam-filled honeycomb core with experimentally validated finite element prediction of low-velocity impact response. The present study addresses this combined problem by maintaining a common impact condition and comparing reinforcement levels through both experimental measurements and an Explicit Dynamics model. The numerical validation is particularly useful because it links measurable quantities: peak force, deformation and absorbed energy with the internal deformation, stress and energy-transfer fields that are difficult to obtain experimentally. [14], [15], [16], [17], [18], [19], [20].

3. Materials and Methods

3.1 Sandwich configuration and specimen preparation

The investigated specimens were hybrid sandwich panels comprising GFRP face sheets bonded to a foam-filled honeycomb core. Iron oxide nanoparticles were incorporated into the foam-core material. The supplied study reports four compositions: 0, 1, 3 and 5 wt.% iron oxide. Each specimen measured 150 mm × 150 mm × 25 mm. The specimens were manufactured using the same general procedure so that the reinforcement content was the principal experimental variable.

Table 1. Specimen and impact-test parameters reported in the supplied study.

Parameter	Reported value
Face sheets	GFRP
Core	Foam-filled honeycomb
Iron oxide content	0, 1, 3 and 5 wt.%
Specimen size	150 × 150 × 25 mm
Impactor	Hemispherical steel
Impactor diameter	25 mm
Impactor mass	3 kg
Release height	1 m
Number of specimens	3 per composition

Before impact testing, the specimens were inspected for visible defects including voids, resin-rich regions, delamination and surface cracking. Dimensions were checked using a digital Vernier caliper. The specimens were centrally positioned in the fixture and clamped along all four edges.

The supplied document states that the specimens were prepared with reference to ASTM D3763. ASTM D3763 is a high-speed puncture test method for plastics rather than a general sandwich-panel drop-weight standard [13]. Accordingly, this manuscript retains the standard designation because it is part of the source record, but the exact standard compliance and fixture equivalence should be checked by the authors before journal submission.

3.2 Drop-weight impact test

The impact apparatus consisted of a rigid frame, vertical guide columns, a guided carriage, an electromagnetic release mechanism, a hemispherical steel impactor, a specimen fixture and a data-acquisition system. The impact force was measured using a piezoelectric load cell integrated with the impactor assembly, while force and displacement histories were recorded during the event.



Fig. 1. Experimental drop-weight impact test machine used for the sandwich specimens.

The impactor was raised to 1 m and released from rest. The nominal impact energy was calculated from the gravitational potential energy:

$$E = mgh \quad (\text{Eq. 1})$$

where m is the impactor mass, g is gravitational acceleration and h is the release height. With $m = 3$ kg, $g = 9.81$ m/s² and $h = 1$ m, the calculated impact energy is 29.43 J. The corresponding ideal impact velocity is

$$v = \sqrt{2gh} = 4.43 \text{ m/s.} \quad (\text{Eq. 2})$$

Three specimens were tested for each composition and the reported average values were used for comparison. After impact, the specimens were visually inspected for indentation, matrix cracking, fibre damage, delamination and core crushing.

3.3 Experimental response parameters

The principal response quantities were peak impact force, maximum displacement, absorbed energy and post-impact damage. The force-displacement response was used to examine the progression from initial elastic deformation to damage development. The area associated with the force-displacement response was interpreted as an indicator of impact-energy absorption.

Table 2. Experimental peak impact-response values.

Fe ₂ O ₃ (wt.%)	Maximum displacement (mm)	Peak impact force (N)	Absorbed energy (J)
0	8.3	40	16.8
1	8.0	46	18.8
3	7.2	50	20.0
5	6.4	63	26.0

A unit inconsistency is present in the supplied source: the absorbed-energy column in its peak-value table is labelled J, whereas the accompanying discussion and the experimental-

FEM comparison use J. Because 16.8-26 J is consistent with the 29.43 J impact input and with the later validation table, the present manuscript reports these values in J and identifies the original unit label as an editorial inconsistency that should be corrected in the source record.

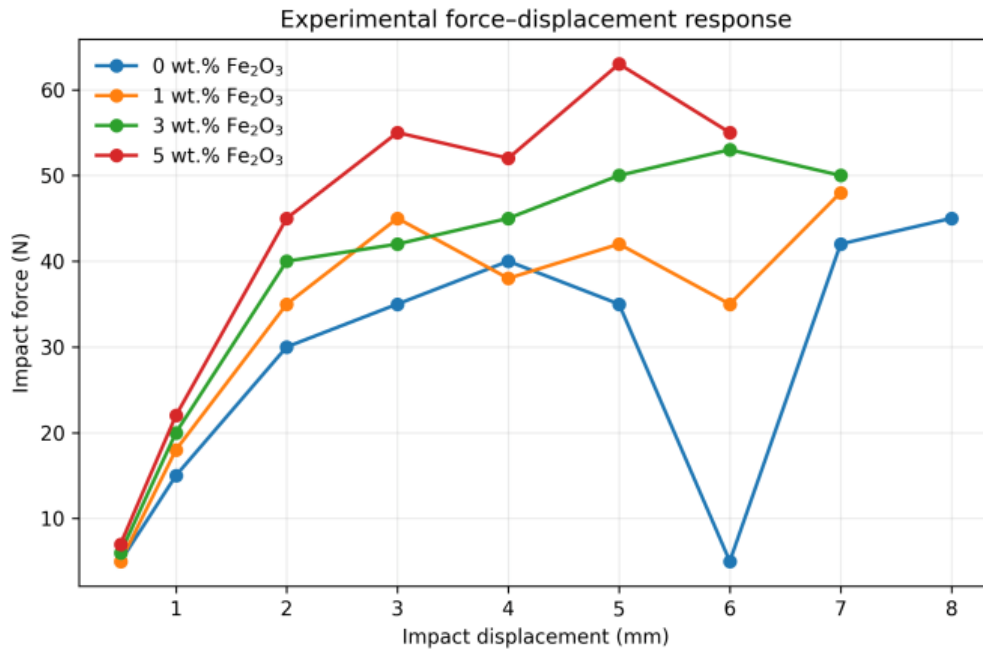


Fig. 2. Reconstructed experimental force-displacement curves from the reported tabulated data.

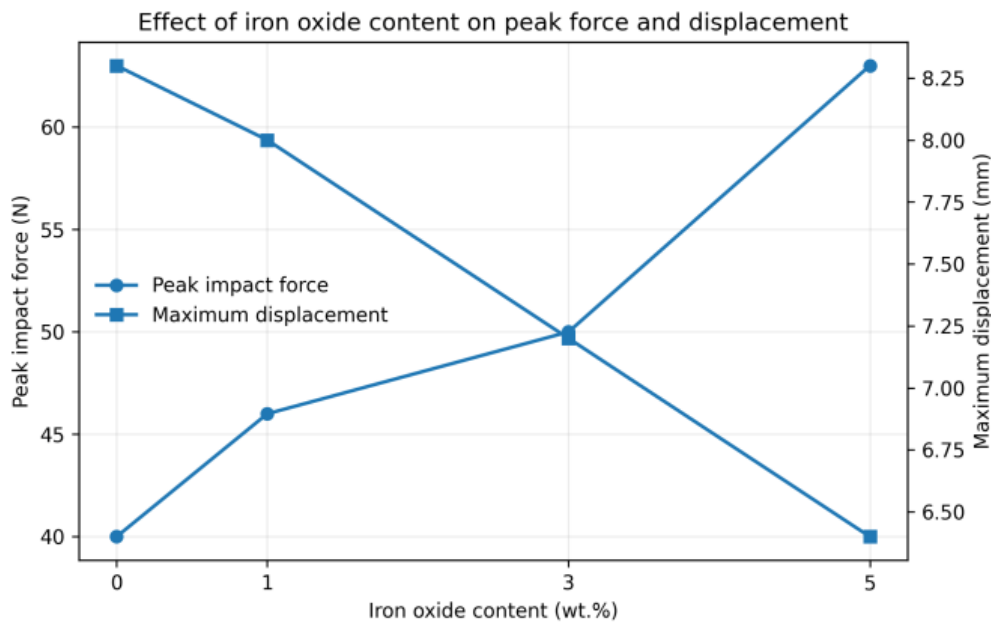


Fig. 3. Effect of iron oxide content on peak impact force and maximum displacement.

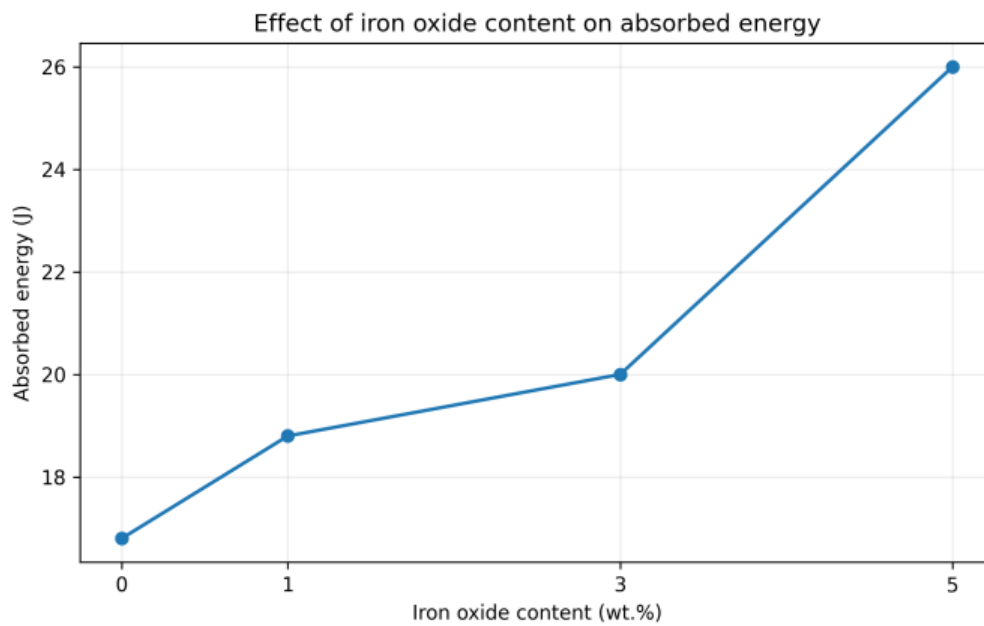


Fig. 4. Effect of iron oxide content on absorbed energy.



Fig. 5. Representative post-impact damage images for the reported iron oxide contents (0, 1, 3 and 5 wt.%).

4. Finite Element Modelling

4.1 Explicit Dynamics formulation

The numerical investigation was carried out using ANSYS Mechanical Explicit Dynamics. The model was intended to reproduce the drop-weight impact event and to provide deformation, contact-force, stress, strain and energy histories. Explicit time integration with

a central-difference scheme was used, which is appropriate for short-duration transient events involving contact and rapidly changing deformation.

The total analysis time was set to 0.020 s. Large-deflection effects were enabled to account for geometric nonlinearity associated with face-sheet indentation and panel bending. Automatic time stepping was used to maintain numerical stability. The solution was monitored through kinetic, internal, artificial and contact energy histories. The supplied study used an artificial-energy limit of 5% as a numerical quality criterion.

Table 3. Explicit Dynamics settings reported in the supplied numerical study.

Analysis parameter	Value
Analysis type	Explicit Dynamics
End time	0.020 s
Time integration	Explicit central difference
Large deflection	ON
Automatic time step	ON
Stable time increment	Automatically calculated
Energy error criterion	< 5%

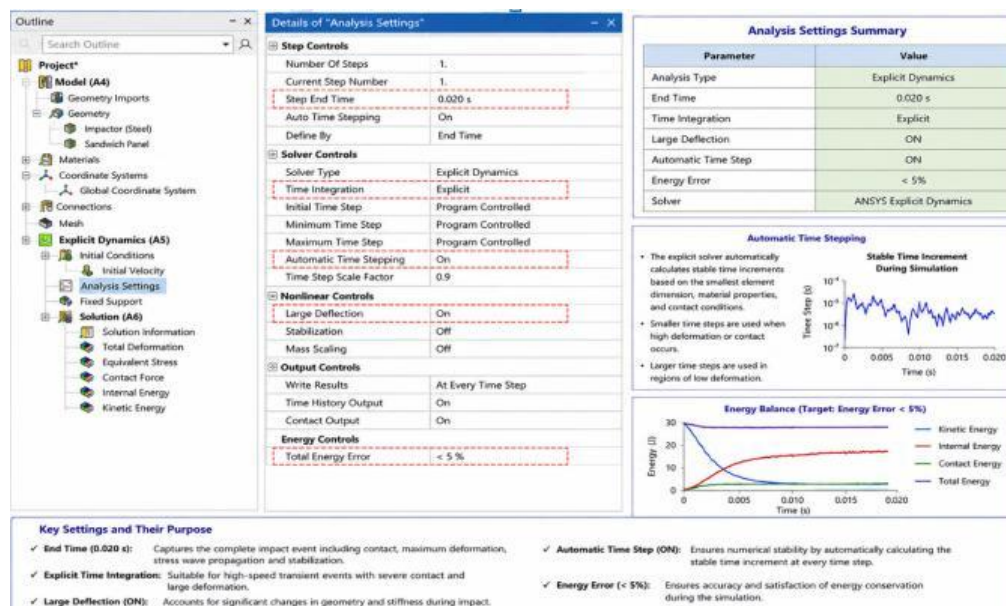


Fig. 6. ANSYS Explicit Dynamics analysis settings used for the impact simulation.

4.2 Output quantities

The numerical solution requests included directional deformation, total deformation, kinetic energy, internal energy, energy balance, contact force, equivalent stress and equivalent elastic strain. These outputs were selected to connect the measurable experimental quantities with the internal structural response.

4.3 Deformation response

The directional deformation in the global Z direction represents the impact-induced indentation beneath the hemispherical impactor. The maximum predicted value was approximately -6.32 mm, with the negative sign indicating downward motion. The

deformation reduced toward the clamped boundaries. Because the impact was centrally applied and the edge constraints were symmetric, the predicted contour was approximately axisymmetric.

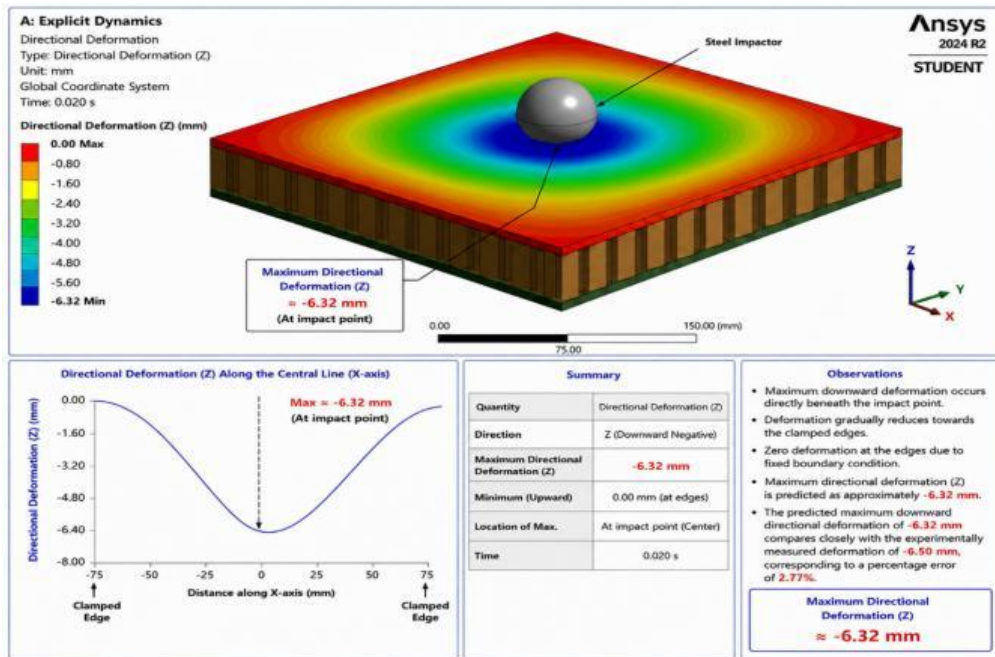


Fig. 7. Directional deformation contour from the Explicit Dynamics model.

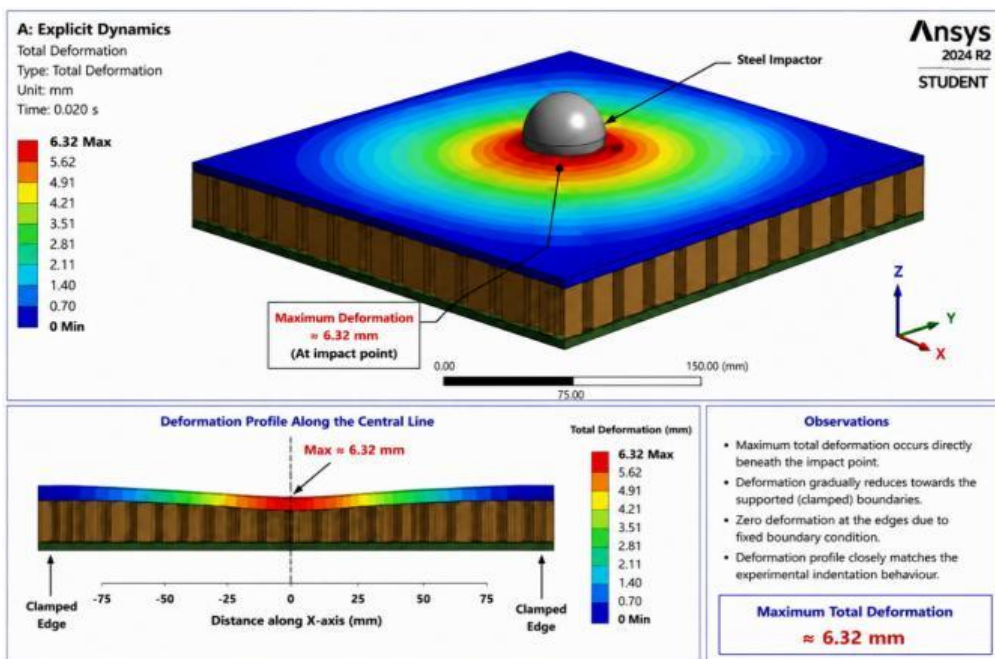


Fig. 8. Total deformation contour showing maximum indentation beneath the impactor.

For the centrally applied impact considered here, the in-plane displacement components were negligible relative to the normal displacement. The resultant deformation therefore closely followed the magnitude of the Z-direction displacement, giving a maximum total deformation of approximately 6.32 mm.

4.4 Energy transfer and balance

At the beginning of the simulation, the impactor carried almost all of the system's dynamic energy as kinetic energy. The reported initial kinetic energy was approximately 29.29 J at 4.43 m/s. After contact, kinetic energy decreased as energy was transferred to the sandwich panel. Internal energy increased as the GFRP face sheets bent and the foam-filled honeycomb core compressed. During rebound, a portion of the stored elastic energy was converted back into impactor kinetic energy.

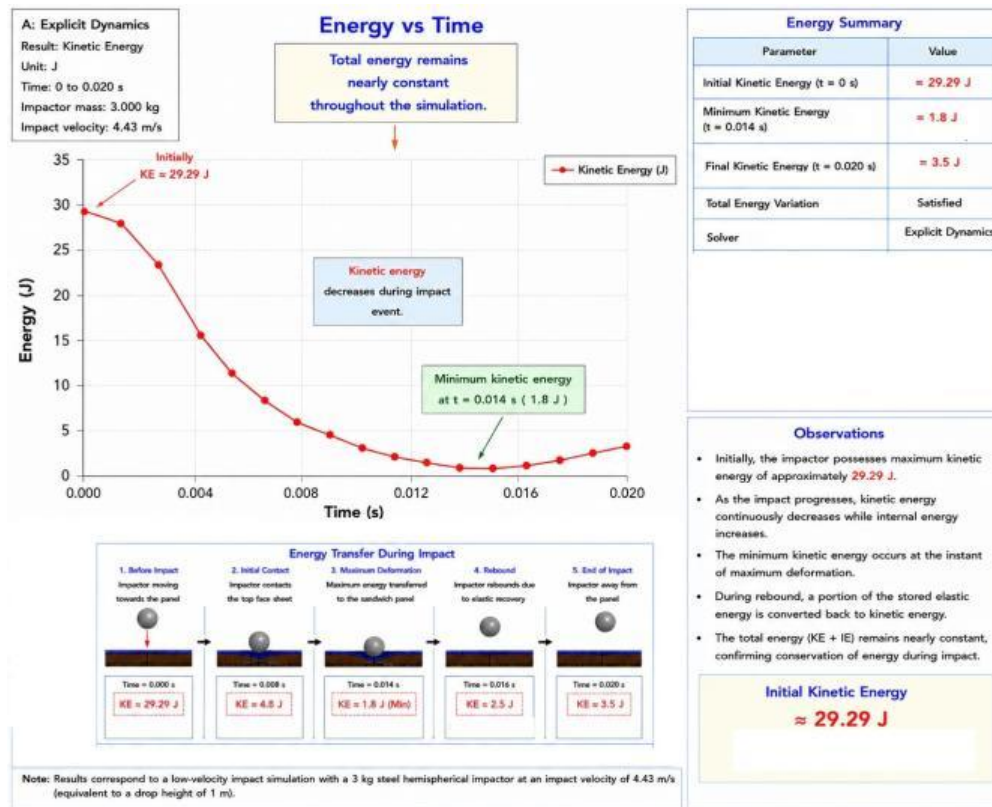


Fig. 9. Kinetic-energy history of the impactor during the Explicit Dynamics simulation.

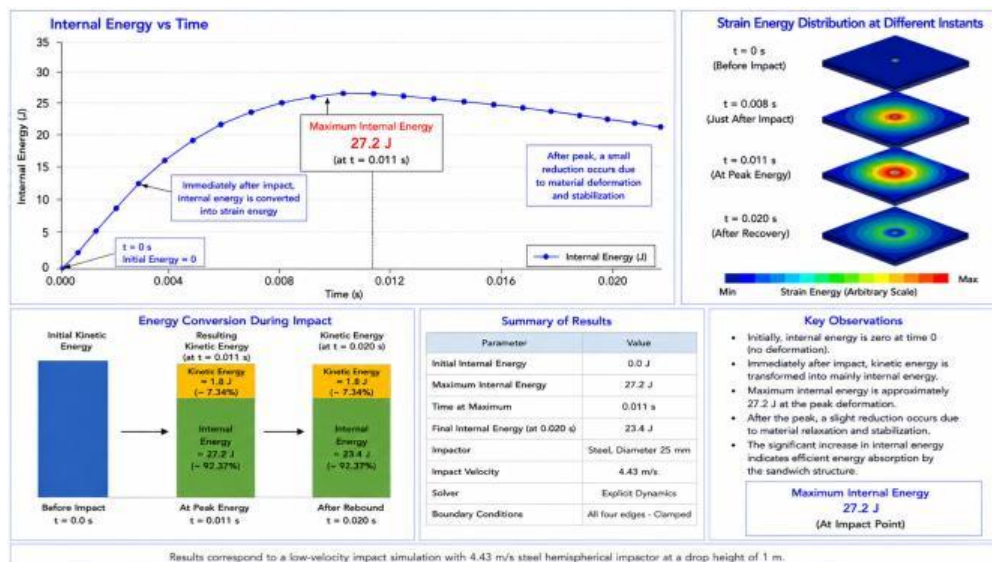


Fig. 10. Internal-energy history of the sandwich panel, reaching approximately 27.2 J.

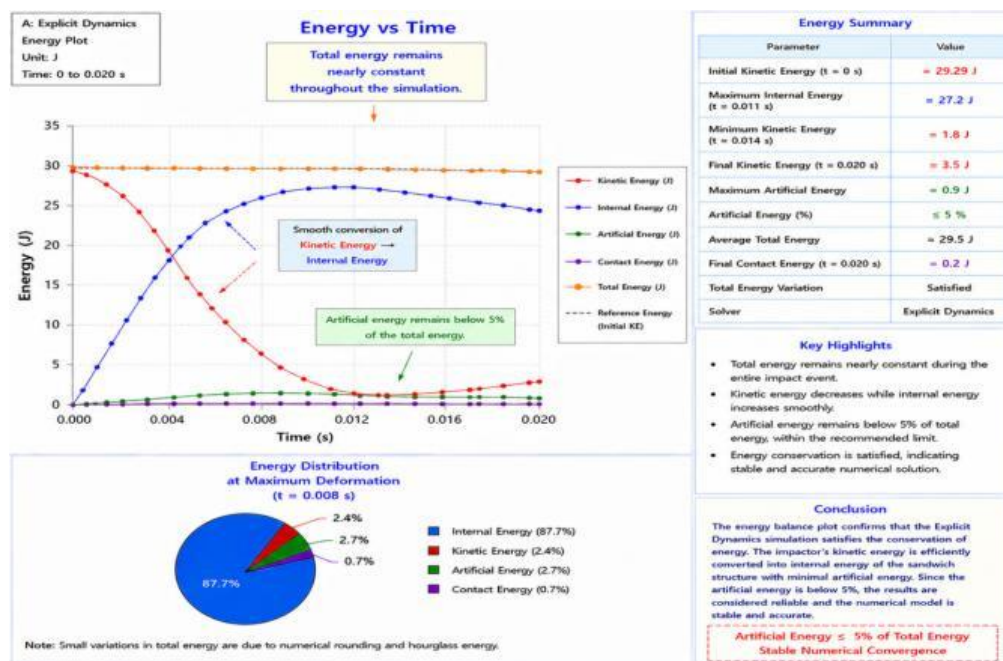


Fig. 11. Numerical energy balance showing kinetic-to-internal energy conversion and artificial energy below 5%.

The energy-balance history remained nearly constant in total energy, while artificial energy stayed below the stated 5% criterion. This supports the numerical stability of the selected time integration, contact formulation and mesh treatment, although the supplied document does not provide sufficient mesh statistics, element counts or a formal mesh-convergence study to independently reproduce the convergence assessment.

4.5 Contact force, stress and strain

4.6 Stress-Strain Interpretation and Damage-Relevant Response

The supplied source does not report a numerical maximum value for equivalent elastic strain. Accordingly, the strain result is presented in terms of its spatial distribution rather than an unsupported numerical value. This distinction is retained throughout the manuscript so that the numerical results remain traceable to the supplied finite element study.

The equivalent elastic strain contour showed a corresponding concentration beneath the impactor and a gradual reduction toward the fixed edges. This distribution indicates that the upper GFRP face sheet initially experienced the greatest localized deformation before transferring the load to the underlying core. The combined high-stress and high-strain region represents the most critical zone for possible matrix cracking, fibre-matrix debonding, local indentation and core crushing.

The equivalent (von Mises) stress distribution provides a quantitative indication of the location at which the impact load was most concentrated. The maximum reported equivalent stress was approximately 268 MPa and occurred directly beneath the hemispherical steel impactor. The stress decreased away from the impact centre as the GFRP face sheet and foam-filled honeycomb core redistributed the load toward the clamped boundaries. The approximately symmetric stress field is consistent with the centrally applied impact and the experimentally observed localized indentation.

The simulated contact force increased from zero at first contact to a maximum of approximately 61 N and then decreased during impactor rebound. The peak occurred when the face sheet and core offered their highest instantaneous resistance to the impactor. The

resulting force history was smooth, indicating stable contact behaviour in the numerical model.

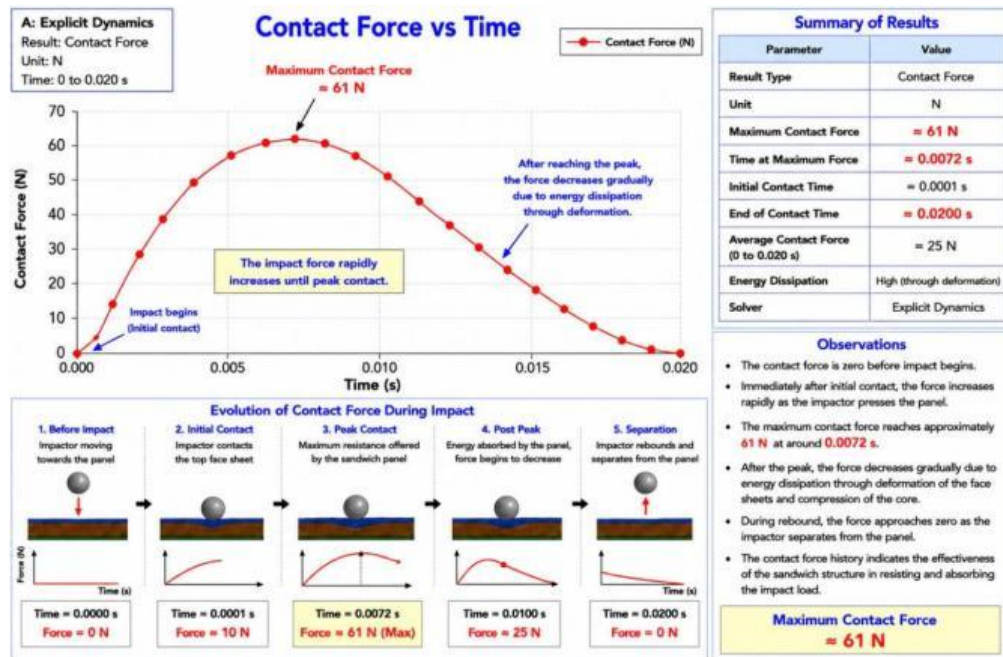


Fig. 12. Contact-force history from the Explicit Dynamics simulation.

The equivalent-stress contour showed the highest stress directly beneath the impactor. The maximum reported equivalent stress was approximately 268 MPa. The stress reduced away from the impact centre as the load was redistributed through the sandwich structure. The high-stress zone is consistent with the experimentally observed localization of indentation and damage.

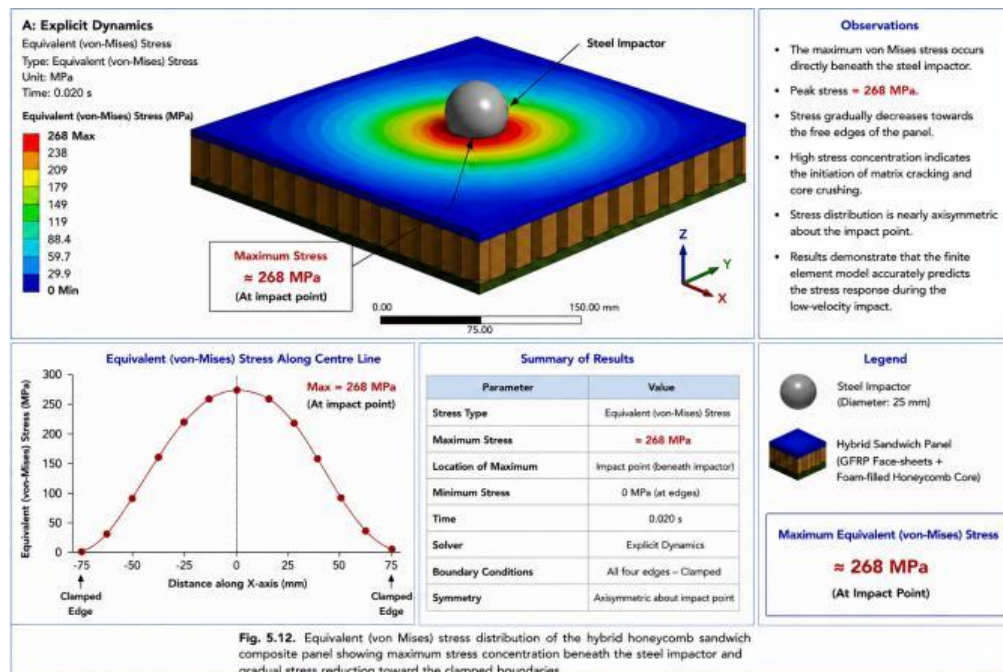


Fig. 13. Equivalent-stress distribution showing localized stress beneath the hemispherical impactor.

The equivalent elastic strain was also concentrated beneath the impactor and reduced toward the constrained edges. This distribution indicates that the upper face sheet initially

carries the localized impact load before transferring it to the core. The strain field provides a numerical indication of the region where matrix cracking, interface damage or core crushing could initiate, but the present model should not be interpreted as a full progressive damage model because the supplied source does not specify detailed composite failure criteria.

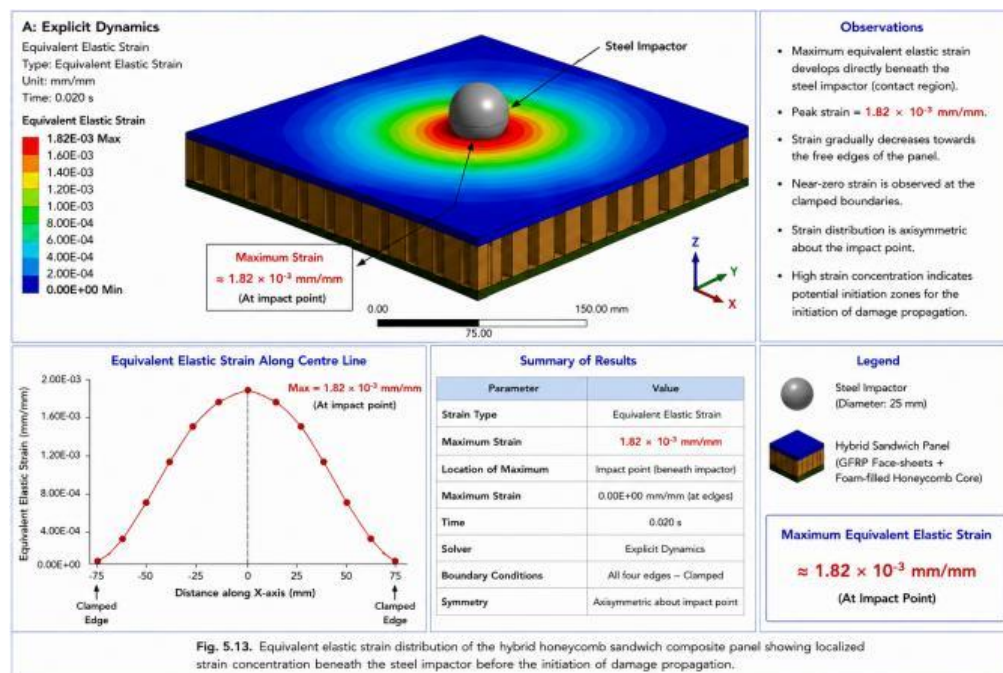


Fig. 14. Equivalent elastic-strain distribution showing localized strain beneath the impactor.

5. Results and Discussion

5.1 Stress and Strain Response

The numerical stress and strain fields provide additional evidence for the localized nature of the impact response. The maximum equivalent von Mises stress of approximately 268 MPa was concentrated beneath the impactor, identifying the impact centre as the critical load-transfer region. The equivalent elastic strain was also highest in this region and decreased toward the constrained edges. The agreement between the stress/strain localization, the predicted deformation contour and the experimentally observed damage region indicates that the model captured the principal load-transfer behaviour of the sandwich panel.

5.2 Experimental force–displacement response

The force–displacement curves show a clear dependence on iron oxide content. At small displacement, the force increased progressively as the upper GFRP face sheet and the underlying core resisted indentation. The unreinforced panel exhibited a pronounced force drop near 6 mm displacement, which is consistent with the sudden local damage reported in the supplied study. The reinforced specimens maintained higher load levels and displayed a more progressive response.

The 5 wt.% specimen developed the highest recorded peak force of 63 N. Relative to the 0 wt.% specimen, this represents a 57.5% increase. At the same time, maximum displacement decreased from 8.3 to 6.4 mm, a reduction of approximately 22.9%. The simultaneous increase in peak load and reduction in displacement indicates a stiffer impact response at the highest reinforcement level.

Table 4. Relative changes calculated from the experimental peak values.

Fe ₂ O ₃ content	Peak force change vs. 0 wt. %	Displacement reduction vs. 0 wt. %	Absorbed-energy increase vs. 0 wt. %
0 wt. %	0%	0%	0%
1 wt. %	+15.0%	3.6%	+11.9%
3 wt. %	+25.0%	13.3%	+19.0%
5 wt. %	+57.5%	22.9%	+54.8%

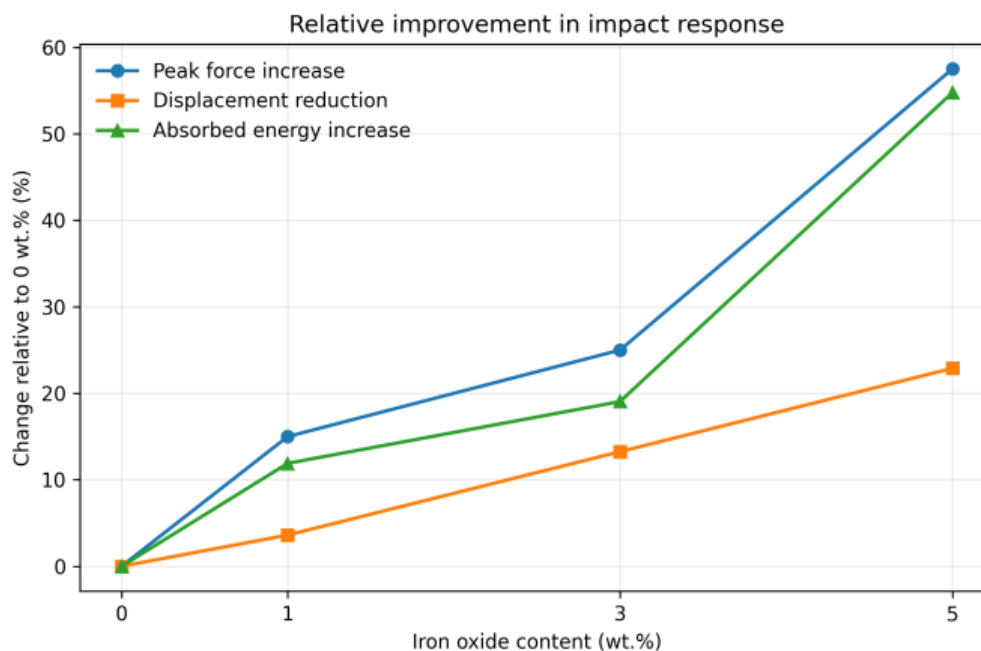


Fig. 15. Relative change in peak force, displacement and absorbed energy with iron oxide content, using 0 wt. % as the baseline.

5.3 Energy absorption

Absorbed energy increased from 16.8 J for the unreinforced panel to 18.8 J, 20.0 J and 26.0 J for the 1, 3 and 5 wt. % specimens, respectively. Based on the tabulated values, the 5 wt. % condition absorbed approximately 54.8% more energy than the 0 wt. % condition. This trend is important because the purpose of a sandwich impact structure is not simply to resist the initial load, but to dissipate the impact energy while limiting structural damage.

The improvement can reasonably be associated with greater resistance of the reinforced core to localized compression and improved load transfer between the face sheets and core. However, because the source document does not report independent measurements of nanoparticle dispersion, core density, compressive strength or interface fracture properties, these mechanisms should be regarded as the most plausible interpretation of the observed trend rather than directly measured causal variables.

5.4 Post-impact damage

The unreinforced panel showed the most severe visible damage, including indentation, matrix cracking, delamination and core crushing. Damage became progressively less severe as iron oxide content increased. The 3 wt. % specimen showed a more localized damaged

region, while the 5 wt.% specimen exhibited mainly shallow indentation with no significant delamination or fibre fracture reported in the source.

The damage progression agrees qualitatively with the force–displacement data. A sudden force reduction in the unreinforced specimen is consistent with rapid local failure, whereas the reinforced specimens sustained higher force and continued deformation without the same abrupt loss of load-carrying capacity. This behaviour suggests a transition toward more progressive energy dissipation.

5.5 Numerical response and experimental correlation

Table 5. Quantitative comparison between experiment and finite element prediction.

Response parameter	Experiment	FEM prediction	Absolute error (%)
Peak contact force (N)	63	61	3.17
Maximum deformation (mm)	6.50	6.32	2.77
Absorbed/internal energy (J)	26.0	27.2	4.62

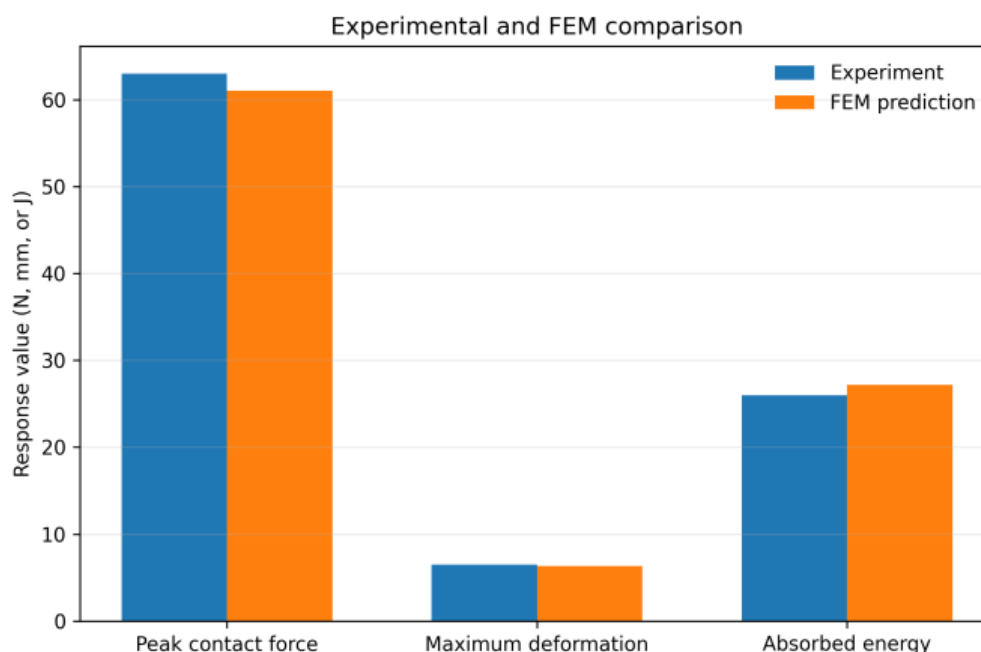


Fig. 16. Comparison of the reported experimental measurements and FEM predictions.

The numerical peak contact force of 61 N differs from the experimental value of 63 N by 3.17%. The maximum deformation differs by 2.77%, with 6.32 mm predicted compared with 6.50 mm measured. The numerical internal energy of 27.2 J differs from the reported experimental absorbed energy of 26.0 J by 4.62%. The mean of the three absolute percentage deviations is approximately 3.52%.

The close agreement indicates that the model captures the principal global response of the tested sandwich panel. The deformation contours place the maximum response at the centre, consistent with the experimental indentation. The stress field is also concentrated beneath the impactor, matching the observed damage location. Similar experimental–numerical strategies have been used successfully in the literature to connect impact force, damage and energy absorption in sandwich structures [6,11].

The remaining differences can be attributed to factors that are difficult to reproduce exactly in a numerical model, including manufacturing tolerances, local material heterogeneity, clamping conditions, uncertainty in material properties and simplifications in the constitutive representation. The source does not provide a complete set of orthotropic GFRP properties, foam/honeycomb constitutive data, interface properties, mesh statistics or contact coefficients, so the reported validation should be interpreted as validation of the available model outputs rather than a complete reproducibility record.

5.6 Practical significance

The experimental results indicate that the 5 wt.% iron oxide condition provides the strongest overall impact response among the tested compositions. It combines the highest peak force, the lowest maximum displacement and the highest absorbed energy. From an engineering perspective, this combination suggests improved resistance to localized indentation and greater capacity to dissipate a fixed impact energy. The validated numerical model further provides a means of examining stress and energy transfer that would otherwise require additional experimental instrumentation.

The results should nevertheless be used within the limits of the tested configuration. The study considered a single impact energy, a single impactor geometry and a single specimen size. It therefore establishes a useful performance comparison among the reported reinforcement levels, but it does not establish an optimum iron oxide concentration for all sandwich designs or loading conditions.

6. Conclusions

- The investigated GFRP/foam-filled honeycomb sandwich panels showed a clear improvement in low-velocity impact response as the reported iron oxide content increased from 0 to 5 wt.%.
- Peak impact force increased from 40 N at 0 wt.% to 63 N at 5 wt.%, corresponding to a 57.5% increase.
- Maximum displacement decreased from 8.3 mm to 6.4 mm, corresponding to a 22.9% reduction.
- Absorbed energy increased from 16.8 J to 26.0 J, corresponding to an approximately 54.8% increase based on the tabulated values.
- Post-impact damage became progressively more localized with increasing reinforcement; the 5 wt.% specimen showed the least visible damage in the supplied observations.
- The ANSYS Explicit Dynamics model predicted 61 N peak contact force, 6.32 mm maximum deformation and 27.2 J internal energy. The corresponding deviations from experiment were 3.17%, 2.77% and 4.62%, respectively.
- The average absolute deviation of the three primary validation parameters was approximately 3.52%, and the artificial-energy contribution remained below the 5% criterion reported in the source study.
- The combined results support the use of iron oxide reinforcement as a promising approach for improving the impact response of the investigated sandwich configuration and support the use of the validated numerical model for future parametric design studies.

7. Limitations and Recommendations for Further Work

The supplied study provides strong comparative impact results, but several details required for full independent reproduction are not reported. These include the exact GFRP lay-up

and fibre volume fraction, matrix and core material grades, nanoparticle size and morphology, nanoparticle dispersion procedure, adhesive/interface properties, honeycomb cell geometry, foam density, mesh type and size, element count, material constitutive parameters, contact/friction coefficients and formal mesh-convergence results.

Future work should therefore investigate a wider range of reinforcement contents, multiple impact energies and impactor geometries, and repeated-impact or compression-after-impact performance. Microscopic or non-destructive damage characterization such as optical microscopy, ultrasonic inspection or computed tomography would strengthen the interpretation of internal damage. A progressive composite damage model with explicitly defined intralaminar, interlaminar and core-failure criteria would also improve the predictive capability of the numerical model.

A further useful direction is to establish a quantitative relationship between iron oxide content, core compressive properties and impact energy absorption. Such a relationship would allow the reinforcement level to be optimized not only for peak force and displacement, but also for specific energy absorption, residual strength and structural mass.

8. Data Availability

The numerical and experimental values reported in this manuscript are derived from the supplied study document. The original source contains the reported test curves, photographs, ANSYS contour plots and validation values. Additional raw time-history data were not provided in the source and are therefore not reproduced or inferred here.

9. Conflict of Interest

The supplied source document does not state a conflict-of-interest declaration. A journal-specific declaration should be inserted by the authors before submission.

10. Author Contributions

Author-contribution details were not provided in the source document and should be completed by the authors according to the target journal's CRediT requirements.

The numerical stress-strain assessment further identified a maximum equivalent stress of approximately 268 MPa at the impact centre, while the equivalent elastic strain remained concentrated in the same region and decreased toward the clamped boundaries. These findings identify the impact centre as the critical zone for localized deformation and possible damage initiation and strengthen the interpretation of the experimental force, displacement and energy results. Since the source document does not report a numerical maximum equivalent-strain value, the strain result is intentionally reported only in terms of its spatial distribution.

References

- [1] E. C. Kosgey, R. Kumaresan, K. Kanny, and F. M. Mwangi, "Low-velocity impact behaviour of sandwich structures: a comprehensive review," *Progress in Additive Manufacturing*, vol. 11, pp. 3057-3096, 2026, doi: 10.1007/s40964-025-01489-4.
- [2] Y. Karsandik, B. Sabuncuoglu, B. Yildirim, and V. V. Silberschmidt, "Impact behavior of sandwich composites for aviation applications: A review," *Composite Structures*, vol. 314, Art. 116941, 2023, doi: 10.1016/j.compstruct.2023.116941.

- [3] F. Tarlochan, "Sandwich Structures for Energy Absorption Applications: A Review," *Materials*, vol. 14, no. 16, Art. 4731, 2021, doi: 10.3390/ma14164731.
- [4] J. H. Lee, S. K. Cheong, and K. H. Shin, "Impact characteristics of a honeycomb sandwich panel," *Key Engineering Materials*, vols. 326-328, pp. 1761-1764, 2006, doi: 10.4028/0-87849-415-4.1761.
- [5] P. M. Schubel, J.-J. Luo, and I. M. Daniel, "Low velocity impact behavior of composite sandwich panels," *Composites Part A: Applied Science and Manufacturing*, vol. 36, no. 10, pp. 1389-1396, 2005, doi: 10.1016/j.compositesa.2004.11.014.
- [6] M. Meo, R. Vignjevic, and G. Marengo, "The response of honeycomb sandwich panels under low-velocity impact loading," *International Journal of Mechanical Sciences*, vol. 47, no. 9, pp. 1301-1325, 2005, doi: 10.1016/j.ijmecsci.2005.05.006.
- [7] T. Anderson and E. Madenci, "Experimental investigation of low-velocity impact characteristics of sandwich composites," *Composite Structures*, vol. 50, no. 3, pp. 239-247, 2000, doi: 10.1016/S0263-8223(00)00098-2.
- [8] Z. Sekhavat Pour and M. Ghaemy, "Thermo-mechanical behaviors of epoxy resins reinforced with silane-epoxide functionalized α -Fe₂O₃ nanoparticles," *Progress in Organic Coatings*, vol. 77, no. 8, pp. 1316-1324, 2014, doi: 10.1016/j.porgcoat.2014.04.001.
- [9] T. Sun, H. Fan, Z. Wang, X. Liu, et al., "Modified nano Fe₂O₃-epoxy composite with enhanced mechanical properties," *Materials & Design*, vol. 87, pp. 10-16, 2015, doi: 10.1016/j.matdes.2015.07.177.
- [10] H. M. Naguib, M. A. Ahmed, and Z. L. Abo-Shanab, "Studying the loading impact of silane grafted Fe₂O₃ nanoparticles on mechanical characteristics of epoxy matrix," *Egyptian Journal of Petroleum*, vol. 28, no. 1, 2019, doi: 10.1016/j.ejpe.2018.10.001.
- [11] H. Lv, S. Shi, B. Chen, J. Ma, and Z. Sun, "Low-velocity impact response of composite sandwich structure with grid-honeycomb hybrid core," *International Journal of Mechanical Sciences*, vol. 246, Art. 108149, 2023, doi: 10.1016/j.ijmecsci.2023.108149.
- [12] Özer et al., "The Effect of Nano-Iron Oxide Particle on Mechanical Properties of Glass Fiber Reinforced Composites," *Polymers for Advanced Technologies*, 2025, doi: 10.1002/pat.70341.
- [13] ASTM International, "ASTM D3763-23: Standard Test Method for High Speed Puncture Properties of Plastics Using Load and Displacement Sensors," ASTM International, 2023, doi: 10.1520/D3763-23.

- [14] S. Abrate, "Localized impact on sandwich structures with laminated facings," *Applied Mechanics Reviews*, vol. 50, no. 2, pp. 69-82, 1997, doi: 10.1115/1.3101689.
- [15] G. Caprino and R. Teti, "Impact and post-impact behavior of foam core sandwich structures," *Composite Structures*, vol. 29, no. 1, pp. 47-55, 1994, doi: 10.1016/0263-8223(94)90035-3. [15], [17], [18]
- [16] R. A. W. Mines, C. M. Worrall, and A. G. Gibson, "The static and impact behaviour of polymer composite sandwich beams," *Composites*, vol. 25, no. 2, pp. 95-110, 1994, doi: 10.1016/0010-4361(94)90003-5.
- [17] J. A. Nemes and K. E. Simmonds, "Low-velocity impact response of foam-core sandwich composites," *Journal of Composite Materials*, vol. 26, no. 4, pp. 500-519, 1992, doi: 10.1177/002199839202600403.
- [18] M. A. Hazizan and W. J. Cantwell, "The low velocity impact response of foam-based sandwich structures," *Composites Part B: Engineering*, vol. 33, no. 3, pp. 193-204, 2002, doi: 10.1016/S1359-8368(02)00009-4.
- [19] H. Guo, H. Guo, H. Yuan, H. Yuan, J. Zhang, and D. Ruan, "Review of sandwich structures under impact loadings: Experimental, numerical and theoretical analysis," *Thin-Walled Structures*, vol. 196, Art. 111541, 2024, doi: 10.1016/j.tws.2023.111541.
- [20] "Low-velocity impact response of composite sandwich structures: Modelling and experiment," *Composite Structures*, vol. 168, pp. 322-334, 2017, doi: 10.1016/j.compstruct.2017.02.064.