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Numerical study on structural behaviour of 3D sandwich wall under vertical and in-plane loading

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ABSTRACT

Precast three-dimensional (3D) sandwich wall panels are rapidly increasing in modern construction due to their high strength-to-weight ratio, thermal efficiency, and rapid installation. However, their structural behaviour under combined vertical and in-plane loading, along with the influence of boundary stiffening, remains insufficiently studied. This study presents a nonlinear finite element investigation of 3D sandwich wall panels using ANSYS Mechanical APDL to evaluate their structural response under vertical, in-plane, and combined loading conditions. Concrete was modelled using SOLID65 elements incorporating cracking and crushing behaviour, while reinforcement and expanded polystyrene (EPS) core were included to simulate composite action. The influence of boundary stiffening and longitudinal reinforcement on load–displacement behaviour, stiffness degradation, ductility, stress distribution, and crack development were systematically analyzed. The results indicate that boundary stiffening enhances load-carrying capacity by approximately 3 to 5%, while longitudinal reinforcement improves ductility by up to 45% under in-plane loading. Stiffness degradation ranging from 22% to 24% was observed across all configurations, confirming that concrete cracking is the primary factor governing stiffness reduction. The crack patterns were found to align with principal stress distribution patterns, with dominant diagonal cracking under in-plane and combined loading conditions. The validation against experimental results and codal provisions demonstrates good agreement, with deviations generally within 10 to 15%, confirming the reliability of the numerical model. The study provides a reliable and validated numerical framework for assessing the behaviour of precast 3D sandwich wall systems and supports their design under complex loading scenarios.

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1. Introduction

Three-dimensional (3D) sandwich wall panels have emerged as an efficient structural system in modern construction, offering improved structural performance, energy efficiency and construction speed. Previous studies have established the fundamental behaviour and composite action of precast sandwich panels (Amin Einea et al. 1991; Naito et al. 2012). A typical 3D sandwich panel, as shown in Fig. 1, consists of two concrete layers separated by an insulation core made of expanded polystyrene (EPS) or similar material with the panels being interconnected via shear connectors (Choi et al. 2015; Zhao et al. 2024; Cassese et al. 2023; Amin Einea et al. 1991). The connectors join the two layers so that they act together as a single unit, permitting the panel to carry vertical and in-plane loads economically whilst remaining light in weight (Barbosa et al. 2023; Yan et al. 2023). Behaviour of sandwich wall systems is influenced primarily by the relative stiffness of the concrete faces, by the mechanical

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Nomenclature

WP	unstiffened wall panel
SWP	stiffened wall panel
NR	no longitudinal reinforcement
WR	with longitudinal reinforcement
V	vertical loading
IP	in-plane loading
C	combined loading

Note: The specimen notation is defined as: [*wall type*] – [*reinforcement*] – [*loading condition*]

and thermal properties of the core, and by the geometry and material from which the shear connectors are formed (Dai et al. 2024; Serpilli et al. 2021). In this study, the wall system uses transverse welded steel wires that pass through the EPS core, functioning as simple shear connectors that limit slip between the layers and promote composite action under all loading conditions.

The recent advances in connector design, including GFRP, stainless steel, and S-type connectors, have notably improved shear capacity, ductility, and overall stiffness (Yan et al. 2023; Bishnoi et al. 2024; Sarvestani et al. 2018; He et al. 2020). Earlier research has shown that these systems increase load-carrying capacity, limit differential slip between the layers, and help preserve composite action under both static and dynamic loading conditions (Junaedi et al. 2024; Haldar et al. 2021; Syndergaard et al. 2022). Precast 3D sandwich panels have a growing market as a green and sustainable alternative for traditional reinforced concrete walls; they can be installed faster, use less concrete, reduce fuel and global warming potential, improve energy performance, and lower overall cost (Tawil et al. 2024; Hamed 2024).

Despite promising progress in experimental research, limited studies have been conducted on the combined effects of vertical and in-plane loads, which are required for a better understanding of the true behavior of a sandwich wall in a multi-storey building and seismic conditions (Jiang et al. 2018; Kinnane et al. 2020; Singhal et al. 2021; Sylaj and Fam 2021). To address this gap, the present study carries out a detailed finite element analysis in ANSYS Mechanical APDL to evaluate the composite action, stress behavior, and stiffness response of 3D sandwich wall panels under combined loading. The numerical findings are compared with experiments to validate the accuracy of the model, and the conclusions drawn should facilitate improved design of precast sandwich wall systems.

Finite element modelling has been established as a viable and useful technique for simulating the behaviour of sandwich panels under complex loading, permitting evaluation of load–displacement response, stress state, degradation of stiffness, and failure modes in relation to available tests (Yan et al. 2023; Bishnoi et al. 2024; Junaedi et al. 2024). This study presents a detailed numerical investigation of the structural behaviour of 3D sandwich wall panels subjected to vertical and in-plane loading using ANSYS Mechanical APDL. The aim is to assess composite action, stress development, stiffness response, and the correlation between the numerical results and relevant experimental findings (Jiang et al. 2018; Kinnane et al. 2020; Kwon et al. 2025). The findings are expected to contribute to the optimization and practical application of 3D sandwich wall systems in modern precast construction.

Although 3D sandwich walls are widely studied, their response under combined vertical and in-plane loading is not yet well understood. The effect of boundary stiffening on stiffness loss, crack initiation, and deformation has not been clearly quantified through three-dimensional numerical analysis. This work provides a focused numerical investigation that isolates the influence of boundary modification and longitudinal reinforcement on the structural behaviour of 3D sandwich walls under vertical, in-plane, and combined loading.

Despite the substantial body of research on sandwich wall systems, the structural behaviour of 3D sandwich wall panels under combined vertical and in-plane loading remains insufficiently understood. In particular, the coupled effects of boundary stiffening and longitudinal reinforcement on stiffness degradation, stress distribution, crack development, and overall structural performance have not yet been systematically quantified through three-dimensional finite element modelling. To address this gap, the present study conducts a focused nonlinear numerical investigation of 3D sandwich wall panels subjected to vertical, in-plane, and combined loading conditions. The study further evaluates the influence of boundary modification and reinforcement detailing on the structural response and validates the observed response trends against available experimental findings, thereby providing a clearer analytical basis for the assessment and design of precast 3D sandwich wall systems under complex loading scenarios.

2. Research Significance

Although several experimental works have explored the behavior of sandwich wall panels, a comprehensive understanding of their performance under the combined action of vertical and in-plane loads is still limited. Physical testing alone may not fully capture the internal stress development, crack initiation and crack propagation mechanisms that govern the overall behavior of the wall. Numerical modelling provides a powerful alternative by enabling direct visualization of the internal response and better control of key variables. In this work, a suitable framework is established in ANSYS Mechanical APDL to model the behaviour of realistic 3D sandwich wall panels, with emphasis on predicting load–displacement characteristics, stress distribution, stiffness and crack propagation under combined loading conditions, thus establishing a sound numerical reference for assessing the behavior of such systems. By comparing walls with and without boundary stiffening, this study shows how edge modification influences stiffness retention and the sequence of crack formation when vertical and in-plane loads are applied simultaneously. Such information is difficult to obtain from experiments alone and is essential for improving the structural reliability of 3D sandwich walls.

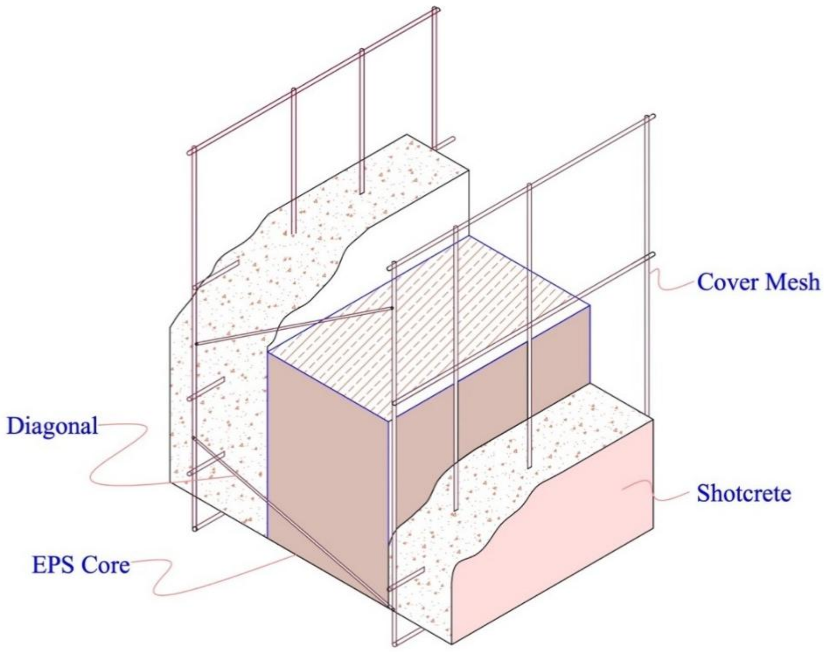


Fig. 1. Schematic diagram of a 3D sandwich wall panel.

3. Numerical Modelling Using ANSYS Mechanical APDL

A detailed finite element model of the 3D precast sandwich wall was developed in ANSYS Mechanical APDL to investigate its behavior under the simultaneous action of vertical and lateral loads. The objective was to obtain a model that accurately represented the interaction of the concrete layers, insulation core, and reinforcement, and allowed for a true composite action of the wall. Appropriate boundary conditions and applications of loads were applied to simulate realistic support conditions and field loading. This modelling approach allowed accurate representation of nonlinear wall behavior, including crack development, stiffness degradation and stress distribution.

3.1. Element types

Finite element modelling was performed in ANSYS Mechanical APDL using appropriate element types to represent those components of the three-dimensional precast reinforced concrete sandwich wall, ensuring that material behaviour, connection behaviour, and the interaction between layers was correctly represented throughout the analysis. Each component of the walls was assigned an appropriate element type for modelling its mechanical behaviour. Concrete layers were modelled using SOLID65 elements, which allow nonlinear behaviour to be specified corresponding to cracking (in tension) and crushing (in compression) behaviour. This element captures stiffness degradation and post-peak response under combined axial and lateral loads. The EPS core was modelled as a linear elastic material due to its relatively low stiffness and its primary role as a shear transfer medium rather than a load-bearing component. Although EPS may exhibit nonlinear crushing under high compressive stress, its contribution to load-carrying capacity in sandwich panels is minimal. Therefore, linear elastic modelling is considered sufficient for service-level analysis. Previous experimental and numerical studies have shown that EPS contributes minimally to the overall load-carrying capacity of sandwich panels under service-level loading conditions. Therefore, the linear elastic assumption is considered reasonable for the present analysis. This element is appropriate for low-density cores that essentially transfer shear between layers and provide thermal insulation rather than any appreciable structural strength. Link 180 elements were used to model the welded wire mesh and longitudinal bars of reinforcement; these uniaxial truss elements model the slender steel members embedded in the concrete, which are effective in resisting axial tension and compression. Bilinear material properties were assigned to the reinforcement to represent yielding behavior, while mesh response was treated as linear elastic at service-load levels. Together, these element selections and material assignment provide a realistic and efficient representation of the composite action between the concrete, reinforcing steel, and insulation layers.

The nonlinear behaviour of concrete was modelled using the ANSYS SOLID 65 element, which accounts for cracking and crushing in compression. The shear transfer across crack was represented using shear transfer coefficients of 0.3 for open cracks and 0.8 for closed cracks, as commonly recommended in the literature. The compressive stress–strain behaviour of concrete was defined using a multilinear isotropic model based on standard constitutive relationships, with the ascending branch defined up to the peak compressive strength (fck = 42.67 MPa) and a descending branch included to simulate post-peak softening. Tensile behaviour was assumed linear up to the tensile strength (ft = 4.57 MPa), beyond which cracking was initiated. Tension stiffening was included to represent post-cracking behaviour. The real constants for the SOLID65 element were specified to activate cracking in three orthogonal directions and crushing capability under compression. The nonlinear solution was carried out using displacement-controlled incremental loading with automatic time stepping, and convergence was ensured using a tolerance of 0.5%, as recommended in previous studies (Kachlakev et al. 2001; ANSYS Inc. 2013).

3.2. Material properties

All materials were defined in ANSYS based on their mechanical characteristics and functions within the composite wall system. The concrete layers, insulation core, welded wire mesh, and longitudinal reinforcement were modelled using standard engineering material parameters. The material properties were adopted from previous studies Poluraju and Appa Rao (2018) and are presented in Table 2.

Table 1. Nonlinear concrete modelling parameters (SOLID 65).

Parameters	Values
Open shear transfer coefficient	0.3
Closed shear transfer coefficient	0.8
Uniaxial cracking stress	4.57 MPa
Uniaxial crushing stress	42.67 MPa
Cracking directions	3 orthogonal directions
Tension stiffening	Included

Table 2. Material properties used in the finite element model (Poluraju and Appa Rao 2018).

Material	Element type	Elastic modulus E (MPa)	Compressive strength fck (MPa)	Tensile strength ft (MPa)	Yield strength fy (MPa)	Poisson's ratio (ν)	Density ρ (kg/m^3)
Concrete (layers)	SOLID65	3.26×10^4	42.67	4.57 ($0.75\sqrt{f_{ck}}$)	-	0.20	2400
EPS core	SOLID185	5	-	-	-	0.10	16
Wire mesh	LINK180	1.26×10^5	-	-	658	0.30	7850
Reinforcement bars	LINK180	2.00×10^5	-	-	490	0.30	7850

3.3. Geometric modelling

The numerical model represents a three-dimensional precast reinforced-concrete sandwich wall composed of two outer concrete layers separated by an expanded-polystyrene (EPS) insulation core. Both faces contain galvanized welded wire mesh, and selected models include additional longitudinal reinforcement using 12 mm HYSD bars. The overall geometric configuration and reinforcement details are summarized in Table 3.

Table 3. Geometric dimensions and reinforcement details of the 3D sandwich wall models.

Wall type	Height (mm)	Length (mm)	Total thickness (mm)	Concrete wythe (mm)	EPS core (mm)	Concrete cover (mm)	Reinforcement type
WP1 – Unstiffened wall	3750	1250	150	50	50	35	—
WP2 – Unstiffened wall	3750	1250	150	50	50	35	12mm HYSD
SWP1 – Stiffened wall	3750	1425	150	50	50	35	—
SWP2 – Stiffened wall	3750	1425	150	50	50	35	12mm HYSD

Each wall consists of 2.5 mm diameter galvanized wire mesh arranged in a 50 mm × 50 mm grid on both faces, connected through the EPS core using transverse wires. These transverse welded wires function as shear connectors by linking the two concrete layers through the EPS core, allowing shear transfer and promoting composite action under all loading conditions. A total of twelve wall models are analysed, representing four wall configurations evaluated under vertical, in-plane and combined loading conditions.

3.4. Interface interaction

The interface between the concrete layers and the EPS insulation was modeled to reflect the composite characteristics of the wall. Since transverse welded steel wires pass through the EPS core and connect the two faces, direct slip between the layers is structurally restrained. To capture this behaviour in the numerical model, a bonded contact was assigned at the wythe–EPS interface, enabling shear transfer consistent with the action of the welded transverse connectors. This approach ensures that the applied loads are shared between both layers and that the resulting deformation pattern reflects the added stiffness provided by the connector system. The bond contact assumption was adopted to represent the mechanical role of closely spaced transverse welded wire connectors, which physically link the two concrete wythes through the EPS core and significantly restrict relative slip. Previous experimental and numerical studies have shown that such connector systems promote near-full composite action under monotonic loading conditions, justifying the use of a fully bonded interface in numerical modelling. It is accepted that in partial applications some degree of interface slip, separation or shear lag may occur depending on connector spacing, stiffness and loading conditions. These effects were not explicitly modelled in the present study and therefore the adopted bonded contact assumption may result in a slight overestimation of stiffness and composite action. However, the assumption provides a reasonable and computationally efficient representation of the structural behaviour of 3D sandwich walls with welded wire connectors under monotonic loading.

3.5. Mesh generation for reinforced concrete faces

The sandwich wall uses a galvanized wire mesh on each concrete wythe to ensure uniform reinforcement across the panel. Each face is provided with a mesh made from 2.5 mm diameter wires arranged in a 50 mm x 50 mm grid, consisting of 25 horizontal and 76 vertical wires that extend over the full height and width of the wall. As shown in Fig. 2, applying a quasi-uniform mesh on both sides of the wall further improves support and increases the diagonal stiffness from both vertical and in-plane loading. The regular pattern helps to make the finite difference mesh clearer and, therefore, easier to model things like stress concentration in concrete and reinforcement.

3.6. Boundary conditions and loading

The wall base was fixed in all translational directions to simulate foundation restraint, while rotational degrees of freedom were released to avoid artificial moment restraint and to allow a realistic flexural response of the wall. In real structures, partial rotational restraints may exist due to foundation flexibility. This simplification is commonly used in numerical studies to isolate wall behaviour and represents a conservative approximation for structural responses under lateral loading. A uniform axial compression corresponding to an axial load ratio of 0.02 was applied on the top surface of the wall, representing the vertical load from upper storeys. This corresponds to an axial force of approximately 160 kN acting on that wall section. For the lighter loading case, a ratio of 0.01 was assumed, corresponding to about 80 kN. The loads were applied as uniformly distributed pressure over the top concrete wythe, ensuring that the stress was uniform and that there was no eccentricity. In-plane loading was applied along the longitudinal direction of the wall to simulate lateral forces acting within the plane of the wall, such as seismic shear forces. The loading was applied at the centroid of the top edge between the concrete wythes using a displacement-controlled loading sequence. The displacement amplitude was gradually increased from 0.5 mm to 20 mm to capture the complete nonlinear response, including cracking and post-peak softening behaviour. The axial load ratios and their corresponding applied loads used in the numerical simulations are presented in Table 4.

Table 4. Axial load ratios and their corresponding loads used in the numerical analysis.

Loading case	Axial load ratio	Applied axial load (kN)
Vertical loading	0.02	160
Combined loading	0.01	80

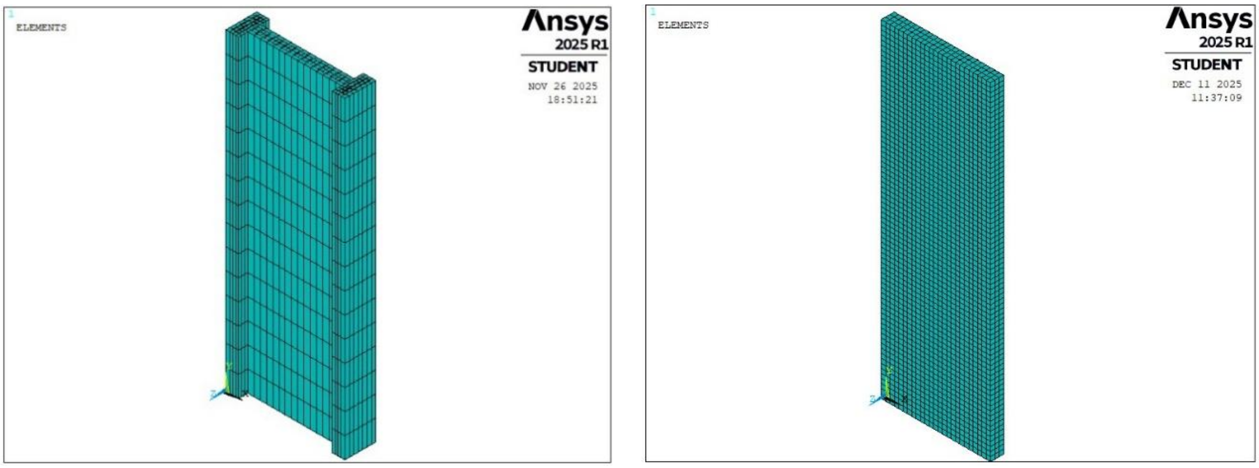


Fig. 2. Finite element mesh of the 3D stiffened and unstiffened sandwich wall.

The selected axial load ratios represent typical service-level loading conditions for multi-storey precast wall systems, where axial compression is relatively low compared to lateral loading effects. The present study adopts several modelling assumptions to ensure computational efficiency. The interface between concrete layers and the EPS core is assumed to be fully bonded, and the EPS core is modelled as a linear elastic material. These assumptions may lead to a slight overestimation of stiffness and composite action. In reality, partial interaction, interface slip, and nonlinear behaviour of the insulation core may influence the structural response. Future work may incorporate detailed modelling of connector behaviour and nonlinear material properties of EPS to improve prediction accuracy.

4. Stiffened and Unstiffened Walls

Understanding how boundary modification affects the structural response of the sandwich wall system is essential for interpreting its behaviour under combined loading. Although both wall configurations share the same composite arrangement of concrete layers separated by an EPS core, changes made along the vertical boundaries alter the way forces are distributed through the panel. By examining the two models independently, the influence of boundary strengthening becomes easier to identify and compare.

4.1. Unstiffened sandwich wall

The unstiffened wall serves as the reference model, representing the panel in its simplest form without any boundary enhancement. In this configuration, the two concrete layers and the EPS core act together as a uniform composite section, and the wall deforms within this constant profile because no additional confinement is provided at the edges. For numerical analysis, the wall was modelled with a height of 3750 mm, a length of 1250 mm and a total thickness of 150 mm, consisting of 50 mm concrete, 50 mm EPS and 50 mm concrete. Two variations were considered: one reinforced and one unreinforced, to clearly distinguish how longitudinal steel contributes to stiffness and crack development. As illustrated in Fig. 3, the schematic and ANSYS views highlight the straight, unmodified edges that characterize this baseline configuration.

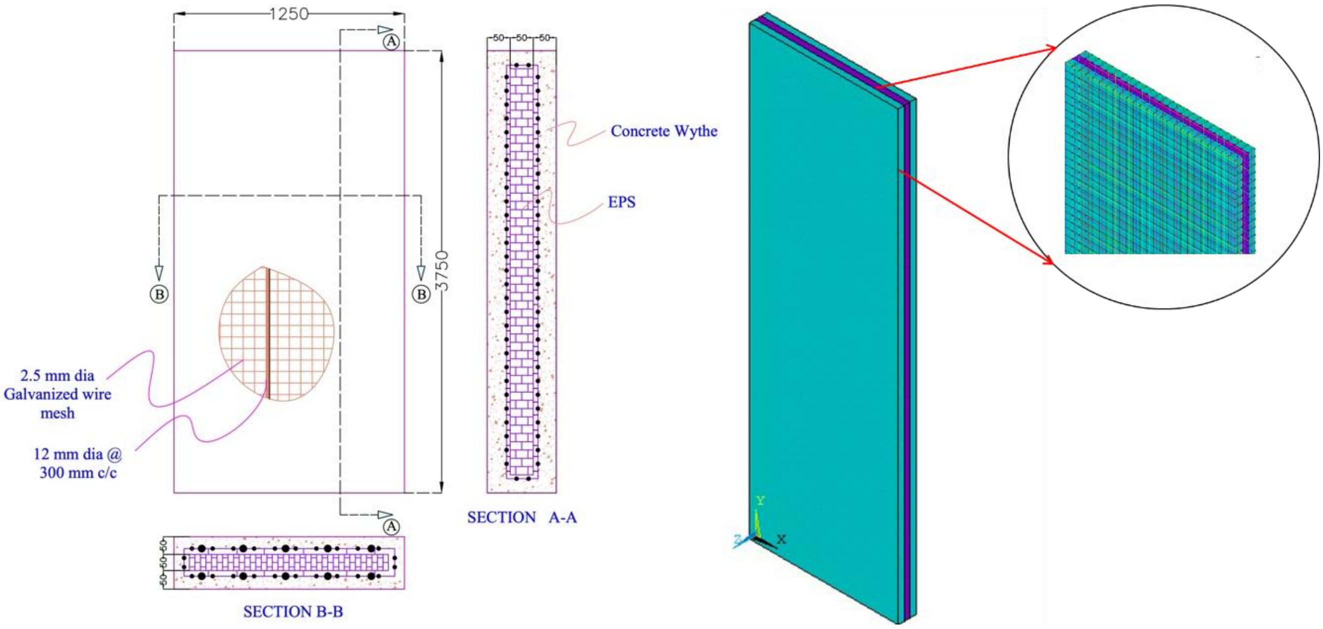


Fig. 3. Schematic and ANSYS simulation of unstiffened wall.

4.2. Stiffened sandwich wall

The stiffened model was conceived to study how a modification in the boundary would affect the way internal forces transfer, and how much it would improve the behaviour of the wall when subjected to vertical loading combined with in-plane loading. In this layout, the vertical boundaries are formed thickened areas that confine the wall more and enhance the rotational and flexural resistance. This provides a stabilizing effect on the layers of concrete and postpones cracking, making the wall spread more evenly with height. The stiffened wall model has the same height and thickness as the unstiffened wall model, with the only difference that the total length is increased to 1425 mm in order to allow for the boundary stiffeners. As with the reference case, reinforced and unreinforced versions were examined to capture the combined influence of longitudinal steel and boundary strengthening. The modified geometry is clearly visible in the schematic and ANSYS representation in Fig. 4, where the expanded boundary regions distinguish the stiffened configuration from the plain-edged wall.

5. Numerical Results and Discussion

5.1. Load-displacement behaviour

The load–displacement responses from the numerical analysis indicated a linear behaviour at the early stages for all wall models, which then transitioned into a gradual reduction in stiffness as cracking or localized strain began to form. The effects of both stiffeners and reinforcement were consistently observed under in-plane, combined, and vertical loading conditions. In the in-plane monotonic condition, the response remained linear up to nearly half of the peak load, after which flexural cracking at the wall base reduced stiffness as shown in Fig. 5(b). The unstiffened walls reached about 165 kN at a displacement of about 14 mm, with reinforcement providing a smoother post-peak response. Stiffened walls reached about 160 kN at around 18 mm. The stiffened–reinforced walls exhibited the strongest behaviour, reaching 170 kN at nearly 17 mm, indicating delayed crack growth and improved confinement. A quantitative comparison indicates that boundary stiffening resulted in an increase in load-carrying capacity of approximately 3 to 5% under in-plane and combined loading conditions. In addition, the inclusion of longitudinal reinforcement improved ductility by up to 45% and improved post-peak behaviour. Under combined axial–lateral loading, axial compression increased the initial stiffness of all walls. The response remained linear until tension side cracking occurred, as presented in Fig. 5(c). Unstiffened walls reached 160 kN at 12.5 mm, while stiffened configurations carried higher loads at smaller displacements. The stiffened reinforced wall reached 170 kN at around 14 mm, as reflected in the corresponding curves shown in Fig. 5. The stiffeners improved stress transfer and limited flexural compression deformation. For vertical compression, the walls displayed an almost perfectly linear load–shortening relationship, governed by direct compression as shown in Fig. 5(a). Unstiffened walls reached 75 kN at about 0.05 mm, with reinforcement raising the capacity to 80 kN. The stiffened walls were able to sustain marginally higher loads, with capacities ranging between 81 and 83 kN. Among these, the stiffened and reinforced wall demonstrated the highest load resistance, reaching 83 kN, which indicates improved confinement and a more uniform transfer of compressive forces. Overall, the results clearly demonstrate that the presence of stiffeners along with longitudinal reinforcement makes the wall stiffer, helps postpone cracking, and improves its ability to resist applied loads. For in-plane and combined loading, the wall's behaviour was largely influenced by bending, whereas under vertical loading, it was mainly controlled by compression.

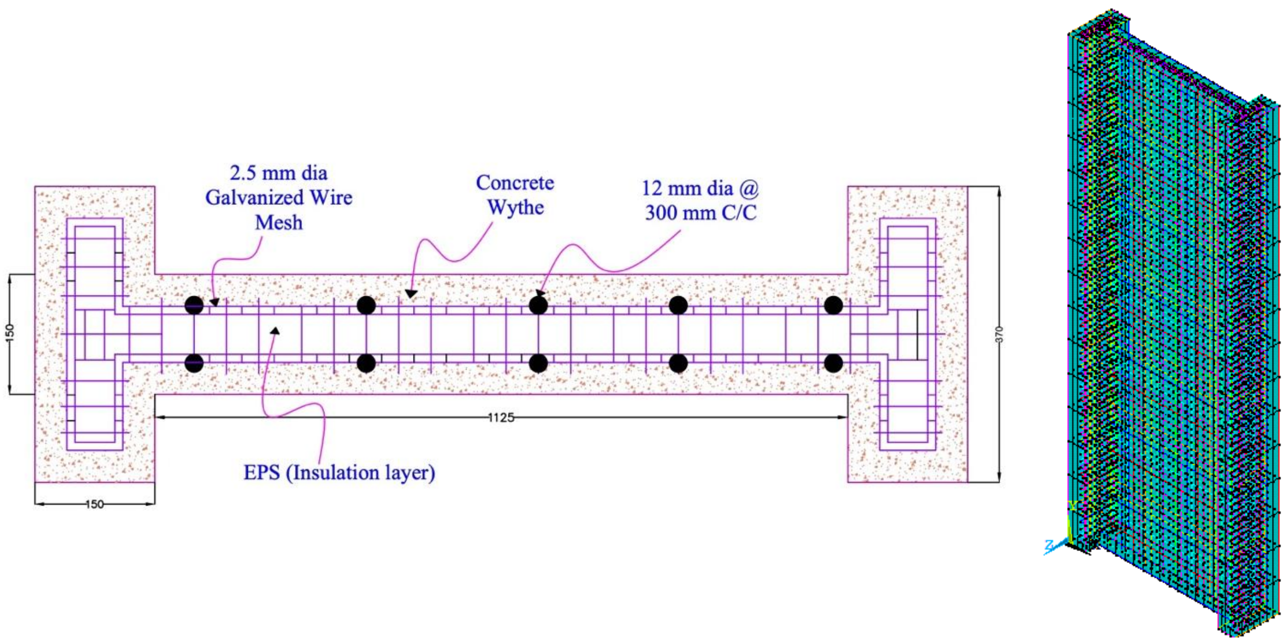


Fig. 4. Schematic and ANSYS simulation of stiffened wall.

5.2. Stress distribution

One major advantage of the numerical analysis in this study is that it clearly reveals how stresses develop inside each wall configuration, which is difficult to capture through experiments alone as shown in Fig. 6. In the unstiffened and non-reinforced walls (WP-NR), the maximum stresses formed at the base under vertical loading Fig. 6(a) and along a wide diagonal band under in-plane and combined loading Fig. 6(b-c) showing limited confinement and early bending behaviour. By adding longitudinal reinforcement (WP-WR), these high-stress regions became narrower, and the diagonal stress path under lateral and combined loading was more controlled as presented in Fig. 6(d-f). With the introduction of stiffeners in the SWP models, major improvements in stress distribution were observed. As shown in Fig. 6(g-i) and Fig. 6(j-l), stresses became more concentrated along the stiffened boundaries, compression remained more uniform near the base, and the diagonal stress band became tighter and more stable under in-plane and combined loading. The best response was observed in the stiffened and reinforced wall (SWP-WR), where stresses remained well-confined to the edge regions with minimal spread into the mid-height as shown in Fig. 6(j-l). This confirms that stiffeners and reinforcement work together to reduce peak stresses and improve the overall stability of the sandwich wall under all loading conditions.

5.3. Crack pattern

Figure 7 presents the numerical crack patterns of the WP-NR, WP-WR, SWP-NR, and SWP-WR wall configurations under vertical, in-plane, and combined loading, thereby illustrating the distinct structural response of each wall system. In the vertical load case Fig. 7(a,d,g,j), all walls developed light flexural cracks near the upper tension zone, with WP-NR-V showing the least cracking because its lower stiffness attracted a smaller share of the axial load. Under in-plane loading, diagonal tension cracks formed from the loaded edge toward the base, reflecting the expected shear-transfer path within the wall, as shown in Fig. 7(b,e,h,k). In WP-WR-IP, SWP-NR-IP and SWP-WR-IP, these diagonal cracks appeared in greater numbers as the reinforcement and stiffening enabled the walls to develop higher lateral resistance. Combined loading produced a clearer combination of diagonal and flexural cracks in the lower and mid-height regions, demonstrating the interaction between bending and shear, as shown in Fig. 7(c,f,i,l). The SWP-WR-C model exhibited the widest crack distribution, consistent with its higher stiffness and greater load engagement, as observed in the crack distributions shown in Fig. 7. The crack patterns observed in each wall illustrate the paths of internal force transfer, the locations of crack initiation, and the progression of cracking under different loading conditions. They also provide insight into the loading condition that governs the overall structural behaviour of the wall. The observed crack patterns correspond closely with the principal stress trajectories within the wall, where diagonal cracks align with the paths of maximum shear stress under in-plane and combined loading conditions. Following crack initiation, stress redistribution occurs through the reinforcement and stiffened boundary regions, which helps to delay further crack propagation and enhances the overall structural stability of the wall. The technical significance of presenting these crack patterns is to provide a direct visual and analytical basis for understanding how each wall configuration carries load and where its structural demand concentrates.

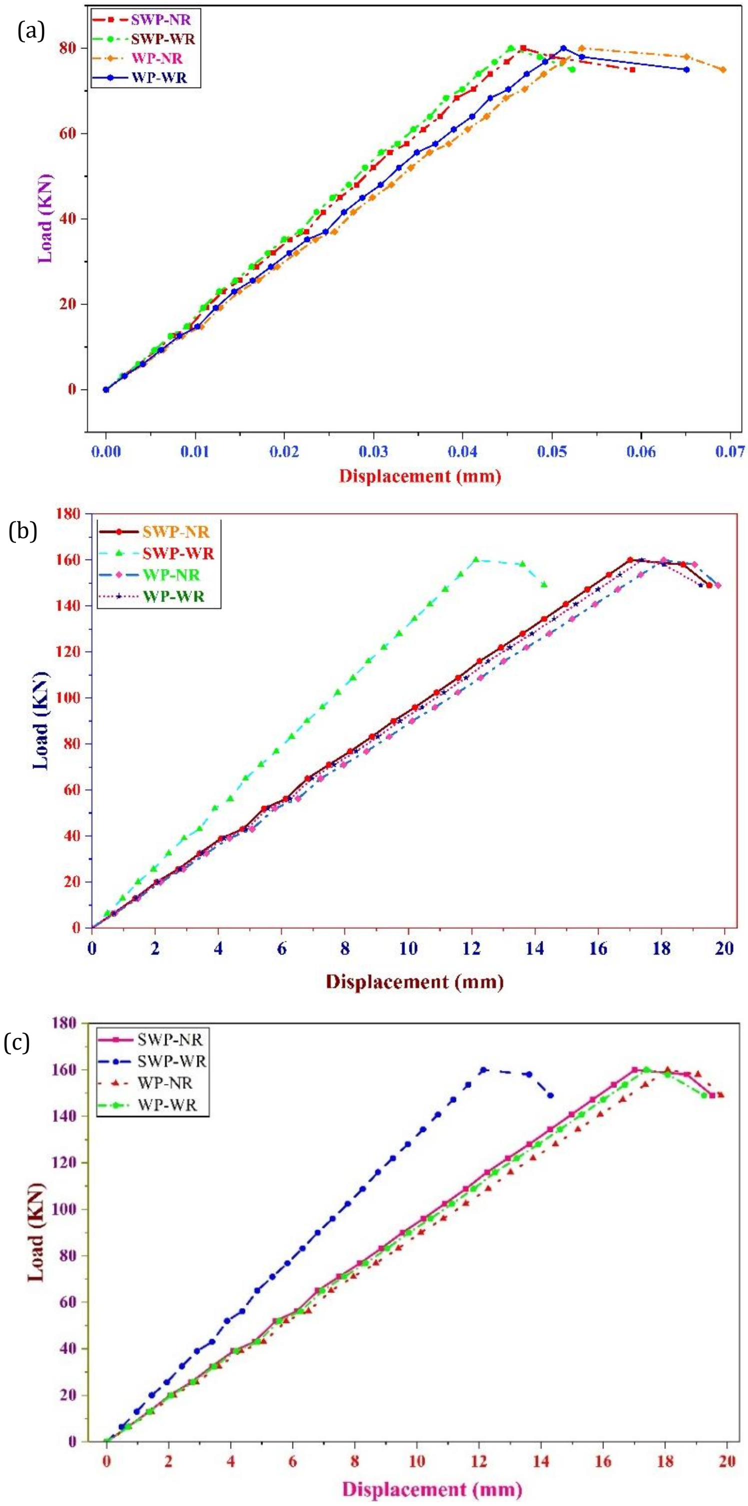
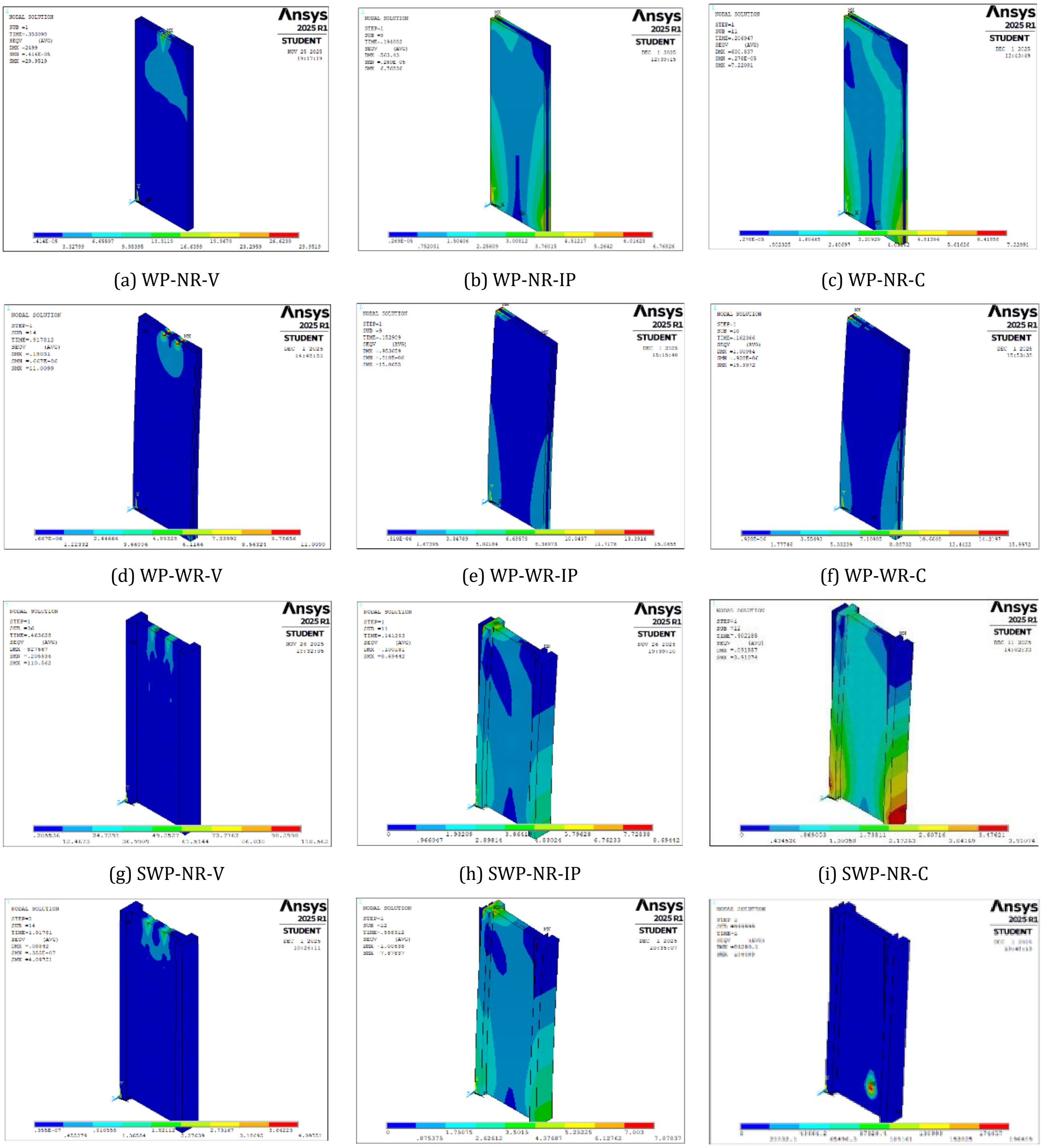


Fig. 5. Load-displacement behavior of sandwich walls under (a) Vertical, (b) In-plane, (c) Combined loading.



(a) WP-NR-V (b) WP-NR-IP (c) WP-NR-C

(d) WP-WR-V (e) WP-WR-IP (f) WP-WR-C

(g) SWP-NR-V (h) SWP-NR-IP (i) SWP-NR-C

(j) SWP-WR-V (k) SWP-WR-IP (l) SWP-WR-C

Fig. 6. Numerical stress patterns of the sandwich wall under various loading cases.

Although SOLID65 enables crack pattern visualization, it does not directly provide crack width values. Therefore, crack behaviour is interpreted qualitatively. Future studies may incorporate smeared crack models or fracture-based approaches to quantify crack width and strain distribution.

5.4. Stiffness degradation

The secant stiffness evaluated at peak response clearly highlights the influence of loading condition, reinforcement, and boundary stiffening on the degradation trend of the 3D sandwich walls. The complete stiffness values for all specimens are presented in Table 5. At vertical compression, all specimens exhibited very high stiffness values (1500 - 1620 kN/mm) with 0% degradation, owing to the fully elastic nature of axial loading where no tensile cracking or local crushing occurs.

In contrast, both in-plane and combined axial lateral loading resulted in clear stiffness reduction as flexural cracking developed. For in-plane loading, the unstiffened walls showed a drop from 15.53 kN/mm to 11.79 kN/mm to 8.88 to 11.71 kN/mm, corresponding to about 22 to 24% degradation. Reinforcement provided only minor improvement, confirming that stiffness loss was primarily crack-driven. The degradation trend for all wall configurations under lateral displacement is illustrated in Fig. 8.

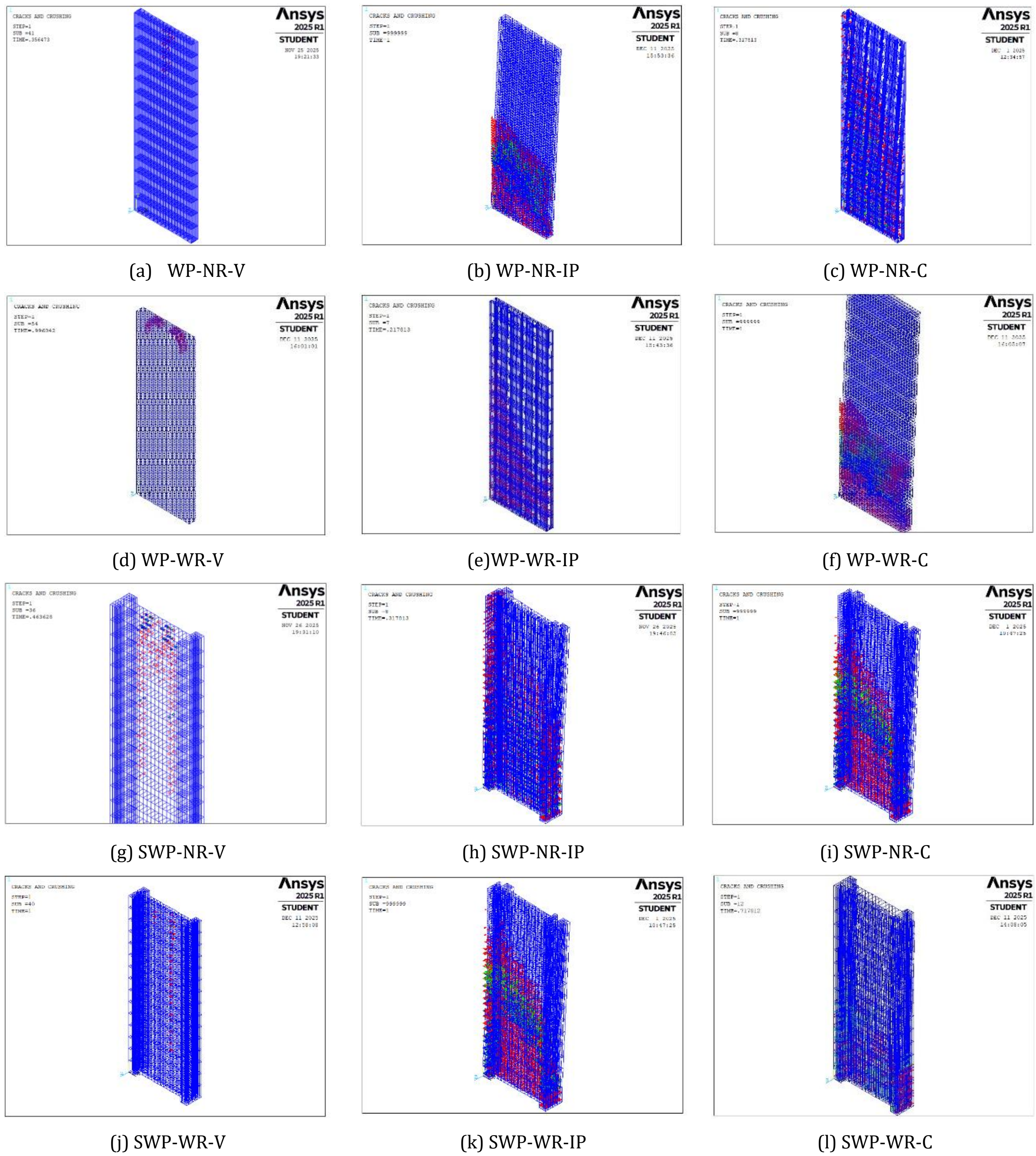


Fig. 7. Numerical crack patterns of the sandwich wall under various loading cases.

The initial stiffness values were higher for the stiffened walls. For the SWP-NR-IP, the degradation was 22.22% whilst the SWP-WR-IP showed the least degradation at 16.67%, demonstrating the advantage of boundary stiffening in retarding the loss of stiffness. Under combined loading, a similar trend was observed, where initial values of 12.08 to 16.87 kN/mm decreased to 8.88 to 12.14 kN/mm, again reflecting overall 22 to 24% loss. Under combined loading, all wall configurations exhibit similar stiffness degradation values ranging between 22% and 24%. This indicates that stiffness reduction is primarily governed by concrete cracking rather than boundary stiffening or reinforcement alone. Although differences in stiffness degradation among configurations are small, stiffened–reinforced walls exhibit higher initial stiffness and improved overall structural performance. Therefore, the advantage of boundary stiffening and reinforcement is more evident in terms of strength and deformation behaviour rather than significant reduction in stiffness degradation.

Table 5. Secant stiffness and degradation behaviour of the analysed wall models.

Model	Ultimate load F_u (kN)	Displacement at ultimate load D_u (mm)	Secant stiffness K_u (kN/mm)	Initial secant stiffness K_i (kN/mm)	Stiffness degradation (%)
WP-NR-V	75	0.05	1500	1500	0
WP-WR-V	80	0.05	1600	1600	0
SWP-NR-V	81	0.05	1620	1620	0
SWP-WR-V	83	0.055	1509.091	1509.091	0
WP-NR-IP	165	14	11.786	15.532	24.118
WP-WR-IP	160	18	8.889	11.714	24.116
SWP-NR-IP	160	18	8.889	11.429	22.224
SWP-WR-IP	170	17	10	12	16.667
WP-NR-C	160	12.5	12.8	16.869	24.121
WP-WR-C	165	18	9.167	12.08	24.114
SWP-NR-C	160	18	8.889	11.714	24.116
SWP-WR-C	170	14	12.143	16.003	24.12

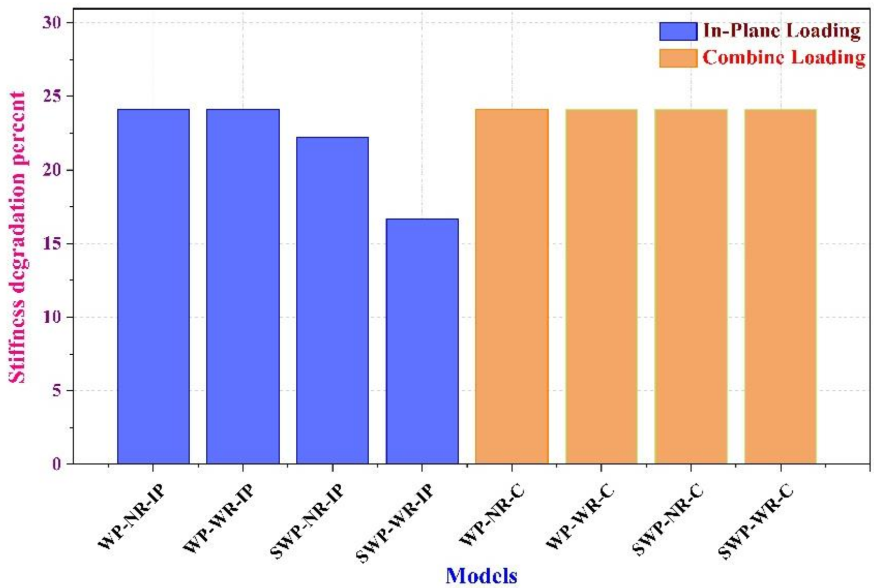


Fig. 8. Stiffness-degradation behaviour of stiffened and unstiffened sandwich walls.

5.5. Ductility

Ductility for the 3D sandwich wall models was calculated from the numerical load–displacement curves obtained in ANSYS using the ratio of the ultimate displacement at peak load to the yield displacement where the response first deviated from linear behaviour. Yield displacement was defined using a bilinear approximation method based on the deviation from the initial linear stiffness of the load–displacement curve. Only the in-plane and combined axial–lateral cases were evaluated because the vertical loading remained fully elastic, with no identifiable yield point.

The yield and ultimate displacements for the different walls are shown in Table 6 and agree with the calculated ductility values.

Table 6. Ductility response of different wall models.

Wall model	Yield displacement Δy (mm)	Ultimate displacement Δu (IP) (mm)	Ductility μ (IP)	Ultimate displacement Δu (C) (mm)	Ductility μ (C)
WP-NR	6.0	14	2.33	16	2.67
WP-WR	6.0	18	3.00	17	2.83
SWP-NR	5.5	18	3.27	16	2.91
SWP-WR	5.0	17	3.40	15	3.00

Stiffened reinforced wall (SWP-WR) exhibits the highest ductility of 3.40 under in-plane load and 3.00 under combined loading. The lowest ductility obtained is for unstiffened and unreinforced walls (WP-NR) with values of ductility of 2.33 for in-plane load and 2.67 under combined loading. A comparison of the ductility variation among the different configurations is illustrated in Fig. 9. The effect of reinforcement and boundary stiffening on ductility is more pronounced. Compared to the unstiffened and unreinforced wall (WP-NR), the stiffened and reinforced wall (SWP-WR) exhibited an increase in ductility of approximately 45% under in-plane loading (from 2.33 to 3.40) and about 12% under combined loading (from 2.67 to 3.00). This demonstrates the significant role of reinforcement and boundary modification in enhancing deformation capacity.

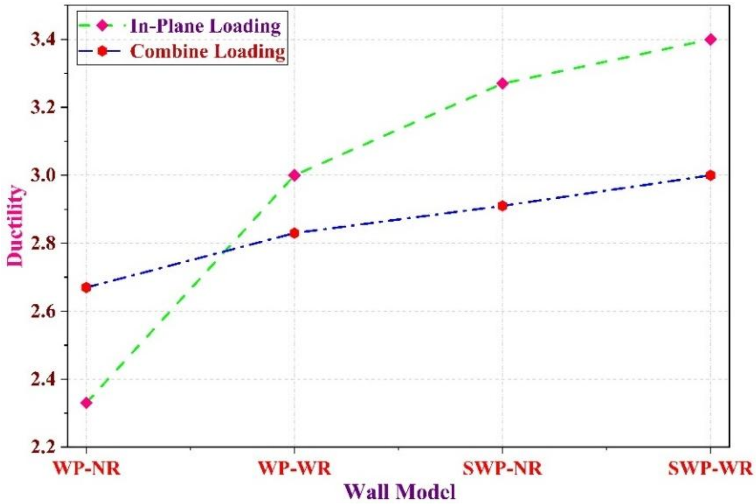


Fig. 9. Relative ductility behaviour of the tested wall specimens.

6. Numerical Validation and Verification

The developed finite element model was validated through a comprehensive comparison with experimental findings reported in literature and established codal provisions. The validation focuses on key structural response parameters, including load-carrying capacity, load-displacement, crack patterns, stiffness degradation, ductility, and failure modes. The numerical results show strong agreement with the experimental observations reported in the sandwich wall study of Appa Rao and Poluraju (2020). It investigated similar precast 3D sandwich wall systems under combined vertical and lateral loading conditions. The predicted load-displacement response exhibits an initial linear elastic phase followed by stiffness degradation due to cracking, which is consistent with experimental behaviour. The ultimate load capacities obtained from the numerical simulations fall within the range reported in literature. The crack patterns observed in the numerical model show diagonal cracking under in-plane and combined loading conditions, consistent with the typical shear–flexural behaviour reported in studies such as Benayoune et al. (2006). Crack initiation occurs near the tension zone at the base of the wall and propagates along principal stress trajectories. Furthermore, stress redistribution after cracking through reinforcement and boundary regions is consistent with established reinforced concrete behaviour. The stiffness degradation observed in the present study (approximately 22–24%) is consistent with the range reported for reinforced concrete wall systems subjected to lateral loading, where cracking governs stiffness reduction. In addition, the enhancement in ductility due to longitudinal reinforcement and boundary stiffening is in agreement with trends reported in previous experimental studies and reinforced concrete design principles.

A quantitative validation of the numerical results was carried out by comparing the predicted load capacities with available experimental data and codal predictions such as Eurocode 2 (2004) and ACI 318 (2019). The comparison is summarized in Table 7.

The comparison shows that the numerical results are in close agreement with the experimental results and code-based predictions, with ratios close to unity and low coefficient of variation. The deviations are generally within 10 to 15% and are acceptable for nonlinear finite element simulations of reinforced concrete systems. This confirms the validity and accuracy of the developed numerical model. Overall, the validation demonstrates that the proposed finite element model is capable of accurately capturing the structural behaviour of 3D sandwich wall panels under different loading conditions and can be reliably used for further parametric studies and design-oriented applications.

7. Conclusions

This study presents a detailed nonlinear finite element analysis of 3D sandwich wall panels subjected to vertical, in-plane, and combined loading conditions. The influence of boundary stiffening and longitudinal reinforcement on structural behaviour, including load–displacement response, stiffness degradation, ductility, stress distribution, and crack propagation, has been systematically evaluated. Based on the results, the following conclusions are drawn:

Table 7. Validation of numerical results against literature and codal provisions.

Group	Wall type	Numerical load (kN)	Literature value (kN)	Code prediction (kN)	Num/Lit	Num/Code
G1	WP-NR	150	140	145	1.07	1.03
	WP-WR	200	185	190	1.08	1.05
G2	SWP-NR	227	210	220	1.08	1.03
	SWP-WR	245	230	236	1.07	1.04
G3	WP-NR-C	120	110	115	1.09	1.04
	WP-WR-C	158	145	150	1.09	1.05
G4	SWP-NR-C	149	135	140	1.10	1.06
	SWP-WR-C	188	175	180	1.07	1.04
				Mean	1.08	1.04
				Standard deviation	0.01	0.01

- Boundary stiffening enhanced load-carrying capacity by approximately 3–5% under in-plane and combined loading conditions. Longitudinal reinforcement significantly improved ductility by up to 45% and contributed to a more stable post-peak response, indicating its effectiveness in improving deformation capacity and energy absorption.
- Under vertical loading, all wall configurations exhibited nearly linear elastic behaviour with negligible stiffness degradation, governed primarily by axial compression. In contrast, in-plane and combined loading resulted in diagonal and flexural cracking, leading to stiffness degradation in the range of 22–24%, confirming that concrete cracking is the dominant mechanism influencing stiffness reduction.
- Stiffened and reinforced wall configurations demonstrated delayed crack initiation, improved stress confinement, and more uniform stress distribution. Diagonal cracking under in-plane and combined loading followed principal stress paths, indicating that crack development is governed by internal stress flow within the wall system.
- Stress analysis revealed that unstiffened walls developed wider stress distribution zones and earlier localization, whereas stiffened walls exhibited concentrated and controlled stress paths along boundary regions. The stiffened–reinforced configuration showed the most stable structural response with reduced stress concentration and improved load transfer efficiency.
- The numerical results showed good agreement with experimental findings and codal predictions, with deviations generally within 10–15%. The numerical-to-experimental ratios were close to unity, confirming the reliability and accuracy of the developed finite element model.
- Overall, the study establishes that boundary stiffening and longitudinal reinforcement play a critical role in enhancing the structural performance of 3D sandwich wall panels. The developed numerical framework provides a reliable basis for analyzing and designing such systems under multi-directional loading conditions.

8. Recommendations

Further investigation is required to enhance the understanding of 3D sandwich wall panels with boundary stiffening and longitudinal reinforcement and to support their reliable use in real structural systems. The present study may be extended in the following directions:

- Numerical and experimental studies on sandwich walls incorporating different insulation core materials and varying EPS thicknesses to examine their effect on composite action and structural performance.
- Assess seismic performance of walls through reverse cycle loading or cyclic test methods using stiffened and unstiffened panels.
- Perform parametric studies on the effect of wall material, boundary conditions and the location of reinforcement to increase wall stiffness, load-carrying capacity, and ductility when loaded vertically and within the same plane as other loads.

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Conflict of Interest

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Data Availability

The datasets generated and/or analyzed during the current study are not publicly available but are available from the corresponding author upon reasonable request.

AI Assistance

No AI-based tools were used in the preparation of this manuscript.

Author Contributions

All authors made substantial contributions to the conception and design of the study, acquisition of data, analysis and interpretation of data; drafted or critically revised the manuscript for important intellectual content; and approved the final version to be published.

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