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Original Article

Loading Behavior of Sandwich Wall Infill with Opening: An Experimental Study

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Abstract *- A new construction element is currently being developed as an innovative building solution. This element is a single prefabricated unit structured as follows: It has an outer layer made of reinforced concrete, a middle layer consisting of insulation material, and an inner layer made of another sheet of reinforced concrete. Sandwich wall panels can serve both functions of insulating the building thermally and transferring load when they are erected between each other. For this experiment, specimens of sizes 1m x 1m and 0.1m overall thickness are being cast with varying EPS core thicknesses of 25mm, 50mm, and 75mm tested under an even vertical load distribution. These specimens are being bonded by reinforcement, with an opening in the middle measuring 0.15m x 0.15m. A wall is being evaluated to determine how structurally sound it is in comparison to a standard wall system in various structural parameter aspects. The wall specimen can support a failure load of 406 kN, i.e., 95% of the maximum load that a typical wall specimen can support. Additionally, it has a less thick core region of 25 mm and a very little 0.21 mm deflection on the forward-facing side of the panel. The failure deformation measurements indicate that concrete reaches its limit at 0.002350, while steel fails at 0.001190. The current study's findings suggest that insulated structural panels with openings are preferable to conventional walls. To create an efficient infrastructure for balanced and sustainable industrialization and nurture inventiveness, the adoption of this new technology is considered.*

Keywords *- Expanded polystyrene, Thermal insulation, Core, opening, Sustainable industrialization.*

1. Introduction

Sandwich wall panels' superior structural efficiency, low weight, and superior thermal insulation qualities have drawn much interest from the construction sector. The typical composition of these panels consists of a thermal insulating core bonded by two outer layers made of a high-strength material, like steel or reinforced concrete. Despite thorough investigations into how solid sandwich wall panels react to various loads, there is a significant lack of research regarding the performance of sandwich wall infills that contain openings. Sandwich wall infills frequently call for utility, door, or window openings in real-world applications. These apertures may considerably change the load distribution and structural integrity of the panel. A dearth of thorough experimental data on the loading behavior of sandwich wall infills with apertures persists despite their extensive application in contemporary construction. Engineers and designers find it difficult to forecast such structures' performance and safety because of this information gap. Sandwich wall infills with openings present additional challenges for stress distribution, possible concentrations of stress, and altered failure mechanisms. Furthermore, there might be a range of implications on the overall structural behavior depending on the size, shape, and placement of these openings. Understanding these factors is crucial for developing accurate design guidelines and ensuring the safety and efficiency of buildings incorporating sandwich wall infills with openings. The objective of this work is to fill this research gap by carrying out a methodical experimental analysis of sandwich wall infills with openings' loading behavior. We aim to offer important insights into the structural performance, failure mechanisms, and load-bearing capability of these elements by investigating different opening configurations under varied loading circumstances. The outcomes of this investigation will aid in the advancement of more precise design techniques and might result in ideal arrangements for sandwich wall infills, including apertures in construction applications.

1.1. Literature Survey

Sandwich wall panels are still in high demand worldwide today. The demand for these panels has increased even more as a result of the building industry's transition to off-site and modular construction techniques. Furthermore, sandwich panels are becoming a popular choice for both new construction and retrofitting projects due to strict building standards for energy efficiency. Advanced composite structures, known as sandwich wall panels, have become increasingly prevalent in contemporary engineering and building. These panels are made of a thicker, lighter core material fused to two thin, robust face sheets. This design produces a structure with low weight and great strength and stiffness, which makes it perfect for a variety of uses in industrial and architectural contexts. Modern needs for energy efficiency, speedy construction, and structural performance have been met by the creation of sandwich wall panels, which constitute a significant leap in construction technology. These panels can significantly reduce the overall weight of the building.

Additionally, these innovative panels are designed with superior insulation properties, which can lead to decreased energy usage for heating and cooling [1]. Sandwich wall panels benefit significantly from the incorporation of lightweight concrete [21]. Precast wall panels benefit from the synergistic effect of Thermocol cores and wire mesh layers [22]. The structural strength of the panel comes from its outer layers, while the core focuses on insulation and maintaining the panel's form [23]. Precast insulated mortar concrete sandwich panels have demonstrated the capability to function as an effective structural alternative to traditional concrete floors in housing construction [20]. Sandwich panels constructed with less rigid core materials showed increased susceptibility to localized damage when subjected to concentrated loads. These panels also experienced inward buckling of the compressed face sheet at lower overall load capacities [18].

Research has shown that the Insulated Concrete Form construction system exhibits favorable plastic deformation characteristics when subjected to axial compression loads. As a result, ICF is recommended for building construction, as it allows for optimal utilization of the wall's properties up to its maximum strain capacity [19]. For thinner panels (those with a higher slenderness ratio), adding more insulation significantly boosted their load-bearing capacity without increasing the overall wall thickness [2]. The relationship between panel slenderness and ultimate strength showed a more complex, non-linear pattern [3]. The panel's shape and proportions significantly affect both its deformation behavior and its strength [4]. The thermal resistance is typically higher for three-layered panels due to the increased material and complexity of the heat movement [5]. Adding fibres to the concrete core greatly improves the bending strength and post-yield deformability of the panel [6]. The combination of increased mortar thickness and optimally placed reinforcement can lead to panels that are not only stronger but also more ductile and resistant to sudden failure [7]. The polystyrene core may contribute to shear transfer between the outer layers, though to a lesser extent than in fully composite panels [8]. The similar crack patterns suggest that sandwich members may have comparable strength and serviceability characteristics to solid members [9].

The relationship between core density and strength is very reliable and consistent [10]. As the concentration of EPS beads increases, both the material's ability to resist bending and its ability to conduct heat decrease [11]. The presence of these openings can reduce the ability of structural members to bear and transfer loads effectively. Engineers and architects must balance functional requirements with structural integrity, often requiring additional reinforcement or alternative load paths around openings [12]. To emphasize the importance of careful planning in the layout of openings and the selection of appropriate support conditions to maintain structural integrity and load-bearing capacity [13].

Eurocode's 'sandwich' model method is suitable for calculating and optimizing steel reinforcement requirements in reinforced concrete wall panels used in industrial structures. This method proves to be a reliable tool for the design process of such structural elements [14]. Sandwich panels have been identified as highly effective structural components for installation on the perimeter of buildings subjected to blast loads. However, when the spacing between tubes in these panels exceeds an optimal value, it leads to excessive deformation without the desired progressive lobe formation [15].

The primary failure mode observed in these panels was localized separation between the core and the outer layers. The panels' performance is significantly influenced by two key factors: the ratio of L/d and the stiffness of the core material [16]. A composite wall was constructed using rigid polyurethane foam and MgO board. The observation that the MgO board's load-carrying capacity governs the wall's behavior is significant. It implies that while polyurethane foam may contribute to other properties (like insulation), it is not the primary factor in structural performance [17]. The study challenge of comprehending the loading behaviour of sandwich wall infill with openings can be effectively addressed with the help of the tests and data provided in this article. Practical implications for planning and evaluating the stability of such wall systems arise from observations on the crack movement and the flexing of panels with increasing stress.

1.2 Precast Light Weight Sandwich Wall Panels

Precast wall panels offer multiple advantages in construction. They reduce the superstructure's overall load while providing excellent heat and sound insulation. These panels feature fewer joints and can be installed rapidly and easily. They also increase load-bearing capacity and lower construction expenses.

Additionally, they are environmentally friendly, producing minimal waste during demolition. The construction industry benefits from the versatility of mass-produced, customized wall panels. These components are simple to manage and replace, making them suitable for a wide range of applications.

1.3. Expanded Polystyrene (EPS) Core

Expanded polystyrene is a lightweight, rigid insulation material composed of small, tightly packed plastic beads. In its resin state, Expanded Polystyrene (EPS) is processed. During the expansion process, a pentane gas that is present in the resin is safely expelled. The EPS resin can increase in size by up to 40% when steam is added. Then, the expanded pellets are put into a block moulder. Low heat conductivity, great compressive strength, lightweight, and inertness are all characteristics of EPS. For the majority of its qualities, EPS density can be regarded as the primary index. The density also affects other mechanical parameters of EPS. The deformation behaviour of expanded polystyrene under compression is isotropic [25]. An EPS's manufacturing cost is thought to be directly proportional to its density. Additionally, density affects non-mechanical features such as insulating coefficients. The selection criteria as per IS 4671 (1984) for EPS core thickness in this study are its insulation requirements, which also include thermal conductivity value, load-carrying capacity requirements of various category structures, acoustical properties, water absorption property, density, mechanical properties like compressive strength, stress-strain characteristics, elastic modulus, poison’s ratio, durability, etc. [24].

2. Novelty of the Research

The novelty of this research lies in its focused experimental investigation of sandwich wall infills with Expanded Polystyrene (EPS) cores, specifically incorporating openings. While solid sandwich panels have been studied, this research uniquely examines the effects of openings in EPS-core panels. The study provides new empirical data on how openings affect load distribution, stress concentrations, and failure modes in EPS sandwich infills. The experimental results could inform new or updated design guidelines for sandwich wall infills with openings, addressing a current gap in structural engineering practices. This research offers information on how sandwich wall panels with openings behave structurally under different circumstances. This contributes to the current understanding of this area of study. The data analysis conducted in the research helps identify failure sites, evaluate structural integrity, and establish relationships between load, strain, deflection, and crack formation. Observations on crack propagation and panel flexing with increasing load offer practical implications for designing and assessing the stability of such wall systems.

3. Materials and Preliminary Test Results

In the production of lightweight walls, the outer concrete layers are formed using a mix of high-grade Portland Cement (53 Grade), manufactured sand (M Sand), and small coarse aggregates measuring 10 mm in size. Every batch that was used was the purest, most flawless, and free of impurities. For the study, we used M_{30} grade concrete, and the quantities per m^3 of concrete are as follows: cement = 440 kg/m^3, water = 176.38 kg/m^3, coarse aggregate = 824 kg/m^3, fine aggregate = 982 kg/m^3 admixture = 4.84 kg/m^3 (1.1% of cement) w/c ratio = 0.4 as per IS 10262 (2009) mix design [26, 27]. In order to join the three layers together, steel bars are provided, like a steel reinforcement cage, on both sides.

The reason they were used in this study was because of their flexibility, which made cutting and bending them without damage easy. The reinforcement details are 8mm mild steel bars used for both vertical reinforcement and transverse steel at 150 mm c/c spacing evenly in either direction, with a clear cover of 15mm required for concrete layers. For the core layer of various specimen types, expanded polystyrene sheet material in thicknesses of 1/4 mm, 1/2 mm, and 3/4 mm is utilized.

The EPS has a density of 15 kg/m^3 with good physical and mechanical characteristics, that is, thermal conductivity at 0^o C and 10^o C is 0.34 mW/cm deg and 0.37 mW/cm deg, respectively, thermal stability is 1%, compressive strength at 10% deformation is 0.7 kg/cm^2, moisture absorption is 2%, and cross-breaking strength is 1.4 kg/cm^2 as per IS 4671 (1984) [28]. These characteristics improve the specimen's structural efficiency and suitability for experimental research.

Table 1. Material test results for mixed proportion

S.No.	Sand	
1	Relative density	2.67
2	Particle size distribution	2.59
3	Moisture retention	0.6 %
	10 mm aggregate	
1	Relative density	2.64
2	Particle size distribution	5.67
3	Moisture retention	0.49 %
	Cement	
1	Relative density	3.15
2	Setting time of cement	33min (Initial)
3		586 min (Final)
4	Standard Consistency	30%
5	Particle size distribution	5 %
6	Soundness of cement	0.5 mm

Table 2. Concrete strength test results

Concrete Tests	Average Concrete Strength
Maximum Crushing Stress of Cube (N/mm^2)	31
Indirect Tensile Strength of Cylinder (N/mm^2)	2.61
Bending Strength of Prism (N/mm^2)	3.73

3.1. Hardened Concrete Testing

Tests on hardened concrete are carried out to verify and regulate the calibre of the concrete components utilized in the construction process. Apart from ensuring quality control, conducting distinct tests on hardened concrete is crucial for ascertaining its physical attributes, including its strength and elastic properties. A preliminary test of the materials is performed to determine the mix proportion for casting specimens. Before being used for an experimental study, the hardened concrete specimens—such as the cube, cylinder, and prism are tested after 28 days of curing to make sure they have reached the desired strength and quality. Testing procedures are followed as per IS 516 (1959) and IS 5816 (1999) for all three types of specimens [29,30].

Fig. 1 Casting and testing of concrete specimens

4. Fabrication of Sandwich Panels

In the experiment, a sandwich wall panel measuring 1 m by 1m by 0.1 m was constructed using expanded polystyrene sheets positioned as the central core layer and formed of concrete (M30 grade) on both sides. Enough reinforcement, in the shape of 150 mm-spaced bars with an 8 mm diameter, is used to link the three layers together. In the centre of the panel is a 0.15 by 0.15 m window opening. The lowest layer of concrete is first filled and smoothed, utilizing the opening of a steel mould that is manufactured to match the panel specimen's specifications. To form the panel's core, reinforcement is initially laid on the base concrete layer. An EPS sheet of specified thickness is then placed over this. To enhance adhesion, another reinforcing cage is set atop the EPS. Next, a concrete layer matching the thickness of the base is poured over the cage. The completed panel is then left to cure for four weeks before testing.

4.1. Specimen Details

- Sandwich Wall Type 1 (SWW Type 1) is made up of a 150 x 150 mm window opening, a bottom concrete layer measuring 37.5 mm, a center EPS layer measuring 25 mm, and a top concrete layer measuring 37.5 mm.
- Sandwich Wall Type 2 (SWW Type 2) is made up of a 150 x 150 mm window opening, a bottom concrete layer measuring 25 mm, a center EPS layer measuring 50 mm, and a top concrete layer measuring 25 mm.
- Sandwich Wall Type 3 (SWW Type 3) is made up of a 150 x 150 mm window opening, a bottom concrete layer measuring 25 mm, a center EPS layer measuring 75 mm, and a top concrete layer measuring 25 mm.
- Conventional Wall (CW) is made up of a 150 x 150 mm window opening, a bottom concrete layer measuring 50 mm, a center EPS layer measuring 0 mm, and a top concrete layer measuring 50 mm.

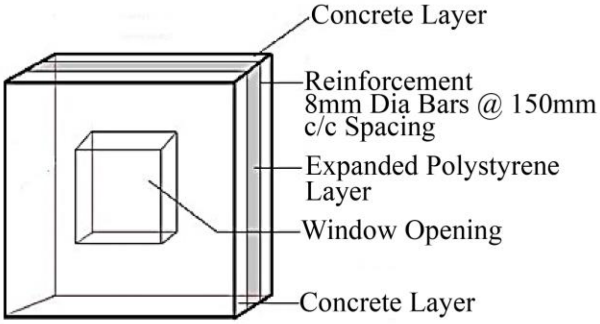

Fig. 2 Wall specimen sketch

4.2. Openings in the Wall

Wall openings, like windows and doors, can have a big effect on structural performance because they change the way the wall system behaves structurally and redistributes loads. The following are some of the main explanations for how wall apertures impact structural performance:

- It interrupts the continuous loading path, which may result in concentrated loads along the apertures' margins, necessitating the inclusion of reinforcement to keep the structure from collapsing.
- A wall's structural integrity is undermined at the corners and margins of apertures, which are areas of concentrated stress.

- Walls resist horizontal forces like wind and seismic stresses, which helps a building's lateral stability. The presence of apertures may weaken the wall's resistance to shear stresses, particularly if the apertures are big or positioned unevenly. This could risk the structure's overall stability.
- The material of the wall becomes discontinuous around openings, which may reduce the wall's overall stiffness and strength.
- A wall's ability to withstand bending, shearing, and axial loads is significantly reduced when it has apertures in it. The wall becomes more prone to deformation and failure under applied stresses when the material is removed to create openings because it has a reduced total cross-sectional area and stiffness.

The location, size, and shape of wall openings have a significant impact on the stresses resulting from applied vertical loads and the stability of the structure. It also lessens the structural wall's strength and stiffness, which has an impact on how well they perform seismically. Although it is commonly known that opening size has a substantial impact on a wall's structural response, opinions regarding the behavior of walls at various opening locations are unclear.

Beam elements behave significantly above and below openings. Column element activity was seen in areas next to openings where the load was concentrated. It was discovered that fractures eventually break through one of the structure's column-like sections, reaching the corners of the voids inside of them. The presence of openings in walls creates areas of concentrated stress around them, making the structural analysis of these walls more challenging and intricate.

Creating or modifying wall apertures may change the distribution of stress within the wall, which could negatively impact the behavior of the wall. It is generally acknowledged that the consequences of small openings can sometimes be overlooked, even if the existence of a large aperture usually dramatically alters the structural system. When a wall has apertures, its ultimate load capacity is much less than that of a similar solid wall. The ultimate load is determined by how quickly the column or beam strips surrounding the aperture fail; however, the minimum opening size required for the side restraints to have a major effect on the ultimate capacity is still unresolved.

In terms of measurements, IS standards offer recommendations for the minimum sizes of windows based on variables, including the room's size, purpose, and local climate. These dimensions ensure proper ventilation, natural lighting, and compliance with safety regulations. There are no specific dimensions for openings in the wall. For this study, the window opening at the center of the panel, provided with a dimension of 150mm x 150mm, has been selected.

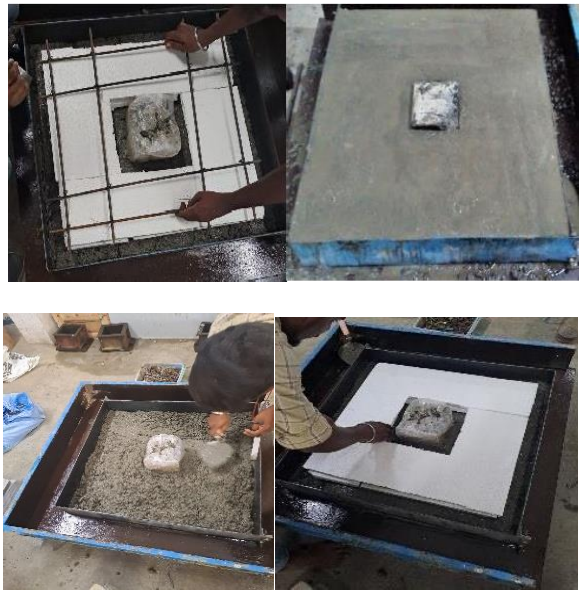

Fig. 3 Fabrication of specimens

5. Experimental Work

The structural performance of a wall panel is evaluated using the testing methods listed below: The specimen's surface is prepared for testing after letting the wall firm for around 28 days of cure. Putting in place the use of a steel plate that covers the top surface of the wall entirely to ensure appropriate vertical load distribution. Wall placement in a loading frame of 50 tons with an exact axis loading plan is necessary for a safe and stable fixity during testing. When prepared, the calibrated loading frame equipment applies downward forces at a controlled rate of 0.1 kilonewtons per second. This precise control and calibration ensure accurate measurement of the loads applied to the test specimens. It is positioned within the loading frame to gauge the even vertical load that is applied. The strain gauges of grid size 60mm are fastened to the wall at strategic places to continuously monitor the strain measurements in the four-channel strain indicator when the load is applied to record measurements and observations at every load level. Dial test indicators (0.01–50 mm) on both wall sides are used to record the load and related precise deflection data at each step. Initial and ultimate crack growth monitoring and documentation of crack patterns are included in the crack measurement. Analyzing the panel's structural behavior requires identifying the crack initiation location. In order to guarantee the wall's structural effectiveness, the following requirements must be met:

- Panel’s highest load capable to withstand Being conscious of how the panel flexes with increasing load.
- Determining and measuring the maximum strain of the material.
- Observing how the cracks in the panel are propagated. Figuring out the specific failure modes the panel exhibited.
- Evaluating the tested panel's structural integrity in

comparison to a standard wall. This comparison reveals the differences and usefulness between the tested panel and a traditional construction technique.

- Data analysis to find failure sites, perform structural evaluations before and after tests, and look for relationships.

Fig. 4 Load application and structural performance evaluation

6. Test Results

6.1. Ultimate Strength of Wall Panel

Sandwich walls ought to be built with allowable compressive stress and no tension. It is important to remember that a wall with heavier vertical loads will be able to withstand lateral loads more effectively than one with lighter vertical loads. This point should be considered when planning the structure to achieve economy in structural design. Its load-carrying capacity is the most crucial criterion of all the structural elements. The most effective specimen of all, the 25mm EPS core thickness specimen, which can support a high failure stress of 406 kN, exhibits its first crack at 378 kN when compression loading is applied. It has been noted that the specimen can support 95% of the conventional wall specimen's ultimate crack load. Thus, it is structurally acceptable to use this kind of sandwich wall panel with a lower-density core insulating material.

The thickness of the expanded polystyrene layer has an inverse relationship with the panel's ultimate compressive strength. The maximum sustainable load of the wall panel decreases with increasing EPS layer thickness. During compressive loading, air trapped in the EPS foam cells is squeezed, increasing strain rate sensitivity and viscous forces that rise with the loading rate. A key component of shear transfer mechanisms is the relationship between the EPS layer and steel or concrete. Thicker EPS layers may impact shear strength and elastic modulus because they may change how well shear transfers across layers. The specimens' initial and final crack loads are listed in the table below.

Table 3. Primary crack load

S.No.	Wall Types	Primary Crack Load (kN)	Average Primary Crack Load (kN)
1.	SWW Type 1	377	378
		360	
		397	
2.	SWW Type 2	285	280
		260	
		295	
3.	SWW Type 3	205	214
		215	
		222	
4.	CW	401	404
		402	
		409	

Table 4. Maximum failure load

S.No.	Wall Types	Primary Crack Load (kN)	Average Primary Crack Load (kN)
1.	SWW Type 1	404	406
		398	
		416	
2.	SWW Type 2	342	329
		311	
		334	
3.	SWW Type 3	272	252
		241	
		243	
4.	CW	443	427
		435	
		433	

6.2. Deformation Characteristics

The ability to withstand sideways displacement and resist tipping forces has grown in significance. Generally, there are two ways a structure can satisfy these criteria. The first is to enlarge members beyond what is necessary to maximize their strength. By molding the structure into something stiffer and more stable, the second, more advanced approach reduces deformation and increases stability. The shear wall type provides stability against horizontal loads like wind and earthquakes by transferring these forces to the foundation while also contributing to the overall stiffness and strength of the structure. Due to their robust nature, steadiness, and resistance to deformation, shear walls are frequently used to withstand sideways forces. They usually have relatively little in the perpendicular direction, but they are rather stiff in their plane. Therefore, the floor diaphragms' ability to avoid wall buckling and stiffen the wall is essential to their satisfactory performance. For a number of functional reasons, such as the placement of windows, doors, and service ducts, many shear walls require a uniform arrangement of openings. These kinds of openings have the potential to somewhat reduce the rigidity of the shear wall, depending on their size and shape. It has been noted that shear wall openings of varying sizes influence lateral deflections more than openings of smaller sizes. Another crucial aspect is the form of the apertures. Most design codes disregard the reinforcement's contribution to the wall's final strength and load-carrying capability if it is installed in a single layer of mesh. However, the reinforcement adds to the member's total ductility at the moment of failure. A progressive increase in deflection is observed as the load increases. Under continuous vertical loading, the back of the wall panel experiences significant deformation until it reaches its breaking point. This occurs for all three wall types, each with a different core thickness. In contrast, the front of the panel shows minimal deformation. The most resilient specimen (with a 25 mm core) shows maximum deflections of 0.21 mm on the front and 0.52 mm on the back. This represents a 40% reduction in deflection compared to a standard wall specimen. From the point of initial cracking to the final load failure, the rate of deflection remains steady. The highest values of deflection between the front and rear panels that were noted are listed in the tabular list below.

Table 5. Deformation details

Wall Types	Δ_{min} (mm)	Δ_{max} (mm)
SWW Type 1	0.21	0.52
SWW Type 2	0.46	1.24
SWW Type 3	0.57	2.53
CW	0.73	0.87

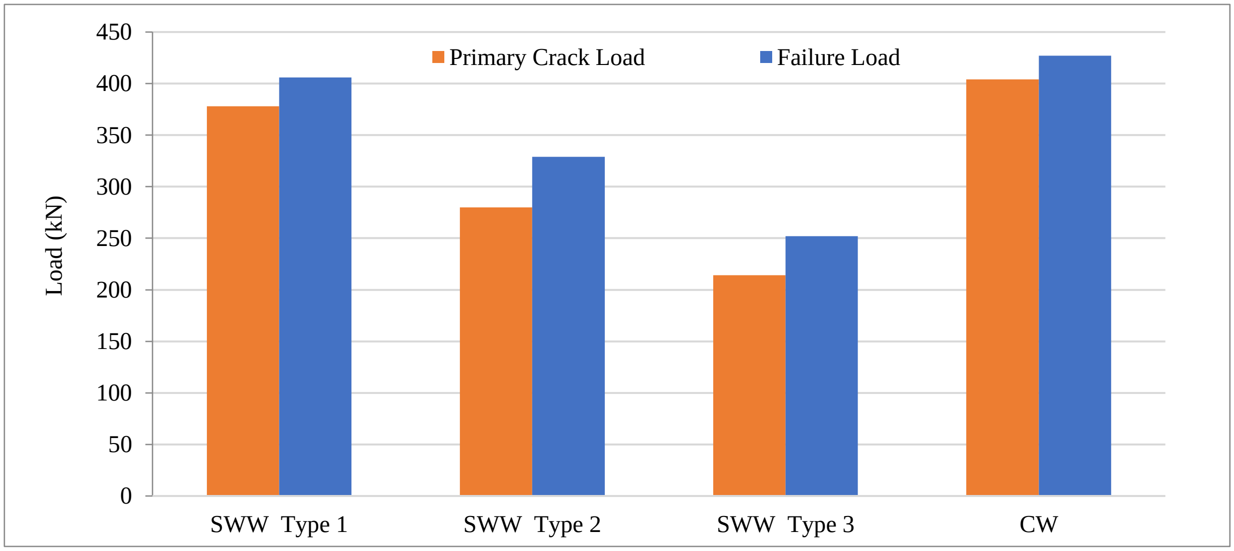

Fig. 5 Load-bearing capacities of different wall panel types

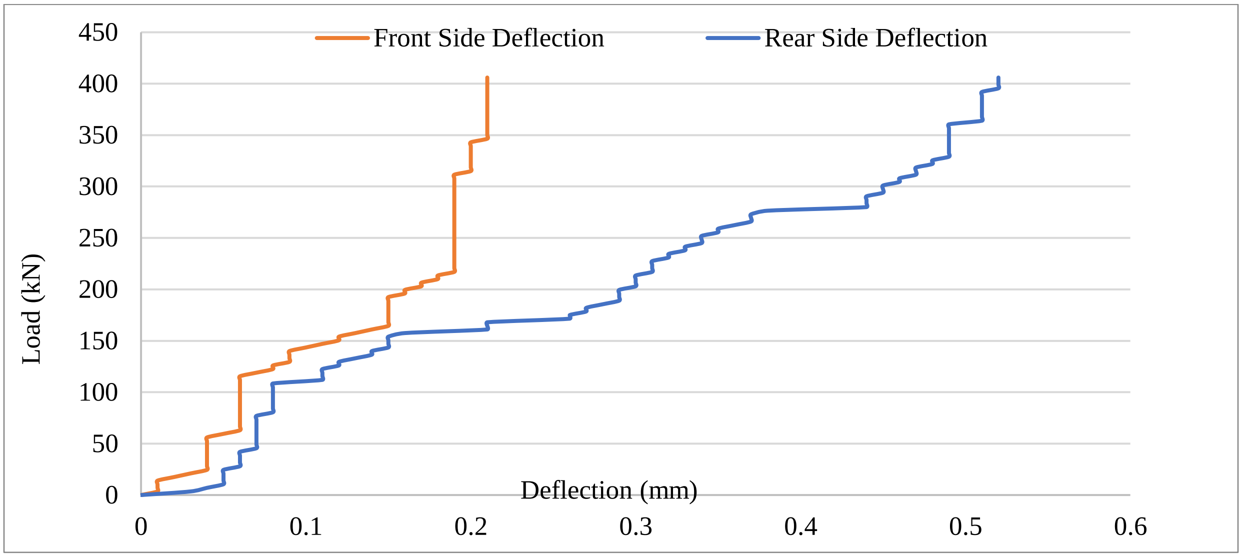

Fig. 6 Load V_s Δ_{max} for SWW type 1

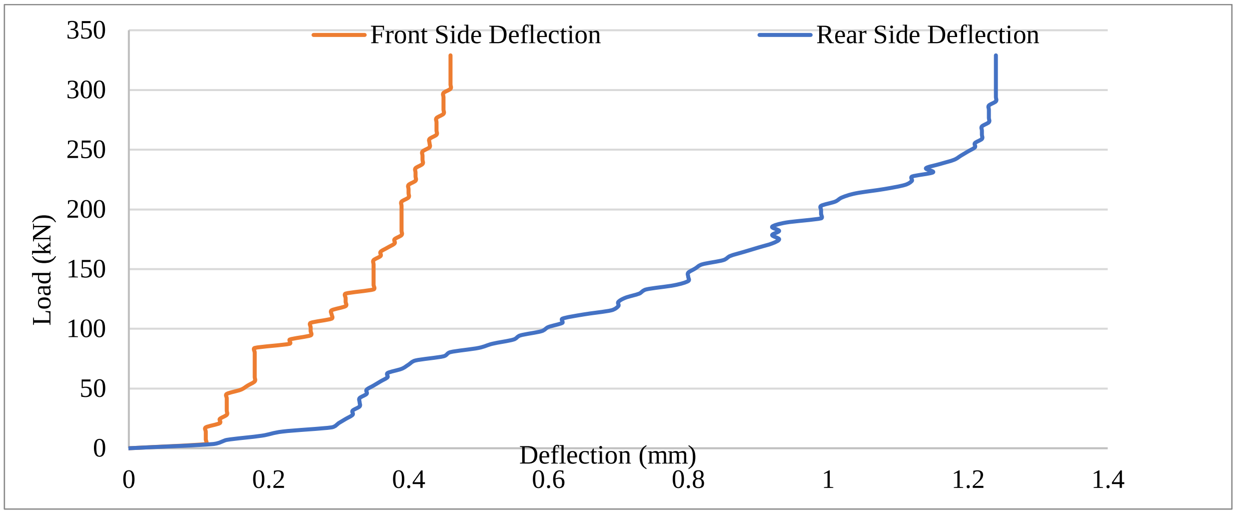

Fig. 7 Load V_s Δ_{max} for SWW type 2

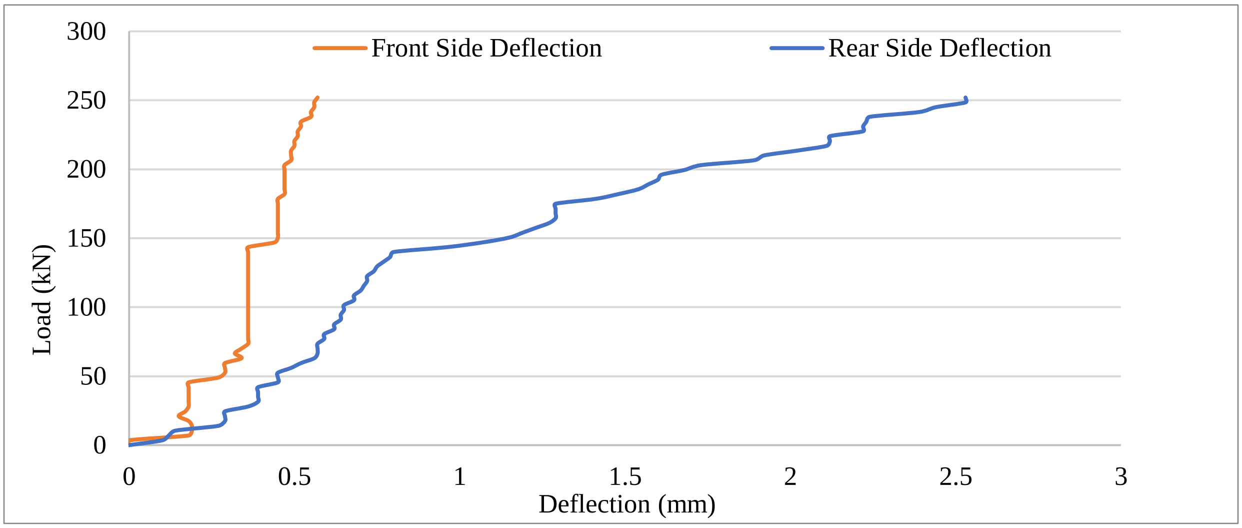

Fig. 8 Load V_s Δ_{max} for SWW type 3

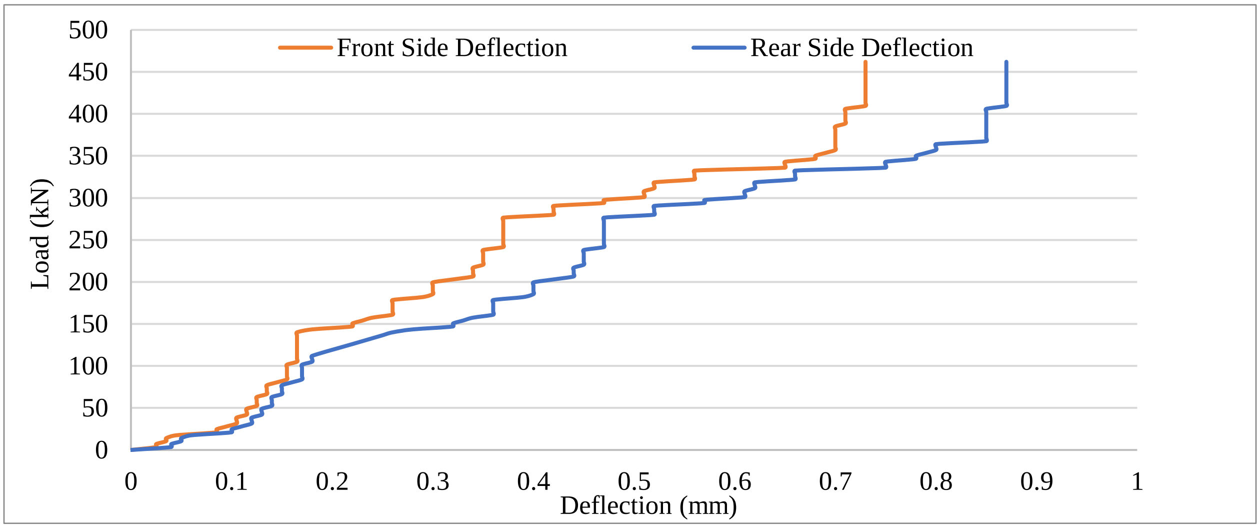

Fig. 9 Load V_s Δ_{max} for CW

6.3. Strain Propagation in Steel and Concrete

In an experiment, the deformation under stress in a sandwich panel made of bonded steel and a concrete layer varied the thickness of the EPS layer across different panels. The experiment involved applying stress to these panels and precisely measuring the resulting deformation using strain gauges. Increasing the thickness of the EPS core is associated with higher ultimate strain values in both the steel and concrete components.

This is a crucial finding since it shows that the variation greatly influences the sandwich panel's load-carrying capability and deformation behavior in EPS core thickness. Comments on the rigidity of steel and a relatively reduced minimum strain capacity for concrete provide further insight into material characteristics and responses to stress. The table enables a comparison of the effects of EPS core thickness variations on the maximum strain values in the sandwich panel's steel and concrete components.

Table 6. Strain accumulation in steel

Wall Types	**ϵ_{max}(Steel)**
SWW Type 1 (1/4th EPS Layer)	0.000884
SWW Type 2 (1/2th EPS Layer)	0.001488
SWW Type 3 (3/4th EPS Layer)	0.002480

Table 7. Strain accumulation in concrete

Specimen Details	**ϵ_{max} (Concrete)**
SWW Type 1 (1/4th EPS Layer)	0.000400
SWW Type 2 (1/2th EPS Layer)	0.000750
SWW Type 3 (3/4th EPS Layer)	0.001190

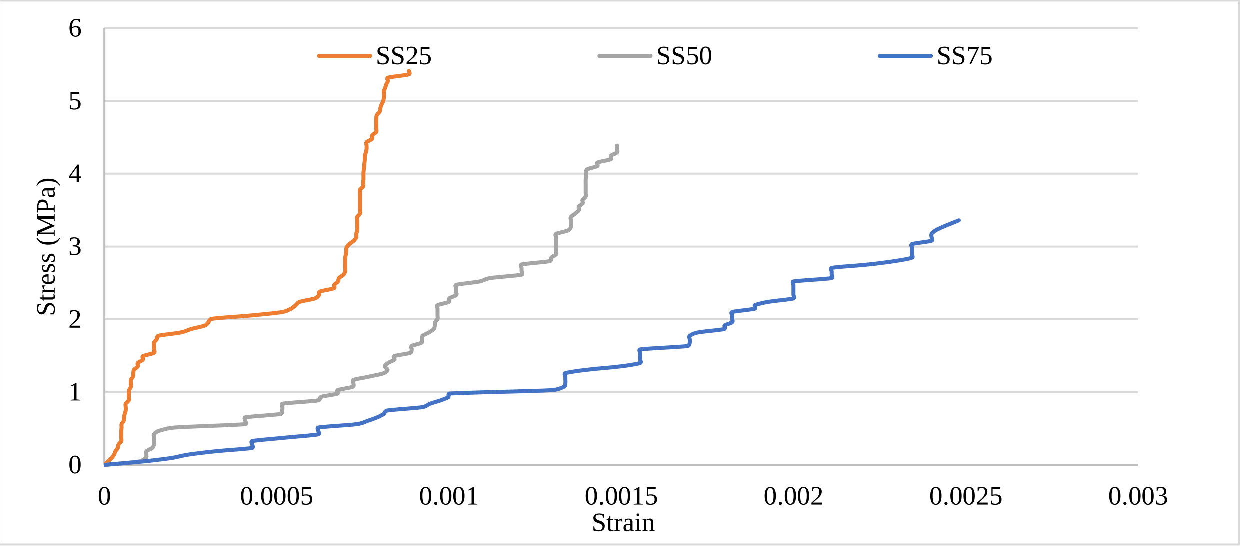

Fig. 10 $\sigma - \epsilon$ curve plotting for steel bonded in wall panel

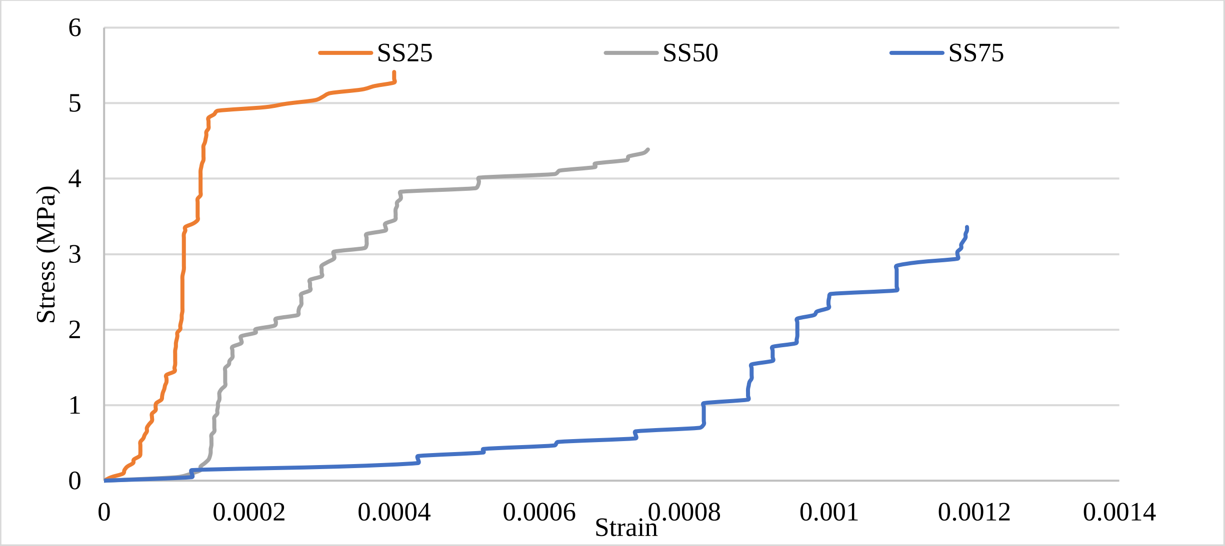

Fig. 11 $\sigma - \epsilon$ curve plotting for concrete layered element in wall panel

6.4. Cracking Patterns in Panels

The bulk of large cracks are located at window openings, corners, and edges. Although they only spread slowly from the initial loading phases to the collapse stage, these locations have an impact on the structural soundness. When the tension applied from the outside exceeds the material's true strength, cracks usually result. It also shows how ductile nature is, which is essential for construction in seismically dangerous areas to prevent unanticipated failure. The composite action and enhanced shear contact between the sandwich layers are demonstrated by the low-density core and concrete layer not debonding. The first fracture in the wall originated horizontally at the base right of the wall due to applied stress, and all the walls usually follow this pattern of cracking. As the vertical stress increased, the first diagonal crack emerged. Later, for 25 mm EPS core specimens, the tension steel imparted the process and produced a larger diagonal crack (corner-to-corner), which led to the development of additional diagonal cracks and diagonal failure at an ultimate load of 406 kN. But it stops the abrupt failure that happens when the fissures open. Large cracks began to form around the panel opening and extended to the walls' edges as the load grew. At its most severe, any failure, either early interface debonding failure or material failure, occurs. The form and position of the wall's aperture, as well as the way the concrete, reinforcement, and EPS sheet interacted, all had an impact on the type of wall failure and the development of cracks. As the wall nears its breaking point under maximum stress, the top and bottom edges of the panel show almost no signs of damage or compression. This indicates that the failure mechanism is likely occurring within the panel's structure rather than at its extremities. This is followed by premature material failure and spalling of the concrete due to brittleness, which causes local buckling from excessive compressive stresses. A few tiny surface cracks are also discernible.

Fig. 12 (a) Surface crack (b) Edge crack (c) Corner crack (d) Opening crack (Close-up View)

6.4.1. Panel's Response to Stress-Induced Cracks

As shown in Table 8, the crack monitoring is carried out by measuring the crack width using a concrete crack measuring microscope. Wall type 1 has the majority of the observed cracks to be narrow and hairline, making it appropriate for mild to moderate exposure conditions. SWW type 3, which is inappropriate for harsher and more hostile exposure, only had one medium crack visible. The permissible limit for crack width for exposures is checked as per IS 456 (2000) [24].

Table 8. Failure crack details

Specimen Type	Step of Loading	Load	Crack Growth Measurement
		kN	millimetre
SWW Type 1	Crack Initiation Load	378	0.088
	Failure Load	406	0.100
SWW Type 2	Crack Initiation Load	280	0.128
	Failure Load	329	0.236
SWW Type 3	Crack Initiation Load	214	0.326
	Failure Load	252	0.362
CW	Crack Initiation Load	404	0.126
	Failure Load	427	0.178

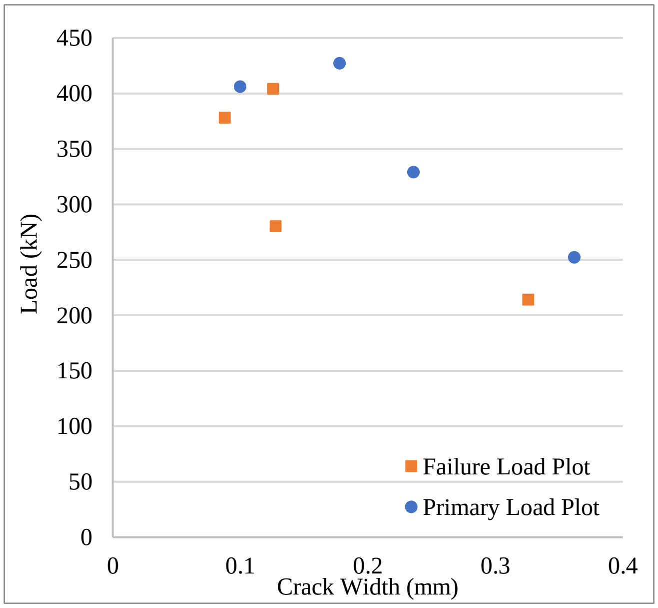

Fig. 13 Load vs Crack width plot

Table 9. Overall performance metrics

Performance Metrics	EPS Core Thickness - 25mm	EPS Core Thickness - 50mm	EPS Core Thickness - 75mm
Load Bearing Capacity	High load resistance	Moderate load resistance	Low load resistance
Deflection	Low deflection	Moderate deflection	High deflection
Strain in concrete	Less distortion	Average distortion	More distortion
Strain in steel	Minimal extension	Intermediate extension	Extensive extension
Crack Development	Limited crack propagation	Fair crack growth	Severe crack propagation

7. Conclusion

When compared to traditional wall systems, wall panels with core insulation can provide a number of performance benefits, particularly in terms of things like thermal efficiency, acoustic insulation, and overall energy performance.

Among all tested specimens, the one with the thinnest core, measuring 25 mm in thickness, demonstrates the highest ability to bear loads. Following the emergence of the first initial fracture at around 93% of the ultimate load, numerous tiny and macro fissures form in and around the panel opening. The wall specimen can support a maximum load of 406 kN, i.e., 95% of the maximum load that a typical wall specimen can support. It proves that a higher panel core thickness reduces the final load-carrying capacity of the panels, just like it does for traditional walls. Experiments confirm the theoretical prediction that stress concentration zones around wall openings could lower the wall's capacity to withstand the load. A wall panel with a 25mm thick Expanded Polystyrene (EPS) core and no openings demonstrates impressive strength, withstanding a substantial failure stress of 504 kN. This specimen's performance is noteworthy, as it can bear 98.6% of the load that typically causes a standard wall to crack completely. However, this high load-bearing capacity may not be maintained if the wall design includes openings, such as windows or doors, which could significantly alter its structural integrity and overall load-carrying ability.

- The highest deflection observed for a wall panel with a 75 mm core thickness was 2.53 mm. Specimens with a lower core thickness deflect at a slower rate, and it is possible that increasing the EPS thickness will improve rigidity and decrease deflection in the panel. Whereas a structural component that is resistant to bending forces is the EPS core.

- Up to its total disintegration, the low-density expanded polystyrene layer exhibits acceptable volume consistency. The material strain limit reaches 0.002350 and 0.001190, respectively, for steel and concrete, and the panel displays elastic behavior all the way through the loading procedure.

- For an expanded polystyrene core panel 75 mm thickness, the larger propagation of crack at a critical load of 252 kN is 0.362 mm. Depending on the exposure conditions, the use of a 75 mm thick EPS core specimen may be restricted since its serviceability and durability may exceed the permissible limit.

- The panel can withstand a maximum compressive stress of 5.41 N/mm² before failing completely. The panel begins to show signs of significant damage, marked by the appearance of the first major crack at a compressive stress of 5.04 N/mm².

- The crack patterns expected around the openings when it is loaded vertically are corner cracks, top horizontal cracks, sill cracks, diagonal cracks, adjacent vertical cracks, flexural cracks, and junction cracks. Among these theoretically predicted patterns of cracks, most of the patterns of cracks are clearly observed.

- Composite walls should be utilized as a dividing wall in multistory buildings and as a structural wall in low-height buildings.

7.1. Future Study

The experimental study can be carried out further:

- By altering different lightweight core materials.
- Thermal and noise insulation performance.
- For different joints and connections.
- Plumbing works in the panel.
- Durability studies on the wall panel.

Credit Author Statement

- Mr. R. Rajeshwaran: Conceptualization, Funding Acquisition, Visualization, Writing original draft, Investigation.
- Dr. J. Logeshwari: Methodology, Validation, Supervision, Project Administration.
- Mrs. R. Abirami: Data curation, Resources, Formal analysis.

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