

Influence of Reinforcement Detailing on Load-Carrying Capacity and Composite Behavior of HDP- Core Precast Concrete Sandwich Panels

R. Rajeshwaran^{1,2†}, R. Abirami², Thirilo Chandar³, C.B. Shanmugam³

¹ Assistant Professor, Department of Civil Engineering, St. Peter's Institute of Higher Education & Research, Avadi, Tamil Nadu, India.

² Department of Civil Engineering, Aarupadai Veedu Institute of Technology, Vinayaka Mission's Research Foundation, (Deemed to be University), Tamil Nadu, India.

³ PG Student, Department of Civil Engineering, Aarupadai Veedu Institute of Technology, Vinayaka Mission's Research Foundation, (Deemed to be University), Tamil Nadu, India.

†Corresponding author: R.Rajeshwaran; vtd987@veltech.edu.in; rajeshwaranr.civil@spiher.ac.in

Abstract

This research investigates the structural and thermal performance of lightweight precast concrete wall panels incorporating high-density polystyrene (HDP) as an insulating core.

The study aims to develop a load-bearing wall system that reduces self-weight while enhancing thermal efficiency compared to conventional solid concrete walls. M30 grade concrete was designed and verified through standard material characterization tests, including specific gravity, sieve analysis, water absorption, consistency, setting time, and compressive strength in accordance with relevant IS codes. Sandwich wall panels were fabricated with constant insulation thickness and two different reinforcement spacing (300 mm and 150 mm).

To assess the effect of reinforcement density on structural response. Axial compression tests were performed using a loading frame, and load deflection behavior, crack propagation, and ultimate load capacity were recorded. According to experimental data, panels with a 150 mm reinforcement spacing outperformed panels with a 300 mm spacing in terms of ultimate load capacity and lateral deflection. The insulated panels showed notable weight reduction with increased thermal resistance and sufficient load-carrying capability. SAP software-assisted numerical modeling demonstrated a high degree of agreement with experimental findings. The findings demonstrate that thermally insulated lightweight precast wall panels provide an efficient, sustainable, and structurally reliable alternative for modern energy-efficient building applications.

1 Introduction

Global demand for sustainable and Energy-efficient building materials has increased due to the quick growth of infrastructure and urbanization. The International Energy Agency states that buildings use a significant amount of the world's energy, under scoring the pressing need for structural systems that are thermally efficient [1]. Despite being widely used and structurally reliable according to established design guidelines like ACI 318-19 and Eurocode 2 [3], [15], conventional reinforced concrete wall systems significantly increase structural dead load and operational energy demand because of their high density and inadequate thermal insulation. As a result, one of the main goals of contemporary structural engineering research is to reduce self-weight while increasing thermal efficiency. Precast concrete construction has become a viable way to increase labor efficiency, quality control, and building speed [2]. Suggestions for innovative design given in the PCI Design Handbook makes use of precast systems in load bearing structural applications. But, conventional type of precast concrete panels at some cases have higher thermal conductivity which leads to higher cooling energy requirement, especially in high temperature places. To overcome this

condition, precast concrete sandwich wall panels made of insulating cores have become an emerging trend in the construction field. These sandwich panels usually contain two reinforced concrete layers separated by core insulating materials like expanded polystyrene (HDP) or high-density polystyrene (HDP), which offers both better strength criteria and good thermal insulation. Previous studies have concluded that sandwich panels can greatly reduce total structural weight without reducing composite interaction action between the layers. Experimental works have noted that adequate heat transfer mechanisms and proper detailed reinforcement play a major role in the composite behavior and load-bearing capacity. The inclusion of any insulated cores provided with effective shear connectors and designed reinforcement may give excellent thermal performance without any degradation in axial strength. The loading structural response for the panels also depends on percentage of reinforcement, spacing of bars, bonding strength between layers etc. The hardened concrete tests like compressive strength (ASTM C39) and in direct tensile strength (ASTM C496) are used to find out the mechanical behavior of concrete. These concrete tests ensure any testing structural capabilities and also confirm the tested results. Along with laboratory tests, finite element analysis is also done with structural software, like SAP, which is widely applied for load simulation and deflection characteristics behavior and to validate experimental results. Numerical projections bring confidence in adopting unique wall pattern designs for real-world construction field applications. Despite thorough investigations on insulated sandwich panels, there is a scarcity of research on the collective efforts of these above factors in insulated panels is a significant gap in this research. Therefore, this research work conducts experimental study on light weight precast sandwich wall panels having HDP insulating cores and analyzes the effect of reinforcement spacing and output of ultimate load carrying capacity, deflection profiles, and failure crack development. The results need for improvement of development of structurally sound, energy-efficient design, and integration of sustainability in precast wall systems which fit for environmentally construction techniques.

2 Materials Used

2.1 Cement

This study employed an OPC of 53 grades that complied with the IS 12269 :2013 requirements. The preliminary tests of cement, like the standard consistency test and initial & final setting time tests, were conducted. The binding quality of the cement were determined with the tests for proportioning the concrete of M₃₀ grade with consistent growth of strength over time.

2.2 Fine Aggregate

The fine aggregate used is river sand in Zone II grading according to IS 383:2016. The sieve analysis has been conducted to determine the fineness modulus and particle size distribution. For arriving mix ratio, specific gravity and water absorption tests conducted which fell within permissible limits, guaranteeing required workability and durability.

2.3 Coarse Aggregate

The nominal size (20 mm) coarse aggregate is used in the concrete blend for fabricating the panel concrete layer. The aggregates quality & grading standards checked as per IS 383 :2016. The aggregates properties such as specific gravity, impact value, and water absorption is checked for their appropriateness for structural use before usage. The angular texture of the aggregates possess to have better mechanical interlocking properties under loading and shows higher crushing strength [19].

2.4 Water

The water used for mixing and curing process should be a potable water that should be pure from impurities and devoid of contaminants. The quality of water used must follow IS 456:2000 requirements to avoid any detrimental effects on hydration process of strength gain and durability.

2.5 Insulation Core Material

High-Density Polystyrene (HDP) sheets as the core layer shows better insulation in wall panels. This sheets were chosen due to its light weight properties, less thermal conductivity, and ability to resist wetness. All panels maintained a standard thickness of polystyrene to warrant uniform insulation efficiency and effective structural interaction between the layers of panels. Using HDP made the panels much lighter and better at keeping heat out.

2.6 Reinforcement

The reinforcement cage was designed using deformed MS steel bars with a yield strength of Fe 500 grade, as per IS 1786:2008 standards. Two different cage configurations of reinforcement system, with spacing of 300 mm and 150 mm of 6mm dia bars, were tested to assess their structural effects on uniform axial load performance and deflection.

characteristics behavior. The tensile and mechanical properties of the steel rods used were confirmed with basic test results before the cage fabrication process.

2.7 Concrete Mix Design

The Mix concrete was designed to attain an M_{30} grade attainment strength as per the IS 10262 :2019. Test batches of specimen were fabricated with good workability to check tensile, bending, and compressive strength for the grade confirmation. The final mix ratio was arrived to ensure strong bonding between the layers of concrete and polystyrene core, thus improve the efficiency of high composite action in the lightweight sandwich wall panels.

3 Methodology

An experimental program was created to test how well lightweight insulated prefabricated wall panels hold up under axial stress.

3.1 Material properties

The samples are cast after the laboratory tests conducted on all panel materials to ensure conformity with IS standards. Binding material - Cement is tested for its standard consistency, fineness initial and final setting time, and specific gravity, density. The sand and coarse aggregates were sieved to determine specific gravity, water absorption to confirm their grade before mixing. The reinforcing steel bars was tested for its yield strength, maximum strength and tensile properties. These preliminary studies confirmed the suitability for the production of M30 quality structural concrete.

3.2 Mixing/casting test

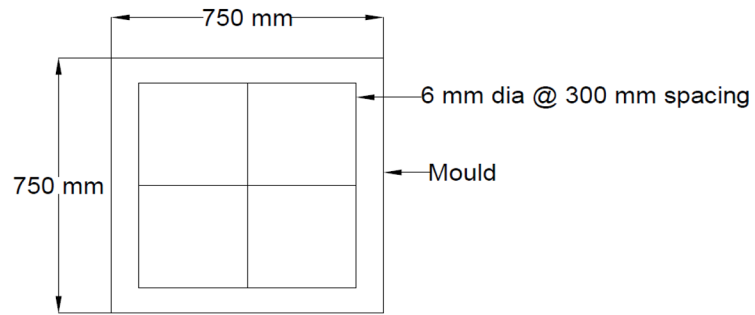
Concrete placement was carried out in accordance with IS 10262:2019 to achieve a target characteristic compressive strength of 30 MPa. Test mixes were prepared to optimize workability and strength parameters. Standard cube samples were injected and tested after 7 and 28 days to validate the mixture before starting panel manufacturing.

3.3 Specimen fabrication

The wall panels were manufactured as prefabricated sandwich concrete elements consisting of two concrete lintels (25 mm each) separated by an insulating layer of high-density polystyrene (HDP). The dimension of wall panel is 1m x 1m x 0.1m. The insulation thickness was kept constant for all samples to ensure uniform thermal performance i.e. 50 mm. Clip shaped MS shear connector made of 10 mm thickness, 30 mm x 150 mm dimension, provided across the 50 mm HDP core in the 1000 m panel length. The shear connector [18] to ensure proper shear transfer and composite action is embedded into each concrete layers, leaving the middle core portion passing through the 50 mm HDP insulation. Two reinforcement structures were adopted. Sample S1 has a pitch of 300 mm and sample S2 has a pitch of 150 mm. Variation of reinforcing bar spacing was introduced to study its effect on the bearing capacity and behavior of the structure. Reinforcement cages were prepared and precisely placed within the form work to ensure proper coverage and leveling of the concrete. The concrete was placed in layers and compacted by mechanical vibration to eliminate voids and ensure good bonding between layers. The design limits for the reinforced concrete layers used is based on the general provisions of IS 456:2000 for reinforced concrete structural members.

3.4 Curing process

After casting, the samples were removed from the mold after 24 h and subjected to water vulcanization for 28 days. Adequate curing was ensured to ensure sufficient hydration and strength development. All samples were tested after reaching the required curing period.



Acti
Can

Fig. 1 Specimen 1 rft details

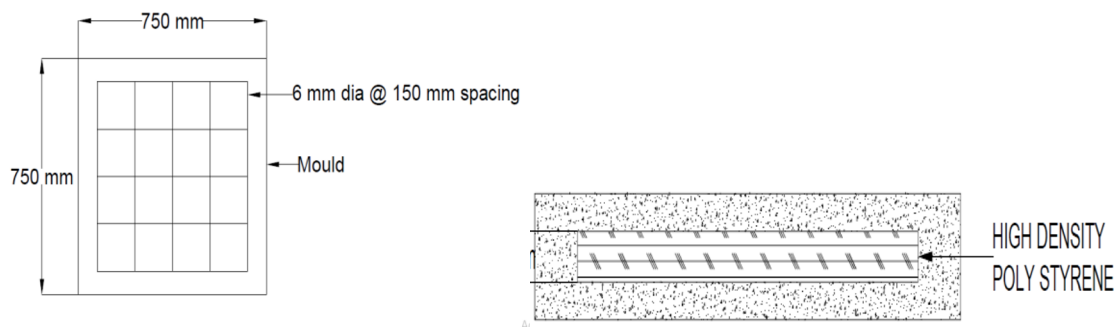


Fig.2 Specimen 2 rft details



Fig.3 Specimen C/S

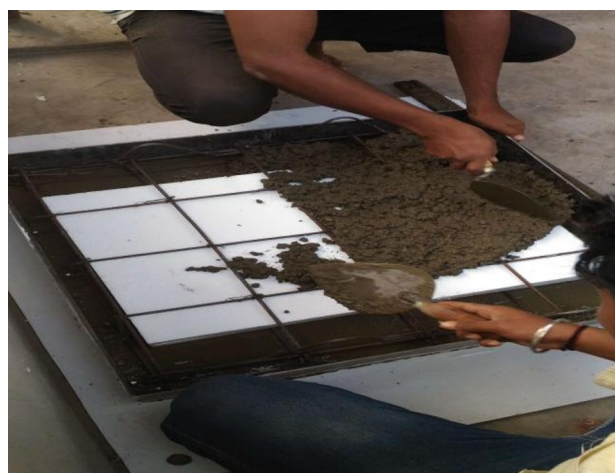


Fig.4 Specimen preparation

3.5 Experimental Setup and Testing Procedure

Axial compression tests were conducted using a calibrated loading frame of capacity 1000kN and rate of loading 0.3 mm/ min. The wall panels were positioned vertically to simulate load-bearing conditions. Load was applied gradually and uniformly until failure. The uniformity of loading is achieved using steel plates of 20 mm thickness provided throughout the length of the panel.

During testing, the following parameters were recorded:

- Applied load
- Axial deformation
- Lateral deflection
- Crack initiation and propagation
- Ultimate load capacity

Load–deflection behavior was plotted to analyze stiffness characteristics and structural response. The failure mode and crack patterns were carefully observed to assess the effective structural performance under uniform vertical compression.



Fig.5 Testing of Specimen

3.6 Numerical Validation

Apart from experimental investigation, numerical analysis was also performed using structural analysis software (SAP). The finite element analysis model visualizes exact panel geometry, materials used for modelling properties, and assigned boundary conditions. The analytical test results after run of analysis were compared with experimental data outputs to validate panel loading structural behavior and ensure the obtained reliability of acceptable conclusions.

4 Preliminary Examinations

The fabrication of the insulated precast wall panels has to be done after, an wide set of initial laboratory assessments which was performed to evaluate the required mechanical and physical properties of the materials used for fabrication. These measures were important to ensure support to relevant IS codes and to confirm that the fabricated materials would meet the expected M_{30} concrete strength.

The cement characteristics were arrived through standardized testing procedures given. OPC - Ordinary Portland Cement of 53 grades, compliant with Indian standards 12269:2013 standards, was tested. The specific gravity of cement is 3.15, the standard consistency is 31%, and the initial & final setting times of cement are 42 minutes & 285 minutes, respectively. These measurements were correct and within acceptable range of limits, confirming for good hydration process and better workability.

The fine aggregate used for manufacturing specimens was natural river sand conforming to Zone II grading as listed in IS 383:2016. Sieve analysis done to find the fineness modulus which is 2.68, indicating a medium grading of fineness suitable for structural concrete works considered. The specific gravity and water absorption values of fine sand observed is 2.63 and 1.2% respectively. The obtained grading curve satisfies codal standards, ensuring voidless particle packing and good workability.

For coarse aggregate, aggregates with a nominal workable size of 20 mm were used. The water absorption of aggregates is 0.5%, while the specific gravity is 2.74. The AIV aggregate impact value was determined to be 18%, propose excellent durability and also suitability for many structural applications. The angular texture characteristics of the aggregates shows improved interlocking capability and high compressive strength.

Steel bars of 500 grade, which possess high yield strength, were tested according to IS 1786:2008. The yield strength measured at 512 MPa, and the ultimate tensile strength obtained is 585 MPa. The rate of elongation at test area is well complied with codal specifications, affirming required ductility under loading.

The properties of the core high-density polystyrene (HDP) insulation are also reported. The density of the sheet tested is 30 kg/m³, and the thermal conductivity was measured is 0.032 W/mK. The sheet material testing possesses minimal water absorption which indicates good durability and consistent thermal resistance during seasonal cycles provided within the sandwich panel system.

Compressive strength cube tests were performed on standard size cube samples of 150 mm at curing period of 7 and 28 days. The average compressive strength at 7th day was found to be 24.8 MPa, whereas at 28 days, it is increased to 41.6 MPa, both cases exceed the target characteristic strength calculated 30 MPa. The higher compressive strength compared to the target mean strength is due to arrival of proper mix proportioning, a low w/c ratio, good tested quality aggregates, and effective curing methods adopted. These outcome results confirmed the effectiveness of the nominal grade mix design for structural testing purpose. The final material test results are summarized in Table I.

Table 1 Summary of Material Properties

Material	Property	Test Result
Cement	Specific Gravity	3.15
Cement	Standard Consistency	31%
Cement	Initial Setting Time	42 min
Cement	Final Setting Time	285 min
Fine Aggregate	Specific Gravity	2.63
Fine Aggregate	Fineness Modulus	2.68
Fine Aggregate	Water Absorption	1.2%
Coarse Aggregate	Specific Gravity	2.74
Coarse Aggregate	Water Absorption	0.5%
Coarse Aggregate	Impact Value	18%
Reinforcement (Fe500)	Yield Strength	512 MPa
Reinforcement (Fe500)	Ultimate Strength	585 MPa
HDP Core	Density	30 kg/m ³
HDP Core	Thermal Conductivity	0.032 W/mK
Concrete	Water–Cement Ratio	0.45
Concrete	Slump	75 mm
Concrete	7-Day Strength	24.8 MPa
Concrete	28-Day Strength	41.6 MPa

Table 2 Mix Design Details for M30 Grade Concrete

Parameter	Value
Grade of Concrete	M30
Target Mean Strength	38.25 MPa
Water–Cement Ratio	0.45
Cement Content	400 kg/m ³
Fine Aggregate Content	696 kg/m ³
Coarse Aggregate Content	1144 kg/m ³
Water Content	180 liters/m ³
Mix Proportion (C :FA : CA)	1 :1.74 : 2.86
Slump Value	75 mm
Exposure Condition	Moderate
Maximum Aggregate Size	20 mm

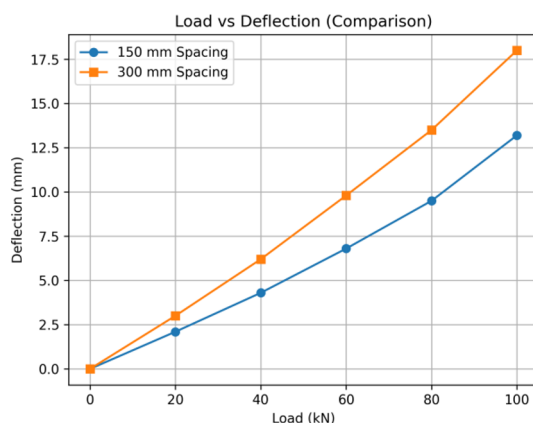
The mix design was designed for M₃₀ grade as per the design requirements of IS 10262:2019. Considering the necessary standard deviation, the target mean compressive strength of the mix was calculated to be 38.25 MPa. Water - cement ratio is 0.45 to ensure required strength and better durability. The cement content calculated = 400 kg/m³, and the fine aggregate & coarse aggregate contents were determined to be 696 kg/m³ and 1,144 kg/m³, respectively. To achieve the required workability, the total water content is taken as 180 liters per cubic meter of concrete casted. The test batch sets confirmed value of 75mm, which is suitable for casting specimens to test prefabricated panels. The final mix design ratio is 1:1.74:2.86 which ensures good adhesive between the layers of formation and effective layer interaction between the composite and the core insulation layer.

5 Results and Discussion

5.1 Load–Deflection Behaviour

The reaction of insulated precast wall panels under axial load and deflection was continually measured throughout the compression testing process. Both samples displayed linear elastic properties until reaching around 35-40% of their ultimate load capacities, which supported successful composite interaction between the concrete layers and the HDP insulating core. After this point, nonlinearity became obvious due to the production of micro-cracks and a drop in stiffness.

Sample S1, with a reinforcement spacing of 300 mm, demonstrated significantly larger lateral deflection under all loading phases. At a load of 250 kN, S1 recorded a lateral deflection measurement of 4.8 mm, while Sample S2, which had a 150 mm spacing, only revealed 3.6 mm, demonstrating an almost 25% decrease in displacement. As the load neared failure, S1 experienced 8.9 mm of deflection at 90% of its ultimate load, whereas S2 was limited to a maximum of 6.7 mm. The greater performance of S2 is attributable to its higher density of reinforcement, which led in improved axial stiffness and better management of fracture development. The higher slope found in the load deflection curve for S2 suggests increased rigidity and enhanced structural stability when subjected to Compressive pressures. The wall panel slenderness ratio ($h/t = 10$) falls under category of moderate slender wall and minor eccentricity with



bending occur during testing.

Fig.4 Load Vs deflection Profile

5.2 Maximum Capacity for Carrying Loads

The highest maximum load capacity measured for S1 was 355 kN, while S2 obtained a better capacity of 420 kN. The high reinforcement ratio provided in S2 leads to less stress concentration and postponed the initiation of instability of panels, which in turn provides high axial load resistance feature. This results clearly illustrate that the detailing of steel reinforcement plays a vital role in influencing the axial compressive strength behavior shown in precast insulated core sandwich wall panels.

5.3 Composite Efficiency Factor

The composite efficiency factor (η) for panel was calculated as per the guidelines of PCI to arrive the degree of composite action. $CEF = \text{ultimate load obtained from testing} / \text{calculated theoretical capacity } (P_{fc} = 0.4f_{ck}A_c)$. Using a tested concrete strength value of 41.6 MPa and a total panel concrete C/S area of 50,000 mm², the full panel composite capacity was calculated as 832 kN. As a result, CEF is 0.43 for specimen S1 (300 mm spacing) and 0.50 for specimen S2 (150 mm spacing). The higher CEF value for S2 shows developed composite action due to optimum spacing of reinforcement.

5.4 Crack Development and Failure Pattern

Crack initial formation was first found at around 60% of the peak load for both type of samples. For S1, fractures emerged at 215 kN and expanded broadly along the entire height of the panel. On the other hand, S2 exhibited mild first cracking at about load of 245kN, suggesting better resistance to acting tensile stress. The wider crack width in S1 before final failure reached near 1.8 mm of deflection, while S2 showed very narrower fractures crowned at about 1.1 mm. The lesser spacing of reinforcement arrangements effectively limited the faster growth of cracks and expedited better crack pattern distribution.

The failure of both type panels was accurately marked by vertical plane cracks (Fig. 5) followed by localized end collapse in the area where the vertical load was applied. S1 revealed significant lateral axis buckling before failure, indicating a lack of layers efficient confinement. In comparison, S2 shows a more aligned failure behavior with decreased lateral displacement and enhanced good structural integrity. The observed failure mode in tested panel is a compression controlled with local buckling nature, characterized by cluster of vertical cracking and localized crushing near the loading zone.



Fig.5 Crack patterns

5.6 Stiffness Characteristics

The linear portion of the load versus deflection curve gives the initial axial stiffness of panels. The stiffness of sample 1 was found to be 52 kN/mm, where as sample 2 is recorded as 62 kN/mm, which is a 19% improvement as considered. Good post-elastic behavior and improved limit in serviceability performance are indicated by sample panel 2's progressive stiffness drop beyond the linear elastic range.

5.7 Strain Distribution Along Wall Height at Ultimate Load

Concrete and Steel strain for applied load is recorded using electrical resistance strain gauges (KYOWA type, 120 Ω resistance and 5 mm gauge length) which is attached to the reinforcement cage and concrete surface casted. The gauges locations were marked at 1/4, 1/2, and 3/4 heights of the 1000mm wall panel. Maximum strain occurred at the mid-height (1/2 H) of panel due to peak stress concentration along the panel's length. Specimen S2 (150 mm reinforcement spacing arrangement) showed lesser strain values compared to 300 mm spacing specimen S1, indicating good stiffness.

Table 3 Strain Values at Ultimate Load

Specimen Details	Peak Load (kN)	Location of gauge	Concrete Strain (µε)	Steel Strain (µε)
S1 (300 mm c/c)	355	1/4 H (250 mm)	780	970
		1/2 H (500 mm)	890	1110
		3/4 H (750 mm)	830	1040
S2 (150 mm c/c)	420	1/4 H (250 mm)	700	860
		1/2 H (500 mm)	760	970
		3/4 H (750 mm)	710	900

5.8 Weight Reduction and Structural & Cost Efficiency

The integration of the Polystyrene core insulation leads to reduced dead weight nearly 22-25% compared to a same dimension conventional solid reinforced M₃₀ concrete wall. (1 m × 1 m × 0.1 m). Apart from this reduced weight, both specimens S1, S2 exhibited considerable carrying load capacity. The P/W ratio calculated for panel S2 was is 1.18 kN/kg where it is 0.98 kN/kg for panel S1, these ratio differences indicates balanced state of efficient design. The comparison ensures that the insulated panel provides a acceptable balance between total self-load reduction and higher axial load capacity. In addition to this, the HDP core is importantly reduce U-value due to its low thermal conductivity (0.032 W/mK), which brings improved thermal insulation performance of the wall compared to solid concrete walls [16], [20]. Cost analysis for a conventional wall panel M₃₀ of dimension 1 m × 1 m × 0.1 m, the estimated cost is Rs. 1100 (Concrete = Rs. 750 + Reinforcement = Rs.350). The HDP-core sandwich panel costs approximately = Rs.1025 (Concrete = Rs.375 + Reinforcement = Rs.280 + HDP core = Rs.250 + connectors/fabrication= Rs.120). Thus, the proposed HDP core panel provides 7% reduction in cost compared to the solid wall.

5.9 Numerical Simulation and Analytical Validation

The numerical simulation for validation was conducted through finite element modeling analysis using structural analysis software SAP. The solid geometry of the panel model, composed panel material properties, assignment of boundary conditions, and load detailing arrangement were all accurately assigned to witness the testing laboratory conditions. The M₃₀ grade of concrete layer in panel was represented in analysis as a non-linear element with an appropriate calculated elastic modulus, while the steel reinforcement cage designed & modeled with embedded bar elements. The panel model with uniform mesh size of 25 mm is generated to get accurate stress and deformation characteristics of the panel.

The numerical simulation analysis gives result of ultimate load capacities of 340 kN for S1 and 405 kN for S2 respectively. The difference between the experimental values and analytical results fell within the range of 4 to 6%, exhibits a high correlation and ensures the numerical panel model's reliability. The simulated load & deflection profile graphs closely resembled the experimental data, especially in the elastic domain range of loading.

The configuration of stress contour maps from the FEM finite element model showed maximum compressive stresses concentrated around the load distributed area, aligning with the mode of failure pattern observed during experiments. The analytical model verified proper stress distribution throughout the panel and decreased lateral deformation in the steel configuration with 150 mm spacing of reinforcement. The close results of agreement between the experimental and numerical output supports the structural practicality of the proposed new insulated precast wall panels.

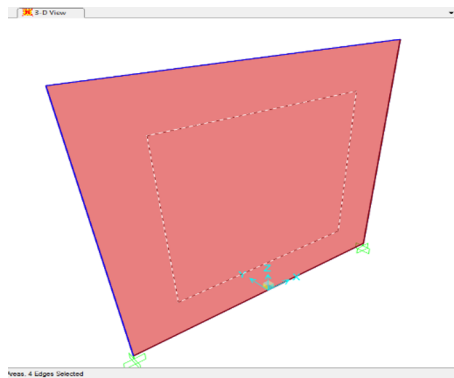


Fig6 Wall panel model

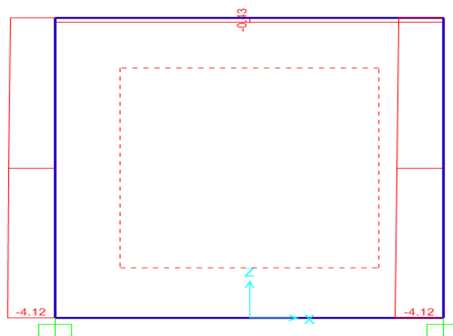


Fig 7. Axial force details

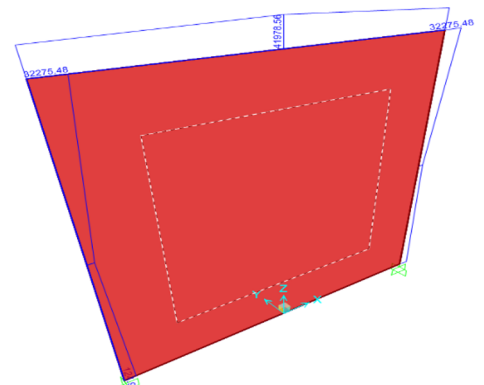


Fig.8 Shear details

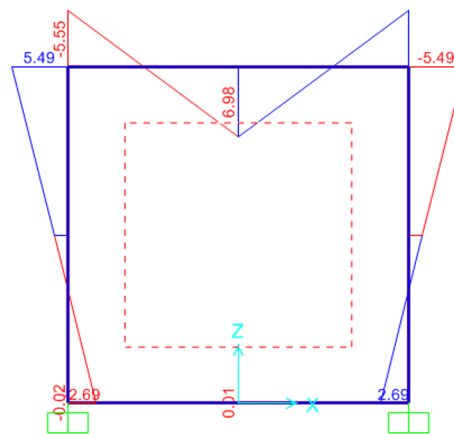


Fig. 9 Moment details

5.10 Comprehensive Performance Evaluation

The analysis of experimental and numerical computational data that pattern of reinforcement spacing has a greater impact on weight reduction, deflection, stiffness, load carrying capacity, fracture mechanism control, and failure characteristics during loading. In each performance metric, the 150 mm spacing reinforcement arrangement presents better than the 300 mm spacing of reinforcement. Polythene Core thermally insulated lightweight precast wall panels provides a sustainable and better structurally sound substitute for conventional building applications, as incontestable by their less self-weight, magnified structural efficiency, improved crack resistivity, and robust analytical model validation.

6 Conclusion

This tested experimental results shows that reinforcement pattern details play a major role in improving the effective structural performance of core insulated sandwich wall panels. Specimen S2 (150 mm c/c spacing) with reduced nominal reinforcement spacing achieved a peak ultimate load of 420 kN compared to 355 kN for specimen S1 (300 mm c/c spacing). This accurately gives to an 18.3% improvement percent. The increase in load bearing capacity of panels is explained by a rate of higher reinforcement with better stress redistribution, which also brings improved restraint effect, and increased composite interaction behaviour between concrete layer elements. Provision of spacing distance effectively drops the stress concentration in panel and reduced the uniform vertical axial compression instability. Detailed studies finalizes that optimizing the steel rebar spacing significantly improves the nature of compressive and axial load-bearing performance of core based sandwich wall panel systems. This result mainly highlights the importance of provision of appropriate reinforcement details in order to achieve improved structural parametric efficiencies and expected load-bearing properties of prefabricated insulated wall panels.

REFERENCES

- [1] International Energy Agency, *Energy Efficiency 2022*, Paris, France: IEA Publications, 2022.
- [2] Precast/Prestressed Concrete Institute, *PCI Design Handbook: Precast and Prestressed Concrete*, 8th ed., Chicago, IL, USA: PCI, 2017.
- [3] American Concrete Institute, *ACI 318-19: Building Code Requirements for Structural Concrete*, Farmington Hills, MI, USA: ACI Committee 318, 2019.
- [4] M. Pessiki and J. Mlynarczyk, "Experimental evaluation of the composite behavior of precast concrete sandwich wall panels," *PCI Journal*, vol. 48, no. 2, pp. 54–71, Mar.–Apr. 2003.
- [5] K. A. Harries, B. A. Zeno, and J. Shahrooz, "Behavior and strength of insulated concrete sandwich panels," *ACI Structural Journal*, vol. 101, no. 5, pp. 617–625, Sept.–Oct. 2004.
- [6] B. Benayoune, S. Samad, A. Trikha, A. A. Abang Ali, and S. H. M. Ellinna, "Structural behavior of precast concrete sandwich panels," *Construction and Building Materials*, vol. 21, no. 3, pp. 677–685, 2007.
- [7] Computers and Structures Inc., *SAP Integrated Software for Structural Analysis and Design*, Berkeley, CA, USA, 2020.
- [8] A. A. Hassan and A. Rizkalla, "Analysis and design of precast concrete sandwich panels with FRP shear connectors," *ACI Structural Journal*, vol. 107, no. 5, pp. 558–567, Sept.–Oct. 2010.

- [9] S. Einea, M. Salmon, and J. Fogarasi, “State-of-the-art of precast concrete sandwich panels,” *PCI Journal*, vol. 36, no. 6, pp. 78–98, Nov.–Dec. 1991.
- [10] B. Frankl, “Design of load-bearing sandwich wall panels,” *PCI Journal*, vol. 38, no. 3, pp. 56–67, May–June 1993.
- [11] A. A. Benayoune, S. Samad, A. A. Abang Ali, and A. Trikha, “Response of precast reinforced composite sandwich panels to axial loading,” *Construction and Building Materials*, vol. 22, no. 3, pp. 580–592, 2008.
- [12] A. Fam and S. Sharaf, “Flexural performance of sandwich panels with GFRP reinforcement,” *Journal of Composites for Construction*, vol. 14, no. 4, pp. 388–397, Aug. 2010.
- [13] ASTM C39/C39M-21, *Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens*, West Conshohocken, PA, USA: ASTM International, 2021.
- [14] ASTM C496/C496M-17, *Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens*, West Conshohocken, PA, USA: ASTM International, 2017.
- [15] European Committee for Standardization, *EN 1992-1-1: Eurocode 2 – Design of Concrete Structures*, Brussels, Belgium, 2004.
- [16] Ashby, M. F. (2011). *Materials selection in mechanical design* (4th ed.). Oxford, UK: Butterworth-Heinemann.
- [17] Bureau of Indian Standards. (2000). *IS 456:2000: Plain and reinforced concrete—Code of practice*. New Delhi, India: Bureau of Indian Standards.
- [18] Busher, S., & Govindarajulu, K. V. (2023). Thermal performance and reduced carbon footprint of precast concrete sandwich wall panels with composite shear connectors – An experimental assessment. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, 45(4), 12201–12214.
- [19] Kumar, P., Kumar, R., Surabhi, Rahman, M. R., & Khan, S. (2024). Development of sustainable precast concrete sandwich wall panels using artificial aggregates and mineral admixture. *E3S Web of Conferences*, 596, 01006.
- [20] Sharma, A., & Bansal, P. P. (2022). Structural and thermal performance of precast concrete sandwich wall panels with insulation cores. *Journal of Building Engineering*, 44, 102622.