Monitoring of Lateral Pressure and Tie Stress for a Novel Prefabricated Wall

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Abstract. With the increasing demand for environmentally friendly construction practices, the development of prefabricated assembled structures has gained momentum through the widespread adoption of construction industrialization. This research aims to investigate the mechanic performance for a novel prefabricated external shell and cast-in-place core concrete wall. Full-scale experiments are conducted to measure strains in the tie pieces and the prefabricated external shell during and after the cast-in-place. The recorded strains reveal the influence of the initial set of concrete, as well as the heat of hydration during and after the cast-in-place core, on the strains of the tie pieces and the prefabricated external shell. The strain-time curves illustrate an initial increase followed by a subsequent decrease in tensile strains from tie pieces and prefabricated external shell. The conclusions drawn from this study are invaluable for advancing the promotion, application, and design refinement of this particular type of prefabricated wall.

Keywords: Prefabricated walls; prefabricated external shell and cast-in-place core; formwork; tie piece; strain measurement

1 INTRODUCTION

The industrial development of prefabricated concrete structures in China has undergone three distinct stages: the first stage (1950 -1970), focusing on standardized components with limited structural forms; the second stage (1970 -2000), dedicated to the development of standardized functional modules and unified design; and the third stage (2000-present), marked by improved building industrialization, propelled by national and local polices and the integration of intelligent construction practices. In contemporary times, various load-bearing components essential for buildings, such as beams, slabs, columns, walls, stairs, can be prefabricated in factories and assembled on-site. Stakeholders, including manufactures, design units, construction units, and academic scholars, are actively exploring strategies to enhance cost-effectiveness and efficiency ensuring structural safety and reliability. Aligned with principles of sustainability, cost reduction, and ease of transportation and installation, the prefabricated external shell

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and cast-in-place core formwork system has gained popularity. This innovative prefabricated wall comprises an integrated consisting of a non-detachable cement-based composite shell, steel skeleton and tie pieces, mechanical and electrical pipelines. This system is essential for environmentally friendly construction practices and is referred to as the prefabricated wall.

The specific components of a novel prefabricated wall (Figure 1) include: (1) Template System: Comprising composite concrete panels, reinforced mesh with designed cavities, tie pieces connecting the panels, and embedded parts. The panel, constructed from composite cement mortar with added fibers, enhances load-bearing performance tie-piece anchoring. (2) Steel Skeleton: Determined by design, processed, and installed in the factory. It includes template tie pieces at the intersections of transverse and longitudinal reinforcements, and embedded pipelines and wire boxes based on design requirements. (3) Template Tie Pieces: Fabricated using 6 mm reinforcement or 2 mm-thick and 20 mm-wide galvanized steel piece. The anchoring head is specially treated to increase contact area, anchoring strength, expand the formwork support range, and reduce surface bending stress. These tie pieces strategically placed at the steel skeleton intersections, have minimal impact on the concrete vibration construction. (4) Accessories: Supporting transportation, installation, and debugging, including embedded lifting parts, horizontal lifting adjustment accessories, and vertical adjustment accessories.

This novel prefabricated wall represents a significant advancement in construction technology, providing a sustainable, efficient, and cost-effective solution for contemporary building projects.

Various scholars, including Li et al.[1], Xu et al.[2], Zhao et al.[3], and Wang et al.[4], have extensively developed and implemented the prefabricated composite prefabricated shear wall system. Their comprehensive investigations cover asppects such as production, design, construction, and application of formwork. Relevant technical specifications have been issued [5]. This prefabricated wall represents an evolved approach to prefabricated assembly construction, streamlining the construction processes for traditional on-site cast-in-place concrete shear wall and the production process for existing prefabricated concrete solid shear walls in component factories. The prefabricated wall addresses the inefficiencies associated with traditional on-site construction, specifically in the "formwork, steel skeleton, pipelines, and plastering" sub-projects. In this system, these sub-projects are completed at different times and locations in the factory, while the core concrete pouring and associated processes continue on-site.

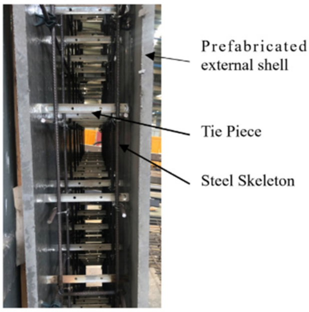


Fig. 1. Formwork system

Characterized by lightweight and flexible, the prefabricated external shell offers advantages such as ease of reinforcement inspection, pre-embedded pipelines, simplified node structure, and increased market application value of the product.

Beyond these characteristics, the formwork system boasts additional advantages. The panel, constructed from thin cement-based materials without requiring steam curing, minimizes formwork maintenance cost. The lightweight components further lead to cost savings in transportation and lifting. The system's design eliminates the need for tension screws, as it can independently bear lateral pressure during concrete pouring. Vertical reinforcement connections are achieved through lap joints, mechanical connections, and welding in cast-in-place structures, mitigating potential technical risks during reinforcement grouting sleeve connections.

While these research results have been successfully applied in the construction of hotels, office buildings, and residential buildings, there remains a gap in quantitatively understanding the stress behavior of the tie pieces and formwork during the pouring process and that of the concrete from initial setting to final setting. Although Johnston[6] and Assaad and Khayat[7] have provided references for lateral pressure estimation, there is still a need for a detailed quantitative analysis. This research, funded by the Jiaxing Public Welfare Research Program (No. SQGY20210025) and the Science and Technology Committee of Shanghai Tianhua Design Group Co., Ltd., and supported by Shanghai Hengxu Energy Conservation and Environmental Protection Technology Co., Ltd., addressed this gap through full-scale pouring tests on the formwork with prefabricated external shell and cast-in-place core. Building upon preliminary research by Zhang and Tang[8], as well as Shu et al. [9], this article provides a comprehensive overview of some full-scale tests and their results. The discussion focuses on strain variation patterns of tension components and formwork, and assesses the overall safety of formwork.

2 EXPERIMENT SCHEME

The primary objective of the full-scale test conducted in this study is to evaluate the safety of the prefabricated shell of the formwork when concrete is poured into the core. Specifically, the mechanical properties of tie pieces and formwork are assessed during the pouring process, initial setting, and final setting of the concrete at the construction site. The focus is on ensuring that the prefabricated shell remains structurally sound and meets material strength requirements.

2.1 Design of Formwork Specimens

In accordance with practical application requirements, Shanghai Tianhua Design and Research Institute has designed four single walls (DWQ1 to DWQ3) and four L-shaped walls (Pool E, Pool S, Pool W, Pool N). Reinforcement has been configured based on the service load of the exterior wall of the basement on the first floor.

Table 1. Specimen Numbers and Geometric Dimensions

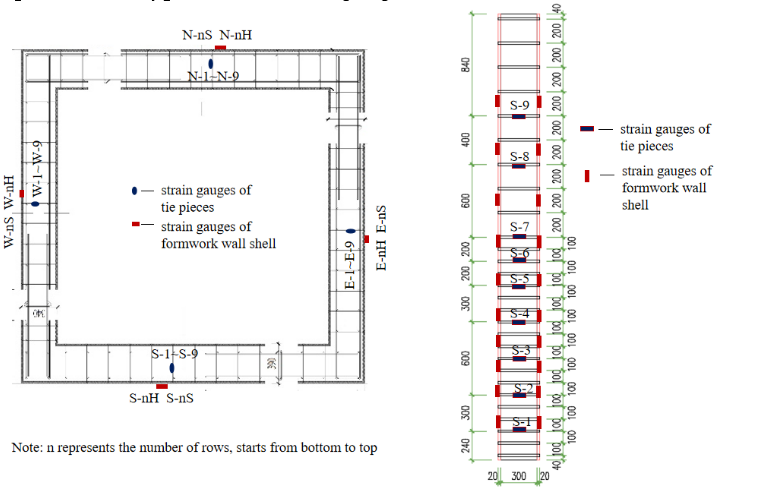
Test piece name	Width/m	Height/m	Thickness/m	L-shaped long external package/m
DWQ1	1.7	3.7	0.30	—
DWQ2	1.7	3.7	0.35	—
DWQ3	1.7	4.7	0.35	—
Pool E	2.36	3.7	0.39	0.62
Pool S	2.36	3.7	0.34	0.62
Pool W	2.36	3.7	0.39	0.62
Pool N	2.36	3.7	0.34	0.62

Table 1 provides the specimen numbers and geometric dimensions. The prefabricated shell, serving as the formwork, is 20 mm thick, made of cement-based concrete material with a weight of 20-21 kN/m3 and an elastic modulus of 3.40-4.50 × 104 N/mm2.The compressive and tensile strengths are 36.4 MPa and 4.50 MPa, respectively. Both sides of the prefabricated shell are equipped with 2 mm-thick and 20 mm-wide tie pieces (Figure 1) and structural reinforcement. The tie pieces are galvanized steel sheets with a tensile strength of 235 MPa. Curing is conducted on both sides of the casing through one-time molding.

2.2 Selection and Layout of Strain Gauges

The strain gauges on the outside of the prefabricated shell and tie pieces are resistance strain gauges produced by Chengdu electronic measuring technology Co. Ltd. and Beijing Yiyang Yingzhen Testing Technology Co., Ltd. These gauges, primarily made of copper nickel alloy, have an inherent resistance value. Under external tensile and compressive stress, changes in their sections result in resistance changes, which are measured and converted into strain values.

Figures 2-3 depict the layout of strain gauge on the outside of the formwork shell and the tie pieces. The types of the strain gauges are listed in Table 2.



(a) Arrangement plan (b) S-side (south side) sectional view

Fig. 2. Arrangement of points to be measured

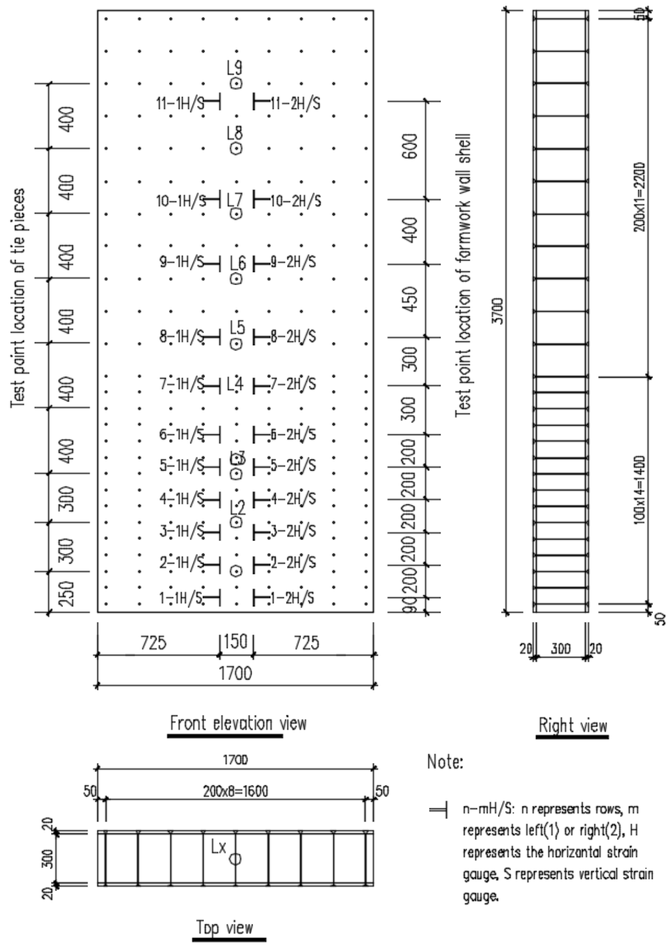


Fig. 3. Points to be measured for single-formwork tie pieces and formwork shells

Table 2. Model and relevant parameters of strain gauge

Installation location	Type	Resistance	Sensitivity factor
Formwork shell	B×120-50AA	120.0±0.3Ω	2.08±1%
Tie piece	B×120-4BB	120.0±0.3Ω	2.08±1%

3 TESTING PROCESS AND RESULTS

The core concrete pouring and data collection for the experiment were conducted from July 5th to July 12th, 2022. Figure 4 provides a visual representation of a typical pouring specimen and on-site data collection equipment.

(a)Single wall (b) L-shaped wall (c)Data acquisition instrument

Fig. 4. Concrete Pouring and Data Collection

3.1 Three Pieces of Independent Wall DWQ1-DWQ3

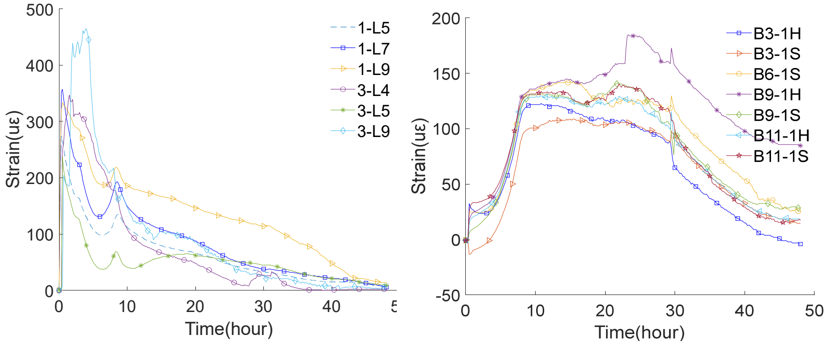
A total of 27 strain sensors were embedded in the tie pieces of three single walls, with 10 strain sensors successfully capturing data and 6 sensors providing reasonable data.

Table 3. Corresponding Wall Numbers, Elevations, and Strain Gauge Distribution of Each Elevation for Tie Pieces

Number	Wall number	Elevation (m)	Strain gauge distribution at each elevation (m)							
			0.54	0.84	1.44	1.64	1.84	2.44	2.84	3.44
1C5(1-L5)	DWQ1	1.64				√				
1C7(1-L5)	DWQ1	2.84							√	
1C9(1-L5)	DWQ1	3.44								√
2B2(1-L5)	DWQ2	0.54	√							
2B6(1-L5)	DWQ2	1.84					√			
3B18(1-L5)	DWQ3	0.54	√							
3B20(1-L5)	DWQ3	1.44			√					
3B21(1-L5)	DWQ3	1.64				√				
3B22(1-L5)	DWQ3	1.84					√			
3B23(1-L5)	DWQ3	2.44						√		

Table 3 presents the corresponding wall numbers, elevations, and statistics of various elevations, while Figure 5 (a) illustrates the variation patterns of the tie pieces over time.

The strain sensors on the formwork shells of various walls exhibited consistent variation patterns. Figure 5 (b) displays the variation of strain at selected measuring points on the formwork shell over time.



(a)Tie pieces (b) Formwork shells

Fig. 5. The variation patterns of measured strains over time

3.2 L-shaped Enclosures

A total of 36 strain gauges were embedded on the four sides of the tie pieces, with 18 successfully capturing data. Table 4 provides the corresponding azimuth, elevation, and statistics of various elevations.

Table 4. Corresponding Azimuth, Elevation, and Strain Gauge Distribution of Each Elevation for Tie Pieces

Number	Side	Elevation (m)	Strain gauge distribution at various elevations (m)							
			0.24	0.54	0.84	1.44	1.64	1.84	2.44	2.84
E-10	East	0.24	√							
E-11	East	0.54		√						
E-12	East	0.84			√					
N-10	North	0.24	√							
N-16	North	1.84						√		
W-1	West	0.24	√							
W-3	West	0.84			√					
W-5	West	1.44				√				
W-7	West	1.84						√		
W-8	West	2.44							√	
W-9	West	2.84								√
S-1	South	0.24	√							
S-2	South	0.54		√						
S-3	South	0.84			√					
S-5	South	1.44				√				
S-6	South	1.64					√			
S-8	South	2.44							√	
S-9	South	2.84								√

The strain variation over time on the formwork shell (south side) and the tie pieces (south side) is presented in Figure 6. To assess the impact of temperature, 10 temperature sensors were buried along the height direction in the cavity formed by the two shells. The burial depth is specified in Table 5, and Figure 7 illustrates the corresponding temperature changes at the commencement of concrete pouring.

Table 5. Burial Depth of Temperature Sensors

Thermometer number	1	2	3	4	5	6	7	8	9
Burial elevation (m)	0.35	0.70	0.95	1.25	1.55	1.85	2.15	2.65	3.15

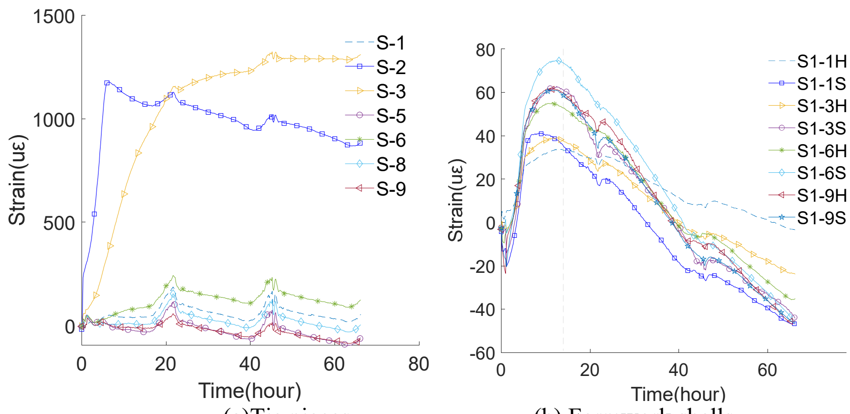


Fig. 6. The variation patterns of measured strains over time

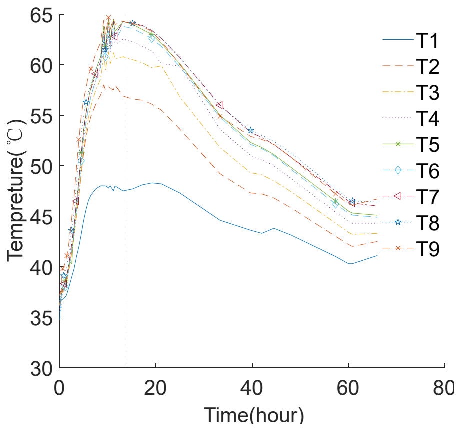


Fig. 7. Temperature changes over time after the start of core concrete pouring

In summary, the experiment covered three independent walls and L-shaped enclosures, with detailed strain gauge distributions and temperature monitoring providing valuable insights into the behavior of tie pieces and formwork during and after the concrete pouring process.

4 ANALYSIS AND DISCUSSION OF TEST RESULTS

The strain changes in the tie pieces exhibit two distinct stages: a gradual increase between 0.5 hours and 2 hours, reaching a peak, followed by a slow decrease. This pattern was observed in both single walls and enclosed-wall specimens. All strain values were less than 2,000 με, indicating safety the permissible range. The initial rise in strain suggests that during concrete hardening, the heat of hydration causes core concrete expansion. However, tie pieces resist this expansion, leading to increased tensile strain.

The strain changes on the formwork shells reveal three distinct stages: an initial rapid rise, a subsequent parabolic increase with a slight slowdown, and a gradual decrease. These trends align with studies by Assaad and Khayat [10] and Omran and Khayat[11] based on North American standards[12-13]. The strain on single wall formwork shells peaked between 8 hours and 14 hours. The reduction in lateral pressure of PVC formwork, as described in literature [14-15] , is attributed to concrete thixotropy. The rising stages in strain are linked to hydration heat, core concrete temperature increase, and volume expansion.

Concrete temperature at various heights increased rapidly with 6 hours, with an average rise rate of 4ºC/hour. Subsequently, the temperature rise rate decreased until reaching its peak, with the highest temperature recorded at 64.7°C. The observed temperature changes align with the rapid generation of hydration heat, causing expansion that exceeds volume shrinkage during setting and hardening. Thus, in turn, leads to increased tensile strain on tie pieces and formwork shells.

5 CONCLUSION

The strains on the tie pieces and prefabricated external shells exhibit consistent patterns from pouring initiation to two days after pouring. Strain values suggest tie pieces and prefabricated external shells possess adequate strength to resist lateral pressure generated by the cast-in-place core. Key conclusions include:(1) Tie pieces show two distinct stages: rapid rise and slow drop;(2) The prefabricated external shells show three stages: rapid rise, parabola rise, and drop; (3) Peak stain values: Single wall-within 14 hours, maximum 144.8 με (excluding sudden stress changes), Enclosed wall-within 12 hours, maximum 74.6 με; (4) Tensile strains meet allowable limits.

Further research areas: Detailed analysis of tie piece tensile stress changes along wall elevations, exploration of prefabricated external shell lateral pressure distribution in vertical, horizontal, and along-wall elevation directions.

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