Experimental Investigation of Steel Plate-Concrete Composite Shear Walls: Strength Improvement and Seismic Performance

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Abstract: This research investigates the behavior of steel plate-concrete composite shear walls with different corrugation patterns, focusing on strength improvement and seismic performance. Material properties, such as high-quality steel sheets and tubes, and high-strength bolts as connectors, are examined. Accurate material models represent steel and concrete behavior. A comprehensive loading protocol simulates real-life conditions using axial and lateral loads. Experimental results reveal enhanced strength and seismic performance in the composite shear walls compared to conventional walls. Corrugated sheets and boundary tubes improve lateral load resistance and ductility. The study's optimized design guidelines facilitate the implementation of these walls in high-rise and seismic-resistant structures. Material selection and shear connectors play vital roles in ensuring robust connections and structural integrity. The proposed models accurately predict steel and concrete behavior. Results provide insights into load-deformation behavior, hysteresis loops, and energy dissipation capacity. The tests demonstrate excellent ductility, multiple yielding mechanisms, and energy dissipation. Failure modes include concrete crushing, steel yielding, and connection failure. The research advances knowledge in steel plate-concrete composite shear walls. Design guidelines and recommendations support the development of efficient and resilient structural systems.

Keywords : Steel plate-concrete-composite; Shear walls; Strength improvement; Seismic performance; Experimental investigation; Design guidelines.

I. INTRODUCTION

Steel plate-concrete composite shear walls have gained significant attention in recent years due to their potential to enhance the performance of traditional reinforced concrete (RC) shear walls. These composite systems consist of steel plates embedded within concrete infill, providing a synergistic combination of the two materials' properties. The integration of steel plates and concrete infill offers several advantages such as enhanced strength, stiffness, ductility, and constructability (Zhao et al., 2020; Haghi et al., 2018). A number of studies have investigated the behavior and performance of steel plate-concrete composite shear walls. Zhao et al. (2020) conducted experimental investigations on the seismic performance of composite shear walls with steel plate-concrete infill. Similarly, Haghi et al. (2018) studied the seismic performance of composite shear walls and evaluated their behavior under different loading conditions. Experimental studies by Zhu et al. (2019) examined the mechanical behavior of corrugated steel plate shear walls. Olabi et al. (2017) investigated the cyclic behavior of corrugated steel plate shear walls filled with engineered cementitious composites. Other researchers have focused on the numerical modeling and analysis of composite shear walls. Wei et al. (2019) conducted experimental and numerical studies on novel steel plate-concrete composite shear walls. Emami et al. (2021) provided a comprehensive review on the performance of steel plate-concrete composite walls in past earthquakes. Saatcioglu et al. (2016) investigated the seismic behavior and design aspects of steel plate-concrete walls. The cyclic performance of large-scale steel plate-concrete composite shear walls was examined by Li et al. (2018), who studied their response under low-cyclic loading. Parsaei et al. (2020) considered the effect of soil-structure interaction on the seismic response of steel plate-concrete composite shear walls. Uang et al. (2015) provided insights into the design and retrofitting of buildings using steel plate shear walls for seismic resistance. The behavior of composite shear walls with openings has also been investigated. Panagiotou et al. (2017) conducted cyclic tests on full-scale steel-plate composite walls with stiffened openings. Xu et al. (2020) performed experimental studies on steel plate composite walls under cyclic loading, including those with openings. The structural behavior of steel plate shear walls has been extensively studied. Zhou et al. (2019) investigated the behavior of steel plate shear walls and proposed design guidelines. Anastasopoulos et al. (2016) studied the cyclic behavior of steel plate shear walls with internal stiffening plates. Furthermore, the incorporation of energy dissipation devices in composite shear walls has been explored. Liu et al. (2018) analyzed the inelastic behavior of corrugated steel plate shear walls with shape memory alloy energy dissipation devices. The thickness of the concrete infill has been identified as a critical parameter. Wu et al. (2019) studied the effects of infill thickness on the performance of steel plate reinforced concrete walls. Additionally, alternative configurations and systems have been investigated. Lu et al. (2017) examined the behavior of buckling-restrained steel plate reinforced concrete walls under in-plane cyclic loading. He et al. (2021) conducted analytical and experimental studies on the behavior of steel plate-concrete composite walls. Wilkinson et al. (2020) investigated the performance of a low-damage steel plate shear wall in fire. The performance of composite shear walls with energy dissipation devices has also been studied. Xiao et al. (2019) conducted an experimental study on composite steel plate shear walls with energy dissipators. Xiong et al. (2020) investigated the seismic behavior of steel plate-concrete composite walls with shape memory alloy bars as energy dissipators. In summary, the behavior, design, and performance of steel plate-concrete composite shear walls have been extensively investigated in recent years. These studies have provided valuable insights into the seismic performance and overall structural integrity of buildings utilizing these composite systems. The aim of this research is to examine the reverse cyclic response of steel plate-concrete composite shear walls featuring diverse geometric corrugation patterns. The study focuses on evaluating how various parameters impact the enhancement of strength and seismic performance in these composite structural elements. The outcomes of this research will provide valuable insights for the development of optimized design guidelines and recommendations, facilitating the effective implementation of steel plate-concrete composite shear walls in high-rise buildings and structures that require resistance to seismic forces.

II. METHODOLOGY

A. Finite Element Modeling

The steel plate-concrete composite shear walls will be modeled using a detailed finite element approach in the ABAQUS software. The walls will be discretized into a mesh of finite elements, allowing for a precise representation of their geometry and behavior under different loading conditions. To accurately capture the mechanical response of the composite system, appropriate material properties will be assigned to the steel plates and concrete components. The steel plates will be modeled using isotropic linear elastic material properties, considering their high tensile strength and stiffness. The concrete will be modeled using a suitable constitutive model, such as the concrete damaged plasticity model, which accounts for nonlinear behavior, cracking, and crushing of the concrete under various loading scenarios. The interfaces between the steel plates and concrete will be carefully modeled to simulate the bond and interaction between these two materials. Contact elements or cohesive zone models will be employed to capture the interface behavior, accounting for the transfer of shear and normal stresses, as well as potential slip and separation. To enhance the accuracy of the finite element models, geometric imperfections, such as initial out-of-plane displacements and local imperfections, will be introduced to simulate the realistic behavior of the composite shear walls. Additionally, boundary conditions and loading scenarios will be carefully defined to replicate the expected in-service conditions, including seismic actions.

B. Validation with Experimental Data

To ensure the reliability and accuracy of the finite element models, experimental data from relevant studies will be used for validation purposes. Specifically, the research by Qiuhong Zhao et al. (2020) on the cyclic behavior of corrugated double-skin composite walls will serve as a benchmark. The experimental results obtained from their study will be compared with the numerical predictions of our finite element models, providing a means to validate the accuracy of our simulations.

III. RESULT AND DISCUSSION

A. Material Properties

The steel plate-concrete composite shear walls comprise a combination of concrete and structural steel elements. The corrugated sheets and boundary tubes are fabricated using high-quality steel, while the concrete is used as the infill material. Robust connections are ensured through the use of shear connectors in the form of high-strength grade steel bolts. The material properties of the steel elements employed in the composite shear walls vary according to their specific functions. The faceplate, with a thickness of 2.7 mm, exhibits a yield strength of 307 MPa and a tensile strength of 445 MPa. It has a Young's modulus of 2.02 × 105 MPa and a yield strain of 1518. On the other hand, the boundary elements consist of steel tubes measuring 3.5 mm in thickness, with a yield strength of 328 MPa and a tensile strength of 386 MPa. These steel tubes possess a Young's modulus of 2.02 × 105 MPa and a yield strain of 1622. The tie elements, represented by high-strength bolts, possess a yield strength of 640 MPa and an ultimate strength of 800 MPa. In terms of material constitutive models, an ideal elastoplastic model is employed to represent the steel elements. This model assumes a bilinear stress-strain (σ-ε) relationship with 1% strain hardening, as illustrated in Figure 1. On the other hand, the infilled concrete is characterized using a damaged plasticity model that incorporates specific constitutive parameters. The stress-strain relationship for concrete is derived from the findings of Guo et al. and includes parameters such as uniaxial compressive stress (σc), uniaxial tensile stress (σt), uniaxial compressive strain (εc), and uniaxial tensile strain (εt). For instance, based on the values obtained from Guo et al., the concrete properties are represented by fc = 35 MPa, ft = 2.39 MPa, Ec = 29200 MPa, aa = 2.07, ad = 1.17, at = 1.78, εcu = 1590με, and εtu = 76με.

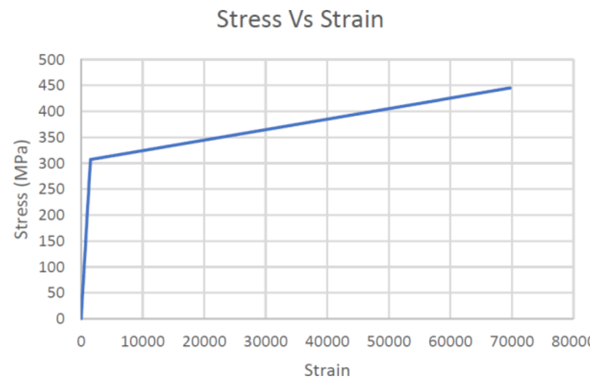


Fig 1 Stress-Strain curve of structural steel

B. Loading Protocol

To evaluate the performance of the steel plate-concrete composite shear walls, a comprehensive loading protocol was implemented. The specimens were subjected to axial and lateral loads to simulate real-life conditions. The testing procedure began with the application of an axial load of 1,100 kN, followed by quasi-static cyclic lateral loading. The loading protocol utilized in this study was adapted from the work of Ji et al. (2017). Figure 2 provides an illustration of the target loading history, presenting the drift ratio (the ratio of horizontal displacement at the loading beam to the effective height of the wall) and the corresponding loading cycle number for each drift level. Each loading cycle involved both pushing and pulling the specimen to the opposite position. It is important to note that both the axial and lateral loads were consistently applied at a location situated 150 mm from the top surface of the specimen. By implementing this loading protocol, the experimental setup closely replicates the anticipated behavior of the steel plate-concrete composite shear walls under realistic loading conditions. The subsequent sections will present the obtained results and provide a comprehensive discussion on the performance and structural response of the composite shear walls when subjected to the applied loading regime.

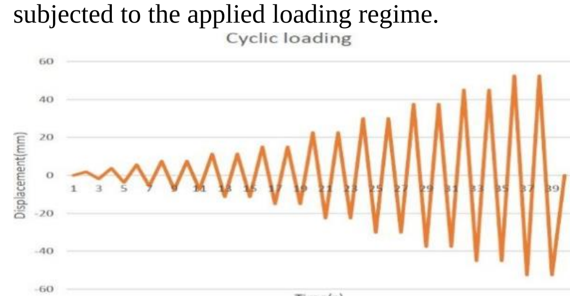


Fig. 2 Lateral loading protocol

C. Finite element model validation

The structure was created using the software Abaqus.

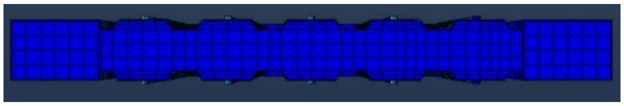


Fig 3 Geometric pattern of Composite shear wall modelled using Abaqus

Three element types were used. The concrete was modeled as solid element, plate as shell and the bolts as one-dimensional line element. All the elements were bonded together.

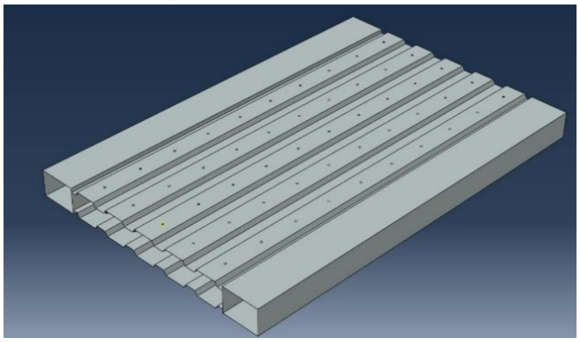


Fig.4 Steel faceplate modelled using Abaqus

Specimen consisted of boundary element as Concrete-filled steel tubes (CFT) column with 150 × 100 mm cross section. The thickness of CFT column is 3.5mm, Youngs modulus is 2.02×105MPa, Poisson's ratio is 0.3, Yield strength is 328 MPa and a Tensile Strength of 386 MPa.High strength bolts with 8mm diameter was used as tie connectors. The nominal Yield stress is 640 MPa and Ultimate strength is 800 MPa. The mesh size was adopted to be 25mm. boundary conditions were provided in such a way that the base is fixed against all the degrees of freedom. Trapezoidal wall was created.

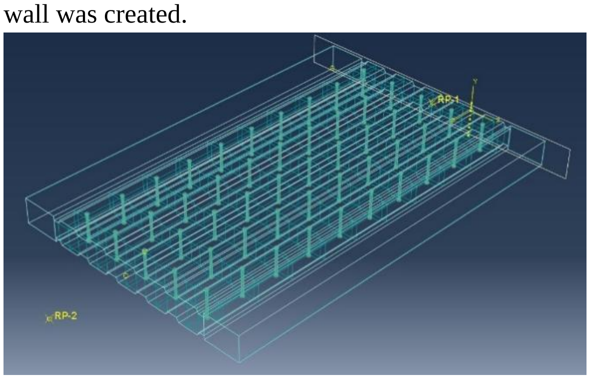


Fig.5 High strength tie bolts

The crest width was provided as 80 mm, trough as 40 and transition 10mm. total width of wall including the boundary elements was 1000 mm and the height of the structure 1500 mm.

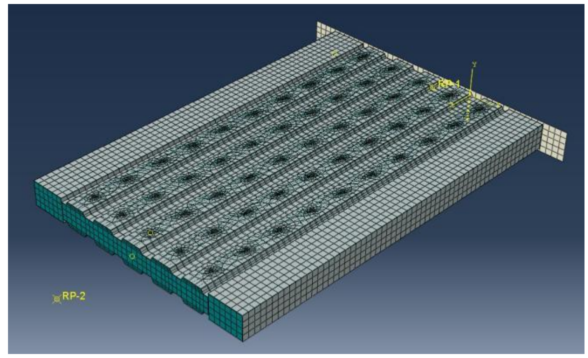


Fig.6 Meshed Composite shear wall modelled using Abaqus

The geometry was created as per the specifications provided. Materials were assigned to the different components in the structure and then meshed to a size of 25mm. Boundary conditions are provided.

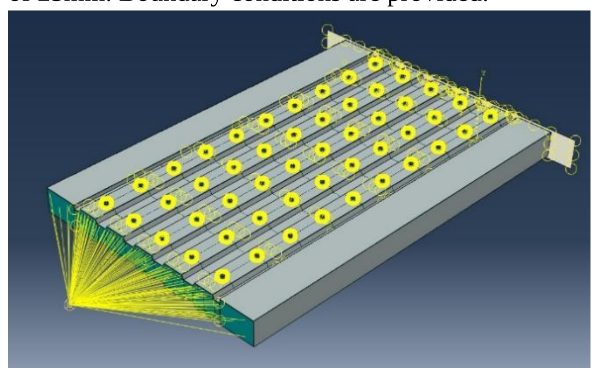
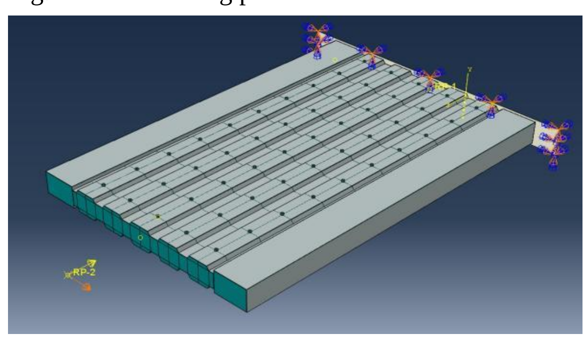


Fig.7 Interaction details of shear wall modelled using Abaqus

The loading beam was simplified into a rigid surface and coupled with a reference point at the centroid, where the axial load and lateral displacements were applied. The foundation beam was simplified into a rigid baseplate with all degrees of freedom restrained.

Fig.8 Lateral loading protocol



D. Analysis result.

It is observed that the results obtained from Abaqus with mesh size of 25mm have good agreements with those from the experimental test results that is carried out by Zhao et al. (2020)

Fig 9 Experimental test results from Zhao et al. [1]

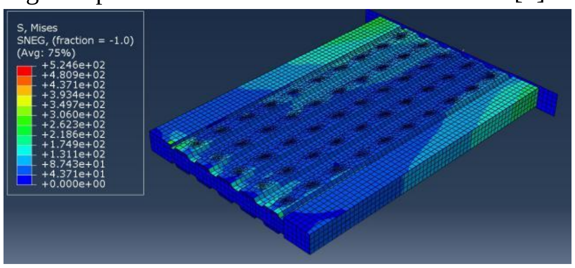


Fig 10 Von Mises Stress diagram

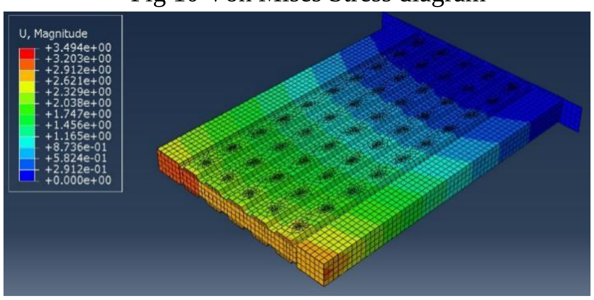


Fig 11 Total deformation

IV. CONCLUSION

The main objective was to evaluate how various parameters affect the strength improvement and seismic performance of these composite structural elements. The findings obtained from this study have significant implications for the development of optimized design guidelines and recommendations for the effective implementation of steel plate-concrete composite shear walls in high-rise and seismic-resistant structures. The examination of material properties revealed that the composite shear walls consist of concrete and structural steel elements. High-quality steel was used to construct the corrugated sheets and boundary tubes, while high-strength grade steel bolts were employed as shear connectors. Accurate material constitutive models were applied to represent the behavior of steel and concrete under different loading conditions. The loading protocol adopted in this research, which involved axial and lateral loads, closely simulated real-life scenarios. The findings presented in this study serve as a valuable resource for researchers, engineers, and professionals involved in the design and implementation of composite structural systems. Further research and analysis in this area can build upon the knowledge and understanding gained from this study, leading to the development of safer and more resilient structures.

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