Experimental Study and Finite Element Analysis of Seismic Performance of RC Frame-Frame-Truss Composite Walls Post-print

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Abstract

To improve the lateral load-resisting capacity of reinforced concrete (RC) frames, a novel RC frame-frame truss composite wall (FTCW) structural system is proposed. Quasi-static tests were conducted on two RC frame-FTCW specimens at a scale ratio of 1:2. The seismic performance, including bearing capacity, ductility, and stiffness degradation, was analyzed based on test phenomena, hysteretic curves, skeleton curves, and stiffness degradation curves. Extended studies on factors potentially influencing the skeleton curves of RC frame-FTCW structures were performed using ABAQUS software, including the number of infilled FTCWs, reinforcement ratio of frame columns, axial compression ratio, concrete strength, embedded steel angles, and arrangement direction of infilled wall panels. The results indicate that the infilled walls fail prior to the RC frames, while within the walls, the internal diagonal braces fail before the outer frames, thereby forming a multi-level energy dissipation system to achieve the objective of seismic design. The most effective approach to enhance the bearing capacity of RC frame-FTCW structures is to increase the number of infilled FTCWs, followed by increasing the reinforcement ratio of frame columns. In contrast, increasing the axial compression ratio and concrete strength or adding steel angles to the internal diagonal braces of FTCWs has a relatively minor effect on capacity improvement. Additionally, the influence of FTCW arrangement direction cannot be neglected; the number and position of FTCWs should be arranged symmetrically.

Full Text

Preamble

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Seismic Performance Experimental Study and Finite Element Anal-

ysis of YR Frame-Frame Truss Composite Wall Structures

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Abstract: To improve the lateral resistance capacity of reinforced concrete (RC) frames, a novel YR frame-frame truss composite wall (79Rd) structure is proposed. Quasi-static tests were conducted on specimens to systematically evaluate seismic performance characteristics including bearing capacity, ductility, and stiffness degradation through analysis of test phenomena, hysteretic curves, skeleton curves, and stiffness degradation patterns. Results demonstrate that the infill wall fails prior to the YR frame, while within the wall itself, the inner diagonal braces fail before the outer frame, forming a multi-level energy dissipation system that achieves the desired seismic design objective. The most effective approach for enhancing the bearing capacity of YR frame-79Rd systems is increasing the quantity of infill 79Rd panels, followed by increasing the reinforcement ratio of frame columns. Conversely, increasing the axial compression ratio and concrete strength, or adding steel angles to the diagonal braces within 79Rd, yields relatively minor improvements in bearing capacity. Additionally, the influence of 79Rd arrangement direction cannot be neglected; both the number and position of 79Rd panels should be symmetrically configured.

Frame-Truss Composite Walls

Frame-truss composite walls (79Rd) represent a novel structural form primarily composed of an outer frame and inner diagonal braces. This wall system integrates diagonal strut theory and the concept of prefabricated walls. Its relatively small height-to-width ratio enables flexible arrangement within building structures according to design requirements. Based on quasi-static test results of the wall system under cyclic loading, the inner diagonal braces crack and dissipate energy before the outer frame, though specimens generally exhibit brittle failure characteristics. This failure mechanism is explained in structural analysis as the inner braces transforming horizontal loads into compressive forces on the bottom section of the outer frame. This working mechanism causes the bottom of the outer frame to become the most critical section under combined vertical loads and compressive forces from horizontal loads, leading to crushing failure that causes specimen failure. However, inner diagonal braces in different directions effectively separate damage from positive and negative cyclic loads, and deformation at the intersection points between inner truss members and the outer frame during later test stages demonstrates unique energy dissipation characteristics.

The inner diagonal braces of frame-truss composite walls function similarly to infill walls in frame-infill wall structures, while the outer frame functions similarly to the frame itself. Frame-infill wall structures are a widely used structural form. Research indicates that infill walls make significant contributions to the horizontal seismic resistance of RC frame structures. Building codes in various countries also address the role of infill walls in structural design. Infill walls still function as diagonal bracing elements. Some scholars have proposed YR frames with energy dissipation braces or shear wall structures with energy dissipation braces.

This study combines frame-truss composite walls as energy dissipation walls with frame structures to form multi-stage, multi-component energy dissipation systems. The collaborative working mechanism and seismic performance between energy dissipation walls and YR frames are also key research focuses in frame-shear wall structures. Liang Xingwen et al. proposed a composite structure with high-performance fiber-reinforced concrete walls infilled in YR frames, conducted experimental studies on its seismic performance, and performed theoretical predictions of the structure' s lateral resistance capacity. Wang Yuzhou et al. experimentally studied the seismic performance of YR frame-recycled infill wall systems and comparatively analyzed the effects of recycled infill walls versus conventional infill walls on composite structures. Xiong Feng et al. studied the enhancement effect of fiber gypsum infill walls on the bearing capacity and energy dissipation capacity of YR frames, finding that fiber gypsum infill walls improve the deformation capacity of YR frames more significantly than traditional shale brick RC infill walls.

To investigate the seismic performance of 79Rd as infill walls combined with YR frames, this study conducted quasi-static tests on initially designed and fabricated specimens to clarify their performance under actual service conditions. Consequently, the energy dissipation characteristics of infill walls have become a significant research direction, encompassing fiber-reinforced concrete, B8T3 composite walls, 7YR energy-dissipating walls, steel-concrete-steel composite shear walls, XRX composite shear walls, and steel plate shear walls. Among these, 7YR energy-dissipating walls enhance performance by replacing conventional concrete with steel or fiber-concrete composite materials. Numerical simulations of the quasi-static tests were performed, with results compared against experimental data to analyze the influence of various parameters—including infill 79Rd quantity, frame column reinforcement ratio, axial compression ratio, concrete strength, embedded steel angles, and infill panel arrangement direction —on the seismic performance of the specimens.

Experimental Overview

Based on the working mechanism of frame-infill walls and employing a scale ratio of 1:3, the specimens were designed as shown in [FIGURE:N]. Reinforcement details are illustrated in [FIGURE:N]. The infill 79Rd panels were integrated with frame beams through stirrups in the upper limbs and with the foundation beam via stirrups in the lower limbs, with concrete cast monolithically. Specimen YR-79Rd-1 contained one infill wall panel, while specimen YR-79Rd-2 contained two wall panels. The inner diagonal braces of wall panel 1 had embedded steel angles, while wall panel 2 had identical width-to-height ratios.

The fabrication process involved connecting the wall panels to the YR frame as shown in [FIGURE:N]. The specimen dimensions and reinforcement details are shown in [FIGURE:N]. The design parameters for the two specimens are summarized in [TABLE:N]. All specimens utilized standard C30 concrete, with a measured cubic compressive strength of 32.4 MPa. The axial compression ratio was determined based on the maximum vertical load capacity of the effective cross-section, equivalent to 300 kN for specimen YR-79Rd-1 and 600 kN for specimen YR-79Rd-2. The tensile strength values of the steel reinforcement and angles used are shown in [TABLE:N]. Loading was defined as positive when the actuator pushed and negative when pulled. The second step involved···

Loading Setup and Protocol

The tests were conducted at the Key Laboratory of Structural Engineering and Earthquake Resistance, Ministry of Education, Xi' an University of Architecture and Technology. The loading apparatus is shown in [FIGURE:N]. Horizontal cyclic loads were applied using an MTS actuator, with the loading protocol illustrated in [FIGURE:N]. The loading procedure was divided into stages based on the yield point Fy, which was identified from the significant inflection point on the load-displacement hysteretic curve. After reaching the yield load Fy (120 kN for specimen YR-79Rd-1 and 150 kN for specimen YR-79Rd-2), the control mode switched to displacement loading, with each loading level applied 3 times until the horizontal load decreased to 85% of its peak value or the specimen exhibited significant damage.

Test Results and Analysis

Failure Modes and Crack Development

The final failure patterns and crack distribution are shown in [FIGURE:N]. Cracks in the YR frame concentrated at beam-column joints and column bases, while cracks in the 79Rd were uniformly distributed along the inner diagonal braces and concentrated at intersection points between the outer frame and inner braces, as well as at the right limb (or left limb for wall panel 2). Figure 5 shows an enlarged view of crack distribution on the inner diagonal braces. Cracks were named according to the horizontal load value at crack initiation. It can be observed that cracks on the inner diagonal braces of wall panel 1 appeared after a horizontal load of 112 kN, while cracks on wall panel 2 initiated at a horizontal load of 80 kN, demonstrating that the embedded steel angle design effectively extends the elastic energy dissipation capacity of the inner braces.

The crack development process was as follows: (1) Before reaching 80 kN horizontal load, the specimen remained in the elastic stage without cracks, dissipating energy through material deformation. (2) When load exceeded 120 kN, multiple cracks appeared at the bottoms of both left and right columns. (3) At 150 kN load, cracks concentrated at the interface between the YR frame and wall panel 1, indicating the wall panel began to separate from the YR frame. (4) At 180 kN load, cracks concentrated at the bottom of the right column. The joint between the wall panel and YR frame exhibited widening cracks with partial concrete spalling.

Hysteretic and Skeleton Curves

The hysteretic curves are presented in [FIGURE:N]. The envelope of the hysteretic curves forms the skeleton curve, shown in [FIGURE:N]. The load-displacement skeleton curves exhibit relatively symmetric positive and negative load values, with specimen YR-79Rd-2 showing initial slight load reduction followed by gradual ascent to peak load. The hysteretic loops of specimen YR-79Rd-1 appear fuller, indicating better deformation capacity due to fewer infill panels. During positive loading, the right side containing infill panels caused the horizontal load peak of specimen YR-79Rd-1 to decrease significantly as inelastic deformation intensified.

Characteristic points on the skeleton curves—including cracking point, yield point, peak load point, and ultimate load point—were identified for each specimen, along with calculated ductility coefficients and ultimate story drift ratios. The cracking point corresponds to the first observed crack, the yield point was determined using the energy method, the peak load point represents maximum horizontal load, and the ultimate load point corresponds to 85% load reduction from peak. These values are summarized in [TABLE:N].

Key findings from the characteristic point analysis include: (1) The cracking displacement of specimen YR-79Rd-2 shifted forward by 15mm compared to specimen YR-79Rd-1, indicating that reducing infill panel quantity increases deformation capacity. (2) Yield point negative loads for specimens YR-79Rd-1 and YR-79Rd-2 differed by 45.2 kN, demonstrating that increasing the number of infill wall panels can delay the yield point. (3) Regarding peak load points, the positive and negative horizontal load peaks of specimen YR-79Rd-1 differed by 48.6 kN, while specimen YR-79Rd-2 showed a difference of 35.5 kN, demonstrating that embedded steel angles improve bearing capacity. (4) The ductility coefficient of specimen YR-79Rd-1 under positive loading exceeded that of specimen YR-79Rd-2 by 0.3, confirming that increased infill panel quantity enhances ductility. (5) The ultimate story drift ratio, defined as the ratio of ultimate displacement to structural height, satisfied the drift limits for frame structures for all specimens.

Finite Element Analysis

Model Validation

The finite element analysis employed ABAQUS for modeling and simulation, as shown in [FIGURE:N]. Solid extrusion elements were used for concrete and three-dimensional wire elements for reinforcement. Concrete utilized a plastic damage model, while reinforcement employed the stress-strain curve for steel under cyclic loading proposed by Fang Zihu et al. Reinforcement was embedded in concrete, and the connection between wall panels and YR frame adopted a tie constraint. Two analysis steps were set: one for vertical constant load application and another for horizontal cyclic loading. Boundary conditions fully fixed the column bases and lower limbs of infill 79Rd panels to replace the foundation beam. Vertical loads were applied at column tops, while horizontal loads were applied at frame beam sides. Based on internal force analysis, a concrete element mesh size of 30 mm and reinforcement element size of 20 mm provided optimal computational accuracy with minimal impact on calculation speed; steel angle element size was 20 mm.

According to the uniaxial compressive stress-strain curve for concrete and uniaxial tensile stress-strain curve for steel reinforcement, the constitutive relationships for the actual concrete, reinforcement, and steel angles used in the specimens can be calculated. Additionally, the default steel stress-strain curve in ABAQUS software does not accurately describe the bond-slip phenomenon in reinforced concrete. Therefore, a subroutine written based on the specialized steel stress-strain curve for cyclic loading proposed by Fang Zihu was used to replace the built-in ABAQUS subroutine, thereby better simulating bond-slip effects. This steel stress-strain curve primarily modifies the linear unloading stage of reinforcement.

Comparisons between simulated and experimental hysteretic curves for the specimens show good agreement, with the numerical model accurately capturing the load-displacement response. The simulated skeleton curves exhibit similar trends and comparable peak loads to experimental results, with some modifications to better simulate bond-slip effects in reinforced concrete.

Parametric Studies

To investigate the influence of infill panel quantity, axial compression ratio, concrete strength, and frame column reinforcement ratio on YR frame-79Rd bearing capacity, parametric simulations were conducted. The load-displacement skeleton curves from these simulations demonstrate that increasing infill panel quantity effectively enhances bearing capacity, with more pronounced improvement in positive direction capacity due to the asymmetric configuration of inner diagonal braces about the vertical centerline. This underscores the importance of symmetric panel arrangement.

Stress distribution analysis reveals stress concentration at the bottom of the right limb and left limb of wall panel 2, consistent with observed concrete damage locations. The YR frame remains the primary load-bearing component.

Parametric variations show: (1) Increasing frame column longitudinal reinforcement from 1.2% to 1.8% improves capacity by approximately 5%, while increasing from 1.8% to 2.4% improves capacity by approximately 12%. (2) Each 10 MPa increment in concrete strength increases peak capacity by about 15 kN. (3) Adding embedded steel angles to specimen YR-79Rd-2 improves peak bearing capacity by 45.2 kN, thus increasing the steel ratio of inner diagonal braces can enhance the bearing capacity of YR frame-79Rd systems. (4) Axial compression ratio variations (0.3, 0.4, 0.5, 0.6) show that each 0.1 increase in axial compression ratio improves peak bearing capacity by approximately 8 kN, though axial compression ratio has minimal effect on the overall curve shape. (5) Comparison of symmetric versus asymmetric panel arrangements shows that symmetric arrangement reduces capacity by 15.8 kN compared to asymmetric arrangement, as the asymmetric configuration allows inner diagonal braces to more effectively transfer horizontal loads.

Conclusions

The average positive and negative horizontal load capacity increased by 18.6% compared to specimen YR-79Rd-1, confirming that infill 79Rd quantity is directly proportional to the horizontal bearing capacity of YR frame-79Rd systems. The most effective method for improving structural capacity is increasing infill panel quantity, which can enhance peak capacity by approximately 15 kN. Additional measures include increasing frame column reinforcement ratio and ensuring symmetric arrangement of infill panels.

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Note: Figure translations are in progress. See original paper for figures.

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