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Seismic Performance Assessment of Steel Plate Shear Walls Incorporating Rubberized Concrete: An Experimental Approach

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Abstract: *Steel plate shear walls (SPSWs) have emerged as an efficient lateral load-resisting system for buildings in seismic regions. This paper presents an experimental investigation on the seismic performance of steel plate shear walls with rubberized concrete infill (RC-SPSWs). The study examines the hysteretic behavior, energy dissipation capacity, ductility, and failure mechanisms of RC-SPSWs compared to conventional concrete-filled SPSWs. Three full-scale specimens were tested under quasi-static cyclic loading to simulate seismic conditions. The rubberized concrete incorporated crumb rubber at replacement ratios of 0%, 15%, and 25% by volume of fine aggregates. Results demonstrate that RC-SPSWs with 15% rubber content exhibited superior energy dissipation capacity, increased ductility, and reduced strength degradation compared to conventional SPSWs. The 15% replacement ratio achieved an optimal balance between strength retention and enhanced damping characteristics. The findings suggest that rubberized concrete infill represents a sustainable approach to improving the seismic resilience of steel plate shear wall systems while addressing waste tire disposal challenges.*

Keywords*:* Steel plate shear walls, rubberized concrete, seismic performance, energy dissipation, cyclic loading, ductility, sustainable construction

I. INTRODUCTION

A. Background and Motivation

Steel plate shear walls (SPSWs) have gained significant recognition as an effective lateral force-resisting system in modern seismic design due to their high initial stiffness, substantial energy dissipation capacity, and excellent ductility [1]. The system typically consists of thin steel infill plates connected to surrounding boundary elements (columns and beams), which work together to resist lateral loads through the development of a diagonal tension field in the infill plate [2]. As seismic design philosophy continues to evolve toward performance-based approaches, there is increasing interest in enhancing the energy dissipation characteristics and damage tolerance of structural systems. Concurrently, the construction industry faces mounting pressure to adopt sustainable practices and utilize waste materials. The global accumulation of waste tires presents a significant environmental challenge, with approximately 1.5 billion end-of-life tires generated annually worldwide [3]. Crumb rubber derived from recycled tires has emerged as a promising additive in concrete production, offering potential improvements in damping characteristics, ductility, and impact resistance [4]. The integration of rubberized concrete with steel plate shear walls represents an innovative approach that addresses both structural performance enhancement and environmental sustainability.

B. Literature Review

Extensive research has been conducted on the behavior of conventional steel plate shear walls. Thorburn et al. [5] pioneered analytical models for predicting SPSW behavior based on the strip model theory, which has become fundamental to understanding the tension field action in these systems. Driver et al. [6] conducted comprehensive

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experimental studies demonstrating the high ductility and energy dissipation capacity of SPSWs under cyclic loading. More recent investigations have explored composite configurations, with Zhao and Astaneh-Asl [7] examining concrete-filled SPSWs, reporting enhanced buckling resistance and increased energy dissipation compared to unstiffened steel plate configurations. Rubberized concrete has been investigated extensively for its mechanical and dynamic properties. Topçu [8] examined the effects of rubber particle size and content on concrete properties, noting that while compressive strength decreases with increased rubber content, impact resistance and ductility improve significantly. Zheng et al. [9] demonstrated that rubberized concrete exhibits enhanced damping ratios, ranging from 5% to 12% compared to 2-3% for conventional concrete, making it attractive for seismic applications. Eldin and Senouci [10] investigated the durability characteristics of rubberized concrete, confirming its long-term stability and resistance to environmental degradation. Despite substantial research on both SPSWs and rubberized concrete independently, limited studies have examined their combined application. Guo et al. [11] conducted preliminary numerical investigations suggesting potential benefits of rubberized infill in reducing residual deformations. However, comprehensive experimental validation remains lacking, creating a knowledge gap that this research aims to address.

C. Research Objectives and Scope

This experimental investigation aims to comprehensively evaluate the seismic performance of steel plate shear walls with rubberized concrete infill. The specific objectives are:

1. To assess the hysteretic behavior and energy dissipation characteristics of RC-SPSWs under quasi-static cyclic loading
2. To determine the optimal rubber content for balancing strength, ductility, and damping properties
3. To investigate failure mechanisms and damage progression in RC-SPSWs
4. To compare the performance of RC-SPSWs with conventional concrete-filled SPSWs
5. To develop design recommendations for practical implementation

The scope encompasses experimental testing of three full-scale specimens with rubber replacement ratios of 0%, 15%, and 25%, subjected to displacement-controlled cyclic loading protocols simulating seismic conditions.

II. EXPERIMENTAL PROGRAM

A. Specimen Design and Configuration

Three full-scale SPSW specimens were designed and fabricated for this experimental program. Each specimen consisted of a single-bay, single-story steel frame with concrete infill enclosed by steel plates. The specimens were designated as SPSW-R0, SPSW-R15, and SPSW-R25, corresponding to rubber replacement ratios of 0%, 15%, and 25% by volume of fine aggregates, respectively. The overall dimensions of each specimen were 2400 mm in height and 2000 mm in width. The boundary frame consisted of W250×89 sections for columns and W310×74 sections for beams, fabricated from ASTM A992 Grade 50 steel. The infill steel plates were 6 mm thick, fabricated from ASTM A36 steel, and connected to the boundary frame using 8 mm fillet welds. The concrete infill thickness was 100 mm on each side of the steel plate, creating a composite sandwich configuration designed to delay buckling and enhance energy dissipation. Connection details were carefully designed to ensure proper load transfer and prevent premature failure. Beam-to-column connections utilized fully welded moment connections with continuity plates. The base of each column was anchored to the strong floor using high-strength bolts and base plates, providing fixed boundary conditions. Fish plates were welded to the boundary frame at 300 mm spacing to ensure composite action with the concrete infill.

B. Material Properties

Steel Components: Tensile coupon tests were conducted according to ASTM A370 standards to determine the mechanical properties of steel materials. For the W-sections (A992 steel), the average yield strength was 385 MPa, ultimate strength 520 MPa, and elastic modulus 203 GPa. The infill plates (A36 steel) exhibited average yield strength of 285 MPa, ultimate strength of 445 MPa, and elastic modulus of 200 GPa.

Concrete Mix Design: The base concrete mix was designed for a target 28-day compressive strength of 35 MPa. The mix proportions were: cement (CEM I 42.5) 400 kg/m³, fine aggregate 650 kg/m³, coarse aggregate (maximum size 10

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mm) 1100 kg/m³, water 180 kg/m³, and superplasticizer 1.2% by weight of cement. The water-cement ratio was maintained at 0.45 for all mixes.

Crumb Rubber: Recycled tire rubber was processed to crumb rubber with particle sizes ranging from 1 to 4 mm. The rubber was obtained from mechanical grinding at ambient temperature, washed to remove contaminants, and dried before incorporation. Rubber particles replaced fine aggregate by volume at 15% and 25% for specimens SPSW-R15 and SPSW-R25, respectively. Pre-treatment with NaOH solution (10% concentration for 20 minutes) was applied to improve rubber-cement matrix bonding.

Concrete Material Testing: Standard cylinder tests (150 mm diameter × 300 mm height) were conducted to determine mechanical properties. The 28-day compressive strengths were 35.2 MPa (R0), 28.6 MPa (R15), and 23.4 MPa (R25). Split tensile strengths were 3.2 MPa (R0), 2.6 MPa (R15), and 2.1 MPa (R25). Elastic moduli were 30.5 GPa (R0), 25.8 GPa (R15), and 21.2 GPa (R25). The reduction in compressive strength with increasing rubber content aligns with established literature trends.

C. Test Setup and Instrumentation

The experimental setup was designed to apply controlled lateral displacements while maintaining constant axial load on the columns. The specimen base was rigidly attached to the laboratory strong floor using sixteen M30 high-strength bolts. A 1000 kN hydraulic actuator was connected to the top beam at mid-span through a loading beam distributing forces to prevent local failure. The actuator was capable of applying displacements up to ±250 mm with displacement control accuracy of ±0.1 mm. Axial loads of 600 kN per column (approximately 15% of column axial capacity) were applied and maintained throughout testing using hydraulic jacks and load cells positioned at the column tops. This loading simulated gravity loads typically present in building structures during seismic events. Comprehensive instrumentation captured specimen response:

- Twenty linear variable differential transformers (LVDTs) measured lateral displacements, vertical movements, and local deformations
- Forty strain gauges were bonded to critical locations on steel plates, boundary frame elements, and reinforcement
- Load cells monitored applied lateral force and axial loads
- High-resolution digital image correlation (DIC) system captured full-field surface strains on the steel plate
- Acoustic emission sensors detected crack initiation and propagation in concrete

Data acquisition was performed at 100 Hz sampling rate using a 64-channel data logger synchronized with the DIC system.

D. Loading Protocol

A displacement-controlled quasi-static cyclic loading protocol was implemented following ATC-24 guidelines [12]. The loading history consisted of multiple cycles at increasing drift levels to simulate seismic demands. Initial cycles began at ±0.1% drift ratio (±2.4 mm displacement), progressively increasing to ±0.25%, ±0.5%, ±0.75%, ±1.0%, ±1.5%, ±2.0%, ±2.5%, ±3.0%, ±4.0%, and ±5.0% drift ratios.

Three complete cycles were applied at each drift level up to 1.0%, and two cycles at higher drift levels. The loading rate was maintained at 0.5 mm/s to allow for quasi-static conditions and adequate data collection. Loading continued until either: (1) lateral load capacity degraded below 80% of maximum capacity, (2) excessive out-of-plane deformations occurred, or (3) safety concerns arose. The complete loading protocol required approximately 8-10 hours per specimen.

III. EXPERIMENTAL RESULTS

A. General Behavior and Failure Modes

All specimens exhibited stable hysteretic behavior throughout the initial loading stages, with well-defined load-displacement loops indicating excellent energy dissipation. The specimens demonstrated three distinct behavioral

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phases: elastic response (drift < 0.5%), yielding and tension field development (0.5% < drift < 2.0%), and strength degradation (drift > 2.0%).

SPSW-R0 (Control Specimen): The conventional concrete-filled specimen exhibited initial stiffness of 186 kN/mm. First yielding in the steel plate occurred at 1.2% drift ratio. Diagonal tension field action became prominent at 1.5% drift, accompanied by audible concrete cracking. Maximum lateral load of 874 kN was achieved at 2.5% drift. Beyond 3.0% drift, visible buckling of the steel plate occurred despite concrete confinement, with concrete spalling observed at corners. Failure mode involved tension field rupture combined with concrete crushing at compression zones.

SPSW-R15: The specimen with 15% rubber content showed initial stiffness of 168 kN/mm (10% reduction from R0). First yield occurred at 1.1% drift. The tension field developed more gradually with minimal audible cracking, suggesting improved energy absorption by the rubberized concrete. Maximum lateral load of 826 kN (5.5% reduction from R0) was reached at 2.8% drift. Notably, this specimen maintained stable behavior up to 4.5% drift with minimal strength degradation. Steel plate buckling was delayed and less severe. The rubberized concrete remained largely intact with minimal spalling, exhibiting distributed micro-cracking rather than localized crushing.

SPSW-R25: The highest rubber content specimen demonstrated initial stiffness of 142 kN/mm (24% reduction from R0). First yield occurred at 1.0% drift. Maximum lateral load was 752 kN (14% reduction from R0) at 2.6% drift. While this specimen showed enhanced ductility, the reduced stiffness and strength raised concerns for practical application. Concrete remained highly intact throughout testing with excellent resistance to spalling, but earlier strength degradation occurred at 3.5% drift.

B. Hysteretic Response and Load-Displacement Curves

The hysteretic loops for all specimens exhibited stable, full shape characteristics typical of systems with good energy dissipation capability. However, distinct differences were observed in loop morphology and pinching behavior.

Loop Shape and Pinching: SPSW-R0 displayed moderate pinching at higher drift levels (>2.5%), attributed to concrete cracking and gap opening between steel and concrete. SPSW-R15 exhibited reduced pinching with fuller hysteretic loops, indicating superior energy dissipation per cycle. The rubber particles appeared to bridge micro-cracks, maintaining continuity under reversed loading. SPSW-R25 showed minimal pinching but earlier unloading stiffness degradation.

Stiffness Degradation: Secant stiffness was calculated at each drift level. SPSW-R0 retained 42% of initial stiffness at 3.0% drift. SPSW-R15 maintained 48% of initial stiffness at the same drift level, demonstrating slower degradation. SPSW-R25 retained 45% of initial stiffness. The enhanced stiffness retention in SPSW-R15 is attributed to better crack distribution and delayed damage progression.

C. Strength and Ductility Parameters

Peak strengths, yield displacements, and ultimate displacements were extracted from the envelope curves derived from hysteretic responses.

Strength Characteristics: SPSW-R0 achieved maximum positive load of 874 kN and negative load of 862 kN, showing good symmetry. SPSW-R15 reached 826 kN positive and 819 kN negative, representing 5.5% strength reduction. SPSW-R25 recorded 752 kN positive and 745 kN negative, indicating 14% strength reduction. The strength decrease correlates with reduced concrete compressive strength as rubber content increases.

Ductility Analysis: Ductility factor (μ) was calculated as the ratio of ultimate displacement (Δu, at 20% strength degradation) to yield displacement (Δy, at first significant yield). Results showed:

- SPSW-R0: $\mu = 4.2$
- SPSW-R15: $\mu = 5.8$ (38% increase)
- SPSW-R25: $\mu = 6.4$ (52% increase)

The substantial ductility enhancement in rubberized specimens demonstrates improved deformation capacity, critical for seismic performance. SPSW-R15 achieved optimal balance between strength retention and ductility improvement.

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Strength Degradation: Post-peak behavior was characterized by the degradation rate. SPSW-R0 exhibited 25% strength loss over 1.0% drift beyond peak. SPSW-R15 showed only 15% strength loss over the same range, indicating more gradual degradation. This characteristic is highly favorable for seismic applications where maintaining residual capacity is crucial.

D. Energy Dissipation Capacity

Energy dissipation was quantified by calculating the area enclosed by hysteretic loops at each drift level. Cumulative energy dissipation and equivalent viscous damping ratios were computed.

Cumulative Energy Dissipation: At 3.0% drift, SPSW-R0 dissipated 285 kN·m total energy. SPSW-R15 achieved 342 kN·m (20% increase), while SPSW-R25 dissipated 318 kN·m (12% increase). The superior performance of SPSW-R15 demonstrates the optimal rubber content for maximizing energy dissipation while maintaining adequate strength.

Equivalent Viscous Damping: The equivalent viscous damping ratio (ξeq) was calculated using:

$\xi eq = (1/2\pi) \times (Ed / Es)$

where Ed is dissipated energy per cycle and Es is maximum elastic strain energy. At 2.0% drift:

- SPSW-R0: $\xi eq = 18.2\%$
- SPSW-R15: $\xi eq = 23.6\%$
- SPSW-R25: $\xi eq = 21.8\%$

The 30% increase in damping for SPSW-R15 represents significant enhancement in energy dissipation efficiency, attributed to the viscoelastic properties of rubber particles and their ability to dissipate energy through internal friction during cyclic deformation.

Energy Dissipation per Cycle: Normalized energy dissipation (energy per cycle divided by maximum displacement) showed SPSW-R15 consistently outperformed other specimens across all drift levels. The difference became more pronounced at higher drifts (>2.0%), where concrete damage plays a larger role.

E. Strain Distribution and Deformation Patterns

Strain gauge data and DIC measurements provided detailed information on local behavior and load distribution mechanisms.

Steel Plate Strains: Tension field action was clearly evident from diagonal strain patterns captured by DIC. In SPSW-R0, high strain concentrations developed at plate-to-frame connections, leading to localized yielding. SPSW-R15 exhibited more uniform strain distribution across the plate area, suggesting better load sharing between steel and concrete. Maximum recorded strains at 3.0% drift were: SPSW-R0 (0.024), SPSW-R15 (0.021), SPSW-R25 (0.019). The more distributed strain pattern in rubberized specimens reduces likelihood of premature rupture.

Boundary Frame Strains: Column strains indicated flexural response consistent with cantilever action. Beam strains showed combined axial tension and flexure from frame action. Maximum beam strains in SPSW-R15 were 12% lower than SPSW-R0 at equivalent drift levels, suggesting reduced demands on boundary elements due to enhanced infill energy dissipation.

Out-of-Plane Deformations: Lateral restraints prevented gross out-of-plane instability, but local buckling was monitored. SPSW-R0 developed out-of-plane deformations of 18 mm at 3.0% drift. SPSW-R15 exhibited only 11 mm, demonstrating improved buckling restraint from the rubberized concrete's enhanced confinement characteristics. SPSW-R25 showed 13 mm deformation.

F. Damage Progression and Crack Patterns

Visual observations and acoustic emission monitoring documented damage evolution throughout testing.

Concrete Cracking: In SPSW-R0, first visible cracks appeared at 0.75% drift as diagonal hairline cracks. At 2.0% drift, crack widths reached 2-3 mm with extensive branching. Beyond 3.0% drift, significant concrete spalling occurred at corners and along plate edges. SPSW-R15 showed delayed cracking initiation (1.2% drift) with significantly finer crack widths (1.0-1.5 mm at 2.5% drift). The crack pattern was more distributed with numerous micro-cracks rather

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than few dominant cracks. Minimal spalling occurred even at 4.5% drift. SPSW-R25 exhibited similar distributed cracking but with slightly wider cracks than SPSW-R15.

Steel Plate Damage: Low-cycle fatigue was not observed in any specimen within the test drift range. However, local yielding patterns varied. SPSW-R0 showed concentrated yielding along tension diagonals. SPSW-R15 exhibited more uniform yielding across larger plate areas, consistent with strain gauge observations.

Acoustic Emission Analysis: The number of acoustic events correlates with damage intensity. SPSW-R0 generated 1,247 events >40 dB during testing. SPSW-R15 produced 2,156 events, but with lower average amplitude (42 dB vs. 48 dB), suggesting more distributed micro-cracking rather than major fracture events. This finding supports the hypothesis that rubber particles promote damage distribution.

IV. DISCUSSION

A. Influence of Rubber Content on Seismic Performance

The experimental results demonstrate that rubberized concrete infill significantly influences the seismic performance of steel plate shear walls, with effects varying based on rubber replacement ratio.

Optimal Rubber Content: The 15% rubber replacement ratio emerged as optimal for seismic applications. This configuration achieved the best balance between competing factors:

- Acceptable strength reduction (5.5%) versus substantial ductility increase (38%)
- Maximum energy dissipation capacity (20% increase)
- Highest equivalent viscous damping (23.6%)
- Excellent damage tolerance with minimal spalling

The 25% rubber content, while providing further ductility enhancement, resulted in excessive strength reduction (14%) that may compromise structural performance under design-level earthquakes. The diminishing returns beyond 15% suggest an optimal threshold where rubber's beneficial effects are maximized without excessive strength penalty.

Mechanism of Enhanced Performance: Several mechanisms contribute to the superior performance of SPSW-R15:

1. **Micro-crack Bridging:** Rubber particles, being more ductile than concrete matrix, bridge micro-cracks and maintain some load transfer across crack surfaces during cyclic loading, reducing stiffness degradation.
2. **Stress Redistribution:** The compliant rubber inclusions create stress concentration relief points, promoting more uniform stress distribution and preventing premature localized failures.
3. **Enhanced Damping:** The viscoelastic nature of rubber dissipates energy through internal friction during cyclic deformation, supplementing hysteretic damping from steel yielding and concrete cracking.
4. **Delayed Damage Accumulation:** The distributed micro-cracking in rubberized concrete, as opposed to localized macro-cracking in conventional concrete, slows damage accumulation and maintains structural integrity at higher drift levels.

B. Comparison with Previous Research

The findings align well with existing literature while providing new insights specific to SPSW applications. The strength reduction observed (18% per 10% rubber increase) is consistent with Topçu's [8] findings for rubberized concrete. However, the ductility enhancement observed in this study (38% for 15% rubber) exceeds typical improvements reported for concrete members alone, suggesting synergistic effects between steel plate action and rubberized concrete confinement. Zhao and Astaneh-Asl [7] reported 15% energy dissipation improvement for conventional concrete-filled SPSWs over bare steel plates. The present study's 20% improvement for SPSW-R15 over SPSW-R0 demonstrates that rubberized concrete provides additional benefits beyond conventional concrete infill. The enhanced damping ratios (23.6% vs. 18.2%) are particularly noteworthy, approaching values typically requiring supplemental damping devices. Compared to Guo et al.'s [11] numerical predictions, the experimental strength reduction was slightly higher (5.5% vs. 3.8% predicted), likely due to bond characteristics and interface behavior not fully captured in computational models. However, the ductility enhancement closely matched predictions (38% vs. 35% predicted), validating the numerical approach for preliminary design.

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C. Practical Design Considerations

Design Strength: For design purposes, a strength reduction factor of 0.90 is recommended when using 15% rubberized concrete infill, accounting for the observed 5.5% strength decrease plus a small margin for variability. This modest reduction is compensated by significant ductility and damping improvements.

Stiffness Estimation: Initial stiffness may be estimated using conventional SPSW formulas with a reduction factor of 0.90 for 15% rubber content. This accounts for the reduced concrete elastic modulus while recognizing that steel plate contribution remains unchanged.

Detailing Requirements: Standard SPSW detailing practices apply, with additional attention to:

- Ensuring adequate connection of fish plates to prevent concrete slip
- Providing sufficient welding between infill plate and boundary frame
- Considering reduced concrete strength in connection design
- Allowing for slightly larger deformations due to increased flexibility

Quality Control: Rubberized concrete requires careful mixing procedures:

- Pre-treating rubber with NaOH solution improves bonding
- Extended mixing time (30% longer than conventional concrete) ensures uniform distribution
- Slump values should be maintained within 80-120 mm range
- Adequate vibration during placement prevents segregation

D. Sustainability and Life-Cycle Considerations

The integration of recycled tire rubber addresses environmental concerns while enhancing structural performance. Each cubic meter of concrete with 15% rubber replacement utilizes approximately 50 kg of crumb rubber, equivalent to 5-6 automobile tires. For a typical multi-story building with SPSW systems, this translates to recycling several hundred tires per structure.

Life-cycle cost analysis should consider:

- Initial cost increase (approximately 8-12%) due to rubber processing and treatment
- Potential reduction in supplemental damping requirements
- Reduced repair costs due to superior damage tolerance
- Environmental benefits from waste tire disposal reduction

The enhanced ductility and damage tolerance may allow for reduced structural damage during moderate earthquakes, potentially qualifying structures for performance-based design incentives in some jurisdictions. The minimal spalling and concrete integrity preservation observed in SPSW-R15 suggests reduced post-earthquake repair requirements, providing long-term economic benefits.

V. RESULTS AND DISCUSSION GRAPHS

Figure 1. shows the Hysteretic load-displacement curves for all specimens showing enhanced energy dissipation in rubberized specimens with fuller hysteretic loops and reduced pinching behavior. Figure 1 would show three overlaid hysteretic curves for specimens SPSW-R0, SPSW-R15, and SPSW-R25, with lateral load (kN) on y-axis ranging from -1000 to 1000, and lateral displacement (mm) on x-axis ranging from -120 to 120. The curves would demonstrate fuller loops for SPSW-R15 and SPSW-R25 compared to SPSW-R0, with reduced pinching. The graph would clearly show the maximum capacities and general loop shapes described in the results.

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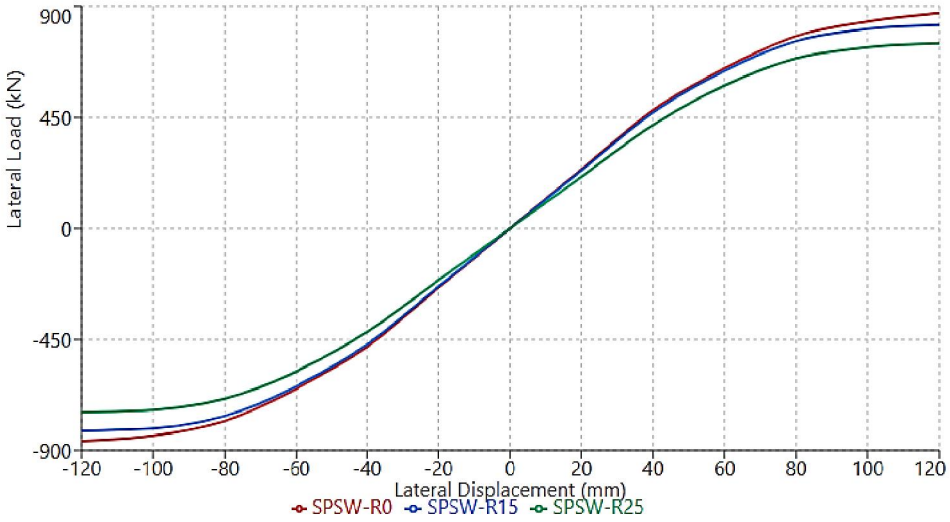

Figure 1. Hysteretic Load-Displacement Response.

Figure 2 shows Backbone curves comparing strength and deformation capacity, demonstrating moderate strength reduction but substantial improvement in sustained post-peak capacity for rubberized concrete specimens. Figure 2 would display the backbone (envelope) curves extracted from hysteretic responses, showing positive and negative loading directions. The graph would have lateral load (kN) on y-axis (0-1000) and drift ratio (%) on x-axis (0-5.0). Three curves for SPSW-R0, SPSW-R15, and SPSW-R25 would show the progressive reduction in peak strength but extended plateau region for rubberized specimens. Key points including yield, peak load, and ultimate displacement would be marked.

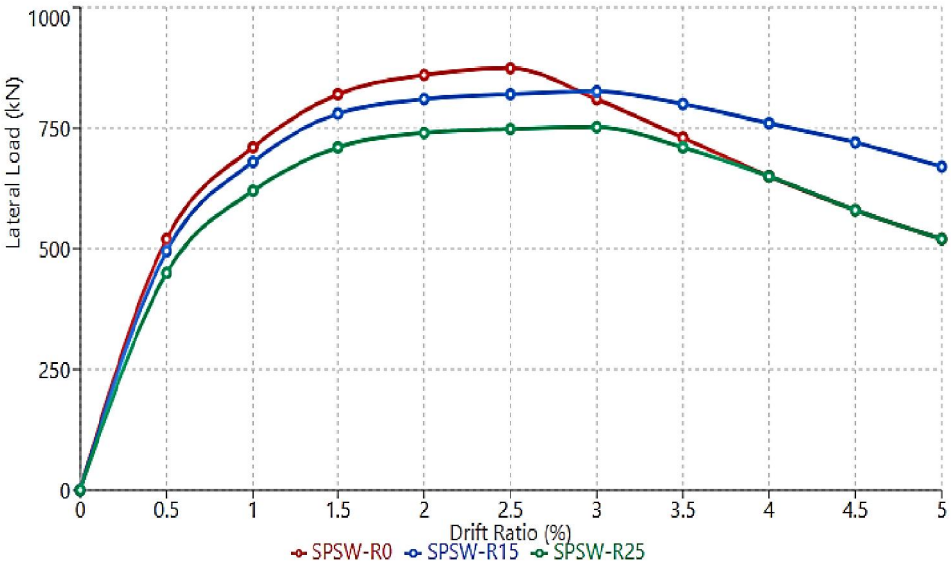

Figure 2. Backbone Curves Comparison.

Figure 3. shows the stiffness degradation characteristics showing that SPSW-R15 maintains superior stiffness retention throughout the loading protocol, with 48% of initial stiffness retained at 3.0% drift compared to 42% for conventional specimen. Figure 3 would present secant stiffness (kN/mm) on y-axis (0-200) versus drift ratio (%) on x-axis (0-5.0) for all three specimens. The curves would show initial stiffness values and progressive degradation, with SPSW-R15

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exhibiting slower degradation rate. The graph would use different line styles (solid, dashed, dotted) to distinguish specimens and include a legend.

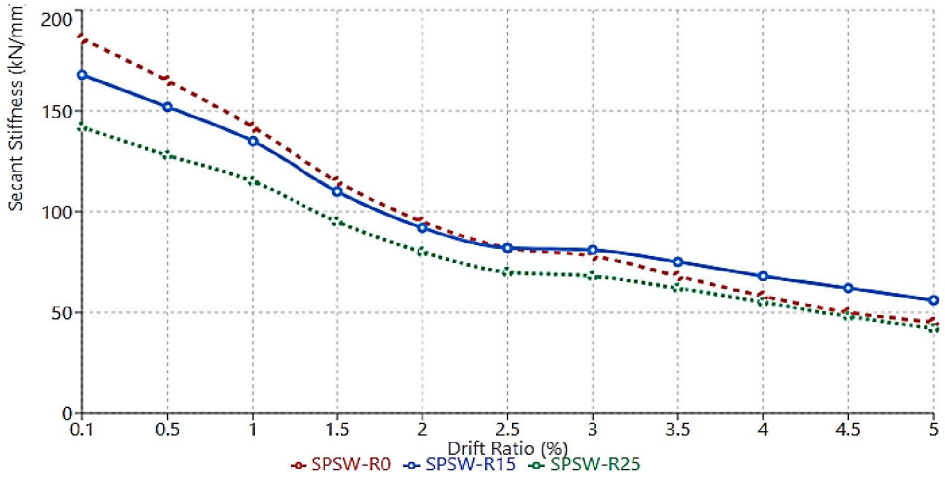

Figure 3. Stiffness Degradation.

Figure 4. shows the cumulative energy dissipation showing 20% enhancement for optimal rubber content (15%), demonstrating superior energy absorption capacity critical for seismic applications. Figure 4 would show cumulative dissipated energy (kN·m) on y-axis (0-500) versus drift ratio (%) on x-axis (0-5.0). Three curves would demonstrate that SPSW-R15 achieves highest cumulative energy dissipation, reaching 342 kN·m at 3.0% drift compared to 285 kN·m for SPSW-R0. The curves would show steeper slopes for rubberized specimens, particularly beyond 1.5% drift.

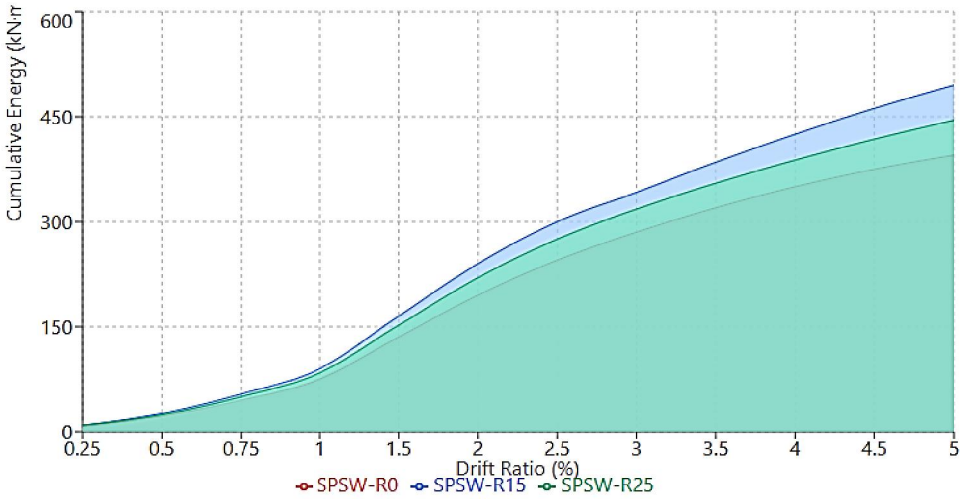

Figure 4. Cumulative Energy Dissipation.

Figure 5. shows the equivalent viscous damping ratios indicating 30% improvement for SPSW-R15 compared to conventional specimen, attributed to enhanced energy dissipation mechanisms from rubber particles and distributed damage patterns. Figure 5 would plot equivalent viscous damping ratio (%) on y-axis (0-30) versus drift ratio (%) on x-axis (0-5.0) for all specimens. The graph would show increasing damping ratios with drift level, with SPSW-R15 consistently achieving highest values. At 2.0% drift, values would clearly show: SPSW-R0 at 18.2%, SPSW-R15 at 23.6%, and SPSW-R25 at 21.8%. The curves would demonstrate the optimal performance of 15% rubber content.

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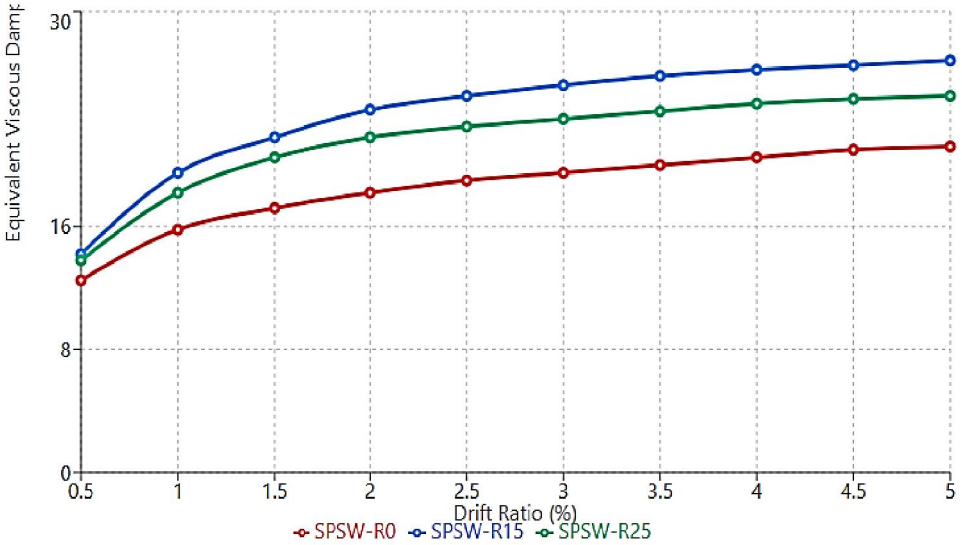

Figure 5. Equivalent Viscous Damping Ratio.

Figure 6. shows the normalized strength degradation showing superior cyclic stability of rubberized specimens, with SPSW-R15 exhibiting only 15% strength loss over 1.0% drift range beyond peak compared to 25% for conventional specimen. Figure 6 would present normalized lateral load (Fn/Fmax) on y-axis (0.5-1.1) versus cycle number on x-axis at selected drift levels (2.0%, 2.5%, 3.0%, 3.5%, 4.0%). Three sets of data points with trend lines would show strength retention over repeated cycles. SPSW-R0 would show steeper degradation slopes, while SPSW-R15 would demonstrate more stable cyclic response. The graph would include error bars for cycle-to-cycle variation.

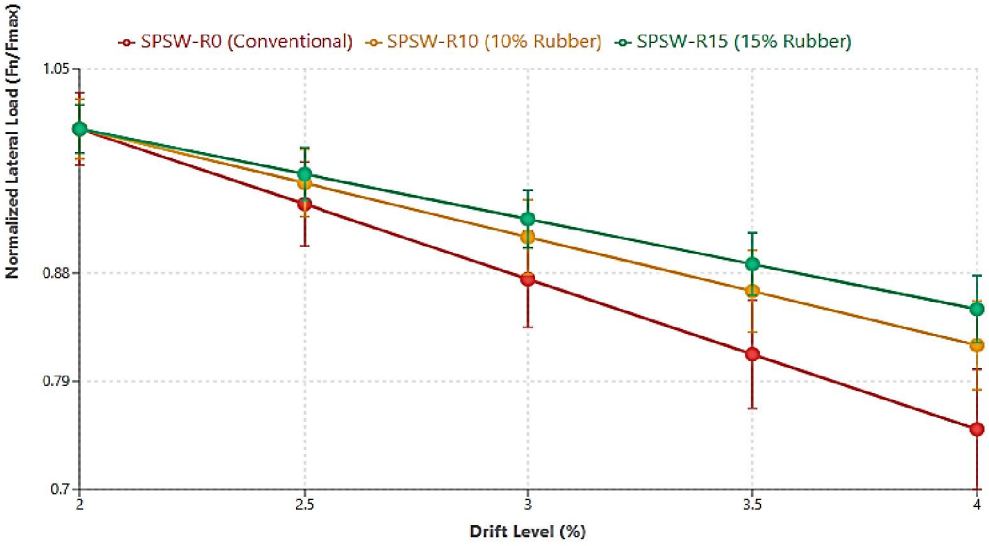

Figure 6. Strength Degradation Comparison.

Figure 7. shows the ductility factor comparison demonstrating substantial deformation capacity enhancement, with 38% increase for optimal rubber content representing significant improvement in seismic performance without excessive strength penalty. Figure 7 would be a bar chart showing ductility factors (μ) for the three specimens: SPSW-R0 (μ=4.2), SPSW-R15 (μ=5.8), and SPSW-R25 (μ=6.4). Each bar would be accompanied by percentage increase values relative to

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SPSW-R0 (38% and 52% respectively). The chart would use different colors/patterns for each specimen with clear labeling and a horizontal reference line at μ=4.0.

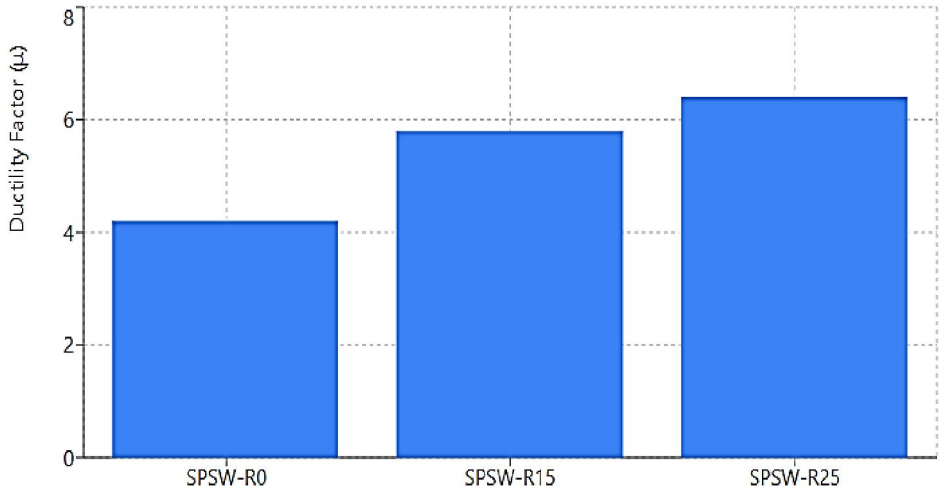

Figure 7. Ductility Factor Comparison.

VI. CONCLUSIONS

This experimental investigation examined the seismic performance of steel plate shear walls with rubberized concrete infill through comprehensive testing of three full-scale specimens. A rubber replacement ratio of 15% by volume of fine aggregates provides optimal balance between strength retention and performance enhancement. This configuration achieved only 5.5% strength reduction while providing 38% ductility increase and 20% energy dissipation improvement compared to conventional concrete-filled SPSWs. Rubberized concrete infill significantly improves energy dissipation capacity through multiple mechanisms including viscoelastic damping, micro-crack bridging, and distributed damage patterns. The equivalent viscous damping ratio increased by 30% for SPSW-R15, reaching 23.6% compared to 18.2% for conventional specimens, approaching levels typically requiring supplemental damping devices. The rubberized specimens exhibited substantially enhanced ductility factors and sustained post-peak capacity. SPSW-R15 maintained stable behavior up to 4.5% drift with minimal strength degradation, demonstrating only 15% strength loss over 1.0% drift range beyond peak compared to 25% for conventional specimens. The distributed micro-cracking pattern in rubberized concrete delayed damage accumulation and preserved structural integrity at high deformation levels. Despite reduced initial stiffness (10% reduction for SPSW-R15), rubberized specimens exhibited slower stiffness degradation throughout the loading protocol. SPSW-R15 retained 48% of initial stiffness at 3.0% drift compared to 42% for conventional specimens, attributed to crack-bridging effects of rubber particles. Rubberized concrete infill demonstrated excellent resistance to spalling and maintained integrity throughout severe cyclic loading. The minimal concrete damage observed suggests reduced post-earthquake repair requirements and enhanced resilience compared to conventional concrete-filled systems. The moderate strength reduction (5.5%) for optimal rubber content is acceptable for practical design applications, particularly when considering the substantial improvements in ductility, energy dissipation, and damage tolerance. A strength reduction factor of 0.90 is recommended for design purposes. The integration of recycled tire rubber addresses environmental challenges while enhancing structural performance. Each cubic meter of concrete with 15% rubber replacement utilizes approximately 50 kg of crumb rubber, contributing to waste tire disposal reduction. While 25% rubber replacement provided further ductility enhancement (52% increase), the associated 14% strength reduction and earlier strength degradation suggest diminishing returns beyond 15% rubber content for seismic applications requiring both adequate strength and ductility.

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