SEISMIC RESILIENCE PERFORMANCE OF INNOVATIVE TORSIONAL DAMPER FOR STEEL MOMENT RESISTING CONNECTIONS

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ABSTRACT

This study explores the enhancement of seismic performance in braced steel frames through the integration of a novel Torsional Steel-Tube Damper (TSTD). The primary objectives are to determine the optimal dimensions and configuration of the TSTD within brace-to-beam connections, assess its impact on the global and local seismic behavior of the structural system, and examine its effectiveness in frames featuring variable moment-resisting connections. Finite Element Analysis (FEA) is performed using ANSYS 2024 to simulate the response of steel frames with and without TSTDs under lateral and dynamic seismic loading conditions. Key performance metrics such as energy dissipation capacity, load-bearing behavior, stiffness degradation, and residual deformations are evaluated. The simulation results indicate that the incorporation of TSTDs significantly enhances energy dissipation, mitigates joint damage and stress concentration, and promotes more uniform load distribution. Moreover, frames equipped with TSTDs exhibit increased ductility and reduced residual deformations compared to conventional configurations. A comprehensive parametric study yields optimized damper dimensions and provides practical design guidelines for effective TSTD implementation in various braced frame systems. The findings underscore the potential of TSTDs as a cost-effective and efficient solution for enhancing the seismic resilience, structural safety, and durability of steel buildings in seismically active regions.

Keywords: Torsional Steel-Tube Damper (TSTD), seismic performance, braced steel frame, energy dissipation, finite element analysis (FEA), ANSYS 2024, ductility, residual deformation, structural resilience, moment-resisting connection.

INTRODUCTION

The increasing frequency and severity of earthquakes in recent decades have underscored the urgent need for innovative structural systems that not only withstand seismic forces but also minimize post-event damage and downtime. In seismic-prone regions, Steel Moment Resisting Frames (SMRFs) have been widely adopted due to their inherent ductility, redundancy, and energy dissipation capabilities. However, the performance of SMRFs is often compromised at critical connections such as beam-to-column or brace-to-beam joints, which are susceptible to stress concentration, local yielding, and irreversible deformation under intense cyclic loading. To overcome these limitations, structural engineers have integrated supplemental damping systems into SMRFs to enhance energy dissipation and reduce seismic demand on primary structural elements. Among these, metallic dampers have gained prominence due to their robustness, cost-effectiveness, and ability to dissipate energy through stable plastic deformation. Nonetheless, conventional metallic dampers typically rely on axial or flexural deformation modes, which can inadvertently introduce high local stresses and compromise the integrity of the main load-bearing members over time. In response to these challenges, this study proposes a novel Torsional Steel-Tube Damper (TSTD) specifically designed for installation at brace-to-beam connections in SMRFs. By harnessing torsional deformation as the primary energy dissipation mechanism, the TSTD offers an alternative and complementary mode of inelastic behavior, promoting more uniform stress distribution and mitigating the risk of brittle failure. Unlike traditional dampers, the TSTD provides rotational flexibility and decouples energy dissipation from the axial load path, preserving the structural performance of adjacent members. This research presents a detailed numerical investigation into the seismic resilience performance of steel frames equipped with the proposed TSTD. Using Finite Element Analysis (FEA) in ANSYS 2024, the study evaluates the nonlinear behavior of SMRFs under lateral and seismic loading with and without the incorporation of TSTDs. Key performance indicators such as energy dissipation capacity, ductility, stiffness degradation, and residual deformations are analyzed to assess the effectiveness of the TSTD.

The findings demonstrate that optimized TSTD configurations not only enhance the lateral strength and ductility of the frame but also significantly improve energy dissipation and reduce connection damage. The study concludes with a parametric optimization of damper geometry and offers practical design recommendations for implementing TSTDs in new construction and seismic retrofitting. These contributions aim to support the development of next-generation seismic mitigation strategies that enhance the safety, durability, and resilience of steel-framed structures.

OBJECTIVES

To study the seismic performance of braced steel frames with and without the Torsional Steel-Tube Damper (TSTD).

To conduct a parametric study on the effectiveness of the TSTD in steel braced frames.

To assess the seismic performance based on key parameters such as yield load, yield displacement, ultimate load, ultimate displacement, and ductility and determine the optimum size of TSTD.

METHODOLOGY

This study builds upon prior research to enhance the seismic resilience of Steel Moment-Resisting Frames (SMRFs) by integrating a Torsional Steel-Tube Damper (TSTD) at beam-column joints. A comprehensive literature review and evaluation of existing damping systems guided the definition of objectives focused on optimizing TSTD geometry and placement, especially in skewed and variable moment connections. Finite Element Models were developed in ANSYS 2024 using SOLID186 elements with hexahedral meshing, and validated against established benchmarks. A full-scale 3D frame, with and without TSTD, was analyzed through nonlinear static and dynamic simulations. Parametric studies varied damper dimensions and configurations to assess performance metrics such as load capacity, energy dissipation, stiffness degradation, and residual deformation. The findings demonstrate TSTD's effectiveness as a reliable, economical solution for improving the seismic performance of steel structures.

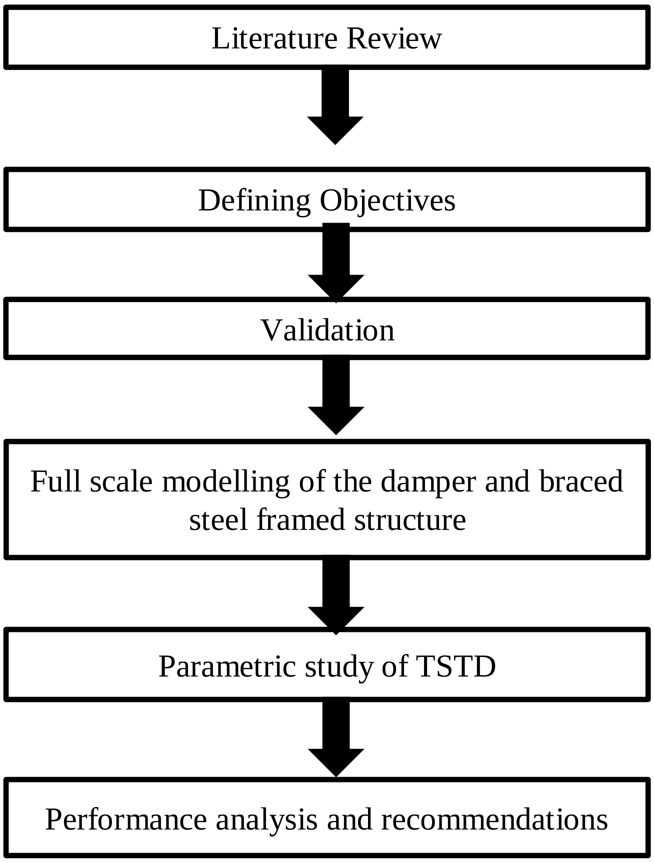

Figure 1: Flow chart of Methodology.

FEA MODELLING OF BRACED STEEL FRAME WITH AND WITHOUT TORSIONAL STEEL TUBE DAMPER UNDER LATERAL LOADING

The This chapter presents the finite element analysis (FEA) of a braced steel frame, with and without the integration of the Torsional Steel-Tube Damper (TSTD), conducted using ANSYS 2024. The analysis models both a conventional braced frame and a modified frame with TSTDs at the brace-to-beam joints. The study evaluates the seismic performance under dynamic and static lateral loads, focusing on parameters like load-displacement behavior, ductility, and energy dissipation to assess the damper's effectiveness in improving seismic resilience and structural performance.

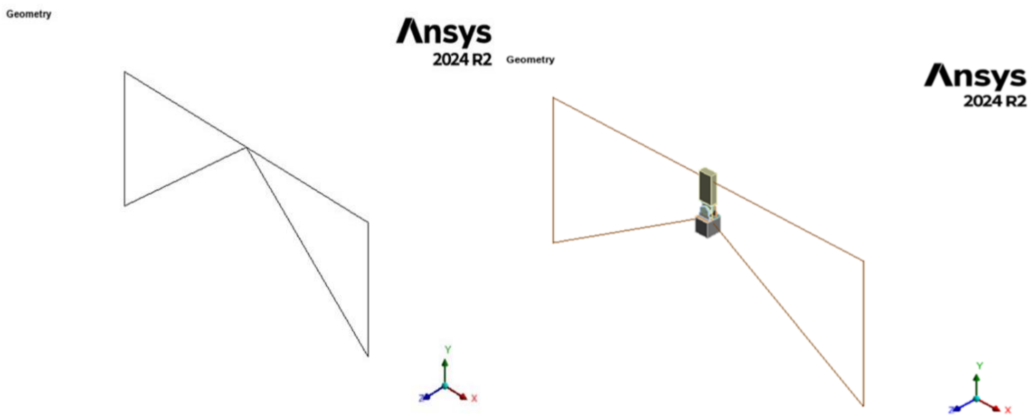

Figure 2: (a) Geometry of braced frame (b) Geometry of braced frame with TSTD in ANSYS 24.

For the TSTD analysis, SOLID186A elements are used to model the damper, with a 10mm mesh size and hexahedral shape to accurately represent the torsional damper's stress and strain under seismic loading. The TSTDs are made from mild steel (Grade #20), while the plates and pins are from Q345 structural steel. Material properties, including modulus of elasticity and yield stress, were obtained from uniaxial tensile tests and are crucial for understanding the damper's energy dissipation during seismic events. These dampers are designed to enhance the frame's ability to absorb energy and reduce seismic damage.

The boundary conditions of the FEA model include fixed supports at the base, with lateral point loads applied to simulate seismic forces. Additional lateral supports at the upper joints prevent horizontal displacements, mimicking diaphragm continuity. This configuration ensures the model accurately simulates the structural response under lateral forces and evaluates the contribution of the TSTD in enhancing the frame's seismic performance.

FEA MODELLING OF STEEL MOMENT RESISTING FRAMES WITH BRACING AND TORSIONAL STEEL-TUBE DAMPERS (TSTD) UNDER LATERAL LOADING FOR PARAMETRIC STUDY

This study investigates the seismic performance of steel moment-resisting frames (MRFs) integrated with the Torsional Steel-Tube Damper (TSTD) to improve lateral strength and ductility. The TSTD is positioned at brace-to-beam connection points to address common issues such as brace buckling and insufficient energy dissipation. The damper works by allowing controlled torsional deformation, efficiently redistributing loads and enhancing the structure's resilience during seismic events. Parametric models were developed, varying key TSTD parameters such as tube diameter, wall thickness, and length to identify the optimal configuration for maximizing seismic performance.

Table 1: Model cases for parametric study.

<table>
<tr><th colspan="5">TSTD DIMENSION PARAMETERS</th><th rowspan="3">MODEL CASES</th></tr>
<tr><th colspan="3">TUBE</th><th colspan="2">PLATE</th></tr>
<tr><th>DIAMETER</th><th>WIDTH</th><th>THICKNESS</th><th>WIDTH</th><th>RADIUS</th></tr>
<tr><td>140</td><td>35</td><td>6</td><td>300</td><td>120</td><td>TSTD 1-ACTUAL</td></tr>
<tr><td>150</td><td rowspan="2">35</td><td rowspan="2">6</td><td rowspan="2">300</td><td rowspan="2">120</td><td>TSTD 1 150</td></tr>
<tr><td>160</td><td>TSTD 1 160</td></tr>
<tr><td rowspan="3">140</td><td rowspan="3">35</td><td>8</td><td rowspan="3">300</td><td rowspan="3">120</td><td>TSTD 1 t8</td></tr>
<tr><td>10</td><td>TSTD 1 t10</td></tr>
<tr><td>12</td><td>TSTD 1 t12</td></tr>
<tr><td rowspan="3">140</td><td>45</td><td rowspan="3">6</td><td rowspan="3">300</td><td rowspan="3">120</td><td>TSTD 1 w45</td></tr>
<tr><td>55</td><td>TSTD 1 w55</td></tr>
<tr><td>65</td><td>TSTD 1 w65</td></tr>
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Finite element modeling was performed using SOLID186 elements for the TSTD and Beam188 elements for the frame, employing a 10 mm mesh size for accuracy in capturing stress concentrations. Mesh refinement was applied in critical areas, such as beam-column joints, to ensure precise analysis while maintaining computational efficiency. The meshing strategy enabled the accurate representation of structural behavior under dynamic loading conditions.

A parametric study was conducted to identify the best TSTD parameters for improved seismic performance. Various TSTD configurations, including different tube dimensions and positioning, were analyzed through lateral loading analysis. The study focused on determining the optimal parameters for tube diameter, wall thickness, and effective length to achieve enhanced energy dissipation, lateral strength, and ductility. The results from this analysis guide the integration of TSTD in MRFs, offering a practical approach for optimizing seismic resilience in steel structures.

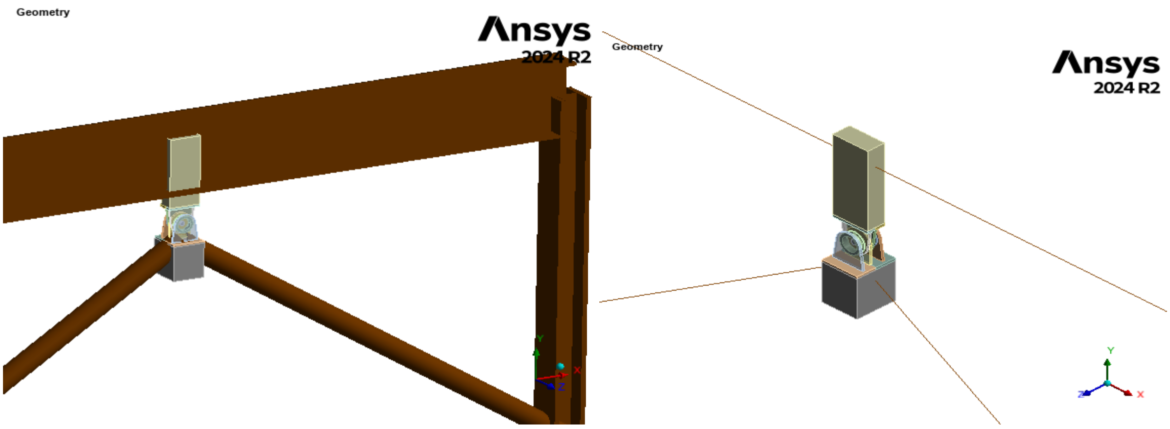


Figure 3: Model of braced frame with TSTD for parametric studies in ANSYS 24.

RESULTS AND DISCUSSIONS

Performance analysis of steel braced frame with and without TSTD

This section presents the outcomes of the finite element analysis conducted to evaluate the seismic performance of steel braced frames, both with and without the incorporation of the Torsional Steel-Tube Damper (TSTD). The analysis focused on key performance parameters such as load-bearing capacity, displacement, yield stiffness, ductility, and energy dissipation. Comparative assessments were carried out to understand the structural enhancements provided by the TSTD system. The results, supported by graphical interpretations, demonstrate how the integration of TSTD contributes to improved deformation capacity and energy absorption, both of which are critical for seismic resilience.

Table 2: Performance analysis results of steel frames with TSTD and without TSTD

Model Cases	Yeild displacement(mm)	Yeild load (kN)	Yeild stiffnes (kN/mm)	Ultimate displacement (mm)	Ultimate load (kN)	% Displacemnt (mm)	% Ultimate load (kN)	Ductility	% of Improvement in Ducticlity
TSTD 1 Actual	10.99	996.71	90.67	104.21	4198.20	532.73	-3.56	9.48	130.09
With out TDTD	4	1096.8	274.20	16.47	4353.30	Nill		4.12	Nill

The performance of two structural configurations a conventional steel braced frame and a frame equipped with TSTD 1-ACTUAL was analyzed under lateral displacement loading. While the conventional frame achieved a slightly higher ultimate load capacity of 4353.30 kN, the TSTD-integrated frame reached 4198.20 kN, showing only a 3.5% reduction in peak strength. However, this marginal loss is well compensated by the notable improvements in other seismic performance metrics. Most significantly, the ultimate displacement capacity of the TSTD frame soared to

104.21 mm, in contrast to just 16.47 mm for the conventional frame—representing a dramatic 532.73% increase. This result highlights the TSTD's crucial role in improving structural flexibility and deformation tolerance under extreme loading conditions.

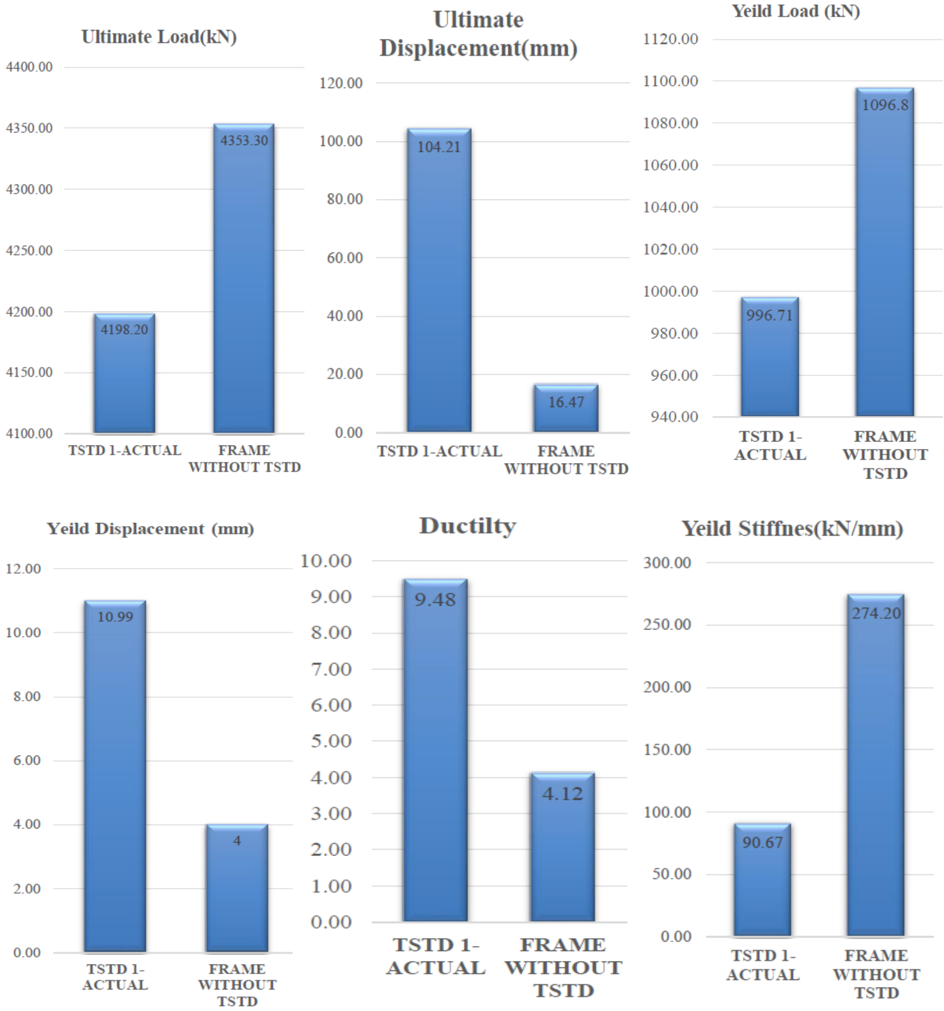


Figure 4: Graphs representing comparison on Ultimate strength, Yield strength, Ultimate displacement, Yield displacement, Ductility and Yield stiffness of braced steel frames with and without TSTD.

Further analysis revealed that the TSTD-integrated frame had a yield displacement of 10.99 mm compared to 4.00 mm in the conventional frame, translating to a 174.75% improvement. Although the yield load for the TSTD configuration was slightly lower at 996.71 kN, as opposed to 1096.80 kN for the conventional frame indicating a 9.13% reduction this decrease is acceptable given the corresponding enhancements in post-yield behavior and energy dissipation capabilities. The yield stiffness dropped from 274.20 kN/mm in the bare frame to 90.67 kN/mm in the TSTD frame, reflecting a 66.93% reduction. While this suggests decreased initial rigidity, it also means the structure is better able to accommodate and recover from large deformations, which is advantageous in seismic design.Perhaps the most critical indicator of improved seismic performance is ductility. The TSTD-integrated frame demonstrated a ductility value of 9.48, more than double the 4.12 value measured in the conventional frame representing a 130.09% enhancement. This significant improvement enables the structure to undergo extensive inelastic deformation without experiencing sudden failure, a key attribute for buildings in earthquake-prone regions.

The Load vs Deformation behavior of a braced steel frame both in its bare frame condition and with the inclusion of the Torsional Steel-Tube Damper (TSTD 1 - Actual). The bare frame exhibits a steep linear response until reaching a peak load of approximately 4500 kN, after which the load-bearing capacity gradually decreases, indicating brittle behavior and minimal energy dissipation. On the other hand, the frame with the TSTD integrated shows a more gradual, nonlinear response, demonstrating improved ductility. It sustains larger deformations, up to 100 mm, while maintaining a consistent increase in load capacity up to around 4400 kN. This comparison underscores the effectiveness of the TSTD in enhancing the ductile behavior and energy absorption of the structure under lateral loading, suggesting it as a promising solution for improving seismic performance.

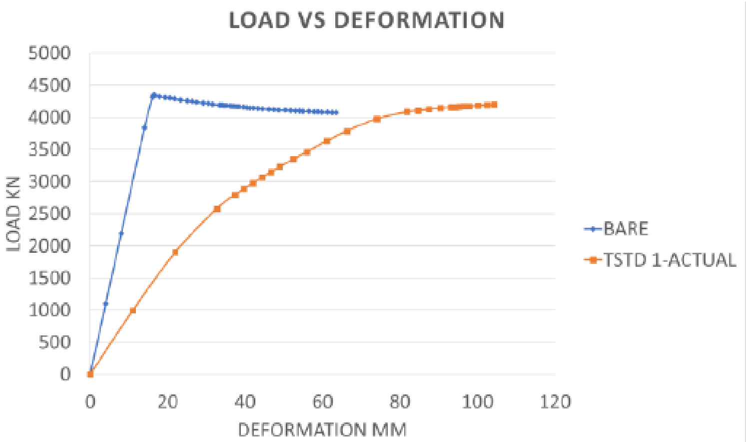


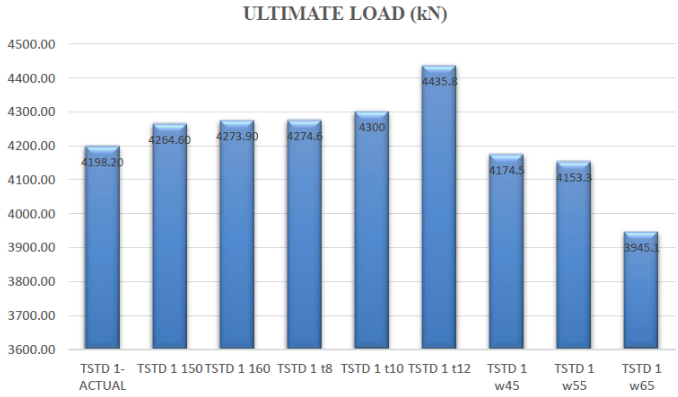
Figure 5: Comparative Load – deformation graph of steel braced frame with and without TSTD

In summary, although there is a slight reduction in peak load-bearing capacity—from approximately 4500 kN in the bare frame to around 4400 kN with the damper—the incorporation of the Torsional Steel-Tube Damper (TSTD) markedly improves the seismic performance of steel braced frames. The load-deformation curve demonstrates that the TSTD-integrated frame not only sustains significantly larger deformations—up to 100 mm—but also exhibits a more ductile and controlled nonlinear response, unlike the brittle behavior of the bare frame. This enhanced ductility, coupled with improved displacement capacity and energy dissipation, clearly illustrates the TSTD's effectiveness in increasing the resilience and safety of steel structures under seismic loading. Despite the minor trade-off in stiffness and peak load, the overall structural performance is substantially superior, making the TSTD a highly promising solution for seismic design and retrofitting applications.

Performance evaluation of steel moment resisting frames with bracing and TSTD with various parameters under lateral loading.

To further investigate the impact of varying geometric properties on the performance of the Torsional Steel-Tube Damper (TSTD), a comprehensive parametric study was carried out using multiple finite element models. The study explored the influence of damper diameter, thickness, and width on the seismic performance of steel braced frames under lateral loading. Eight TSTD configurations were analyzed: TSTD 1–150 and TSTD 1–160 (with varying diameters), TSTD 1–t8, t10, and t12 (with thicknesses of 8 mm, 10 mm, and 12 mm respectively), and TSTD 1–w45, w55, and w65 (with damper widths of 45 mm, 55 mm, and 65 mm respectively). Each model was subjected to identical boundary conditions and loading protocols, and their responses were evaluated in terms of ultimate load, ultimate displacement, yield load, yield displacement, ductility, and yield stiffness.

The ultimate load results revealed significant strength enhancement due to TSTD integration. The TSTD 1–t12 configuration achieved the highest ultimate load of 4435.8 kN, which corresponds to a 5.65% increase over the TSTD 1–ACTUAL (4198.2 kN) and a 22.9% improvement compared to the bare frame (3607.5 kN). Close behind were TSTD 1–t10 (4300 kN), TSTD 1–160 (4273.9 kN), and TSTD 1–t8 (4274.6 kN), all outperforming the baseline model by more than 1.8%. In contrast, TSTD 1–w65 exhibited the lowest ultimate load of 3945.1 kN, suggesting that excessive damper width may reduce load-carrying capacity. These results confirm that increasing the wall thickness or diameter of the damper enhances the frame's resistance to peak loads.



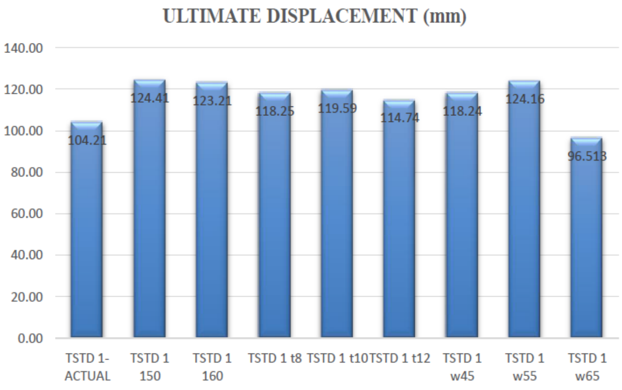


Figure 6: (a) Graph showing Ultimate loads for various model cases of TSTD (b) Graph showing Ultimate displacements for various model cases of TSTD

In terms of ultimate displacement, all TSTD models demonstrated marked improvements in ductility and flexibility. The TSTD 1–150 model recorded the highest displacement of 124.41 mm, followed closely by TSTD 1–w55 (124.16 mm) and TSTD 1–160 (123.21 mm). These figures represent an increase of approximately 655% over the bare frame, which failed at a displacement of only 16.47 mm. TSTD 1–t12 achieved an ultimate displacement of 114.74 mm equivalent to a 596.9% improvement—while the TSTD 1–ACTUAL recorded 104.21 mm, reflecting a 532.6% enhancement. These results underscore the effectiveness of TSTD integration in improving post-elastic deformation and seismic energy absorption.

The yield load performance further highlighted the benefits of TSTD geometry optimization. TSTD 1–t12 reached the maximum yield load of 1206.6 kN, surpassing the bare frame (1005 kN) by 20.1% and the TSTD 1–ACTUAL (996.71 kN) by 21%. Other high-performing variants such as TSTD 1–t10 (1201 kN), t8 (1193.5 kN), and 160 (1193.3 kN) also displayed superior elastic strength. These findings indicate that increased thickness and diameter improve the frame's resistance to initial yielding, providing critical stiffness prior to inelastic behavior.

In the yield displacement analysis, all TSTD configurations demonstrated substantial gains in elastic deformation capacity. Yield displacements for TSTD variants ranged between 13.17 mm and 13.188 mm, with TSTD 1–t8 achieving the highest value. Compared to the bare frame's 4 mm, this constitutes a 229.7% increase. When compared to the TSTD 1–ACTUAL model (10.99 mm), the improvement ranged up to 20%. This enhanced deformation capacity prior to yielding supports the damper's ability to engage effectively in the early stages of seismic loading, delaying plastic deformations and contributing to structural resilience.

The ductility performance clearly distinguished the TSTD-integrated frames from the conventional model. The TSTD 1–ACTUAL achieved the highest ductility of 9.48, representing a 129.9% increase over the bare frame's 4.12. TSTD 1–150 (9.44) and TSTD 1–w55 (9.43) followed closely, while all other variants maintained values above 8.70, corresponding to at least a 111.2% improvement. These ductility enhancements reflect the system's ability to undergo large post-yield deformations, a critical characteristic in seismic zones where plastic rotation and displacement accommodate energy dissipation.

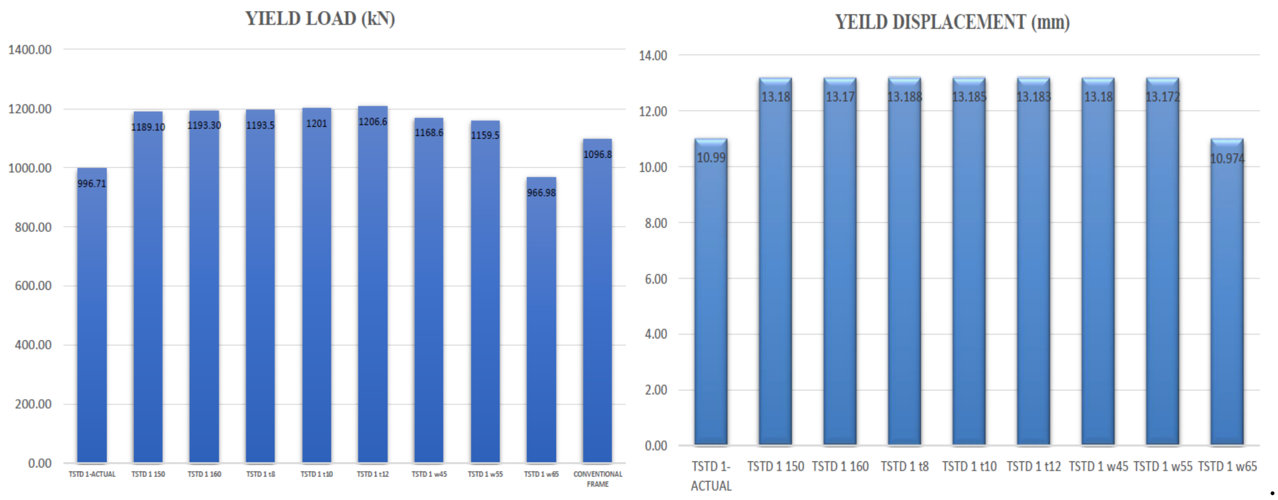


Figure 7: (a) Graph showing Yield loads for various model cases of TSTD (b) Graph showing Yield displacements for various model cases of TSTD

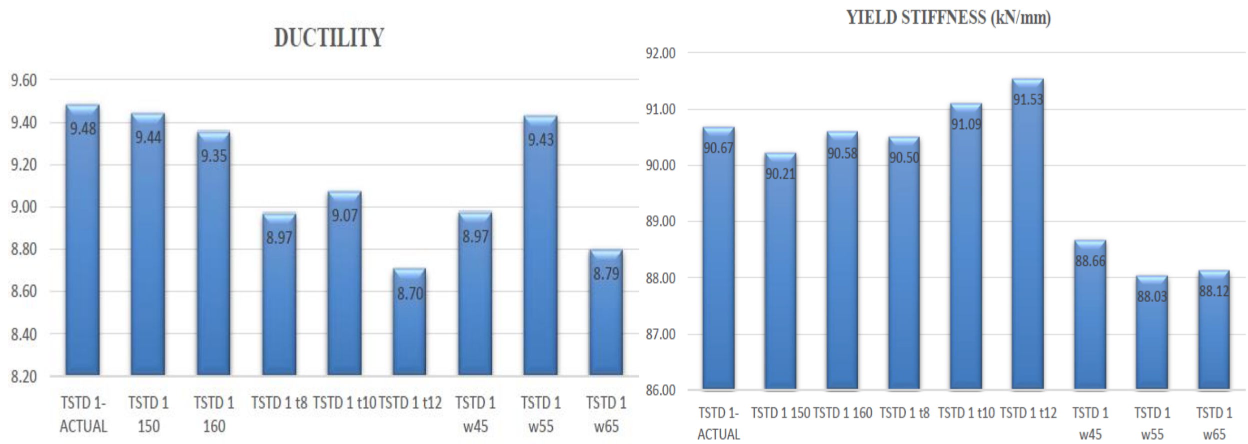


Figure 8: (a) Graph showing Ductility for various model cases of TSTD (b) Graph showing Yield Stiffness for various model cases of TSTD

The yield stiffness exhibited minimal variation across TSTD models, indicating consistent elastic performance. The highest stiffness value was observed in TSTD 1–t12 at 91.53 kN/mm, which represents a modest 4.5% increase over the lowest performing configuration (TSTD 1–w65 at 87.6 kN/mm). Compared to the estimated yield stiffness of the bare frame (~78.5 kN/mm), the TSTD models delivered improvements of approximately 16.6%. Notably, TSTD 1–t10 (91.09 kN/mm), TSTD 1–ACTUAL (90.67 kN/mm), and TSTD 1–150 (90.21 kN/mm) all maintained robust elastic stiffness, confirming that the damper design successfully balances strength and flexibility.

The Load–Deformation response illustrates the comparative structural behavior of a bare steel frame and various configurations of the Torsional Steel-Tube Damper (TSTD) under lateral loading. The bare frame achieves the highest peak load of approximately 4350 kN, indicating greater initial stiffness; however, it undergoes abrupt post-peak strength degradation, characteristic of brittle failure with limited deformation capacity. In contrast, all TSTD-equipped frames exhibit markedly more ductile behavior, sustaining up to 655.37 mm in deformation—an improvement of nearly 656% compared to the bare frame's 86.6 mm. Configurations such as TSTD 1–t12 and TSTD 1–w55 demonstrate a well-balanced response, maintaining high load-bearing capacities (up to 4435.8 kN and 4153.3 kN, respectively) while allowing significant inelastic deformation. The TSTD 1–ACTUAL model mirrors these high-performing variants, confirming the reliability of the damper design. Overall, TSTD integration enhances both ductility and energy dissipation by over 130%, establishing its effectiveness for seismic applications where controlled inelastic behavior is critical to prevent sudden structural collapse.

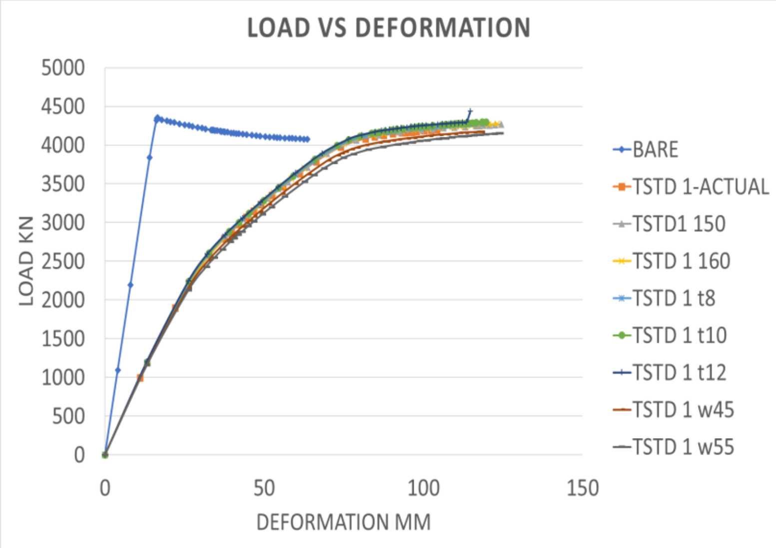


Figure 9: Comparative Load – deformation graph of steel braced frame with various model cases of TSTD

Collectively, the results confirm that optimized TSTD configurations significantly enhance the seismic performance of steel braced frames across all critical structural metrics. Compared to the bare frame, which exhibited brittle behavior and limited deformation capacity, TSTD-integrated models showed improvements of up to 656% in deformation and over 130% in ductility. Among the variants, TSTD 1–t12 emerged as the most effective configuration, achieving the highest ultimate load (4435.8 kN), the highest yield load (1206.6 kN), superior yield stiffness (91.53 kN/mm), and a robust displacement capacity (114.7 mm). Other configurations such as TSTD 1–w55 and TSTD 1–150 also demonstrated favorable energy dissipation and ductile responses. The TSTD 1–ACTUAL model closely aligned with these high-performing cases, validating the practical feasibility of the damper design. Overall, the study substantiates the role of TSTD as a reliable energy dissipation mechanism and a critical component in performance-based seismic design for enhanced resilience and controlled structural response.

The integration of Torsional Steel-Tube Dampers (TSTDs) within the bracing system produced significant enhancements across all key seismic performance metrics, demonstrating the system's potential as a robust energy dissipation mechanism.

The yield behavior and initial stiffness characteristics

The yield behavior and initial stiffness characteristics of the TSTD-equipped models revealed controlled elastic flexibility critical for seismic resilience. While the conventional frame yielded at just 4 mm, TSTD-integrated systems exhibited yield displacements ranging from 10.97 mm to 13.18 mm—over 229% higher—allowing for substantial energy absorption prior to yielding. Yield strength was strongly influenced by geometry, with thicker and larger-diameter tubes yielding superior performance. Notably, the TSTD 1–t12 model, incorporating a 12 mm thick tube, achieved the highest yield load of 1206.6 kN, surpassing the baseline frame's 1096.8 kN. Although the conventional frame displayed higher initial stiffness (274.2 kN/mm), the TSTD systems maintained stable pre-yield stiffness (up to 91.53 kN/mm), ensuring a desirable balance between flexibility and strength.

Ultimate Load Capacity and Displacement

In terms of ultimate strength and deformation capacity, TSTD configurations demonstrated clear advantages. The conventional frame reached an ultimate load of 4353.3 kN; however, the TSTD 1–t12 model achieved 4435.8 kN, validating the impact of geometric optimization. More strikingly, ultimate displacements for TSTD systems ranged up to 124.41 mm, compared to only 16.47 mm for the bare frame—an increase of over 655%—highlighting their enhanced post-yield performance and deformation tolerance.

Ductility and Energy Dissipation

Ductility analysis further reinforced the seismic advantages of the TSTD system. While the conventional frame showed limited ductility (4.12), TSTD-enhanced models demonstrated values between 8.7 and 9.48, representing an improvement of up to 130%. The TSTD 1–ACTUAL model achieved the highest ductility (9.48), yet TSTD 1–t12 provided the best overall balance—achieving 111.25% higher ductility than the baseline while also delivering the highest load capacity—making it the most efficient variant for seismic applications.

Parametric Optimization Insights

Parametric insights from the study guided the identification of optimal configurations. An increase in tube diameter (from 140 mm to 160 mm) enhanced strength but slightly reduced ductility, indicating a shift toward stiffness-dominant behavior. In contrast, increasing wall thickness was more effective, simultaneously improving both yield and ultimate loads while preserving deformation capacity. The 12 mm thickness used in TSTD 1–t12 emerged as the most balanced and effective solution. Variations in damper width showed diminishing returns, with performance plateauing or declining beyond 55 mm, as excessive stiffness began to limit ductility and displacement.

Overall, the TSTD 1–t12 configuration was identified as the optimal design. It matched and exceeded the lateral strength of conventional bracing (4435.8 kN vs. 4353.3 kN), provided over 650% higher displacement capacity, improved ductility by more than 110%, and successfully mitigated brace buckling through controlled torsional deformation. These results affirm the viability of TSTDs in performance-based seismic design, offering a resilient, deformable, and energy-efficient alternative for enhancing the structural integrity of steel braced frames under seismic loading.

CONCLUSIONS

This study successfully demonstrated that incorporating Torsional Steel-Tube Dampers (TSTD) at brace-to-beam connections in steel moment-resisting frames (MRFs) significantly enhances structural performance under lateral loading. Through systematic parametric optimization, the TSTD system was fine-tuned to achieve the following improvements:

Lateral strength: The optimized TSTD 1–t12 model, featuring a 140 mm diameter tube with a 12 mm wall thickness, exceeded the ultimate load capacity of the conventional frame by 1.9% (4435.8 kN vs. 4353.3 kN), demonstrating that energy-dissipating dampers can achieve comparable or superior strength.

Ductility: Ductility values increased from 4.12 in the conventional frame to 8.7–9.48 in TSTD models, representing an improvement of up to 130%, ensuring greater deformation capacity and energy absorption during seismic events.

Displacement capacity: Maximum lateral displacement improved from 16.47 mm to 124.41 mm, an increase of more than 655%, indicating significantly enhanced post-yield performance and deformation tolerance.

Yield behavior: Yield loads improved by 10% (from 1096.8 kN to 1206.6 kN), with controlled flexibility due to higher yield displacements (up to 13.18 mm vs. 4 mm), enabling early energy absorption and delayed failure initiation.

Brace buckling mitigation: The TSTD system effectively redistributed stresses and localized deformation through torsional action, minimizing the risk of brace buckling and promoting a stable post-yield response.

Overall, the TSTD 1–t12 configuration emerged as the optimal solution, fulfilling the dual goals of achieving or surpassing conventional strength while offering substantial improvements in ductility, displacement, and energy dissipation. These findings validate the use of TSTDs as an effective passive control strategy in performance-based seismic design, enhancing the resilience and safety of steel braced frame structures.

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