Numerical Study on Effectiveness of Torsional Steel Tube Damper

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***Abstract*—The safety of the structure under earthquake excitation is a great matter of concern nowadays. In the design of modern buildings seismic loading effects are an important part of the structural design. Seismic energy dissipation systems help to protect the critical components in the building system by dissipating energy through their own mechanisms. Framed systems are widely used to enhance the performance and stability of structural systems under earthquakes due to their economy and easiness of fabrication. The introduction of dampers along with the bracing system improves energy dissipation capacity. Steel dampers are metallic dampers with energy dissipation through the yielding of steel components. The study deals with the effectiveness of a torsional steel tube damper (TSTD) under cyclic loading conditions. The damper behaviour is influenced by the properties of the steel tube present in the TSTD.**

The present study is based on a numerical investigation of the damper under cyclic loading using a finite element model developed in Ansys Workbench 2022 R2. The study investigates the effect of effective length-to-thickness ratios on the energy dissipation properties of the damper. The influence of the grade of steel utilized for the steel tube was also studied. The hysteresis curves, maximum moment, and energy dissipation of the damper were analyzed to assess the performance of the damper. It was observed that the damper always shows stable hysteresis behaviour under various parameters.

Keywords—metallic damper; finite element analysis; torsional steel tube damper; steel tube; cyclic loading; energy dissipation

I. INTRODUCTION

Nowadays, an earthquake's potential impact on building safety has long been a concern. There are more and more dampers and energy-dissipating parts being produced today for mechanical dampening. Dampers are energy-dissipating devices used in buildings to protect them from earthquake excitation effects. The damper is a mechanical system that dissipates the earthquake energy and yields during an earthquake. They absorb the energy lost during an earthquake, reducing the amount of force that the structure must withstand. A metallic damper with a torsional yielding mechanism is known as a torsional steel tube damper (TSTD). It mainly consists of steel tubes and plates in which energy dissipates through the plastic deformation of steel tube material. When external force acted upon the damper the steel tube was subjected to pure torsion and energy dissipation occurs. The study conducted by Lie et al. describes the configuration and operation of the suggested damper, and four TSTD specimens are put through a cyclic loading test to look at their hysteretic behaviour [1]. Mao et al. studied the performance of displacement amplified torsional damper (DATD) under seismic excitation. To compare the impact of DATD on damping and energy dissipation, FE software is used to analyse the dynamic time histories of frame structures with and without DATD [2]. Luo et al. found that lead-filled steel tube dampers (LFSTDs) typically underwent one of two failure modes: shear, bending, or a combination of the two [3]. Guo et al. conducted a study on the seismic behaviour of shear-bending yielding coupling (SBYC) dampers using cyclic tests. The results of the research revealed that the shear plate had a high buckling mode and that the tensile strips of the two adjacent bending plates were gradually distributed throughout them [4]. Zhou et al. proposed a laminated Visco-elastomer-filled steel tube damper (LVSTD), which has a novel hybrid damping capability while also overcoming the steel tube's buckling characteristic and investigating the mechanical behaviour, low-cycle fatigue behaviour, and failure mode of LVST damper. During the cyclic loading, the specimen shows a stable hysteresis response and maximum forces [5]. Quan et al. found out that the metallic corrugated shear panel dampers had excellent plastic deformation and substantial hysteretic loops (CSPDs). The direction of the corrugated shear panels had the most effect on how well they dispersed energy, and the outcomes demonstrated that the horizontal corrugated direction performed best [6]. In this study, variations of strength and energy dissipation of TSTD under various parameters were examined. The effect of steel tube materials, the effect of gap distance and the effect of the effective length of steel tube in the torsional steel tube damper were studied.

II. NUMERICAL MODELLING

The Finite Element (FE) modelling was done in Ansys Workbench 2022 R2. The model was developed based on the experimental data of the work done by Lie et al. [1]. The validation of the model was done with the experimental results obtained by Lie et al.

A. Geometrical Modelling

Table I represents the dimensions of the steel tube present in TSTD. Fig. 1 represents the geometry of the steel tube and the notations such as “D”, “L”, and “T” denote the outer diameter, effective length and thickness of the steel tube respectively. The dimensions of the outer plate, inner plate, middle plate and pin dimensions were taken from previous studies [1]. A chamfer of a 2 mm radius was provided at each corner of the steel tube.

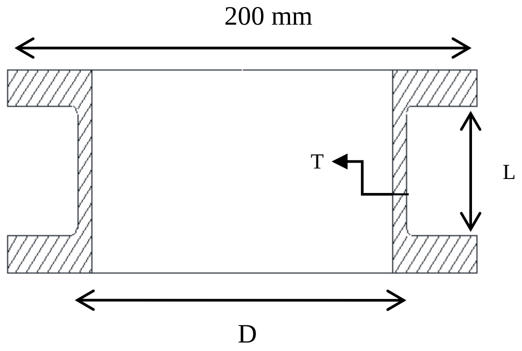


Fig. 1. Geometry of steel tube used for the parametric study

TABLE I. DIMENSIONS OF THE MODEL USED FOR VALIDATION

Specimen	T (mm)	L (mm)	D (mm)
TSTD1	6	35	140
TSTD3	6	35	100

B. Material Modelling

The structural steel of Q345 and mild steel of #20 were used to model the steel plates and steel tube in the TSTD. Table II represents the uniaxial tensile strength test results by Lie et al. [8].

TABLE II. MATERIAL PROPERTIES

Material	Young's Modulus (MPa)	Yield Stress (MPa)	Ultimate Stress (MPa)
#20	203200	283	468
Q345	203600	405	570

C. Finite Element Modelling

The finite element model was developed from the experimental setup [1] conducted by Lie et al. on TSTD1. Fig. 2 shows the finite element model of the TSTD1 developed in Ansys Workbench 2022 R2 along with the boundary conditions. The Multilinear Kinematic Hardening parameter was used in Ansys for material calibration. Quadrilateral SOLID186 elements were utilized for the damper plates instead of linear elements to avoid the effect of shear locking, the default setting in Ansys software. For the components remaining, SOLID187 elements were provided to reduce computational complexity. It was found that the results converge at mesh sizes of 8 mm for the steel tubes and 20 mm for other components. Further reduction in mesh sizes increases the computational time, but there was no appreciable increase in accuracy.

The half model was created during the geometric modelling stage due to its symmetry in this model and its boundary conditions. The symmetric region property in the Ansys Mechanical software is implemented to generate the full model. The bottom end plate has all the degrees of freedom arrested and assigned as fixed support. A loading beam was provided at the top plate to transfer the cyclic displacement. Cyclic displacement loading is assigned on the face of the loading beam along the X-direction. The displacement-controlled loading protocol defined in terms of the drift ratio was provided. Quasi-static cyclic loading was adopted based on the SAC1997 loading protocol. The loading protocol consists of 48 steps, each containing two cycles of the corresponding amplitude. The rotation angle is the ratio between the rotation angle and the length of the loading beam, indicating the rotation of the tube. Bonded contact was provided in Ansys Mechanical to simulate the welded connection between the damper plates and the common connecting plate. A frictionless connection was made between the inner plate, the pin, and the middle plate. Fig. 3 shows the finite element meshed model of TSTD1 used for the validation.

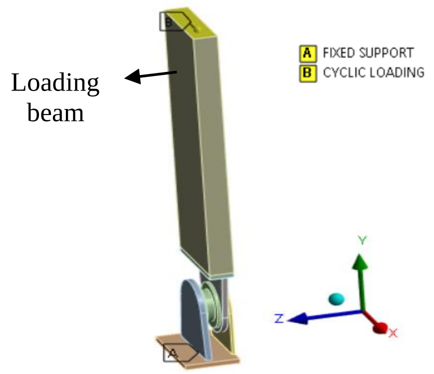


Fig. 2. FE model of TSTD1 with boundary conditions

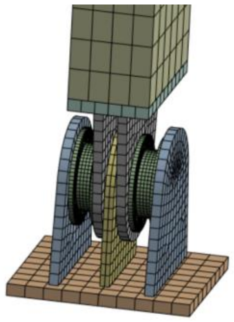


Fig. 3. FE meshed model

D. Validation

The finite element model is validated using the results from the experimental study by Lie et al. [1]. Fig. 1 and Table I show the geometric details of the model used for validation. The comparison of experimental and numerical results of TSTD1 and TSTD3 shows a deviation of 1.13% and 4.90% respectively. Fig. 4 and Fig. 5 represent the hysteresis curves of TSTD1 and TSTD3 respectively. The failure was observed at the yielding section of steel tube present in the torsional steel tube damper. The plastic strain was concentrated at the edge of the steel tube. Fig. 6 shows the failure mode of TSTD1 under cyclic loading conditions.

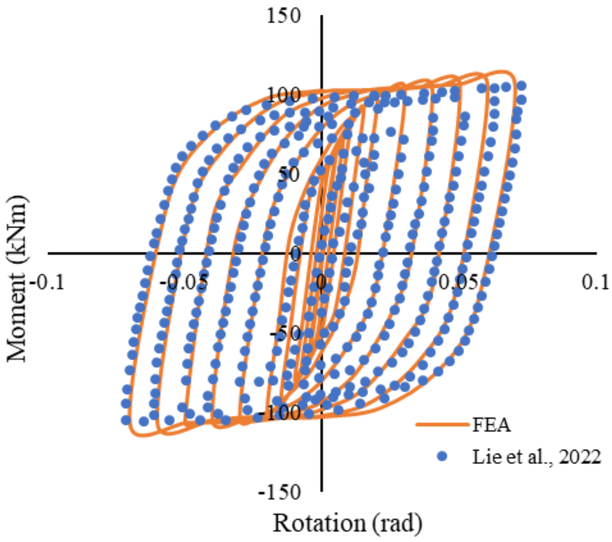


Fig. 4. Comparison of FE and experimental hysteresis curves of TSTD1

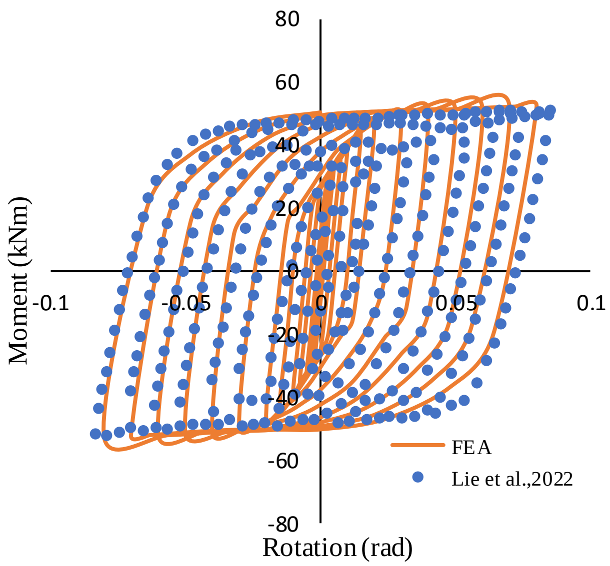
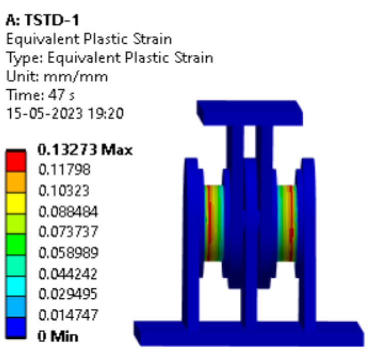
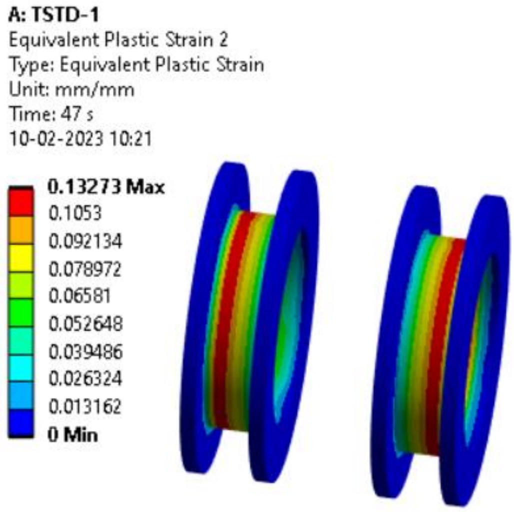


Fig. 5. Comparison of FE and experimental hysteresis curves of TSTD3



(a)



(b)

Fig. 6. Failure mode of TSTD1

III. PARAMETRIC STUDY

The validated model was utilized for extensive parametric study. Various dimensions and ratios of steel tubes present in the TSTD were studied to find the cyclic response. The parameters such as effective length-thickness ratios, the effect of steel tube material and the gap distance between the middle plate and inner plate were studied.

A. *Effect of Effective Length to Thickness Ratio (L/T)*

Models with varying steel tube thicknesses were modelled keeping the other dimensions such as effective length (L) and diameter of steel tube (D) constant. The effective length was 35 mm, and the diameter was 100 mm. The thickness of the steel tube was taken in the range of 2 mm to 10 mm. Fig. 7 represents the skeleton curves of the hysteretic response OF TSTD. It was observed that with an increase in the thickness of the steel tube, the maximum moment and cumulative energy dissipated was increased. When the L/T ratio reaches a value of 3.5, the TSTD showed the maximum strength. As the L/T ratio varies from 17.5 to 3.5, the strength increased by 278.18%. On comparing with the strength of TSTD3, the L/T ratio reaches a value of 3.5 an increase of 49.22 % strength than that of TSTD3. It was observed that the increase in the L/T ratio decreases the energy dissipation of TSTD, which means the energy dissipation was inversely proportional to the L/T ratios. Maximum energy dissipation occurs at smaller L/T ratios. Compared with the TSTD3, the steel tube with 10 mm thickness exhibits a 42.28% improvement in energy dissipation.

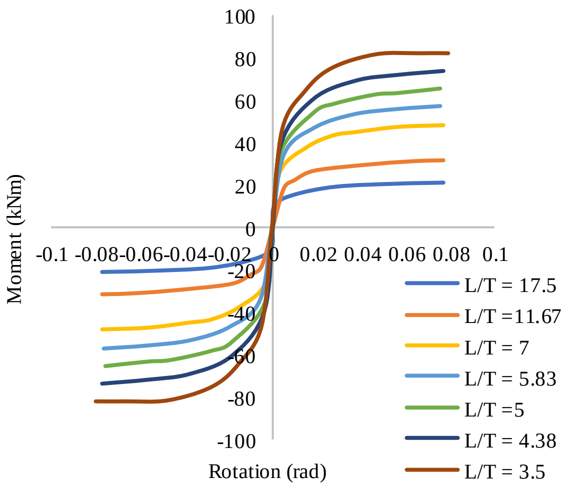


Fig. 7. Skeleton Curves – Effect of L/T Ratio

B. *Effect of Steel Tube Material*

The steel tube of different material grades was taken to study the influence of the strength and energy dissipation of the damper. Other dimensions were kept the same as that of TSTD1. The Chaboche kinematic hardening was adopted for the Q235 steel tube and multilinear kinematic hardening was adopted for other steel grades. Fig. 8 represents the skeleton curves of the hysteretic response of TSTD. All materials showed stable hysteresis behaviour. Low-yield steel failed earlier than high-yield steel, which caused a decrease in the cumulative energy of the damper. The steel tube of Q235 shows the maximum moment and #20 shows the maximum energy dissipation. It was observed that steel with low yield stress failed earlier than steel with larger yield stress and this will lead to a decrease in the dissipation of energy. The decreased cumulative energy dissipation trade-off for increased ductility for the damper. Compared with Q345 steel, Q235 steel exhibits a maximum strength of 127 kNm. Varying the steel tube material enhances the rotational stiffness of the damper.

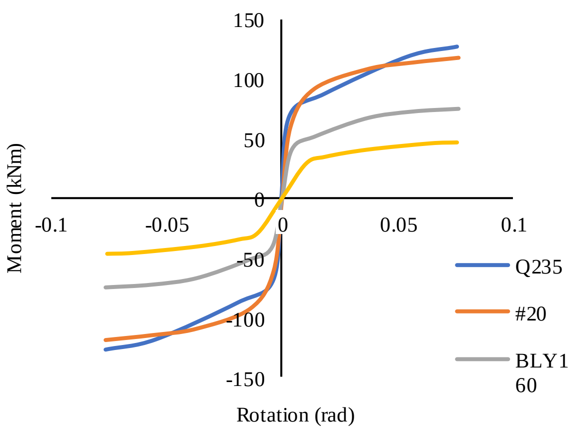


Fig. 8. Skeleton Curves – Effect of steel tube material

C. *Effect of Gap Between Middle Plate and Inner Plate*

TSTD1 was the validated model used for this study. In that model, a 5 mm gap was used to provide separation between the inner plate and middle plate to ensure their rotation during the cyclic loading. This study considers a gap of 5 mm to 20 mm to identify its effect on the maximum strength and energy dissipation of TSTD. Models with varying gap distances were modelled keeping the other dimensions such as effective length (L), diameter (D), and thickness of steel tube (T) constant. The effective length was 35 mm, the diameter was 140 mm, and the thickness was 6 mm. Fig. 9 represents the schematic diagram of TSTD.

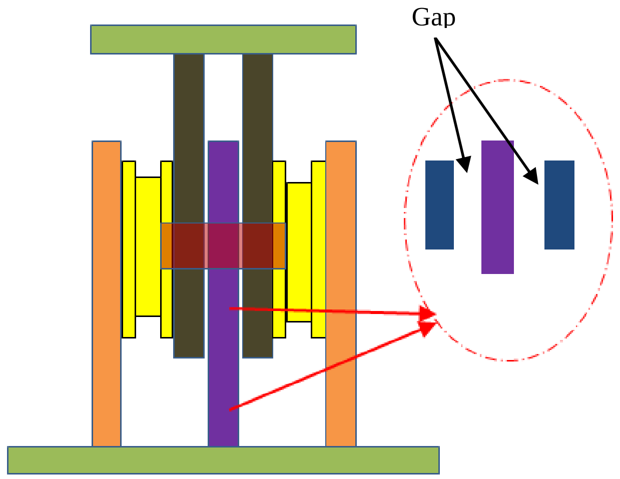


Fig. 9. Schematic of TSTD

The skeleton curves of the hysteretic response are depicted in Fig. 10. It was observed that an increase in the gap distance from 6 mm to 10 mm between the inner plate and middle plate increases the strength of TSTD about 57.2% more than that of the model with a 6 mm gap distance. A gap distance of 10 mm shows a maximum strength than that of TSTD1 with a 5 mm gap distance. When the gap distance varied between 15 mm to 20 mm, there were no significant changes in the ultimate strength of the damper. The damper with a 10 mm gap showed maximum energy dissipation than that of higher distances.

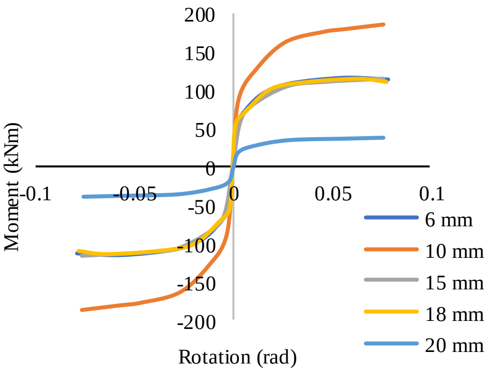


Fig. 10. Skeleton curves– Effect of gap distance

IV. CONCLUSION

The numerical model of the torsional steel tube damper was modelled in the FE software Ansys Workbench 2022 R2. The conclusions obtained from the parametric study are:

- Concentration of equivalent plastic strain at the end of the tube shows the failure mode of TSTD.
- Uniform yielding in the tube wall exhibits better energy dissipation to the damper.
- Thickness of the steel tube significantly improves the rotational strength.
- Increase in thickness improves the rotational strength up to 82 kN from 21.82 kN (278.18 % increase).
- Low-yield steel fails earlier, which leads to decreased cumulative energy dissipation.
- #20 steel shows higher energy dissipation than Q235. Compared with BLY160 steel, #20 dissipates 74% more energy.
- 10 mm gap distance shows maximum rotational strength and energy dissipation.
- An increase in the gap distance from 6 mm to 10 mm between the inner plate and middle plate increases the strength of TSTD about 57.2% more than that of the model with a 6 mm gap distance.

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