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Experimental evaluation of metallic hybrid damper device using comb teeth damper and friction damper

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ABSTRACT

Passive energy dissipation devices are systems installed in structures to reduce vibrations and dissipate the seismic energy during earthquake events. Generally, the passive dampers such as fluid viscous damper, viscoelastic damper, metallic damper and friction damper are being used in Reinforced Concrete (RC) and steel buildings worldwide. Hybrid passive damper is the combination of two dampers made into a single device, which performs better in all seismic zones. This study presents the development of a novel hybrid passive damper (CTFD) composed of a comb teeth damper (CTD) and a friction damper (FD). Monotonic lateral load test was conducted on CTD, FD and CTFD to determine the lateral load carrying capacity, ductility ratio, initial stiffness and energy dissipation capacity. The amount of energy dissipated by hybrid damper is 52.9% more than CTD and 79.3% more than FD.

Keywords: comb teeth damper, friction damper, hybrid passive damper, drift, energy dissipation.

INTRODUCTION

India's one of the devasting earthquakes known as Bhuj earthquake occurred on January 26.2001 with a magnitude of 7.7 on Richter scale caused nearly 20.000 deaths, 400.000 building collapsed and with a huge economic loss of $10 billion [1–2]. Rapid industrialization, population growth and urbanization has increased demand in housing sector to build more structures. According to Bureau of Indian standards IS 1893:2016 [3] more than 60% land mass in India are vulnerable to earthquakes. Adopting earthquake resistant design and supplementing building with energy dissipation devices are some of the effective solutions preventing buildings from collapse.

In order to control the structural vibrations in buildings caused by earthquake various methods and techniques have been proposed and adopted. Among them passive control system is the most popular and widely used. The passive control system can be further classified into energy dissipation devices, base isolation and energy transfer. Passive energy dissipation devices can be classified into viscoelastic devices, hysteretic devices and re-centering devices. The viscoelastic devices consist of viscoelastic solid damper and viscoelastic fluid damper. The examples of hysteretic devices are metallic yielding damper (MYD) and FD. The Re-centering devices are pressurized fluid damper, preloaded spring friction damper and phase transformation damper. Shape memory alloy materials and magnetorheological dampers are introduced in vibration control in buildings and pipes [33, 36].Tuned mass damper are also used in steel frame buildings [32]. In recent years, metallic and friction damper are extensively studied for their great performance in seismic areas [34, 35]. Skinner et al. [4] pioneered the use of metallic dampers in structures through his foundational theoretical studies and experimental research. [5–7] Various researchers have developed metallic damper based on materials and geometry with different shapes like U shape, X shape, J shape, triangular shape and T-shaped. Metallic damper dissipates the seismic energy by yielding of metal plates in any one of the ways, namely, axial, flexural, shear or torsional by Arvind et al. [8]. The primary feature of metallic dampers is their ability to add damping and stiffness to a structure and without relying on any electricity supply. They have stable hysteretic behaviour, easy to fabricate, inexpensive and easy to repair.

Pall and Marsh [9] introduced friction damper by implementing the concept automotive braking system in building. Friction damper dissipates the seismic energy through sliding of plates and yielding of bolts. Various researchers have worked and improved friction damper [10, 11] based on bolt connection [12–14] and based on materials [15–17]. These dampers are effective when dealing with a single type of seismic excitation. FD work well either for earthquakes of low peak ground acceleration (PGA) or high PGA, but not both simultaneously. Recently, a few researchers have explored by combining two devices into single device to protect the structures under various PGAs and to increase seismic performance of the building.

Kim and Shin [18] combined steel slit damper a type of metallic yielding damper with friction damper to retrofit a structure. The slit-friction hybrid damper outperformed traditional slit and friction dampers nearly by 47% of equivalent yield strength. Seven artificial earthquakes were used for fragility analysis. The best retrofit combination is increasing the column size with hybrid damper served the purpose.

Ranaei and Akbar [19] used flexural yielding strips with viscoelastic damper. The natural rubber with flexural yielding strips can withstand more cycles with 75 mm displacement than butyl rubber with strip damper with 55 mm shear displacement. Chang-Hwan Lee et al. [20] has integrated non uniform strips with friction damper strategically placed in wall. The hourglass-shaped strip damper (HSD) and a dumbbell-shaped strip damper (DSD) were the types of MYD used in the study. The DSD has 18.18% increase in energy dissipation than HSD. Joohno Lee et al. [21] developed a hybrid damper with slit damper and rotational friction damper for steel structures. The result showed that 6% to 42% reduction in design level acceleration. Dheeraj et al. [22] incorporated X shaped plates (MYD) with Friction damper. The hybrid damper performed better in reduction of inter-storey drift, base shear and roof displacement by nearly 50–60%. Yan et al. [23] studied experimental behaviour of lead extrusion with composite friction damper. The experimental results concurred with numerical results of 60 kN load and 30 mm displacement. NourEldin et al. [24] introduced shape memory alloys (SMA) with silt damper (MYD). The nonlinear dynamic analysis showed that the reduction in top displacement and drift by 48% and 68%, respectively. Shams and Ghobadi [25] introduced self-centring system with SMA and pall friction damper adding post tensioned bolts. Average of 35% reduction in inter storey drift from 3 storey to 12 storey. Avestaeifar and Khezrzadeh, [26] fused variable width steel strip with friction pads in friction damper. The effective viscous damping was found to be 35% to 40% for all specimens. The PHFMD-C outperformed with energy dissipation by 365 kJ with cumulative displacement of 3923 mm.

From the detailed literature study on hybrid dampers by Arvind and Santhi [27], it has been found that the hybrid damper performs better than individual damper in both low and high intensity earthquakes. It also showed only a few types of dampers were combined and designed for steel structures; a very limited work was carried out for concrete structures. The scope of this paper is to develop a new hybrid passive damper suitable for Indian scenarios implementing for RC structures, capable to withstand low, medium and high PGA.

The current study focuses on the development of a novel hybrid passive energy dissipation device intended to augment the seismic performance of RC structures when subjected to earthquakes of varying peak ground accelerations. This CTFD consists of a CTD and a FD. The system exhibits a two-stage response; at low PGA seismic events, energy dissipation is achieved solely through the comb teeth damper by yielding mechanism, while during high PGA earthquakes, both the friction damper and comb teeth damper engage concurrently to dissipate the input seismic energy. Monotonic lateral load tests have been conducted on specimens of comb teeth damper, friction damper and CTFD to evaluate the ultimate load bearing capacity and displacement.

MATERIAL AND METHODS

In India, mild steel is one of the commonly used structural material for construction purposes. Structural steel (E250) is widely favoured for its cost-effectiveness, availability, and ease of fabrication across various locations. In this investigation, three types of dampers, namely, comb teeth damper, friction damper and the hybrid damper consisting of the combination of comb teeth damper and friction damper were fabricated using mild steel material. These specimens were made from 16 mm thick structural steel plates using a laser cutting machine, which minimized the residual stresses. The chemical composition of mild steel material was conducted as per JIS G 1253:2002 and the observed values are shown in Table 1. The values satisfy the requirement of standard code IS 2062-2011 grade E250A.

The mechanical properties of the mild steel were determined through tensile testing of mild steel coupons, following IS:1608-1:2019 standards. Figure 1 shows the details of the specimen before and after the tensile loading.

Figure 2 shows the stress-strain curve of the specimen, and it was observed that the yield strength was 300 MPa and the ultimate strength was 415 MPa. The elongation of the specimen after fracture was 21%, and the yield ratio was 0.72.

Table 1. Chemical composition of mild steel E250A

Elements	Observed values in %
Carbon (C)	0.136
Silicon (Si)	0.001
Manganese (Mn)	0.512
Phosphorus(P)	0.012
Sulphur(S)	0.012
Carbon equivalent (CE)	0.227

Fabrication of comb teeth damper (CTD)

Garivani et al. [28] pioneered the development of the CTD for steel buildings. The geometric design of CTD is similar to slit damper. The

(a) Before Test

(b) After Test

Figure 1. Tensile test specimens

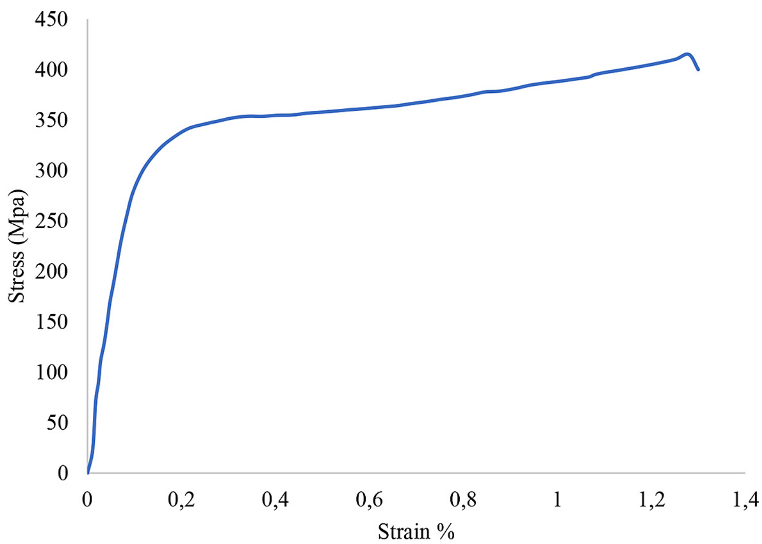


Figure 2. Stress strain curve of the material used

CTD contains several parallel steel links or teeth that absorb seismic energy through flexural yielding in a single plane as shown in Figure 3a. The links are designed in such a way that stresses are evenly distributed along the teeth.

The shape of teeth $b(x)$, stiffness of single teeth, K_l^e, yield strength, f_{yCTD} and yield displacement, δ_{yCTD} can be calculated using equations given below.

$$b(x) = 2\,\lambda\sqrt{x} \tag{1}$$

$$K_l^e = \frac{E\,t\,\lambda^3}{h^{\frac{3}{2}}} \tag{2}$$

$$f_{y\,CTD} = \frac{2}{3}\,t\,\lambda^2\,\sigma_y \tag{3}$$

$$\delta_{y\,CTD} = \frac{2\sigma_y\,h^{\frac{3}{2}}}{3\,E\,\lambda} \tag{4}$$

where: E, t, h, x, σ_y, λ, are elastic modulus, thickness of the plate, height of teeth, distance from loading point, material yield stress and geometrical function constant, respectively as shown in Figure 3(b). In order to overcome the buckling failure of CTD a clamp was provided to restraint the effect.

A parametric study was performed by Arvind et al. [8] on CTD with 4 nos. and 5 nos. of teeth for various thicknesses, namely, 5 mm, 10 mm, 15 mm, 20 mm, 25 mm and 30 mm. Among these models, 5 CTD with 15 mm thickness of steel plate showed higher load capacity, initial stiffness and energy dissipation capacity. Based upon the knowledge gained from the parametric study, the present study involved the 5 CTD with 16 mm thickness of mild steel plate. The overall height and width of CTD are 300 mm and 550 mm, respectively. The width of teeth is 54 mm, and the height of link is 255 mm. The fillet radius is 10 mm, λ value is 1.75 $mm^{0.5}$ and, the clamp height is 50 mm. High strength bolt and nut of M16 grade was used for clamp and fastening the specimen as shown in Figure 4. Two clamps were placed on both the sides of the specimen in the mid-height to prevent the out of plane buckling of the specimen. Figure 4 clearly shows the parts and assembly of CTD.

Fabrication of friction damper (FD)

Many researchers have studied the seismic energy dissipation through friction between the plates by using different materials such as brake pads, brass plate, steel plate, aluminium alloy and stainless steel [29-31]. Among them, mild steel plate was considered for good abrasion resistance, cost effective and easily available in all regions.

Friction damper consists of three mild steel plates fastened by high strength bolt and nut. The height and width of the front and back plates is 300 mm and 550 mm, respectively. The dimension of the inner plates is 550 × 40 mm which are placed at the top and bottom of the assembly. All the plates have a thickness of 16 mm, with the inner plate serving as a friction interface between the front and back plate. The parts of friction damper and its assembly is shown in Figure 5.

Fabrication of hybrid damper (CTFD)

The hybrid damper considered in this study is the combination of comb teeth damper and

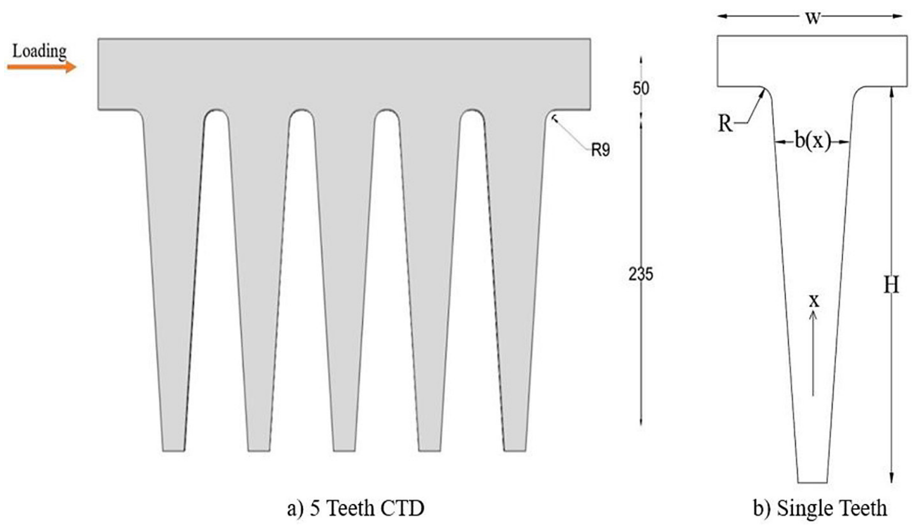
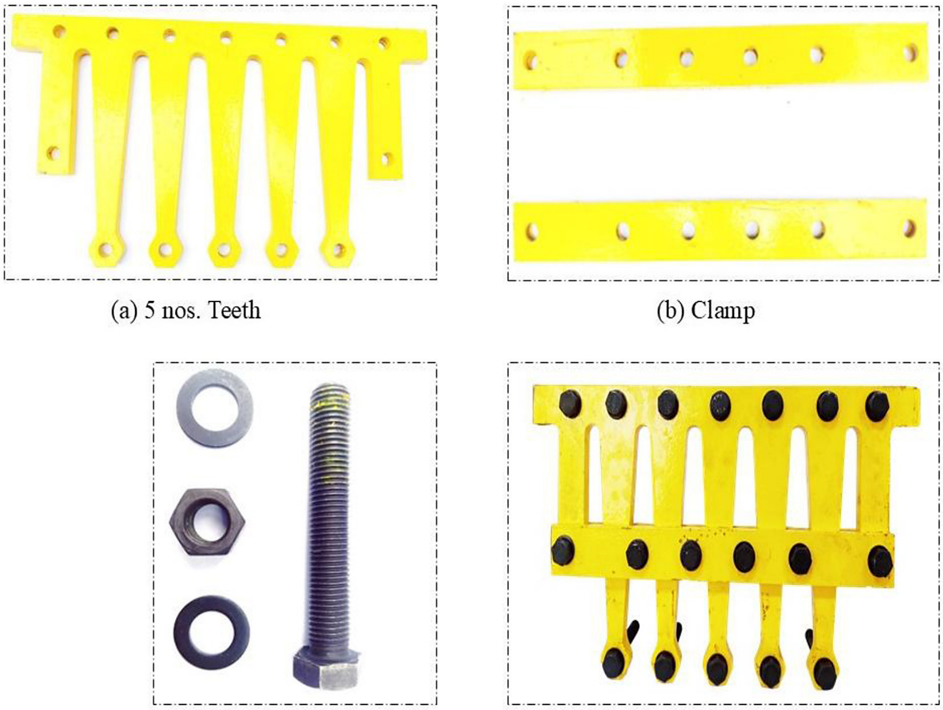


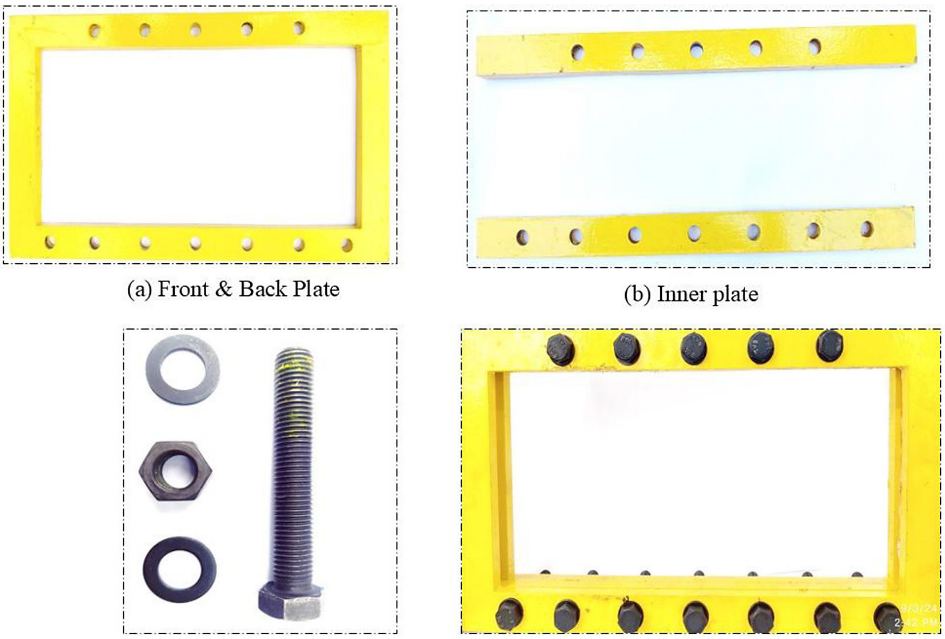
Figure 3. Comb teeth damper -typical & variables of CTD



(a) 5 nos. Teeth (b) Clamp

(c) Bolt, Nut & Washer (d) Comb Teeth Damper

Figure 4. Parts of comb teeth damper and assembled CTD



(a) Front & Back Plate (b) Inner plate

(c) Bolt, Nut & Washer (d) Friction Damper

Figure 5. Parts of friction damper and assembled FD

friction damper. Initially comb teeth damper is positioned, followed by attaching two outer plates which are then fastened together with high strength bolts as shown in Figure 6. The overall dimensions of hybrid damper (CTFD) are similar to CTD and FD.

EXPERIMENTAL SETUP AND INSTRUMENTATION

To assess the performance of CTD, FD and hybrid CTFD forced controlled monotonic lateral loading tests were conducted. A-type

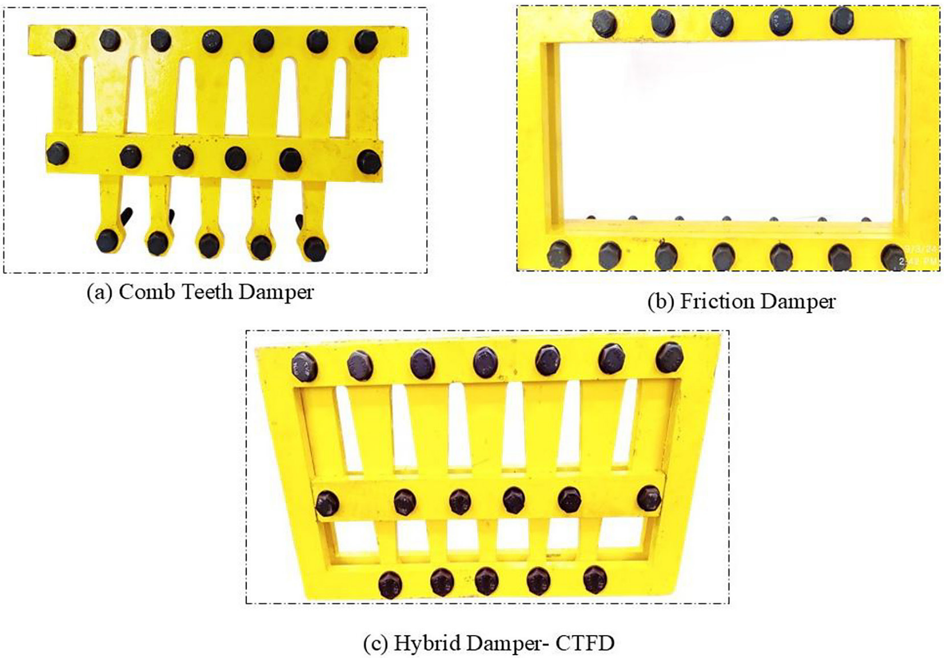


Figure 6. Parts of hybrid damper and assembled CTFD

self-restraining 3-D loading frame was used to conduct the monotonic lateral load on damper specimens. A 50-ton capacity load cell was connected to an actuator, which was utilized to apply load on the damper specimens and the corresponding displacement was measured by using LVDT of 200 mm displacement capacity. The experimental setup with damper specimens is shown in Figure 7.

RESULTS AND DISCUSSION

Yield and ultimate load capacity of dampers

The dampers were tested for lateral load till failure and the corresponding lateral displacement was observed. The CTD started yielding at the load of 10 kN with a displacement of 4.35 mm. The clamps lay hold the teeth from out of

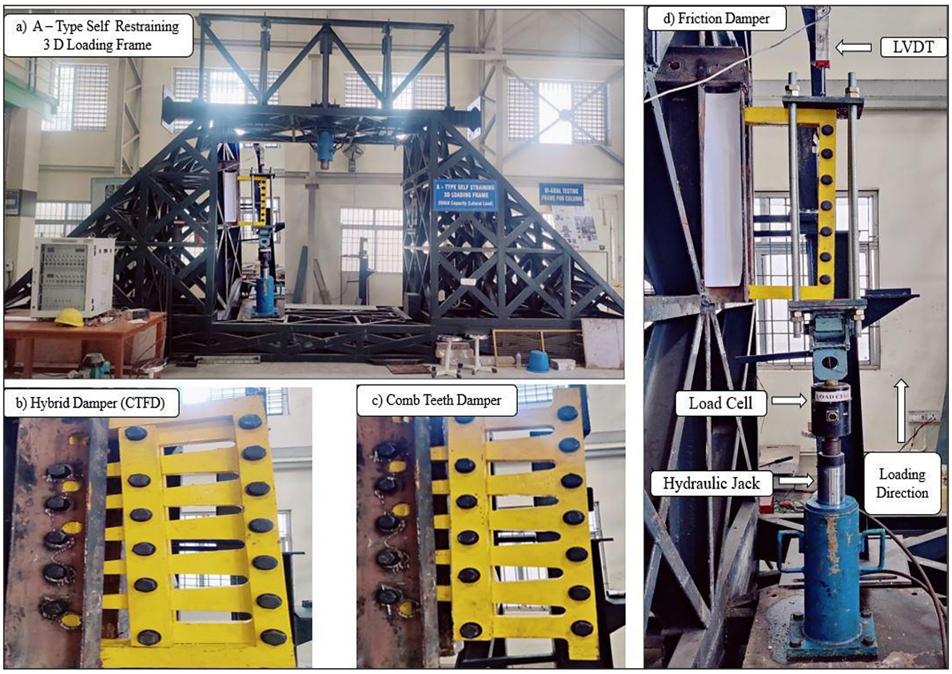


Figure 7. Experimental setup of CTD, FD and CTFD

plane buckling and uniform yielding of all teeth was observed as shown in Figure 8a. The teeth remained intact throughout the testing, exhibiting effective yielding behaviour up to a maximum load of 45 kN with the corresponding displacement of 80 mm. The FD started to yield when the load reached 60 kN having displacement of 42 mm. As loading continued, it reached its maximum (ultimate) capacity at 86 kN, at which point the displacement had increased to 135 mm. The bolt in the bottom of the outer plate was strained completely and the plate was fractured as shown in Figure 8b. The friction between the outer and inner plates during load transfer has caused the strain in the inner plates, as depicted in Figure 8c and the outer plates cracked as seen in Figure 8d due to the shear in the bolt Figure 8e. The hybrid damper registered the yield point at the load of 135 kN with a corresponding displacement of 30 mm. The damper reached its ultimate point at 210 kN with 85 mm displacement. The photographs of failed hybrid damper are shown in Figure 9. In the hybrid damper, initially, the CTD yielded and carried the load; once it reached its

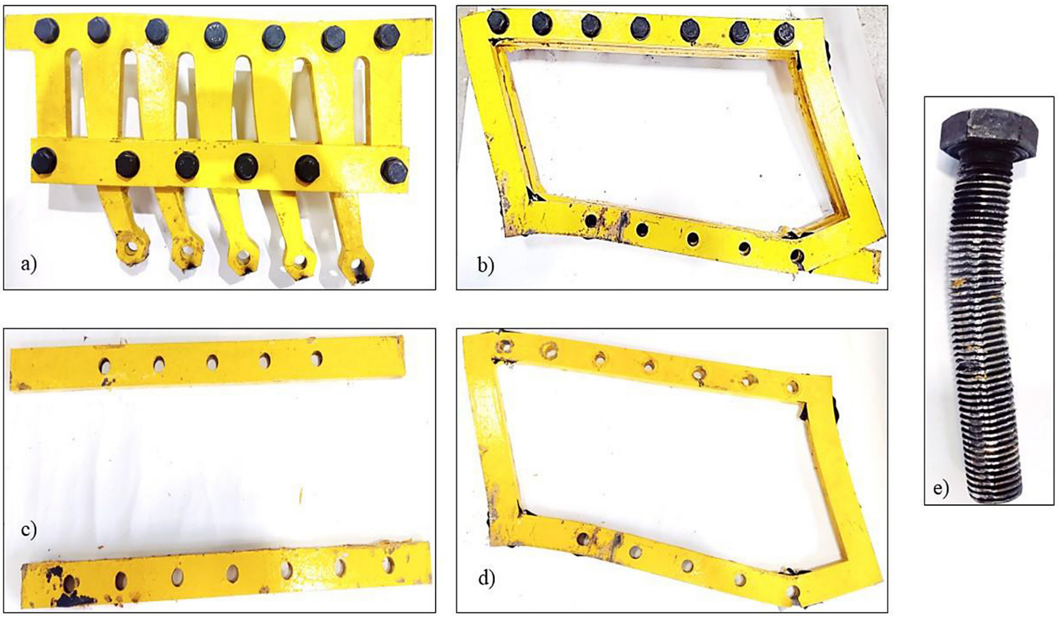


Figure 8. (a) Yielded CTD, (b) failed FD, (c) inner plates of FD, (d) outer plate of FD, (e) failed bolt

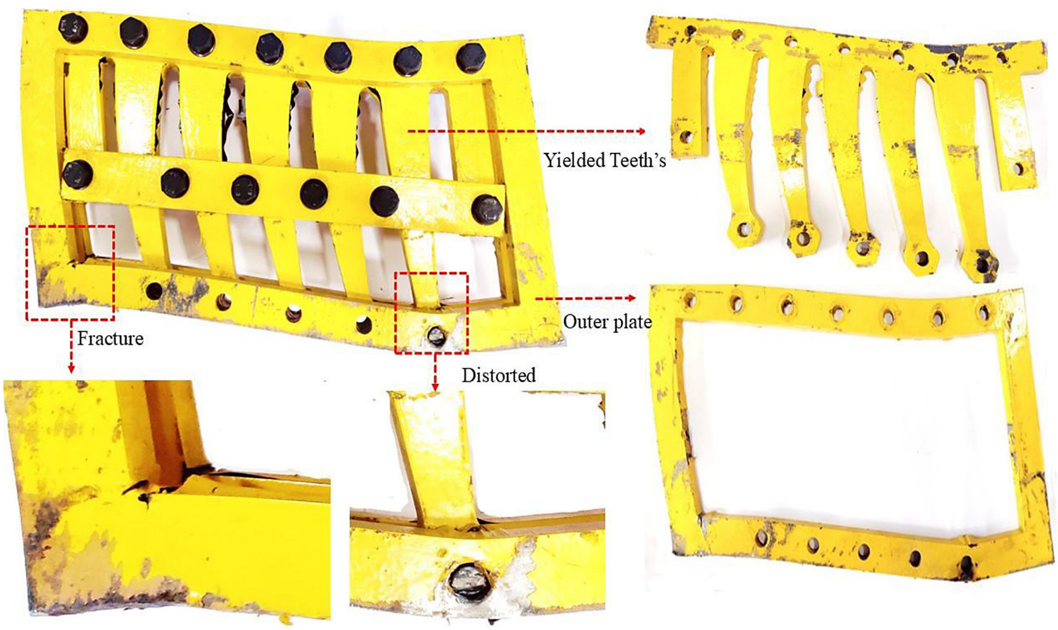


Figure 9. Hybrid damper (CTFD) after failure

limit, the load was transferred to FD. After that both devices shared the increased load until their eventual failure.

Initial stiffness of the dampers

Figure 10 shows the load versus displacement behaviour of CTD, FD and CTFD. The CTD and FD has an initial stiffness of around 1.25 kN/mm whereas the hybrid CTFD exhibits a higher initial stiffness of 4.6 kN/mm. When comparing the stiffness of CTFD with CTD and FD, it is found that CTFD offers 3.68 times more than CTD and FD. This kind of behaviour is one of the desirable factors for seismic resistance of building frames. Figure 11a, b, and c shows the lateral load versus displacement with bilinear curves of CTD, FD, Hybrid CTFD and Figure 11 (d) demonstrates the typical energy stored and energy dissipated using bilinear behaviour. The amount of energy stored in CTD, FD and CTFD is 248.44 J, 2145 J and 1979 J, respectively. The ductility ratio of the dampers is shown in Figure 12, and it is observed that the ductility ratio of the CTD is higher than FD and CTFD though it has less lateral load capacity. Figure 13 gives the

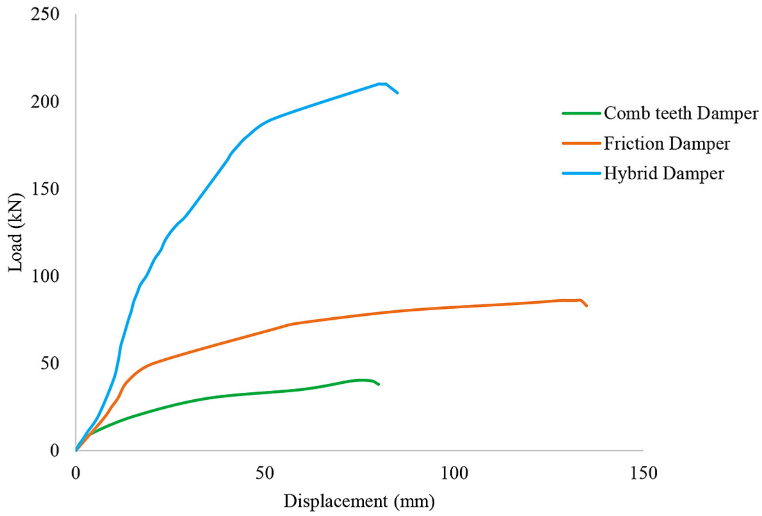


Figure 10. Load vs displacement of CTD, FD and CTFD

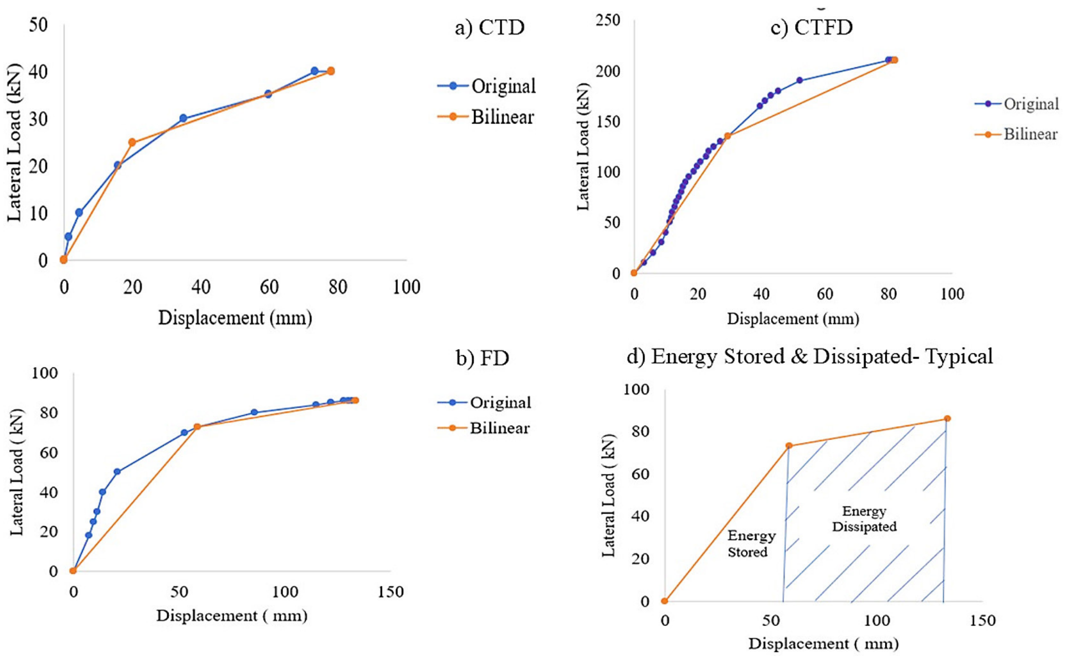


Figure 11. Bilinear curves of FD, CTD, hybrid damper

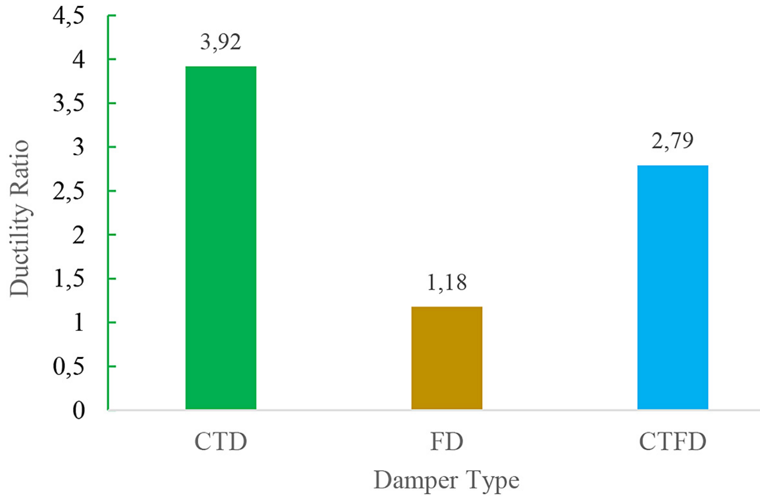


Figure 12. Ductility ratio of FD, CTD, hybrid damper

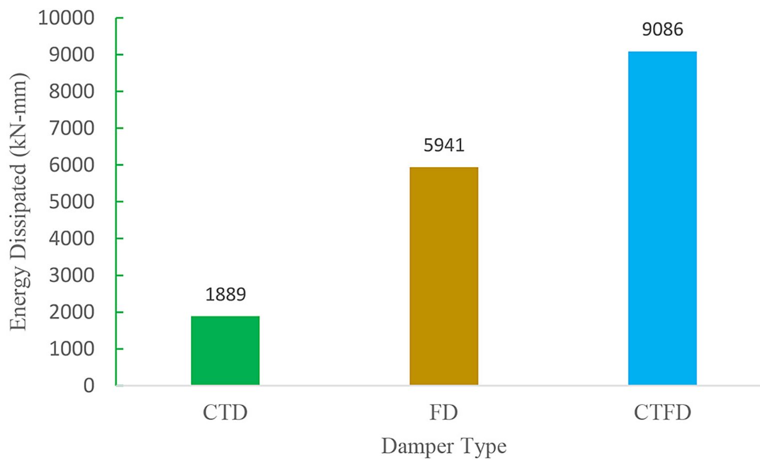


Figure 13. Energy dissipated of FD, CTD, hybrid damper

energy dissipation capacity of dampers considered under study. From the results, it has been observed that the hybrid damper exhibits an increase in energy dissipation of 52.9% more than CTD and 79.3% more than FD.

CONCLUSIONS

A hybrid damper combines two passive damping devices into a single system to reduce vibrations in various structures. These integrated devices are generally installed in buildings and bridges to minimize undesirable vibrations and enhance overall structural stability. In this study, a hybrid damper is developed using CTD and FD to dissipate more energy for seismic performance of structures in high seismic prone regions. From the current study, the following conclusions are drawn. Experimental tests were conducted on CTD, FD and CTFD to determine the maximum lateral load carrying capacity and displacement. The results showed that CTFD performed better than CTD and FD by 89% and 43% in lateral load carrying capacity. When comparing the stiffness of CTFD with CTD and FD, it is found that CTFD offers 3.68 times more than CTD and FD. This kind of behaviour is one of the desirable factors for seismic resistance of building frames.

The proposed hybrid damper has 50% more lateral load and energy dissipation than other hybrid dampers reported in the literature. The energy dissipation capacity of the hybrid damper is 52.9% more than CTD and 79.3% more than FD. This significant increase in energy dissipation capacity proves the effectiveness of hybrid dampers that can be adapted for high-rise buildings to improve resilience against earthquakes.

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