Aluminium Shear Yielding Damper (Al-SYD) as an Energy Dissipation Device in Truss Moment Frames (TMFs)

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ABSTRACT
Aluminium Shear-Yielding Damper (Al-SYD) as an energy dissipation device has been found to be very effective in improving the seismic response of ordinary structures. In the present study, the application of Al-SYD has been studied for improving the seismic behaviour of TMFs, which have demonstrated poor seismic performance in the past earthquakes due to their low energy dissipation potential. A 1:6 reduced scale model of a single storey industrial building frame was designed and fabricated. Single-axis shake table tests were carried out using the scaled Taft motion (1952 Kern County) for a wide range of intensity ranging from PGA of 0.05*g* to 2.40*g* (8.3% to 400% DBE). The Al-SYD TMF attracted lesser base shear and overturning moments as compared to the TMF for all simulation tests. The peak base shears were reduced by 36% to 82% and maximum drifts were found equal to that of the TMF for all the ground motions applied.

Keywords: Aluminium Hysteretic Damping, Shake Table Testing, Energy Dissipation, Shear Link

1. INTRODUCTION

Steel open web truss moment frames are commonly used for building structures to support gravity loads and to resist lateral forces during earthquake. TMFs are economical as compared to solid web beam frames in large spans structures like warehouses, industrial building, shopping malls etc. Moreover, truss moment framing systems also allow the extra benefit of utilization of open spaces in the web for piping and duct work and do not cause any obstructions within a bay. A detailed analytical and experimental investigation was carried out at The University of Michigan starting from 1989 to 1998 in order to study the seismic behaviour of TMFs. The main objectives of the study were to evaluate the problems with TMFs and suggesting an alternate design methodology for improving their performance under severe ground motions (Goel and Itani 1994; Goel and Basha 1995).

Inelastic deformation of metallic devices can also be used for energy dissipation in structures (Soong and Dargush 1997). Flexure yielding steel dampers such as TADAS, ADAS had also been used in previous studies to maximize energy dissipation potential (Whittaker et al. 1991; Tsai et al. 1993). The present study is performed in consideration to enhance the energy dissipation in TMFs without considerable decrease in stiffness of the structure. The performance of TMFs could be improved by introducing a mechanism or a device that can absorb seismic energy. Energy dissipation devices can be used to further enhance the energy dissipation potential of a system without any significant damage in the gravity load resisting members. The basic function of EDDs is to reduce and/or absorb a portion of the input energy, and thereby reducing the energy dissipation demand on primary structural members and minimizing possible structural damage. The EDDs has also an added advantage of replacement after the occurrence of an earthquake.

Aluminium shear link is one such device which utilizes metallic hysteresis for enhanced seismic energy dissipation. Shear link is an I-shaped aluminium beam which is designed to yield in shear mode (Rai and Wallace 1998). The shear yielding of aluminium had been found to be very ductile and very large inelastic deformations are possible without tearing or buckling (Jain et al. 2008). The low yield strength of aluminium in shear allows the use of thicker webs which further reduces the chances of web buckling. The yielding in shear mode maximizes the material participating in plastic deformation without excessive localized strains. Aluminium shear link has been found to be excellent energy dissipation device and is very effective in limiting the energy demand on the primary structure members of the system (Sahoo and Rai 2009). A typical shear link and its arrangement in Al-SYD TMF are shown in Fig. 1.1.

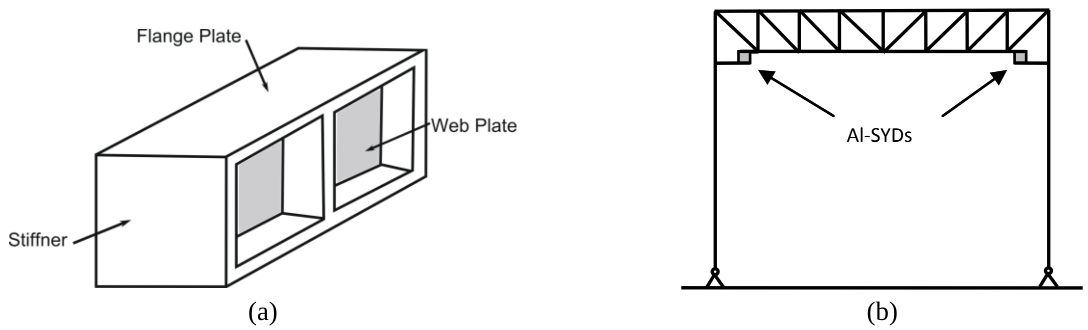

Figure 1.1. (a) Schematic diagram of typical Shear-link (b) Arrangement of Shear Link in Al-SYD TMF

2. EARTHQUAKE SIMULATOR TESTING

Shaking table tests were conducted to evaluate the load resistance mechanism, failure/damage pattern and the hysteretic behavior of shear-link systems and to provide the data for developing suitable design procedures for proportioning various elements of the overall system.

2.1. Prototype building

A single storey large span industrial building was assumed to be located in seismic Zone V (very severe, PGA = 0.36*g*) on stiff soil (Type II, Shear wave velocity of 200-700 m/s) as per IS 1893(Part-1) [BIS 2002] with 5% damping. Fig. 2.1 shows the plan view of the prototype building and cross-sectional view of the test frame. The building was assumed to be 27 meters in width (3 bays @ 9 m) in N-S direction and 90 meters (9 bays @ 10 m) in the E-W direction. The height of the building was 9.5 meters with horizontal and accessible roof. The N-S direction had 8 rows of frames B, C, D, E, F, G, H and I in which central frame was lateral load resisting frame and the shear links present in those lateral load resisting frames were designed for the code level lateral load. The rest of the frames were assumed to resist only gravity loads without any contribution in resisting lateral loads. Table 2.1 summarizes the design calculations for the prototype frame.

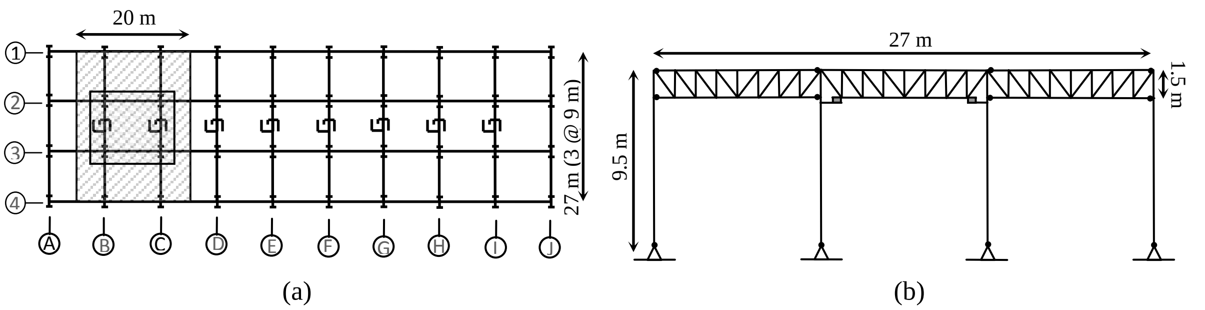

Figure 2.1. (a) Plan view of the prototype building and tributary area (b) Cross-sectional view of the frame

Table 2.1. Design calculations

Zone factor, $Z = 0.36$ Importance factor, $I = 1$ Response reduction factor, R = 5 Fundamental natural period, $T_s = 0.085h^{0.75} = 0.46$s Average response acceleration coefficient, $S_a/g = 2.5$ (for 5% damping) Design seismic coefficient, $A_h = 0.09$	Design seismic coefficient, $A_h = \frac{ZI}{2R}\frac{S_a}{g} = 0.236$ Dead load on roof = 0.63 kN/m^2 Dead load of wall = 0.38 kN/m^2 Live load on roof = 1.5 kN/m^2 Seismic weight on roof = 2886.75 kN Design base shear/frame (assuming 5% eccentricity) = 42.22 kN

Proportioning of shear-link

Design Shear (kN)	Design Shear		Web Area Required (mm^2)	Web Area Provided (mm^2)	Dimensions of the shear link
	Strain, γ_d	Stress, $\tau_{avg,max}$* (MPa)			
205.22	0.10	86.94	2360	2400	Length of web, $l_w = 400$ Thickness of web, $t_w = 6$

* $\tau_{avg,\max} = 2.6\sigma_{0.2}\gamma_d^{\,0.2}$ $\sigma_{0.2} =$ 53 MPa

2.2 Reduced scale model

Length scale ratio of 1:6 was chosen for present study considering practical limitations. An acceleration scale of 3 was considered to reduce the imposed load on the model for the simulation of similar stresses in columns and for adequate dynamic simulation, time and frequency scale ratios were modified according to applicable similitude relations, as shown in Table 2.2. Various sections used in manufacturing structural members of the frame such as columns, chords, vertical and diagonal members of the structure are provided in Table 2.3 along with their yield and ultimate strength. Fig. 2.2 shows the schematic diagram of the truss frame along with the fabricated shear link. The shear links were fabricated by machining a solid aluminium bar of 50×50 mm square cross section. Shear links were heat treated (annealed) after machining to release any previous stresses or any stresses generated during the machining processes. The 0.2% proof stress for unannealed 6061-T6 alloy was about 180 MPa while after annealing the yield stress reduced to 53 MPa.

Table 2.2. Model scaling requirements

Parameter	**Scale factors**	**Dimension**	**Modified replica model**
Length, *L*	S_l	L	1/6
Area, *A*	S_l^2	L^2	1/36
Mass, *M*	$S_eS_l^2$	M	1/108
Force, *F*	$S_eS_l^2$	MLT^{-2}	1/36
Acceleration, *a*	S_a	LT^{-2}	3
Frequency, ω	$S_l^{-1/2}$	T^{-1}	$\sqrt{18}$
Time, *t*	$S_l^{1/2}$	T	$1/\sqrt{18}$

Table 2.3. Various sections used and their yield and ultimate strength

Sl. No.	**Truss Frame**	**Section**	**Yield Strength (MPa)**	**Ultimate Strength (MPa)**
1.	Chords (upper and lower)	2 Angles 25×25×1.5 mm	385	502
2.	Diagonals	Angle 18×18×1.6 mm	395	519
3.	Verticals	SHS 15×15×1.17 mm	480	556
4.	Columns	ISLB 75	324	468

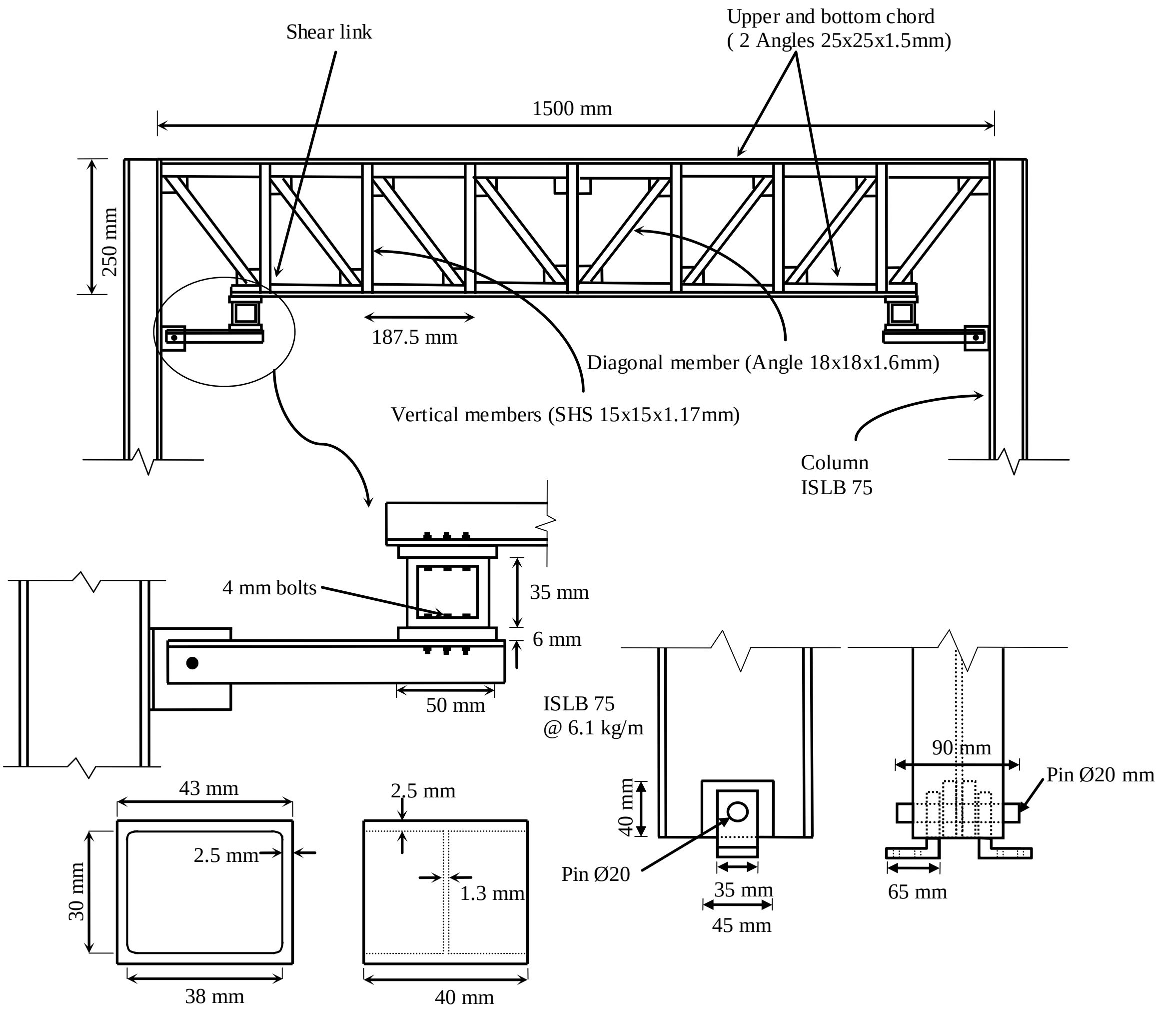

Figure 2.2. Schematic diagram of the shear link and model

2.3 Loading history and earthquake simulation

Two frames were fabricated and mounted side by side on the uni-axial shake table (1.8 m x 1.5 m) (Sinha and Rai 2009). Fig. 2.3 shows the specimen mounted on the shake table along with shear link in the Al-SYD TMF. For dynamic loading of the structure Taft N21E component of the 1952 Kern County earthquake (PGA 0.156*g*) was used. The Taft motion was chosen for dynamic loading due to the fact that, after required scaling its response spectra shows a close match with design response spectra of IS 1893. Design response spectra of IS 1893 for a Design Basis Earthquake (DBE) in zone V (PGA 0.18*g*) matched reasonably when TAFT motion was scaled to PGA 0.20*g* as shown in Fig. 2.4(a). The original time length of the motion is 56.16 s which was compressed by a factor of $\sqrt{18}$ to satisfy similitude relations, shown in Fig. 2.4(b). The loading of the specimens started with Taft 0.05*g* (PGA 0.05*g*) and further Taft motions were applied up to PGA 2.40*g*.

2.4 Dynamic characteristics of test frame

The natural frequency and damping as obtained from free vibration test for Al-SYD TMF and TMF were 3.13 Hz and 2.59% and 4.13 Hz and 0.81%, respectively. Forced vibration test was performed using an electro-dynamic mass shaker which was capable of providing force of 133 N over a wide range of frequency from 0 Hz to 200 Hz. In-plane natural frequencies for Al-SYD TMF and TMF were obtained to be 3.26 Hz and 4.08 Hz, respectively from sine sweep test.

(a) (b)

Figure 2.3. (a) Specimen mounted over the shake table (b) Arrangement of shear link in Al-SYD TMF

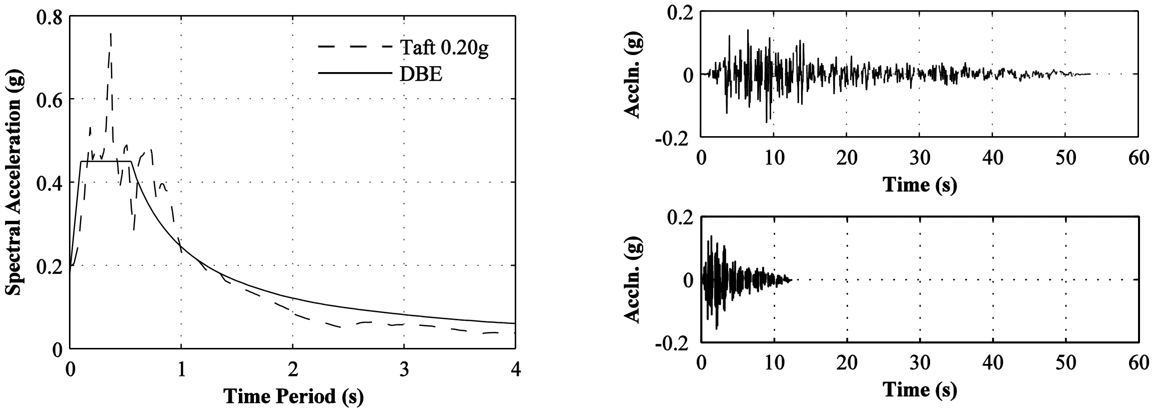

Figure 2.4. (a) Comparison of DBE for Zone V (PGA 0.18*g*) with Taft (PGA 0.20*g*) (b) Original and compressed Taft N21E ground motion

3. EVALUATION OF SHAKE TABLE TEST RESULTS

3.1 Overall behaviour of Al-SYD TMF and TMF

Scaled Taft motions of increasing PGA from 0.05*g* to 2.25*g* (8.3% to 375% DBE) were applied on Al-SYD TMF. Fig. 3.1 shows the various states of shear link after application of ground motion of increasing PGA levels. The natural frequency of the structure remained equal to that of undamaged specimen (3.13 Hz) up to ground motion of 0.30*g* PGA due to elastic behaviour of shear link. The first change in natural frequency was observed after the application of Taft motion with PGA 0.45*g* due to the yielding of the shear links. Slight permanent deformation and rocking was visible in shear links after the yielding, and these were prominent after the application of PGA 0.90*g*. The buckling in the web panel of the shear links was first observed after the application of Taft motion with PGA 1.50*g*. Buckling was visible in all the shear links after the application of Taft motion with PGA 1.65*g*. Tearing first occurred in SL2-Left Frame during Taft motion with PGA 1.80*g*, whereas tearing in the other three links was observed only after the application of ground motion with PGA 1.95*g*. Tearing in SL2-Left Frame caused the reduction in natural frequency of the structure from 2.49 Hz to 2.34 Hz. Further reduction in the natural frequency was observed when excessive tearing in all the shear links occurred during the application of Taft motion with PGA 2.25*g*, which was found to be 2.1 Hz from its previous value of 2.34 Hz.

TMF was tested for PGA levels ranging from 0.05*g* to 2.40*g* (8.3% to 400% DBE). The undamaged natural frequency of the TMF was obtained to be 4.21 Hz, not much reduction in stiffness was observed with increasing PGA levels. Natural frequency of 4.00 Hz was obtained after the application of PGA 1.65*g*.At this ground motion chipping off of the white wash in columns was observed which might have occurred due to the excessive straining of the columns. The members of the truss girder remained elastic even after the application of Taft 2.40*g*.

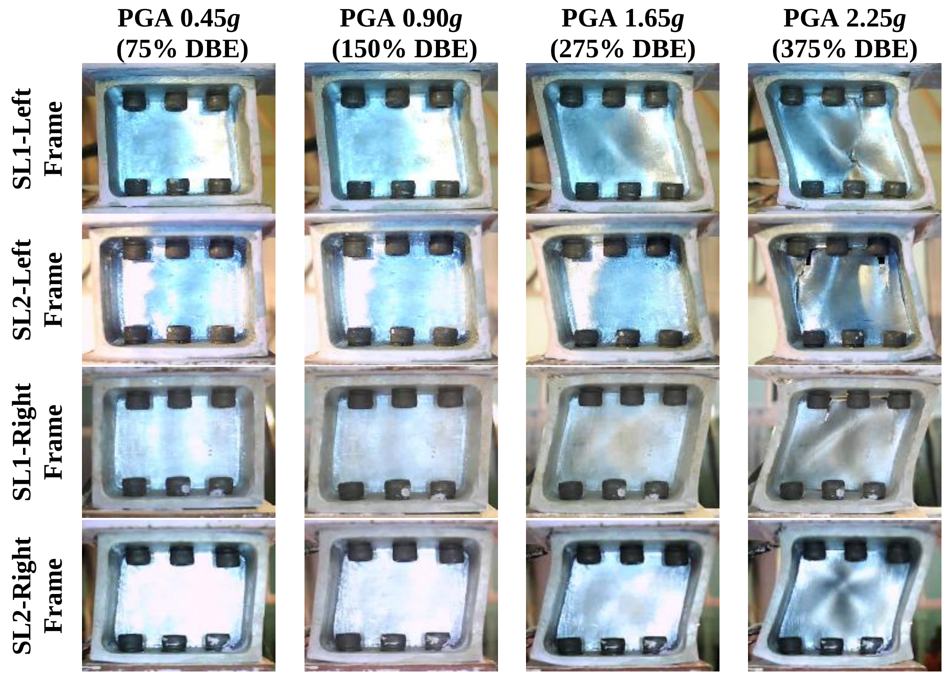

Figure 3.1. Visual observations at various DBE levels

3.2 Acceleration response

The comparison of roof acceleration time history (at 100% and 200% DBE) and roof acceleration response with increasing PGA levels between Al-SYD TMF and TMF are shown in Fig. 3.2 and Fig. 3.3, respectively.

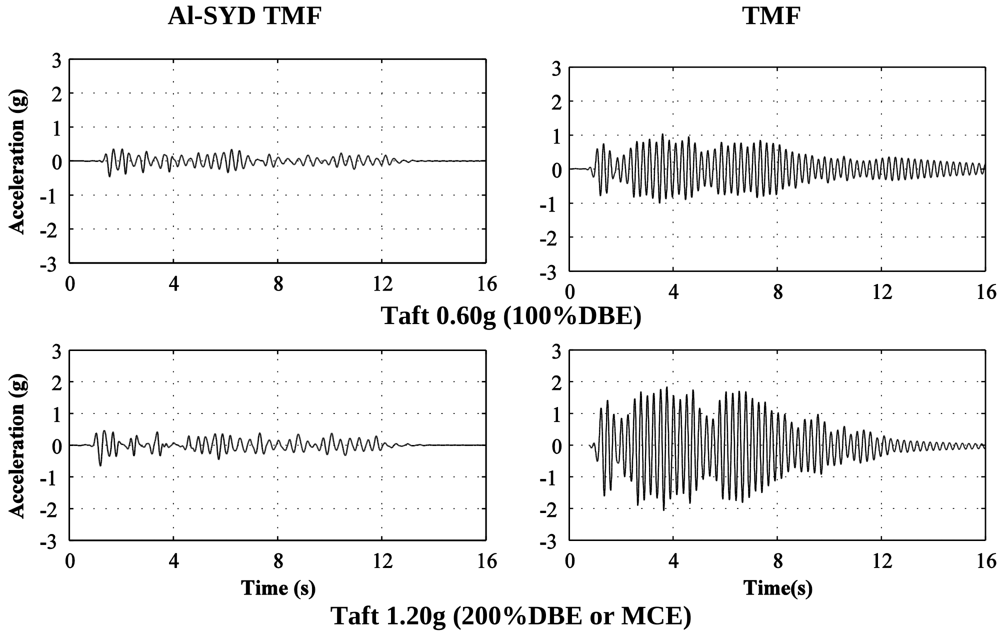

Figure 3.2. Acceleration time history comparison between Al-SYD TMF and TMF

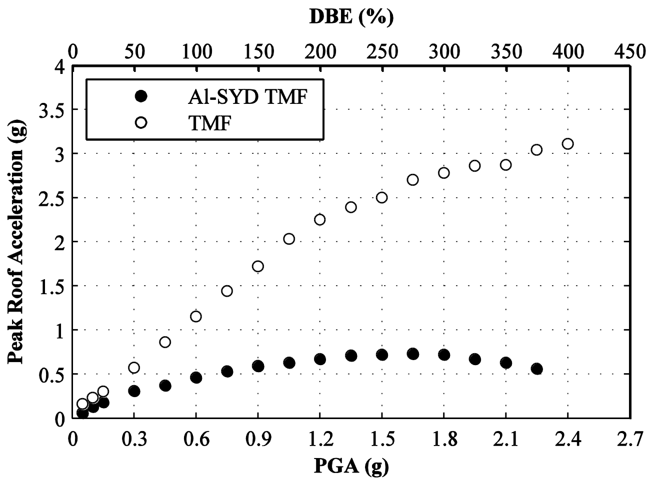

Figure 3.3. Comparison of peak roof acceleration experienced by Al-SYD TMF and TMF

The peak roof accelerations experienced in Al-SYD TMF increased linearly up to 0.30*g* PGA ground motion. After 0.30*g* PGA ground motion, the yielding of shear links caused reduction in rate of increase of peak roof acceleration. The increasing trend was observed up to Taft with PGA 1.65*g* and the corresponding peak value was found to be 0.73*g*. After this PGA level, reduction in the peak acceleration response was observed due to the onset of inelastic buckling of web panels in the shear links. On the contrary, for TMF the peak acceleration response was found to be increasing for all the ground motions applied. The maximum roof acceleration was found to be 3.11*g* for the ground motion of 2.40*g* PGA. Reduction was observed to be in the range of 0.18 to 0.60 times that of TMF for all the ground motions, which implies that the Al-SYD TMF experienced significantly lower accelerations. Therefore, it can be concluded that Al-SYD was very effective in reducing the forces transferred to the structure due to its excellent damping and energy dissipation characteristics.

3.3 Displacement response

The comparison of roof displacement time history response and percentage drift at various PGA levels for Al-SYD TMF and TMF are shown in Fig. 3.4 and Fig. 3.5, respectively.

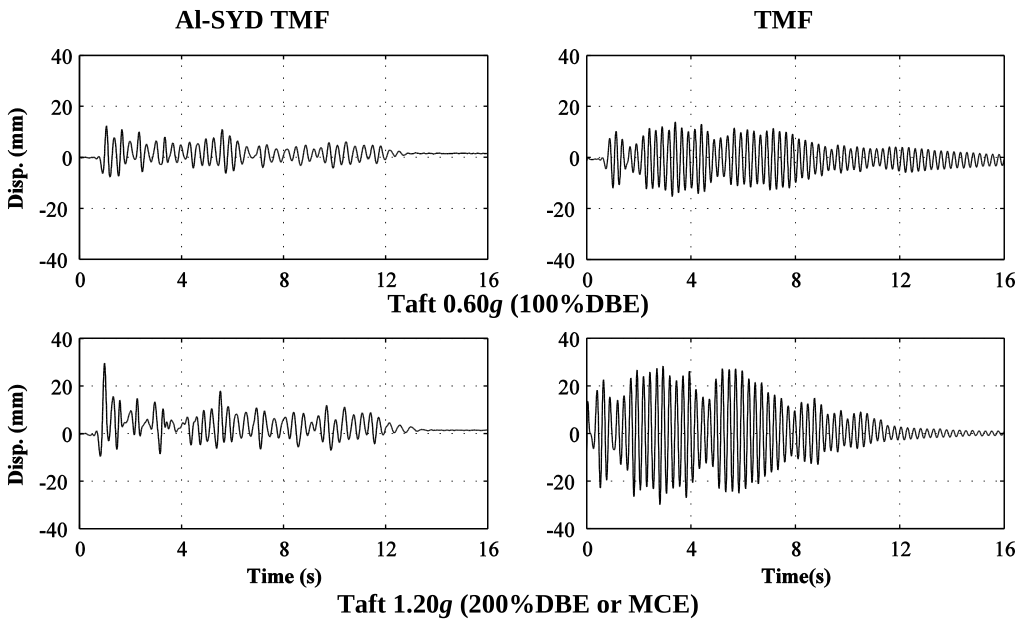

Figure 3.4. Displacement response comparison for different Taft Intensities

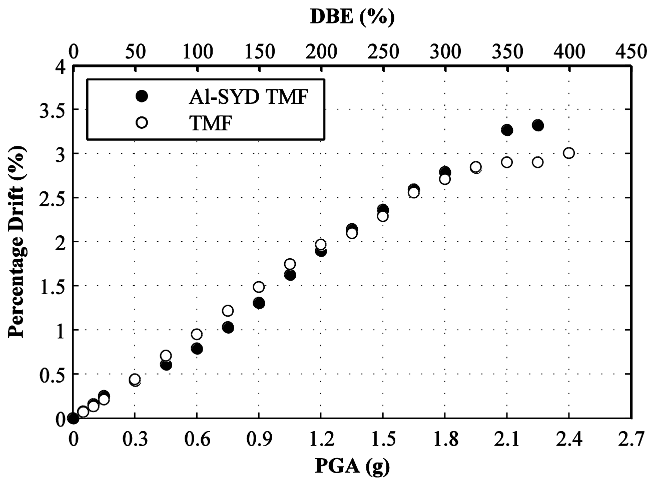

Figure 3.5. Comparison of maximum roof drift in Al-SYD and TMF at various DBE levels

Maximum roof drift for both type of frames was found to increase linearly with increasing PGA values. In Al-SYD TMF, the linear increase in drift of the structure continued up to the end of the test (PGA 2.25*g*), whereas in TMF the drift increased linearly up to Taft motion of PGA 1.80*g*. For further ground motions of higher PGAs, the rate of increase of drift in TMF decreased due to the enhanced inelastic activity in the columns. The drift obtained for both Al-SYD TMF and TMF matched closely up to PGA 1.95*g*. The linear increase of drift with the increasing PGA levels remained unaffected by the yielding and inelastic buckling in the web of the shear links. The drifts obtained for both frames were less than 1% and 2% at 100% and 200% DBE, respectively.

3.4. Energy dissipation

In the present study, hysteretic areas for various ground motions applied in case of Al-SYD TMF and TMF were obtained by plotting roof displacement of the structure with the inertia force. Fig. 3.6 shows hysteretic area loops for some selected Taft motions of different PGA levels as obtained for Al-SYD TMF and TMF.

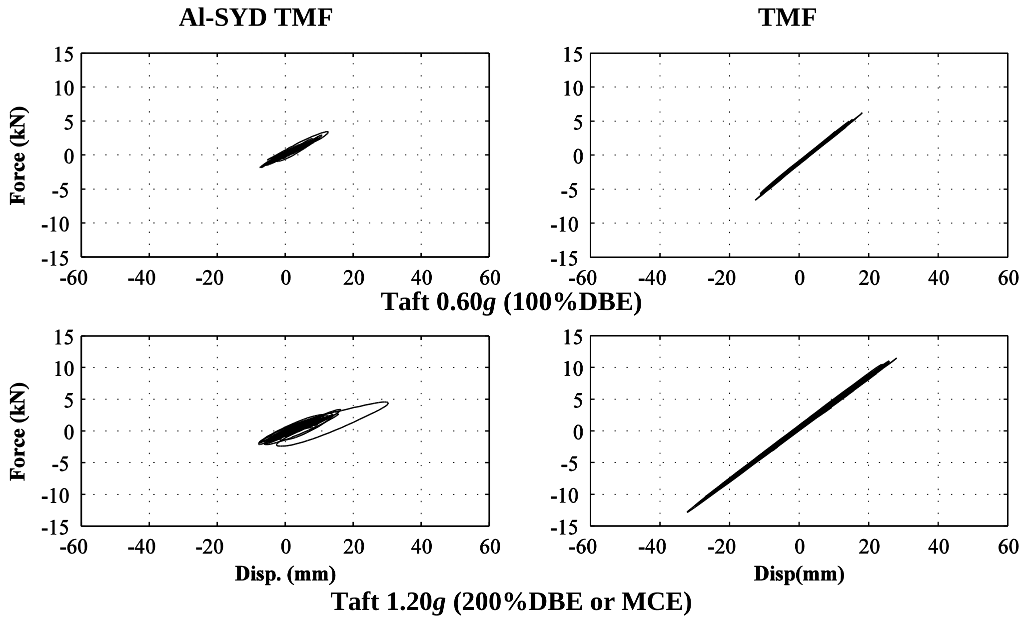

Figure 3.6. Hysteretic area plot for Al-SYD TMF and TMF at various PGA levels

The hysteretic plots for Al-SYD TMF were found to be smaller as compared to that obtained from TMF due to the lower force experienced by the Al-SYD TMF. Continuous leaning of hysteretic plots toward the displacement axis shows the reduction in stiffness of the structure with the increasing PGA levels. The hysteretic loops obtained for TMF were quite narrow till 1.50*g* PGA ground motion which shows no or very less inelasticity in the system.

4. ANALYTICAL STUDY OF PROTOTYPE FRAME

Analytical studies on the Al-SYD TMF and the TMF model were performed using SAP 2000 [CSI, 2009]. The shear link was modelled using two multi-linear plastic link elements to account for the length of the link. The load deformation behaviour of the shear link was provided by defining a backbone curve. The yield and ultimate strength of the link element was defined to be half as that of the shear link. As the shear link shows full hysteretic loops till 20% strain (Jain et al. 2008), link elements were also allowed to deform till 20% after that their strength was reduced to 1/3 of the ultimate strength to model the failure of the link element as shown in Fig. 4.1. Lateral displacement of the roof and peak roof acceleration responses were monitored for all the ground motions applied in nonlinear direct-integration time history analysis. The roof response acceleration and roof displacement obtained through experiments for both the tests were scaled up accordingly as per the scale ratios discussed previously. Analytical and experimental comparison between TMF and Al-SYD TMF in terms of roof displacement and base shear as obtained using peak roof acceleration response is shown in Fig. 4.2.

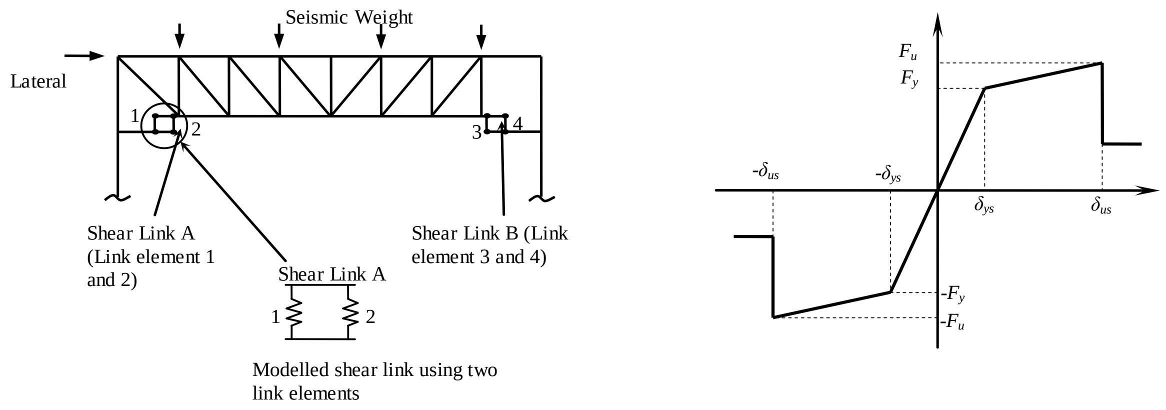

Figure 4.1. Modeling of shear link with multi-linear plastic element and backbone curve defined in SAP2000

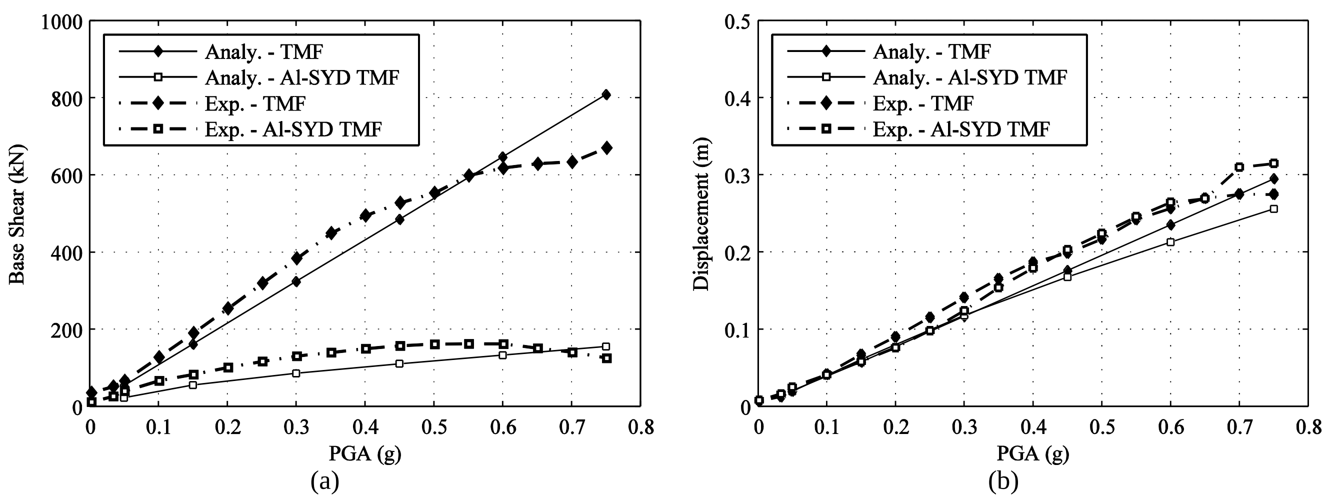

Figure 4.2. Base Shear and (b) Roof Displacement comparison between Analytical and Experimental analysis of TMF and Al-SYD TMF

5. CONCLUSIONS

The Al-SYD TMF attracted less base shear as compared to the conventional TMF for all simulation tests. The reduction in peak base shears and overturning moments were observed in the range of 36% to 82% for all the ground motions applied. Consequently, design forces in columns were smaller in Al-SYD TMF as compared to that in TMF. The roof drifts obtained in Al-SYD TMF and TMF increased linearly with the increasing intensity of ground motion and the displacement values were found to be approximately same for both the cases. In Al-SYD TMF all the members of the truss girder remained elastic up to very high PGA levels, inelastic activity was confined in shear links only, except slight yielding in the column-truss chord joint was observed at very high PGA levels. The yielding and buckling of shear links did not cause much reduction in stiffness but significant drop in stiffness was observed after the complete tearing of web panels of the shear links. Shake table tests on the small scale model clearly indicated that aluminium shear links possess greater energy dissipation potential and excellent damping characteristics which caused significant reduction in roof acceleration and roof displacement in Al-SYD TMF as compared to that in TMF.

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