Vibration control of steel frames with setback irregularities equipped with semi-active tuned mass dampers

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Research Article

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Abstract

Vibration control of structures has been a focus of research worldwide. Although, several studies have examined the efficiency of semi-active tuned mass dampers (SATMDs) to control the seismic vibration of structures, only a few have focused on the influence of SATMDs on steel moment resisting frames in irregular structures having setbacks. In the current investigation, the use of SATMDs for the vibration control of structures with setbacks subjected to earthquake records has been evaluated. In order to assess the nonlinear seismic performance of buildings with setbacks, the inter-story drift ratio, story displacement, and base shear factor were examined as engineering demand parameters. The results reveal that the use of SATMDs reduced the seismic response of regular and irregular frames with setbacks. However, the use of these control devices requires more attention for structures with significant setbacks because, in some cases, the response of a structure with SATMDs can be greater than of an uncontrolled structure. The investigations also showed that placement of the control systems at the highest (top) level of the structure significantly reduced the structural vibration of both types of structure.

Introduction

Different types of vibration control devices and techniques have been suggested to reduce the lateral response of man-made structures subject to dynamic loads such as those from wind and earthquakes. One practical and reliable device for vibration control is the tuned mass damper (TMD) as proposed by Frham (1911). The main advantage of this device is that it can easily be used in the design of new buildings and for rehabilitation of existing structures. In order to prepare for frequency-dependent damping, a TMD system is usually installed at the top floor of a regular structure (Bathaeiet al. 2018). This system, which comprises additional mass, springs and dampers, is attached to the main structure and transfers the structural vibration energy to the TMD system.

With the increasing use of new vibration control systems such as TMDs, several numerical and experimental investigations have been carried out on the vibration control of structures using passive, active and semi-active control system strategies (Hrovatet al. 1983; Abe 1996; Kim et al. 2003; Chey et al. 2010; Fisco and Adeli 2011; Lin et al. 2012; El-Khoury and Adeli 2013; Kim et al. 2015; Ghaedi et al. 2017; Pirmoradian 2017). TMDs were developed to control vibrations in structures as passive control systems. These passive systems do not require an external power source, while active control systems require an active external power source to transfer the required force in order to decrease the lateral response of the structure.

Semi-active control systems also can be used to control the lateral response of a structure under seismic and wind loads. In such approaches, the TMD is equipped with a semi-active (SA) damper that provides time-varying damping. This type of vibration control device is known as a semi-active tuned mass damper (SATMD). While an active control system requires a significant source of external energy to efficiently decrease the structural response, a semi-active control system requires only a small amount of active energy to reduce the vibration of the structure. In addition, semi-active control systems can provide more reliable and cost-effective vibration control of civil structures than passive control systems (Hrovat et al. 1983).

The mass, stiffness and strength distribution in the horizontal and vertical plans of a structure have significant effects on its seismic response to strong ground motions (Shahrooz and Moehle 1990; Osman 2002; Tremblay and Poncet 2005). Setback structures are irregular frames which exhibit undesirable seismic behavior under strong earthquakes (Shahrooz and Moehle 1990; Tremblay and Poncet 2005; Pirizadeh and Shakib 2019). Vibration control to reduce the response of a structure with this type of irregularity is a challenge and requires more investigation (Tremblay and Poncet 2005; Akyürek 2019). The current study investigated vibration control of setback structures under the effect of seismic loads with the application of SATMDs. The vertical location of the SATMDs in mid-rise steel frames having different setback configurations were examined.

Literature Review

A far-reaching literature review was undertaken on passive, active and semi-active vibration control approaches. Several studies on the lateral vibration of irregular frames with setbacks is presented below.

2.1 Passive approaches

The effect of bidirectional tuned mass dampers (BTMDs), a passive control method, on the lateral response of irregular buildings was studied by Gutierrez Soto (2012). The results showed that structural rigidity has a significant influence on buildings equipped with BTMDs. Lin et al. (2010) suggested that passive tuned mass dampers (PTMDs) had a substantial effect on structural vibration caused by near-fault earthquakes, including more forward-and-backward cycles. Bigdeli and Kim (2016) studied the effect of the mass and damping of a passive controller on the lateral response of structures. They showed that the contribution of total damping on reducing the response of structure was significant for TMDs.

Massumi et al. (2017) suggested a new multi-objective vibration control strategy to reduce the response of buildings under the effects of different loads. In order to decrease the response of the structures, Clark (1988) proposed an innovative design procedure for attaching multiple passive TMDs to the main structure. Sacks and Swallow (1994) carried out an experimental study on the reducing the structural response of a tall structure and reported acceptable performance of a structure with passive TMDs.

Jin et al. (2016) minimized the response of the beam by applying inerter-based passive vibration control systems and found that their performance was better than traditional dynamic vibration strategies. Khazaei et al. (2020) studied the efficiency of vibration control in regular and irregular high-rise steel structures with multiple tuned mass dampers (MTMDs) using a passive approach. The results showed that the success of MTMDs depends on the symmetry of the TMDs relative to the center of mass of the structures.

2.2 Active approaches

A neuro-genetic algorithm for non-linear active vibration control of a three-dimensional (3D) building was presented by Jiang and Adeli (2008). The results showed that their procedure had a substantial effect on both vertical and horizontal building irregularities. Samali and Al-Dawood (2003) studied the efficiency of active tuned mass dampers (ATMDs) using a fuzzy logic controller to reduce the response of the structure under seismic loads. Amini et al. (2013) suggested a new approach to achieving optimal control loads for ATMDs. Their results indicated that their approach substantially reduced the displacement response of the structure.

2.3 Semi-active approaches

Pinkaew and Fujino (2001) studied the effect of semi-active TMDs (SATMDs) under harmonic excitation and found that SATMDs were more cost-effective compared to active strategies and were more efficient than passive strategies. Ground-hook tuned mass dampers (GHTMDs) are semi-active vibration control systems introduced by Setarh (2001). It has been observed that the efficiency of decreasing the seismic structural behavior using a GHTMD is greater than for conventional TMDs. Lin et al. (2010) investigated the seismic response control of structures using semi-active-friction TMDs (SAF-TMDs) and reported that the performance of SAF-TMDs were more efficient than passive-friction TMDs. Lin et al. (2012) carried out an experimental study on structural control reduction and reported that the results of the theoretical and experimental studies were similar.

Chey et al. (2010) simulated a useful design concept for a vibration control system that uses both PTMDs and SATMDs. Chung et al. (2013) suggested a SATMD that includes a novel phase control algorithm and validated their suggestion with experimental studies. Although PTMDs are sensitive to the device frequency ratio, sensitivity studies have shown that the performance of the SATMDs was better than PTMDs and that they were not limited to the controller frequency ratio.

Lavan and Daniel suggested a seismic design approach for MTMDs and their optimal location for 3D buildings, including for several types of irregular frames under the effect of seismic loads (Daniel and Lavan 2013; Lavan and Daniel 2013; Daniel and Lavan 2014). Melkumyan (2013) evaluated the efficiency of a single TMD and MTMDs as vibration control systems for existing structures. The results showed that the use of three TMDs that depend on the first three modes was the most efficient strategy. Mohhebi et al. (2014) developed an optimal seismic design and evaluated its use for nonlinear steel structures with MTMDs under different ground motions. They reported that, whereas the efficiency of

TMDs strongly depended on the device parameters and the earthquake characteristics, the use of MTMDs reduced the seismic behavior of these structures.

Gutierrez Soto and Adeli (2014) found that the efficiency of decreasing the structural response depended on the frame rigidity and was greater for tall buildings. Application of SATMDs by assessing parameters such as damping and stiffness to control the behavior of structures under effects of an earthquake was studied by Sun and Nagarajaiah (2014). They found that SATMDs performed better than TMDs for controlling the seismic response of regular frames under effects of near-fault earthquakes. Kim et al. (2015) studied vibration control of buildings with SATMDs and reported that the SATMDs decreased the vibrations of structures, regardless of the earthquake parameters. Bathaei et al. (2018) suggested innovative fuzzy algorithm control of structural responses using a SATMD+MR damper which was applicable for both near-fault and far-field earthquakes.

In order to limit the space required for TMDs, Elias et al. (2019) suggested the use of distributed tuned mass dampers (DTMDs) located on different floors. Lu at al. (2018) investigated the effect of the mass ratio of TMDs on the super high-rise structures to control structural vibration. Vibration control of high-rise irregular reinforced concrete structures by TMDs was studied by Reddy et al. (1994) and the results showed that the performance of the TMDs did not change significantly with the addition of shear walls.

Elias et al. (2019) showed that TMDs could control the acceleration behavior more efficiently than displacement of a tall building under the effect of wind and seismic loads. Shih and Sung (2020) improved a special type of SATMD with an impulsive reaction. Kim (2020) proposed an innovative method to simulate and evaluate the seismic response of structures with SATMDs using a recurrent neural network (RNN). The results showed that the RNN significantly increased the accuracy of the seismic response and decreased the cost of software analysis over conventional finite element methods. The performance of SATMDs to reduce the structural vibration of footbridges under synchronous lateral excitation was studied by Ferreira et al. (2019). Their results showed that SATMDs had more efficient potential to reduce the vibrations of the structure compared to PTMDs.

2.4 Setbacks

Shahrooz and Moehle (1990) carried out an analytical and experimental study on the response of steel structures with setbacks and proposed a lateral-load design procedure for such structures. Karavasilis et al. (2008) studied the inelastic lateral response of plane steel moment resisting frames (MRFs) with setbacks under earthquake loads and presented a formula that considers the setback effects. Several investigations on the inelastic seismic response of structures with setbacks indicate that, compared to regular frames, there was a noticeable change in the seismic response of frames with setbacks (Shakib and Pirizadeh 2014). Furthermore, the seismic response of structures with setbacks that are located on the soft soil was more complex and should be considered when designing this type of structure (Shakib and Homaei 2017). Nievas and Sullivan (2015) successfully proposed the use of a direct displacement-based design method for MRFs with setbacks. A simple and economical procedure for evaluating the seismic performance of steel MRFs with setbacks that depends on reliability- performance-based methods was proposed by Pirizadeh and Shakib (2019).

Although structures with setbacks have been constructed worldwide, there are only a few studies that have focused on both their seismic behavior and probable rehabilitation. In this investigation, the efficiency of SATMDs to control vibrations in steel MRFs with different types of setbacks under the effect of earthquake events was evaluated. The most suitable position of the SATMDs to achieve the most efficient reduction in the seismic response of irregular frames has been presented.

Building Frame Models And Ground Motions

Ten ductile (special) steel MRFs, nine with different types of setbacks and one reference (regular) frame were studied. They were located in Tehran in a highly active seismic zone site with design acceleration coefficient of 0.35g. They were designed in accordance with the Iranian Code of Practice for Seismic-Resistant Design of Buildings (4^{th} edition, standard 2800). High deformation without substantial strength or stiffness degradation is expected for this type of frame.

The buildings configurations were designed according to the recommendations of Shakib and Pirizadeh (2014) to consider irregularities at a typical story height of 3 m and width of 5 m. The dead and live loads were 700 and 200 kgf/m^2, respectively, and structural occupancy was assumed for residual applications. All beams and columns for both the irregular and regular structures were designed according to the Iranian Steel Design Code, which is based on the force-based approach using the load and resistance factor design method (LRFD). The frame elements were composed of conventional steel from Iran having a yield strength and modulus of elasticity of F_y 240 MPa, F_u = 370 MPa and E = 200 GPa, respectively. The beam section ranges were 2IPE270 and 2IPE300 with box sections of 0.34 ´ 0.34 ´ 0.03 m to 0.36 ´ 0.36 ´ 0.03 m assigned to the column elements. Fig. 1 shows the 3D view and plan view of the reference structure.

The geometric representations of frames with setbacks were similar to the reference frame. Regular and irregular frames included those with bays in each direction and floor-to-floor heights of 5 and 3 m, respectively. The area setback ratio (R_A) and height setback ratio (R_H) were used to develop a rational grouping of irregular frames (Shakib and Pirizadeh 2014). These groupings were used to develop a comprehensive comparison between the seismic response of the regular and irregular frames with SATMDs. Fig. 2 shows the elevation views of steel frames with different setback irregularities.

OpenSees software was used to develop the numerical model and perform the nonlinear time history analysis (McKenna 2011). In order to simulate the numerical model for the frames, Steel01, Fiber Section and Nonlinear Beam-Column were used for the uniaxial bilinear steel material, sections and elements of the frames.

For all modeled structures, both modal and push-over (non-linear static) analyses were performed to determine the dynamic characteristics and structural capacity, respectively. After that, non-linear time history analysis was carried out to determine the seismic response of both types of frame under uncontrolled and controlled conditions. Table 1 lists the fundamental period of vibration (T_1), yield drift ratio (Θ_y), and coefficient of yield strength (C_y) for the reference frame and irregular frames with setbacks. Fig. 3 shows the capacity curves (base shear normalized with respect to the frame weight, V_b/W, versus roof drift ratio) were drawn from the results of nonlinear static analysis of the regular and irregular structural models. Fig. 3 and Table 1 show that, as the setback parameter values increased, especially when R_A and R_H were greater than 50%, the capacity of the irregular structure was significantly less than for the reference frame. For example, parameters Θ_y and C_y for the reference frame were 1.1 and 0.14 and for the irregular frame (No. 09) were 0.70 and 0.06, respectively.

Table 1. Dynamic and mechanical properties of frame models

Frame model	T_1 (s)	Θ_y (%)	C_y
00.Reference	1.92	1.1	0.14
01.R_A0.25_R_H0.30	1.78	1.1	0.13
02.R_A0.25_R_H0.50	1.77	1.0	0.12
03.R_A0.25_R_H0.70	1.81	1.0	0.12
04.R_A0.50_R_H0.30	1.64	1.0	0.12
05.R_A0.50_R_H0.50	1.58	1.0	0.11
06.R_A0.50_R_H0.70	1.68	1.0	0.11
07.R_A0.75_R_H0.30	1.47	1.0	0.11
08.R_A0.75_R_H0.50	1.33	0.7	0.07
09.R_A0.75_R_H0.70	1.35	0.7	0.06

Standard 2800 was followed to perform nonlinear time history analysis of frames from the PEER-NGA database. Seven strong ground motions that featured hazard characteristics that were relatively similar to this code were selected (Table 2). In the Iranian Seismic Design Code, the soil class chosen was type III ($175 < V_{s30} < 375$ m/s). In the first stage, seismic events with limitations such as an average soil shear-wave velocity of $175 < V_{s30} < 375$ m/s and a relatively strong ground motion of large magnitude (6 < M

<7.6) were selected to consider far-field events without pulse effects. In this case, the closet distance to the fault rupture was limited (20 < R < 50 km).

Next, the mean linear acceleration response spectrum (damping = 5%) for all selected ground motions was calculated and compared to the standard acceleration response spectrum of the Iranian Seismic Design Code (standard 2800). The comparison of the mean linear acceleration response spectrum of the selected event and standard 2800 of 0.2T to 1.5T (where T is the fundamental building period) showed acceptable matches (Fig. 4).

Table 2. Seismic characterization of selected ground motion records (PEER-NGA database)

No.	Event name	year	Station	Magnitude	R (km)	V_s30 (m/s)
1	Northridge-01	1994	Lawndale—Osage Ave	6.69	39.91	311.86
2	Landers	1992	Thousand Palms Post Office	7.28	36.93	333.89
3	Landers	1992	North Palm Springs Fire Sta #36	7.28	26.95	367.84
4	Kobe	1995	Yae	6.9	27.77	256
5	Imperial Valley-06	1979	El Centro Array #13	6.53	21.98	249.92
6	Morgan Hill	1984	Fremont-Mission San Jose	6.19	31.34	367.57
7	Loma Prieta	1989	Salinas-John & Work	6.93	32.78	279.56

In past studies on vibration control of structures using passive, active and semi-active control methods, it is evident that the advantages of semi-active control were greater than for the other two approaches. With regard to the cost efficiency of the semi-active over the active control methods, equipment that is less costly and consumes less energy is required. The performance efficiency of the semi-active surpassed that of the passive methods because the passive control had limitations on reducing the vibration of a structure under the effect of earthquakes having different frequency contents (Fisco and Adeli 2011; El-Khoury and Adeli 2013; Pirmoradian 2017).

In order to reduce the lateral vibration of structures, four semi-active strategies have been proposed in which displacement based by on-off ground-hook control (on-off DGB) was most suitable scheme and led to positive control of the structural vibration (Koo et al. 2004). The structural mass displacement and relative damper velocity were used to determine the level of on-off DBG damping as: **see formula 1 in the supplementary files section.**

where, x_1 is the structure mass displacement and v_{12} is the relative damper velocity(Koo et al. 2004). In on-off DGBs, the damper is controlled in the on state as well as the off state. When choosing between the upper and lower limits, the relative velocity across the damper should be multiplied by the absolute displacement of the main structure (Koo et al. 2004). Fig. 5 shows the ground-hook damper lumped-parameter scheme.

Ioi and Ikeda proposed empirical formulas for use when optimizing the parameters in the damped system. Optimal frequency ratio f_{opt} and optimal damping ratio ξ_{opt} are shown in Eqs. (2) and (3) (Ioi and Ikeda 1978; Ramezani et al. 2017; Ramezani et al. 2019):

See formulas 2 and 3 in the supplementary files section.

where $\bar{m}$ is the damper mass ratio and ξ_s is the structural damping ratio. If the damper mass ratio is equal to 2% and the structural damping value is assumed to be 0.05, then the optimal frequency and damping ratio for the damped system will equal 0.96 and 0.09, respectively (Bathaei et al. 2018). For on-off DBG, the upper and lower state parameters for damping were 0.15 and 0.03, respectively. Their average value will be approximately equal to ξ_{opt}.

To simulate the performance of SATMD for controlling structural vibrations in OpenSees, a Zero-Length element was defined for which damping depended on Eqs. (1), (2) and (3). This produces a controllable damping ratio that changes during the vibration.

Vibration Control Of Structures

The efficiency of SATMD devices for reducing the seismic response of both regular and irregular structure models was assessed. Three conventional engineering parameters, the inter-story drift ratio (IDR) demand, story displacement demand and base shear of the structure under the effect of selected earthquakes were studied. The SATMDs were located on different stories and seven time-history analyses were tested using the selected earthquake records. The mean maximum IDR and maximum story displacement were drawn as a line graph and the mean maximum base shear was calculated for each structure. The exact location of the SATMD devices is denoted as a number at the end of the SATMD statement. For example, graph SATMD1 shows the average response of the frame with a SATMD located on story 1under the effect of seven ground motions.

4.1 Inter-story drift ratio

The effect of SATMDs on decreasing the IDR demand of buildings subjected to ground motions is presented in Fig. 6. It is clear that the maximum IDR demand for the uncontrolled regular (reference) structure (No. 00) and the irregular structures (01, 02, 03, 04, 06 and 07) for most frames were in the middle stories (3rd to 6th). However, for irregular frames 05, 08 and 09, the maximum IDR demand occurred in the middle and top stories (7th to 10th), which were located above the setback stories.

Fig. 6 reveals that the use of SATMD devices in stories 1, 2, 3 and 4 had either a lower or negative effect on reducing IDR demand in all models in comparison with the uncontrolled models. The overall maximum IDR demand for irregular frames equipped with SATMD devices decreased strongly, indicating that the SATMD devices worked efficiently. In frames 00 (reference/regular), 01, 02, 03, 04, 06 and 07, the efficiency of the SATMD for reducing the IDR demand occurred in the stories in which the maximum IDR demand occurred (middle stories). The top and bottom stories did not experience a significant decrease. In frames 05, 08 and 09, the greatest decrease in IDR occurred in stories 7, 10 and 9, respectively. It appears that the efficiency of the SATMD devices to control the seismic response of irregular frames was better than for the reference frame (No. 00).

The ability of these devices to decrease the IDR is related to the location where the vibration control equipment is attached. For example, when the SATMDs were located on the fourth floor and the roof, the maximum IDR demands of controlled irregular frame 01 for story 4 decreased by 2% and 12%, respectively, compared to the uncontrolled frame. However, totally the vibration of the middle stories decreased more than of the top and lower stories. The ability of the SATMDs at different locations to control the vibration of irregular structures with setbacks (include of different parameters R_A, R_H) was greater than for the reference frame (Fig. 6).

It can be seen that all irregular frames with SATMDs having dampers on the top story recorded the lowest IDR values during an earthquake event. For example, the irregular frames (01, 04 and 07) with SATMD4 (story 4) and SATMD10 (roof) recorded the maximum IDR in the middle story (4) and a 20% decrease in the maximum IDR for SATMD10 in the uncontrolled frame. However, the location of the SATMDs did not strongly affect the structural response of the regular frames as well as irregular frames. The dampers located on the lower stories showed limited effects on the seismic control of the irregular frames that were similar to those for the regular frame.

The maximum IDR for frames 00 to 07 showed a clear trend and occurred in the middle stories (5 and 6). The maximum IDR trend for frames 08 and 09 differed. In frame 08, the maximum drift values occurred in the top stories, with an increase beginning at story 5. In frame 09, the maximum IDR trend started from story 5 toward story 10 and the IDR values in top stories were similar. It seems that the maximum IDR trend for structures with significant setback parameters ($R_A \geq 0.50$, $R_H \geq 0.50$) migrated from the middle stories toward the top stories (6 to 9).

Damage indexes measure the amount of damage to a structure. Different damage indexes have been proposed for different types of structures. In this study, the damage to frames equipped SATMDs was measured using the HAZUS damage index according to the IDR demand (HAZUS, 1999). Table 3 shows the relation between IDR and the HAZUS damage state for steel MRF structures that are low-rise (1-3 stories), mid-rise (4-8 stories) and high-rise structures (8+ stories). The HAZUS damage index indicated that the SATMD caused reduce the damage state from extensive to moderate damage. Fig. 6 shows that the damage state of the controlled regular frame did not change relatively compare to the irregular frames.

When R_A limited ($R_A \leq 0.5$), the decrease in IDR demand was clear for irregular frames (No. 01 to 06) for most cases where the SATMDs were located on different levels, however, in some cases, the maximum

IDR demand of a controlled structure increased and showed no clear trend for controlling the structure (No. 07 to 09). For example, the maximum IDR demand for the regular frame and irregular frames (03, 06, 09) with SATMDs on stories 1 and 2 increased compared to the uncontrolled irregular frames (Fig. 6). It seems that the use of SATMDs in irregular structures requires different SATMD parameters as well as analysis under the effects of a variety of earthquake events. Fig. 6 shows that the IDR demand in irregular structures with significant setbacks ($R_A > 0.50$, $R_H > 0.5$) showed no obvious trend and their seismic performance with SATMDs at times produced negative results, which is vital to consider for such structures.

Table 3. IDR of MRF based on HAZUS (HAZUS, 1999)

Damage state	Low-rise	Mid-rise	High-rise
Slight	0.006	0.004	0.003
Moderate	0.010	0.0066	0.005
Extensive	0.024	0.016	0.012
Complete	0.060	0.040	0.030

4.2 Story displacement demand

The effect of the use of SATMD devices on different stories to control the maximum lateral displacement of both structure types was examined. Fig. 7 clearly shows that SATMDs could be used to control story displacement of regular frames as well as reduce the displacement demand by irregular frames with different setbacks. For example, a comparison of uncontrolled and controlled frame types for the regular frame and irregular frame No. 06 shows that the maximum displacement of the roof decreased about 5% and 25%, respectively. When the SATMDs were attached to the roofs of all structures, their performance was clear. Fig. 7 shows that the efficiency of SATMDs on frames with moderate setback area ratios ($R_A \leq$ 0.25) was not as great as for the other irregular frames. It is clear that SATMDs efficiently reduced the story displacement demand in most structures. If the purpose is focused control of story displacement, the SATMD showed acceptable positive results.

Fig. 7 shows that the effect of SATMD location on reduction of the story displacement demand is similar to the IDR demand. The highest story was the best place to attach the SATMD to the frames, while the efficiency of SATMDs on stories 1 and 2 was negative could cause an increase in displacement of the stories. Fig. 7 shows that the SATMDs reduced the story displacement of irregular frames more than of the regular frame, 10% ,2%, each.

Fig. 8 shows the time history for 4th story of frames with SATMDs located on the roof (SATMD10) under effect of the Northridge01earthquake record. The story was selected because their graphs (Fig. 6) show that, in most cases, the maximum IDR demand was in the middle stories. It seen, as R_A increased ($R_A \geq$ 0.50), the peak displacement story (PDS) in 4th story decreased significantly. The PDS for irregular frames 04, 05, 06 and 07 in the controlled structure decreased by more than 20%.

In most cases of controlled structures with SATMDs, except the reference frame and irregular frames at $R_A \geq 0.75$ and $R_A \leq 0.25$ (01, 02, 03, 08 and 09), after maximum story displacement was recorded, the response of the structure decreased sharply. This could depend on SATMD parameters becoming more active after reaching the peak point of the reaction.

4.3 Base shear factor

The base shear factor is the maximum base shear recorded during an earthquake event over the total weight (V_b/W) for the uncontrolled and controlled frames. Fig. 9 shows that, for all models, the base shear factor for the controlled models was less than for the uncontrolled models. It can be seen that an increase in irregularity factors R_A and R_H increased the base shear factor.

The location of the SATMD will influence the base shear factor. It is clear that, for this parameter, regardless of the irregularity factors, the best location for the SATMD was the highest level leading to efficient control of the base shear factor of the structure. Moreover, it could be seen that, as R_A and R_H increased, the difference between the base shear factors for controlled structures and uncontrolled structures decreased.

When a SATMD was added to the structure, part of the input energy from the earthquake was absorbed by the SATMD and released as input energy with damping and kinetic energy. This energy absorption decreased the IDR, story displacement and base shear in the controlled structures.

Conclusion

The objective of this study was to determine the efficiency of SATMD devices for controlling the seismic response of regular and irregular steel MRF structures under earthquake excitation. It appears that the use of SATMDs for reducing the vibration of structures can be efficient without a specific increase in maximum IDR, story displacement and base shear demand.

Engineers can attach SATMDs to existing regular and irregular frames and as a useful option for the control of vibrations in existing buildings. The roof story is the best place for SATMDs when reducing the seismic response of structures. Attaching SATMDs to lower stories may increase the vibration response of the structure. In order to assess the effect of SATMDs for controlling the vibration of structures, the engineering demand parameters of maximum IDR demand, story displacement demand, and base shear were considered. Following results are extracted from this study:

- The use of SATMDs for irregular frames with setbacks had a significantly greater effect on seismic control than for regular frames.
- The maximum IDR trend for structures with limited setback parameters ($R_A < 0.50$, $R_H < 0.50$) is located in the middle stories (4th to 6th).
- The maximum IDR trend for structures with significant setback parameters ($R_A \geq 0.50$, $R_H \geq 0.50$) migrated from the middle stories toward the top stories (6 to 9).
- The damage state of irregular frames with setbacks changed from extensive to moderate.
- The SATMDs on lower stories (1, 2, 3, 4) of controlled frames had negative effects on IDR in comparison with the uncontrolled frame.
- Generally, the displacement in the stories of all structures decreased significantly without exception.
- The influence of SATMD to reduce displacement was evident after the peak of the earthquake.
- The base shear factor of all structures with SATMDs decreased relative to uncontrolled structures; however, this factor increased as the setback increased.
- It appears that the highest level (roof) is the best location for the SATMD in irregular frames as well as for the regular frame.
- In some irregular frames, the use of a SATMD in other stories can cause negative effects on the seismic response of controlled structures. The IDR demand at these locations for uncontrolled structures was less than for the controlled structures.

Declarations

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Conflict of interest/Competing interests (The Authors declare that they have no conflict of interest)
Availability of data and material (Data and material are available)
Code availability (The developed codes are available)
Plant reproducibility (Not applicable)
Clinical trials registration (Not applicable)
Gels and bolts/ Image manipulation (Not applicable)
High-risk content (Not applicable)

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Figures

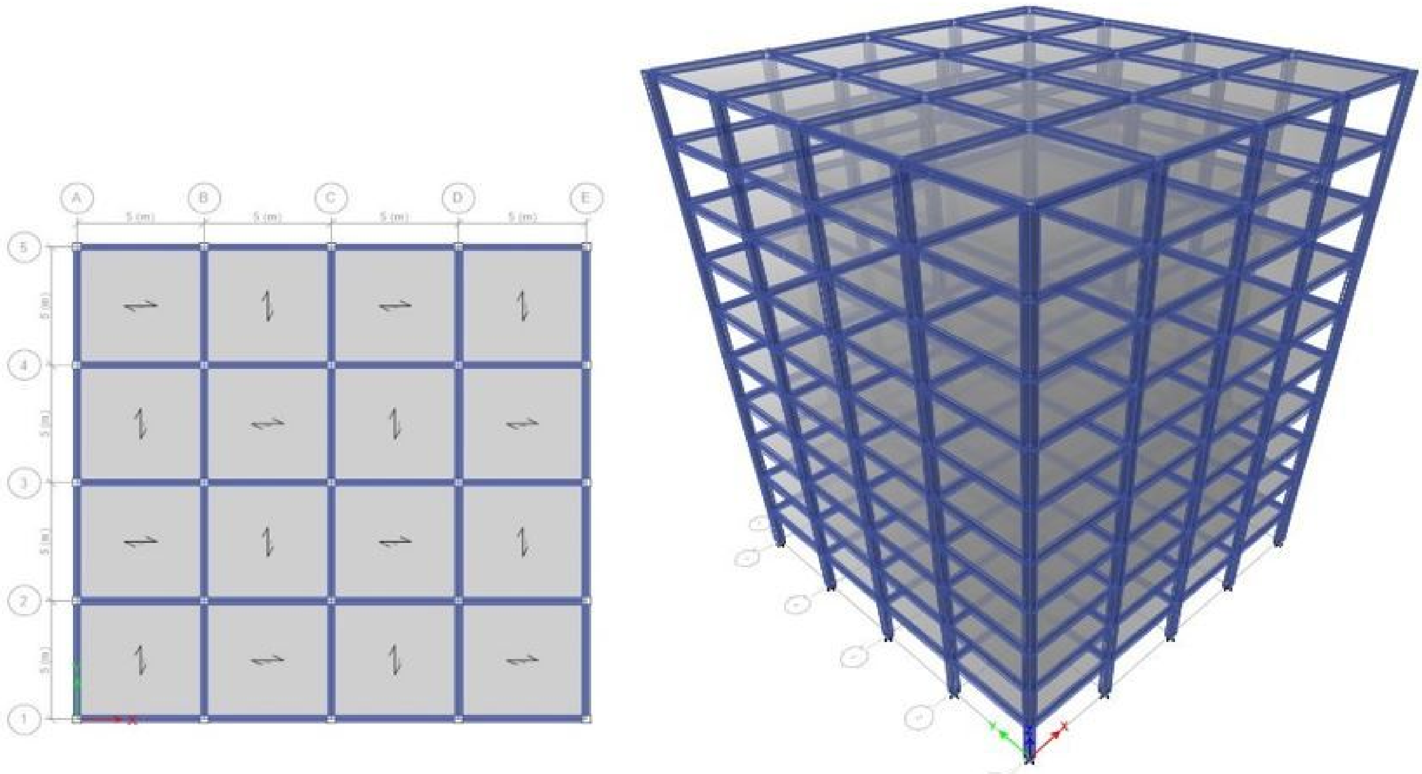

Figure 1

3D view and plan of reference frame

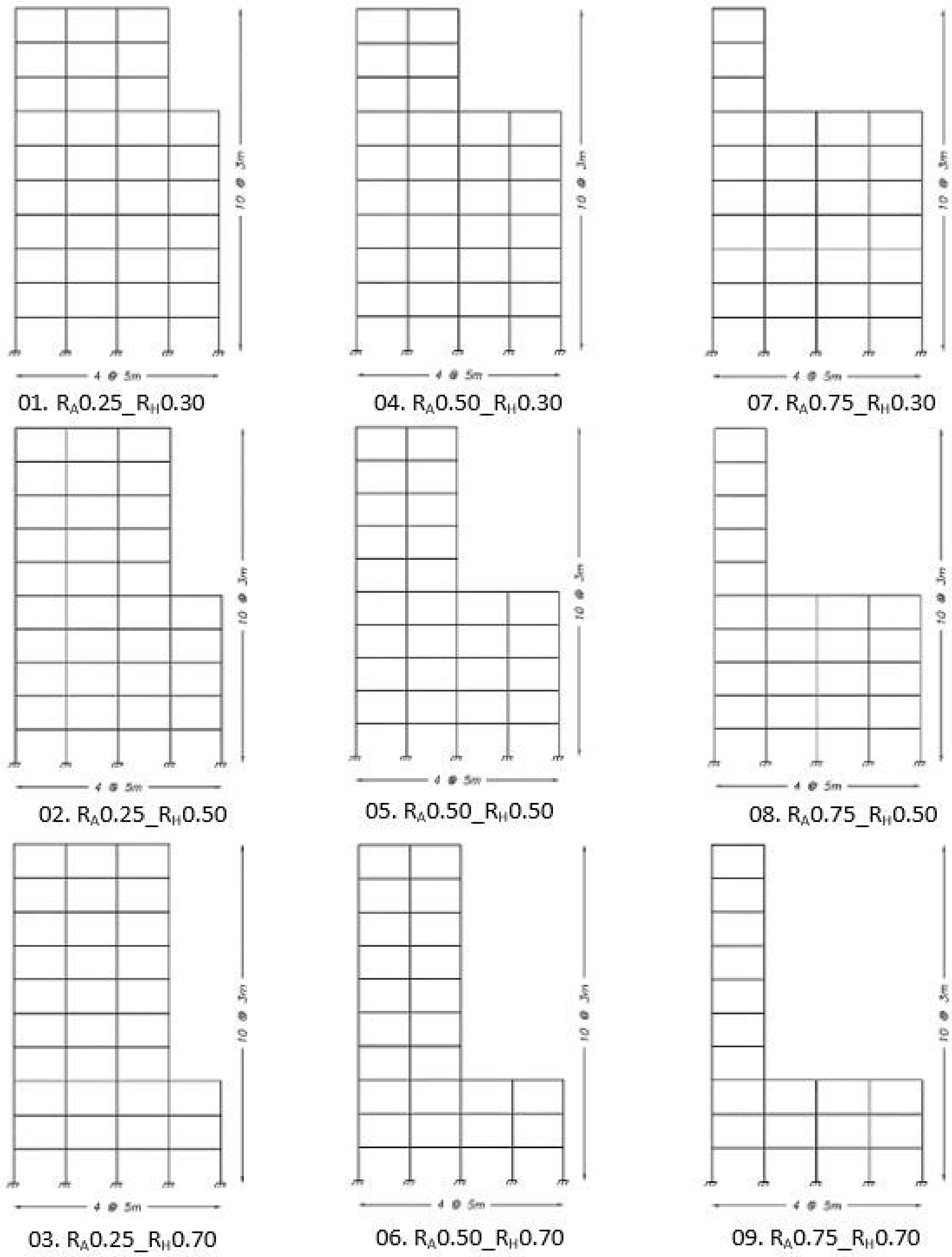

Figure 2

Steel frames with different setbacks

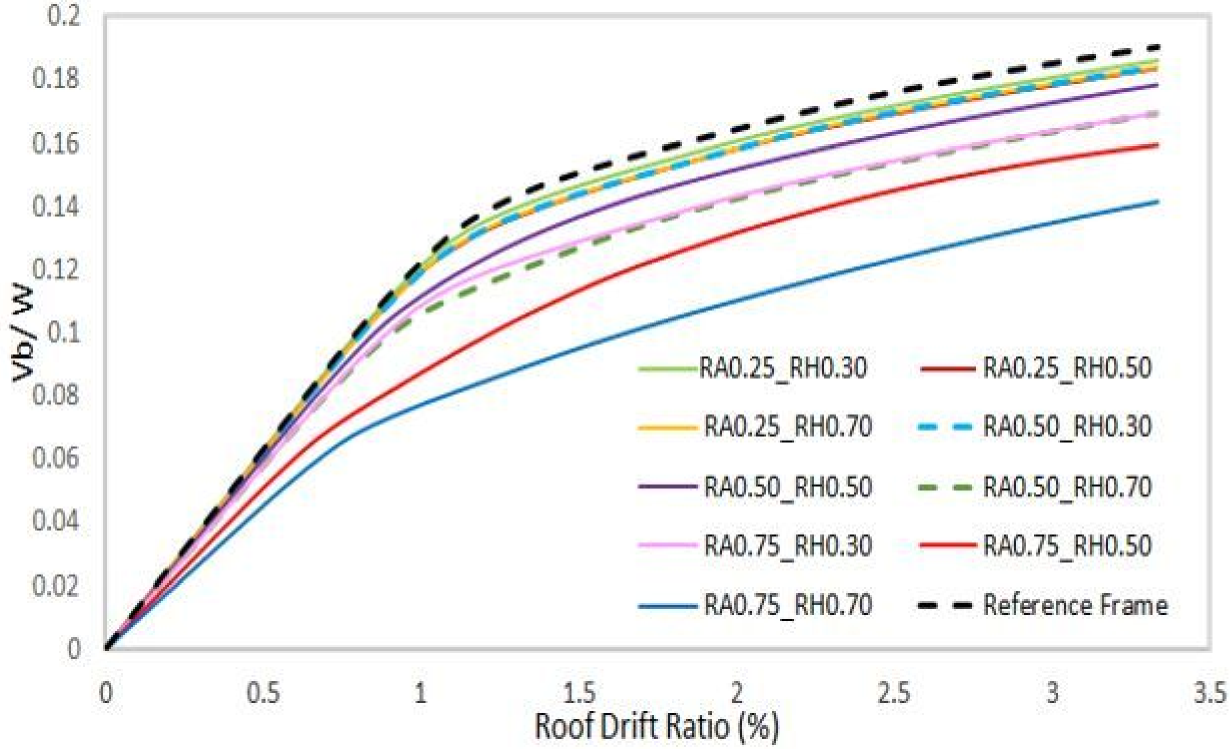

Figure 3

Capacity curves, Vb/W vs. roof drift ratio of case-study steel frames

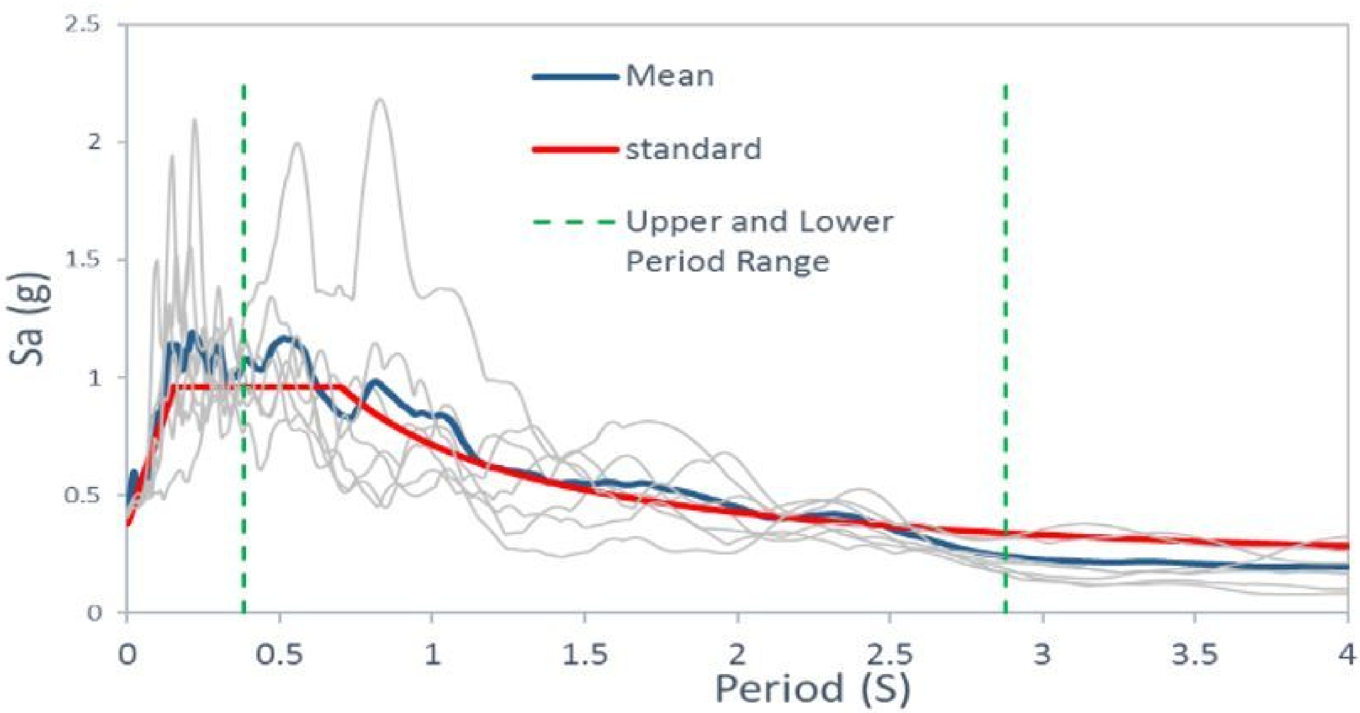

Figure 4

Target spectrum and mean response spectrum of selected ground motions

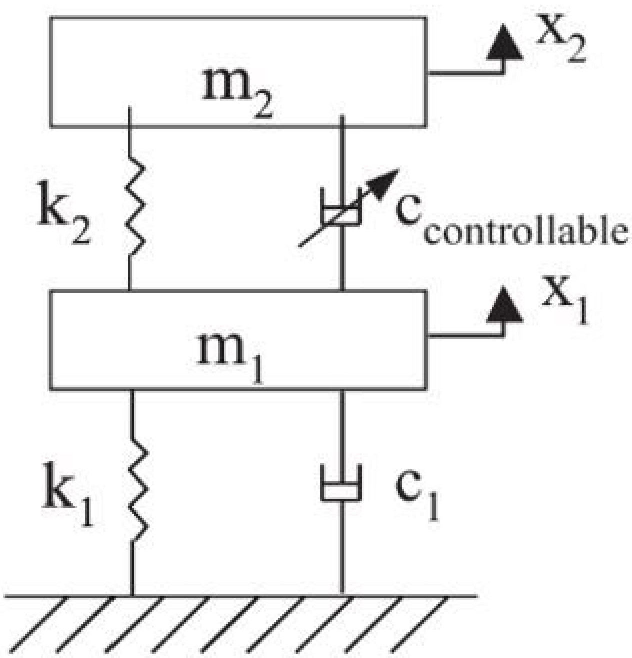

Figure 5

Ground-hook absorber scheme (Koo et al. 2004)

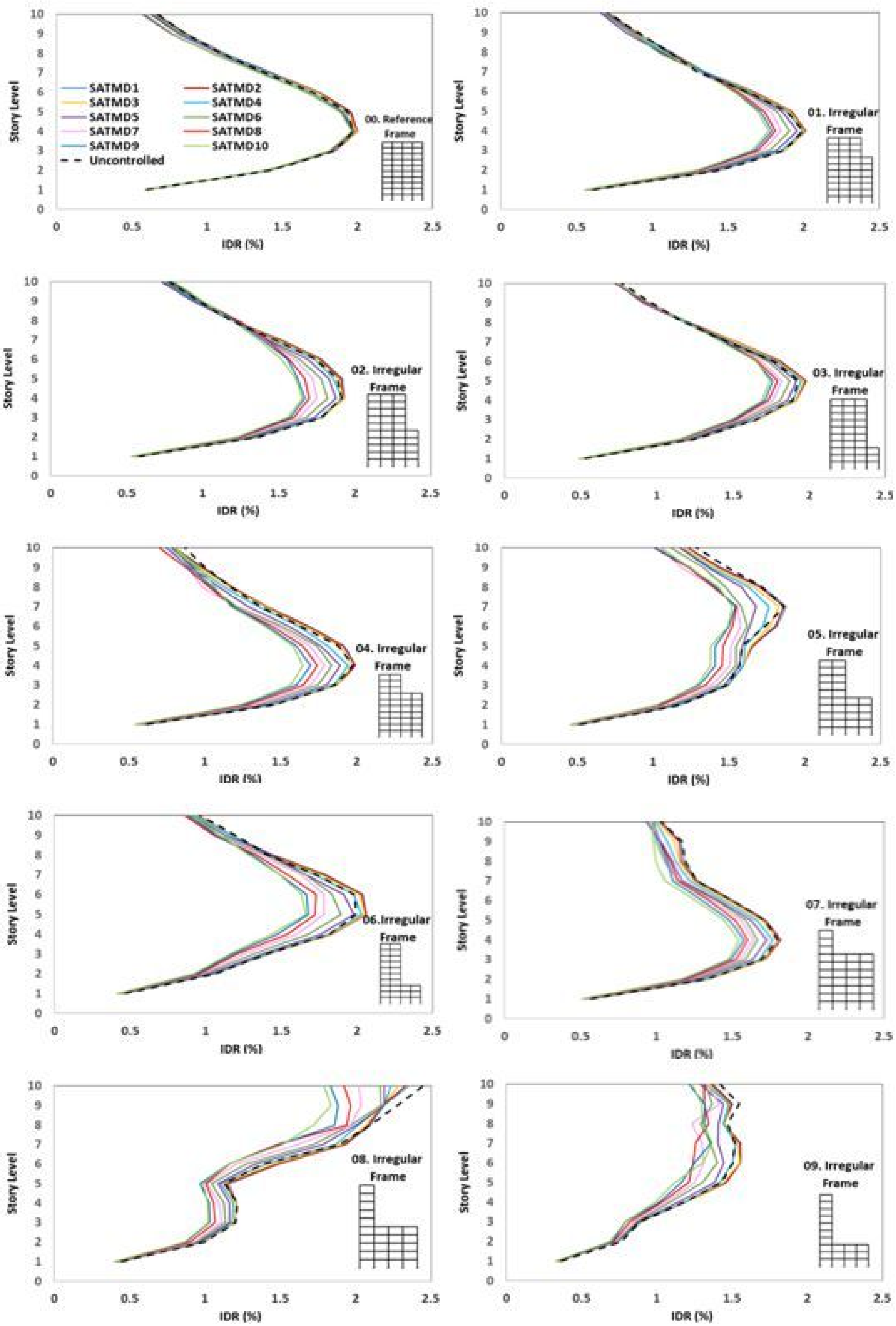

Figure 6

Height-wise IDR demand distribution for all frames

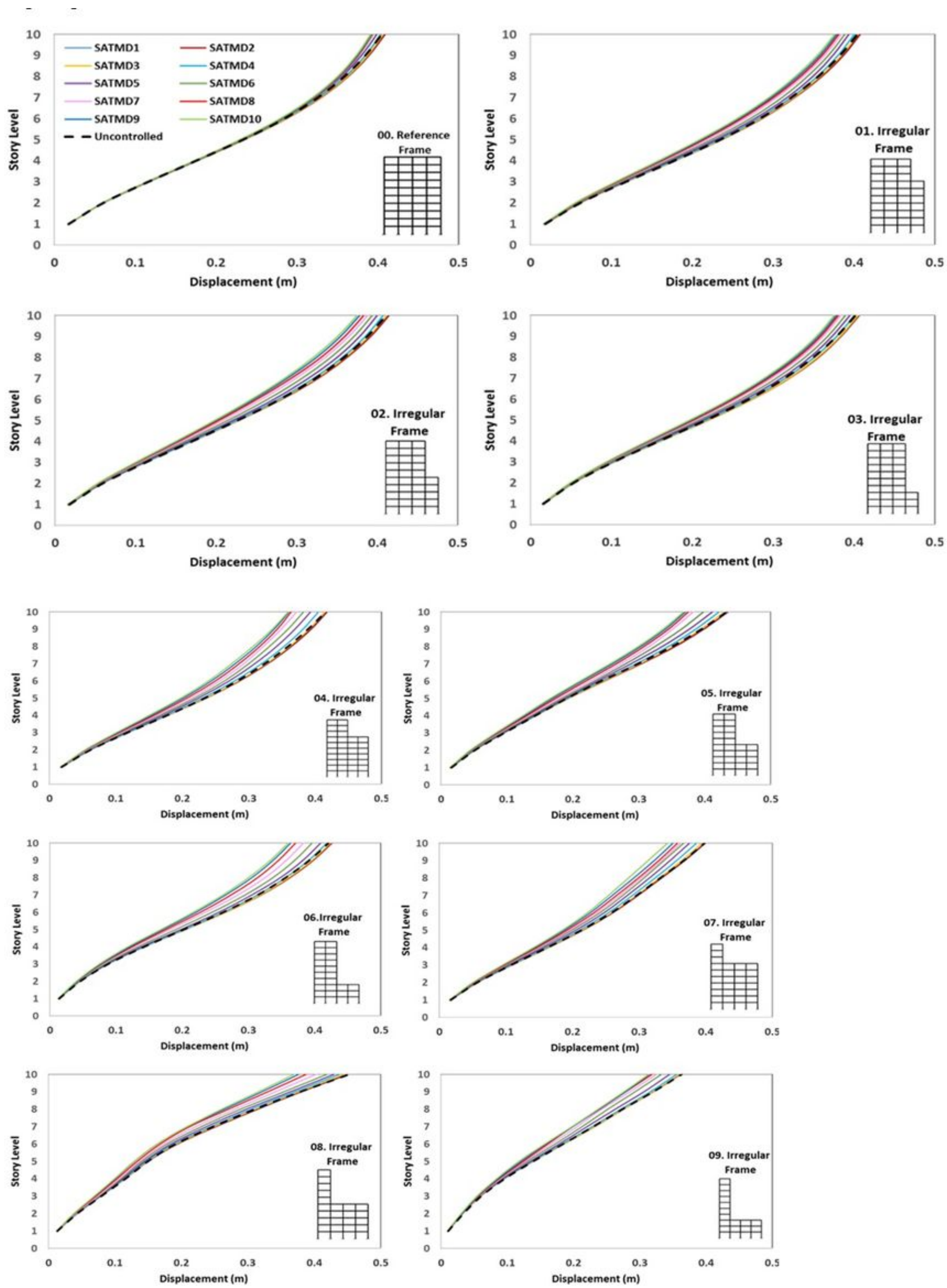

Figure 7

Height-wise displacement demands distribution for all frames

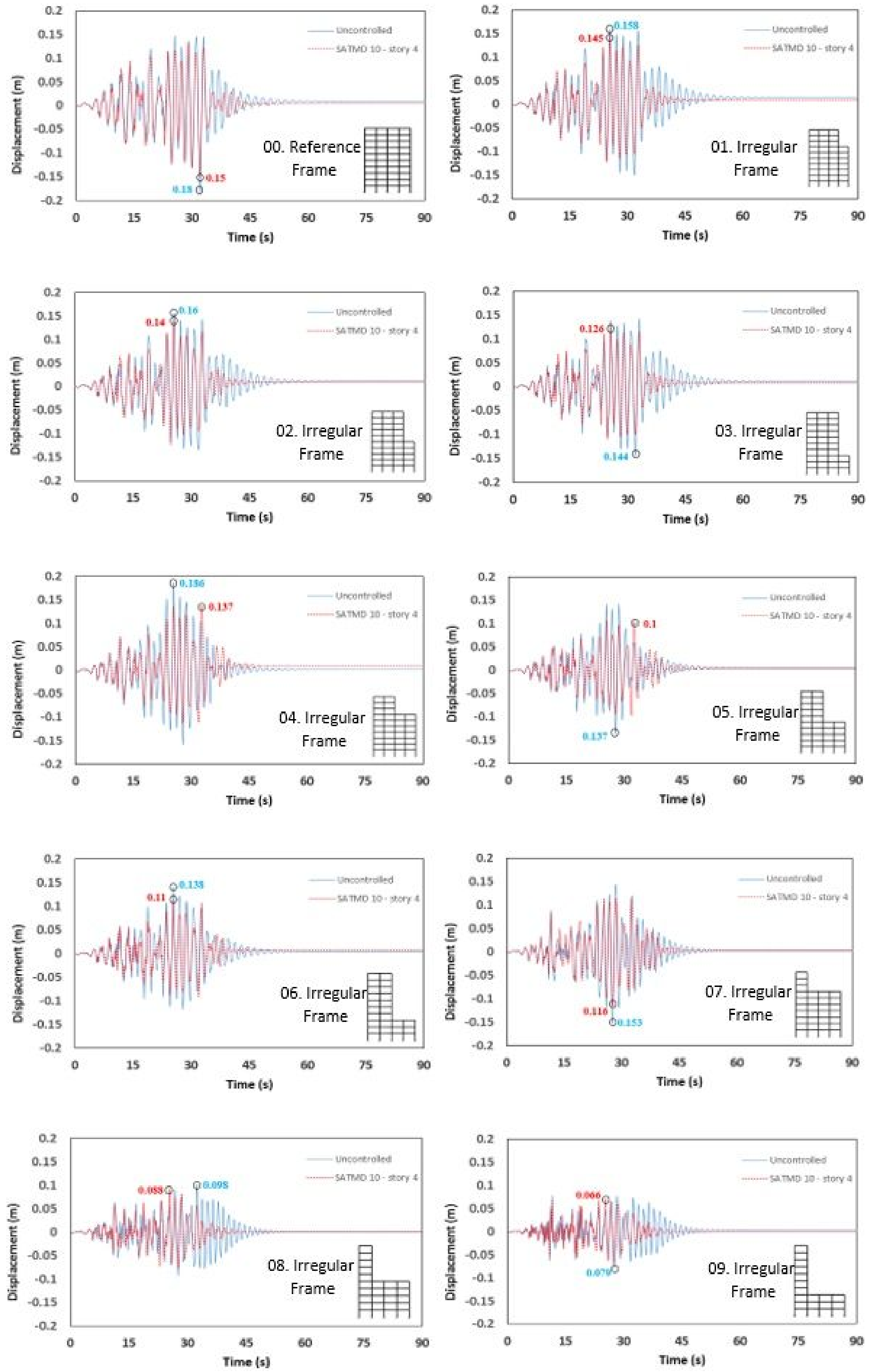

Figure 8

Time history displacement of story 4 for SATMD10

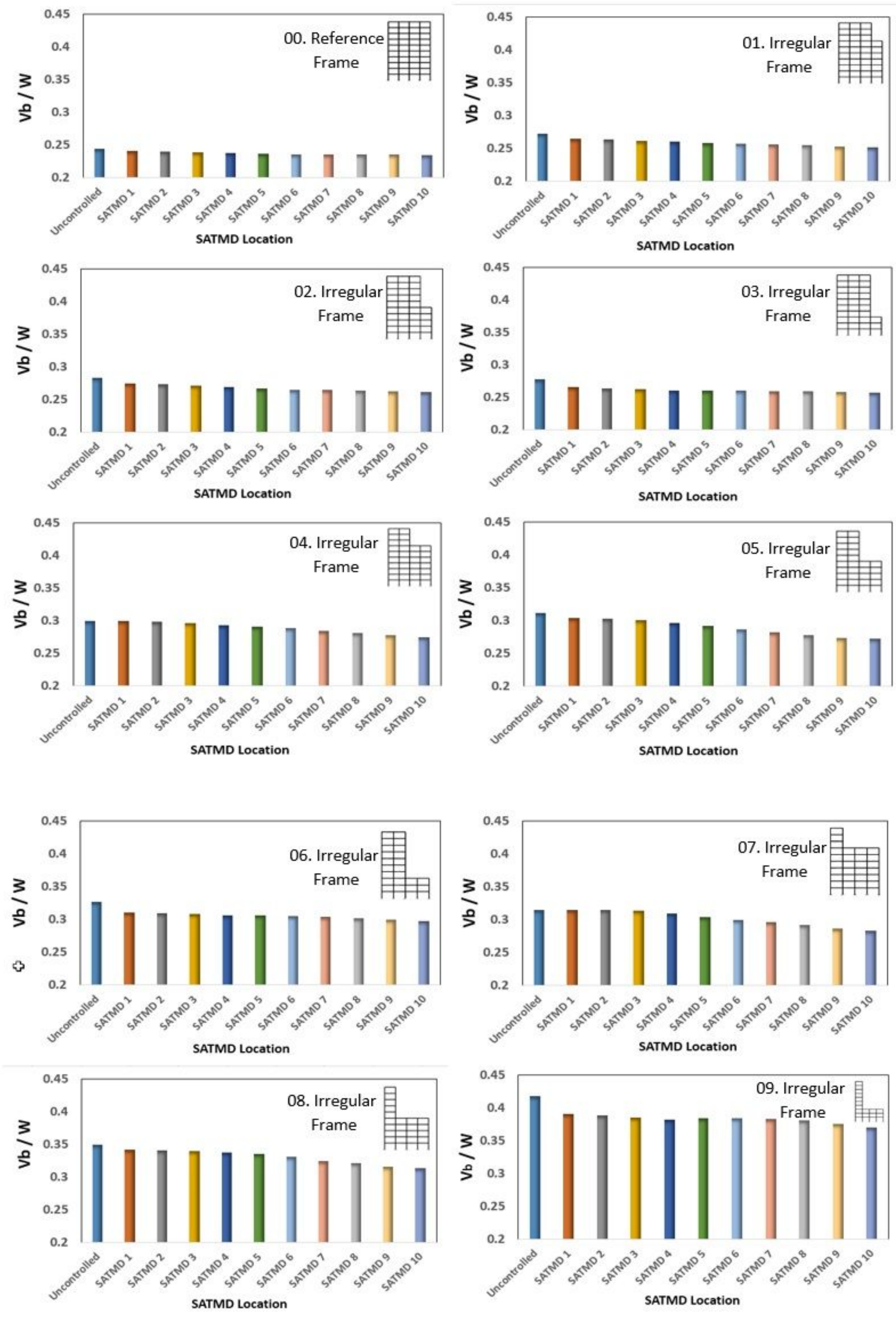

Figure 9

Maximum base shear for all frames