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Multiple failure criteria-based fragility curves for structures equipped with SATMDs

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Abstract. In this paper, a procedure to develop fragility curves of structures equipped with semi-active tuned mass dampers (SATMDs) considering multiple failure criteria has been presented while accounting for the uncertainties of the input excitation, structure and control device parameters. In this procedure, Latin hypercube sampling (LHS) method has been employed to generate 30 random SATMD-structure systems and nonlinear incremental dynamic analysis (IDA) has been conducted under 20 earthquakes to determine the structural responses, where failure probabilities in each intensity level have been evaluated using Monte Carlo simulation (MCS) method. For numerical analysis, an eight-story nonlinear shear building frame with bilinear hysteresis material behavior has been used. Fragility curves for the structure equipped with optimal SATMDs have been developed considering single and multiple failure criteria for different performance levels and compared with that of uncontrolled structure as well as structure controlled using passive tuned mass damper (TMD). Numerical analysis has shown the capability of SATMDs in significant enhancement of the seismic fragility of the nonlinear structure. Also, considering multiple failure criteria has led to increasing the fragility of the structure. Moreover, it is observed that the influence of the uncertainty of input excitation with respect to the other uncertainties is considerable.

Keywords: fragility curves; semi-active tuned mass damper; multiple failure criteria; structural uncertainty; SATMD uncertainty

1. Introduction

The tuned mass damper (TMD) is a passive structural control mechanism that absorbs seismic energy by oscillating under dynamic loads such as wind and earthquake. The capability of TMD in mitigation of structural response has led to receiving much attention during past years and even implementation in many actual buildings (Bagheri and Rahmani-Dabbagh 2018). Due to the fact that TMD should be tuned to a fixed frequency, it may have no benefits during some earthquakes which induce the structure to vibrate in other frequency bands. Furthermore, under severe earthquakes, the structure undergoes nonlinear behavior which may detune the TMD and consequently will lead to inefficiency. Alternatively, the semi-active tuned mass damper (SATMD) with variable damping (Santos and Coelho 2019, Sun *et al.* 2018, Shi *et al.* 2018) or variable stiffness (Karami *et al.* 2019, Tang *et al.* 2018, Wang *et al.* 2018) has been proposed to overcome the disadvantageous of conventional TMDs. Many studies have focused on the performance assessment and optimal design of SATMDs for linear and nonlinear structures in a deterministic manner.

However, loading uncertainties caused by the random nature of earthquakes could heavily affect the efficiency of SATMDs. Thus, the uncertainties in applied excitation should be considered in assessing the performance of SATMDs in a probabilistic framework. A systematic way to probabilistic analysis and reliability assessment of structures dealing with the randomness of the input excitation is the development of fragility curves. Fragility curves represent the conditional probability of being in or exceeding some performance capacities over prescribed intensity measure. Seismic fragility analysis was first used for the safety assessment of nuclear power plant (Kaplan *et al.* 1983). In the following, it has extended for bridges (Soltanieh *et al.* 2019, Xiang and Alam 2019) and buildings (Minas and Galasso 2019, Pnevmatikos *et al.* 2019).

During the past decade, many investigations have been done on fragility and risk analysis of structures equipped with control systems such as passive, active and semi-active mechanisms. Some researchers have conducted fragility analysis of isolated structures (Bao *et al.* 2018, Shoaei *et al.* 2018) and structures equipped with passive dampers (Taiyari *et al.* 2019, Scozzese *et al.* 2019, Silwal and Ozbulut 2018, Landi *et al.* 2017). Also, the effectiveness of semi-active dampers and active control systems has been studied (Kim and Bai 2016, Wilbee *et al.* 2015, Barnawi and Dyke 2014, Barnawi 2008, Taylor 2007). As a result of most studies, it has been found that semi-active control systems have the capability of reducing the fragility of the structure more effective than passive control systems. Studies on fragility and risk assessment of mass damper mechanisms are very limited, where focuses only on the passive TMD (Shu *et al.* 2017, Lee *et al.* 2012, Wong and

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Harris 2012, Farrokhi and Rahimi 2017). However, further insights are needed to assess the performance of SATMDs in improving the fragility of the structures. For this purpose, an investigation has been presented by the authors to demonstrate the efficiency of the SATMDs (Bakhshinezhad and Mohebbi 2019) which has shown the superiority of SATMD with respect to passive TMD in fragility mitigation. In all these studies, only single failure criterion has been used in fragility definition and also the uncertainties of the structure and TMD parameters have been neglected.

In the previous investigations, the complexity of fragility analysis of structures retrofitted with control systems led to the adoption of numerous simplifications related to failure definition and structural model uncertainties, without explicit consideration of control device's uncertainties and failure modes. With regard to failure definition of the entire building, many existing studies considered only single failure criterion (e.g., drift, base shear, acceleration and etc). However, a complicated structure which is a combination of several structural and non-structural components may be sensitive to different responses and discrete failure modes may occur simultaneously. In literature, different combinations of multiple failure criteria have been recommended for failure definition in the probabilistic analysis (Risi *et al.* 2019, Cattari *et al.* 2019, Simoes *et al.* 2019, Cimellaro and Reinhorn 2011, Gavin and Yau 2008). Furthermore, because of practical limitations, structural control systems may have their own failure modes, where it has been disregarded in numerous researches performed in this field. In particular, SATMD is constructed with a specific stroke length and could vibrate just in this range and exceeding the relative displacement from this limit leads to failure. Therefore, for a structure equipped with SATMD system, it is more appropriate to define the whole failure based on multiple failure criteria related to the entire structure and the stroke length of the device. With regard to structural model uncertainties, many existing procedures employed oversimplified uncertainty model that neglect the effects of different sources of uncertainties in structural parameters and even control system characteristics. Particularly, in the case of mass damper mechanisms, these uncertainties which relate to mass, stiffness and damping of TMD can have a significant influence on the performance of the control system. Thus, it is required to account for the effects of the uncertainties of the structure and SATMD parameters.

In this paper, a procedure to develop the fragility curves for structures equipped with SATMDs considering multiple failure criteria of the structure and control device has been presented. This procedure accounts for the uncertainties of the structural parameters and control device characteristics using the "Latin hypercube sampling (LHS) method, given its capabilities, to generate sample SATMD-structure systems. Fragility curves have been developed considering single and multiple failure criteria where the effect of different failure modes on the fragility accounting the correlation between them have been studied and the performance of the optimal SATMDs in reducing seismic fragility of the nonlinear structure has been investigated.

In the following sections, first, the concept of fragility curves and multiple failure criteria fragility considering series combination between failure modes will be described. Successively, uncertainties related to the input excitation, structural parameters and control device properties will be characterized. Finally, as numerical analysis, the incremental dynamic analysis will be conducted on a nonlinear shear building equipped with SATMD and the fragility curves will be developed, followed by discussion and conclusions.

2. Fragility curves

Failure definition is a major task in assessing the probability of failure and subsequently the fragility of a seismic structure. Based on reliability theory (Nowak and Collins 2000), the failure is defined by limit state function or performance function as following

$$g = f(C_R, R) = C_R - R \tag{1}$$

By extending this definition to the whole structure, R can be the response of the entire building such as drift, acceleration, base shear and etc., C_R is the capacity threshold related to the response R. if $g>0$, structural performance is acceptable and the structure is safe. Conversely, when $g\leq0$, the response is equal or exceeds the capacity, then the structural performance is not acceptable and the structure is failed. Fragility represents the conditional probability of being in or exceeding some capacity thresholds by structural demand responses over prescribed intensity measure. The mathematic formulation of fragility is defined as follows

$$F(im) = P\left[g \leq 0 \middle| IM = im\right] = P\left[R \geq C_R \middle| IM = im\right] \tag{2}$$

where IM denotes the intensity measure of the input excitation.

2.1 Multiple failure criteria

An important issue in seismic fragility analysis is to define failure for the whole structural system. Based on the type and application of the structures, different safety and serviceability criteria may be used for fragility definition. For this purpose, many global responses of the structure such as drift, displacement, acceleration, base shear and etc., can be considered as failure criterion. Also, the stroke length of SATMD is a failure criterion for the control device. With regard to dealing with multiple failure criteria, the ith performance function related to ith failure mode is as follows

$$g_i = C_{R-i} - R_i \tag{3}$$

where C_{R-i} is the capacity threshold of the ith failure mode, and R_i is the corresponding global response of the structure or control device. The failure probability of a structural system depends on the system configuration which is among series or parallel systems. A series system fails when even just one failure mode occurs and a parallel system fails when all of the failure modes are attained. In this paper, a series combination has been assumed for the structural system which has been commonly used for this type of studies in the literature (Tubaldi *et al.* 2014). The probability of failure of a series structural system is the summation of probabilities of different failure criteria as follows

$$P_f\,(system) = \bigcup_{i=1}^{N} P_{f-i} \tag{4}$$

where N denotes the number of considered failure modes. Regarding the statistical dependence among failure modes, the failure probability of the series structural system belongs to the following range (Ditlevsen and Madsen 1996)

$$\max_{i=1}^{N}\left[P_{f-i}\right] \le P_f\,(system) \le 1 - \prod_{i=1}^{N}\left[1 - P_{f-i}\right] \tag{5}$$

The lower bound corresponds to the case that all failure modes are fully coupled which has led to an un-conservative estimate of failure probability. Conversely, the upper bound relates to the case that all failure modes are statistically independent which provides a more conservative and commonly used failure probability. As the fragility is the probability of failure in specified intensity measure, the bounds of the fragility of the whole structural system considering multiple failure criteria can be derived as follows

$$\max_{i=1}^{N}\left[F_{f-i}(im)\right] \le F_{system}(im) \le 1 - \prod_{i=1}^{N}\left[1 - F_{f-i}(im)\right] \tag{6}$$

2.2 Capacity thresholds

Several failure criteria based on various responses of the structure subjected to earthquake have been used for fragility analysis in the literature. Nevertheless, code based capacity thresholds in seismic provisions are limited. In this research, the maximum inter-story drift ratio as the safety criterion and maximum absolute acceleration as the convenience criterion regarding the entire building as well as SATMD stroke length are the considered failure criteria.

2.2.1 Drift ratio criterion

FEMA 356 (2000) recommends using the inter-story drift ratio (θ) to identify structural performance levels. Inter-story drift ratio is the ratio of the relative displacement between the successive stories to the story height. Capacity thresholds for inter-story drift ratio associated with steel moment frames are selected following FEMA guideline equal to 0.7%, 2.5%, and 5%, respectively for Immediate Occupancy (IO), Life Safety (LS) and Collapse Prevention (CP) performance levels. It is noteworthy that to explain the procedure of developing fragility curves, these values have been used for the case study of this research as instance.

2.2.2 Absolute acceleration criterion

Capacity of acceleration should be determined based on tolerable thresholds for non-structural components or sensitive equipment. Because of the lack of quantitative measure for capacity of acceleration, reasonable values have been considered. These values have been assumed equal to 0.7 g, 1 g, and 1.3 g, respectively for IO, LS, and CP performance levels.

2.2.3 Stroke length criterion

With regard to SATMD system, the stroke length is a specific factory product property which can be defined by the designers according to practical limitations. The maximum value of 0.5m would be acceptable for SATMD stroke length which is the same for all performance levels.

3. Uncertainties within the SATMD-structure system under earthquake

Properly accounting for the effects of various sources of uncertainties is an essential task in fragility assessment of structures equipped with semi-active tuned mass dampers. The significant uncertainties involved in such this problem which could heavily affect the performance of the controlled structure are uncertainties of the seismic excitation, structural parameters, SATMD properties and capacity thresholds as discussed in the following subsections.

3.1 Uncertainty of the seismic excitation

The uncertainty associated with the seismic excitation is comprised of the seismic intensity measure (*IM*) and the record-to-record variability which have been accounted here using incremental dynamic analysis (IDA) procedure (Vamvatsikos and Cornell 2002). In this procedure, the uncertainty of *IM* has taken into account by scaling the excitations to specified *IM* levels and increasing them up to total failure occurrence of the structure. On the other hand, to account the effects of record-to-record variability, a set of real different earthquakes with different characteristics have been considered.

3.2 Uncertainty of the structure and SATMD parameters

The effect of uncertainties in parameters of the structure and SATMD are taken into account by modeling them as random variables. In this study, the uncertainties assumed for the structure were: mass, damping, elastic stiffness and post-elastic stiffness. These random variables are the same for all stories. The exception is the mass since it was assumed that the mass can vary from story to story, it was modeled with independent random variables for each story (Dolsek 2009). Ellingwood *et al.* (1980) have suggested that the proper statistical model for the mass is the normal distribution with the coefficient of variation of 0.1. Regarding the uncertainty in viscous damping of the structure, Parker *et al.* (2003) have summarized the conclusions of several investigations based on experimental tests and monitored data under real earthquakes and recommended the coefficient of variation of 0.4 for viscous damping of the structure. Also, normal distribution has been employed for damping by following (Dolsek 2009). In this

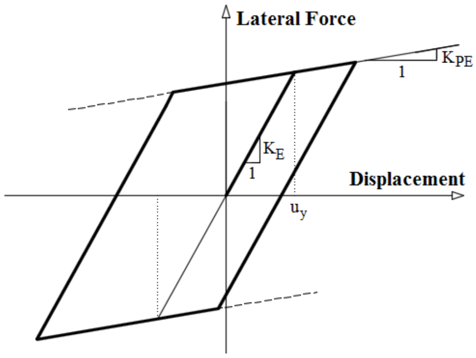

Fig. 1 Bilinear elastic-plastic stiffness model

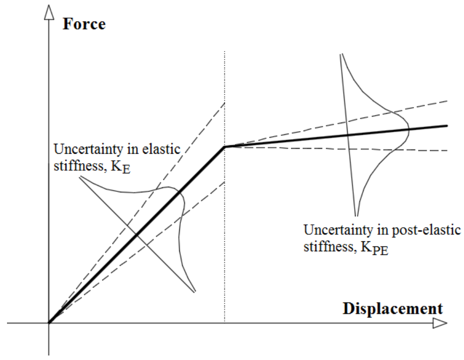

Fig. 2 Uncertain hysteresis model

paper, nonlinear shear building frame with bilinear hysteretic behavior has been used as structural stiffness model as shown in Fig. 1. K_E is the elastic stiffness, K_{PE} is the post-elastic stiffness, and u_y is the yielding drift. Uncertainty in hysteretic behavior of the structure has been assumed by modeling elastic and post-elastic stiffness as random variables as shown in Fig. 2. For the case study structure and earthquakes considered in this research, the uncertainty of the yielding drift has no significant effect on the responses. However, for other structures, it may be proper to consider yielding drift as a random parameter. Ellingwood *et al.* (1980) have recommended the coefficient of variation between the values of 0.1 to 0.3 for the resistance of steel structures. Regarding the distribution of stiffness, Sues *et al*. (1985) assumed a lognormal distribution for elastic stiffness of a shear building and Kazantzi *et al.* (2014) found lognormal distribution is more proper for post-elastic stiffness. Here, the elastic stiffness and post-elastic stiffness have been considered as discrete lognormal random variables with a coefficient of variation of 0.1 and with a correlation of 0.5 between them. With regard to the uncertainties among TMD device, there are three main parameters including mass, damping and stiffness. Mass of the device is less uncertain, so it is reasonable to consider it as a deterministic parameter. However, the damping and stiffness of the device can vary from nominal (design) values due to some reasons of manufacturing tolerances, error in detecting characteristics in the testing process, and environmental effects and aging during lifetime (Scozzese *et al.* 2019). Thus, it is more appropriate to consider damping and stiffness of the TMD as random variables. In ASCE/SEI 41-13 (2014), it is explicitly expressed that the variation of 0.15 to 0.2 shall be considered into the damping coefficient of viscous dampers. Therefore, the damping coefficient of the TMD has been considered as a random variable with a normal distribution with a coefficient of variation of 0.15. Such uncertainty is also assumed for the stiffness of the TMD device and for minimum and maximum bound of semi-active damping and stiffness of SATMD devices. The probabilistic distributions and coefficient of variations of the random variables involved with this problem adopted from literature or assumed rationally are reported in the Table 1, where the mean values considered are the values of deterministic parameters. The Latin hypercube sampling technic (McKay *et al.* 1979) has been used to generate a set of 30 sample SATMD-structure systems which stratifies across the range of a sampled variable more effective than Monte Carlo sampling technic. Thus, LHS requires fewer samples than the Monte Carlo sampling method to estimate small failure probabilities accurately. This sample number is sufficient to accurately account for the effect of uncertainties, where has led to estimate the coefficient of variation of failure probability lower than 5% for all cases.

3.3 Uncertainty of capacity thresholds

The capacity thresholds are actually uncertain variables themselves (Risi *et al.* 2019) which their dispersions relate to building type and construction quality assurance. FEMA

Table 1 Statistical properties of structure and SATMD parameters

	Parameter	Symbol	Distribution	COV	Reference
Structure	mass	M	Normal	0.1	Dolsek 2009, Ellingwood *et al.* 1980
	Viscous damping	C	Normal	0.4	Dolsek 2009, Porter *et al.* 2003
	Elastic stiffness	K_E	Lognormal	0.1	Ellingwood *et al.* 1980, Sues *et al.* 1985, Kanzantzi *et al.* 2014
	Post-elastic stiffness	K_{PE}	Lognormal	0.1	Ellingwood *et al.* 1980, Sues *et al.* 1985, Kanzantzi *et al.* 2014
TMD	Viscous damping	c_d	Normal	0.15	Scozzese 2019, ASCE-41-13 2014
	Stiffness	k_d	Normal	0.15	ASCE-41-13 2014
SATMD	Minimum viscous damping	$c_{d,\min}$	Normal	0.15	ASCE-41-13 2014
	Maximum viscous damping	$c_{d,\max}$	Normal	0.15	ASCE-41-13 2014
	Minimum stiffness	$k_{d,\min}$	Normal	0.15	ASCE-41-13 2014
	Maximum stiffness	$k_{d,\max}$	Normal	0.15	ASCE-41-13 2014

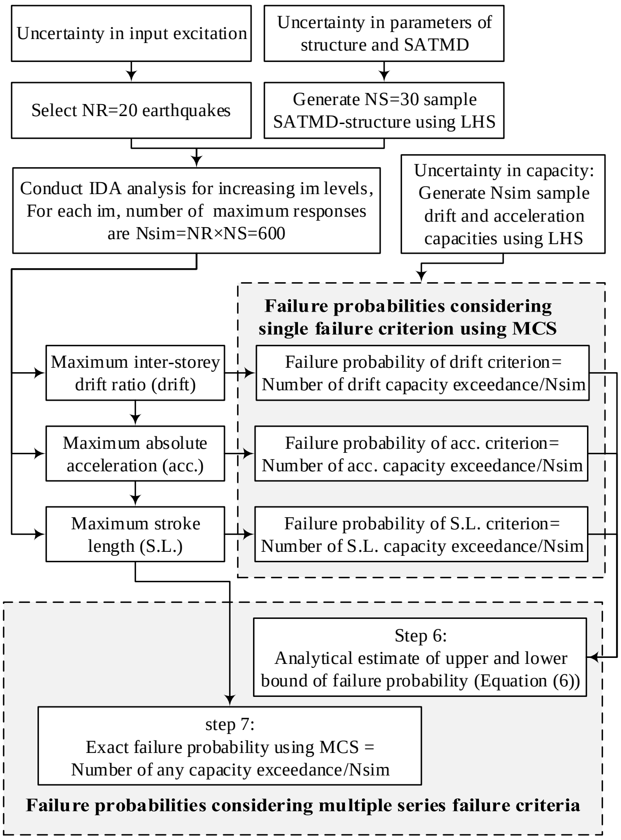

Fig. 3 Flowchart of the procedure for developing fragility curves

P58 (2012) recommends the dispersion of 0.1 for structures with an average quality of construction. In this paper, the capacity thresholds of drift ratio and absolute acceleration are assumed as random variables with lognormal distribution which random numbers have been generated by using LHS technic. The mean value of capacities considered those are presented in section 2.2 and the coefficient of variation of 0.1 assumed for them. The uncertainty for SATMD stroke length has been omitted, as this parameter is rationally a certain value based on the manufacturing process.

4. Procedure for developing fragility curves

The procedure for developing fragility curves of the structure equipped with SATMDs considering single and multiple failure criteria and accounting for uncertainties of input excitation, structural parameters, SATMD properties is described in the following steps and the flowchart presented in Fig. 3.

Step 1: for a given structure with specific site properties, consider N_r=20 real probable earthquake records with different characteristics.

Step 2: design the variable damping or stiffness SATMD system for the deterministic structure based on solving an optimization problem with the objective function of minimization of maximum inter-story drift and/or maximum absolute acceleration rely on the procedure presented in Bakhshinezhad and Mohebbi (2019).

Step 3: Simulate N_s=30 sample structures equipped with SATMD system by generating random numbers for uncertain parameters of the structure and SATMD using LHS method according to statistical properties listed in Table 1.

Step 4: Conduct nonlinear incremental dynamic analysis for the structure equipped with SATMD systems as well as for the uncontrolled structure and the structure equipped with passive TMD and determine maximum responses of the structure. Each structural model is subjected to N_r=20 earthquake, so the number of simulations is $N_{sim}=N_r\times N_s$=600 for each *IM* level.

Step 5: Generate random numbers for capacity thresholds of drift and acceleration with the number of N_{sim} according to sub-section 3.3.

Step 6: For each failure criterion including drift, acceleration and stroke length, calculate performance functions according to Eq. (1). Count the number of times that each failure mode has attained for the discrete single criterion, $N_{f\text{-}s}$, (calculate number of times that $g\leq0$ over 600 simulations). Evaluate the probability of failure (P_f) using Monte Carlo simulation (MCS) method (Nowak and Collins 2000) which is the ratio of the number of failure to the number of simulations. The failure probability for single failure criterion is calculated by $P_{f\text{-}s}=N_{f\text{-}s}/N_{sim}$. (Using Eq. (6), the upper and lower analytical estimate of multiple criteria fragility could be evaluated which considers fully dependency or independency among failure criteria. For instance, these multiple criteria fragilities only have been investigated in sub-section (5.5).)

Step 7: Regarding multiple failure criteria, count the number of times that any of multiple failure modes have occurred ($N_{f\text{-}m}$), which assumes series combination. The failure probability considering multiple failure criteria is derived using MCS method by $P_{f\text{-}m}=N_{f\text{-}m}/N_{sim}$. This multiple failure criteria fragility considers the actual correlation between failure criteria which expected to be among upper and lower bound mentioned in previous step.

Step 8: Develop fragility curves by plotting the P_f versus *IM*.

5. Numerical analyses and discussion

In this section, the methodology of developing fragility curves for the nonlinear structure equipped with variable damping or stiffness SATMD system rigorously accounting for uncertainties of input excitation, structural parameters and SATMD properties has been presented through numerical analysis. Multiple failure criteria including inter-story drift ratio and absolute acceleration related to the structure as well as SATMD stroke length have been used to define the whole structural failure as a series system. SATMD has been installed on the top floor of an eight-story nonlinear shear building frame as shown schematically in Fig. 4 which has been used in many studies on controlling nonlinear structures (Yang *et al.* 1988, Dadkhah and Mohebbi 2019). All characteristics are similar for all stories. The elastic stiffness is K_E=3.404×10^5 kN.m^{-1} and post-elastic stiffness is K_{PE}=3.404×10^4 kN.m^{-1}. The story mass is

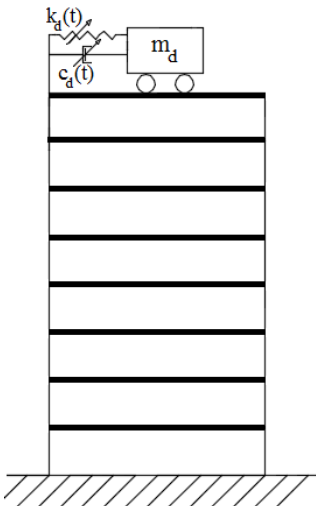

Fig. 4 Shear building model equipped with variable damping or variable stiffness SATMD on the top floor

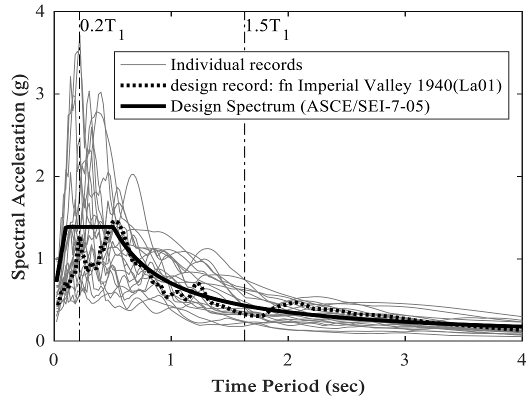

Fig. 5 Acceleration response spectrum of the selected and design earthquake records and the design response spectrum at downtown Los Angeles for site class D

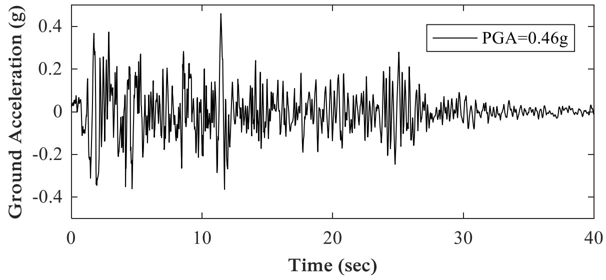

Fig. 6 Time history of ground acceleration of the design record (La01)

m=345.6 tons and linear viscous damping coefficient is c=734.3 kN.s.m^{-1} which corresponds to 0.5% damping ratio of the first vibration mode of the structure. Story height is 3.2 m and yielding inter-story drift is u_y=2.4 cm. Fundamental period of the structure based on its initial stiffness is T_1=1.087 sec. It is noteworthy that in this paper, adoption of shear building frame as structure case study is only for simplifying the numerical simulation and also reducing computational effort. For structures with realistic behavior such as steel and concrete buildings, the proposed procedure for developing fragility curves can be used, too. In this case, the real behavior of structure should be considered in numerical simulations.

5.1 The set of ground motions

There are no clear code guidelines about the required number of records for fragility analysis, but about twenty records could be enough to assess seismic demand accurately (FEMA-P58 2012). A set of 10 pairs of earthquakes with the probability of occurrence of 10% in 50 years proposed for SAC project and recommended in ASCE/SEI-7-05 design code for downtown Los Angeles have been used for fragility analysis which their properties have been presented in Table 2. It has been assumed that the structure to be located on stiff soil which corresponds to site class D based on this code. Fig. 5 shows the acceleration response spectrum of the selected earthquakes and ASCE design spectrum for 5% critical damping.

For designing the semi-active control system, it is required to employ a design record which is more proper to have the most compatibility to the design spectrum than other earthquakes. The cumulative difference between design spectrum and spectral acceleration over periods from $0.2T_1$ to $1.5T_1$ has been calculated for each record. The f_n component of the Imperial Valley 1940, El Centro earthquake has the minimum difference with reference to design spectrum, thus, it has been selected as the design record where its acceleration time history has been shown in Fig. 6.

5.2 Optimal design of SATMD systems for the deterministic nonlinear structure

In this section, variable damping and stiffness SATMD with the mass ratio of μ=15% installed on the top floor of the considered nonlinear shear building have been designed based on an optimization procedure that the details of the procedure have been presented in Bakhshinezhad and Mohebbi (2019). The semi-active control algorithm has consisted of two stages including Newmark-based instantaneous optimal control algorithm for determining control force and clipped control law for evaluating the values of damping or stiffness of the semi-active devices. Based on this procedure, three different controllers with objectives of (1) minimization of only maximum drift, (2) minimization of only maximum acceleration, and (3) minimization of both maximum drift and acceleration, of the structure under design record with a constraint on SATMD stroke length equal to 0.5 m have been designed. The properties of the TMD including mass, stiffness and damping have been designed based on Sadeck *et al.* (1997) procedure which are 355.1 tons, 8383.6 kN.m^{-1} and 1594.5 kN.sm^{-1}, respectively, and have also been used to design SATMDs.

The maximum inter-story drift and absolute acceleration of the structure equipped with variable damping or stiffness SATMDs designed based on different criteria as well as structure equipped with passive TMD, normalized to the uncontrolled structure responses, have been reported in Fig. 7.

Table 2 Selected earthquake records used in the current study

Earthquake code	Earthquake name	Year	Station	Magnitude	Distance (km)	PGA (g)
La01	Imperial Valley-fn	1940	El Centro	6.9	10.0	0.46
La02	Imperial Valley-fp	1940	El Centro	6.9	10.0	0.68
La03	Imperial Valley-fn	1979	Array #05	6.5	4.1	0.39
La04	Imperial Valley-fp	1979	Array #05	6.5	4.1	0.49
La05	Imperial Valley-fn	1979	Array #06	6.5	1.2	0.30
La06	Imperial Valley-fp	1979	Array #06	6.5	1.2	0.23
La07	Landers-fn	1992	Barstow	7.3	36.0	0.42
La08	Landers-fp	1992	Barstow	7.3	36.0	0.43
La09	Landers-fn	1992	Yermo	7.3	25.0	0.52
La10	Landers-fp	1992	Yermo	7.3	25.0	0.36
La11	Loma Prieta-fn	1989	Gilroy	7.0	12.0	0.67
La12	Loma Prieta-fp	1989	Gilroy	7.0	12.0	0.97
La13	Northridge-fn	1994	Newhall	6.7	6.7	0.68
La14	Northridge-fp	1994	Newhall	6.7	6.7	0.66
La15	Northridge-fn	1994	Rinaldi RS	6.7	7.5	0.53
La16	Northridge-fp	1994	Rinaldi RS	6.7	7.5	0.58
La17	Northridge-fn	1994	Sylmar	6.7	6.4	0.57
La18	Northridge-fp	1994	Sylmar	6.7	6.4	0.82
La19	North Palm Springs-fn	1986	-	6.0	6.7	1.02
La20	North Palm Springs-fp	1986	-	6.0	6.7	0.99

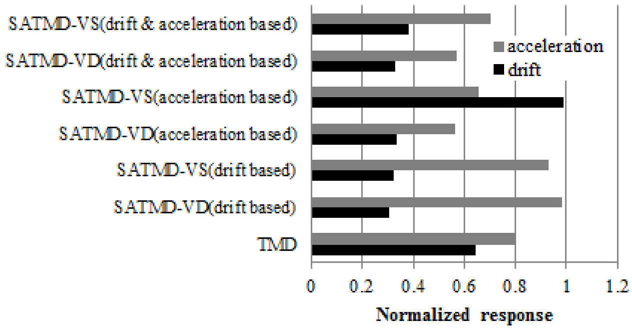

Fig. 7 Maximum inter-story drift and absolute acceleration of SATMDs and TMD normalized to the uncontrolled structure responses

With reference to safety criterion, for reducing the damage of the structural components, the objective of minimization of maximum drift of the structure could be used in the design process of SATMDs. Particularly, under the design record, optimal variable damping and stiffness SATMDs have reduced the drift of the structure near to 69% comparing to the uncontrolled structure. With reference to convenience criterion, for reducing the damage of the non-structural components or maintenance the functionality of sensitive equipment, it is more appropriate to consider minimization of maximum acceleration as the design objective. It is observed that variable damping SATMD have more capability than variable stiffness SATMD which reduced maximum acceleration about 44%. Consequently, considering both safety and convenience criteria, SATMDs could be designed for minimization of maximum drift and acceleration simultaneously. SATMD with variable damping showed more effective performance under design record which reduced the drift and acceleration about 67% and 43%, respectively.

5.3 Incremental nonlinear dynamic analysis results

Different IMs such as Peak Ground Acceleration (PGA), Peak Ground Velocity (PGV), spectral acceleration (S_a), spectral displacement (S_d) and etc. could be chosen for the seismic probabilistic analysis. In fact, the IM should be selected by accounting the criteria of efficiency and sufficiency. Many Studies (Biasio 2014, Haj-Najafi and Tehranizadeh 2015) demonstrated that using spectral acceleration has the capability of reducing the response dispersion appropriately and, thus, estimating confident responses. In this paper, the spectral acceleration, $S_a(T_1, \xi=0.5\%)$, at the fundamental period of the structure and for the damping ratio of $\xi=0.5\%$, is assumed as IM. Hereinafter, it is denoted as S_a and is considered to increasing from 0 to 4 g with steps of 0.2 g in IDA. In this section, incremental nonlinear dynamic analysis has been conducted to evaluate the responses of the uncontrolled structure and the structure equipped with passive TMD, variable damping SATMD and variable stiffness SATMD considering the effects of the uncertainties in the input excitation, parameters of the structure and properties of the control devices. In this regard, for each IM level, the differential equation of motion (Bakhshinezhad and Mohebbi 2019) has been frequently solved within a total number of 4800 simulation runs. The IDA curves corresponding to inter-story drift and absolute acceleration which is the median of the maximum responses over sample models and over earthquake records have been reported according to Fig. 8. It is observed that, by contrast to the design record, variable stiffness SATMD reduces the maximum drift and acceleration of the structure more effective than variable damping SATMD.

5.4 Fragility curves considering single and multiple failure criteria

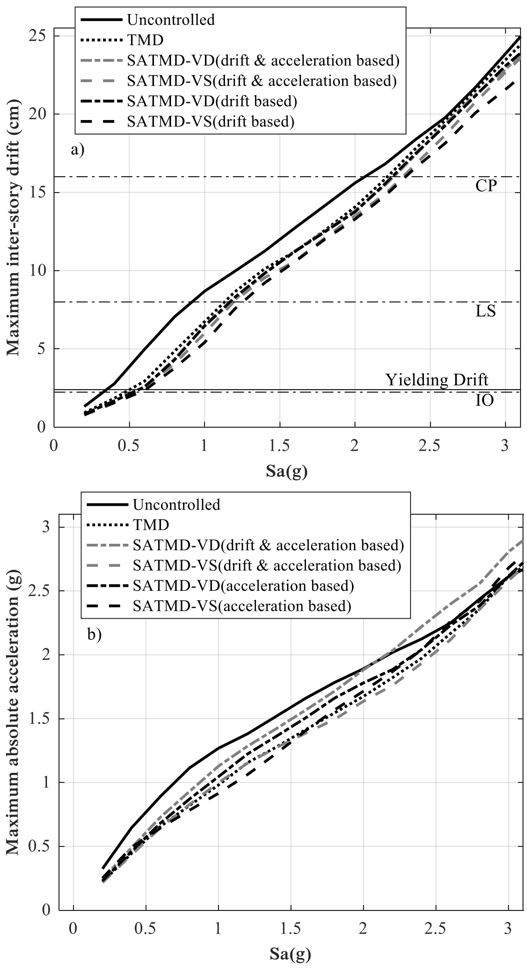

Fig. 8 IDA curves of (a) inter-story drift and (b) absolute acceleration, for uncontrolled structure and controlled by SATMDs and TMD

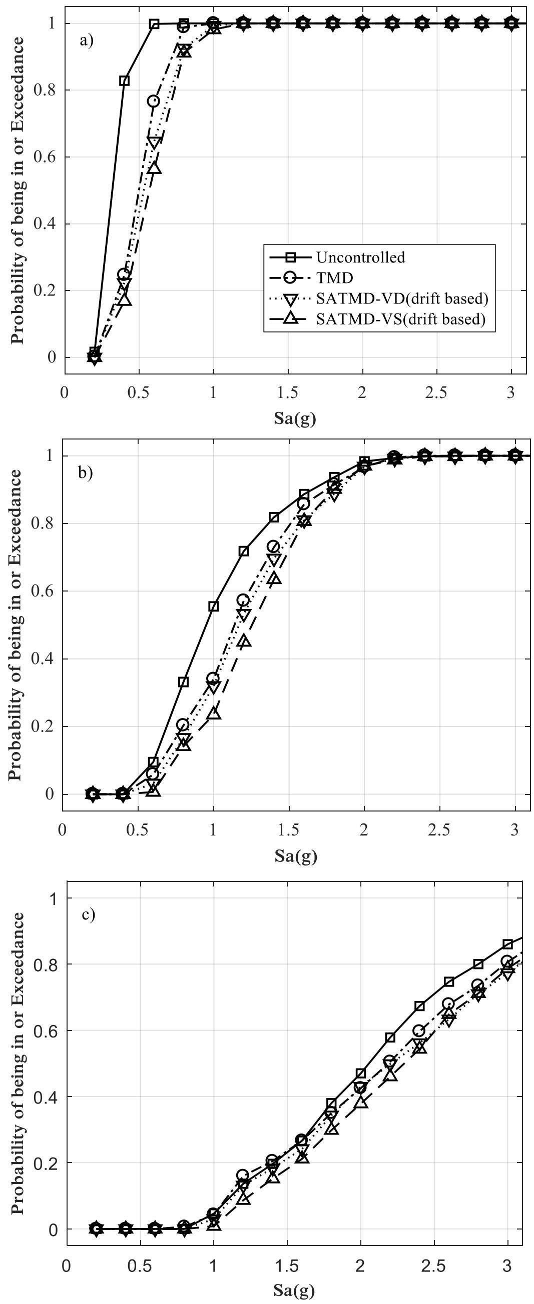

Fig. 9 Fragility curves of the structure equipped with SATMDs, TMD and uncontrolled structure considering drift ratio criterion of (a) IO, (b) LS and (c) CP performance level

In this section, optimal SATMD systems have been used for seismic response control of the nonlinear structure. Fragility curves of the structure equipped with variable damping or variable stiffness SATMDs designed based on different criteria have been developed and compared to fragility curves of the uncontrolled structure and equipped with passive TMD for different performance levels considering single and multiple failure criteria. The probabilities of failure in each IM level have been computed through the MCS method taking into account the uncertainties of the input excitation, structural parameters and SATMD properties.

Fig. 9 presents fragility curves considering the single failure criterion of drift ratio for different performance levels. The used SATMDs here are those that are designed based on minimization of maximum drift of the structure. It is observed that, using optimal SATMD systems enhance the seismic fragility of the structure, whereas the enhancement of variable stiffness SATMD is slightly more effective than variable damping SATMD. Also, the effectiveness of designed SATMDs in reducing drift ratio fragility is more than passive TMD. In particular, variable stiffness SATMD has decreased the fragility of the structure about 66%, 32% and 9%, respectively at IO(S_a=0.4 g), LS(S_a=1 g) and CP(S_a=2 g) performance levels with respect to the uncontrolled structure.

The fragility curves corresponding to the single failure criterion of acceleration have been shown in Fig. 10. The SATMDs designed based on minimization of maximum acceleration of the structure have been used to mitigate the acceleration fragility. It is observed that variable stiffness SATMD showed more effective performance than variable damping SATMD to mitigate the fragility of the structure. Particularly, the optimal SATMD with variable stiffness enhanced seismic fragility of the structure about 47%, 42% and 27%, respectively at IO(S_a=0.6 g), LS(S_a=1 g) and CP(S_a=1 g) performance levels.

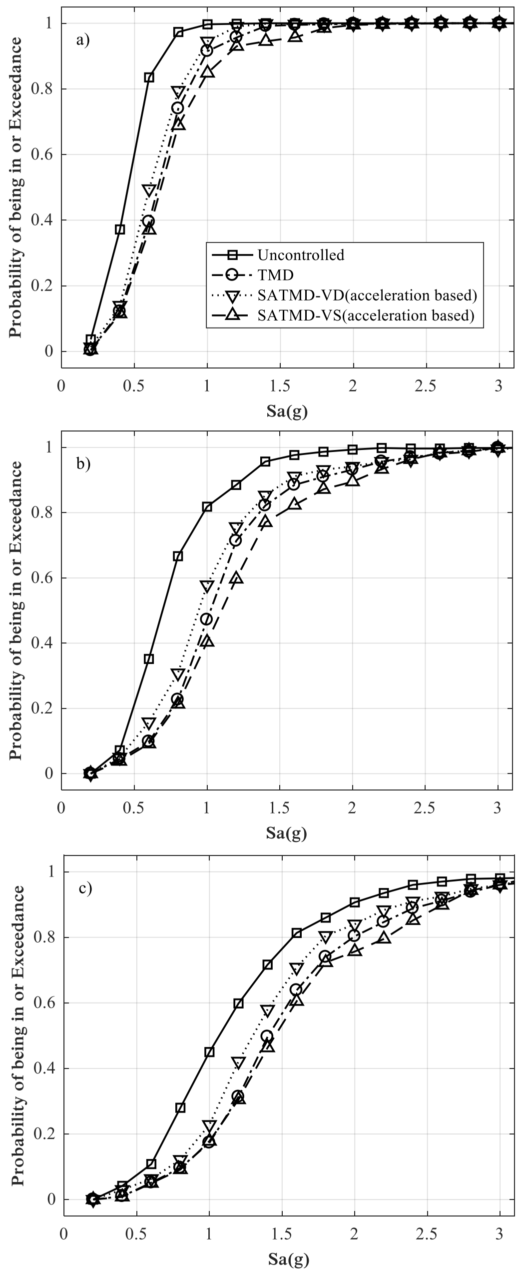

Fig. 10 Fragility curves of the structure equipped with SATMDs, TMD and uncontrolled structure considering acceleration criterion of (a) IO, (b) LS and (c) CP performance level

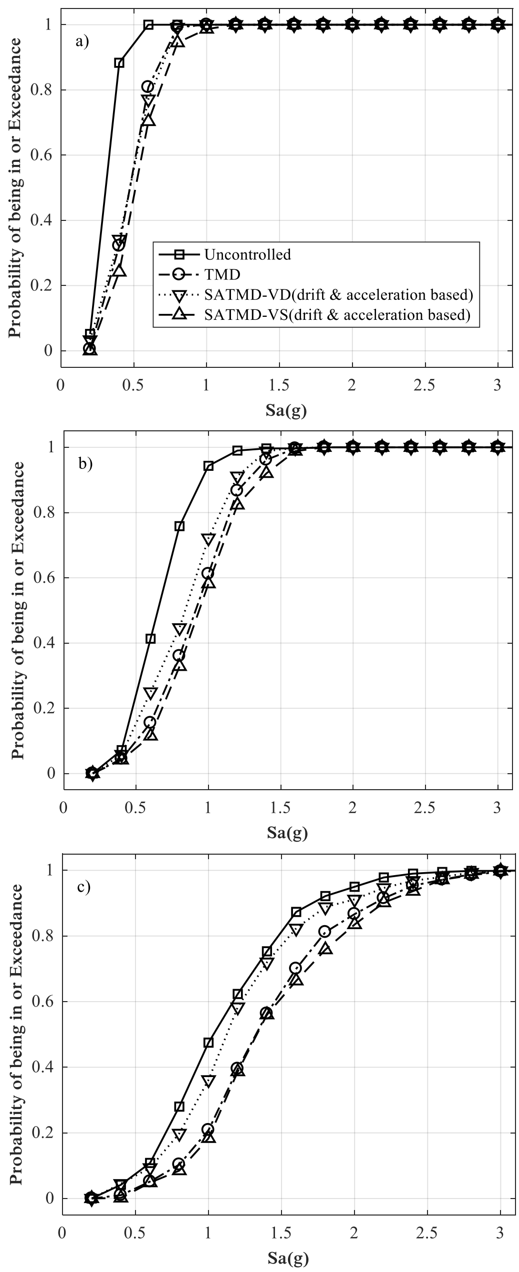

Fig. 11 Multiple failure criteria fragility curves of the structure equipped with SATMDs, TMD and uncontrolled structure of (a) IO, (b) LS and (c) CP performance level

Fig. 11 compares the fragility curves of the structure considering multiple failure criteria for different performance levels. These fragilities have been determined based on step 7 in section 4 and therefore account for the actual correlation between failure criteria. The SATMDs which are designed based on minimization of both drift and acceleration are used. Considered failure criteria for the uncontrolled structure are building drift ratio and acceleration. However, for SATMDs and TMD systems, stroke length failure criterion is additionally accounted for developing the fragility probability. Results indicate that the optimal SATMDs have the capability to improve seismic fragility of the structure considering multiple failure criteria. However, variable stiffness SATMD is more reliable than variable damping SATMD. As an instance, variable stiffness SATMD has reduced the seismic fragility of the structure about 64%, 36% and 29%, respectively at IO(S_a=0.4 g), LS(S_a=1 g) and CP(S_a=1 g) performance levels.

In addition, by comparing the performance of SATMDs with their passive counterpart, TMD, it is observed that in the case of drift ratio failure criterion both variable damping and stiffness SATMDs have the capability to reduce the fragility of the structure more than TMD. As an instance, variable stiffness SATMD reduced drift ratio fragility of the structure about 20% at IO performance level and intensity measure of S_a=0.6 g with respect to the structure controlled by TMD. Furthermore, in the case of acceleration failure criterion, results show that the fragility of variable damping SATMD is higher than TMD through all performance levels. However, variable stiffness SATMD has mitigated the fragility slightly more effective than TMD, whereas, as an example, it has reduced the fragility about 12% with respect to the TMD at LS performance level and S_a=1.2 g. On the other hand, slight effectiveness of the variable stiffness SATMD in comparison with TMD is also observed in multiple failure criteria fragility.

In particular, this semi-active system has reduced multiple failure criteria fragility about 8% with respect to TMD at IO performance level and S_a=0.4g. Consequently, the optimal SATMDs which have been designed with appropriate design criteria based on minimization of maximum drift and/or acceleration for a specific structure, have the ability to enhance the seismic fragility and provide reliability and robustness for the structure especially, under severe earthquakes that structure undergoes nonlinear behavior and TMDs are practically detuned.

5.5 Effect of different failure criteria on the fragility of SATMD systems

In this section, for the case of SATMD with variable stiffness, single failure criterion fragilities have been compared with each other and with multiple failure criteria fragility. Also, multiple failure criteria fragility determined based on MCS method (step 7 in section 4) is compared to the upper and lower bound of analytical estimate of multiple failure criteria fragilities (based on step 6 in section 4) which relate to statistical dependence among the failure criteria.

Fig. 12 shows the exact fragilities of the structure equipped with variable stiffness SATMD (designed based on minimization of both drift and acceleration) considering single and multiple failure criteria computed using MCS method as well as the upper and lower estimate of multiple fragilities for IO, LS and CP performance levels, respectively. Results show that considering multiple failure criteria simultaneously has led to appearing higher fragility than single failure criterion which the increase is more for LS performance level. As an example, the multiple failure criteria fragility is respectively 31% and 9% higher than single failure criterion fragility of drift and acceleration at LS performance level in S_a=1 g. This fragility increase is a disadvantage of using multiple failure criteria. However, the profit of using multiple failure criteria in fragility analysis is the capability of taking into account all probable safety and serviceability criteria of complicated seismic structures even equipped with structural control systems with their own discrete failure criteria. Comparing the effects of different failure criteria, it is observed that drift ratio fragility is higher at IO performance level, whereas acceleration failure criterion shows the higher fragilities for LS and CP performance levels. Also, considering stroke length failure criterion has led to the lowest fragility which is almost negligible comparing to drift and acceleration failure criteria. This phenomenon is reasonable for the SATMD with the mass ratio of μ=15% and for the SATMDs with lower mass ratios, larger relative displacement would cause to appear considerable failure probabilities.

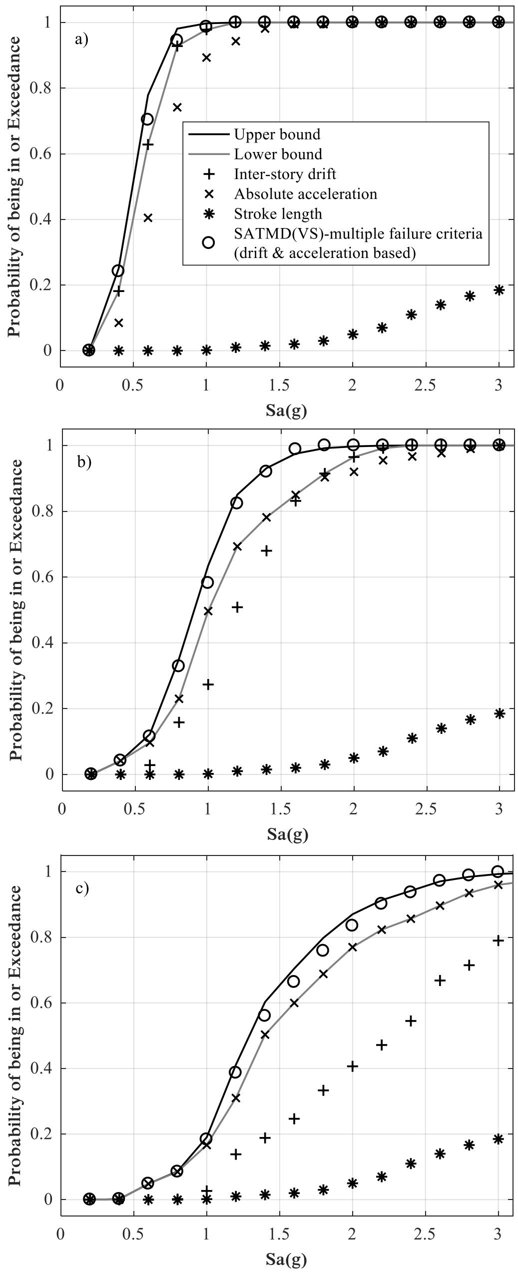

Fig. 12 Fragility curves of variable stiffness SATMD considering single and multiple failure criteria of (a) IO, (b) LS and (c) CP performance level

Comparing multiple failure criteria fragilities obtained using MCS method with analytical estimates shows that the exact MCS failure probabilities are almost coincident with the upper bound of the analytical estimate which corresponds to the statistical independent assumption of failure criteria (un-conservative). Consequently, statistical independence assumptions between different failure criteria could be more proper for the structures equipped with SATMDs. Similar results are obtained also for variable damping SATMD and passive TMD.

5.6 Effect of uncertainties of structure and SATMD parameters on the fragility

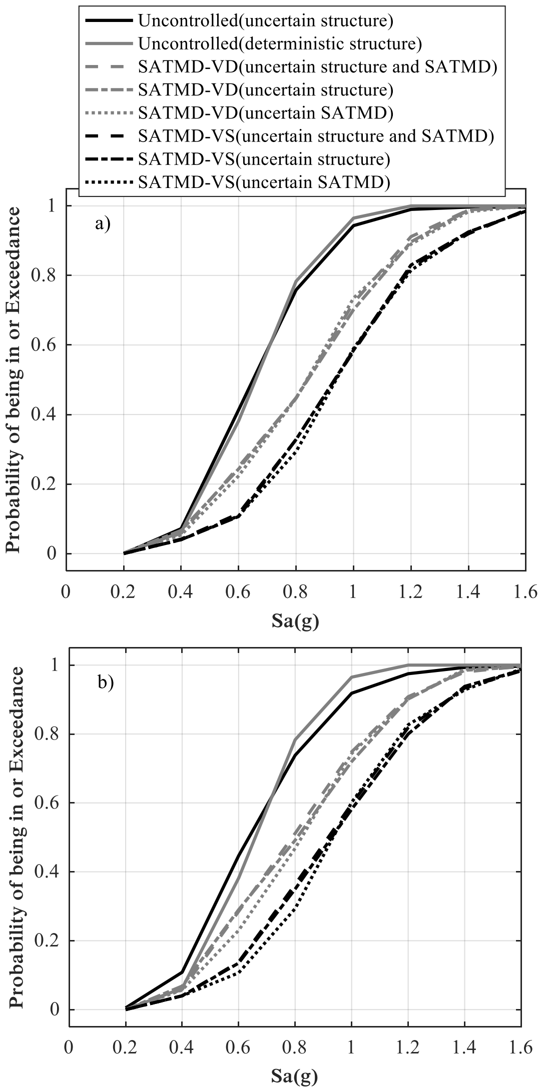

Fig. 13 Multiple failure criteria fragility curves of the structure equipped with SATMDs and uncontrolled structure for (a) lower level of uncertainties and (b) higher level of uncertainties

In this section, the effects of uncertainties of structural parameters and control device properties on the fragility have been compared for LS performance level. For this purpose, the fragility curves have been developed employing three following cases: (1) uncertain structure and SATMD (as previous sections); (2) uncertain structure and deterministic SATMD; and (3) deterministic structure and uncertain SATMD. It should be noted that in all of these cases the uncertainty of input excitation is accounted. Fig. 13(a) compares the multiple failure criteria fragility curves of the uncontrolled structure and equipped with SATMDs with the level of uncertainty presented in Table 1.

For this level of uncertainty which is the minimum level according to the literature, it is observed that the tolerance values of the multiple failure criteria fragilities among three cases of uncertainty consideration are lower than 5% in all intensity levels. Furthermore, for the higher level of uncertainties (i.e., coefficient of variation of 0.3 for elastic and post-elastic structural stiffness and 0.2 for parameters of SATMDs), these fragility curves have been developed and shown in Fig. 13(b). Results show that considering the uncertainties of structural parameters can vary the fragility up to 10% and SATMD parameter uncertainties can alter the fragility near to 5%.

Consequently, the values of the fragility have mainly affected by the uncertainty of the input excitation which is more effective than the uncertainty of the structural parameters and SATMD properties. Such this result has also been concluded in (Cattari *et al.* 2019, Simoes *et al.* 2019). However, it is more proper to account for all sources of uncertainty to estimate the fragility accurately.

6. Conclusions

In this study, fragility curves for the structure equipped with semi-active tuned mass dampers have been developed considering multiple failure criteria including drift ratio as safety criterion, absolute acceleration as convenience criterion as well as SATMD stroke length. Also, the effect of uncertainties of input excitation, structural parameters and SATMD properties has been considered. An eight-story nonlinear shear building frame has been used for numerical analysis. Latin hypercube sampling method has been employed to generate 30 sample SATMD-structure systems. Incremental nonlinear dynamic analysis has been conducted using 10 pairs of real earthquake records and Monte Carlo Simulation method has been used to evaluate the failure probabilities in each intensity level. Fragility curves considering single and multiple failure criteria have been developed for the structure equipped with optimal SATMDs and compared to that of uncontrolled structure and equipped with TMD.

Numerical analysis has shown that using optimal variable damping or variable stiffness SATMDs has significantly reduced seismic fragility of the structure considering single failure criterion of drift ratio and acceleration as well as multiple failure criteria which is obvious qualitatively from the fragility curves, whereas variable stiffness SATMD showed more effective than variable damping SATMD. In particular, variable stiffness SATMD enhanced multiple failure criteria fragility of the structure about 64%, 36% and 29%, respectively at IO(S_a=0.4 g), LS(S_a=1 g) and CP(S_a=1 g) performance levels.

From comparing the performance of SATMDs with passive TMD, it is observed that variable stiffness SATMD have the capability of reducing the fragility effectively with respect to TMD. As an instance, variable stiffness SATMD decreased drift ratio fragility of the structure about 20% at IO performance level and S_a=0.6 g with respect to the structure controlled by TMD.

Also, from comparing the effects of different failure criteria on the fragility, results have illustrated that considering multiple failure criteria caused to increase the fragility in comparison with using single failure criterion. Moreover, it has been demonstrated that statistical independence assumptions between different failure criteria could be more proper for the structures equipped with SATMDs and TMD. In addition, it should be noted that the value of the fragility is mainly affected by the uncertainty of the input excitation where the uncertainties of the structure and SATMD parameters are less effective. However, the uncertainties of the structure and SATMD could alter the fragility up to 10% and 5%, respectively.

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