Reliability analysis of a reinforced concrete building equipped with hybrid control systems under multiple hazards

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Abstract

The aim of this study is to investigate reliability of a hybrid vibration mitigation technique in a reinforced concrete (RC) building. A numerical model of a RC building controlled by hybrid controllers consisting of base-isolation (BI) and tuned mass dampers (TMDs) is used to study its response to wind and earthquake ground motions. Different levels of hazard are considered and response quantities such as base shear, top floor acceleration and displacement are studied. Probabilities of exceeding limit states of collapse and serviceability are evaluated with and without the hybrid control systems. It is observed from the results that vibration mitigation is achieved from the hybrid system employed in the RC building varies significantly with the type of excitation. However, it is more reliable as compared to the BI system. It demands for a system having optimized parameters such that during the service life of the building, provides reliable performance under multi-hazard scenarios.

Keywords: Building; Earthquake; Reliability; Wind

1. Introduction

Tuned mass dampers (TMDs) are one of the widespread control methods for mitigation of structural vibrations. Their applications in various conditions and loads have been addressed by several researchers [1-20]. A detailed literature survey on passive TMDs is presented in Elias and Matsagar [21].

Base-isolation (BI) has been one of the most popular and established methods of earthquake response reduction. This method depends on isolation devices such as friction pendulum (FP) or lead rubber bearings (LRB) at the base of the structure. The isolation device has much lower lateral stiffness than the structure, and the isolated structure is therefore more flexible than the fixed-base one. This results in elongation of natural period of vibration, and as a consequence acceleration demand on the superstructure is reduced. This reduces design forces on the superstructure. As a side effect of increased flexibility, displacement demand on the structure gets amplified, and extra damping is required to keep displacement demand within suitable limits. There is a tradeoff between the extent to which acceleration and displacement demand can be controlled by BI system combined with additional damping devices [22].

TMD is efficient in response mitigation of BI systems if the loading frequency is lower than the natural frequency of the structure [23]. Better efficiency in seismic response mitigation can be achieved by advanced TMD optimization methods [24]. Use of TMD with inerter (TMDi) are being studied recently for seismic response mitigation of BI buildings [25-28]. Effectiveness of single tuned mass dampers (STMD), multiple tuned mass dampers (MTMD) and distributed multiple tuned mass dampers (d-MTMD) on seismic response control of BI buildings was investigated by Stanikzai et al. [29, 30]. They found that d-MTMDs were more effective and practical than other schemes. Use of a tuned liquid damper (TLD) as a cost-effective method to reduce wind induced vibrations of BI structures is presented by Love et al [31]. Very recently, a comparison of TMD, a New TMD (New TMD) and a tuned liquid column damper (TLCD), for response mitigation of a BI structure is considered [32].

Past studies focus on either wind or earthquake ground motion and do not adequately address uncertainties in these actions when accessing reliability of vibration control schemes. This study incorporates both wind and earthquake action and uncertainties therein to evaluate performance of different control methods.

2. Mathematical model

Figure 1 shows a schematic representation of the structure being considered, a *N*-story BI building a) without TMD, b) installed with a TMD at the top floor, and c) installed with a multiple TMDs at the top floor (BI+MTMDs), and (d) installed with several TMDs distributed over the building (d-MTMDs). The floor masses m_1 to m_N are lumped, whereas, m_b and m_n are mass of BI and total mass of TMD respectively. A TMD in this context consists of a mass (m_d), a spring (k_d) and a dashpot with damping coefficient (c_d) attached at top or any other floor. The displacement of the floors is denoted by X_1 to X_N and X_b and x_d are the displacement of BI and TMD respectively. The stiffnesses of floors are denoted by k_1 to k_N. More details on the structure and the base isolation system can be found in References [33, 34]. The design of TMDs is based on the procedure outlined in Elias and Matsagar [35]. The governing equation of motion for the system under consideration can be written as

$$[M]\{\ddot{x}(t)\} + [C]\{\dot{x}(t)\} + [K]\{x(t)\} = F_t \quad (1)$$

where $[M]$, $[C]$ and $[K]$ are the mass, damping and stiffness matrices of the structure $\{x\} = \{X_1, X_2, \cdots X_N, X_b, \cdots x_{T1}, x_{T2}, \cdots x_{Tn}\}^T$, $\dot{x}$ and $\ddot{x}$ are the unknown relative (floor, isolator and TMD) displacement, velocity and acceleration vectors, respectively; In case of earthquake $F_t = -[M]\{r\}\{\ddot{x}_g\}$ where $\ddot{x}_g$ is earthquake ground acceleration and $\{r\}$ is the vector of influence coefficients. However, in case of wind, the forces are applied on main building but not on BI and TMDs. The matrices of hybrid system can be found in Reference [30].

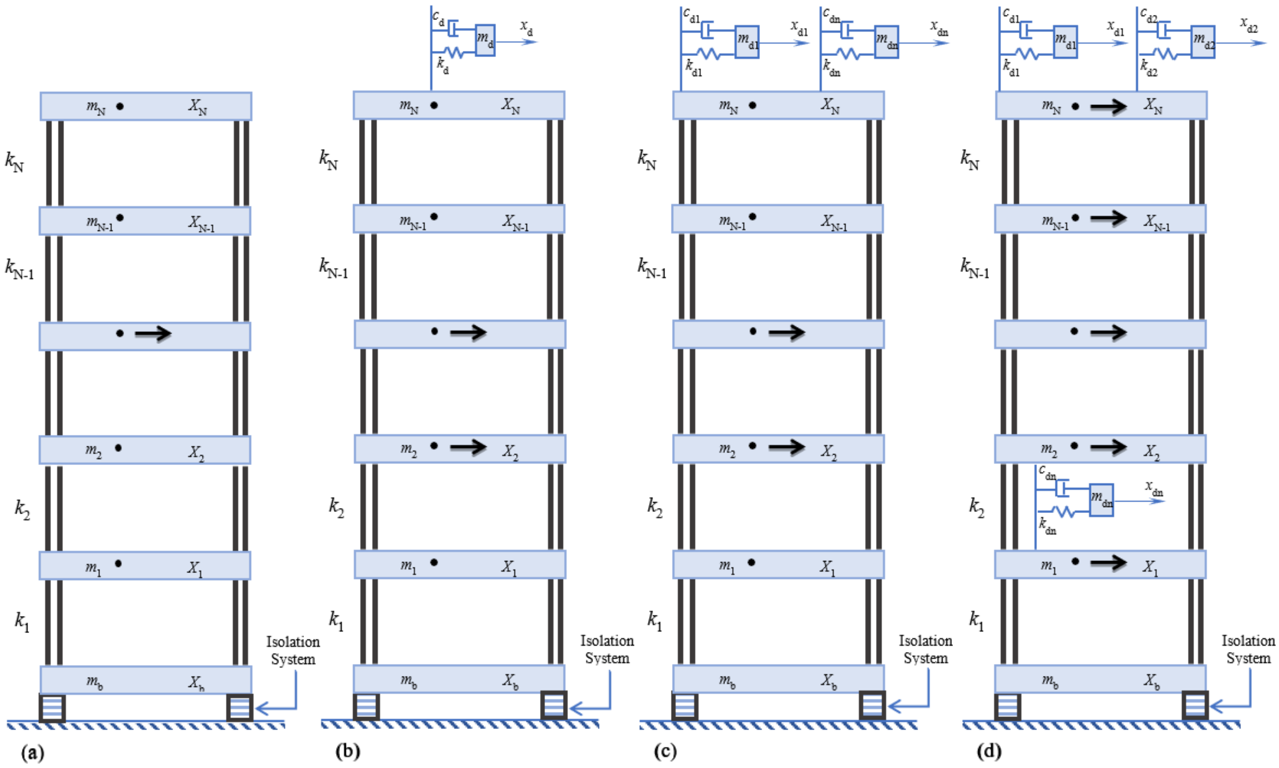

Fig. 1 – Mathematical model of a *N*-story building with (a) BI, (b) BI + STMD at top floor, (c) BI + MTMDs at top floor, and (d) BI+d-MTMDs.

3. Numerical Study

In this study, a five-story reinforced concrete (RC) building as described in Reference [34] is considered. The isolation period of the LRB is 2 sec. Each floor is assumed to have a mass of 20.4 ton and stiffness of 39700 kN/m. Damping in the superstructure is considered to be 2% in all of its vibration modes. The damping ratio of the LRB is assumed to be 5% and its yielding displacement is 5 cm. The yield restoring shear-force of the LRB is taken as 2% of the total building weight.

Figures 2 through 4 show the variation of top floor displacement and acceleration, and base shear for BI, BI+STMD, BI+MTMDs, and BI+dMTMDs while subjected to wind forces. The wind velocities are increased up to 70 m/sec. The wind forces are not applied on the TMDs and nor on BI, only applied on main floor of the structure. It is evident from Figures 2 through 4 that the TMD schemes are not effective for lower wind velocity. This is because at low displacement, the TMDs are not activated. It is observed that the performance improves as the wind velocity, and consequently the displacement demand on the structure increases. But the advantage of adding the TMDs become apparent only after the structure has undergone excessive displacement, which would most likely have caused the LRBs to fail. In this sense, it can be concluded that the TMDs are not useful in controlling the wind-induced displacement response of the building. Considering a limiting bearing displacement of about 45cm, the corresponding wind speed is about 35m/s, at which the TMDs are effective in controlling top floor acceleration as is evident from Figure 3. However, acceleration control is more of a serviceability requirement and should be relevant for more frequent winds with lower wind velocity, in which cases, the TMDs don’t seem to provide any advantage. Similarly, they are found to be ineffective in controlling base shear caused by the wind force as shown in Figure 4.

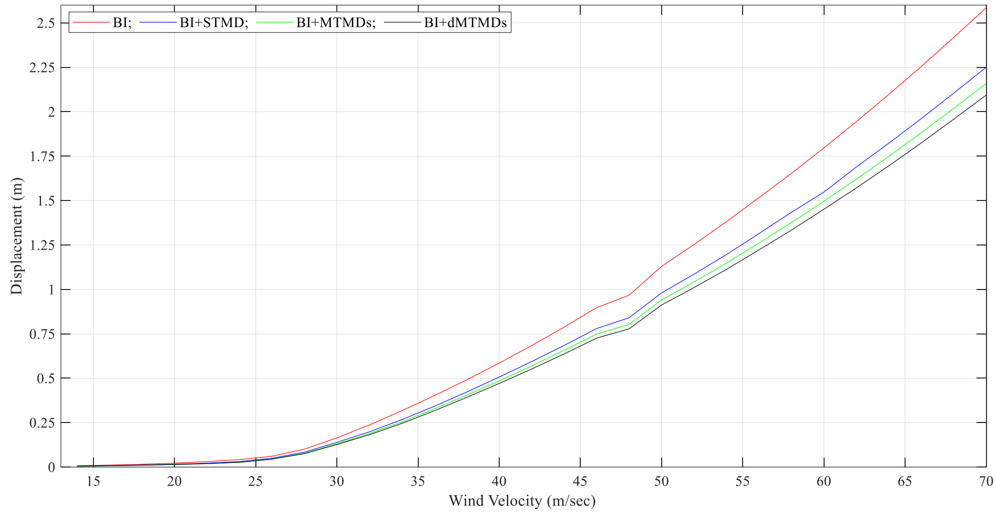

Fig. 2 – Variation of displacement response reduction with increasing wind velocity.

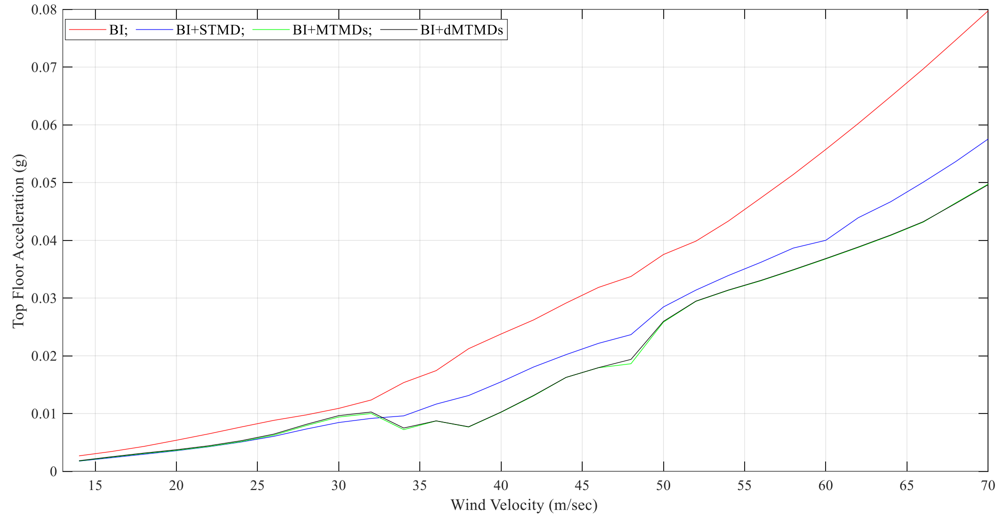

Fig. 3 – Variation of acceleration response with increasing wind velocity.

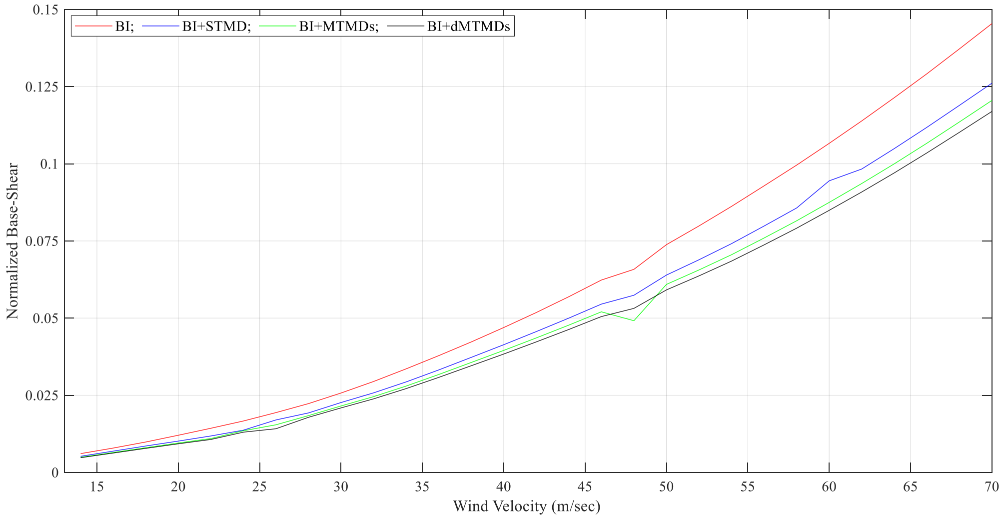

Fig. 4 – Variation of base-shear response with increasing wind velocity.

Figures 5 shows the variation of average reduction in peak bearing displacement as a function of the isolation period normalized by the dominant period of 20 DBE level ground motion (T_e) [15]. The results show that the effectiveness of TMD is very sensitive to the dominant period of ground motion up to $T_b/T_e = 3$. For ground motions with higher frequency content, the effectiveness is not sensitive to this ratio, and is constant around 10%. It is also interesting to note that the STMDs are not as effective, and in some cases, detrimental when it comes to displacement control.

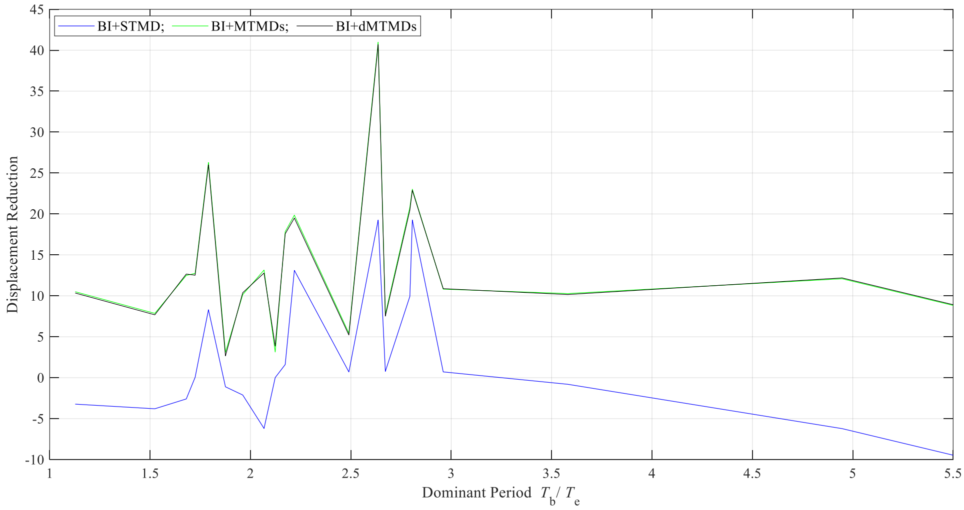

Fig. 5 – Variation of average reduction in bearing displacement for earthquakes with different dominant periods

Distributed MTMDs and MTMDs were found to be more efficicient than STMDs. As the isolation system yields, the TMDs can get detuned from the main structure thereby not being effective in vibration control. As MTMDs are tuned to a band of frequencies rather than a single frequency as in STMD, they are less prone to detuning. However, when the inelastic deformation is excessive, detuning can be expected. Similar observations were observed for roof acceleration shown in Figure 6.

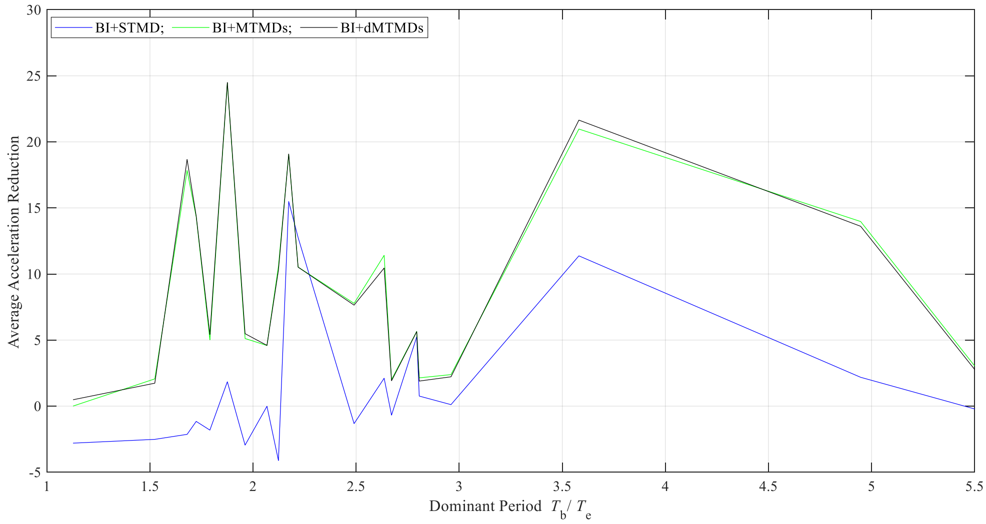

Fig. 6 – Variation of average reduction in peak roof acceleration for earthquakes with different dominant periods

4. Reliability Study

In this section, limit states are defined for the isolator displacement. The limit state is defined as 25 cm for minor damages, 35 cm for moderate damages and 45 cm for complete damage of the isolator. In third case the isolator needs to be replaced by a new one.

Figures 7 through 9 show the probability of failure of the isolator under earthquakes by considering 25 cm minor damages, 35 cm moderate damages and 45 cm total damages respectively. Peak ground acceleration (PGA) of the selected earthquakes varied up to 2 *g*, where *g* is the gravitational acceleration.

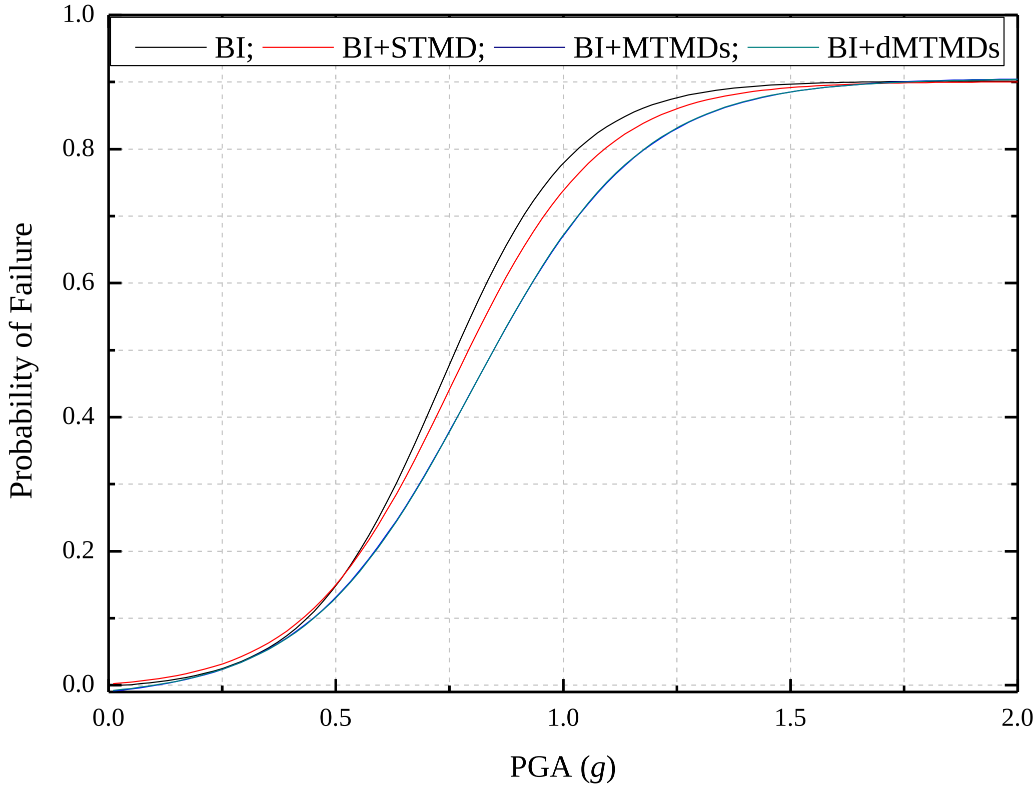

Fig. 7 – Probability of minor damages.

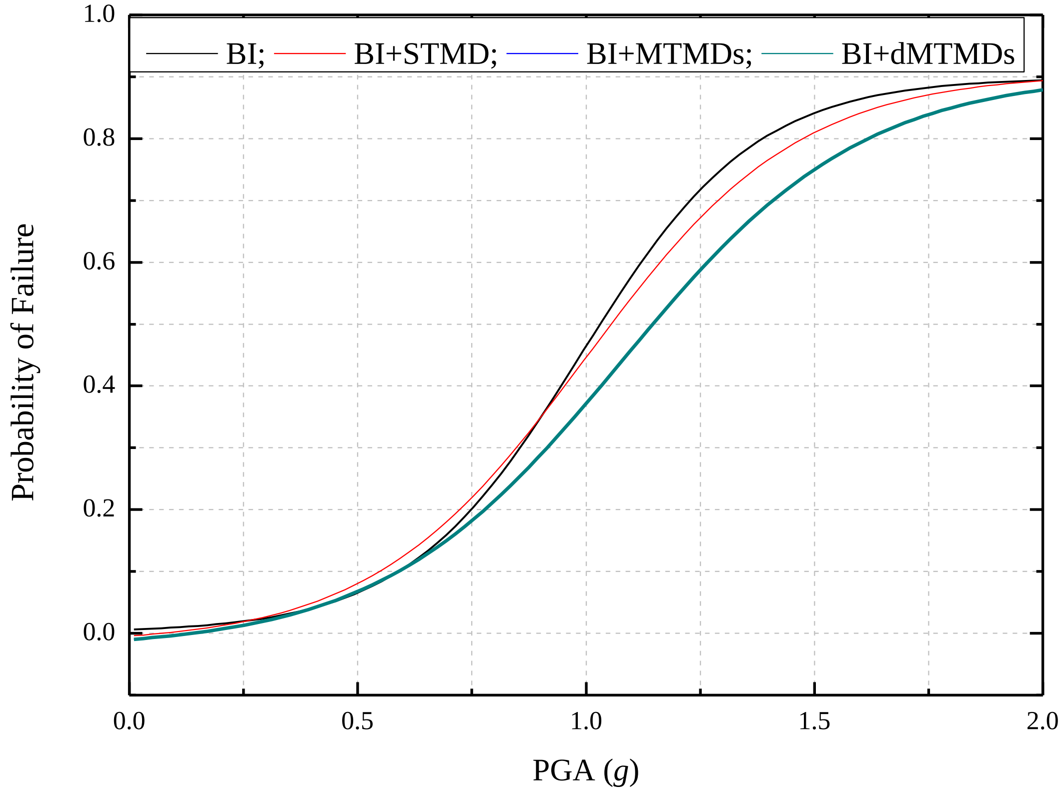

Fig. 8 – Probability of moderate damages .

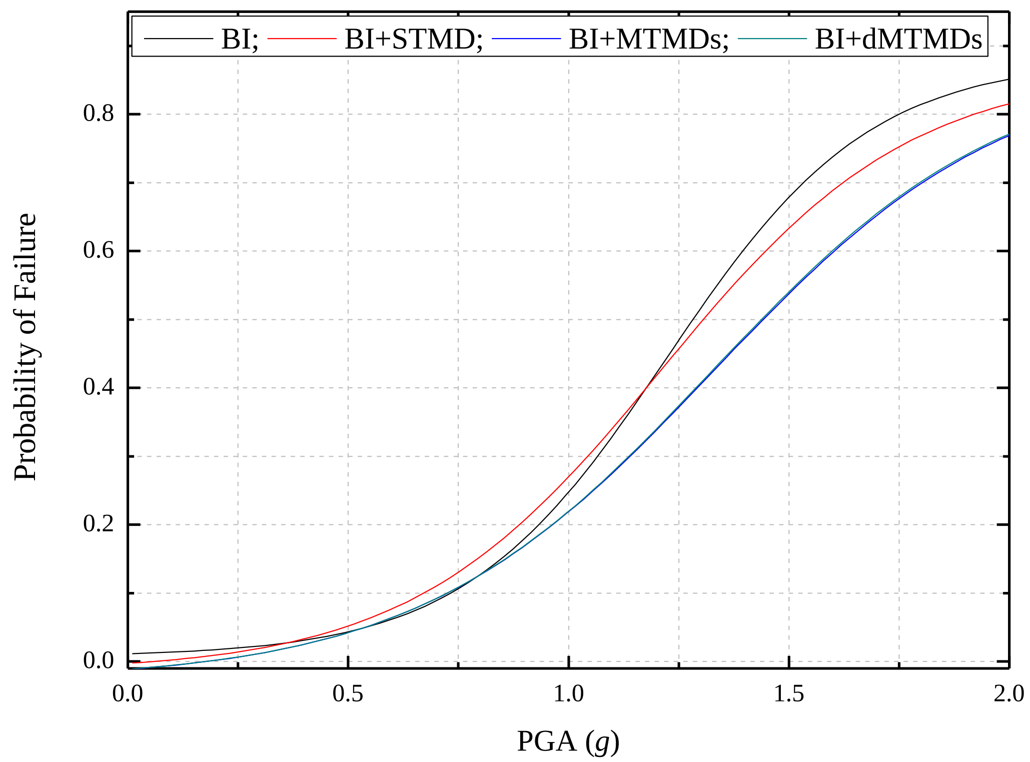

Fig. 9 – Probability of total damage.

It is observed that for the limit state of 25 cm, the TMD schemes are somewhat effective in the PGA range of 0.75 *g* to 1.25 *g*. With PAG of 1.5g or higher, the probability of having minor damage is around 90%. As for the higher damage states, the effectiveness of the TMDs seems similar, around 10% in critical cases.

4. Conclusions

The study on reliability of tuned mass damper (TMD) added on base isolated (BI) building is presented. Three TMD schemes placed on BI building, as single TMD (STMD) placed at top (BI+STMD), multiple TMDs (MTMDs) at top floor (BI+MTMDs), and distributed MTMDs placed at varies floors (BI+dMTMDs) for response mitigation of a five-story reinforced concrete (RC) building is presented. The following conclusions can be drawn.

1. TMD schemes are not useful in controlling wind-induced response of the base isolated building, which is relatively short with only 5 storys.
2. TMD schemes can provide up to 10% reduction in seismic response control of the building in critical loading scenarios.

It is to be noted that the TMD schemes presented here are designed using a general formulation and are not optimized to the specific structure it is used in. Furthermore, the base isolation system is also not specifically optimized for the building. Given the potential inelastic deformation of the base isolation system and subsequent detuning of the TMDs, it implies that TMDs that are effective for a given ground motion might not be effective for another. With more specific knowledge of the expected hazard and corresponding scenarios of ground motion at a given site, both the isolation system and the TMDs can be specially optimized to be effective for those scenarios. Effectiveness of hybrid systems optimized in this manner remains to be studied.

4. Acknowledgements

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5. Copyrights

6. References

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