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Multi-objective optimal design of inerter-based dampers for earthquake protection of buildings trading seismic performance to inerter force[1]

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1 INTRODUCTION & SCOPE OF WORK

Seismic protection of new buildings is addressed either through ductile design for earthquake resistance (e.g., *Avramidis et al, 2016*) or by incorporating supplemental damping devices and/or base isolation systems (e.g., *Christopoulos and Filiatrault 2006*). The second approach aims to reduce risk for excessive downtime and structural repair costs in the aftermath of severe seismic events. It commonly involves designing passive viscous and viscoelastic dampers, placed in between building floors with the aid of stiffeners and connectors, to achieve, ideally, linear structural response during major earthquakes. Alternatively, dampers and stiffeners are used to attach a secondary free-to-oscillate mass (close) to the top floor of buildings tuned to counteract the lateral earthquake-induced building motion. In all cases, stiffness and damping properties of the above passive vibration control configurations are designed/tuned to enhance the seismic performance of the uncontrolled (host) building structure by mitigating critical to seismic loss earthquake response quantities, hereafter termed engineering demand parameters (EDPs), such as inter-storey drifts and floor accelerations.

In this context, in recent years, new breeds of passive vibration absorbers emerged for the earthquake protection of building structures coupling conventional viscous dampers, stiffeners and, even, secondary oscillating masses, with an inerter device. The inerter, conceptually introduced by *Smith (2002)* as a linear massless two-terminal mechanical element, resists relative acceleration by a force proportional to a constant termed inertance, *b*, and measured in mass units (kg). In the three most widely studied inerter-based vibration absorbers (IVAs) shown in Figure 1(a), the inerter is functioning either as a motion amplifier [tuned-viscous-mass-damper (TVMD) configuration detailed by *Ikago et al (2012)*], mass amplifier [tuned-mass-damper-inerter (TMDI) configuration introduced by *Marian and Giaralis (2013, 2014)*], or mass substitute [tuned-inerter-damper (TID) configuration introduced by *Lazar et al (2014)*]. Previous work has shown that through proper tuning, IVAs achieve enhanced earthquake-induced vibration suppression and/or weight reduction compared to conventional dampers/absorbers [see e.g., *Giaralis and Taflanidis (2015, 2018)*], but at the expense of increased control forces exerted from the IVA to the host building structure [see e.g., *Ruiz et al (2018)* and references therein]. These potentially large forces are typically not accounted for by current IVA tuning approaches.

To address the above issue, a bi-objective IVA design approach has been recently developed by *Taflanidis et al. (2019)* which identifies the compromise between the competing objectives of (i) suppressing earthquake-induced vibrations in buildings, and (ii) avoiding development of excessive IVA (control) forces. The approach is only briefly presented in this extended abstract. For technical details the interested reader is referred to *Taflanidis et al. (2019)*. Major research outcomes and conclusions, partially supported by selective numerical results pertaining to a benchmark 9-storey steel frame building, are then summarized.

[1] This is an extended abstract of the work reported in *Taflanidis et al. (2019).*
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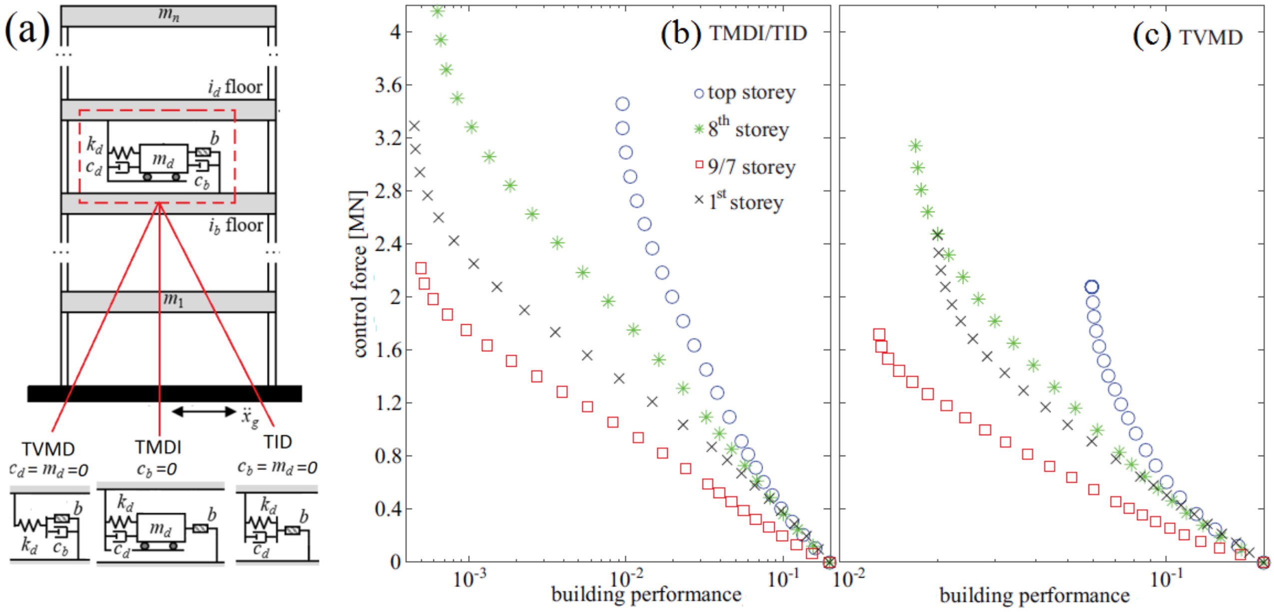

Figure 1. *Different IVAs studied (a) and Pareto fronts for different placements for (a) TMDI/TID and (b) TVMD.*

2 METHODOLOGY

The developed IVA design approach aims to tune stiffness, k_d, damping, c_d or c_b, and inertia, i.e., secondary mass m_d and/or inertance b, IVA properties given a linear host structure base-excited by colored stochastic excitation, $\ddot{x}_g$, as shown in Figure 1(a). A pertinent multi(bi)-objective optimal design problem is formulated and numerically solved via the epsilon-constraint method. One rigorous and one simpler optimal design formulations are considered with respect to the metric used to quantify objective (i), i.e., host building seismic performance. The rigorous formulation quantifies objective (i) through an equally weighted sum of probabilities that EDPs of interest within a performance-based seismic design context (i.e., storey drifts and/or floor accelerations) exceed a pre-specified threshold. These probabilities were calculated semi-analytically through first-passage reliability criteria using the EDP out-crossing rates (see also *Taflanidis and Beck 2006)*. The variant, simpler, formulation quantifies structural performance using equally weighted sum of EDP variances in accordance to traditional optimal tuning methods for inertial/mass dampers in stochastically excited structures. In both formulations, objective (ii), developed inerter force, is quantified through the variance of the force transferred from the IVA to the host building. In the numerical part of the work of *Taflanidis et al. (2019)*, comprehensive optimal Pareto designs are furnished, obtained by both problem formulations, for the TMDI, TID and TVMD in various practically relevant placements along the height of a benchmark (realistic) 9-storey steel building developed by *Ohtori et al (2004)* subject to a filtered Kanai-Tajimi stationary seismic ground excitation with parameters corresponding to soft soil conditions. Moreover, the efficacy of the above IVA designs optimized under stationary excitation and structural response conditions is verified for a non-stationary stochastic excitation model consistent with the stationary one in terms of duration and frequency content capturing typical evolutionary features of the amplitude of recorded earthquake accelerograms. The comparison between stationary and non-stationary performance is enabled by adopting equivalent with the stationary case metrics for quantifying objectives (i) and (ii) under non-stationary excitation/response conditions computed via standard Monte Carlo simulation.

3 RESEARCH OUTCOMES

It is numerically shown that the developed bi-objective design approach can trace effectively the compromise between the two considered competing objectives (building performance in terms of storey drifts and floor accelerations versus IVA control force exerted to the host building), providing a range of Pareto optimal IVA designs to choose from. This is herein illustrated in Figures 1(b) and 1(c) furnishing optimal Pareto IVA design solutions for four different placements of TMDI/TID and TVMD, respectively, at the top (9^{th}) floor, penultimate (8^{th}) floor, ground floor as well as two last/top-floors spanned using an internal atrium. These novel pareto fronts showcase that considerable reduction of IVA control force transferred to the building of up to 3 times can be achieved with small deterioration of building performance compared to the extreme Pareto optimal IVA design targeting maximum building vibration suppression level. It is further seen that TID and TMDI achieve practically the same building performance and significantly outperform the TVMD. Moreover, IVA placement at the ground storey improves performance across both objectives (i) and (ii) considered compared to placement at the top storey and even more so does IVAs spanning the two upper stories. This indicates that proper placement of the IVA device is an important consideration.

A further outcome illustrated through further numerical work reported in *Taflanidis et al. (2019)* is that the simplified design formulation minimizing the sum of EDP variances may provide significantly suboptimal performance compared to reliability-based performance criteria related to the probability of trespassing acceptable EDP thresholds which are better aligned with the modern performance-based seismic design framework. Lastly, the assumption of stationary excitation/response conditions for IVA optimal design neither affects the quality of the converged Pareto optimal solutions nor the identified corresponding trends compared to non-stationary conditions and, therefore, stationary colored noise excitation models capturing local soil conditions suffice for effective IVA tuning for the seismic protection of building structures.

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