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Effective damping and frequencies of viscous damper braced structures considering the supports flexibility

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ABSTRACT

This paper presents a study on the optimal sizing of damping braces of MDOF systems equipped with viscous dampers where, unlike well-established computer-based optimisation methods, the deformability of the elastic supports is integrated by means of a novel non-iterative design tool. Mainstream optimisation methods usually focus on sizing supplemental damping devices neglecting the damper supports' flexibility and therefore their effect on the overall structural damping and frequencies of vibration. In this work, the damping braces are modelled by way of viscous-elastic assemblies using the Maxwell representation. The equations of motion are formulated in the state-space representation to facilitate the assessment of the viscous-elastic assemblies' effects. The system solution presented in form of contour plots is then used as a prime tool to select the design parameters for both dampers and supporting braces, while preserving a desired level of added damping. In addition, it is shown how this approach also gives the engineer the flexibility of either fixing a damper size to then determine the required supporting brace stiffness or fixing the supporting brace stiffness to then determine the maximum achievable damping. A case study taken from the literature is presented to illustrate the advantages of the proposed approach.

1. Introduction

In earthquake-prone areas a large number of structures need to be upgraded due to increased hazard levels or new code provisions, especially if they are mission critical structures. In such cases higher performance levels are also desired and passive control systems, such as supplemental damping or seismic isolation systems, may represent the solution to achieve the desired enhanced performance. Supplemental damping systems increase energy dissipation capacity, absorbing a quota of the energy that reaches the structure by means of special devices called dampers. When these devices are placed into the structure, a brace is typically needed to attach them to adjacent floors. In most analysis, these braces are neglected and assumed to have infinite stiffness if compared to both the floor and the device inherent stiffness. Nevertheless, dimensions of the steel braces often need to be limited for functional and aesthetic requirements, so that their stiffness cannot be considered to be infinite.

Brace stiffness can significantly alter the effectiveness of the damper connected to it, and in structures with multiple dampers this can be a challenging scenario to model. The brace compliance reduces the displacement effectively transferred from the structure to the damper and introduces a shift in terms of phase and frequency in the system dynamic response. These issues have been studied by several researchers seeking for more accurate design procedures. However, because of the complexity of the previously proposed design procedures, many designers still prefer to assume that the supporting braces are infinitely stiff.

The present paper is aimed at proposing a non-iterative procedure for the seismic design or retrofit of new or existing buildings with viscous dampers supported by elastic-deformable braces. Here dampers are arranged together with the supporting brace in a viscous-elastic assembly and are represented by the Maxwell visco–elastic model. In a previous work, the authors have introduced a state-space representation for the design of seismic retrofit of an existing residential building [1]. Starting from a target damping level corresponding to a damping coefficient defined in accordance with FEMA provisions [2], the authors selected the brace +damper system capable to produce the desired level of damping. The state-space representation considered here provides a convenient and compact way to model dynamic systems with multiple inputs and outputs. The main advantage of this representation is that the system dynamics can be formulated in such a way that all the physical characteristics, including dampers and supporting braces, can be condensed into a single matrix, the so-called the

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system matrix. Hence, by studying the eigenvalues of that system matrix we can assess the behaviour of the whole systems and make decisions on the more beneficial configurations of added damping devices without needing additional iterative calculations.

The current paper presents further developments of the state-space modelling of brace+damper systems and provides additional results on the combined effect of additional damping and stiffness. In addition to damping increase, the need to properly account for frequency variation of the controlled structure due to brace damper compliance is highlighted. A case study is used to show how the non-iterative proposed analysis provides valuable information that not only helps selecting the more suitable brace-damper arrangement and but also reveals its effects on the overall structural dynamics. Performance indices are used to assess the structural response under earthquake base excitation for the different dissipative systems.

2. Optimal location and sizing of viscous dampers

A variety of procedures have been proposed in the literature for optimal location and sizing of viscous dampers. For linear multi-degree-of-freedom (MDOF) systems, Gurgoze and Muller [3] considered the optimal positioning of a viscous damper based on an energy criterion. Zhang and Soong [4] proposed a sequential optimization approach based on a controllability index for the optimal placement of devices. Gluck et al. [5] have obtained storey-wise optimum damping distribution using the solution for the linear quadratic regulator problem. In addition, Loh et al. [6] have proposed two design methods based on control theory: one is derived from the linear quadratic regulator, and the other from modal control theory. Tsuji and Nakamura [7] proposed a united optimization procedure of both structure and dampers. Using this technique, they have minimized total storey-stiffness of a structure satisfying constraints in terms of inter-storey drifts. Takewaki [8] and Takewaki et al. [9] used a gradient based approach for optimal placement of dampers by minimizing a norm of the response transfer function evaluated at the undamped first mode frequency of the structure. Moreschi [10] posed the optimal placement of viscous dampers as a discrete combinatorial optimization problem, and used genetic algorithms to obtain the device locations and sizes. In Mahendra and Moreschi [11], a gradient-based approach is described for optimal design of linear damping devices, such as viscous or visco-elastic dampers. The performance index to be minimized is defined as a function of the response of the system, which is obtained by considering a stochastic description of the input motion.

In all of these procedures however, the effects of brace stiffness were not accounted for. In the study presented by Singh et al. [12], it was noted that the brace flexibility reduces the effectiveness of the added viscous dampers and, using gradient–based optimisation algorithms, it was concluded that a brace stiffness five times the storey stiffness would be adequate to preserve the dampers' effectiveness. The influence of brace stiffness on response reduction was also studied by Takewaki and Yoshitomi [13] using five different brace stiffness. It was similarly noted that the brace stiffness affects the optimal damper distribution and structural performance and was highlighted that the brace stiffness should be taken into account during the design of the dampers. For structures with toggle braces, studies by Huang [14,15] showed that the efficiency of the toggle brace–damper system depends significantly on the support brace stiffness.

Although the importance of brace stiffness is generally recognised, most practitioners still neglect the effects of the effective stiffness of the supporting brace when modelling the damping assembly assuming a pure damper behaviour. Relevant studies tackling this issue have been published over the last decade. Park et al. [16] used a gradient–based optimisation algorithms to obtain the optimal parameters for both dampers and their supporting braces in structures subjected to seismic motions. More recently, Chen and Chai [17] also proposed a gradient–based numerical procedure for determining the minimum brace stiffness together with a set of optimal damper coefficients to meet a target response reduction. A gradient-based evolutionary algorithm was also proposed by Fujita et al. [18] where, given a total damper area as a unique cost parameter, the optimal distribution of dampers and supporting members is iteratively found. The method operates in the frequency domain and was demonstrated using a planar shear building model.

It is worth noting that by adding the braces' stiffness as unknown variables to any numerical optimisation procedure, the search space doubles size. This adds complexity to the optimisation problem, requiring more computational effort and becoming increasingly difficult to ensure convergence to a global minimum. That is way a less complex optimisation problem with a reduced number of variables might be preferred.

As an alternative procedure on this direction, Londoño et al. [19] proposed the use of one of the existing damper sizing strategies (where damper coefficients are typically optimised assuming infinitely stiff braces) followed by a non-iterative filtering method to select the stiffness of all braces in a way that the damper efficiency is preserved; thus, effectively including the brace stiffness in the design process without increasing complexity. Another related approach was proposed through the brute-force search analysis completed by Fu and Kasai in [20], where the authors recommended for near–optimal solutions a ratio between the damper loss stiffness to storey stiffness in the range 1.0–1.5 and a ratio between the brace stiffness to storey stiffness in the region of 10.

In this work, a general MDOF system equipped with viscous dampers is analysed in state-space representation, explicitly modelling the supporting members' flexibility. The authors aim at showing that in addition to the effective added damping, the effective resulting frequency has important effects on the structural dynamics and need to be properly accounted for. Unlike previous contributions, an easy-to-use design tool is employed here to show these combined effects. The proposed non-iterative procedure also allows to achieve a desired damping ratio, simultaneously providing the system's frequency variation, by either (i) fixing a damper configuration and then selecting the necessary supporting braces' stiffness or (ii) defining a supporting brace configuration and then obtaining the necessary damper sizes. Effective performance is checked a posteriori by time history analysis in terms of properly defined performance indices.

3. Modelling the brace-damper compliance in state-space representation

3.1. SDOF

For the sake of simplicity, we firstly consider the single–degree–of–freedom structure (SDOF) shown in Fig. 1a, where the supplementary viscous damper is connected to the structure via a supporting brace of stiffness k_b. Note that additional dynamics arise from the inclusion of the brace's flexibility. The force generated by this brace–damper configuration can be represented by a purely viscous damper and purely elastic spring connected in series as shown in Fig. 1b.

The system dynamics under earthquake excitation can be described by means of the set of Eqs. (1), where m, c and k represent the structural mass, damping and stiffness; x is the structural displacement relative to ground and $\ddot{x}_g$ is ground acceleration. Note

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