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Effectiveness of fluid-viscous dampers for improved seismic performance of inter-storey isolated buildings

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ABSTRACT

The use of fluid viscous dampers (FVDs) together with isolators, frequent in near-fault buildings, is effective in reducing displacements of the isolation layer. Such a hybrid system is also beneficial in the case of inter-storey isolation with the aim of limiting P-Δ effects. However, previous research on base isolation shows that this additional damping may also be detrimental, as inter-storey drifts and floor accelerations may increase.

This paper analyses the effectiveness of FVDs for enhanced seismic performance of systems with inter-storey isolation. A seven-floor building, with natural and lead rubber bearings between the second and third levels, was used as a case study, and a multi-objective optimal design was performed to identify the best damper parameters. In particular, time-history analyses with various natural records were carried out and two competing objectives were examined: minimisation of the deflection of the isolation layer and minimisation of the total drift of the superstructure.

The results show not only the effectiveness of optimal FVDs but also the fact that their optimal linearity degree depends to a great extent on the non-linear seismic response of the structure, i.e., on the type of earthquake. The simplest design approach, consisting of applying an optimization algorithm for each design accelerogram, did not seem, in this case, to be sufficient to identify the best overall design solution. The design consequences of these findings are discussed.

1. Introduction

Inter-storey seismic isolation has attracted increasing interest in recent years, particularly in densely populated areas, as an alternative mitigation strategy to base isolation for both new and existing buildings. As the name suggests, the isolation system is incorporated between storeys rather than at the base of the structure, in view of architectural concerns, feasibility of construction, and performance benefits. Although base isolation for multi-storey buildings is a well-known technique applied worldwide, it may sometimes clash with substantial economic and technical problems, which may limit its application.

In particular, installing base isolation is straightforward for new buildings, but becomes complicated and expensive for existing ones, since excavation and temporary support works are required. Instead, the installation of inter-storey isolation is relatively simple and generally less expensive and disruption-free. It also allows extra floors to be constructed on an existing building (if its vertical capacity allows this) without increasing the total base shear demand, and thus represents an innovative and realistic retrofitting approach [1,2].

Firstly, base isolation is not as effective for medium/high-rise buildings as inter-storey isolation, because of the flexibility and bending-type behaviour of the latter [3]. Secondly, storey isolation can greatly increase design flexibility in high-rise and multipurpose buildings, by separating them into two independent structural parts which can be designed with different shapes, materials and functions, thus allowing them to become unique architectural features [4]. Examples of this application to irregular high-rise buildings are the Iidabashi First Building [4] and the Shiodome Sumitomo Building [5] in Japan, two multipurpose buildings having substructure and superstructure with different structural shape. In China, this technique was used to isolate 50 buildings (seven- or nine-storey RC frames) in Beijing, built on top of a two-storey platform covering a very large ($\sim 3\,km^2$) railway area [6]. Built relatively recently, in the National Taiwan University campus, the Civil Engineering Research Building is a nine-storey pre-cast RC structure with an inter-storey isolation system installed between the second and third floors, which also includes viscous dampers [7]. Lastly, moving the isolation layer to the upper storeys reduces the need for a

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seismic gap, which is necessary to accommodate the expected displacement of isolators, but also expensive and sometimes impractical in densely-built urban areas.

This isolation strategy, which can be achieved by inserting isolators inside the columns of a chosen storey (especially for retrofitting applications) or between RC slabs (i.e., the top and base of the substructure and superstructure, respectively), substantially converts the masses above the isolation layer into tuned masses, retaining their structural functions in addition to the control function; in other words, the principle of operation may be appropriately described as a non-conventional tuned mass damper (TMD) with a large mass ratio [8].

Fluid viscous dampers (FVDs) and other damping devices are often used together with isolators. Their primary function is to reduce the seismic demand which, in some cases, requires isolation devices of considerable size and cost to avoid their buckling or rupture. This is particularly true in the case of near-fault (NF) ground motions, characterized by intense long-period pulses of motion, for which several authors have shown the need for additional damping [9–11]. However, such hybrid systems are also very effective in the case of inter-storey isolation, reducing P-Δ effects due to drift between the structural parts separated by the isolation layer.

Kelly [12] questioned the usefulness of this supplementary damping on the basis of analytical treatment of a linear two degrees-of-freedom (DOF) base-isolated structure. He concluded that it reduced the efficiency of the isolation system by exciting higher modes, leading to higher floor accelerations and inter-storey drift. This was disputed by Hall [13] who, through time-history analyses of a 2-DOF linear system, demonstrated that supplementary damping can reduce the displacement demand of the isolation system and may also reduce drift. Further studies demonstrating these advantages of added linear viscous damping were performed by other authors, such as: Hall and Ryan [14], who carried out response history analyses on high damping rubber bearings and linear viscous dampers; Jangid and Kelly [15], who studied the effects of isolation damping on the performance of various isolation systems under near-fault motion; Alhan and Gavin [16], who performed time and frequency domain analyses on an eight-storey structural model, isolated with both linear viscously damped and non-linear yielding hysteretic systems; Politopoulos [17] who, again investigating a base-isolated 2-DOF system, confirmed the conclusions of Hall [13], and also showed how additional damping can reduce floor spectra values in the vicinity of the first mode - at the expense, however, of a possible increase of the same values near higher modal frequencies. Providakis [18,19] and Fathi et al. [20] have recently provided other numerical studies on supplementary linear viscous damping; Providakis studied two realistic base-isolated RC buildings, examining both lead rubber bearings (LRB) and single friction pendulum (FPS) isolators, and Fathi et al. investigated ideal moment-resisting steel frames, base-isolated with LRB devices. Some of their conclusions were similar: for instance, an increase in the damping ratio reduces the base displacement for both near-fault (NF) and far-fault (FF) earthquakes, while sometimes amplifying floor accelerations. However, results regarding inter-storey drift are conflicting; according to Providakis [18,19], if the damping ratio increases, drift decreases in the case of NF and increases in that of FF, which may be the result of 'too much damping' in the weaker FF motions.

Some interesting applications of FVDs in isolation systems, in the USA and particularly in California, are reported in Wolff et al. [21]. These authors observed that, despite the now widespread use of non-linear FVDs, the application of FVDs in isolation systems has progressed toward using linear dampers. Another example in which linear FVDs were placed in a storey isolation system is the previously mentioned building in the National Taiwan University campus [7].

A non-linear FVD (i.e., with damping exponent α of less than 1) dissipates more energy per cycle than a linear one (i.e., with α approximately equal to 1), considering the same maximum damping force and displacement amplitude. It also provides a safeguard by limiting the transmission of damping force at high velocities beyond the design value [22,23]. Instead, in the case of sinusoidal or similar motions, a linear damper allows containment of the total force at maximum displacement, when the damping force is ideally nil. According to Ziyaeifar and Noguchi [3], in partial mass isolation, a high damping force reduces the isolation effect, blocking the sliding gap offered by the isolation layer. This fact practically sets a limit for the appropriate value of the linear damping ratio, which may be increased when a non-linear viscous device is used, as it is capable of providing lower damping force together with a higher energy dissipation rate. However, tests conducted by Wolff et al. [21], who compared the effectiveness of linear and non-linear FVDs, used together with low damping rubber bearings and high damping FPS isolators, showed that linear damping is more suitable to contain increases in inter-storey drift and floor acceleration, particularly in the case of high damping isolators, despite the apparent advantages of non-linear devices.

Although not new, this topic is still of great interest. The main effects of additional damping on base-isolated buildings are clear, but recent results obtained by several authors are not always easy to compare, because they are also strongly influenced by the initial hypotheses, including damper features. In addition, the use of FVDs in buildings isolated at storey level, rather than at the base, has its own peculiarities, and the effectiveness of FVDs for the improved seismic performance of such structures has not yet been investigated.

Within this context, this paper presents a multi-objective optimization study of an FVD mounted on an inter-storey isolation system, consisting of both natural rubber bearings (NRBs) and lead rubber bearings (LRBs). For this purpose, a reference seven-storey building was examined, with substructure and superstructure modelled as linear and separated between the second and third floors by an isolation layer with non-linear hysteretic behaviour depending on both displacement (due to LRBs) and velocity (due to the FVD). Time-history simulations were performed for various natural accelerograms, scaled to the same peak ground acceleration (PGA) of 0.25 g, for comparison. Although several multi-objective structural optimization studies have been carried out over the last 20 years, this type of investigation, to the authors' knowledge, still seems to be missing in the scientific literature. For example, as regards storey isolation, optimization studies concern the number and position of the isolation layers along the height of the building [24,25] and the properties of its isolators [8,26]; whereas, as regards FVDs, these studies concern their optimal allocation inside buildings [27] and optimal parameters in controlling vibration in stay cables for bridges [28,29], but only a few of them deal with FVD optimization when used together with isolators, and they also focus only on linear dampers [30]. Indeed, previous studies of the effectiveness of additional damping in base-isolated buildings have always been addressed by assuming FVD features. In particular, in this study, the fast, élitist Non-dominated Sorting Genetic Algorithm NSGA-II [31] was used to find a set of optimal Pareto solutions, or optimal combinations of damper parameters, i.e., damping coefficient c (ranging from 1 to 10^7 N(s/m)$^{\alpha}$) and exponent α (0.1–1.0). For this purpose, two objective functions were chosen and pursued simultaneously, which are: minimisation of isolation layer deflection, and minimisation of total superstructure drift. Furthermore, the following constraint was assumed in the analysis: the total drift of the superstructure must be limited to that calculated without using FVDs. The results show the potential of optimal FVDs in improving the seismic response of isolated inter-storey buildings, and include the maximum values of base shear force, FVD force, inter-storey drift and floor acceleration of both superstructure and substructure, shown as ratios between the cases with and without dampers, and plotted versus isolator drift reduction due to the dampers. Certain correlations between the frequency-domain velocity response of the isolation layer and the linearity degree and performance of the FVD are highlighted, and show that optimal α depends to a great extent on the non-linear seismic response of the structure, and thus on seismic action. Lastly, the design consequences of these research findings are discussed.