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SEISMIC PERFORMANCE ASSESSMENT OF CONVENTIONAL AND RETROFITTED BUILDINGS CONSIDERING NONSTRUCTURAL SYSTEMS

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Abstract

Inadequate nonstructural seismic performance during recent earthquakes has led to extensive repair costs and lengthy functional disruptions. This study investigates the application of fluid viscous dampers (FVDs) to minimize nonstructural damage. Studies on damper placement have focused on structural parameters, however repair costs are a more appropriate measure. Damper placement and amount of supplemental damping are examined. A conventional 16-storey concentrically braced frame (CBF) building and six FVD retrofitted designs are created. Nonlinear time history analyses are performed in OpenSees and the FEMA P-58 performance assessment procedure is used to calculate repair costs.

The conventional building sustained extensive damage to structural and nonstructural systems. The FVD retrofitted designs achieved reductions of approximately 50% in both the ultimate limit state (ULS) and serviceability limit state (SLS) repair costs. Negligible SLS structural damage occurred, which is critical for achieving immediate occupancy. Increasing the total damping from 20% to 35% reduced repair costs by an additional 5% to 7% for the ULS, in contrast to a previously suggested maximum damping of 20% to 25%. Stiffness proportional placement produced lower repair costs than uniform placement, supporting placement techniques that concentrate dampers near the bottom of the structure. Limitations of the Eurocode 8 damage mitigation methodology were exposed. It was found that an interstorey drift limit of 0.5% should be prescribed for CBF structural damage prevention rather than 1%. The 0.5% limit did not prevent nonstructural damage. Advanced placement techniques may further decrease repair costs and is the subject of ongoing research by the authors.

Keywords: seismic performance assessment; nonstructural systems; fluid viscous dampers; damper placement

1. Introduction

Conventional seismic design philosophy permits undesirable levels of nonstructural damage as demonstrated by recent earthquakes [1], [2]. Nonstructural systems include building contents, architectural components, and mechanical, electrical and plumbing systems. These systems are essential to building operations and comprise the majority of building investment as shown in Fig. 1. Nonstructural damage causes lengthy functional disruptions and accounted for several billion dollars of losses in 2010 alone [3]. Conventional seismic design limits interstorey drift ratios (IDRs) but does not limit floor accelerations. Several major nonstructural systems are acceleration sensitive, such as suspended ceiling systems. Attaining a target level of seismic performance mandates the harmonization of structural and nonstructural performance levels.

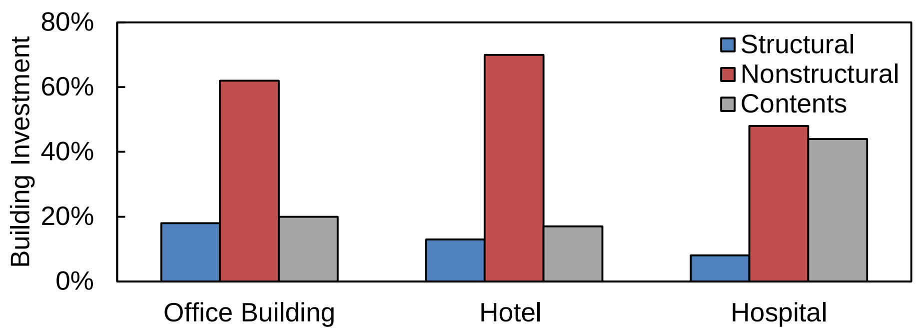

Fig. 1 – Distribution of building investment for three building categories. Data from [4]

Supplemental damping devices can substantially reduce drifts and improve the seismic performance of buildings [5]. Of these devices, fluid viscous dampers (FVDs) are unique as the devices can improve both interstorey drifts and floor accelerations [6], [7]. The distribution of dampers within a building is a critical decision, as damper placement affects structural response and the required damper investment. Despite this, building codes do not prescribe a damper placement method. Many damper placement techniques have been proposed in literature and limited comparisons of techniques have been conducted [8]. Most studies comparing FVD placement techniques for optimal performance evaluate structural parameters such as interstorey drift [8], [9].

Seismic performance assessments allow for changes in structural parameters to be expressed in repair costs [10]. Gidaris and Taflanidis conducted research on earthquake losses using a limited set of assembly-based vulnerabilities [11]. Damper placement methods and total supplemental damping should be assessed in terms of repair costs rather than a set of structural parameters. Repair costs allow damping variables to be accurately compared and cost-effective best practices to be determined. There is also a need to clarify what seismic performance improvements can and cannot be achieved using supplemental damping.

This study assesses the seismic performance of a 16-storey steel concentrically braced frame (CBF) building that is representative of conventional multistorey buildings constructed in seismic regions. Seismic performance is expressed in repair costs. This design provides a benchmark on which to evaluate retrofit alternatives using FVDs. The effect of damper placement and of total amount of supplemental damping on seismic response is then investigated. The final aim of the project is to develop a FVD placement strategy that minimizes structural and nonstructural repair costs.

2. Methods

2.1 Multistorey Office Building

A Eurocode [12] compliant building design was created in order to evaluate the seismic performance of conventionally designed structures. The structure is a 16-storey steel office building. The lateral load resisting system consists of concentrically braced frames located on the structural perimeter. A peak ground acceleration of 0.31g was used for the design, representing an area with significant seismic events. The fundamental period of the building (T_1) is 2.34 seconds. An elevation and a plan view are shown in Fig. 2. Further building design information can be found in [13].

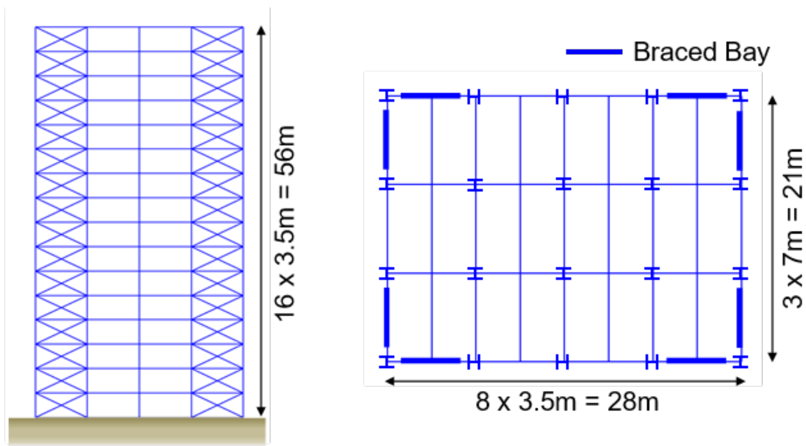

Fig. 2 – Elevation and plan views of the multistorey office building

2.2 Supplemental Damping

The amount of supplemental damping in a building significantly influences structural response during an earthquake. Occhiuzzi found a maximum of 20% to 25% total damping in the first mode to be ideal, as additional damping increases acceleration and has negligible further reductions in IDR [14]. Christopoulos and Filiatrault stated that a maximum total damping of 35% in the first mode can reasonably be achieved with FVDs [5].

Specifying a desired performance level allows the required amount of supplemental damping to be determined. Performance levels are often expressed by IDR limits. ASCE 41 suggests an IDR of 0.5% to achieve immediate occupancy (IO) performance for steel braced frames [15]. This is a typical value rather than a standard limit and is based on structural performance rather than nonstructural performance. Eurocode 8 prescribes IDR limits of 0.5% and 1% for nonstructural and structural immediate occupancy, respectively [12].

ASCE 7-10 Table 18.6-1 [16] and Eurocode 8 Cl. 3.2.2.2 [12] were used to determine the required total damping based on a ratio of the bare frame performance and the desired performance. Supplemental damping is the total damping less the inherent damping. The peak IDR of the conventional building at the ultimate limit state (ULS) was calculated to be 1.6% through modal response spectrum analysis in SAP2000. Targeting a ULS drift of 0.5% corresponding to ASCE immediate occupancy was unfeasible, as this would require over 70% damping. A ULS drift target of 1% was selected, corresponding to structural immediate occupancy as stated by Eurocode 8.

The supplemental damping required to attain the ULS drift target was determined. An inherent damping value of 5% was designated. The required supplemental damping was calculated as 15% using the Eurocode method and as 20% using the ASCE method. These values are also consistent with the maximum efficient damping recommended by Occhiuzzi [14]. A third level of 30% supplemental damping was selected, corresponding to the maximum amount of damping that can be practically reached using FVDs according to [5].

2.3 Damper Placement

This preliminary study is limited to linear dampers. The force output of a linear fluid viscous damper j is given by Eq. (1), where C_j is the viscous damping coefficient and $\dot{u}_{rj}$ is the relative velocity of the damper ends.

$$F_j = C_j \dot{u}_{rj} \tag{1}$$

In order to size and place the dampers, the supplemental damping targets to be introduced by the FVDs were converted to viscous damping coefficients. The energy method from Whittaker et al. [17] was used and is reproduced in Eq. (2), where ξ_d is the supplemental damping ratio, θ_j is the angle of damper inclination, ϕ_{rj} is the relative first modal displacement, and ϕ_i is the modal displacement of mass m_i.

$$\xi_d = \frac{T_1 \sum_j C_j \cos^2 \theta_j \phi_{rj}^2}{4\pi \sum_i m_i \phi_i^2} \tag{2}$$

This initial study is limited to two placement techniques: uniform damping and stiffness proportional damping. Uniform damping evenly distributes the total supplemental damping between each storey. This simple technique is one of the most commonly used placement methods. Stiffness proportional damping distributes the dampers in proportion to the relative storey stiffness. This placement method results in damper coefficients concentrated in the lower storeys, with reduced coefficients in the upper storeys. Stiffness proportional damping serves as a preliminary measure of advanced placement techniques, as many proposed methods have minimal damping in the upper storeys and concentrate dampers near the bottom of the structure [8]. Damper placement within each storey of the building was not considered.

Seven designs were created to investigate the effect of damper placement and of total amount of supplemental damping on seismic performance. CBF refers to the conventional structure without supplemental damping. U15, U20 and U30 refer to the uniform damping placement designs with 15%, 20% and 30% supplemental damping respectively. K15, K20 and K30 refer to the stiffness proportional damping designs with 15%, 20% and 30% supplemental damping respectively. These damping ratios were calculated using Eq. (2), and the actual modal damping ratios will be confirmed in a future paper as recommended in [14].

2.4 OpenSees Models

A 2D model of the structure was created in the finite element program OpenSees in order to conduct nonlinear analysis. A leaning column was employed to account for P-Δ effects from the vertical loads acting on gravity columns in the tributary plan area. Inherent damping was incorporated using mass and tangent stiffness proportional Rayleigh damping of 5%. The first and third periods were used to determine the Rayleigh damping parameters as these modes account for 92% of the effective mass. The first period was elongated to account for the expected nonlinear brace buckling, preventing the generation of artificial damping forces [18].

The braces were modelled using the procedure from Uriz et al. [19]. Each brace was modelled using two elements with an initial imperfection of 0.1% at the midpoint to induce buckling in compression. A fictitious load producing 5% of the section yield moment was applied at the midpoint in order to prevent brace straightening and enable buckling. The analytical model was verified using experimental cyclic loading data from [20] as shown in Fig. 3. The hysteretic behaviour is captured, as brace buckling in compression and yielding in tension are accurately predicted. The FVDs were modelled using the viscous uniaxial material available in OpenSees.

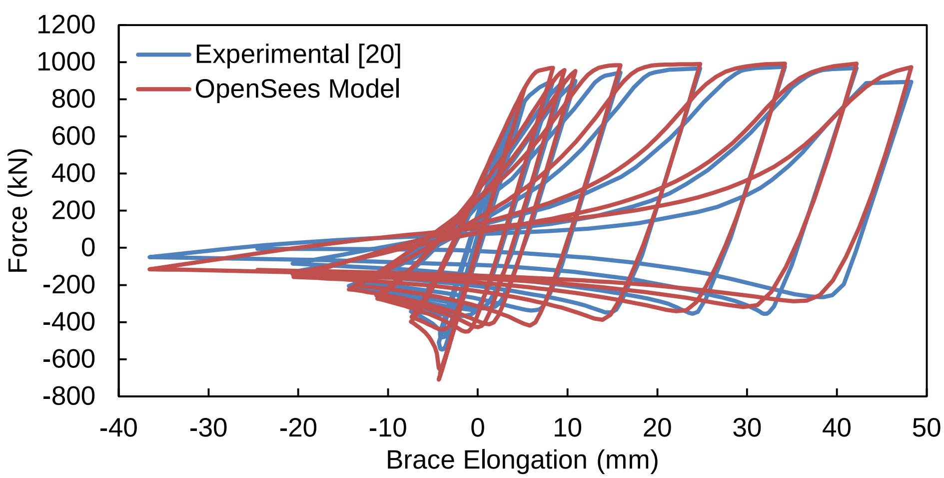

Fig. 3 – Comparison of experimental and analytical brace hysteretic behaviour

2.5 Time History Analysis

Nonlinear time history analyses were performed using recorded ground motion suites representing the ultimate limit state and the serviceability limit state (SLS). The ULS earthquake has a 10% probability of exceedance in 50 years and the SLS earthquake has a 10% probability of exceedance in 10 years. The ground motion records were selected and scaled following the Eurocode 8 requirements, with a factor of 0.5 used to define the SLS spectrum [12]. Records were obtained from the PEER ground motion database [21]. A linear scale factor was applied to each record which minimized the mean squared error between the ground motion spectrum and the target Eurocode spectrum over the period range of $0.2T_1$ to $2T_1$. A maximum of one record was selected per earthquake and the scale factor was limited to 2. ULS ground motions were constrained to have a magnitude greater than 5.5 to match the Type 1 spectrum and all ground motions had an average shear wave velocity appropriate for ground type C [12]. 25 ground motions with the smallest mean squared error were selected for each suite. Fig. 4 compares the ground motion suite spectrum and the Eurocode 8 elastic response spectrum for the ULS and SLS.

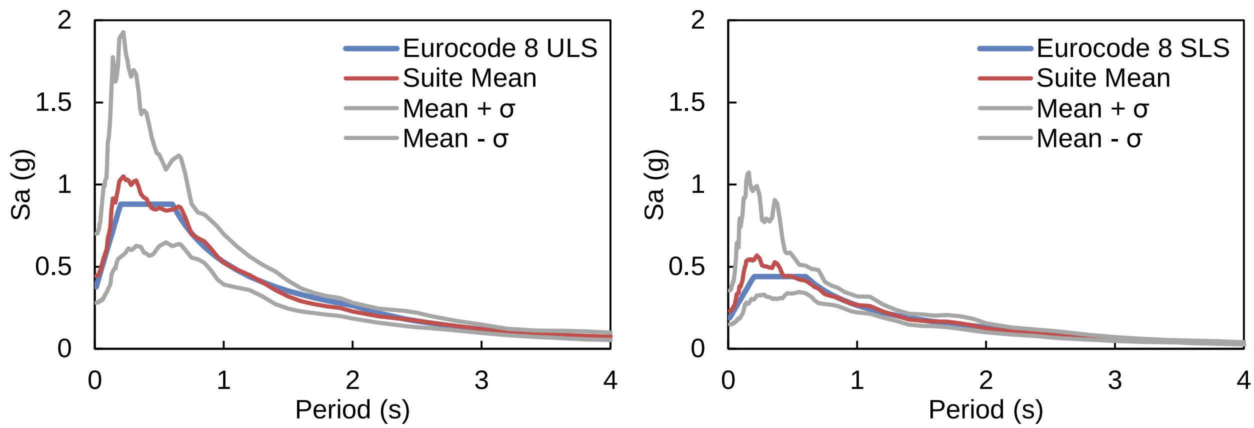

Fig. 4 – Comparison of the ground motion suite spectrum and the Eurocode spectrum for the ULS (left) and SLS (right)

2.6 Seismic Performance Assessment

The FEMA P-58 performance assessment procedure [10] was used to evaluate the seismic performance of the building designs. Structural response parameters from the time history analysis were used in combination with fragility functions to determine repair costs. Fragility functions indicate the probability of exceeding a damage state at a given engineering demand parameter value for a specific component. Fragility functions are usually represented by lognormal cumulative distribution functions. Nonstructural normative quantities corresponding to a commercial office building were considered along with all structural components. A Monte Carlo analysis was conducted using 1000 simulations per limit state.

3. Time History Analysis Results

Structural response parameters used to characterise demands on structural and nonstructural systems are floor absolute accelerations, floor absolute velocities and IDRs. These parameters were determined from the nonlinear time history analyses of the OpenSees models. The mean peak results for the seven designs are shown in Fig. 5 for the ULS and SLS. Peak floor velocity results were omitted, as the values were relatively constant throughout the building and the use of FVDs resulted in negligible changes to floor velocities.

The FVD designs exhibit large reductions in accelerations and drifts with respect to the conventional design. ULS drifts are reduced by 30% to 65% and SLS drifts are reduced by 40% to 60%. All FVD designs prevent the large drifts in storeys 10 through 14 that are experienced by the CBF design. Stiffness proportional damping achieved reduced drifts at the lower storeys compared to uniform damping, but realised larger drifts from storey 12 upwards. The use of FVDs reduced ULS accelerations by 0% to 65% and SLS accelerations by 0% to 60%. Accelerations at the first floor (ground level) remain unchanged from the CBF design. This presents a limitation of FVD retrofits, as FVDs cannot control absolute ground accelerations. Another retrofit strategy must be incorporated to improve acceleration sensitive performance at the ground floor, such as equipment isolation or situating acceleration sensitive nonstructural systems on a higher floor.

The effect of the amount of supplemental damping can be observed by comparing the time history analysis results of the FVD designs. Accelerations are similar for the FVD designs, irrespective of the amount of supplemental damping. In contrast, IDRs noticeably improve as supplemental damping increases. The drift reductions due to a 5% increase in supplemental damping from 15% to 20% are comparable to the reductions gained by a 10% increase in supplemental damping from 20% to 30%. These diminishing returns suggest there is a limit at which further increases to supplemental damping will no longer produce meaningful improvements.

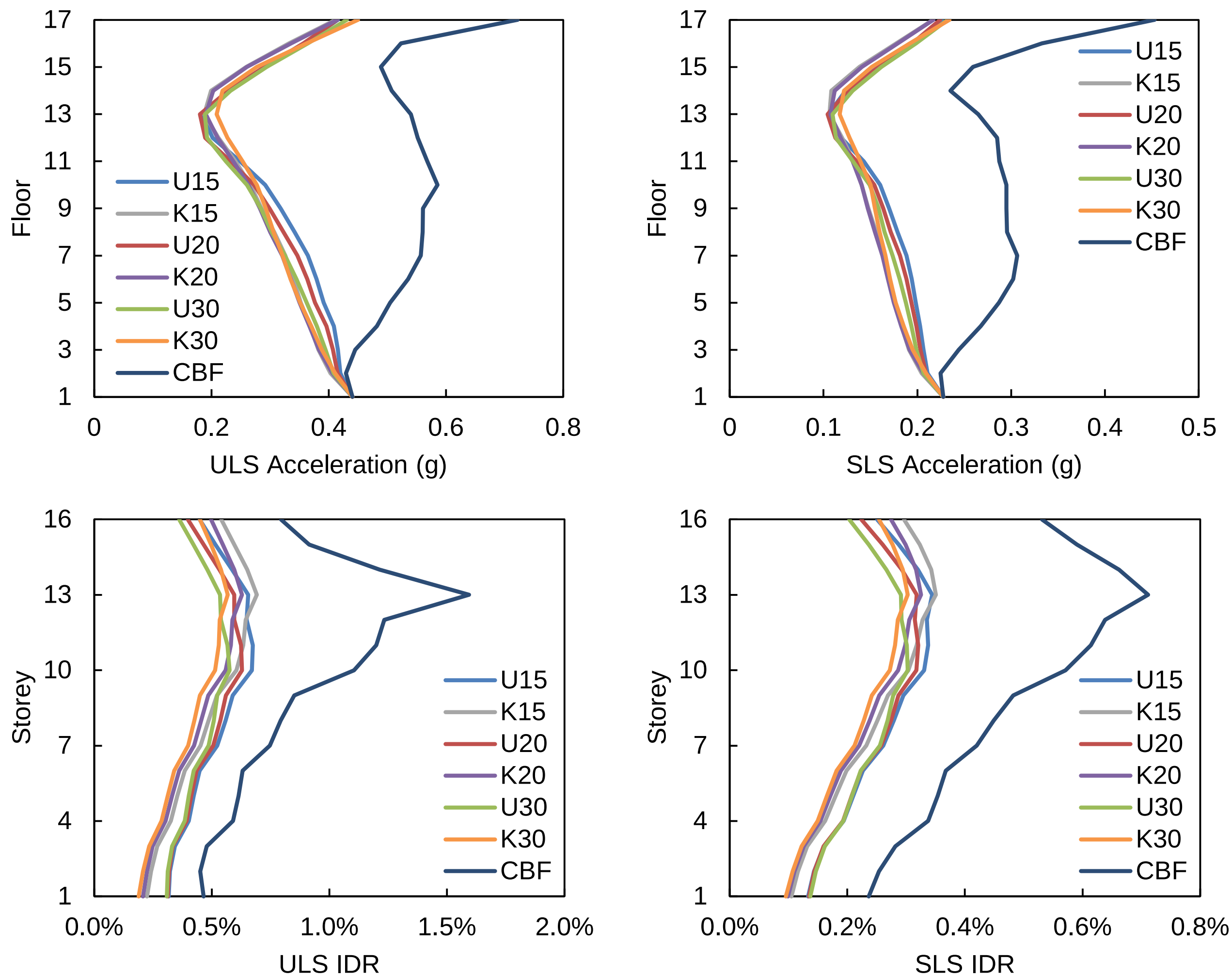

Fig. 5 – Peak absolute accelerations (top) and peak interstorey drifts (bottom) determined from the time history analyses for the ULS (left) and SLS (right)

Occhiuzzi found a maximum of 20% to 25% total damping to be ideal, as additional damping increased accelerations and produced negligible further reductions in IDRs [14]. This was investigated by using the 15% supplemental damping (20% total damping) time history analysis results as a benchmark. Uniform damping and stiffness proportional damping were investigated separately to remove the influence of damper placement. The ULS results are shown in Fig. 6; the SLS results show a similar trend.

Within the investigated range of 20% to 35% total damping, drifts decrease with increasing damping. For uniform damping, the drift improvements in storeys seven and below are minor while significant improvements are achieved in the remaining storeys. For stiffness proportional damping, drift reductions are substantial at each storey. The relationship between acceleration and damping is more complex. For uniform damping, accelerations below floor 12 decrease with increasing damping. No improvements are realised at the upper floors as supplemental damping increases from 15% to 20%, while accelerations increase at these floors for 30% supplemental damping. For stiffness proportional damping, accelerations are comparable between 15% and 20% added damping. Accelerations significantly increase for 30% supplemental damping at floors 9 and above. Due to the complexity of the relationship between structural parameters and damping, expected earthquake damages must be examined in order to quantify the effects of increased damping in meaningful terms.

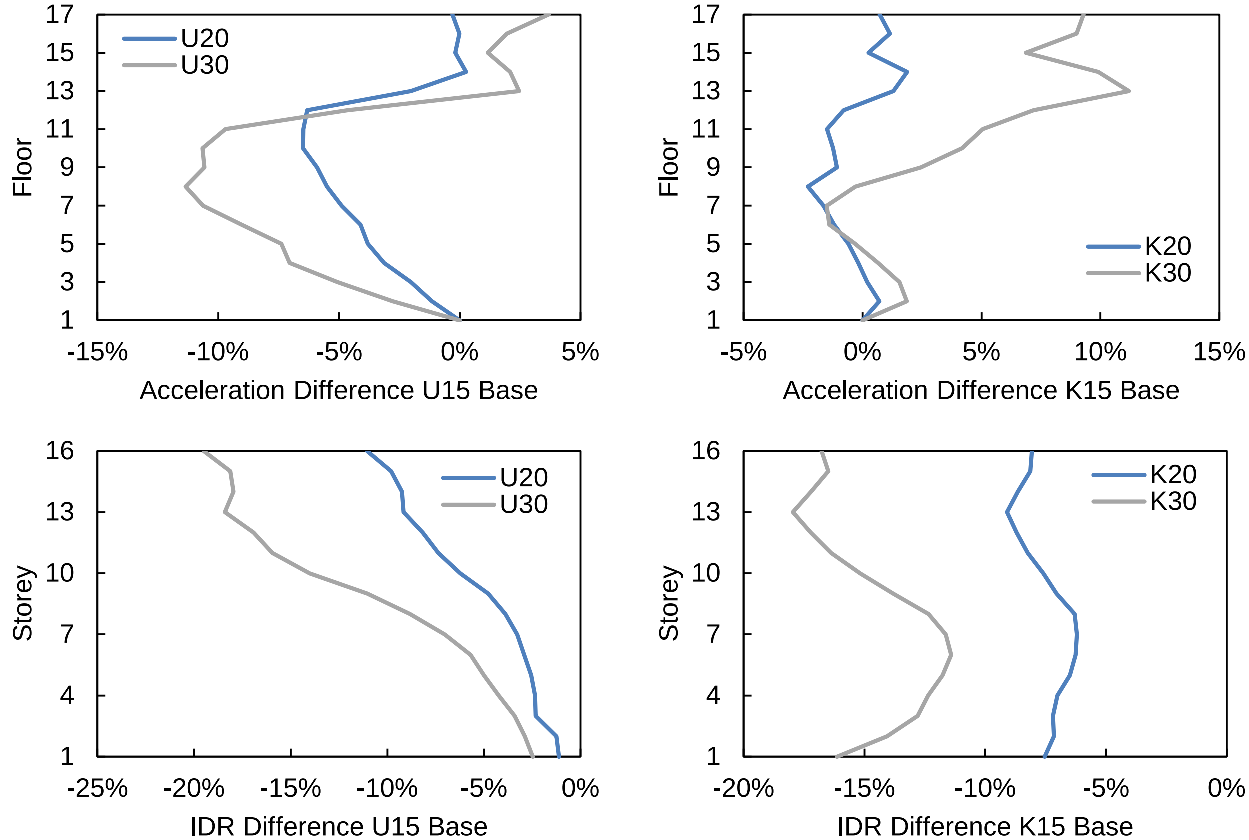

Fig. 6 – Change in acceleration (top) and interstorey drift (bottom) due to increased supplemental damping using 15% uniform (left) and stiffness proportional (right) benchmarks

The investment in dampers should be considered when evaluating FVD retrofit options. Gidaris and Taflanidis derived a cost equation for commercially available dampers shown in Eq. (3), where $Cost_j$ is the cost of damper j and $F_{max,j}$ is the maximum force capacity of damper j in kN [11].

$$Cost_j = 96.88\left(F_{max,j}\right)^{0.607} \quad (3)$$

Total damper costs based on the mean ULS forces are shown in Fig. 7. As expected, an increase in supplemental damping increases the required damper investment. Doubling the added damping from 15% to 30% increases the investment by approximately 25%. Stiffness proportional damping costs approximately 13% more than uniform damping. A total value of $20 million was estimated for the conventional building by professional cost consultants. The total damper investment would therefore increase the building cost by approximately 2%.

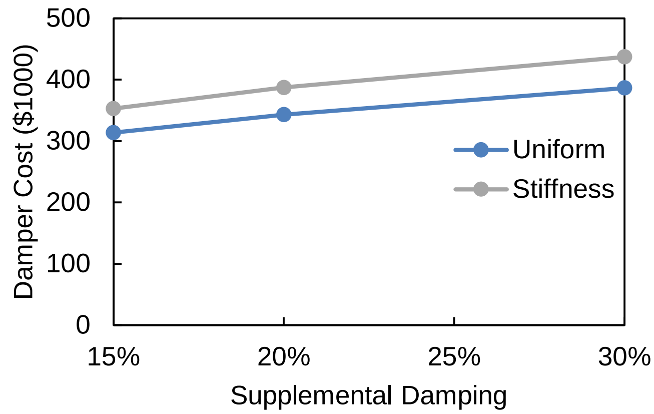

Fig. 7 – Mean damper costs for the fluid viscous damper designs

4. Seismic Performance Assessment Results

The results of the seismic performance assessment are expressed by repair costs in 2011 US dollars. These are direct repair costs and do not include indirect costs due to building downtime as well as flooding due to piping failure. Although these indirect costs are significant, they are difficult to calculate accurately for a general building and are deemed out of scope. The mean total repair costs for the building designs subjected to a ULS or SLS earthquake are shown in Fig. 8. The same trends were observed with the 90th percentile repair costs.

The mean ULS and SLS repair costs for the conventional building are $10 million and $4 million respectively. If repair costs exceed 40% of the building cost, owners often elect to demolish and replace the existing building [10]. The ULS repair costs are approximately 50% of the building cost, implying it is probable that buildings designed to current standards may be demolished and replaced following a ULS earthquake. The SLS repair costs indicate that extensive repairs are required. It is probable that these repairs will disrupt building function for an extended period, failing the SLS condition. These results suggest that modern building standards do not accomplish earthquake resilience: the ability to recover quickly after an earthquake. The complete seismic performance assessment of the conventional building is available in a previous paper [13].

The seismic performance of the FVD designs are significantly improved from the conventional structure. The ULS repair costs range from 43% to 52% of the conventional repair costs. This performance improvement would prevent the need to demolish and replace the retrofitted buildings following a ULS earthquake, in contrast to the conventional building [10]. The FVD designs exhibit a ULS performance that is comparable to the conventional SLS performance. The SLS repair costs of the FVD designs are less than $2 million. Although damage and downtime are expected, this damage is reduced by more than 50% from the conventional design. These results demonstrate that FVDs are a viable solution to improve the seismic resiliency of structures. Two simple damper placement methods have been investigated. Advanced placement techniques may be able to further increase seismic performance and is the subject of ongoing research by the authors. Additional seismic performance improvement strategies may be developed by analysing the repair costs in greater detail.

For the same amount of supplemental damping, stiffness proportional placement produces lower repair costs than uniform placement. The difference in repair costs between the two placement methods decreases as damping increases. Increasing the total damping from 20% to 35% reduces the repair costs by an additional 5% to 7% for the ULS. This is in contrast to a previously suggested maximum of 20% to 25% total damping, beyond which additional damping would increase accelerations and produce negligible further reductions in IDRs [14]. This highlights that retrofit methods may be enhanced by using repair costs, rather than structural parameters, when making decisions. However, the repair cost results suggest there is a limit at which further increases to supplemental damping will produce insignificant seismic performance improvements. Only minor changes to the SLS repair costs were observed among the FVD retrofitted designs.

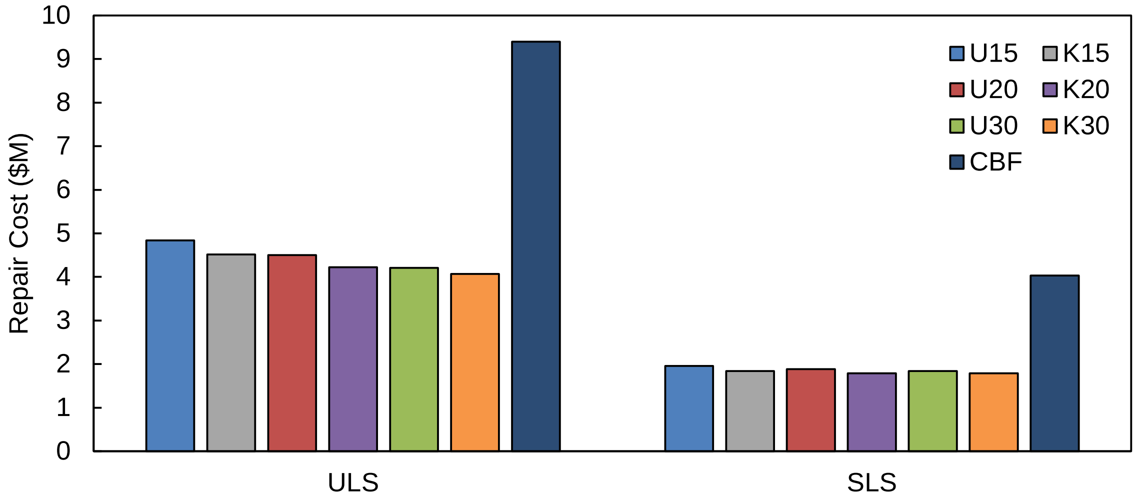

Fig. 8 – Mean total repair costs for the ULS and SLS

ULS repair costs sorted by engineering demand parameter are displayed in Fig. 9 for each design. The SLS results display the same trends. Concerning the conventional structure, IDR and acceleration damage comprise the majority of repair costs for both the ULS and SLS. The level of acceleration damage is comparable to the IDR damage. This indicates that damper optimisation methods which use engineering demand parameters should consider acceleration in addition to the more commonly used IDR.

Concerning the FVD designs, increasing supplemental damping from 15% to 30% further reduces IDR damage but produces marginal changes to acceleration and velocity damage. Other retrofit options such as equipment anchorage and isolation may be used in combination with FVDs in order to further improve acceleration sensitive performance.

It was shown in Fig. 8 that stiffness proportional placement produces lower repair costs than uniform placement for a given amount of supplemental damping. Fig. 9 reveals further information regarding the difference in repair costs and illustrates why the difference decreases as damping increases. At 15% supplemental damping, the acceleration repair costs are greater for uniform placement than for stiffness proportional placement. This difference decreases at 20% supplemental damping. At 30% supplemental damping, the two placement methods produce approximately equal acceleration costs. The velocity repair costs are similar for all models, while stiffness proportional placement produces smaller IDR repair costs than uniform damping for each value of supplemental damping. The time history analysis results, displayed in Fig. 5, show that stiffness proportional damping achieved reduced drifts at the lower storeys compared to uniform damping, but realised larger drifts from storey 12 upwards. This trade-off of reduced IDRs at lower storeys for larger IDRs at upper storeys creates a net decrease in repair costs. This result supports many advanced placement techniques, which prescribe minimal damping in the upper storeys and concentrate dampers near the bottom of the structure [8]. If nonstructural components are evenly distributed throughout a structure, such as in an office building, the trade-off encouraged by these advanced techniques may lead to decreased damage following an earthquake. This highlights the importance of optimising damper placement based on repair costs, rather than structural parameters.

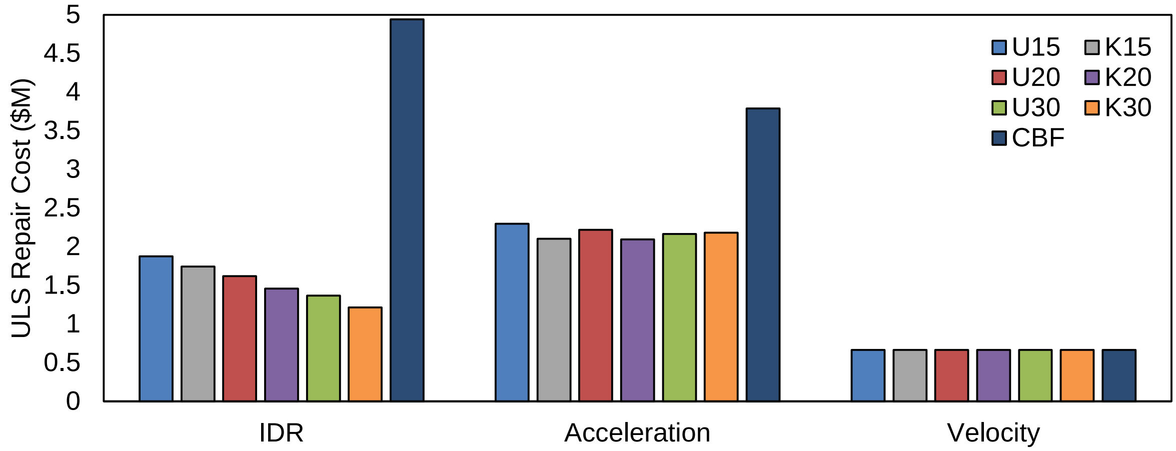

Fig. 9 – ULS mean repair costs per engineering demand parameter

The mean repair costs arranged by structural and nonstructural fragility groups are shown in Fig. 10 for the CBF and U30 designs. For each fragility group, the repair cost is a function of the number of components in the group, the replacement cost per component, and the damage state experienced by each component. Fragility groups that prominently contribute to repair costs are structural components, glass curtain wall cladding, wall partitions, suspended ceilings, HVAC equipment, and office electronics and equipment. Negligible repair costs are due to stairs, access flooring, elevators, piping, fire sprinkler systems and electrical systems.

Considering the conventional design at the ULS, the structural system accounts for 26% of the total repair cost and has the largest cost of the fragility groups. The majority of this cost is due to brace damage. Structural damage is expected for the ULS, as conventional seismic design relies on the structure sustaining large inelastic deformations in members designed to dissipate seismic energy in a controlled manner. Although the inelastic deformations cause irreparable damage in the structural members, the life safety of building occupants is ensured during a major earthquake. The conventional design also experiences structural damage during the SLS, which would introduce significant delays to building re-occupancy and prevent building serviceability.

Nonstructural systems are often omitted or treated in an oversimplified manner during building design. However, 74% of the ULS repair costs and 87% of the SLS costs can be attributed to these systems for the conventional building. This demonstrates the need to consider nonstructural systems during structural design in order to reach the desired level of seismic performance.

Considering the FVD designs, major damage reductions are achieved for all drift sensitive fragility groups (structural, cladding and partitions). Significant performance improvements are exhibited by suspended ceilings, an acceleration sensitive group, while only minor improvements to the other acceleration and velocity sensitive components (HVAC and office equipment) are produced. Negligible structural damage occurs during the SLS. This is a crucial seismic performance improvement and an essential step towards achieving immediate occupancy.

The seismic performance assessment exposed several limitations of the Eurocode 8 damage mitigation methodology for CBF buildings. Eurocode 8 prescribes IDR limits of 0.5% and 1% to prevent nonstructural and structural damage respectively [12]. The FVD designs outperform these limits and should therefore prevent structural damage in the ULS and nonstructural damage in the SLS. Structural damage was sustained in the ULS and prevented in the SLS. This suggests an IDR limit of 0.5% should be prescribed for structural damage prevention in place of 1%. The 0.5% IDR limit did not prevent nonstructural damage in the SLS. These results highlight the need for further review of the Eurocode nonstructural provisions.

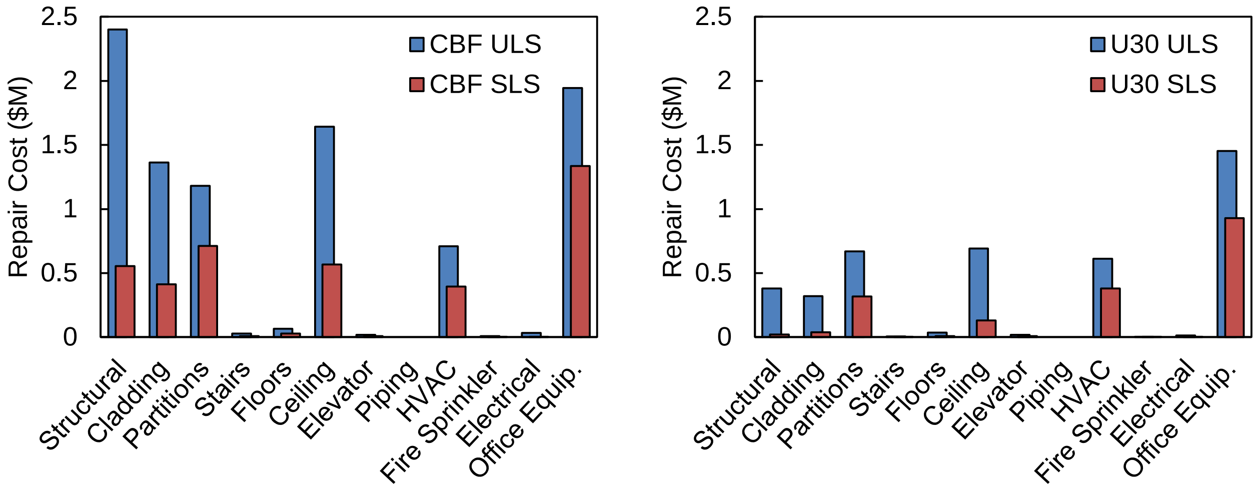

Fig. 10 – Mean repair costs per fragility group for the CBF (left) and U30 (right) designs

4. Conclusions and Future Work

This study assesses the seismic performance of conventional and retrofitted multistorey buildings in terms of expected repair costs. The FEMA P-58 seismic performance assessment procedure was used. The results of the conventional building assessment provide a benchmark on which to compare the effectiveness of FVD retrofits in improving seismic performance. Two damper placement methods and three levels of supplemental damping were investigated.

The seismic performance assessment of the conventional design determined that drift and acceleration sensitive systems experience substantial ULS and SLS damage. Significant repair costs and downtime can therefore be expected in modern multistorey structures following an earthquake, failing the SLS condition. The performance assessment results imply it is probable that buildings designed to current standards may be demolished and replaced following a ULS earthquake due to the high repair costs. This suggests that modern building standards do not accomplish resilience: the ability of a community to recover quickly after an earthquake. 74% of the ULS repair costs and 87% of the SLS repair costs were attributed to nonstructural systems. This demonstrates the need to consider nonstructural systems during structural design in order to reach the desired level of seismic performance.

It was shown that acceleration sensitive damage is comparable to IDR sensitive damage. This indicates that damper optimisation methods which use engineering demand parameters should consider acceleration in addition to the more commonly used IDR.

The FVD retrofitted designs exhibit large reductions in accelerations and drifts for both the ULS and SLS with respect to the conventional design. The ULS and SLS mean repair costs for the FVD designs are in the range of 50% of the conventional repair costs. This performance improvement would prevent the need to demolish and replace the retrofitted buildings following a ULS earthquake, in contrast to the conventional building. Negligible structural damage occurs during the SLS. This is a crucial seismic performance improvement and an essential step towards achieving immediate occupancy. These results demonstrate that FVDs are a viable solution to improve the seismic resiliency of structures. The total damper investment would increase the building cost by only 2%.

Within the investigated range of 20% to 35% total damping, IDRs decreased with increased damping. The relationship between acceleration and damping is more complex with both reductions and increases observed. These damping ratios were calculated using Eq. (2), and the actual modal damping ratios will be confirmed in a future paper as recommended in [14]. Due to the complexity of the relationship between structural parameters and damping, expected earthquake damages must be examined in order to quantify the effects of increased damping in meaningful terms. Increasing the total damping from 20% to 35% reduces the repair costs by an additional 5% to 7% for the ULS. This is in contrast to a previously suggested maximum of 20% to 25% total damping, beyond which additional damping would increase accelerations and produce negligible IDR improvements. This illustrates that retrofit methods may be enhanced by using repair costs, rather than structural parameters, when making design decisions.

For the same amount of supplemental damping, stiffness proportional placement produces lower repair costs than uniform placement. The trade-off of reduced IDRs at lower storeys for larger IDRs at upper storeys creates a net decrease in repair costs. This result supports many advanced placement techniques, which prescribe minimal damping in the upper storeys and concentrate dampers near the bottom of the structure. The trade-off encouraged by these advanced techniques may lead to decreased damages following an earthquake. This highlights the importance of optimising damper placement based on repair costs, rather than structural parameters.

The seismic performance assessment exposed several limitations of the Eurocode 8 damage mitigation methodology for CBF buildings. Eurocode 8 prescribes IDR limits of 0.5% and 1% to prevent nonstructural and structural damage respectively. It was found that an IDR limit of 0.5% should prescribed for structural damage prevention in place of 1%. The 0.5% IDR limit did not prevent nonstructural damage in the SLS. This establishes the need for further review of the Eurocode nonstructural provisions.

The final aim of the project is to develop a FVD placement strategy that minimizes nonstructural repair costs and building service disruptions. Two simple damper placement methods have been investigated. Advanced placement techniques may be able to further increase seismic performance and is the subject of ongoing research by the authors. A combination of different strategies may be incorporated to improve acceleration sensitive performance at the ground floor, such as equipment isolation or situating acceleration sensitive nonstructural systems on a higher floor. Expectations are shifting in modern earthquake engineering, as clients are requesting a rapid return to occupancy after an earthquake event. This research contributes towards meeting these new expectations.

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