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COMPARING SHEAR TYPE METALLIC AND FLUID VISCOUS ENERGY DISSIPATION DEVICES USING REAL-TIME HYBRID TESTING

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ABSTRACT

Passive energy dissipation devices have been implemented in many seismic protection strategies worldwide, particularly in retrofit. Typically placed in parts of a structure experiencing significant relative motion, they work to reduce this motion and thus, structural damage, improving chances of immediate occupancy. There are various types of devices: generally classified by their energy dissipation mechanism. However, few studies explore the benefits and drawbacks of different types of devices, directly comparing their seismic performance. Towards such a comparison two devices, a steel shear and a fluid viscous device have been jointly tested. These devices exhibit very different attributes and to gauge their relative performance, both sinusoidal (behavioural) and real-time hybrid tests are conducted. A relatively new technique, real-time hybrid testing couples the devices to a building model, realistically simulating seismic response under retrofit, capturing difficult to model nonlinear, strain rate and temperature dependent device properties to thus, allow direct assessment of both device state and its influence on the structural system. Though the fluid viscous device appears slightly more effective, device choice is not straightforward. The effect of retrofitting with both devices acting together in a structure is also investigated, it is clear that distributing devices throughout the structure is advantageous.

Introduction

Passive dissipative devices are typically used for wind and seismic resistance. In the seismic case, they have been under development over the past forty years, with a wide variety of designs developed since the 1970's (Buckle and Mayes 1990) and increasing acceptance of these technologies in response to the growing cost and extent of damage caused by earthquakes (EERI 2000). In dissipating a proportion of the energy input to a structure, these supplemental energy dissipation systems reduce interstorey motion and hence structural damage. Devices are differentiated by their means of energy dissipation, and the four main device categories are viscous, visco-elastic, metallic, and friction. They may be used separately or in combination as a hybrid dissipative system: with applications of hybrid energy dissipation systems more frequently presented for base isolation (e.g. Sorace et al. 2007). While extensive research is available on the seismic performance of dissipative devices, collated experimental data typically describes devices

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individually, relative or joint performance must often be indirectly determined.
The objective of this paper is to investigate and compare two dissipative devices, a steel shear and a fluid viscous device, to determine how their different characteristics influence their performance and overall effectiveness as seismic energy dissipaters. Firstly, following a description of the devices, conventional sinusoidal behavioural tests are presented. Secondly results from real-time hybrid tests of the devices in retrofitted building scenarios are described, realistically simulating their seismic behaviour and influence on structural systems. Two simple retrofit scenarios are developed, the first, directly compares the devices' effectiveness at the base of a ten-storey building under seismic loading. The second tests their combined influence in another building, distributing both the steel shear and fluid viscous devices within to comprise a hybrid dissipative system. The results and conclusions presented are not exhaustive but, provide insight into the properties of these devices, the possibilities for comparative techniques, potential for hybrid dissipative systems and demonstrate the capabilities of real-time hybrid testing.

The Two Devices: Steel Shear and Fluid Viscous Device

The two devices under consideration (Fig. 1) operate using very different mechanisms. The steel shear device was manufactured in-house, the fluid viscous device acquired from a manufacturer.

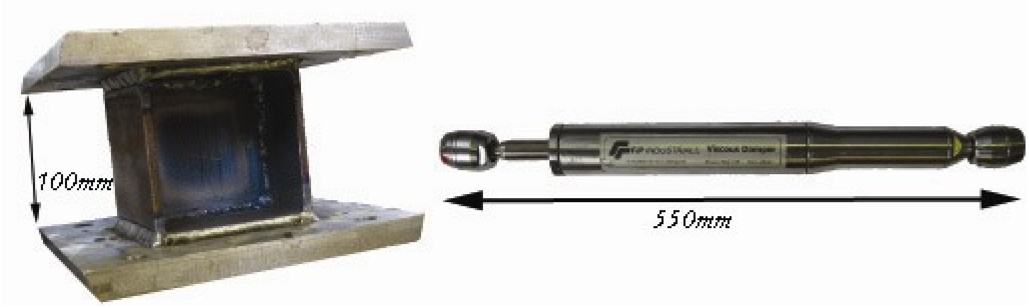

Figure 1. Steel shear device (left), fluid viscous device (right).

Currently under development, the steel shear device is derived from a design suggested by Dorka (Schmidt et al. 2004) and, has been the subject of testing in recent years by a number of researchers (Ojaghi et al. 2008). The device presented dissipates energy through metallic yielding, primarily in shear, of a 2mm thick mild steel web (216MPa yield, 316MPa ultimate strength), welded (bound) inside a 100mm depth S235, 100x100x6.3mm steel box section. The device here is welded onto top and bottom weld plates and may then be bolted directly into place onto a bracing system (chevron type or perhaps atop a shear wall). Metallic devices typically exhibit large energy dissipation capacities and the combined factors of yield strength, ultimate strength, stiffness, ductility and toughness may be used to gauge the energy dissipation performance of metals. Most well known metallic devices, including the ADAS (added damping added stiffness) device (Soong and Dargush 1997), dissipate energy by yielding in bending; shear-yielding devices offer an alternative to bending type devices with the potential of improved fatigue resistance through restricting void openings. In testing presented here, it is assumed that the device is placed so that it is not subject to axial (dead) loads in service. Though axial loads can significantly influence ADAS device response at large displacements, due to the steel shear device operation and preliminary testing performed under axial loading, it is expected that axial loads may not be as significant for this device, though further testing is warranted. This shear device exhibits high energy dissipation capacity and stiffness and thus may require often large and stiff bracing systems to effectively transfer loads. As with all metallic devices, the device is a sacrificial element and requires replacement after major seismic loading. However, it may be regarded as a low maintenance device and due to its simple manufacture and relative low material use is a particularly low cost solution for seismic energy dissipation.

The fluid viscous device presented is currently undergoing extended testing. Historically, such devices have been used for military and aerospace applications (Constantinou et al. 1998) and in the last thirty years, have been applied to structural engineering applications. In general, they dissipate energy by forced fluid flow through orifices in a moving piston, which causes a shearing and deformation of a highly viscous silicon-based fluid. The device's resistive force is proportional to the product of the viscous damping coefficient and exponential velocity value. The device tested here is nonlinear since its velocity exponent is 0.15; its damping coefficient is 5.1kN-sec/mm, expected capacity, 13.1kN and stroke, ±60mm. Fluid viscous dampers have received notoriety for their high energy dissipation potential and ability to provide a large resistive force even at very low velocities and displacements. In general, an advantage of a fluid viscous device is that its resistive force is out of phase with seismic forces in the structure, such that the device does not add a stress component to the structure at the structure's maximum stressed state. These devices are designed for long life spans, and although they may require maintenance after seismic events, they typically do not need to be replaced. The trade-off is that fluid viscous devices tend to be more expensive than other passive dissipative devices.

Device Testing

To conduct comparative sinusoidal and hybrid tests of the devices, separate tests rigs were developed for each device (Fig. 2). The test rigs were designed to specifically ensure appropriate boundary conditions for one dimensional (lateral) loading of the devices. The specific setup for the shear device is further discussed in Ojaghi et al. (2008). In the hybrid case braces are numerically modelled and device displacement is controlled via a high resolution linear encoder.

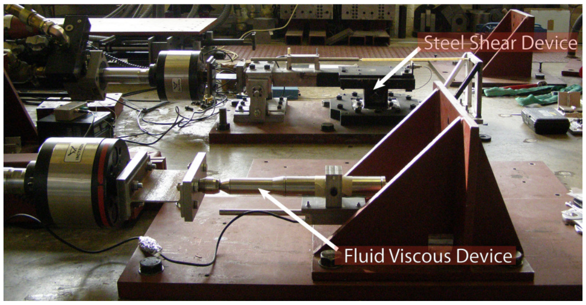

Figure 2. Device test rigs.

Sinusoidal Behavioural Tests

Sinusoidal behavioural tests are a powerful yet relatively simple technique used to infer seismic performance of dissipative devices. Thus, a series of dynamic sinusoidal tests were conducted to characterise individual device properties. First, incremental step tests at constant frequency, varying amplitude were performed (Fig. 3). This test provides a quick snapshot of behavioural traits, including size and shape of the hysteresis (energy dissipation) loop for both devices but, is particularly useful in illustrating the life phases of the steel shear device. Captured, is initial device strain hardening, followed by shear buckling at increasing amplitudes and cycles, with finally degradation occurring as the device cracks. The test also demonstrates the consistent behaviour of the fluid viscous device in the tested range. Secondly, constant amplitude sinusoidal tests at different frequencies were conducted (Fig. 4) though due to its yielding and degradation, a new device was used in each shear device test. While revealing other device traits, these tests are used to identify frequency-dependent properties. In particular, the tests highlight the velocity-dependent behaviour of the fluid viscous device, noted by the increasing energy dissipation with increasing frequency. Though as expected, at higher frequency yielding occurs at higher loads in the steel shear device, overall frequency dependency is less apparent.

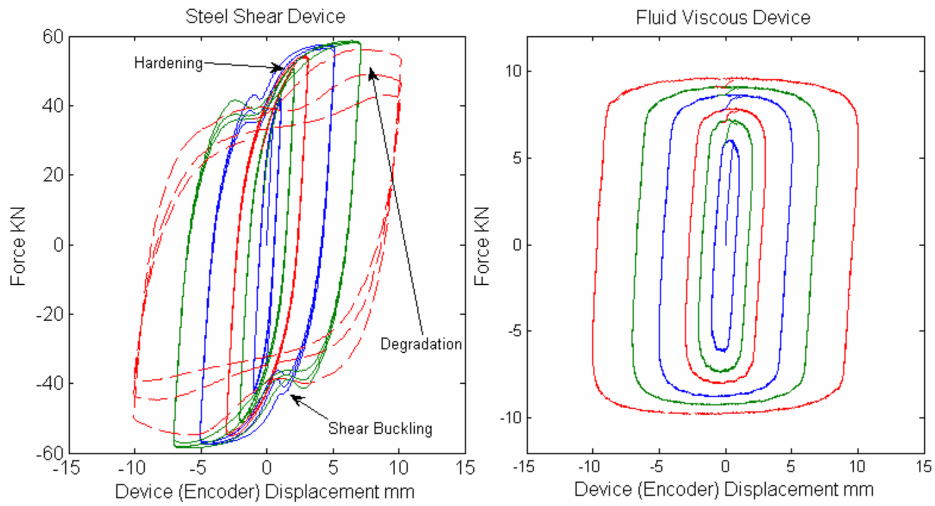

Figure 3. Incremental tests on the steel shear device and the fluid viscous device: Three cycles per amplitude, sinusoidal – 1, 2, 3, 5, 7, 10 mm at 1Hz.

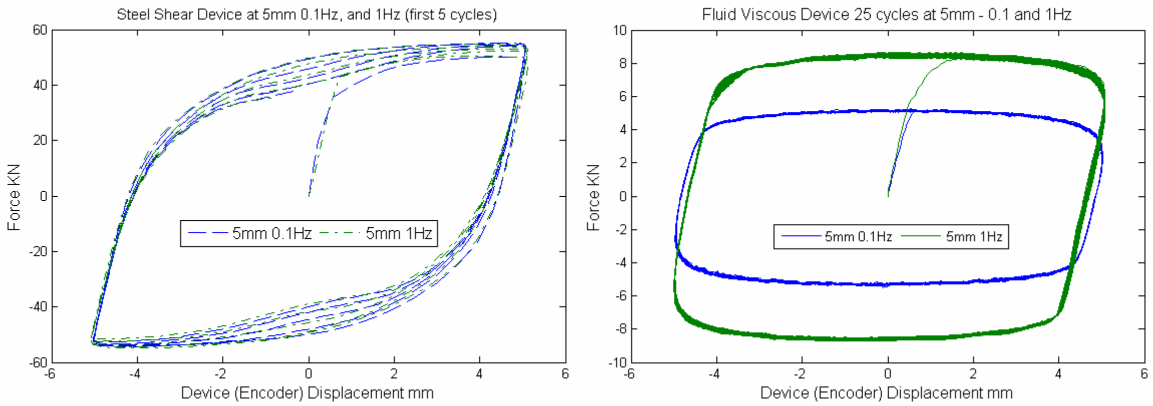

Figure 4. Constant amplitude tests at 5mm - 0.1 and 1 Hz, displaying frequency dependency.

Hybrid Tests of Dissipative Devices in Retrofitted Building Scenarios

To better understand and gain confidence in both seismic effectiveness and performance within a structural system it is important to test and determine how the devices and structural systems respond under realistic seismic loading. Behavioural tests can be used to create numerical models of device behaviour and used together with structural building models can be a basis for determining true seismic response. However, the accuracy of such response depends on how well the numerical models can represent the true dynamic response of the device and can be limited as some device features important to device development cannot be readily represented by numerical models with current techniques. As an alternative, real-time hybrid testing is a relatively novel technique used to allow the direct seismic performance of the physical devices and their influence on the total structural response to be established, negating the need for device models. This testing technique is also chosen as it provides a repeatable and flexible way of testing these devices making it easy to rearrange device placement within a structure to test various retrofit scenarios. The technique couples a numerical building model to physical models of the dissipative devices under seismic loading, and the real-time nature captures the rate effects of the fluid viscous damper and the unpredictable yielding behaviour of the steel shear device. Test control, though not specifically discussed, plays an important part in real-time hybrid testing, especially in regards to multi-axis testing of highly nonlinear specimens. Experimental errors can be significant; therefore, the tests were conducted using a variable delay and amplitude compensation algorithm to account for actuation issues, developed from previous delay compensation algorithms from Bonnet (2006) specifically for testing these and similar devices.

Retrofit Scenarios

Retrofit with dissipative devices is a viable option for upgrading the seismic performance of existing buildings. A direct comparison of individual device performance as well as joint performance in a hybrid dissipative system was conducted using the real-time hybrid testing technique for two simple retrofit scenarios. The objective of such testing was three-fold: to test the dissipative devices under realistic seismic loading and capture nonlinear behaviour, to compare the devices' seismic performance directly and to explore and demonstrate the potential of the real-time hybrid test technique. Two baseline buildings with realistic dynamic characteristics were adapted from Key (1988), representing a simplified constant-stiffness (member) building plan and a cost-effective varying stiffness building plan (Fig. 5). Both buildings are represented by ten-storey, square plan, five-by-five steel moment-resisting frames and inherent structural damping applied using Rayleigh damping, with 2% damping in the first mode and 5% damping in the eighth mode. The buildings were numerically modelled as shear structures with one degree of freedom per floor using linear modal superposition. Simple retrofit scenarios created for the baseline buildings were designed as a basis for comparing the dampers' individual and combined effectiveness in reducing interstorey motion. Although it may be potentially prudent to employ dissipative devices on multiple floors or use more conventional

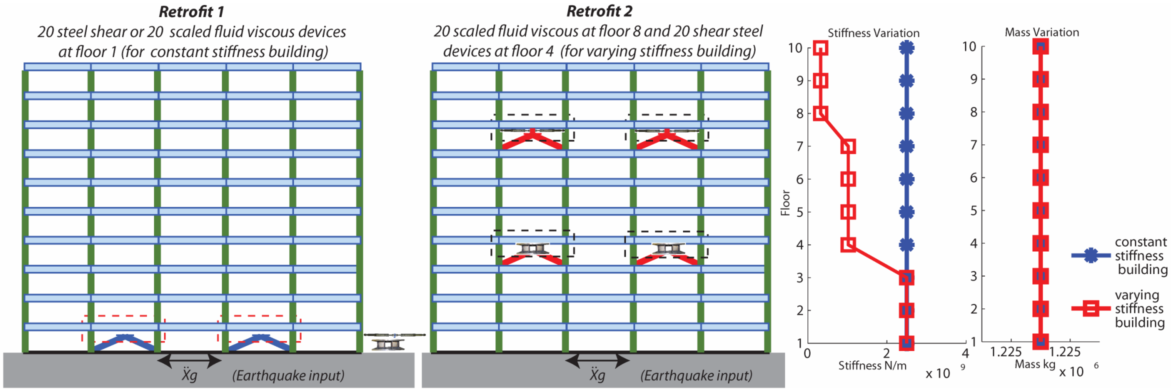

Figure 5. Building retrofit scenarios.

(non-hybrid) retrofit schemes, to serve the purposes of comparison and because of physical lab limitations the number of device placement locations (two) were limited. However, the damper placements were strategically chosen such that the devices' effects were maximised while still considering their physical limitations. Retrofit two also presents the opportunity to explore both the effectiveness of the control systems with multi-axis (multiple actuator/physical models) loading and to demonstrate the importance and effect of device placement throughout a structure.

The purpose of retrofit one was to directly compare the performance of the fluid viscous device and steel shear device. Device placements were chosen at the base for ease-of-installation (in a realistic design case) and because the largest values of interstorey drift and velocity occur here. In retrofit scenario one, each device is placed, in turn, at the base of the building as a retrofit option and tested under the same seismic loading. In retrofit two it was desired to investigate first, the effect of installation with a single device and second, the combined effectiveness of the devices when placed in different locations. In retrofit scenario two, it can be argued that the best location for device placement if only one device location is utilised is no longer necessarily at the base but, on floor 8. Dynamic analysis of the varying stiffness building reveals that interstorey motion is greater in higher floors prior to retrofit and, is particularly high where floor stiffness changes. The peak interstorey drift occurs on floor 8, where stiffness change leads to the most slender members, and the interstorey velocity is also relatively large here. The fluid viscous device was placed here to best utilise its stroke and force capacity. To achieve additional reductions in interstorey motion, the decision for best second device installation location was not so trivial. An argument for floor 9 may be made, as the new location of highest interstorey motion, or perhaps devices should be placed at floor 10. The best choice for device placement may not be straightforward. Moderately large interstorey drifts on floor 4 combined with stroke limitations of the steel shear device made floor 4 a prudent location for the shear steel device.

The devices were installed on stiff chevron braces, regarded as evenly distributed to ensure equal loading and to limit torsional effects that may occur in the real structure but are not modelled. The shear device was tested at full scale, and for fair comparison, the fluid viscous device was scaled 6 times larger, to achieve a comparable maximum force capacity (Fig. 6). While energy dissipation is described by hysteresis loop shape, and is important in direct device comparison, peak force capacity is a more appropriate scaling as opposed to equivalent energy dissipation, since this force must be transmitted through the bracing systems and the rest of the structure.

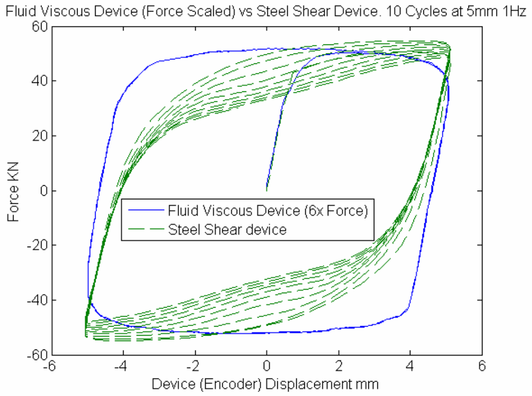

Figure 6. Equivalent scaled devices.

Scaling shown uses the 5mm 1Hz sinusoidal test, as the amplitude and frequency are similar to the approximate response expected. To achieve significant storey drift reduction, 20 steel shear devices and 120 fluid viscous devices (assumed equivalent to 20 large real devices) were used.

Retrofit Scenario Results

Some results are presented from the retrofit scenarios of the structure subjected to 25% of the Manjil 1990 (Abbar 0) earthquake (Figs.7, 8). A long-duration earthquake with peak acceleration of 0.51g and a frequency range of 0-15 Hz, it covers the range of modelled modes of the baseline buildings. Demanding in duration and motion induced, the ground motion is scaled to ensure linear building response suitable for linear simulation and the devices' working displacement ranges. It should be recognised that interaction between ground motion and structural frequencies significantly influences structural response. It is essential to test under realistic situations since including devices will alter the dynamic characteristics of the structure, which may amplify or attenuate vibrations depending on frequency content. The results presented here are not exhaustive but representative of one, particularly demanding, ground motion case.

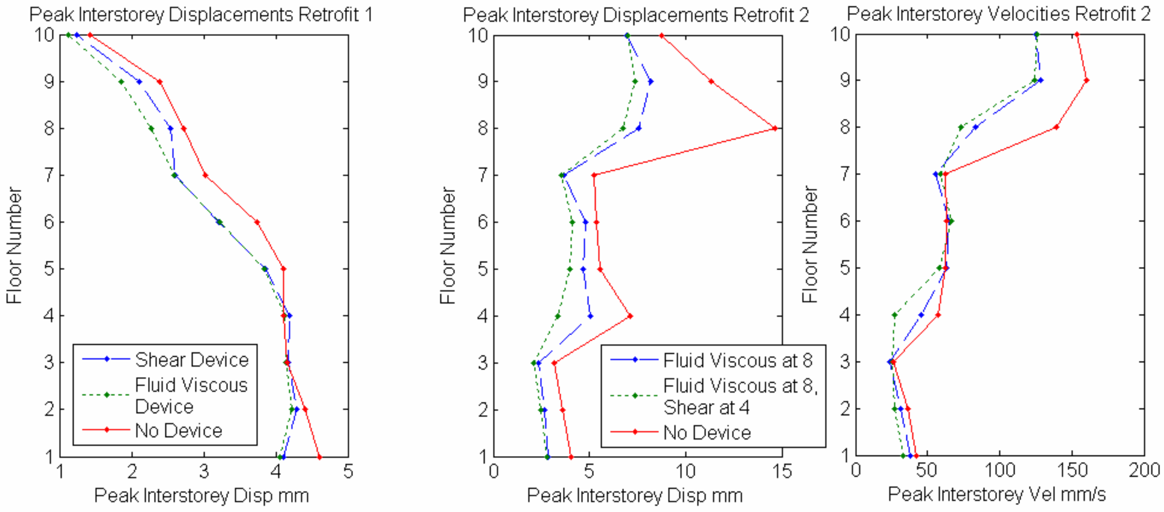

Figure 7. Effects on the peak building response: Retrofit 1 (left), Retrofit 2 (centre, right).

The results from retrofit scenario one (Fig. 7) show the individual ability of both devices to reduce peak interstorey drifts within the structure when installed at the base. While the fluid viscous device performs slightly better, perhaps due to its near square hysteresis loop, the individual effect of the devices is quite similar. Both are effective in reducing interstorey drift not only at the base but also throughout the structure, the maximum level of reduction is around 10-15% for this particular level of damping and scaled ground motion. It is interesting to note that there may be a slight increase in motion at floor 4 especially with the shear device. The shear device is also less effective at reducing motion at floors 8 and 9. The results for retrofit scenario two (Fig. 7) indicate that fluid viscous device placement on floor 8 only is very significant and reduces interstorey motion (displacement and velocity) at floor 8 by at least 50%. Application of the fluid viscous device alone also significantly reduces the interstorey motion on floors 4, 9 and 10 and reduces the interstorey drift of all floors. The addition of steel shear dampers on floor 4 in combination with the fluid viscous devices on floor 8 significantly reduces interstorey motion on floor 4. There are also further reductions in interstorey drift on floors, 5, 6, 8 and 9. It is also interesting to note that interstorey velocities only marginally change (compared to the baseline building) on floors 3, 5, 6, and 7 with retrofit. While peak interstorey drift levels may be dramatically reduced, reduction occurs throughout the time history (Fig. 8) and in dynamic response peak locations of time history response are not necessarily the same. The addition of dampers can remarkably reduce interstorey motion not only on the installation floor but also to varying degrees on other floors. However, with regard to interstorey velocities, the shear steel device appears to have only reduced interstorey velocities significantly at its installation floor and, to some extent, on floor 8. Also shown in Fig. 8 are the hysteresis loops for both devices in retrofit scenario two. The size and shape of the hysteresis loops suggest that both devices are efficient energy dissipaters. The tests were conducted with the devices at ambient temperature capturing specifically the slight temperature effects that are thought to occur with the fluid viscous device. For the level of motion little buckling is noticed for the shear device here.

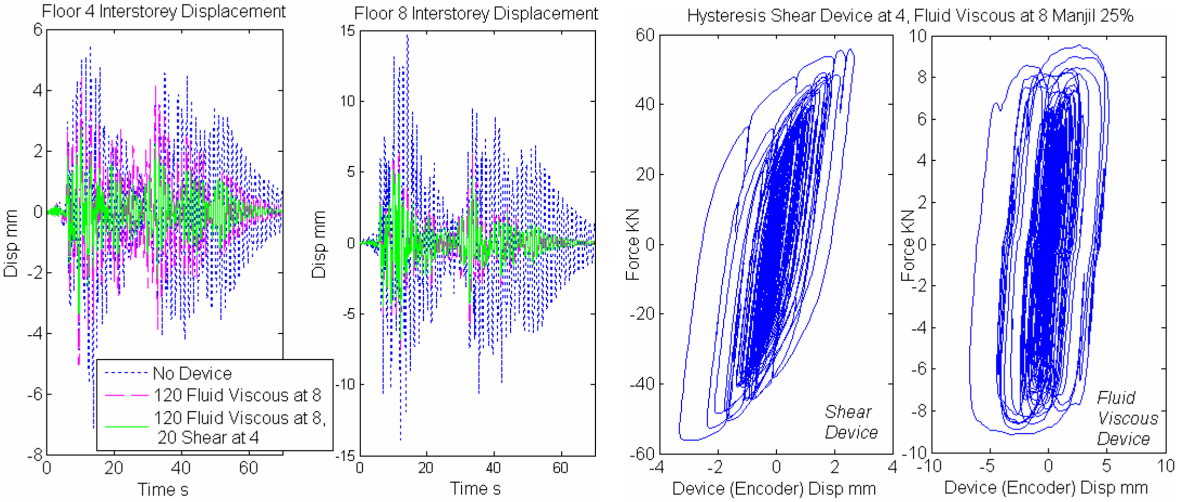

Figure 8. Selected floor time history and device hysteretic response in retrofit scenario 2

Discussions: Benefits and Drawbacks of the Devices

Behavioural tests show that both devices have large energy dissipation capacities due to the size and shape of their hysteresis loops. However, they are vastly different devices. The steel shear device is currently under development and though designed to operate in shear, the thin web used causes shear buckling leading to a load capacity drop at certain points in the device ‘stroke.’ This reduces, albeit slightly, the energy dissipation capacity, while the additional bending may reduce device life. The steel devices’ initial strain hardening is beneficial, signifying reserve energy dissipation capacity and improving performance. While post-yield, this is extensive the increase past the first-cycle (Fig. 4) is not very significant. The device starts to degrade post-buckling, though there is considerable load carrying capacity for some time after. Nonetheless, the device has great potential as a seismic energy dissipater and could be improved. The fluid viscous device is perhaps a more developed device. Its large near-square hysteresis shape suggests excellent dissipative capacity at low and high levels of loading. Although it does not display the beneficial strain hardening of a steel device, it is clear that this device is highly velocity dependent and has much greater resistive capacity at larger velocities. The regularity of hysteresis with repeated cycles is also beneficial since this device is not a sacrificial element. Early tests suggest slight temperature dependency suggesting an optimum working temperature.

In seismic loading, both devices can significantly reduce interstorey motion, and while the fluid viscous device slightly outperforms the steel device, the performance of both devices is similar in reducing motion. In retrofit 1, the building's greater use of steel (increased stiffness) leads to lower drifts, indicating better seismic performance. However, device effectiveness is more easily seen on floors with high interstorey motion such as in retrofit 2 and, while correct placement (location and number of devices) is not trivial, it can have significant positive impacts on the overall seismic performance. The steel shear device has greater raw energy dissipation capacity, in regards to its size and material use, but the fluid viscous device could be scaled and larger devices would be used in-situ. Both devices must be sized appropriately for the maximum expected force and displacement. In removing energy from the system, amplitude response is diminished, and in regards to the building seismic performance the use of dissipative devices is clearly beneficial in reducing interstorey motion. However, it should be noted that changing structural modal properties may bring structural modes closer to the seismic frequency content.

Although performance is important in choosing a particular device, other issues should be considered for example, device directionality but, perhaps more importantly, costs in relation to performance. The steel shear device is of the cheapest to manufacture, requiring little or no maintenance. However, it is a sacrificial element and while it may survive many earthquakes, this is with reduced effectiveness and will need replacement. The larger stroke suggested by the fluid viscous device is advantageous and to achieve similar strokes within the working range of the shear device, a much larger device would be required. However, the fluid viscous device is amongst the most expensive and though regarded as a higher maintenance device, is designed for a long life span. The steel device is a displacement proportional device and the fluid viscous, velocity proportional. This is especially significant as installation of dissipative devices affect load paths in the structure; heavy bracing may be required and perhaps upgrading of structural members, to improve load carrying ability. While the shear device is beneficial in a very large earthquake, it may be more cost effective when installed at lower stories, whereas the fluid viscous device offers more flexibility in bracing. Finally, neither device is self-centring.

Conclusions and Future Work

Sinusoidal behavioural and real-time hybrid tests have been used, respectively, to infer and to directly determine seismic performance of two very different types of dissipative devices; the seismic performance is acquired individually to serve as fair comparison and jointly to find the devices' combined response. While results shown are limited by the scope of this paper, they sufficiently reveal the main device properties, benefits of device use, importance of placement location and, the power of the techniques employed. Both devices are potentially effective seismic energy dissipaters, but their use must be carefully considered. In terms of testing techniques, sinusoidal behavioural tests have limitations since seismic response is inferred. Even when these tests lead to numerical models of seismic response, various device features are difficult to represent with current modelling techniques. The advantage of hybrid testing is that it allows a repeatable direct comparison focusing on device seismic performance and structural response that does not rely on device models, which is ideal for device development. It is also flexible, allowing users to optimise device locations and number. Other researchers may use the same technique and benchmark buildings as direct comparisons with their devices. While shaking table tests can be more realistic, e.g. in simulating connections, hybrid testing faces less severe capacity and cost issues. It can be concluded from hybrid testing of the retrofitted buildings under the Manjil earthquake that dissipative devices reduce interstorey motion differently, depending on their energy dissipation mechanism. The combined application of the shear steel device and fluid viscous device reveals the potential of the real-time hybrid technique for testing two physical devices simultaneously. The combination of the devices resulted in a clear reduction in interstorey drifts by both devices but a less significant reduction in interstorey velocities contributed by both devices, except at the installation floors. Future work intends to further analyse the performance of these devices, consider alternative placement locations, device number, response to other ground motions, as well as comparing other devices.

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