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A review of the state of practice for fluid viscous damper applications in North America and New Zealand

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ABSTRACT

The use of Fluid Viscous Dampers (FVDs) for retrofit and new construction applications is growing around the world. FVDs provide an effective way to reduce seismic demands on structures. In retrofit applications, this allows existing structures to meet increased demands from updated codes or to reduce drifts to accommodate structural system limitations. In new structures, FVDs can be used to decrease cost and environmental impact by reducing elements' sizes in the superstructure and foundation. FVDs also reduce both drift and floor accelerations, helping structures to meet resiliency goals and reduce post-earthquake damage in both structural and non-structural elements.

This paper explores the state of practice for FVD applications in North America and New Zealand. The following cases for FVD application are examined: 1) Retrofit applications in North America for Pre-Northridge Steel Moment Frames and Non-ductile Concrete Moment Frames, 2) Retrofit applications in New Zealand for hollow-core pre-cast concrete slab buildings, 3) New building applications, and 4) Applications of base isolation with supplemental damping with FVDs.

This paper will explore best practices collected through involvement with hundreds of damper projects worldwide. Lessons learned through the entire damper design process, from schematic level decisions through construction implementation, will be explored for both steel and concrete buildings. The purpose of this paper is to broaden readers' understanding of FVD applications in the North American and New Zealand markets with the aim of reducing barriers and to demonstrate the ease of design and implementation of damped solutions.

1 INTRODUCTION

Fluid Viscous Dampers (FVDs) work by forcing a viscous fluid through orifices in and around a piston head as the structure moves back and forth. This fluid flow generates heat which dissipates seismic energy in both earthquake and wind applications. With better knowledge and training, more advanced software and an increasing stock of aging buildings around the world, the use of FVDs is increasing. Currently, FVDs are being used predominantly in retrofit applications in North America, addressing the aging building stock of Pre-Northridge Steel Moment Frames and Non-ductile Concrete Moment Frames common the US west coast. In New Zealand, FVDs are being used to address pre-cast floor buildings. The impacts of COVID on the functions of the building stock is also leading to the exploration of dampers, were building are being switched from office towers to residential and the change in occupancy is requiring retrofits. FVDs hold many advantages over traditional strengthening or stiffening retrofit schemes which will be highlighted in this paper.

Another emerging use of FVDs is in alignment with resiliency and functional recovery movements in both North America and New Zealand. FVDs are being applied to new buildings to help achieve essentially elastic structures following major earthquakes to help achieve immediate occupancy goals in critical infrastructure. In combination with base isolation, FVDs can help reduce drifts across the isolation plane, helping to reduce moat sizes which are becoming significant as seismicity increases in our codes.

The following sections examine applications of FVDs in 1) Retrofits in North America, 2) Retrofits in New Zealand, 3) New construction, and 4) Base isolation with supplemental damping. The authors draw from involvement with hundreds of damper projects in both regions to distil current trends in FVD uses and best practices.

2 RETROFIT APPLICATIONS IN NORTH AMERICA

Following the 1971 San Fernando Earthquake and the 1994 Northridge Earthquake, cities in California began to develop and implement ordinances to improve deficiencies in existing Non-ductile Concrete Moment Frames (NDCMF) and Pre-Northridge Steel Moment Frames (PN-SMF), respectively. The San Fernando Earthquake exposed flaws in the design requirements of NDCMFs, specifically insufficient ductility in the moment frames stemming from insufficient steel reinforcing and confinement. New codes began to require additional reinforcing to provide improved ductility in these structures; however, they did not address what steps were required to improve existing structures. In recent years, six cities in California (Beverly Hills, Burbank, Long Beach, Los Angeles, Santa Monia and West Hollywood) have developed ordinances provide evaluation criteria and recommend compliance paths for these structures (Seismic Ordinances of California). Other cities including San Diego, San Francisco, Long Beach, and Torrance are following step by conducting surveys of the existing NDCMFs stock and developing draft ordinances.

The 1994 Northridge earthquake resulted in a better awareness of potential flaws in PN-SMFs behaviour. While none of the steel moment frame buildings experienced collapse because of the earthquake, post-earthquake evaluation of some structures revealed that connections experienced brittle failures, even at low level seismic drifts (Zepeda et al., 2017*)*. Los Angeles implemented a program that required all steel moment frame buildings within a limited geographic region be inspected and that damaged connections were repaired directly following the Northridge earthquake but has not since developed a retrofit ordinance for PN-SMFs. Only the cities of Santa Monica, Burbank and West Hollywood have implemented seismic retrofit ordinances (Degenkolb).

Because the deficiencies in both the NDCMF and PN-SMF systems are largely driven by excessive drifts (causing large connection rotations), distributed damping with fluid viscous dampers (FVDs) provides an effective and minimally invasive retrofit solution. In the past few years, the authors have explored hundreds of retrofit solutions using distributed damping with FVDs, mostly in PN-SMF buildings in California. Distributed damping tends to include two or more dampers in each direction up the majority of the building height. In taller buildings (> 8 stories) it is common to not add dampers to the upper fifth of the building height and use slightly larger dampers below to achieve the same performance objectives.

Benefits and best practices associated with the use of FVDs in retrofit applications are summarized herein:

- FVDs do not introduce stiffness into the building and therefore they do not change the building period (note this applies generally for damping ratios below 35%).

- Damper bays do not have to stack vertically up the height of the structure (see Figure 2). Because FVDs do not introduce stiffness into the structure, staggering dampers does not create a vertical irregularity as it would with a seismic force-resisting system (SFRS). The ability to stagger the damper locations allows the engineer to be more flexible with architectural needs, avoiding locations that would be more disruptive or expensive to work in.
- Staggering dampers up the building height can also be a strategy to distribute the accumulated damper force across multiple columns, avoiding the need for column strengthening or foundation retrofits.
- Damper installation may occur over a prolonged timeframe to accommodate tenant vacancies or shifting departments. Again, because dampers do not introduce stiffness, there is little concern about adding dampers to stories as they vacate, while not necessarily placing dampers above or below. For completeness, it should be stated that the partially implemented solution will obviously not achieve the fully improved performance associated the final solution. Additionally, it is recommended that dampers be placed symmetrically on any given floor to not introduce torsion through unbalanced damper forces.
- Connecting dampers to existing concrete structures can be complex. Attaching the gusset plates that connect to the damper and extender brace requires a steel plate system, oftentimes in the corner of the beam-column joint which is already heavily congested with reinforcing steel. Some solutions to address these difficulties, include:
    - Steel plates sandwiched on either side of or even around the beams and columns, connected with through-bolts or epoxy anchors (Figures 1a and 1b)
    - A secondary steel frame within the concrete frame with epoxy or through anchors throughout the width/height to distribute the transfer forces and avoid the congested joint area. (Figure 1c)
    - New rebar cages doweled into the existing column to house steel embed plates (Figure 1d)

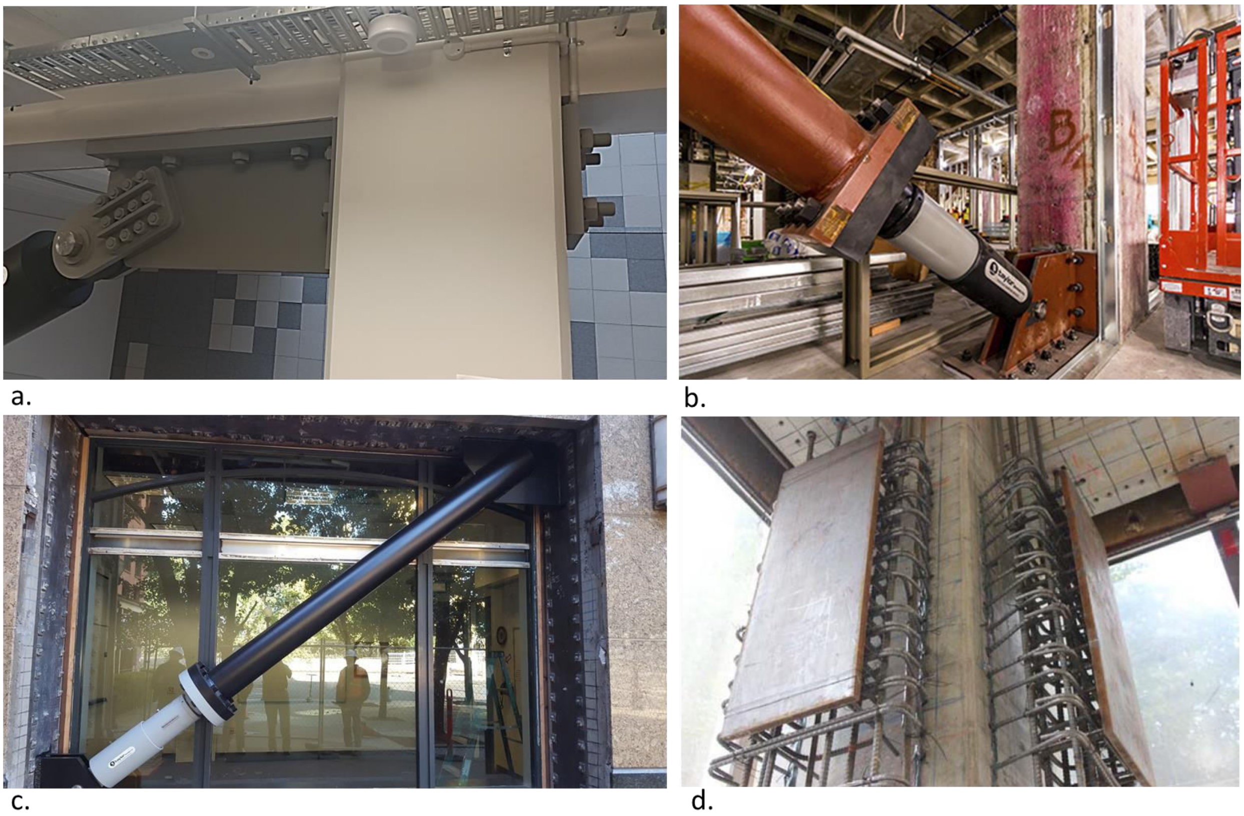
a.
b.
c.
d.

Figure 1: Examples of diverse approaches to adding dampers into pre-existing concrete moment frame structures.

2.1 US Retrofit Case Study – 651 Gateway, South San Francisco, California

This 17-story steel structure was designed in accordance with the 1982 UBC and has a dual lateral system comprised of eccentric braced frames and perimeter PN-SMFs. Evaluation of the PN-SMF connections showed that the beam-to-column connections were deficient which, along with code increased seismicity, contributed to a building with significant peak lateral inter-story drift of over 5% in the BSE-2E earthquake (5% probability of exceedance in 50 years). Retrofitting this structure with FVDs provided a solution which reduced drift and demands on the PN-SMF connections, while avoiding an increased base shear which would have required significant foundation work. Dampers were placed on each floor in the staggered configuration shown in Figure 2, resulting in a total of 127 dampers. Damper sizes were optimized for both cost and performance, avoiding the need to strengthen any columns or foundations due to the added damper forces or to retrofit any beam-column connections. Furthermore, the building behaviour was dominated by a torsional mode, therefore an imbalanced damper arrangement was used, with smaller dampers (lower C values) on one side and larger dampers on the opposite side, to counter the torsional effects.

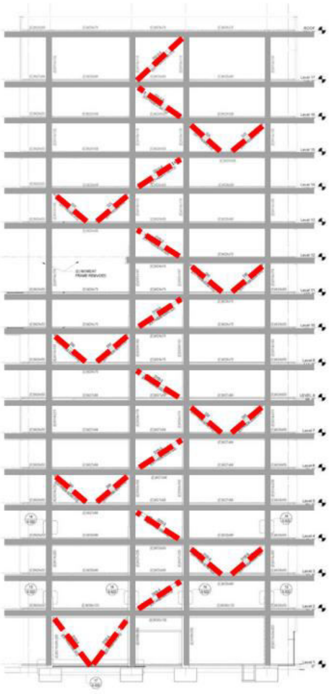

Figure 2. 651 Gateway elevation with finalized damper layout (in red)

3 RETROFIT APPLICATIONS IN NEW ZEALAND

Similar to how NDCMF and PN-SMF buildings are driving retrofit needs in the US, retrofitting pre-cast floor systems in ductile concrete moment frame buildings, along with increased seismicity, appear to be the main reasons for retrofits with FVDs in New Zealand. The performance shortfalls with the pre-cast flooring systems common in parts of New Zealand until the 2000s have been well documented (e.g. Lindsay et al., 2004; Fenwick et al., 2010; SESOC et al., 2009). Failings of this system may be simplified as driven by 1) drift incompatibility between the slab and the seismic force-resisting system (SFRS) and 2) incomplete or insufficient load path for transferring diaphragm actions and inertial forces back into the SFRS.

In these applications, it has been seen that adding dampers can be an effective approach to reducing inter-story drift ratios and to address drift incompatibility concerns. Adding FVDs can, in general, reduce drift from the undamped structure by around 50 percent. In many of the precast flooring projects that the authors have been involved with at early exploratory phases, this results in drift ratios around 0.7%-1.0% in the damped structure. In most cases, however, this does not eliminate the need for some retrofit actions, such as steel angles as a catch system for the precast flooring or perhaps additional drag lines connecting back to the SFRS.

In addition to drift reduction, FVDs have also been used to reduce floor accelerations which is used to justify lower inertial forces in the diaphragm. This approach is proving beneficial in reducing the strengthening required in the floors and the size of connections back into the SFRS.

Another trend that is being seen in New Zealand with respect to the use of FVDs is toward buildings with enhanced sustainability goals. The very act of retrofitting a building, as opposed to demolishing it and building new, is a move toward sustainability. FVDs can further this goal by decreasing the quantity of additional materials that need to be added into the structure as you may traditionally see with a strengthening retrofit scheme, especially where foundation work is required. The dampers themselves are made of steel with a small amount of silicone fluid – a nontoxic and non-flammable substance with stable behaviour over the expected life-span of the building (and beyond).

3.1 New Zealand Retrofit Case Study – 8 Willis St., Wellington

This 12-story reinforced concrete building was retrofitted to 130% NBS (IL2) and was extended both vertically and horizontally. The tenants are Statistics New Zealand and the Ministry for the Environment. The building is on track to achieve 6 Green Star and 6-star NABERNZ featuring solar energy generation and rainwater harvesting. The higher performance was achieved by the addition of just twelve 4000kN Fluid Viscous Dampers. The damper retrofit was minimally invasive especially when compared to alternative structural systems that would normally be required to achieve such a high level of resilience. Dr. Nathan Canney, Taylor Device's Director of Structural Engineering, is pictured with one of the dampers below (Figure 3).

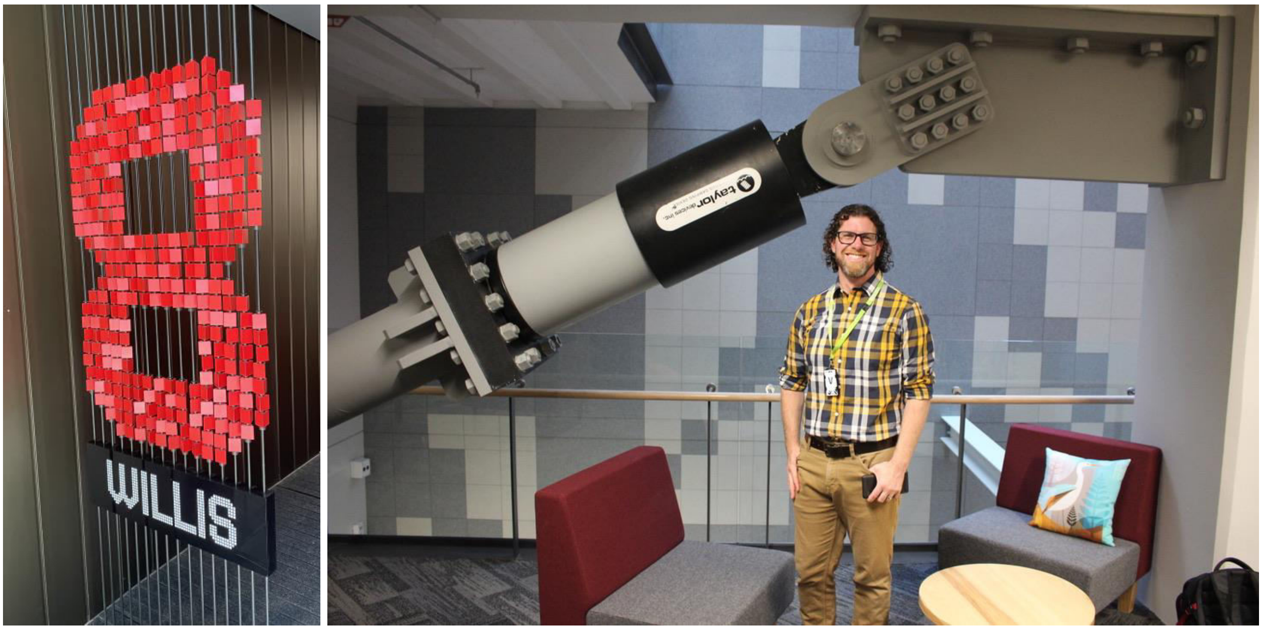

Figure 3. Exposed damper as part of the retrofit at 8 Willis St. in Wellington

4 DAMPER APPLICATIONS IN NEW CONSTRUCTION

The use of dampers in new building construction in North America has largely been in combination with steel moment frame structure where resiliency or functional recovery are key performance objectives for the project. These tend to be critical buildings such as municipal emergency centres and hospitals. Another application has been in buildings with high value content like bio-medical research facilities and life science buildings. In some cases, the addition of dampers is allowing engineers and architects to consider moment frame system where, due to high seismicity, these systems would be otherwise prohibitive to meet drift requirements. Primarily these applications use distributed damping, similar to the retrofit applications.

The authors have been involved in the process of developing a new prescriptive method for the application of dampers to new steel moment frame buildings which relies upon Modal Response Spectrum Analysis instead of Nonlinear Time History Analysis. The procedure (see paper no. 22 from these proceedings) is rooted in the Modal Strain Energy approach to the design of damped systems, but has been validated through the ICC-ES program. Approval of the design approach has included extensive nonlinear analysis with Incremental Dynamic Analysis on over 100 archetype structure to demonstrate the safety of the prescriptive approach. It is hoped that this new method with open up more opportunities to integrate dampers into new buildings, removing barriers of time, money and analytical expertise that currently keep some engineers out of damper design.

Dampers are also being used in high-rise structures as damped outriggers. For a damped outrigger system, a minimal quantity of dampers can be used to significantly reduce overturning forces, steel tonnage and foundation demands (Jackson 2013; Smith and Willford, 2007). Newer studies are exploring the combination of dampers with traditional outriggers, using each system at different heights in the tower to achieve the stiffness needed to resist wind loads while damping out uncomfortable wind vibrations and reducing seismic demands (Xing et al., 2019).

Figure 4. Salt Lake City Public Safety House building

4.1 Case Study – Salt Lake City Public Safety Building

This 6-story, 29,000 sq. meter building in Salt Lake City, Utah, houses police, fire and emergency response call centres for the Salt Lake region. It was designed to meet immediate occupancy performance criteria after experiencing the Maximum Considered Earthquake (MCE), which is approximately the 1/2500 year event. This exceeds the code minimum requirement for an essential services facility which require life safety performance during an MCE event. Dampers were used in combination with SidePlate® moment frame connections to provide a resilient structure which remains essentially elastic for the design earthquake. The damped steel moment frame has 58 FVDs with capacities up to 4700 kN and met the sustainability requirements for LEED Platinum and has Net Zero energy use due to energy recovery system. This building experienced the March 2020 M5.7 Salt Lake City earthquake with no damage.

Figure 5. Dampers with integral extenders within SidePlate® moment frames at the Salt Lake City Public Safety House

5 BASE ISOLATION WITH SUPPLEMENTAL DAMPING APPLICATIONS

Base Isolation with supplemental damping has been used for over 25 years. The first US project was the Arrowhead Medical Centre in San Bernardino, California in 1996 which combined elastomeric bearings with Fluid Viscous Dampers (FVDs). In broad terms supplemental damping reduces the isolation displacement by up to 50 percent. Isolation systems for buildings generally have 20 percent system damping but adding supplemental damping can increase that to around 50 percent.

Early isolation projects incorporated supplemental damping as the elastomeric isolators had minimal inherent damping. The Arrowhead Medical Centre isolators for example were specified with less than 5% damping. High damping rubber isolators were available and had damping in the 10-18% range dependant on the manufacturer. The Hearst Memorial Mining Building and Los Angeles City Hall retrofits both used High Damping Rubber bearings (HDR) in conjunction with FVDs. Later systems with Lead Rubber Bearings such as the Tan Tzu hospital in Taiwan added supplemental damping to a Lead Rubber Bearing System (LRB). The added damping was required due to the building proximity to a fault that generated higher seismic demands and a large velocity pulse.

Currently, isolation systems require supplemental damping to reduce displacements due to the increased seismic demands that are being seen in New Zealand and the USA. The Loma Linda University Medical Centre (LLUMC) and NTT SV1 Data Centre are new projects in California that have dampers with strokes of +/-1067mm and of +/-812mm, respectively. Several projects currently being designed in New Zealand have strokes of up to +/-1000mm.

The two common isolation bearings in use today are friction pendulum bearings and elastomeric bearings with or without lead. Friction pendulum bearings have been made with displacement capacities of over 3m. The large displacements are the result of the longer isolated periods often in the 4-5 second range. Supplemental fluid viscous dampers are used to reduce the displacement and provide additional benefits outlined in the LLUMC case study below. Elastomeric bearing’s displacement capacity is limited by the shear strain in the rubber. Supplemental damping is used to reduce the displacements to be within the bearing’s capacity.

Some of the current stock of isolated buildings will require retrofitting due to increased code specified seismic demands. This is also the case for conventional buildings designed in the same time frames over the last 40 years. Isolators in the US designed prior to the 1994 Northridge earthquake, may not have sufficient displacement capacity (Johnson and Walters, 2016). Isolators designed and fabricated after 1994 generally were designed to larger displacements and supplemental damping could still be a retrofit option due to increased seismicity.

5.1 Case Study – Loma Linda University Medical Center

The LLUMC (Neilson et al, 2017) is a 17 story 93,000 sq. meter hospital located less than 1 km from the San Jacinto Fault. The base isolation system has 126 triple friction pendulum bearings manufactured by Earthquake Protection Systems and 104 Fluid Viscous Dampers manufactured by Taylor Devices. The dampers have an MCE capacity of 3560 kN (800 kips) and a velocity exponent of 0.7. The dampers and isolators have a displacement capacity of +/- 1067mm (+/-42”). The isolation system has an effective period of 4.5 seconds. The total equivalent damping is 50% of critical damping with 20% and 30% of the damping coming from the isolators and dampers respectively.

The addition of the FVDs halved the isolator displacements to 1067mm from 2134mm (+/-84”). This resulted in an optimal cost solution by controlling the isolator and damper unit costs along with the structural framing costs above and below the isolators. In addition, the cost of moat covers, flexible utilities that cross the isolation plane and detailing of stairs and elevators was reduced.

6 CONCLUSIONS

In this paper, we have examined the current state of practice with respect to fluid viscous dampers in North America and New Zealand. Damper application to retrofits, new construction and with base isolation were highlighted, including the most common applications, benefits of using FVDs and best practices. In general, FVDs are a cost effective way to reduce the seismic response of existing buildings to cope with many previously common structural systems that have connection or drift-related deficiencies. The use of dampers to address Pre-Northridge Steel Moment Frames is growing in popularity in the US as is their use to address precast floor issues in New Zealand. The fact that dampers do not introduce stiffness into the structure holds many benefits over other structural solutions, such as not shortening the building period and having flexibility with damper placement up the height of the structure. FVDs are also being used around in both regions to achieve more resilient structures, both in retrofit and new construction applications. Moving forward, FVDs will be an important tool for engineers to consider when examining new and existing buildings, while balancing the myriad demands of resiliency, cost, building operations and post-earthquake functionality.

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