Optimised and adaptive supplementary damped isolation systems

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ABSTRACT

Base isolation with supplemental viscous damping devices effectively manages increased design hazard in structures. This has been demonstrated in a recent high importance project in New Zealand.

The structure was designed to meet SLS1, SLS2, ULS and CALS targets, while minimising horizontal movements and design accelerations to 1m and 0.25g respectively (to the draft TS1170.5 hazard). This was best achieved through a hybrid system with adaptive base isolation, providing smooth behaviour for less severe service events and significant energy dissipation during CALS. The building combines 49 curved surface sliders with 8 hydraulic dampers in the basement to manage displacements up to ±1m and velocities of 2m/s.

While separating period-elongating components from damping components is intuitive, detailing remains challenging. Project-specific needs may dictate this detailing, including preferences for off-the-shelf dampers or spatial constraints within functional areas. For supplemental damped isolation systems, dampers linking non-isolated and isolated structures require careful consideration of relative displacements during cyclic movement.

Early coordination of damper geometry relative to the isolation plane is crucial, affecting clearance zones, damper specifications, and forces on supporting structures. Early involvement of base isolation suppliers proves crucial for achieving optimal system performance.

A practical approach to designing such systems has been developed to encourage wider adoption in New Zealand (Makan 2023). This paper will present specific design considerations, including isolator friction stability, damper buckling, and practical detailing considerations through collaboration between designers and suppliers.

1 INTRODUCTION

Base isolation with supplemental viscous damping devices effectively manages increased design hazard in structures. This has been demonstrated in the design of a high importance project in New Zealand. The concept of incorporating dampers across the isolation plane in base isolation systems is not new and has been successfully implemented in other regions of high seismicity around the world, for both new construction and seismic retrofit projects.

2 BEYOND CODE: DESIGNING FOR SUPERIOR SEISMIC RESPONSE

The reference project is multi-level, IL4, and base isolated – designed to meet SLS1, SLS2, ULS and CALS targets. The design considers the draft TS1170.5 hazard, with Figure 2 below comparing the ULS (1:2500-year) hazard with NZS1170.5:2004 (Standards New Zealand 2004), and the draft 2019 NZSEE seismic isolation guidelines (NZSEE 2019). The base isolation system is supplemented with viscous damping devices which minimises design horizontal movements and accelerations to 1m and 0.25g respectively. These low design accelerations without excessive isolator displacements enabled a mass timber gravity and lateral force resisting system for the superstructure.

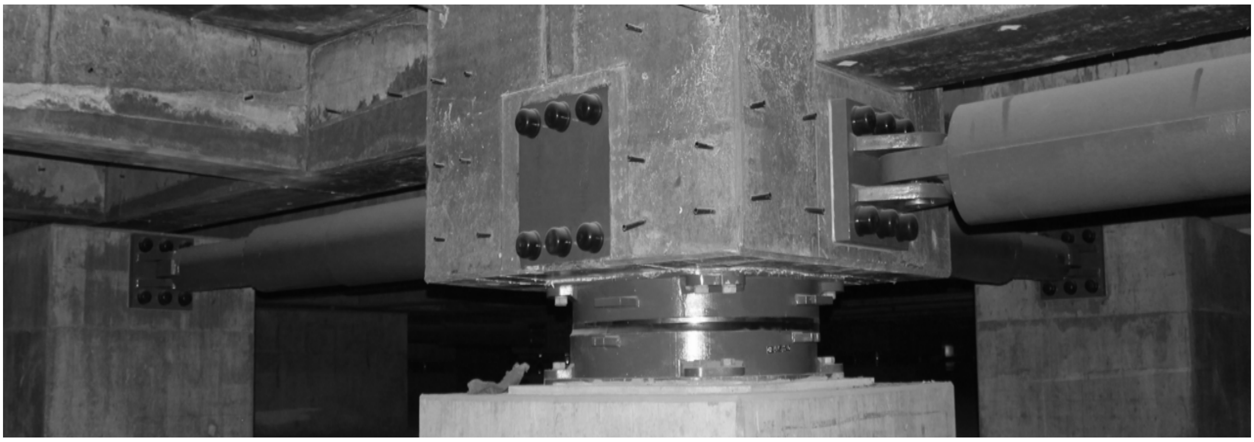

Figure 1: Implementation of supplemental viscous damping devices across isolation plane (image courtesy of Maurer, Grand Mosque of Algiers)

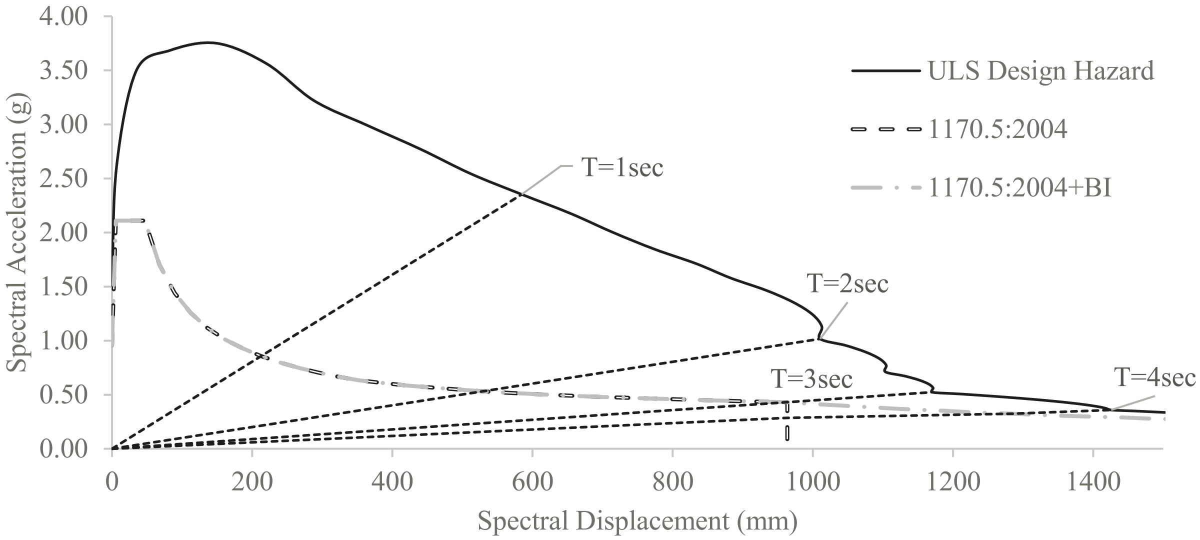

Figure 2: Acceleration-displacement response spectrum, comparing design hazard, 1170.5:2004 and the recommendations from the draft 2019 NZSEE Seismic Guidelines Isolations (BI)

3 COST BENEFITS OF SUPPLEMENTAL DAMPED ISOLATION SOLUTIONS

The cost-benefits of traditional isolation systems in New Zealand are well documented. In general, a reduction in design base shear to the superstructure is achieved by localising displacement demand of the multi-degree of freedom system to an isolation plane. In theory, compared to a non-isolated reference case, the same building concept can be designed more efficiently.

Where large displacement demands are present, traditional approaches can lead to challenges in detailing the isolation plane. This includes, but is not limited to movement joints, lift structure, service reticulation and spatial requirements. Lead rubber bearings require a minimum overlap area of the offset bearing at design displacement, which influences the yield force and the maximum reduction in seismic base shear that the structure can achieve. Curved surface sliding (CSS) bearing yield is a function of axial load, which, while less dependent on design displacement, results in low levels of energy dissipation under lower bound conditions – with most of the reduction in seismic demand attributed to elongating the period. To control displacements in a CSS bearing, a minimum yield force (in the form of increased friction coefficient) is required. In conflict to this displacement-based target, when solving upper bound conditions, the maximum reduction in seismic base shear achievable is often limited.

The limitation of traditional isolation is that it can generally only control one performance objective well, such as displacement, at the expense of others, such as design base shear coefficient.

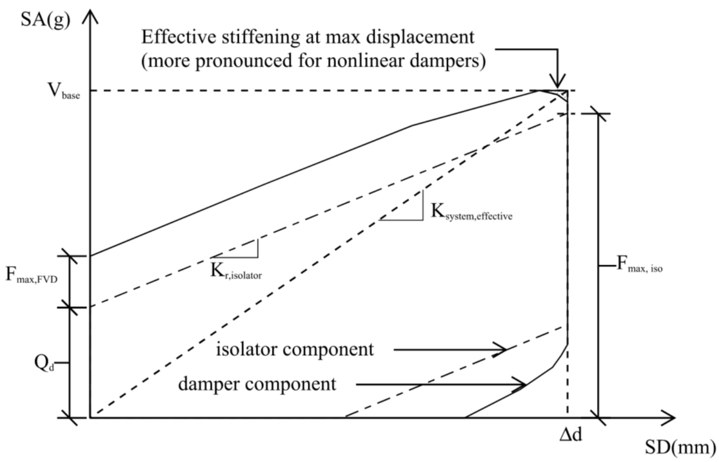

Figure 3: Effective stiffening at max displacement due to supplementary nonlinear dampers

Supplemental damped isolation systems combine two distinct components: displacement-dependent isolators and velocity-dependent viscous dampers. Nonlinear viscous dampers provide an effective stiffening mechanism during critical lower bound performance scenarios like collapse avoidance (CALS), where system velocities are high. This adaptive behaviour is beneficial, as the damping forces naturally reduce during upper bound performance objectives like the ultimate limit state (ULS) when velocities are lower, preventing unwanted increases in seismic base shear.

This complementary performance stems from the phase difference between isolator and damper responses. Isolators generate maximum horizontal forces at peak displacement, while dampers reach their maximum force output at peak velocity, which occurs near the neutral position. This out-of-phase behaviour, particularly pronounced with nonlinear dampers, creates an effective system that combines the benefits of isolation with enhanced energy dissipation.

Whilst large displacements have been used to highlight an edge use case for supplemental systems, it is appropriate to adopt across a wide range of hazards, with a potential net reduction in global project cost when compared to traditional isolation.

While alternative approaches, such as those employing progressive stiffness mechanisms within isolation systems, aim to balance displacement control and energy dissipation, the incorporation of supplemental viscous damping devices offers a distinct and versatile means of addressing a broader range of performance objectives. This approach enables more consistent control over both displacements and accelerations, particularly under varying ground motion characteristics, providing an intuitive advantage in certain applications.

A practical approach to designing such systems has been developed to encourage wider adoption in New Zealand (Makan 2023). It offers an ability for designers to derive key parameters with confidence during the early design phases, such as moat clearance and superstructure design base shear, with some flexibility.

A hybrid system combining Curved Surface Sliders (CSS) with viscous dampers offers enhanced design flexibility through independently adjustable parameters. The CSS radius can be tuned to achieve desired system properties such as low stiffness and long periods, while the combination of CSS sliding friction and viscous damping provides robust energy dissipation.

The nonlinear behaviour of viscous dampers, controlled through their damping exponents, enables precise force management across a range of velocities. This allows designers to optimize damping forces for expected seismic demands while inherently limiting forces during extreme events that exceed design velocities, providing an additional layer of system protection.

Table 1: Cost-benefit comparison of traditional isolation against supplemental damping

Item	**Benefits**	**Costs**
Traditional Isolation	• Widely adopted in New Zealand. • Performance well understood from wider stakeholders.	• Constrained reduction in both acceleration and displacement. • Practicality reduced with larger displacement demands. • Generally only control one performance objective well, such as displacement, at the expense of others, such as design base shear coefficient.
Isolation with Supplemental Damping Devices	• Adaptive system which can target efficient response at a wide range of performance objectives. • Additional damping from viscous dampers is velocity dependent, damping when required, when impact is highest. • Efficient reduction in both acceleration and displacement. • Reduced isolator sizes/cost (30% reduction from traditional design for equivalent design accelerations) • Reduced superstructure demands (when targeted equivalent design displacements). • Enhanced protection of sensitive equipment and contents due to more controlled acceleration responses.	• More complex design and analysis requirements. • Potential need for specialised inspection and testing protocols during installation • Limited local industry adoption. • Additional clearance considerations for componentry. • Additional cost of viscous dampers (noting total structural cost likely equivalent or less with combined system).

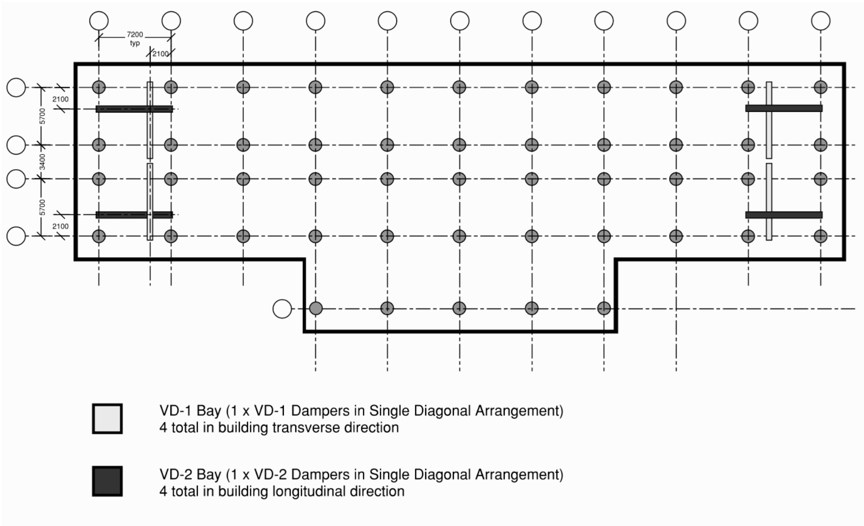

Figure 4: Damper set-out example across isolation plane

4 DETAILING CONSIDERATIONS

A combined system must accommodate large displacements and velocities across the isolation plane. As with traditional isolation, the designer will need to balance these requirements throughout the design phase and understand the impact changing any one of these items will have on the global system.

A key plan highlighting an example of damper set-out is shown in Figure 4 above.

4.1 Key Parameters

Parameters highlighted in Table 2 and Table 3 can be converged upon when adopting the previously mentioned approach (Makan 2023) for isolators and dampers respectively. Example parameters have been extracted from the reference design (incorporating the hazard reflected in the draft TS1170.5).

Table 2: Example of key parameters for Curved Surface Sliding (CSS) bearings and recommended ranges

		Example Parameters	Recommended Ranges
Isolator Size, m (exclusive of mounting plates)		1.40	< 1.50
Effective nominal friction coefficient, %		5	4-8
Bounding	Lower Bound: Upper Bound:	0.81 1.60	ASCE Standard (ASCE/SEI 7-16) or EN15129
Effective single pendulum radius, m		6.42	< 7000
Max Bounded Vector Displacement, m		1.00	< 1.10
Max Bounded Base Shear, %g	CALS: ULS: SLS2:	0.25 0.19 0.10	≤ 0.30 ≤ 0.20 ≤ 0.15

Table 3: Example of Key Parameters for Viscous Damping Devices (VDD) and recommended ranges

	Example Parameters	Recommended Ranges
Installed Damper Angle, degrees	25.0 +/- 0.5	15-30
Pin to Pin Length, m	5.12	Refer Figure 5
Bounding	Lower Bound: 0.85 Upper Bound: 1.15	ASCE Standard (ASCE/SEI 7-16) or EN15129
Nonlinear damping coefficient, C_{NL}, kN·(s/m)$^{\alpha}$	1200	50 – 7000
Damping exponent, α	0.70	0.02 – 2.00
Velocity cap, v_{max}, m/s	0.98	0.05 – 2.00
Max Force, kN	1400	30 – 7000
Half-stroke, $x_{s/2}$, m	$\lvert x_{s/2} \rvert = 0.78$	$\lvert x_{s/2} \rvert \leq 1.10$
Damper Diameter, m	0.34	0.10 – 0.80

There are two common orientations of dampers across isolation planes, horizontal, and inclined – each with varying pros and cons. Horizontal/inclined dampers could be installed within, or outside the building footprint, provided sufficient space is allowed for.

For most applications, installing dampers within the building footprint is more practical spatially. For these types, both options require resolution of an eccentric force (superstructure base shear at isolation plane) relative to where the damper is supported at its base. For horizontal applications, this is typically done with a cantilever reaction block to the foundation with or without a down stand cantilever stub from the isolated transfer structure.

Horizontal dampers will need to accommodate the full isolation plane movement, with sloped dampers having the additional benefit of a reduced half-stroke to achieve an equivalent horizontal movement. A reduced half stroke will reduce damper length and cost and may help other spatial constraints across the isolation plane. While sloped damper configurations generate both horizontal and vertical force components, resulting in somewhat higher axial forces, this arrangement offers economic benefits. The reduced displacement stroke requirement in sloped dampers offsets the increased force demands, leading to overall cost savings in the system design.

Prior to supplier engagement, damper length can be approximated. Damper length primarily depends on the required half stroke, and, to a slightly lesser degree, the required design force. The half-stroke is the required extension/compression required from the mid-stroke position.

A recommended approach is to allow for 3-5 times the required damper half stroke, plus a fixed allowance that is dependent on axial load. A higher multiplier (5 instead of 3) is recommended where enhanced buckling stability is needed. Some preliminary guidance for estimating long stroke, high velocity dampers is provided in Figure 5.

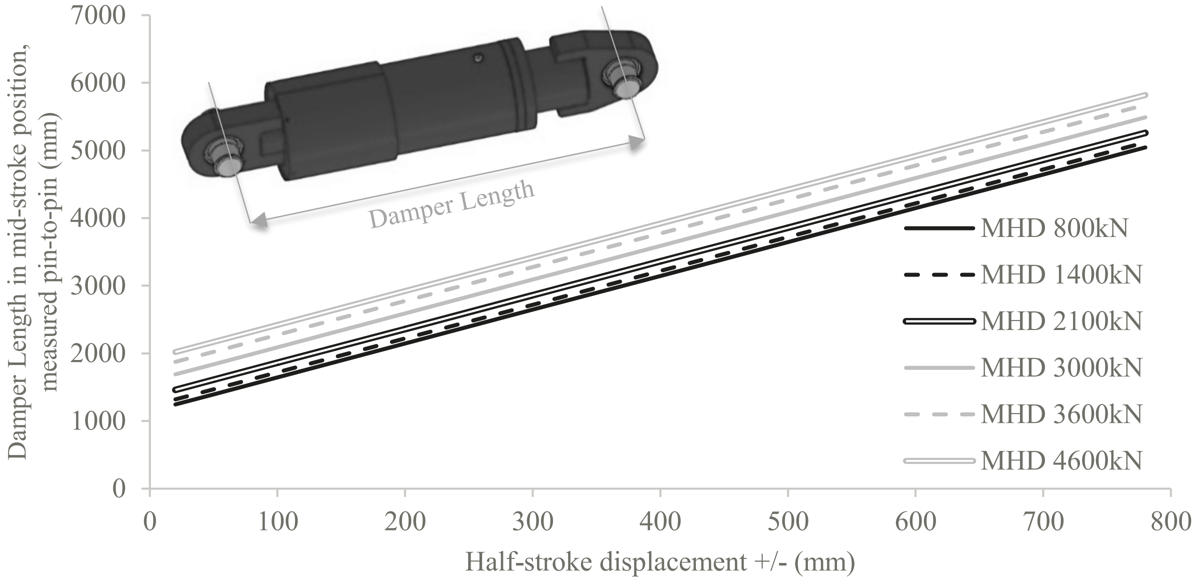

Figure 5: Estimate of damper length (pin-to-pin) dependent on half stroke and design forces

The pin-to-pin dimension and initial installation angle significantly influence damper specifications and performance characteristics. Unlike horizontal dampers, sloped dampers require articulation of the pin (typically spherical bearing) around multiple axes. It is recommended to align the pin vertically, and to not exceed a maximum of +-6 degrees rotation out of plane.

For base isolation applications, construction drawings should clearly specify the required pin-pin dimension of the damper assemblage. The design should accommodate extenders or similar elements to make up any dimensional variations that may be required during installation. This approach enables design progression and spatial coordination to proceed with confidence, minimising the risk of late changes. When establishing these dimensions during the design phase, it is prudent to err on the conservative side with a slight overestimate of required damper length rather than risk underestimating spatial requirements.

4.2 Damper Stability Structure

Whether the damper is installed horizontally or inclined, the centroid of the damper pin connection will likely be eccentric to the "at rest" lateral system. Where small displacement assumptions can be adopted for typical damping applications in buildings, the influence of large displacements need to be accounted for, both in strength and stiffness. Consider the elements required to restrain the degrees of freedom in Figure 7 (a), these will have their own stiffness which effectively delays the damper stroke activation.

Figure 7 (b) shows the effective response of a Maxwell Model, which is often used to represent this behaviour in tradition damper cases. A damper element represents pure viscous behaviour, which is combined with a linear-elastic spring element that represents the connections and extenders.

Experience and recent publications (Xie et al. 2021) that this interaction is significant and needs to be captured to appropriately define the damper properties and actual damped response of the structure. Given large displacements, it is recommended to account for additional stability structures in analytical models. Figure 7 (a) indicatively illustrates analytical stability structure provided to the damper element. Depending on software limitations, axial stiffness of the damper could be modelled explicitly in the damper element, or through modification of element 1 properties. Given the pin location is likely eccentric to the "at rest" lateral system, an additional element (element 2) can be defined with a representative minor axis stiffness. The analyst will need to extend modelled elements to a sufficient level to capture this out of plane behaviour.

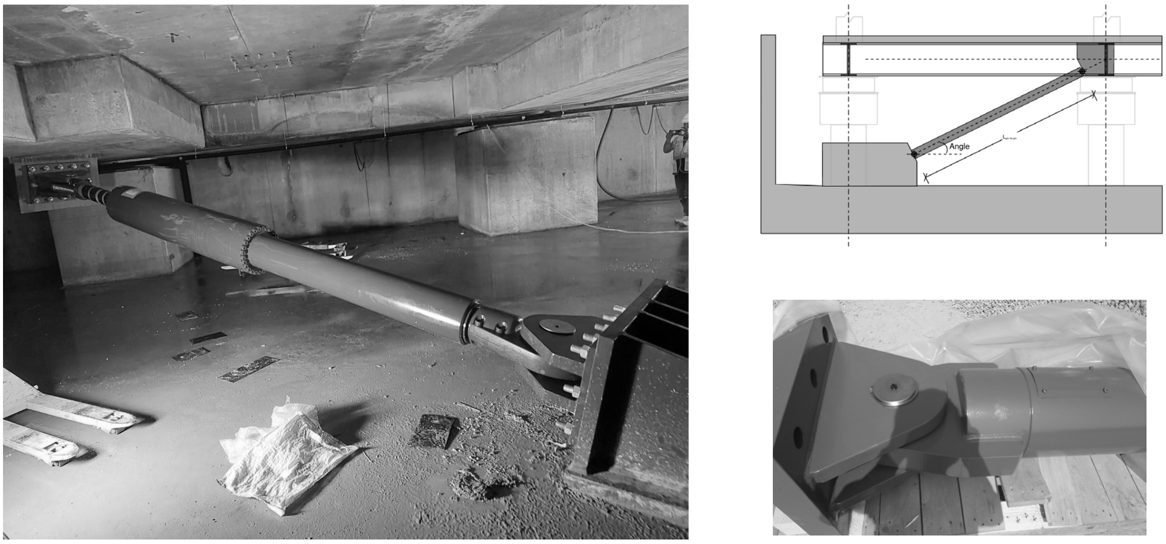

Figure 6: Inclined damper (left), indicative damper shown at an angle, across the isolation plane (top right), and spherical bearing connection (bottom right)

4.3 Isolation Friction Stability

For typical applications in high seismic regions, the seismic velocities are likely to be greater than 100mm/s. At these, or higher velocities, Teflon based materials are expected to begin wearing after 5 cycles. This wear on the Teflon pad occurs mainly at the edges where stress concentrations at max displacement amplitudes approach and typically exceed 300MPa. Typically, Teflon based materials are limited to characteristic stresses in the range of 64-69MPa. Wearing influences the stability and reliability of the friction behaviour, wear particles can both act as lubricant, and increase roughness, leading to non-constant or uncertain behaviour.

Polyethylene based materials generally perform better and is recommended for seismic applications. These exhibit a higher effective friction, at low velocities, while reducing slightly for higher velocities. This can be captured well in bounding analysis at the ULS and CALS performance objectives, with common lower and upper bound coefficients of 0.81 and 1.6 respectively for unlubricated examples.

It is recommended that bounding is also undertaken under serviceability limit states. This differs slightly from standard practice, however better captures known ranges of friction under differing system velocities.

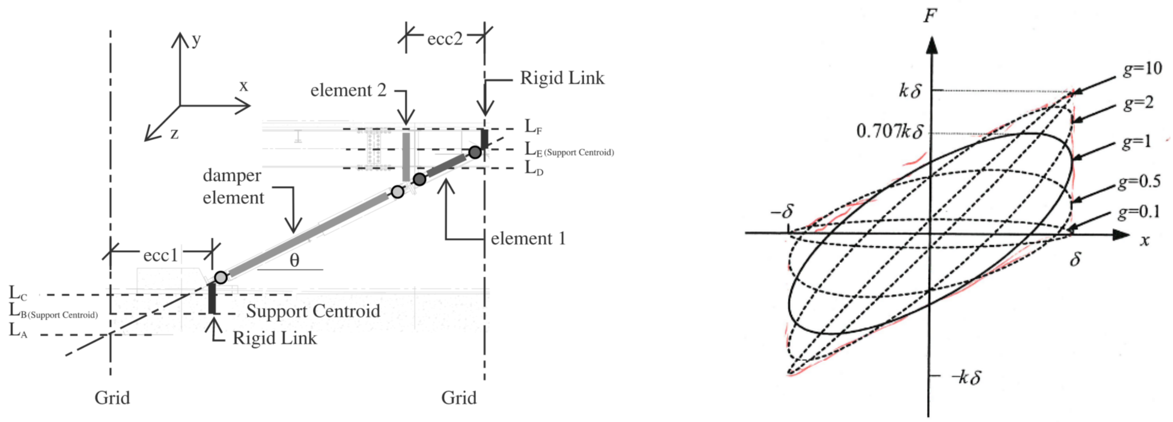

Figure 7: Example of analytical restraints required for high-velocity, high-stroke viscous dampers (a), and (b) Force-displacement response of Maxwell Model.

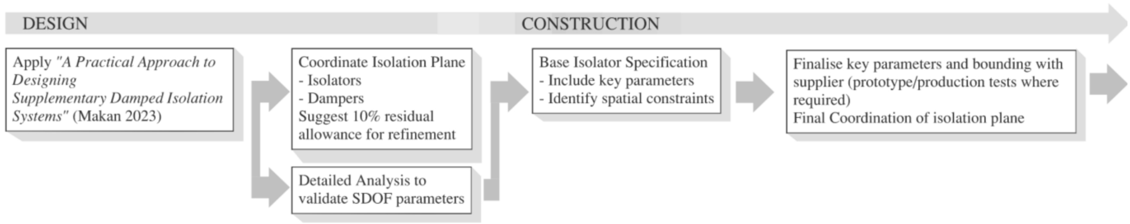

Figure 8: Simplified flow chart to coordinate a supplementary damped isolation plane

5 SUPPLEMENTAL DAMPED SYSTEM DEVELOPMENT AND PROPOSED WORKFLOW WITH SUPPLIERS

A simplified flow chart describing a recommended workflow with suppliers is shown above in Figure 8. Whilst early engagement for this type of system is recommended, various factors can often limit the ability to execute on that. This flow chart is written from the perspective of supplier engagement post Tender, near the conclusion of traditional design phases.

6 CONCLUSIONS

The reference building demonstrates the successful implementation of base isolation with supplemental viscous damping devices to effectively manage increased design hazard without substantial cost increase. This adaptive system achieves optimal performance across multiple performance objectives - from serviceability through to collapse avoidance - while maintaining practical displacement limits and low design accelerations. Coordination between designers and suppliers proved essential for resolving key challenges around isolator friction stability, damper geometry, and practical detailing considerations. The approach developed through this project provides a framework for wider adoption of supplemental damped isolation systems in New Zealand, offering designers an additional tool to achieve enhanced seismic performance outcomes while maintaining practical constructability. Despite additional devices the overall structural cost can be kept on a similar level (or better than) to traditional isolation systems without additional viscous dampers.

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