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Hybrid Damping Systems for Earthquake-Resistant Structures: A Critical Review of Mechanisms, Configurations, Seismic Performance and Open Research Gaps

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Abstract

Traditional earthquake resistance design is based on the strength and ductility of main components, and tolerates yielding, permanent deformation and repair as the cost of preventing collapse. That cost is mitigated by supplemental damping devices, which have different effectiveness under different seismic demands: velocity-dependent fluid devices are effective against far-field drift; but do not close the gap between being yielded and being in plumb; metallic and friction fuses work under long-period pulses, but leave residual drift; and isolation works by reducing force, but increases bearing stroke under near-fault pulses. Hybrid damping systems are systems that use two or more paths of different mechanical characteristics and in which they are passive with passive, dissipation with restoration, or passive with semi-active. This paper provides a systematic critical survey of hybrid damping in earthquake resistant buildings and bridges. It categorises structural control strategies, provides a summary of the constitutive behaviour of the constituent devices, summarizes hybrid configurations at the device and system level, sums up the reduction of response reported in the literature, and investigates the performance of the structural control under near-fault, long-duration, and repeated shaking, with special attention to the residual drift. The provisions of the design codes of ASCE/SEI 7 and EN 15129 and IS 1893 are compared. The review concludes that the majority of studies compare a hybrid with an unretrofitted structure, the benefits of hybrids are seldom specified by ground-motion class, the number of reinforced-concrete hosts is low, the number of highway overpasses is low, and there is no Indian design sequence for two-mechanism devices. These gaps are related to specific lines of research.

Keywords—*Hybrid damping, energy dissipation, fluid viscous damper, metallic damper, self-centring brace, base isolation, near-fault ground motion, residual drift, structural control*

1. Introduction

Earthquakes continue to be one of the most destructive natural hazards and the losses that result from them are dominated by the response of buildings and lifeline structures. Modern seismic codes like IS 1893 (Part 1): 2016 [1] and ASCE/SEI 7-22 [2] safeguard life mostly by the use of the capacity design, where beams are permitted to yield while the columns and the foundations remain elastic and a stable plastic mechanism dissipates the input energy. This prevents collapse, but will allow for damage and permanent offset and expensive repair following a design level event. Since then, performance-based earthquake engineering has turned away from collapse prevention to immediate occupancy and repairability and functional recovery, things that ductility alone will not provide.

However, there is another approach: structural control, where special devices take up or divert the seismic energy instead of primary members [3, 4]. The application of passive energy dissipation devices (fluid viscous, viscoelastic, metallic and friction dampers) and seismic isolation have already been proven in practice [5], [6]. All of them, however, have only one sensorial variable and they provide a single force law. A velocity dependent damper is not able to respond with high force to the slow passage of a long period pulse, a displacement dependent fuse will only trigger once a threshold is reached, then it will leave a plastic offset, while an isolator will change the period but must be able to accommodate large stroke. If multiple objects are named in a design, at least one of them will not be met by a single mechanism.

This is overcome by hybrid damping systems that use two or more mechanisms to provide damping in regions where the other mechanisms are weak [7] [8]. Many different concepts have been investigated including viscous–metallic braces, friction–viscoelastic stacks, self-centring braces with yielding or friction fuses, isolation planes with supplemental dampers, and passive devices with magnetorheological (MR) control. The current reviews are rather general and do not consider whether a second path does complement the first path or not. Accordingly, this review, part of the first author's doctoral work, asks a more

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limited question: What does the literature actually say with regard to the complementary action of combined dissipation paths in earthquake-resistant structures, and what does it not say? The main contributions are:

1) A taxonomy of structural control strategies which positions hybrid systems on the continuum between passive, semi-active and active control, and a compact description of the constitutive behavior of the constituent devices.
2) Comparative analysis and synthesis of device level and system level hybrid configurations, including a matrix of representative studies in the literature and a list of reported reductions in response.
3) A critical review of performance during near fault, long duration and repeated shaking with residual drift as a claim of performance separate from peak drift.
4) A comparison of code provisions and mapping open research gaps to research directions.

2. Background

2.1 Seismic Demand and Performance Objectives

The energy input from the earthquake is in the form of kinetic energy and strain energy and can be either stored temporarily or dissipated. The conventional frame is a different type of structure in which dissipation is performed in plastic hinges, and structural damage is the protection mechanism. There are two aspects of true ground motion which make this somewhat more complicated. In the near fault records with forward-rupture directivity, the structure has to deal with long-period velocity pulses that create significant displacement demand in a small number of cycles, especially for flexible or isolated structures [9]. Long-duration subduction-zone records, on the other hand, bring numerous moderate cycles that mean damage and heat in devices. This can cause significant differences in the protection strategy's response to the two classes.

Modern performance targets also distinguish between “peak” and “residual” responses. If such a building experiences a drift greater than approximately 0.5 % it may not be economically feasible to be repaired. In addition to peak drift, also considered in any protective system, there are the other quantities of residual drift, floor acceleration, isolator stroke and dissipated energy.

2.2 Structural Control Taxonomy and the Hybrid Concept

According to the energy source, and adaptivity, there are two types of structural vibration-control systems as shown in Fig. 1 [3], [4], [7]. Passive: No external power source is needed; the properties are fixed; Semi-Active: They change properties within limited bounds, but require only small amount of power to do so; Active: They use actuators to generate control forces and therefore require power and sensing during shaking. For Hybrid systems, a second passive law or a bounded adaptive law is added to a passive baseline to provide protection in the event of a power or control failure. Comparison of these families is shown in Table I.

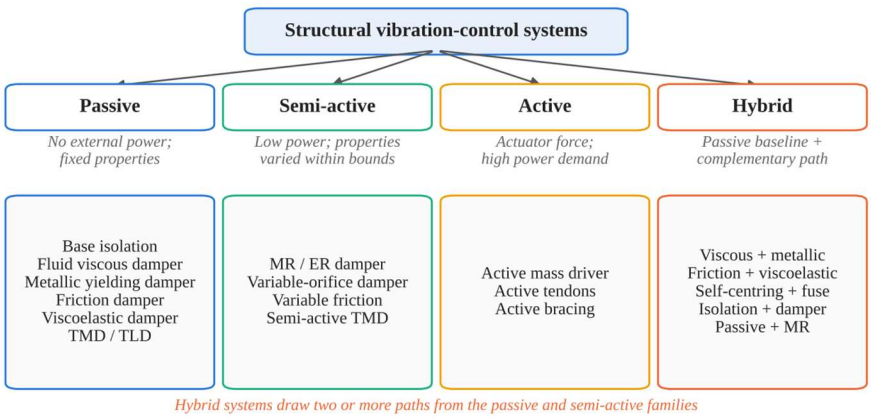

Fig. 1. Classification of structural vibration-control systems according to energy source and adaptivity, showing the device families most commonly combined in hybrid systems (adapted from [3], [4], [7]).

TABLE I COMPARATIVE FEATURES OF CONTROL STRATEGIES

Feature	Passive	Semi-active	Active	Hybrid
External power	None	Low (valve, field)	High (actuators)	None or partial
Adaptivity	Fixed properties	Varied within bounds	Force generated on demand	Fixed baseline plus complementary path
If power is lost	Unaffected	Reverts to passive bound	Control force lost	Passive part continues to dissipate

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Typical devices	Isolation, viscous, metallic, friction, TMD	MR dampers, variable orifice	AMD, active tendons	Viscous–metallic, isolation + damper, passive + MR
Design burden	Sizing and placement	Control law, fail-safe bounds	Stability, delay, certification	Compatibility of laws and force sharing

3. Review Methodology

Literature was collected from journals in earthquake engineering, structural engineering and engineering structures (Earthquake Engineering and Structural Dynamics, Journal of Structural Engineering, Engineering Structures, Earthquake Spectra and others), design standards and documented installations. Studies were accepted if they provided a constitutive description, measured hysteresis, provided a numerical benchmark or provided a code provision or installation record relevant to complementary seismic dissipation. Only active systems whose operation relied on continuous power were listed, and studies that focused only on wind comfort were not included unless they made clear that they were also multi-hazard compatible. These properties were classified as follows: Dissipation path, physical; host, structural; ground-motion class, applied; and response quantity, decisive, since results obtained on different hosts or under different motion classes cannot be compared as if they were observations of one quantity.

4. Constituent Energy-Dissipation Mechanisms

The only thing a hybrid assembly makes sense of is the mechanisms it is composed of. Idealised force–displacement cycles for the main families are presented in Fig. 2, and the quantities sensed by each family and the force returned in each family are summarised below.

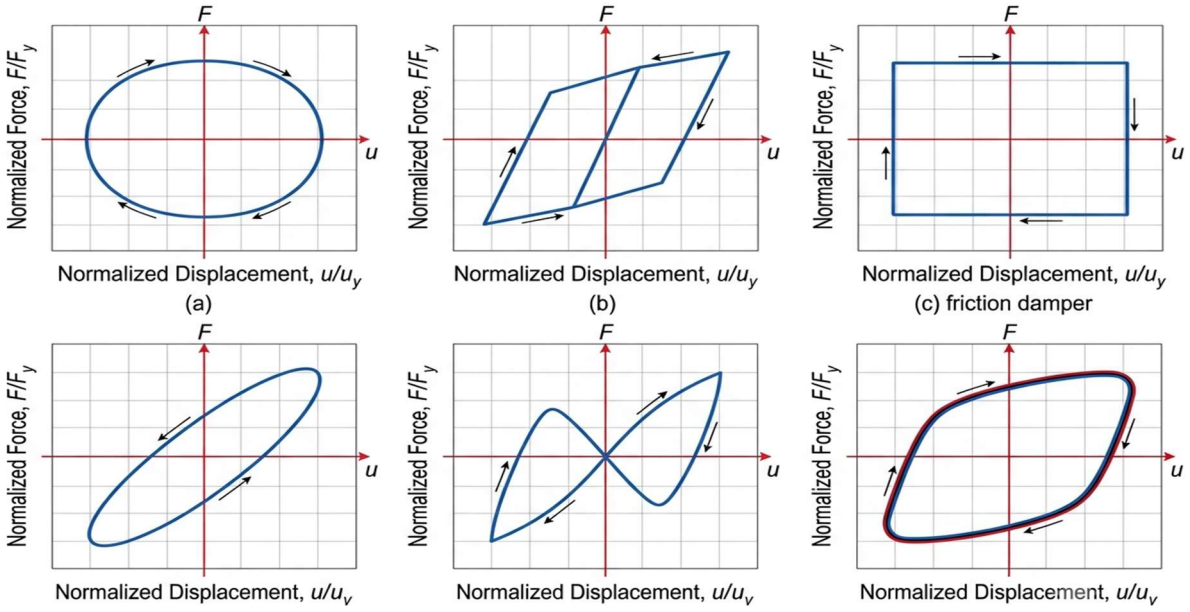

Fig. 2. Idealised normalised hysteresis loops of constituent devices: (a) nonlinear fluid viscous damper, (b) bilinear metallic yielding damper, (c) friction damper, (d) viscoelastic damper, (e) flag-shaped self-centring element, and (f) a parallel viscous–metallic hybrid that inherits features of (a) and (b).

4.1 Velocity-Dependent Devices

The force of a fluid viscous damper is$F = C|v|^{\alpha}\,\mathrm{sgn}(v)$, where C is the damping coefficient, v is the relative velocity and α is the velocity exponent. They are out of phase with displacement, so they provide damping rather than stiffness, and nonlinear dampers ($\alpha < 1$) limit high velocity forces [10, 11]. The drawback of this is the opposite: At rest they exert no force and cannot pick up a dropped frame. Viscoelastic dampers are polymers that shear at very small amplitude, give storage stiffness and loss, and are temperature and frequency dependent [12].

4.2 Displacement-Dependent Devices

The metallic yielding dampers absorb energy by plasticizing steel or other metals. The triangular-plate (TADAS) devices spread yielding along their height and have been designed in such a way that they support a number of stable cycles depending on the ratio of the stiffness of the device to that of the frame, and the stiffness of the yield strength of the device to the storey strength [13]. These are all part of the same family of elements, and recent reviews record the slit, honeycomb and lead variants as well as their limits of low cycle fatigue [15]. Friction dampers slip at a given force and create almost

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square loops [16]. Both families are rate independent and effective in long-period pulses, but they do cause plastic offset, and may increase the floor acceleration, due to the high value of the force when the device is active.

4.3 Restoring and Smart Devices

Self-centring systems consist of a combination of a restoring element (post tensioned bars, pre loaded springs or superelastic shape-memory alloy (SMA)), and an energy dissipating fuse, with a flag shaped loop formed (Fig. 2(e)). Residual drift has been shown to be near zero for post-tensioned connections [17] and self-centring energy-dissipative (SCED) braces [19]–[21] at large deformations. The SMAs offer recentring and moderate dissipation in the same material [22]. In contrast to passive dampers, semi-active MR dampers are capable of varying the yield stress of a controlled fluid between bounds of passive-off and passive-on force envelope that is desirable for hybrid control in case of failure of control [23], [24].

4.4 Seismic Isolation

Isolation increases the fundamental period and localises the deformation at the interface of the isolation, which decreases the superstructure acceleration and drift [25]. However, when subjected to near fault pulses the displacement of the isolator can be very large, while an increase in isolation damping will decrease the displacement of the bearings but may increase the accelerations transmitted to the superstructure [26]. That is why isolation is typically combined with dampers, as it creates the trade-off.

5. Hybrid Configurations and Working Principles

5.1 Device-Level Hybrids

At the device level, two mechanisms are housed together in the same casing or brace, either in parallel (both mechanisms experience the same displacement and force combination is additive) or in series (both mechanisms experience the same force and displacement is additive). This type of viscous–metallic unit operates on the fluid path at any amplitude and springs into action when the drift is larger, as in Fig. 2(f). Vargas and Bruneau demonstrated that the viscous damping of a frame with metallic fuses (when combined with the viscous damping) decreases the displacement demand, but this effect is subject to the ratio of the fuses strength [27]. For a nine-storey steel framed structure, Marshall and Charney used a hybrid of buckling-restrained braces and high damping rubber or viscous devices and concluded that the hybrid performed better than conventional braces and the damping devices with some indices, such as member force, went against the hybrid [28]. In the Indian studies, viscoelastic–friction devices which are used as a single unit for both wind and seismic intensities have been developed [29].

5.2 System-Level Hybrids

Hybrids at the system level are those that distribute various devices throughout a structure. For isolated structures subjected to pulse-type motion, Makris and Chang demonstrated that relatively small friction can effectively decrease displacement, but can increase base shear and offset; they suggest to use friction-type force in combination with viscous force [30]. Studies under isolation plus damper conditions have also verified that the stroke of the isolators can be effectively reduced under near-fault motion, but at the expense of an increase in the acceleration of the superstructure [31, 32]. Kam et al. investigated the advanced flag-shaped system that incorporated self-centring, hysteretic and viscous dissipation and showed that better results can be obtained when near-fault records are used [33]. More recently, design methods have been suggested for the braced frame structure where self-centring braces are used in conjunction with fluid viscous braces [34, 35] and finite-element models have been used to parameterise hybrid self-centring dampers [36]. Selected studies are summarised in Table II.

TABLE II LITERATURE MATRIX OF REPRESENTATIVE HYBRID DAMPING STUDIES

Study	Combination	Host / input	Key observation relevant to this review
Makris & Chang [30]	Isolation + viscous / friction	Isolated SDOF; pulses	Low friction plus viscous force reduces displacement without large base-shear rise
Jangid & Kelly [26]	Isolation damping levels	Isolated building; near-fault	Optimum isolation damping exists; more damping raises acceleration
Vargas & Bruneau [27]	Metallic fuse + viscous	SDOF / frames	Viscous path reduces drift of fused system; benefit depends on fuse strength
Kam *et al.* [33]	Self-centring + hysteretic + viscous	SDOF; 20 near-fault records	Combined dissipation improved peak and residual indices
Marshall & Charney [28]	BRB + viscous / rubber	9-storey steel frame; IDA	Hybrid improves drift; some indices move against it
Erochko *et al.* [21]	Tendon restoring + friction	Full-scale brace test	Full recentring to 1.5 % drift; fabrication tolerance governs small-amplitude response
Addala *et al.* [29]	Viscoelastic + friction	6-storey RC frame	Single device effective for wind and seismic levels

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Qiu *et al.* [34]	Self-centring + fluid viscous braces	Steel braced frames	Viscous braces reduce acceleration left by self-centring braces
Mazloum *et al.* [32]	Isolator + damper	MDOF and 2DOF models	Hybrid mitigates near- and far-field demands

5.3 Passive–Semi-Active Hybrids

Passive–semi-active hybrids are those that have a passive baseline and an MR or variable-orifice device with a tuned force through a control law [23,24]. Reductions, reported, heavily rely on the control algorithm, delay and power reliability of the sensors [4], [8]. As for common building construction, it cannot be taken for granted that the power will not be interrupted during shaking, so the rest of this review focuses on passive–passive pairings.

6. Seismic Performance of Hybrid Systems

6.1 Reported Response Reductions

These ranges of response reduction in the major hybrid families can be combined into a single figure, as done in Fig. 3, relative to the uncontrolled or single-device case. The viscous–metallic braces are reported to reduce peak drift by 30-60 %, and the base shear by 25-50 %; the friction-based braces by 35-70 % in drift, and can be sensitive to the slip load; and the isolation-plus-damper systems by 50-70 % in drift compared to fixed-base construction. The residual drift is found to be smallest for self-centering hybrids, but relatively small acceleration advantage, while passive–MR systems exhibit the largest scatter, depending on the control law. The bands overlap because the studies vary in height, record suite, modelling assumptions and, importantly, the reference case: they are an order-of-magnitude map but not a design value.

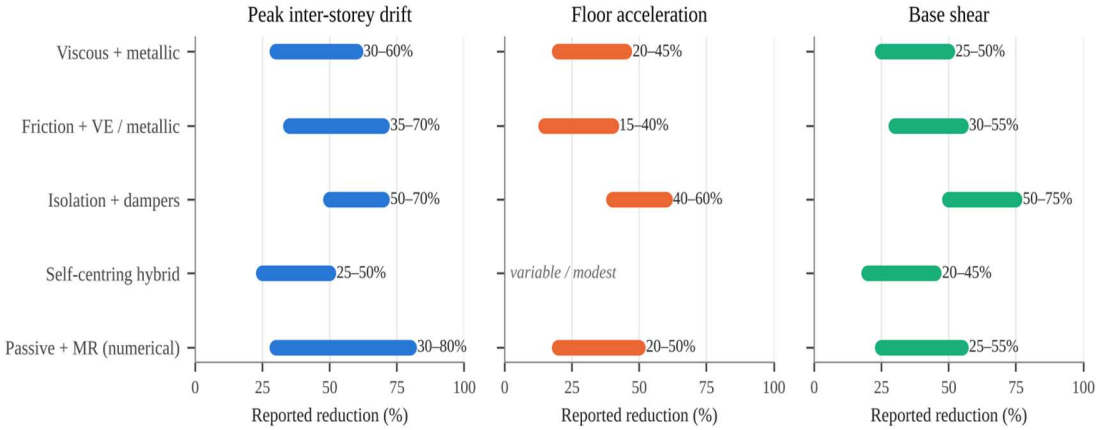

Fig. 3. Ranges of response reduction reported in the literature for selected hybrid configurations relative to the uncontrolled or single-device reference, compiled from the studies reviewed in Sections 4–5.

6.2 Near-Fault and Long-Duration Excitation

Near-fault pulses prefer displacement dependent and restoring paths because long period pulses spend a lesser amount of time at high velocity, and fluid paths work best under many moderate cycles [9], [30]. Single devices can thus swap places in order of motion classes. The other issue with long-duration shaking is cumulative energy in a fluid chamber, and therefore cumulative heating, increases with the number of cycles if peak drift is low. Many published hybrid studies use only a far-field suite, or spectrally match records by removing the pulse, and only a few report cumulative device energy [37]. If not tagged by the motion class, then the reduction figure is not safe to move to a site with a different hazard.

6.3 Residual Drift and Recentring

Residual drift is the most distinguishing index for hybrid assemblies. A fluid damper disappears at zero velocity and is unable to pull a yielded frame back, while a metallic fuse will unload on a steep slope, and will leave a plastic offset. There are also devices that can achieve similar recentring with SMA [22] and [35] that produce a force towards the origin [18] with self-centring braces and post-tensioned connections. Therefore, residual drift should be considered a separate performance claim that should have a different acceptance band than peak drift is given.

6.4 Proportioning and Placement

The mix of the paths and the location of devices will affect hybrid performance. Too high friction or too much metal can prevent the assembly from opening and will make its

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partner dormant, and too little friction or too much clearance between the second path will never allow the assembly to open. A placement study of viscous dampers reveals that all viscous dampers in lower storeys can result in transfer of demand to storeys without dampers [11]. These questions are multiplied for hybrids as they are related to force-share, engagement threshold, placement and stiffness of the connection, but most of the publications fix these parameters at one value, not mapping their influence.

7. Design Codes and Implementation Challenges

Structures with damping systems and isolated structures are covered in separate chapters of ASCE/SEI 7-22 where upper bound properties and lower bound properties of devices must be provided, and prototype and production testing and independent design review [2] must be performed. In Europe, EN 15129 establishes performance and testing standards for anti-seismic devices, such as viscous, displacement-dependent and isolation devices [38]. A similar procedure for sizing supplemental dampers does not exist in Indian standards (with IS 1893 (Part 1): 2016 utilizing the seismic zonation and design spectrum found in India) [1], and none of these codes specify how much force to allocate to two paths in a single damper, an acceptable engagement threshold, or how to review the path-wise energy. Some of the practical difficulties are: Limited full-scale testing of integrated hybrid packages, capacity verification requirements for joint and gusset at the force the system can deliver when under pulse-type motion, the need for fuse replacement after an event, ease of access for inspection and the lack of priced life-cycle data [6].

8. Research Gaps and Future Directions

The reviewed literature is broken down into each mechanism, each host, and each motion class and response quantity, and areas are identified where there are dense and sparse areas. The major gaps to research directions are plotted in Table III.

TABLE III RESEARCH GAPS AND CORRESPONDING RESEARCH DIRECTIONS

No.	Gap identified in the literature	Research direction
1	Hybrids are usually compared with the unequipped structure, not with their own parent devices	Adopt a comparison rule that holds the first-path coefficient constant so that any increment is attributable to the added path
2	Reported benefits rarely labelled by ground-motion class	Analyse far-field, near-fault pulse and long-duration suites separately and report class-labelled medians
3	Residual drift treated as secondary to peak drift	Set separate residual-drift targets and verify recentring under aftershocks
4	RC frames, wall-frames and highway overpasses under-represented	Study multiple host typologies, including beam–column joint and pier-cap checks
5	Force-share, threshold and placement fixed at single values	Parametric and multi-objective optimisation of proportioning, placement and connection stiffness
6	Robustness to property variation and ageing rarely tested	Upper/lower-bound and mixed property surfaces, incremental dynamic analysis [39]
7	No Indian design sequence for two-mechanism devices	Develop a stepwise design and checking procedure consistent with IS 1893
8	Few full-scale tests of integrated packages	Component and shake-table testing of hybrid devices with realistic connections

There are three directions that deserve stressing. The first step in the complimentarity test is to prove it—not assume it: A hybrid is justifiable only if it enhances an index that its superior parent cannot; the energy expended in the second path should be reported to verify its functionality. Second, recommendations should be typology-specific, and the index that carries the hybrid benefit varies by frame type (wall-frames and isolated bridges). Third, guidance on the design process should be explicitly presented in a checking sequence, in advance of the availability of certified hybrid packages, including explicit checks to the joint force, connection stiffness and residual drift.

9. Conclusions

This review article first explored the constitutive behaviour of the individual devices of hybrid damping systems employed in earthquake resistant structures, and then focused on their performance, design provisions and open questions. The main conclusions are as follows:

1. The justification of hybrid systems is that they control a portion of the seismic demand and the other portion is controlled by a second dissipation

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mechanism; the second path may enhance an index that is not being controlled by the first path, such as residual drift in a fluid damper, or floor acceleration in a metallic fuse.

2. There is an encouraging level of reported reductions in peak drift of approximately 30-70 %; however, it is not directly comparable as studies vary in host species, record suite and, most importantly, reference case.
3. The performance of hybrid systems is rank dependent: the results of the far field motion may not apply to near fault pulses or long duration shaking.
4. Self-centring hybrids are most effective in meeting the various residual drift and recentring performance claims and these performance claims have their own acceptance criteria.
5. The Indian procedure of design is missing and the codes do not yet cover issues of isolation and dampers individually, nor do they cover issues of force sharing, engagement threshold or path-wise energy in a two-mechanism device.

Future research needs to be based on class labelled nonlinear analysis of various structural typologies, parent referenced comparison, parametric optimization and physical testing to propose a practical design procedure for hybrid damping in Indian and international practice.

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