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Multi-objective Performance Based Control of Building Frames during Wind and Earthquake Events for Multi-Hazard Mitigation using a New Hybrid Passive Energy Dissipation Device

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Abstract **–** The paper presents a performance based design approach employing a new hybrid passive energy dissipation (PED) device for multipurpose vibration control of Reinforced Concrete (RC) building frames in a multi-hazard environment subjected to critical wind and earthquake events. A versatile and innovative hybrid PED device is proposed in the present study for controlling a broad range of wind and earthquake induced structural vibrations in a multi-hazard scenario. The proposed hybrid PED device implements a novel combination and assembly of viscous and friction elements along with a slip-lock element for controlling the low as well as high amplitude structural vibrations by dissipating the input wind or seismic energy in both low and high intensity multi-hazard events. The viscous element in the hybrid PED device reduces the structural response from the onset of structural vibrations during mild to moderate wind or earthquake events in which the friction element remains inactive. On the other hand, the friction element in the hybrid PED device is activated only in the event of extremely strong winds or severe earthquakes that surpass the slip load of the friction element. Simulated case studies are conducted to numerically evaluate the efficacy of the proposed new hybrid PED device for performance based structural control of RC building frames subjected to a wide range of wind and earthquake induced excitations. Preliminary results of the numerically simulated case studies presented in the paper demonstrate that in principle, the proposed hybrid PED device can be designed using an Energy based plastic design method in the performance based design (PBD) framework for effectively controlling the vibration response of building frames under the action of dynamic wind and earthquake loads within the respective limiting values recommended by published design standards on performance based wind engineering and performance based earthquake engineering of buildings for various performance limit states and hazard levels.

Keywords: Passive Control, Performance based Design, Performance based Wind Engineering, Energy Dissipation Device

1. Introduction

The present study proposes a new hybrid passive energy dissipation (PED) device developed by Madan and Bhalla 2013 [1] for multipurpose vibration control of building frame in a multi-hazard environment susceptible to both earthquake events and wind. Natural hazards such as severe earthquakes and strong winds have been known to cause widespread disaster and damage to building infrastructure resulting in loss of life and property in many regions of the world [2, 3]. Multi-hazard environments are characterized by infrastructure facilities that are vulnerable to multiple natural and accidental hazards that are generally mutually exclusive as they are unlikely to occur concurrently, but are probable to occur at different stages during the serviceable life of the building structures. While there is a large variation in the individual attributes of events caused by different hazards, their resulting effects on the infrastructure are similar. As an example, events induced by seismic hazard vary considerably from events due to wind hazard in terms of the duration, intensity, frequency content and return period of the event. However, the consequences of either earthquake or wind events are identical, such as structural damage and possible loss of life or at least interruption of services and financial costs due to functional downtime and damage requiring costly and time consuming repair before the building can be reinstated to service.

The traditional force based structural design methods prescribed by contemporary standard codes of design practice treat the strength demands for the seismic and wind events separately. The more critical event among the earthquake and wind hazards that imposes the larger strength demand will govern the structural design. Thus, the conventional code prescriptive force based design methodology of considering only the most demanding event among the various potential hazards for the final design implicitly assumes that individual probabilities of the strength demands exceeding the specified limiting values of strength capacities are the same for different hazards. However, the specific design criteria and requirements that need to be fulfilled for a single hazard with the most demanding design event that governs the structural design may conflict with or overlook the design requirements for other hazards. When subjected to a design event due to a different hazard, the structures may not behave predictably nor perform satisfactorily. Moreover, the prevalent code prescriptive force based structural design approach does not evaluate the inelastic displacements of the structure, an inherent limitation of the force based design methodology [4]. The above mentioned limitations of the prevalent force based design philosophy motivated the application of performance based design paradigm for earthquake resistant design of structures towards the end of the previous century. Performance based design (PBD) is inherently a displacement based design technique in which the performance based seismic design (PBSD) criteria based on the earthquake resistant design philosophy is defined as a set of desired performance objectives termed as performance limit states i.e. Immediate Occupancy (IO), Life Safety (LS) and Collapse Prevention (CP) that need to be fulfilled by the structure when subjected to various stipulated seismic hazard levels [4, 5, 6, 7, 8]. In recent years, performance based design (PBD) for wind engineering has gained significance in the emerging structural design philosophy and few performance based wind resistant design (PBWD) frameworks have been proposed by researchers in last two decades [9, 10, 11, 12]. Recently, a pre-standard for performance-based wind design ASCE 2019 [13] was published in which performance objectives for PBWD were expressed in terms of rational performance limit states for wind events i.e. occupant comfort, operational and continuous occupancy and limited interruption for various levels of wind induced excitation and corresponding quantitative acceptance criterion.

Multi-hazard design of infrastructure facilities accounts for more than one natural and / or accidental hazards for purposes of structural design accounting for the interdependence and interaction of the multiple hazards that may occur concurrently or cumulatively in the design life of the structure. As earthquakes and winds have distinctly different attributes in terms of their dynamic characteristics, return intervals and nature of dynamic loading on the structure, a multi-hazard design for both earthquake and wind events necessitates the implementation of new design techniques in the performance based design (PBD) framework and / or application of passive structural control devices for multi-hazard mitigation. Further, since different dynamic response parameters such as maximum deflection, inter-storey drift, peak relative velocity and maximum absolute acceleration are used to quantify the various performance limit states in PBD for earthquake and wind hazards, a displacement based analysis paradigm is necessary for a rational multi-hazard design for these two hazards. As an example, absolute accelerations and velocities of the structure dictate the serviceability limit state for performance based wind resistant (PBWD) design. On the other, maximum deflections and inter-story drifts govern the damage control limit state for performance based seismic design (PBSD). For purposes of multi-hazard structural design, it may be necessary to optimise both the response quantities, however, controlling drifts as well as absolute accelerations are generally competing and conflicting objectives. Structural design and structural control strategies that reduce drift, for example, may result in a significant increase in absolute acceleration and vice versa. The conflicts between performance objectives in structural design and the disparities in structural performance between events of different types of hazards, encountered in the present practice of exclusively considering only the most demanding hazard to dictate the final structural design, have recently led to the development of the more inclusive multi-hazard design paradigm [14, 15, 16].

A unifying physical factor that governs the dynamics of a structure in both earthquake events and wind events is the input kinetic energy imparted by the event to the structure, i.e. the seismic energy and wind energy transferred to the structure as kinetic energy in each event, although the mechanism of energy transfer to the structure is conceptually different in the two events. Once the input kinetic energy due to the earthquake or wind event is transferred to the structure, the structure oscillates or vibrates thus converting the input kinetic energy to potential energy. While undergoing forced vibrations, the structure may remain elastic continuously interchanging the structural energy back and forth between potential energy and kinetic energy, thus resulting in large structural accelerations and velocities. In case the structural deflections or inter-storey drifts exceed the elastic limits of the structural elements in the course of forced vibration response, the input kinetic energy the event must either be absorbed by structure by undergoing large inelastic excursions in the plastic range of displacements thus resulting in structural damage or, alternatively, the input energy must be dissipated by a supplementary energy dissipation device. While the former physical phenomenon exhibited by an elastic structure may violate the serviceability performance limit state in the event of occasional high winds, the latter physical phenomenon in the inelastic range of structural response may violate the damage control limit state in the event of rare and severe earthquakes. Hence, the only conceivable alternative for multi-hazard mitigation for both wind and seismic events that is also viable for reconciling the conflicts between performance objectives in wind engineering and earthquake engineering of structures is the application of structural control technology using passive energy dissipation (PED) devices. In view of the above-mentioned conflicts between the structural performance objectives in events of different hazard types, PED devices promise significant potential for enhancing the structural performance in a multi-hazard environment.

A comprehensive state-of-the-art review of structural control technology till the twentieth century was presented by Spencer Jr, et al., 2003 [17] and Symans et al., 1999 [18]. A review of the subsequently reported research studies on passive structural control indicates that several passive structural control devices have been investigated by researchers in the field of earthquake engineering [19, 20, 21, 22] for seismic hazard mitigation. However, most of the proprietary passive structural control devices reported in the literature such as tuned mass dampers, viscous fluid dampers, viscoelastic dampers, friction dampers and base isolation systems are designed to control either earthquake or wind induced structural vibrations and were thus proposed for mitigation of either earthquake hazard or wind hazard exclusively [21, 22, 23, 24, 25, 26]. There is a need for more innovative and versatile passive control devices that can be effectively designed for vibration control of building structures in both earthquake and wind events for multi-hazard mitigation. Recently, Madan et al. 2013 [1] developed and proposed a new hybrid passive energy dissipation device for multi-objective or multipurpose vibration control of building frames [1] in a multi-hazard environment vulnerable to both earthquake events and wind events with large variations in magnitudes and intensities. The conceptual design of the new hybrid PED device [1] is described in the following section of the paper.

2. Conceptual Design of New Hybrid Passive Energy Dissipation Device

The hybrid passive energy dissipation device proposed in the present study for multipurpose vibration control of building frames integrally combines viscous and friction elements for controlling the low as well as high amplitude structural vibrations by dissipating the input seismic or wind energy in both low and high intensity earthquake events and wind events. Figure 1 illustrates the conceptual design and generic configuration of the new hybrid PED device [1]. The figure depicts the integrated assembly of the hybrid PED device as consisting of three salient mechanical components: a viscoelastic (VE) element with two identical friction elements that are all connected in parallel between common rigid end plates. In order to achieve a symmetrical action of the hybrid PED device, the two friction elements are installed symmetrically with respect to the viscoelastic element with one friction element on each side of the viscous element. As shown in Figure 1, a locking mechanism that can be idealized as a slip-lock element is inserted between the friction element and the rigid end plate in series with each of the two friction elements at their same ends. The other end of both the friction elements is connected directly to the rigid plate at that end. The viscous element is connected directly to the rigid end plates at both ends.

The conceptual design of the new hybrid PED device shown in Figure 1 incorporating the unique combination and assembly of the viscoelastic element and two friction elements with the slip-lock element (a one-time locking mechanism) in a single hybrid PED device theoretically results in a two phase operation of the device: Phase 1 in which only the viscoelastic element deforms and functions to dissipate the input wind or seismic energy while the friction elements remain non-functional acting as simple braces during mild to moderate seismic events until the hybrid device reaches a threshold displacement u□ in either direction (Figure 1), at which the one-time locking mechanism is activated i.e. the slip-lock elements lock by means of a spring loaded key and; Phase 2 after the locking mechanism is activated and the friction elements begin to perform their intended function by dissipating input kinetic energy along with the viscoelastic element once the static frictional force due to static friction in the friction element is exceeded by the externally applied load. When the external load applied on the friction element exceeds a threshold value termed as the slip load of the friction element in the event of severe or rare seismic and wind events, the friction elements also deform to dissipate the input seismic or wind energy. It is worthwhile to note here that the performance based design parameters of the new hybrid PED device proposed in the present study on multipurpose vibration control of building frames in a multi-hazard environment susceptible to wind and earthquake events are the damping coefficient of the viscoelastic element, maximum frictional force due to static friction in the friction element of the hybrid device or the slip load for the friction element, displacement u□ at which the slip-lock element (locking mechanism) of the hybrid device locks and the maximum stroke or displacement capacity of the hybrid PED device.

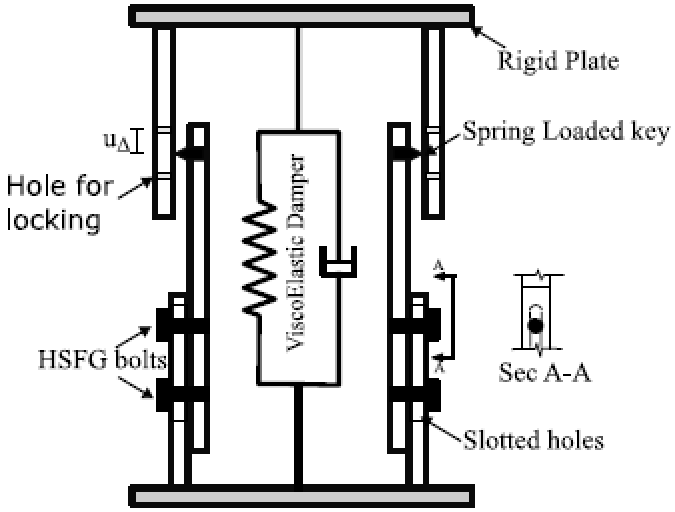


Fig. 1: Schematic diagram for conceptual design of new hybrid passive energy dissipation device [Madan and Bhalla (2013)]

3. Numerically Simulated Case Studies on Practical Reinforced Concrete Building Frames

The practical reinforced concrete (RC) frame building considered in the present research for the numerically simulated case studies is a RC frame structure with a symmetrical plan with five bays of 5.0 m span each in either direction and a regular elevation that is proposed to be constructed as an office building in the highest seismicity zone (zone V) and a cyclonic region along the coastline of India. The elevation of the RC frame building has a story height of 4.2 m at the ground levels and uniform story heights of 3.2 at higher levels without any soft or weak story in the building. For purposes of numerical simulation, the RC frame building is idealized as equivalent two-dimensional plane frames in each principal orthogonal direction, a reasonable assumption for buildings with rectangular plans and regular elevation. The vertical gravity loads (dead load and live load) acting on the tributary area of any individual idealized planar frame are considered as equivalent uniformly distributed loads applied on the equivalent 2-D plane frame model. Three different frame elevations of six (6) stories, fifteen (15) stories and sixty (60) with total heights of 20.2 metres, 49 metres and 193 metres, respectively, were considered for the numerical case studies. A typical elevation of the idealized plane frame considered in the numerically simulated case studies is shown in Figure 2. Three different cases were considered for each elevation of the RC frame building to demonstrate the efficacy of the proposed new hybrid passive device in multi-hazard mitigation for the building frames in a multi-hazard environment susceptible to only wind events and earthquake events. The three diverse cases considered for numerical simulations were: (a) uncontrolled RC frame buildings without hybrid PED devices designed to comply with force-based design criteria (Table 1) of the prevalent Indian Standard Codes of design practice for earthquake resistant design [27] and wind resistant design of buildings [28]; (b) uncontrolled RC frame buildings without hybrid PED devices designed using the plastic design method [29] based on the energy balance concept [30] for performance based seismic design (PBSD) of RC building frames; and

(c) RC frame buildings controlled by implementing new hybrid PED devices designed using the plastic design method based on energy balance concept for PBSD and PBWD of RC building frames implemented with PED devices [31].

The displacement based seismic analyses of the uncontrolled and controlled RC building frames for PBSD of the RC RC frames were performed using the OpenSees software framework for inelastic dynamic analysis (IDA) of the RC frames frames under the action of recorded and synthetic earthquake ground motions. Details of the code prescriptive seismic design design of the RC building frames in compliance with prevalent code-specified force based seismic design criteria using the the SAP software and plastic design methodology based on the energy balance concept for PBSD of uncontrolled and controlled RC building frames as well as numerical modelling of uncontrolled and controlled RC building frames for nonlinear dynamic time-history analysis of the RC frames subjected to earthquake ground excitations using the OpenSees software for IDA may be found elsewhere [31]. The occupancy of the case study RC buildings has been considered as risk category II and risk category III specified by ASCE 7 Pre-standard [32] for earthquake and wind resistant design, respectively, of the case study buildings in compliance with the current code prescriptive force based design criteria using the SAP software. A 500 mm thick RC shear wall had to be provided in the centre bay of the 60-story building structures to check the code specified limitations on drifts and top displacements of the tall buildings.

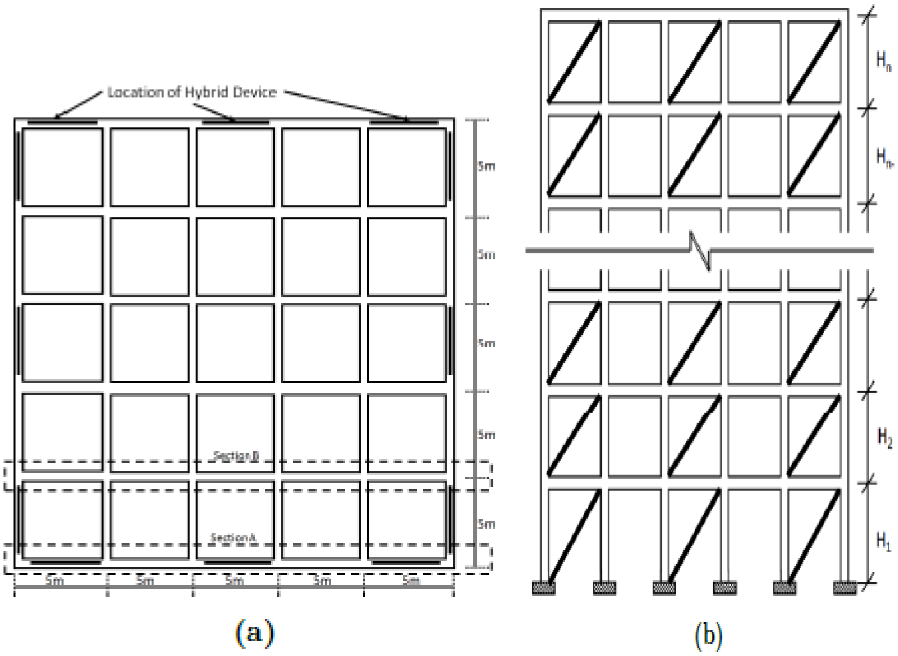


Table 1: Code-prescriptive Parameters
***Seismic Design Parameters [27]*:**
Seismic Zone – V (highest seismicity zone)
Importance Factor – 1.5 (important building)
Response Reduction Factor-5.0(ductile frame)
Occupancy or Function – Office Building
Soil type – Medium (Type II)
Damping Ratio – 5 %
***Wind resistant Design Parameters [28]*:**
Basic wind speed – 47 m/s
Mean Probable Design Life – 100 years
Terrain Category – 2 (open terrain)
Topography - flat
Region – Cyclonic winds

Fig. 2: Typical framing (a) plan and (b) elevation of the multi-story RC building frame considered in the numerical case studies

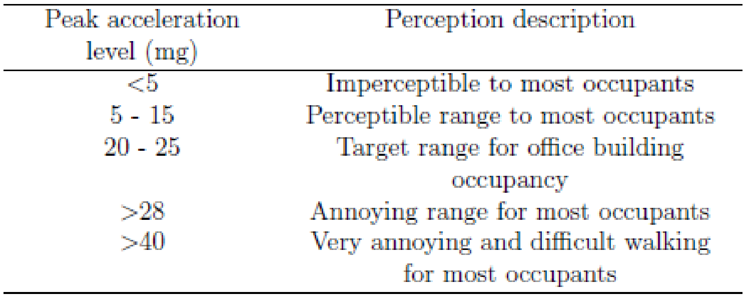
Ten different earthquake ground motions recorded within 25–50 km of the seismological faults with reverse, normal, and strike-slip mechanisms, with Richter scale magnitudes ranging from 6.5 to 7.3.were selected for the displacement based seismic analysis of the RC building frames using IDA. The ground motion records were then scaled to ensure that the average intensity measure (IM) of the ground motion group and the specified level of earthquake hazard are compatible. Each ground motion is scaled to a peak ground acceleration (PGA) equal to the design based earthquake level using the seismic design response spectrum for the highest seismicity Zone V as per the Indian seismic design code [27] with a PGA of 0.18 g. The soil at the building site is considered as medium soil classified as soil type II [27] with a shear-wave velocity ranging from 300 to 750 m/s. Details of the seismic design parameters for the code prescriptive force based seismic design of the RC building frames as well as methodology for generation of the earthquake ground acceleration time-histories considered for displacement based seismic analysis of RC frames using the OpenSees software for incremental dynamic analysis (IDA) in the numerical case studies have been reported elsewhere [31]. The recorded earthquake accelerograms that were selected from the database of the Pacific Earthquake Engineering Research Center [33] for the nonlinear dynamic time-history analysis of the RC frames were mostly near-field or near-fault ground motion records since near-field earthquakes have observed to cause serious damage to long-period structures such as tall building [34] due to the long period velocity in near-field earthquake ground motions that are liable to a generate a shock wave propagation in long period structures.

For purposes of performance based wind resistant design (PBWD) of the RC building frames considered in the case studies, the input kinetic energy imparted to the building frames by the wind events was formulated and computed using the classical Bernoulli equation for total energy in a flow of incompressible fluids (Bernoulli's theorem), which also constitutes the fundamental basis of the code-specified equation for calculating the design wind pressures on buildings. The power spectral density function of longitudinal wind velocity fluctuations [35, 36] was used to generate the along-wind speed time-histories along the height of the building for the nonlinear dynamic time history analysis of the RC building frames subjected to wind induced excitations. Details of plastic design methodology based on the energy balance concept for PBWD of uncontrolled and controlled RC building frames and numerical modelling of uncontrolled and controlled RC building frames for nonlinear dynamic time-history analysis of the RC frames subjected to wind induced excitations as well as the methodology for generation of random time variant wind speed data sets for the displacement-based along-wind dynamic response analysis of the RC frames using the OpenSees software for incremental dynamic analysis (IDA) may be found elsewhere [31].

4. Integrated Plastic Design Methodology for Performance based Seismic and Wind Engineering

Structural performance of the low to high-rise RC building frames during wind events was assessed by comparing the IDA results of global dynamic response of the building structure with an acceptance criteria adopted from a performance based wind engineering (PBWE) framework published by ASCE 2019 and Mohammadi et al. 2019 [37]. The PBWE framework identified three levels or limit states of performance for wind events based on the intensity of wind induced excitations: a) continuing occupancy level in which the structure must remain elastic while the floor accelerations remain within the target serviceability range recommended in Table 2 for occupant comfort during frequent events with mean return intervals (MRI) of less than 10 years; b) operational wherein the structure remains elastic and serviceable for occasional winds with MRI of less than 50 years; and c) limited interruption level in which the structure and components may undergo inelastic excursions within limited nonlinear range of deformations and forces in rare wind events. The intensity of severe and rare wind events was quantified in statistically in terms of MRI of 300, 700, 1700, and 3000 years as per ASCE 41 with immediate occupancy as the target performance level. For performance based seismic design (PBSD), the seismic performance levels i.e. operational, immediate occupancy, life safety and collapse prevention limit states are quantified in terms of the limiting inter-story drift ratios for RC frames as per FEMA 356. The hazard levels of seismic events are statistically defined in terms of probabilities of exceedance: 50% in 50 years, 20% in 50 years, 10% in 50 years, and 2% in 50 years. Structural performance for purposes of both PBWE and PBSD are expressed in the present study in the form of a performance matrix of different combinations of performance levels and wind or earthquake hazard levels. The risk categories of buildings assumed in the present study for PBWE and PBSD were Risk category III and Risk category II, respectively, based on ASCE 7 specifications of risk categories designated to buildings depending on the importance of function and occupancy of a building.

Table 2: Serviceability criteria related to motion comfort (Mohammadi et al. 2019)

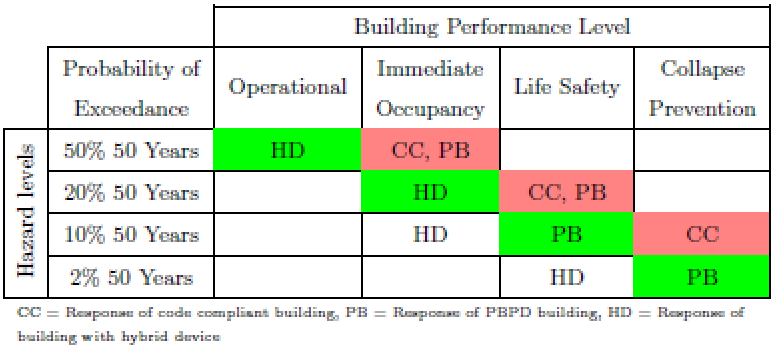


Peak acceleration level (mg)	Perception description
<5	Imperceptible to most occupants
5 - 15	Perceptible range to most occupants
20 - 25	Target range for office building occupancy
>28	Annoying range for most occupants
>40	Very annoying and difficult walking for most occupants

5. Results of Numerical Case Studies on Uncontrolled and Controlled RC Building Frames

For sake of brevity, the paper presents very limited and representative results of the numerically simulated case studies on the assessment of structural performance of RC building frames with three different frame elevations of 6, 15 and 60 storeys of total heights of 20.2 metres, 49 metres and 193 metres, respectively, implemented with the new hybrid PED device for passive structural control and designed using the proposed integrated performance based plastic design (PBPD) methodology based on the energy balance concept for performance based wind engineering (PBWE) as well as performance based seismic design (PBSD) in a multi-hazard environment susceptible to critical wind as well as earthquake events. For purposes of comparison, uncontrolled RC building frames without the new hybrid PED device were also simulated in the numerical case studies that were designed using either the code prescriptive force based design procedure or the proposed integrated performance based plastic design (PBPD) methodology for wind and seismic hazards. Table 3 displays the seismic performance matrix illustrating the comparison of structural performance of the controlled 6 storey and 15 storey RC building frames implemented with the new hybrid PED device designed using the proposed integrated performance based plastic design (PBPD) methodology based on the energy balance concept for controlling earthquake (as well as wind) induced vibrations with respect to the corresponding uncontrolled RC building frames without the hybrid PED device. Similar comparisons for the 60 storey RC building frames are illustrated by the seismic performance matrix presented in Table 4. It may be noted that the green coloured cells in the seismic performance matrices presented in Tables 3 and 4 signify acceptable or desired seismic performance as per FEMA 356 standards, while the pink coloured cells represent unacceptable or undesired seismic performance.

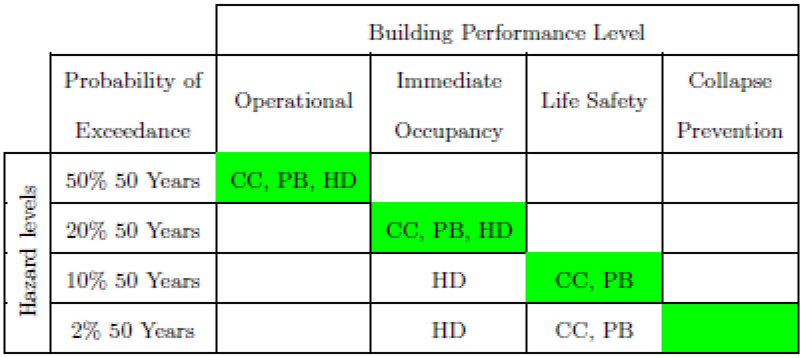
Table 3: Seismic response of 6- and 15- storey buildings



		Building Performance Level			
	Probability of Exceedance	Operational	Immediate Occupancy	Life Safety	Collapse Prevention
Hazard levels	50% 50 Years	🟩 HD	🟥 CC, PB		
	20% 50 Years		🟩 HD	🟥 CC, PB	
	10% 50 Years		HD	🟩 PB	🟥 CC
	2% 50 Years			HD	🟩 PB

CC = Response of code compliant building, PB = Response of PBPD building, HD = Response of building with hybrid device

Table 4: Seismic response of 60- storey buildings

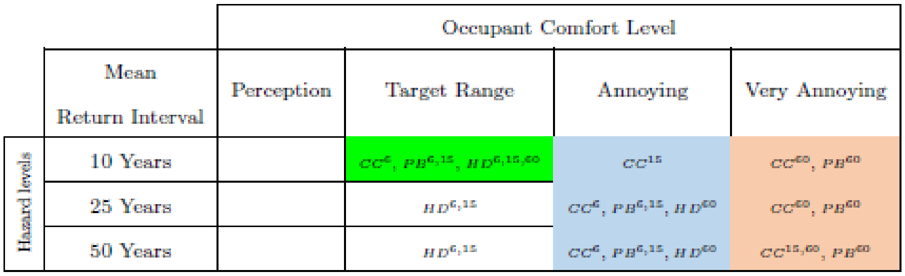


		Building Performance Level			
	Probability of Exceedance	Operational	Immediate Occupancy	Life Safety	Collapse Prevention
Hazard levels	50% 50 Years	CC, PB, HD			
	20% 50 Years		CC, PB, HD		
	10% 50 Years		HD	CC, PB	
	2% 50 Years		HD	CC, PB	🟩

CC = Response of code compliant building, PB = Response of PBPD building, HD = Response of building with hybrid device

Table 5 presents the performance matrix for wind hazards that illustrating the comparison of structural performance in terms of the occupant comfort level of the controlled 6, 15 and 60 storey RC building frames during wind events of three different hazard levels with mean return intervals (MRI) of 10, 25 and 50 year implemented with the new hybrid PED device designed using the integrated performance based plastic design (PBPD) methodology based on energy balance for controlling wind induced vibrations within the continuing occupancy and operational performance limit states with reference to the corresponding uncontrolled RC frames without the hybrid PED device.

Table 5: Peak acceleration response of 6-, 15-, and 60- storey building subjected to wind loading



		Occupant Comfort Level			
	Mean Return Interval	Perception	Target Range	Annoying	Very Annoying
Hazard levels	10 Years		CC^{6}, $PB^{6,15}$, $HD^{6,15,60}$	CC^{15}	CC^{60}, PB^{60}
	25 Years		$HD^{6,15}$	CC^{6}, $PB^{6,15}$, HD^{60}	CC^{60}, PB^{60}
	50 Years		$HD^{6,15}$	CC^{6}, $PB^{6,15}$, HD^{60}	$CC^{15,60}$, PB^{60}

CC^{n} = Response of code compliant building with n storey, PB^{n} = Response of PBPD building with n storey, HD^{n} = Response of building with hybrid device with n storey

6. Concluding Remarks

The present study proposes a new hybrid passive energy dissipation (PED) device for multipurpose vibration control of building frames in a multi-hazard environment susceptible to both earthquake events and wind events of varying magnitudes and intensities. The proposed new hybrid PED device [1] implements a novel combination and assembly of viscoelastic and friction elements for controlling the low as well as high amplitude structural vibrations by dissipating the input seismic or wind energy in both low and high intensity earthquake events and wind events. Results of the numerically simulated case studies. The paper presents the conceptual design of the new hybrid PED device [1] that combines viscous and friction elements along with a slip-lock element (locking mechanism) wherein only the viscoelastic elements function at low wind or earthquake loads to control the low-amplitude structural vibrations due to mild to moderate multi-hazard events (in which the friction element remains non-functional), whereas the friction elements are activated to control the structural vibrations only for large external dynamic loads during severe multi-hazard events, once the lateral external load on a friction element exceeds the maximum static frictional force (slip load) in the friction element. Numerically simulated case studies were performed in the present research to demonstrate the working principle of the new hybrid PED device. Limited preliminary results of the numerically simulated case studies presented in the paper can be interpreted to conclude that, in theory, the new hybrid PED device can be effectively designed designed by the integrated performance based plastic design method using the energy balance concept for controlling the the vibration response of building frames under the action of wind and earthquake induced excitations within the respective respective limiting values for various target performance limit states and hazard levels prescribed by the published design design standards on performance based wind engineering and performance based earthquake engineering of building structures.

References

[1] Madan, A. and Bhalla S. (2013), "A Hybrid Passive Energy Dissipation Device for Multipurpose Vibration Control of Tall Buildings", Indian Patent No. 407996, Filed July21, 2013 (Application no. 859/DEL/2013), Published June 26, 2015.

[2] Kappes, M. S., Keiler, M., von Elverfeldt, K., and Glade, T. (2012). "Challenges of analysing multi-hazard risk: a review." *Natural hazards*, vol. 64, no. 2, pp. 1925–1958, 2012.

[3] Bruneau, M., Barbato, M., Padgett, J. E., Zaghi, A. E., Mitrani-Reiser, J., and Li, Y. (2017). "State of the art of multihazard design." *Journal of Structural Engineering*, vol. 143, no. 10, pp. 03117002, 2017.

[4] Kunnath, S. (2005), "Performance-based Seismic Design and Evaluation of Building Structures", in *Earthquake Engineering and Structural Design*, W.F. Chen and E.M. Lui, Ed.: CRC Press, 2005,

[5] FEMA 356 (2000). "Prestandard and commentary for the seismic rehabilitation of buildings." Federal Emergency Management Agency, Washington, DC.

[6] FEMA 445 (2006). "Next-generation performance-based seismic design guidelines: program plan for new and existing buildings".

[7] ASCE 41 (2017). "Seismic evaluation and retrofit of existing buildings." Prepared by the American Society of Civil Engineers, Reston, Virginia, USA.

[8] Ghobarah, A., "Performance-based design in earthquake engineering: state of development." *Engineering Structures*, vol. 23, no. 8, pp. 878–884, 2001.

[9] Ciampoli, M., Petrini, F., Augusti, G., "Performance-based wind engineering: towards a general procedure", *Structural Safety*, vol. 33, no. 6, pp. 367 – 378, 2011.

[10] Griffis, L., Patel, V., Muthukumar, S., Baldava, S., "A framework for performance-based wind engineering", in *ATC & SEI Conference on Advances in Hurricane Engineering*, *ATC& SEI 2012, ASCE & ATC 2013*, pp. 1205 – 1216, 2012.

[11] Bernardini, E., Spence, S.M.J., Kwon, D.K., Kareem, A., Performance-based design of high-rise buildings for occupant comfort, Journal of Structural Engineering, vol.141 no.10, 04014244, 2015.

[12] Spence, S.M.J., and Arunachalam, S., "Performance-based wind engineering – background and state-of-the-art", *Frontiers in built environment*, open access journal, vol. 8, March 2022.

[13] ASCE (2019). "Prestandard for performance-based wind design." American Society of Civil Engineers, 2019.

[14] Duthinh, D. and Simiu, E., "Safety of structures in strong winds and earthquakes: multihazard considerations." *Journal of Structural Engineering*, vol. 136, no. 3, pp. 330–333, 2010.

[15] Li, Y., Ahuja, A., and Padgett, J. E., "Review of methods to assess, design for, and mitigate multiple hazards." *Journal of Performance of Constructed Facilities*, vol. 26, no. 1, pp. 104–117, 2012.

[16] Chulahwat, A. and Mahmoud, H., "A combinatorial optimization approach for multi-hazard design of building systems with suspended floor slabs under wind and seismic hazards." *Engineering Structures*, vol. 137, pp. 268–284, 2017.

[17] Spencer, Jr., B. F. and Nagarajaiah, S., "State of the art of structural control', *Journal of Structural Engineering, ASCE*, vol. 129, no. issue 7, pp. 845 – 856, 2003.

[18] Symans, M. D. and Constantinou, M. C., "Semi-active control systems for seismic protection of structures: a state-of-the-art review." *Engineering Structures*, vol. 21, no. 6, pp. 469–487, 1999.

[19] Soong, T.T., Reinhorn A. M. and Chu, S.Y., "Active, Hybrid and Semi-active Structural Control – a Design and Implementation Handbook". John Wiley & Sons.

[20] Symans, M., Charney, F., Whittaker, A., Constantinou, M., Kircher, C., Johnson, M., and McNamara, R., "Energy dissipation systems for seismic applications: current practice and recent developments." Journal of structural engineering, ASCE, vol. 134, no. 1, pp. 3–21, 2008.

[21] Javanmardi, A., Ibrahim, Z., Ghaedi, K., Ghadim, H. B., and Hanif, M. U., "State-of-the-art review of metallic dampers: Testing, development and implementation." *Archives of Computational Methods in Engineering*, vol. 27, no. 2, pp. 455–478, 2020.

[22] Jaisee, S., Yue, F., and Ooi, Y. H., "A state-of-the-art review on passive friction dampers and their applications." *Engineering Structures*, vol. 235, 112022, 2021.

[23] Constantinou, M. C., Soong, T. T., and Dargush, G. F., "Passive energy dissipation systems for structural design and retrofit', Research Report, Multidisciplinary Center for Earthquake Engineering Research, Buffalo, NY, 1998.

[24] Curadelli, R. O. and Riera, J. D., "Reliability based assessment of the effectiveness of metallic dampers in buildings under seismic excitations." *Engineering Structures*, vol. 26, no. 13, pp. 1931–1938, 2004.

[25] Vargas, R. and Bruneau, M., "Effect of supplemental viscous damping on the seismic response of structural systems with metallic dampers." *Journal of Structural Engineering*, vol. 13, no. 10, pp. 1434–1444, 2007.

[26] Mazza, F. and Vulcano, A., "Control of the earthquake and wind dynamic response of steel-framed buildings by using additional braces and/or viscoelastic dampers." *Earthquake Engineering & Structural Dynamics*, vol. 40, no. 2, pp. 155–174, 2011.

[27] IS 1893 (Part I) - 2016, "Indian Standard Criteria for earthquake resistant design of structures: Part 1 - Buildings", Bureau of Indian Standards, New Delhi, India, 2016.

[28] IS 875 (Part III) - 2015, "Indian Standard Code of practice for design loads (other than earthquake loads) for buildings and structures: Part 3 - Wind Loads", Bureau of Indian Standards, New Delhi, India, 2015.

[29] Liao, W. and Goel, S., "Performance-based seismic design of RC SMF using target drift and yield mechanism as performance criteria.", *Advances in Structural Engineering*, vol. 17, no. 4, pp. 529–542, 2014.

[30] Lee, S. S., Goel, S. C., Chao, S. H., "Performance-based seismic design of steel moment frames using target drift and yield mechanism." In *Proceedings of the 13th world conference on earthquake engineering*, Vancouver, Canada, 2004.

[31] Addala, M. B., "Structural control of building frames using hybrid passive device based on energy principles," Ph.D. thesis, Department of Civil Engineering, Indian Institute of Technology, Delhi, New Delhi, India, 2022.

[32] ASCE 7 Pre-Standard (2016). "Minimum design loads and associated criteria for buildings and other structures." prepared by the American Society of Civil Engineers, Reston, Virginia USA.

[33] PEER (2005). "PEER ground motion database, Pacific Earthquake Engineering Research Center, [Online]. Available: <https://ngawest2.berkeley.edu/site>.

[34] Madan, A., Hashmi, A.K., "Analytical prediction of the seismic performance of masonry infilled reinforced concrete frames subjected to near-field earthquakes," *Journal of Structural Engineering*, ASCE, vol. 134, issue no. 9, 2008.

[35] Kaimal, J. C., Wyngaard, J. C., Izumi, Y., and Cot, O. R., "Spectral characteristics of surface-layer turbulence." *Quarterly Journal of the Royal Meteorological Society*, vol. 98, no. 417, pp. 563–589, 1972.

[36] Simiu, E. and Scanlan, R. H., "Wind effects on structures: Fundamentals and Applications to Design", Wiley, 1996.

[37] Mohammadi, A., Azizinamini, A., Griffis, L., and Irwin, P., "Performance assessment of an existing 47-story high-rise building under extreme wind loads." *Journal of Structural Engineering*, vol. 145, issue no. 1, 04018232, 2019.