Development and analysis of passive hybrid energy dissipation system for steel moment resisting frame
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ABSTRACT

A passive hybrid energy dissipation system (PHEDS) consists of rate dependent devices in series with rate independent devices, is installed in Steel moment resisting frame (SMRF) to improve energy dissipation capacity while any seismic event. Analytical development of model in SAP 2000 and performance based design of energy dissipating devices (EDD), were the basic objectives of the study. High damping rubber damper (HDRD) is a rate dependent device whereas elastic springs and buckling restrained braces (BRB) are rate independent devices. The analytical models confirmed the expected phased behavior and energy dissipation capabilities. An incremental dynamic analysis (IDA) was carried out to compare the effect of energy dissipating devices on overall seismic response of SMRF, a dual BRB-SMRF system, and a dual PHEDS-SMRF system. The results demonstrate that the PHEDS has potential as an energy dissipation system and improve the performance of the structure during a seismic event.

Keywords: Steel moment resisting frame; passive hybrid damping system; high damping rubber damper; incremental dynamic analysis; nonlinear time history analysis.

1. Introduction

SMRF with deck slab is an innovative construction practice. Commercial building needs structures with long bays without obstructions. Masonry walls are replaced by glass cladding to improve elegance and also to increase work space. Hence, structural action of masonry walls is neglected as those improves lateral stiffness of the structure [MagarPatil and Jangid, 2012]. Long span beams with deck slab supported above, boosts roof drift, roof acceleration and storey displacement too. Hence, in case of seismic events, steel structures behave vulnerably and may result in partial or complete collapse [FEMA, 2000]. Earthquakes generate forces as the building inertia resists motion while foundation shakes with surrounding earth. The magnitude of seismic loads varies with involvement of multiple interacting characteristics of the structure. The practice of simply increasing strength and in turn stiffness tends to increase inertial forces and accelerations [Marshal and Charney, 2010]. The seismic design should be improved by providing a mechanism within the structural system to dissipate energy without damaging structure partially or completely.

Many innovative methods have been investigated, developed and used to improve the performance of the structure. Passive energy dissipation system is one class of it. These systems use the relative difference of displacement or velocities between device attachment points to dissipate energy. The passive energy dissipating systems are again subdivided in two classes, such as rate independent and rate dependent. Rate independent devices also
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called as displacement dependent devices dissipate energy only upon yielding or slipping. Hence, these are hysteretic or metallic yielding and friction devices. BRB, added damping and stiffness devices, pull friction devices, steel caging and high strength elastic springs are the some of the examples of rate independent passive energy dissipating devices. These devices have advantage of large capacity of energy dissipation and significant reduction in storey displacement [Fayeq and Sahoo, 2013; Sahoo and Rai, 2007]. But they also have some disadvantages like they dissipate energy only upon yielding, slipping or displacing which increases forces and acceleration on structure during minor seismic events. Rate dependent passive devices include viscoelastic solid dampers. These devices dissipate energy primarily by relative velocity between device attachment points and the damping coefficient. Viscoelastic Solids dissipate energy when deformed, typically in shear. High damping rubber (HDR) is the viscoelastic solid material. It is used as HDRD to dissipate energy. The ingredients of HDR with admixtures, improves structural strength and stiffness. HDR is basically used in bridges as a highly damped bearing pad. Now it is found to be useful in structural dampers too. The benefits of viscoelastic dampers are damping at all levels of deformation caused during seismic event, increase in stiffness of structural members, and flexibility in application.

The literature in this area shows the deep investigation of possibility of use of passive energy dissipation system in structures. Use of Viscoelastic solid dampers, BRB, Viscous fluid dampers, Visco-Hyperelastic dampers, Visco-Plastic dampers in structures to dissipate energy, can be seen in initial work. The hybrid systems were also investigated for its use in structural frames by developing combinations of rate dependent devices with rate independent devices. Viscoelastic solid damper or viscous fluid damper along with metallic damper is one of them. The aim of using damper was to improve damping while reducing storey displacement. The single degree of freedom study investigated that the viscous dampers reduces effectiveness of the metallic damper and also increases accelerations for very small strain hardening ratio. Visco-Hyperelastic devices or Visco-plastic devices uses HDR along with metallic devices to dissipate energy by developing phased behavior. They behave as visco-elastic solid devices for minor seismic events whereas under large scale seismic events, it is found that energy is dissipated by metal yielding. Visco-plastic devices have benefit of displacement amplification across the rubber element which increases the energy dissipation under small excitation. Another hybrid system investigated is partially restrained moment connections coupled with viscoelastic solid damper connected to chevron bracing (CB) [Merritt et al., 2003]. Initial flexibility and reduced damage to frame are some of the benefits of partially restrained moment connections. The analytical and experimental results demonstrated reduced displacement demand and structural damage. The result of the study illustrate that the best performance with least cost occurs with 10% of critical damping in the first mode. Hence, it is found that development of hybrid passive devices is very complicated phenomena. The only thing which can be done is to allow the elements of hybrid system to function to their strengths. Viscous fluid or viscoelastic dampers provide damping at all levels of excitation but do not add significant stiffness to the structure. Metallic yielding devices provide energy dissipation, but only at the expense of high initial stiffness and only after reaching yield force. Developing an effective combination requires the device to be flexible enough to deform but possess sufficient strength to cause yield or slip.

In this research work, hybrid passive energy dissipation devices are developed which includes HDR with BRB. The HDR consists of vulcanized rubber filled with carbon black and other admixtures to improve the stiffness and damping properties. Metallic devices build up initial stiffness without energy dissipation until yielding. This increased initial stiffness,
increases inertial forces during minor seismic events. But, during moderate or high seismic events, they yield and dissipate energy released. Due to yielding, these devices should be replaced after an event.

2. System development and analytical formulation

Energy dissipating system developed for new or existing structures was to maintain balance between stiffness, strength and damping. The carefully detailed structure using control devices has performed better to maintain the necessary balance. The structural system designed according to conventional methods deforms inelastically and resulted in major damage after an event. The disaster occurred in 1993 Killari earthquake has initiated re-examination of structures and their connections, which were analyzed and designed according to conventional approach. Structural performance and damage prediction can be improved during seismic events by providing a seismic protective system within the framework of performance based structural design (PBSD) [Mazza and Vulcano, 2011]. The performance can be improved by increasing ductility, stiffness, and strength of the structure, or any combination. If the performance based assessment identifies any deficiency in some areas, then modification can be done locally for the isolated members or joints. If any deficiency is found throughout the structure then more detailed assessment is required to be done and accordingly modification can be recommended [Marshal and Charney, 2012; MagarPatil and Jangid, 2012]. Various methods were invented for strengthening structures. Moreover, structural members or elements were examined separately for each strengthening method and most effective one was recommended. The effectiveness of each method was assessed with respect to story drift and roof acceleration [Marshal and Charney, 2009; Symans et al. 2008].

The bracing has the characteristics like good ductility; high energy dissipation while yielding and approximately similar hysteretic response in tension and compression (see Figure 1).

![Figure 1: Hysteretic response of a typical BRB](https://example.com/figure1.png)

**Table 1: Energy Dissipating Systems**

<table>
<thead>
<tr>
<th>SL. No.</th>
<th>Basic Frame</th>
<th>Damping System</th>
</tr>
</thead>
<tbody>
<tr>
<td>01</td>
<td>SMRF</td>
<td>No damping system</td>
</tr>
<tr>
<td>02</td>
<td>MSMRF</td>
<td>BRB of Mild Steel on both sides of Chevron bracing</td>
</tr>
<tr>
<td>03</td>
<td>MSMRF</td>
<td>HDS on both sides of Chevron bracing</td>
</tr>
<tr>
<td>04</td>
<td>MSMRF</td>
<td>BRB of Mild Steel and HDS on both sides of Chevron Bracing</td>
</tr>
</tbody>
</table>
SMRF strengthened with PHEDS was supported on CB, to enhance structural performance to lateral loads like wind load or earthquake load. The SMRF considered is a bare structural frame. It is central frame of a structure having 5 bays in both horizontal directions and nine stories with deck slab loading. The bay width considered is 6m and storey height is 4m. The column and beam sections are selected and provided from Indian standard steel table as given in SAP 2000 [CSI, 2007]. The load calculations are done according to IS 875 – 1987 (part I and II) for dead load and live load whereas seismic excitations are considered for nonlinear time history (NLTH) analysis. The sections are designed and provided according to performance based design (PBD). SMRF is modeled and designed as per Indian standard codal provisions [IS: 1893(Part I)- 2002; IS: 800 – 2007; IS: 875 (Part I, II, III) - 1987]. The arrangement of EDD and the frame is as shown in the Figures 2 and as listed in Table 1. The energy dissipating devices are placed in reduced strength SMRF (see Figure 3). The total stiffness of columns and beams is reduced by 30% and 40% in the modified steel moment resisting frame (MSMRF). The modification in stiffness is examined to maintain the strong column weak beam requirements and also to resist axial forces developed [MagarPatil and Jangid, 2013]. In structural systems, BRB or HDS are used either alone or in combination in modified SMRF and then results are compared. The strength and stiffness of the EDD was based on performance based analysis of the structure to get approximately 10% modal damping in the first mode of the structure. A size was specified and then linear free vibration analysis was done to determine the first mode damping.

![Figure 2](image_url)

**Figure 2:** Structural Models (a) SMRF (b) MSMRF+BRB (c) MSMRF+HDS or MSMRF+AHDS (d) MSMRF+HDS+BRB or MSMRF+AHDS+BRB

The configuration shown in the Figure 4 is a HDS based on a concept of three phase engagement of device. The first phase consists of use of a viscoelastic solid (HDR) as a rate dependent damper. The HDR element effective for all amplitudes of vibration prior to damper lockout is being sized and modelled. A high damping rubber damper (HDRD) was selected for this phase because of its high loss factor, hyperelastic material properties and significant strain capacity. The HDR element is a butyl rubber having hardness value 60. It is sized according to the limitations of HDS dimension. Design and modeling of locking mechanism is second phase where it gets engaged immediately after HDRD and displaces by specified displacement for which it is designed. And then it increases stiffness and sufficient strength to yield force value of BRB. The third phase consists of engagement of rate independent device (BRB). Several alternatives were considered for the selection of the rate independent element. BRB is selected due to its availability in local market, simple to modify.
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and effectivity in energy dissipation at medium to major seismic event level. BRB is mild steel Indian standard pipe filled with mortar.

![Schematic diagram of single story single bay SMRF with EDD](image)

**Figure 3:** Schematic diagram of single story single bay SMRF with EDD (a) BRB on both sides of CB (b) HDS on both sides of CB (c) AHDS on both sides of CB (d) BRB and HDS on both sides of CB (e) BRB and HDS on both sides of CB

The HDS is a three phase energy dissipation system which includes HDR, locking mechanism and BRB as shown in the Figure 4. The HDS was modeled in SAP 2000 using combination of link elements. Multilinear elastic spring in parallel with a linear viscous damper were used to model rubber damper element. A multilinear elastic spring represents piecewise linear force-displacement relationship. It provides several braches of elastic stiffnesses. The variation in the initial stiffness of the rubber damper and increased stiffness when locking mechanism engages was represented by multilinear elastic spring in HDS. Viscous damping component of the rubber was represented by linear damper. These two elements in parallel were then placed in series with a multilinear plastic spring that represents BRB element. The multilinear plastic spring represents yielding including strain hardening. This pattern of link elements was then mirrored on the opposite side of the chevron brace to represent a case where HDS alone was used as EDD (see Figure 5). The case where HDS was used in combination with BRB on either side of CB, to dissipate energy is modeled as shown in the Figure 6. Nonlinearity in the SMRF was modeled by beam plastic hinges, which include strain hardening and interacting axial-flexural hinges in the columns. The strength and stiffness degradation is not included in the hinge models.

The BRB element was used as EDD separately and also used as part of PHEDS. Hence, two different BRBs were used with strength and stiffness difference. Inverted-V CB was used to support energy dissipating devices and also to take part in the structural action against seismic effects (see Figure 7). The system was designed to resist the gravity loads together with a fraction of the brace loads that were induced after buckling of the braces. The approach aims at minimizing the degradation in storey shear resistance typically exhibited by CB subjected to strong ground motions, and it was proposed that such braced frames with EDD be designed for reduced frame sections. The design procedure is applied to typical multi-storey braced frame with EDD to examine its economic impacts. However, the braced frames with stronger EDDs exhibit a much higher storey shear resistance after buckling of the bracing members has occurred. The Chevron bracing used here in this research work is mild steel pipe section filled with concrete. The strength and stiffness of chevron braces was also decided based on performance analysis of the structure (see Table 2). The sections are
confirmed for slenderness ratio ($\lambda = 400$) and design compressive stress ($f_{cd}$) as recommended by IS: 800-2007.

### Table 2: Model properties of BRB and CB

<table>
<thead>
<tr>
<th>BRB/CB</th>
<th>$L$ (mm)</th>
<th>Stiffness (kN/m)</th>
<th>$A$ (mm$^2$)</th>
<th>$A_{st}$ (mm$^2$)</th>
<th>$A_{cr}$ (mm$^2$)</th>
<th>$r_{min}$ (mm)</th>
<th>$\lambda$</th>
<th>$\varnothing$</th>
<th>$F_{cd}$ (MPa)</th>
<th>Buckling class</th>
</tr>
</thead>
<tbody>
<tr>
<td>BRB - A</td>
<td>3000</td>
<td>5500</td>
<td>825</td>
<td>499</td>
<td>2920</td>
<td>21.87</td>
<td>1.00</td>
<td>1.087</td>
<td>150.7</td>
<td>a</td>
</tr>
</tbody>
</table>
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| BRB - B | 3000 | 2600 0 | 390 | 288 | 915 | 12.66 | 1.73 3 | 2.162 6 | 65.75 | a |
| BRB - C | 3000 | 2000 0 | 300 | 234 | 587 | 10.34 | 2.12 2 | 2.953 3 | 45.38 | a |
| CB – P2 | 3970 | 5912 0 | 1716 | 920 | 1990 | 17.80 | 1.63 2 | 1.982 | 82.43 | a |
| CB – P2.5 | 3970 | 8958 0 | 2600 | 1013 | 2153 | 21.40 | 1.35 7 | 1.542 | 99.89 | a |

3. Earthquake Excitation

Seven earthquake time history records such as Bhuj, Chamba, Chamoli, India-Burma Border, Imperial Valley, Northridge and Uttarkashi (see Table 3) were used in the nonlinear time history analysis [MagarPatil and Jangid, 2013; Marshal and Charney, 2010]. The scale factors were selected ranging from 0.2 to 1.5 with 5% damping [Farzad et al. 2004]. For design basis earthquake (DBE), scale factor of 1 was considered whereas for maximum considered earthquake (MCE), the scale factor of 1.5 is considered in the IDA. The dead and live load and their combinations with earthquake load are calculated according to IS: 800 – 2007 for commercial buildings. Wall load is considered in dead load but its structural effect is neglected in the analysis. Response reduction factor considered for the analysis is 5 for SMRF with eccentric bracing system. 30% of earthquake excitation was considered in other direction as per IS: 1893 (Part I) - 2002. Full static percentage of modal load participation ratio is considered for all systems. The dynamic percentage of modal load participation ratio considered is almost full for all structural systems except for steel moment resisting frame.

Table 3: Earthquake records

<table>
<thead>
<tr>
<th>Earthquake Records</th>
<th>Year</th>
<th>Earthquake record description</th>
<th>Recording Direction / Component</th>
<th>PGA (g)</th>
<th>Scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bhuj, India</td>
<td>2001</td>
<td>Ahmedabad, India</td>
<td>N 78 E</td>
<td>0.106</td>
<td>0.982 3</td>
</tr>
<tr>
<td>Chamba, India</td>
<td>1995</td>
<td>Chamba, India</td>
<td>N 00 E</td>
<td>0.146</td>
<td>0.970 5</td>
</tr>
<tr>
<td>Chamoli, India</td>
<td>1999</td>
<td>Gpeshwar, India</td>
<td>N 20 E</td>
<td>0.359</td>
<td>0.899 9</td>
</tr>
<tr>
<td>Imperial Valley, CA</td>
<td>1979</td>
<td>USGS 952, El Centro Array 5</td>
<td>Impvall/H-E05140</td>
<td>0.448</td>
<td>0.966 4</td>
</tr>
<tr>
<td>Ind- Burma Border</td>
<td>1988</td>
<td>Bokajan, India</td>
<td>S 56 E</td>
<td>0.224</td>
<td>1.000 2</td>
</tr>
<tr>
<td>Northridge</td>
<td>1994</td>
<td>USC, 90091 LA, Saturn St</td>
<td>Northr/Stn020</td>
<td>0.453</td>
<td>0.998 5</td>
</tr>
<tr>
<td>Uttarkashi, India</td>
<td>1991</td>
<td>Bhatwari, India</td>
<td>N 85 E</td>
<td>0.252</td>
<td>1.009</td>
</tr>
</tbody>
</table>

4. Results and discussion

Steel moment resisting frame with RCC slab is a new concept of construction. Change in stiffness due to soft story concept in RCC structures made the structural engineers to think
due to the damage occurred during seismic events in India such as Killari Earthquake in 1993 and Bhuj earthquake in 2001. Absence of masonry infill walls in structures renders reduction in story stiffness significantly. Hence, it is required to improve strength using energy dissipating system. The energy dissipaters used here in this research work were BRB and hybrid damping system. They were used alone or in combination to dissipate energy. Figure 8 shows the DBE curve of displacement versus story number. It is found that displacement of the case where MSMRF is used with HDS alone or in combination with BRB is very less as compared to the case where BRB alone used with MSMRF. For BRB alone case, story displacement is more than all other cases for the floors above ninth floor. At plinth beam, story displacement of BRB alone with MSMRF is less as compared to other cases. This is because the reaction offered by BRB is sudden as compared to HDS. These are arranged in such a way that they start playing their role sequentially as their stiffness increases. Hence, it is a phased behavior and responds little late. Roof displacement of the case, where, HDS is used along with BRB as energy dissipater, is 60% less as compared to basic bare SMRF without energy dissipater. The results shown in the graph are average of all time histories and all scales. Figure 9 shows the DBE curve of story drift versus story number that means inter-story drift analysis. HDS has again played very important role. HDS alone or in combination with BRB has confirmed its importance in structures. Roof drift of the cases where energy dissipaters are used is approximately 55% less as compared to SMRF without energy dissipaters except for the case where BRB is used as an energy dissipater. At higher floors story drift is more for this case.

![Figure 8: DBE results of story displacement w.r.t. storey number](image-url)
Figure 9: DBE results of story drift w.r.t. story number

Figure 10 shows the IDA curve of roof drift with respect to scale factor. Roof drift for all cases is less as compared with basic SMRF for all scale factors except for the case where BRB is used as an energy dissipater. Drift in this case is 99% same as that of SMRF alone. This is because; BRB is designed in such a way that the roof displacement of the case should be close to that of basic SMRF to achieve economy. If HDS alone is compared with the case where it is used in combination with BRB, the later has performed well at all levels of the scales. Also, the rate of change of roof drifts with scale factor almost uniform all cases. Due to sudden reaction, roof drift for BRB alone case is much more as compared to the cases as mentioned above. Hence, the combination of HDS and BRB has performed well as far as roof drift is concerned.

Figure 10: IDA results of roof drift w.r.t. scale factor
Figure 11: IDA results of roof acceleration w.r.t. scale factor

Figure 11 shows the IDA curve of roof acceleration with respect to scale factor. Roof acceleration for the cases where HDS alone or in combination with BRB is used as an energy dissipater is less as compared to basic SMRF case and the case where BRB is used alone as an energy dissipater. The rate of increase in roof acceleration is almost uniform with respect to scale factors. Figure 12 shows the IDA curve of base shear with respect to scale factor. Base shear for all cases where energy dissipaters are used, is less as compared with basic SMRF case.

Figure 12: IDA results of base shear w.r.t. scale factor
Figure 13: DBE results of inter-story drift ratio w. r. t. story no.

The case where HDS alone or along with BRB is used, the base shear is less as compared to other cases. Base shear for basic SMRF is more as compared with the cases where the energy dissipaters are used either alone or in combination. The rate of change of base shear with respect to scale factor is also uniform for all the cases. Figure 13 shows the IDA results of inter story drift ratio. Inter story drift ratio is at higher floors as compared to middle some of the floors. At some initial floors, inter story drift ratio is less due to the presence of plinth beam. It is less for the case where HDS along with BRB is used.

Figure 14: Nonlinear static pushover results
For the case where BRB alone is used, inter story drift is more at higher floors as compared to basic SMRF case. HDS alone case has also proved its importance in this area of the result analysis. Figure 14 shows the results of push over analysis. The displacement caused by base force for the case where HDS alone is used with SMRF is less as compared to all other cases. For the case where BRB is used alone in SMRF results in more base shear for same displacement as compared to other energy dissipating cases. The performance point for the case where BRB alone is used is at eighth step where hinges form are within the range of immediate occupation. For the case where HDS alone is used, the performance point is at sixth step where hinges form are again within the range of immediate occupation. The performance point for the case where HDS alone is used with BRB is used is at seventh step where hinges form are within the range of immediate occupation. It means that the demand is within the range of capacity of the structure. The total weight of structural frame is reduced by 20.23% in BRB case, 46.12% in HDS case and 39.49% in combination case. Hence, it is economical to put energy dissipaters in all respects in the structure.

5. Conclusion

The SMRF with RCC slab is a new trend construction practice, used worldwide, nowadays. The modified SMRF with energy dissipaters has performed well for the seven seismic events with scale factors ranging from 0.2 to 1.5. The case, where BRB alone is used as energy dissipating device, is designed in such a way that roof displacement remains close to that of basic SMRF to achieve optimized results. Upon analyzing the frame for a suit of seven time histories, following are the conclusions derived.

1. The story displacement and drift of SMRF is reduced significantly due to provision of EDD.

2. Considerable reduction occurred in roof drift and roof acceleration with increase in scale factor for modified cases.

3. Inter-story drift ratio of the case where HDS alone or in combination with BRB is used, is less at higher floors whereas for BRB alone case, it is more at higher stories as compared to all cases.

4. HDS has confirmed its design objectives by performing its role in well manner in all areas of the result analysis.

5. The BRB alone is not economical to provide and also not performed effectively. BRB provides immediate reaction; hence sudden failure at connections is possible.

6. The combination of HDS and BRB has proved in all respects.

7. The performance based optimization is good technique to get economy in the use of sections.

6 References


