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A Review of Innovative Techniques in Improving the Seismic Behavior of Steel Structures: Rocking Motion and Energy Dissipation Devices

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Abstract

Improving the seismic behavior of steel structures, due to its high importance in reducing human and financial losses in earthquake-prone areas, has always been a key topic in structural engineering. The use of rocking motion and energy dissipation devices are recognized as two innovative and effective approaches in this field. This review article first investigates the principles and fundamentals of rocking motion and its mechanism in reducing seismic forces. Then, various types of energy dissipation devices, including viscous dampers, friction dampers, and metallic dampers, are introduced, and their performance is analyzed. Moreover, it presents case studies and experimental and numerical results related to the use of these techniques in steel structures. The review of these articles shows that the combination of rocking motion and energy dissipation devices can significantly improve the stability and safety of steel structures against earthquakes.

Keywords: Rocking motion, Seismic forces, Energy dissipation devices

Introduction

In recent decades, with advances in structural technology and increased earthquake risks in various regions of the world, the development of new methods for enhancing the seismic performance of structures has become vital and necessary. Steel structures, as one type of structure that has a high capacity to withstand seismic forces, are directly affected by earthquakes and must be continuously improved to ensure safety and service life.

Rocking motion is an innovative method that has attracted the attention of many researchers and engineers in architecture and civil engineering in recent years. This method, especially in tall and flexible structures such as steel structures, shows great potential for reducing seismic forces and absorbing earthquake energy. On the other hand, energy dissipation devices, such as viscous and friction dampers, also play a significant role in improving the seismic behavior of structures because they absorb the energy generated during an earthquake and dissipate it in the form of heat.

This review article provides a deeper examination of these two methods and evaluates the effects and benefits of using rocking motion and energy dissipation devices to improve the seismic behavior of steel structures. This review not only helps engineers and designers in deciding whether to use these techniques but is also effective in the development of new technologies for improving the safety and stability of structures.

Rocking Motion

The study of the seismic behavior of earthquake-resistant structures indicates the development of inelastic deformations and significant forces (up to the ultimate expected capacity at critical sections of seismic-resistant members) during a severe earthquake. Beyond the difficulty of providing the required capacities at the critical sections of a structure, the development of residual deformations and damage to the main members of conventional structures following an earthquake, and consequently the difficulty or impossibility of post-earthquake repairs, have been among the reasons for researchers to propose new earthquake-resistant systems. Among the various modern structural systems, the use of rocking-self-centering steel structures has attracted attention due to the concentration of seismic

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damage in non-primary members, which can be easily replaced, along with the elimination or significant reduction of residual lateral displacements.

The history of research on the engineering application of rocking motion in reducing seismic loads dates back to the 1970s. From a design perspective, the initial focus on the subject was due to the increased sensitivity to overturning moments and seismic uplift forces in structures and long-span bridges in conventional structures. In these conventional structural systems, it was identified that significant tensile forces are generated at the connection level of the structure to the foundation. Furthermore, given the design considerations, providing the necessary tensile capacity to resist these tensile forces was recognized as involving high costs and significant implementation challenges.

In contrast to the need to provide the required tensile capacity at the connection point between the superstructure and the foundation in fixed-base structures, the idea of using uplift-free structures emerged as an alternative option. These structures, through the design and implementation of special details at the base of the columns, enable the occurrence of uplift phenomena caused by rocking motion. In this regard, the development of an earthquake energy dissipation mechanism through uplift at the base and enabling a rocking motion cycle for energy dissipation devices has presented a significant incentive for the use of new structural systems.

Concepts and Characteristics of Rocking Motion Systems

The schematic of a small-scale three-story steel frame (scale 1:2) subjected to shake table tests at the University of California, Berkeley, is shown in Figure 1. The rolling supports provided at the base of the columns allowed for the occurrence of uplift and rocking motion in the laboratory specimen. It is worth mentioning that the laboratory specimen lacked any mechanism for restoring force (except for its self-weight) and energy dissipation devices. The test results, comparing the seismic response of this specimen with another similar frame built with fixed supports, indicate a reduction in member forces and floor accelerations in the structure with rocking motion (Clough, 1997).

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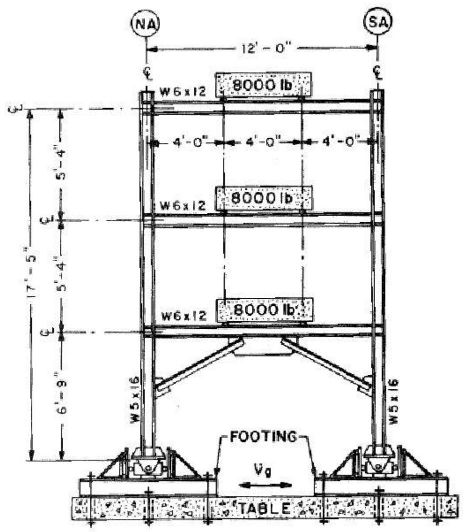

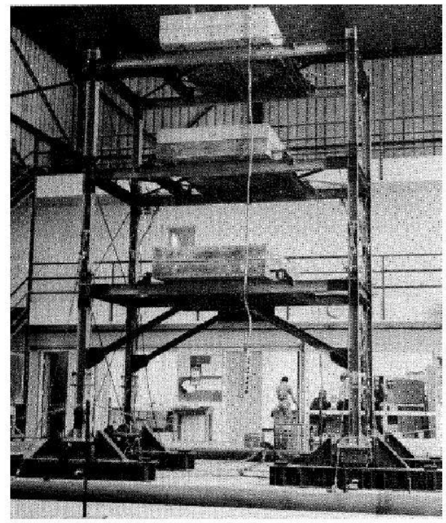

AB

Figure 1: (a) Side view and dimensions of the specimen; (b) Image of the laboratory specimen (Clough, 1997)

The first practical and engineering use of rocking motion self-centering structures dates back to the design and construction of the Rangitikei railway bridge in New Zealand in 1981. Figure 2 shows that this bridge has six spans with a total length of 315 meters and piers with a height of 70 meters, each equipped with two large energy-absorbing members. The structural elements of this bridge are made of prestressed hollow concrete sections, and the rocking motion is enabled according to the details at the piers. The self-centering and restoring characteristics of the system are provided by the self-weight of the bridge. Based on the above description, the structural behavior of the bridge essentially acts like an inverted pendulum (Cornak, 1998).

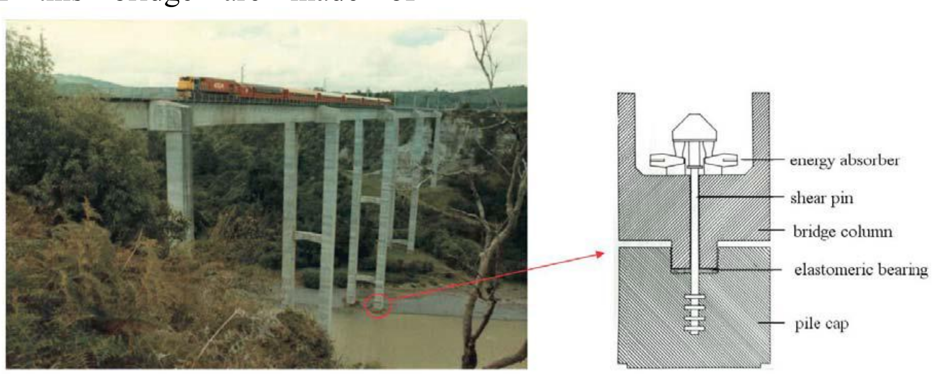

Figure 2: Application of rocking motion and energy dissipation devices at the base of the southern Rangitikei railway bridge (Cornak, 1998)

Furthermore, experiences from previous earthquakes have demonstrated cases where damages and losses were reduced in buildings that experienced rocking motion-

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induced uplift during the earthquake (Rutenberg, 1998 & Hayashi, 1999). Consequently, from an engineering perspective, the possibility of using the advantages of uplift and rocking motion in building structures has also been taken into consideration by researchers. Figure 3, for example, shows a specific detail for the splicing of steel columns allowing for uplift at the splice location, aimed at preventing the development of damage from large axial forces in the columns (Wada, 2001).

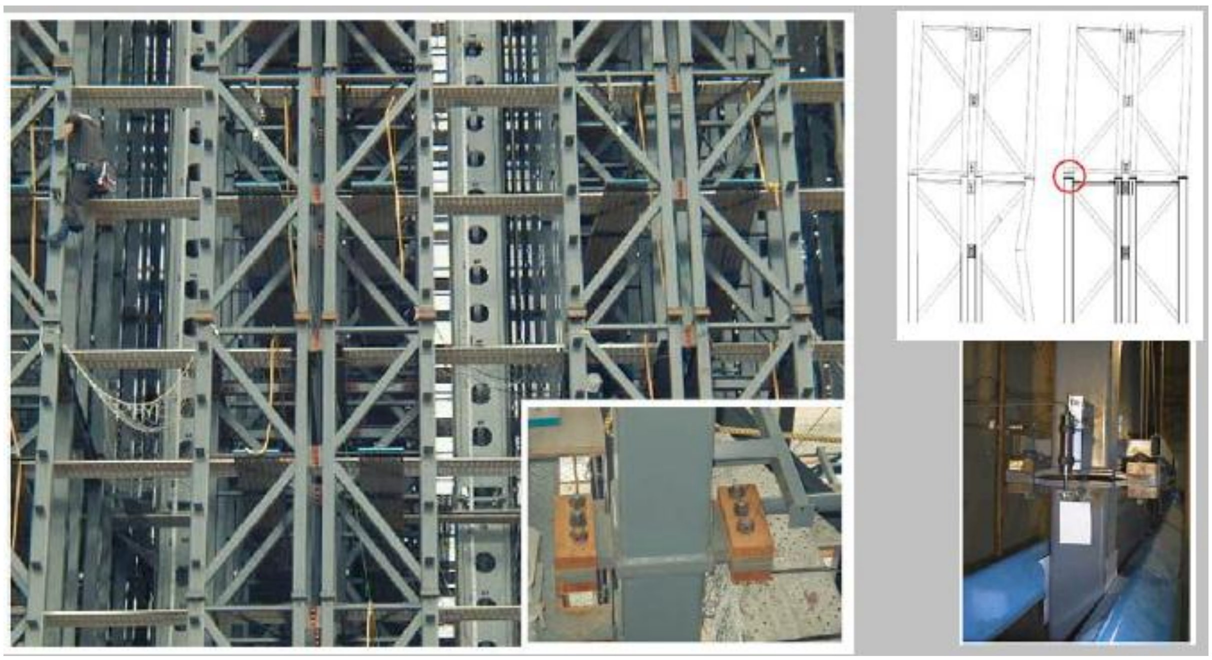

Figure 3: Providing uplift freedom at the splice location of steel columns' splicing in an industrial building (Wada, 2001)

Numerous studies have been conducted in recent years on the potential application of rocking motion at the base of buildings through numerical and experimental studies. For instance, uplift-free structures, facilitated by implementing details like lubricated shear keys, have been used to ease rocking motion in the shake table tests of a 1:9 scale four-story frame (Iwashita, 2002). Additionally, studies have been conducted in Japan on designing yielding base plates for steel structures to create uplift freedom and assess the behavior of these structures (Midorikawa, 2008). An example is shown in Figure 4, which presents a small-scale (1:2 scale) three-story steel frame with yielding base plates subjected to shake table tests.

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Figure 4: Shake table test of a steel frame with yielding base plates (a) Image of the laboratory specimen (b) Close-up view of the yielding base plate (Iwashita, 2002)

In the United States, rocking motion structural systems with the application of butterfly shear fuses in both dual (Ma, 2011) and single configurations (Scholl, 1990) were also examined. As shown in Figure 5, these shear fuses were placed between two adjacent frames in the dual configuration, and at the base of the building in the simple configuration. The schematic representation of uplift-free structures with butterfly shear fuses in simple and dual configurations, along with a close-up view of the butterfly fuse, is shown in the figure.

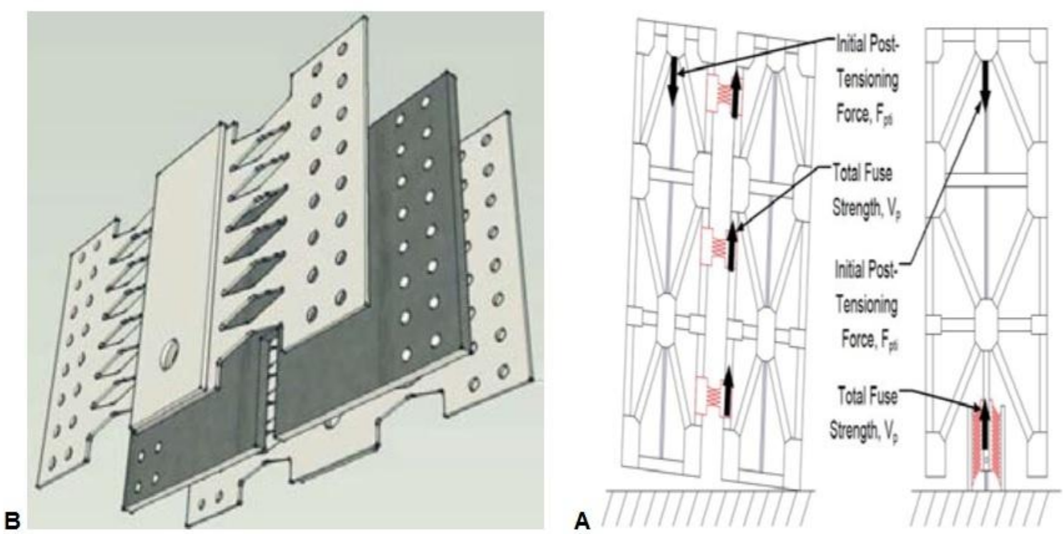

Figure 5: (a) Schematic representation of uplift-free structures with butterfly shear fuses in simple and dual configurations (Ma, 2011) (b) Close-up view of the butterfly fuse (Scholl, 1990)

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Main components of such steel structures with rocking motion:

- Uplift-free steel frames
- Energy dissipation devices also referred to as seismic fuses
- Restoring force devices also referred to as self-centering mechanisms

The aforementioned studies considered the application of yielding base plates and butterfly shear fuses as energy dissipation devices and the use of prestressed cable systems and permanent gravity loads as restoring force devices. More details about these devices are presented in the following sections.

Energy Dissipating Devices

Considering the development of inelastic deformations in conventional structures during a severe earthquake, significant damage to the primary members of the structure is inevitable. Past earthquake experiences, along with numerical and experimental studies, show that inelastic behavior and buckling occur in the bracing members of concentrically braced steel frames, the formation of plastic shear hinges in the bonded beams of eccentrically braced steel frames, and the development of plastic flexural hinges in the beams and, in some cases, columns of steel moment-resisting frames are common as samples of code-conforming structures.

On the other hand, the application of energy-dissipating devices in rocking motion structures can concentrate inelastic deformations and damage in these components during a severe earthquake, keeping the primary structural elements within the elastic range. In addition, some of the energy dissipation systems proposed in previous studies are mentioned, and subsequently, the application of some of them in rocking motion structures is experimentally investigated.

Metallic Yielding Devices

In these devices, energy dissipation is achieved through the yielding of metals and their inelastic deformations under various loading cycles during an earthquake. In most cases mentioned in technical references, the desired energy dissipation is accomplished through the formation of plastic flexural hinges due to out-of-plane deformations in specially designed seismic fuses.

Friction Dampers

Friction energy dissipating devices are one of the important and effective types in improving the seismic behavior of structures. These devices absorb the energy generated by earthquake vibrations and convert it into kinetic or thermal energy, thereby helping to reduce seismic forces and mitigate the relative displacements of the structure during an earthquake.

Viscous fluid and viscoelastic energy-dissipating devices

These devices differ from metallic yielding and friction dampers, which are displacement-dependent systems; instead, they are among the velocity-dependent mechanisms. Viscous fluid dampers consist of a perforated piston that moves within a cylinder filled with pressurized fluid. The energy dissipation is achieved as the fluid passes through the perforations in the piston.

Restoring Force Devices (self-centering devices)

Restoring force devices are other essential components of steel rocking frames, which, in addition to providing stiffness and stability to the system, play a crucial role in overcoming the residual fuse force to return the system to its initial equilibrium state after an earthquake.

Review of Previous Studies

Metallic Yielding Devices

Metallic Added Damping and Stiffness (ADAS) devices refer to a system with a bending yield mechanism perpendicular to the plane. Their effects on seismic behavior

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have been frequently studied by various researchers (Andalib, 2018). Additionally, Triangular-plate Added Damping and Stiffness (TADAS) devices have been used in steel structures due to their bending yield mechanism (Chan, 2009). Technical references also discuss a ductile steel ring system capable of dissipating energy through yielding under bending moments (Hossani, 2011 & Li, 2011). Furthermore, various studies have been conducted on metal-yielding mechanisms under in-plane deformations. For example, research on the application of Yielding Shear Panel Devices (YSPD) is noteworthy (Chan, 2008 & Ma, 2010).
Additionally, some researchers have proposed creating slits in steel plates to achieve desirable rotational behavior. In this regard, the initial steel plate is transformed into a set of parallel link members with smaller width-to-thickness ratios than the original plate, which provides better compactness and, in turn, enhances the plate's shear buckling capacity.

For the proposed systems using relatively thick-slitted steel plates (with width-to-thickness ratios of the link members between 1 and 2), the samples exhibited stable hysteresis loops up to shear strains of 10% to 20% (Pollino, 2007a). In the case of thinner steel plates (with width-to-thickness ratios of link members around 10), shear strains of up to 2.5% were reported before buckling occurred (Pollino, 2008). To improve the in-plane cyclic behavior of the aforementioned yielding devices, the use of honeycomb openings instead of simple slits in the steel plates was proposed, which effectively results in butterfly-shaped link members within the steel plates. It is noteworthy that this configuration, due to the better geometric alignment of the link members with the bending moment diagram, results in a much more uniform distribution of yielding along the entire length of the link members. Based on laboratory reports, selecting appropriate width-to-thickness ratios in this system enabled shear strains of up to 30% before any degradation in the cyclic behavior of the component occurred (Pollino, 2007b). Figure 6 shows examples of yielding energy-dissipating devices recommended in technical references.

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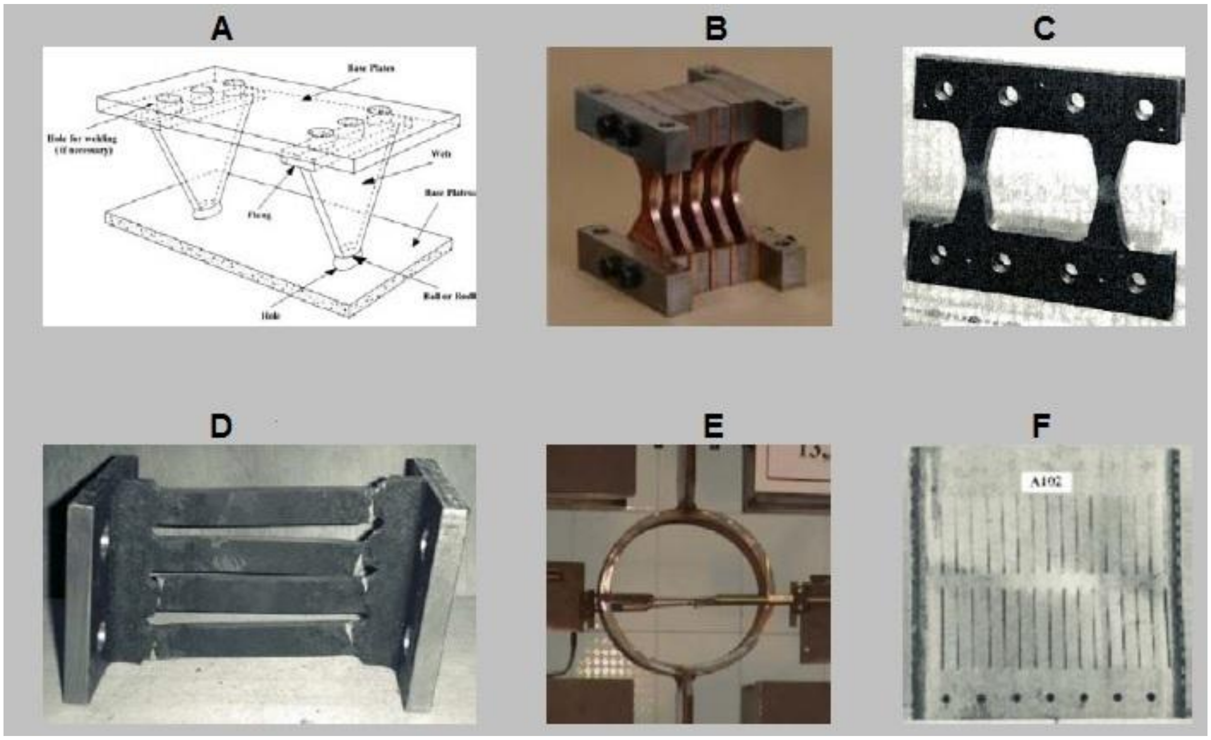

Figure 6: (A) TADAS [21], (B) ADAS [16], (C) Honeycomb damper (Pollino, 2007b), (D) Steel slit damper [27], (E) Steel ring [23], (F) Shear wall with slits (Pollino, 2008).

It is worth mentioning that in addition to the yielding dampers listed above, other yielding mechanisms, such as axial and torsional yielding devices, have also been studied, and their applications are available in the corresponding references (Wu, 2005).

Friction Dampers

The main concept behind friction damper systems is energy dissipation through sliding friction mechanisms, which have been used in steel connections for about three decades. During this time, various friction dampers have been proposed by different researchers for use in steel frames. For instance, the application of Pall friction damper systems at the intersection of cross-bracing members in steel frames has been studied (Aiken, 1993). Moreover, friction dampers have been utilized in practical projects, such as controlling the structure of the headquarters of the Canadian Space Agency (Mualla, 2002). In recent years, a modified model of the Pall friction damper has been proposed, which, in addition to maintaining similar energy dissipation capabilities as the original model, provides greater ease in manufacturing and installation (Grigorian, 1993). The general configuration of the Pall friction dampers in both the original and modified forms is illustrated in Figure 7.

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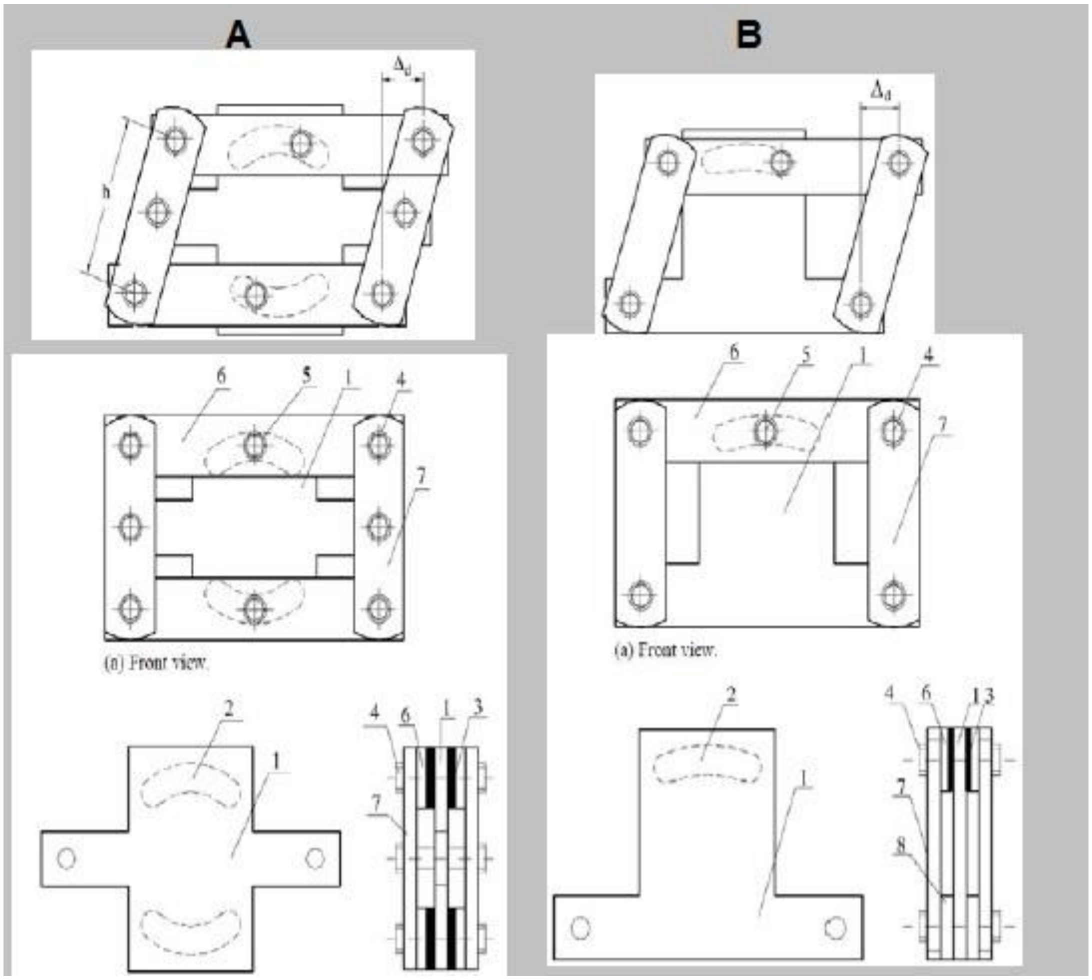

Figure 7: General configuration of the Pall friction damper: (A) Original arrangement (Mualla, 2002), (B) Modified arrangement (Grigorian, 1995)

Furthermore, a friction damper with a cylindrical shell and internal sliding pads was introduced by Sumitomo Metal Industries in Japan, and its performance was examined through comparative laboratory studies of energy dissipation systems at the Earthquake Engineering Research Center, University of California, Berkeley (Butterworth, 1999). Figure 8 shows another proposal by previous researchers (Butterworth, 2000) for designing and manufacturing a friction damper where energy dissipation is achieved through the pendulum motion of the friction member. Additionally, slotted bolted connections (SBCs) have been proposed as an example of friction energy dissipation mechanisms by Popov, Grigorian et al., and their application in diagonal bracing systems has been studied, as shown in Figure 9 (Haghollahi, 2014).

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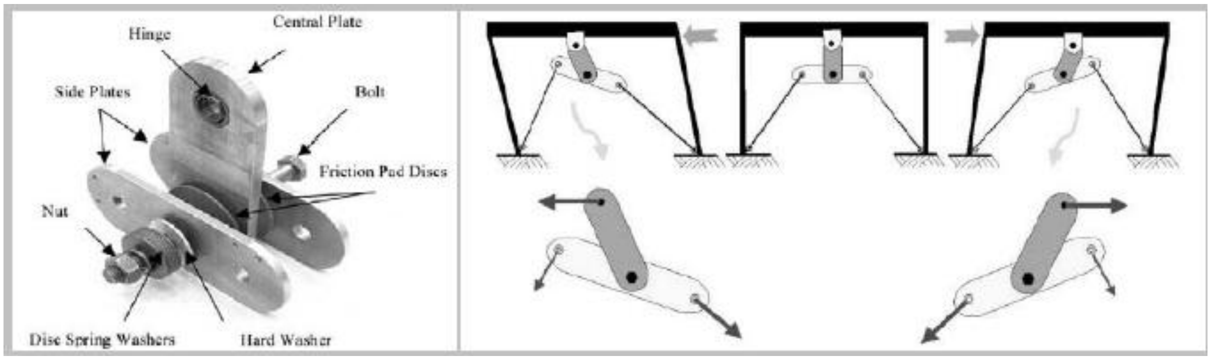

Figure 8: Energy dissipation through the pendulum motion of a friction member (Butterworth, 2000)

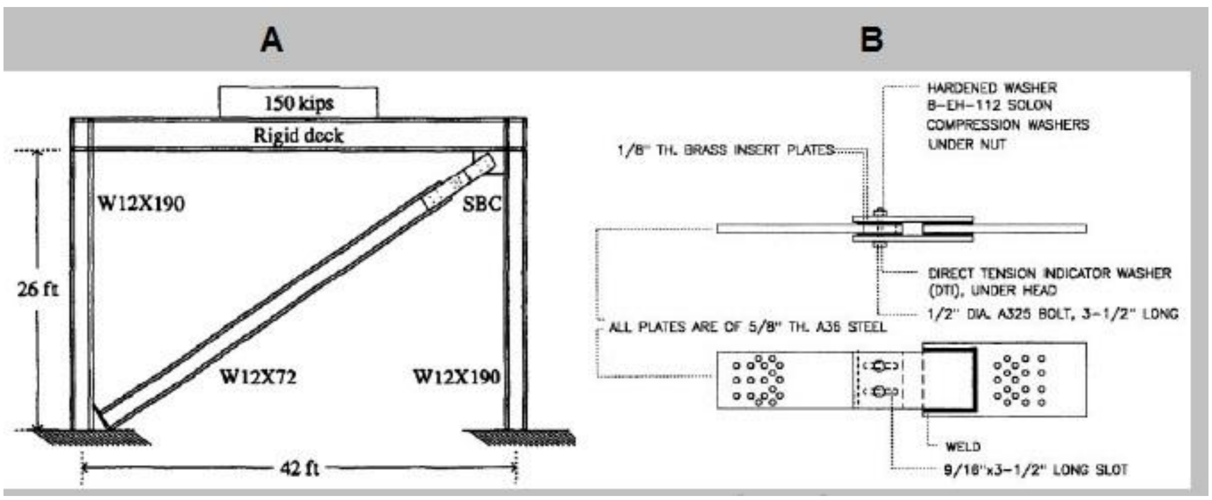

Figure 9: Slotted bolted connections: (A) Application in a diagonal bracing system, (B) Front view and cross-section of the damper (Haghollahi, 2014)

Additionally, in Butterworth's studies, a friction damper similar to the one shown in Figure 10 is proposed for use in Chevron systems (Trembley, 2008). In Iran, a friction damper system similar to Butterworth's, using brake linings instead of brass plates, has been proposed, and its general layout is shown in Figure 11. Tests conducted at the International Institute of Earthquake Engineering and Seismology have confirmed the appropriate behavior of the proposed friction system in terms of energy dissipation (Ashour, 1987).

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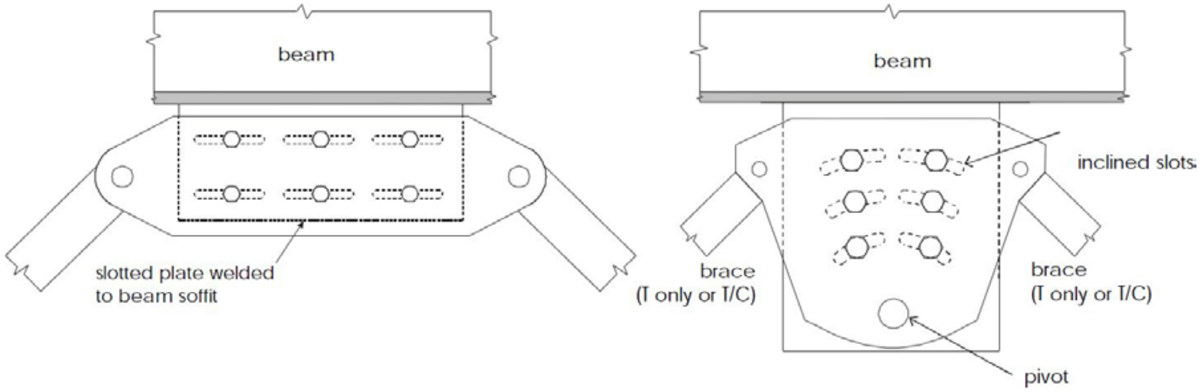

Figure 10: Application of the Butterworth damper in Chevron frames: (A) Horizontal slider, (B) Rotational slider (Trebley, 2008 & Ashour, 1987).

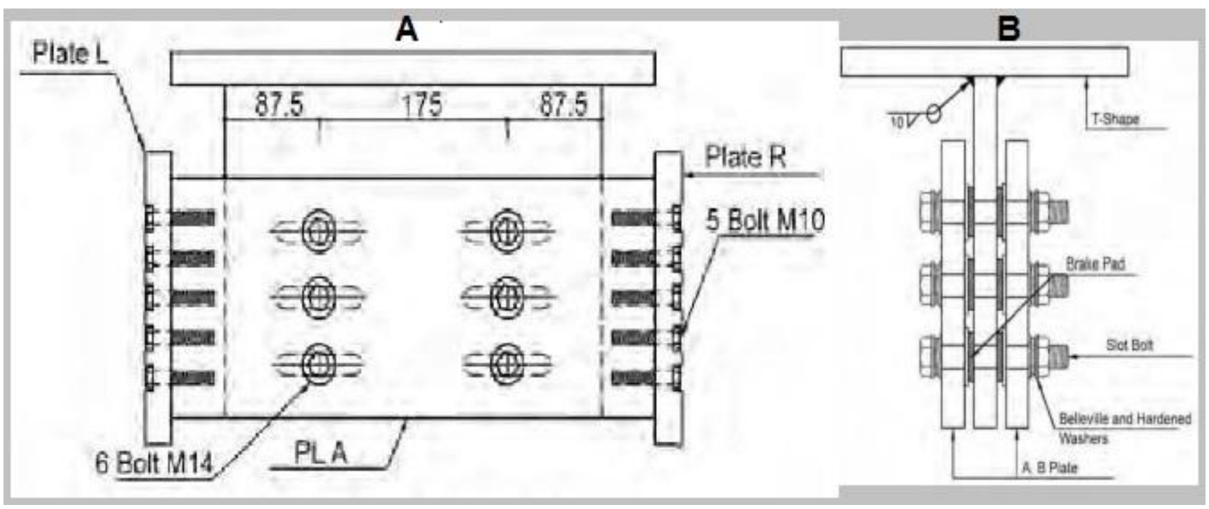

Figure 11: Application of friction dampers with brake linings in Chevron frames: (A) Front view, (B) Cross-section (Trebley, 2008)

Fluid Viscous and Viscoelastic Dampers

Unlike metal and friction-yielding dampers, which are displacement-dependent systems, fluid viscous and viscoelastic dampers are velocity-dependent mechanisms. Fluid viscous dampers consist of a perforated piston moving within a cylinder filled with pressurized fluid, where energy dissipation is achieved through fluid passing through the piston holes. Laboratory studies have shown that fluid viscous dampers, such as the one depicted in Figure 12, can reduce inter-story drifts, acceleration, and shear force of steel frames by one-half to one-third compared to the corresponding values of frames without dampers. However, the application of these dampers involves challenges such as high purchase and maintenance costs (Zhang, 1989).

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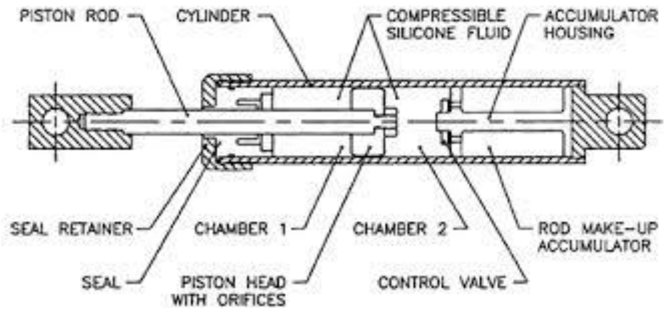

Figure 12: Fluid viscous dampers used for reducing seismic demand in steel frames (Zhang, 1989)

Additionally, as shown in Figure 13, a laboratory study on the application of fluid viscous dampers in rocking steel structures was conducted by Tremblay et al. (Shukla, 1999). In the proposed system, fluid viscous dampers were vertically placed between the foundation and the column base of a two-story small-scale test specimen (with a 1:2 scale ratio). The results from the shake table tests indicated a reduction in seismic demand for base column uplift forces and base shear in the proposed system compared to the corresponding conventional structure.

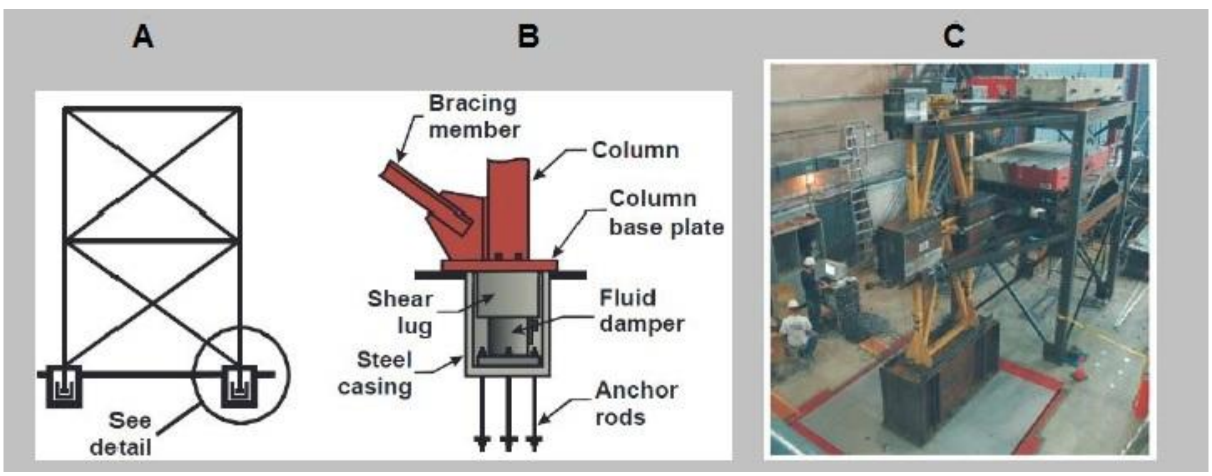

Figure 13: Application of fluid viscous dampers in rocking steel structures: (A) Damper placement in the structure, (B) Damper details, (C) Laboratory specimen preparation (Shukla, 1999)

In Figure 14, a schematic of a proposed viscoelastic damper is presented, as reported in technical references (Popov, 1995). In addition to controlling the wind-induced vibrations in tall buildings, previous studies confirm their acceptable seismic performance (Lee, 2007). Over recent years, the examination of seismic behavior, design guidelines, and the optimal application of viscoelastic dampers in buildings has significantly advanced.

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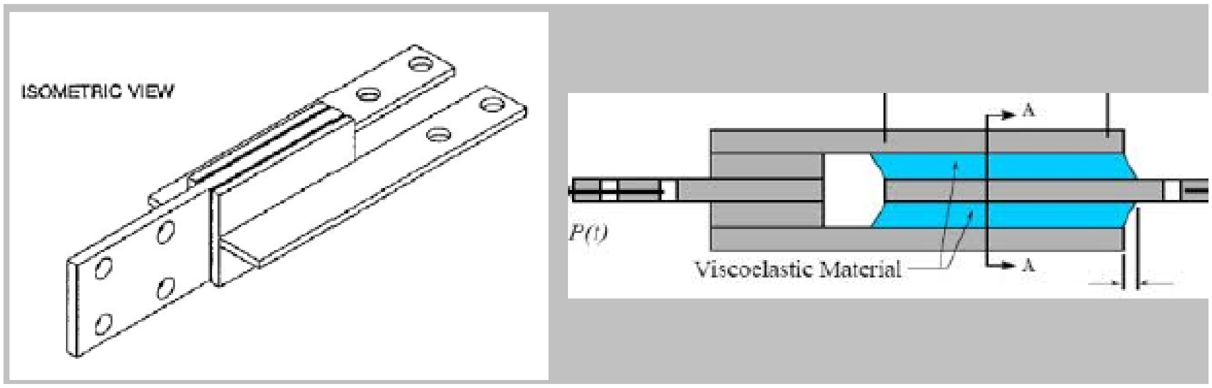

Figure 14: Schematic view of a proposed viscoelastic damper in technical references (Lee, 2007)

Self-Centering (Restoring Force) Devices

Another essential component of rocking steel frames is self-centering devices, which, in addition to providing the system's stiffness and stability, play a critical role in overcoming residual fuse forces to restore the system to its initial equilibrium state after an earthquake. In some studies on rocking steel frames, gravitational forces have been chosen as the sole means of providing self-centering. On the other hand, a review of the studies on rocking steel buildings indicates that for real building counterparts, other sources of self-centering are necessary, such as post-tensioned cables (Hsiao, 2012). Previous studies have cited numerous cases of post-tensioned cables providing self-centering and recentering properties for various structural systems. For example, Kurama et al. (Kurama, 2006) used post-tensioned cables to connect concrete shear walls, as shown in Figure 15. In other studies, as shown in Figure 16, an example of post-tensioned beam-to-column connections is presented, where post-tensioned cables provide the bending resistance and self-centering of the connection (Yang, 2006). In another case, shake table tests showed that installing post-tensioned tendons in a laboratory specimen of a bridge pier reduced the lateral drift ratio from 1% to 0.1%.

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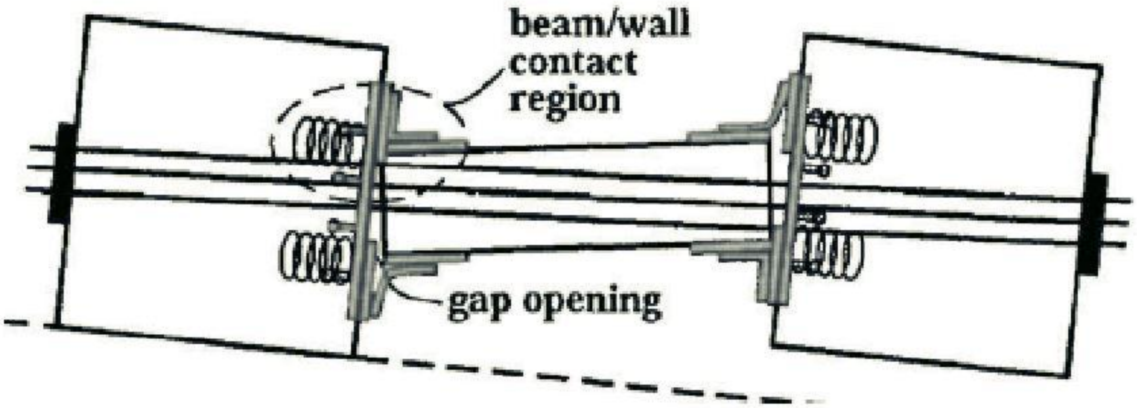

Figure 15: Application of post-tensioned cables for connecting concrete shear walls (Kurama, 2006)

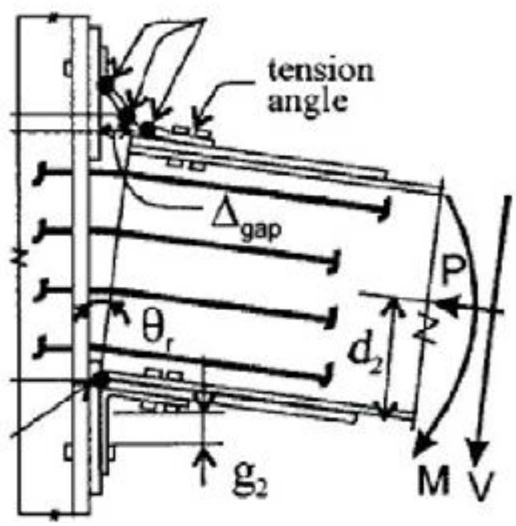

Figure 16: Application of post-tensioned cables in beam-to-column connections (Kurama, 2006)

Conclusion

Based on the main findings of previous studies on the seismic behavior of rocking motion structures, the primary advantage of these systems compared to conventional fixed-base structures is their reduced seismic demand, considering parameters such as base shear and inter-story drift. Moreover, the gaps identified in previous studies on modern rocking structures and the necessity of efforts to fill the existing knowledge gaps were highlighted. Among these, the importance of adopting more realistic assumptions and conditions in a comprehensive comparison of the seismic performance of conventional systems versus modern rocking systems for actual buildings and the examination of key parameters required to develop fragility curves for evaluating the probability of exceeding target damage states in modern structures was emphasized (Riahi Nouri, 2015).

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