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Seismic Performance of Steel Frames Equipped with a Combined Yielding Damper and Rubber Isolator in an Irregular Plan in the Near-Fault Area

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Abstract

Various types of energy dissipation devices such as frictional dampers, viscoelastic dampers, flow dampers, and viscous dampers have been investigated and tested by researchers, taking into account that the remediation goal specifies the desired extent of damage. In general, these devices are expected to be good candidates for projects that have a performance level of (I.O) or (L.S). One of these devices is viscous dampers, which are velocity-dependent devices. The use of viscous dampers to reduce the dynamic response of buildings to earthquake excitation has been widely accepted due to their increased damping, lack of activation threshold, and economic efficiency. By knowing the relationships governing single-degree-of-freedom and multi-degree-of-freedom vibrations and generalizing them to structures, the damping phenomenon can be introduced as a means of dissipating seismic energy entering a structure during earthquakes and cyclic loadings. In order to expect controlled damping from the system, this damping must be applied to the structure through new members called dampers. These new members, which are responsible for dissipating the energy entering the structure, behave independently of the initial displacement and the applied forces, and their behavior changes only with changes in velocity. There are two general approaches to earthquake-proofing structures: the first approach is based on strength and ductility design, whose philosophy is based on two principles: creating strength and stiffness in structures to control lateral displacement and prevent the destruction of structural and non-structural members under the influence of small and medium earthquakes, and creating ductility and high energy absorption capacity in structures to prevent structural collapse in severe earthquakes. The main problem with this approach is that if we want the structure to behave in the linear elastic phase, the structural sections are designed completely uneconomically and cannot be implemented. The second approach is to use methods to increase the structural period and the structural performance in the linear elastic phase. The most important method for increasing the period of a structure is to use seismic base isolation systems.

Keywords: Damper, Plan irregularity, Rubber base isolation, Dynamic analysis.

1 | Introduction

The way vertical and lateral loads are transferred in a structure depends on the combination and arrangement of the vertical load-bearing members of the structure, such as columns, beams, and lateral load-bearing

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members, such as braces, and the way these members are connected. This combination is called a building system. Although EBF frames have very good behavior in many areas, if the connection beam fails due to earthquake loads, serious damage will be caused to the floor beam, and since this member is considered a main structural member, repairing the structure will also be difficult.

All these reasons and some others increase the desire to find new earthquake-resistant systems with better behavior in terms of ductility and lateral stiffness. In conventional building structures, earthquake-resistant design is based on post-yield ductility of structural members to provide dissipation of earthquake energy; While the input energy dissipation can be concentrated at predetermined points by using energy-dissipating devices or dampers, the nonlinear behavior of the main members that are also in the path of gravity load can be avoided. Therefore, the possibility of failure in the main components is minimized, and it is the dampers that absorb the input energy and can be easily replaced in the event of a possible failure.

Among the most effective energy absorbers are flowing metal dampers. These types of dampers have been considered since the early 1970s to absorb energy entering structures. Their working principles are usually based on the ductile yielding of mild steel. The idea of using separate metallic hysteresis dampers within a structure to absorb seismic energy began with the experimental and conceptual work of Koley et al. [1] and Skinner et al. [2]. They introduced and tested several types of simple steel tools as energy-dissipating devices. Among these tools were thin U-shaped steel sheets.

The results of their reciprocating tests showed that U-shaped steel plates can withstand very large displacements in the inelastic range and dissipate energy through plastic deformations of the mild steel. Other tools introduced by them as flowing metal dampers were the torsion beam and the bending beam. In the following years, other shapes were introduced by other researchers as metal dampers, the most famous of which are the X-shaped damping and stiffness enhancing elements (ADAS), which are designed based on the flexural yielding of mild steel sheets. Wada et al. [3] conducted a laboratory study on a steel slotted damper. The slotted damper was assembled in the main frame at the location of a bracket mounted on the beam. The results of the cyclic loading test showed that the steel slotted damper had a stable hysteresis loop. Lee et al. [4] used a steel slotted damper at the connection of the cross braces to prevent buckling of the cross braces and absorb energy from earthquakes. During this research, which was conducted both experimentally and theoretically, the ultimate energy absorption capacity of a steel slotted damper under shear forces was investigated. Li et al. [5] predicted the load-displacement curve under uniform load using the three-line model method. Their research results showed that the steel slotted damper exhibited stable hysteresis behavior when subjected to shear forces.

2 | Vertical Load Bearing Systems

The vertical load-bearing system is a part of the structure that is used to support gravity loads [6].

I. Vertical loads are first applied to the roof of the structure (the first load-bearing element) and then transferred to the beams (the second load-bearing element).

II. Beams are the second load-bearing element and take the load from the roof and transfer it to their two ends, the connection point to the column.

III. Columns, which are the third load-bearing element, transfer loads from the supports at both ends of the beam to the foundation (the fourth load-bearing element). *Fig. 1*

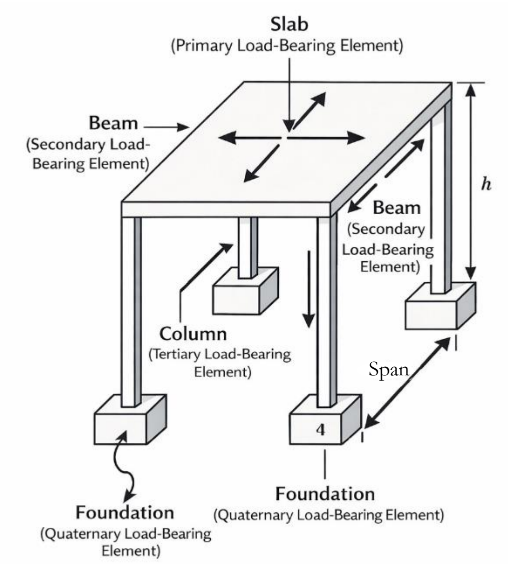

Fig. 1. Vertical load-bearing systems.

The nature of the load transfer through the beams to the supports and the method of placement of the beams (beam casting) depends on the following factors:

I. Type of usable section according to architectural design

II. Support distances and beam span length according to structural design

III. Method of load transfer by load-bearing components

IV. Selected support system

The vertical loads acting on the structure include the weight of the building, the weight of people, and the weight of equipment in the building.

3 | Lateral Load Bearing Systems

The lateral load-bearing system is a part of the entire structure that is used to withstand lateral loads caused by wind and earthquakes [7], [8]. In tall buildings with metal frames composed of beams and columns, their strength and resistance to lateral forces (wind or earthquake) depend on the degree of tightness of their beam and column connections. If the connections between the beam and column are strong enough that the angle between them does not change, the building can withstand lateral forces and not deviate from the vertical.

If there is no clamping between the beam and the column, and for example, the connections are close to a hinged state, when lateral forces are applied, the angle between the beams and columns will change and the building will lean to one side. It is clear that in this situation, the equilibrium state is not stable and will eventually lead to the failure of the building.

In the latter case, if we make a span of the building frames in height by placing the left and right pieces in triangular shapes, a solid and unchanging shape will be created in the central part ABCD, and the other parts of the building will take on a stable state by relying on it. Because the angles of any triangle will not change without changing the length of its sides; in other words, a lot of force is required to change the length of the sides. Types of lateral load-bearing systems include: torsional frame, shear wall, and bracing. *Fig. 2*.

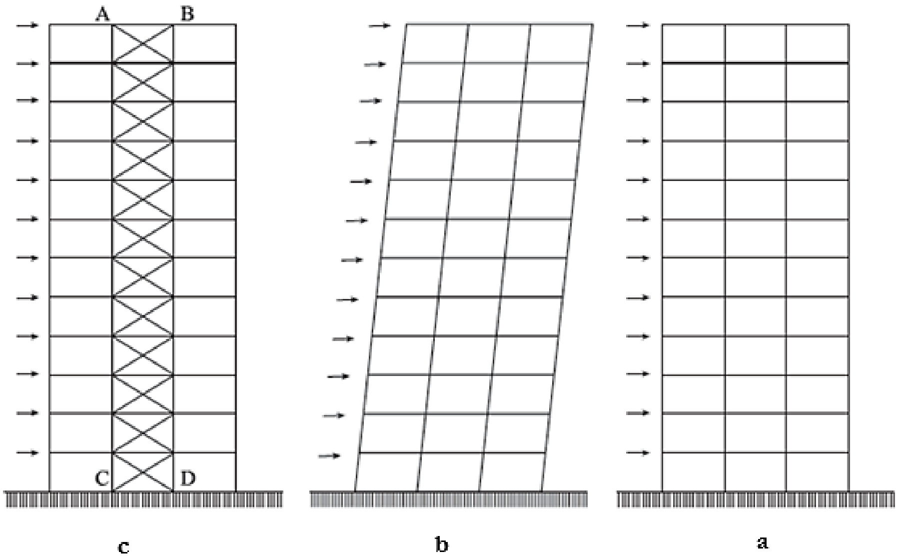

Fig. 2. The effect of the lateral load system on the behavior of the structure.

4 | The Role of Various Bracing Systems in Strengthening Steel Structures

Basically, when examining and comparing different bracing systems, the following two general criteria should be considered:

I. The structure must have sufficient stiffness to maintain deformations below the level at which damage from conventional earthquakes would be non-structural.

II. Its ductility should be such that it does not suffer structural system damage or general destruction in severe earthquakes.

Using the two general criteria above is our model for examining different and different systems, which can be divided into three general categories: concentric braces (CBF), eccentric braces (EBF), and knee braces (KBF).

5 | CBF Concentric Bracing

More or less everyone is familiar with the concentric cross bracing system, which is the oldest and most famous bracing system. The main characteristic of this system is that the neutral axes in different members intersect at a common point. One of the most important properties of concentric bracing is its high stiffness. For this reason, it is usually used as the number of floors and height of a building increase (i.e., when displacement effects become significant and decisive) and when the use of other systems becomes uneconomical. Despite their very high and good stiffness, and in addition to their ease of design and implementation, concentric cross braces have two basic drawbacks:

I. Architectural restrictions on doors and windows

II. Very low ductility and energy absorption capacity, which is mainly due to general or local buckling of the brace compression member and to some extent the weakness of the joint connections.

The first problem, namely the architectural limitations of cross braces, has been overcome by some designers with other forms of this type of brace, including Z braces (one-way), V braces, 8 braces (chevron), K braces, and diamond braces (*Fig. 3*).

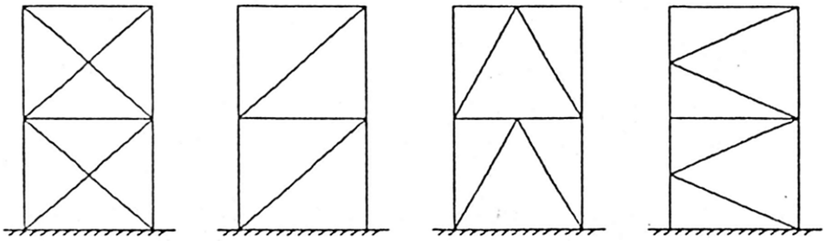

Fig. 3. Examples of concentric frames.

6 | EBF Off-Axis Bracing

This brace was first proposed and introduced in 1977 by Professor Popov at the University of Berkeley. One of the most important advantages of these braces is their high maneuverability in terms of architectural issues (*Fig. 4*). In this system, the connection point of the brace members is intentionally not located at the intersection of the beam and column. As a result, the complexity of the connection point is avoided.

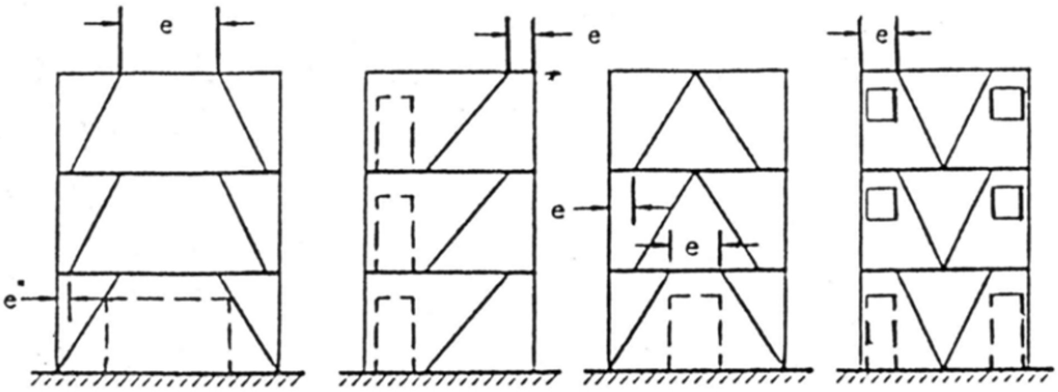

Fig. 4. Examples of off-center frames (EBF).

7 | Damping

Just as by knowing the elastic modulus of a material, we can perform calculations related to materials composed of that material, by knowing the damping of a material, we can achieve a more accurate analysis of systems composed of that material. Given that the internal damping (which depends on the material) in solids changes under the influence of various factors such as thermal effects, fatigue phenomena, and the Bashinger phenomenon, in order to have materials with a known damping, we must minimize the effects of these factors in the desired materials. Bashinger phenomenon: This phenomenon represents the energy dissipated due to the nonlinear behavior of a structure under deformations or cyclic (periodic) forces.

In general, dampers are used to reduce the dynamic response of a structure to wind and earthquake loading. The functional mechanism of such devices is such that by performing specific deformations and mechanical actions, they absorb and dissipate a large amount of energy entering the structure due to dynamic loading. The performance of such devices reduces the energy received by other structural members, resulting in less deformation. These devices can be easily installed in existing structures or replaced if necessary after loading (earthquake events).

Energy loss in dampers occurs in the form of conversion of kinetic energy to heat by friction or movement in a viscous fluid or yielding of metals, etc., which absorb energy in the loading cycle by forming residual loops. The structure requires a certain stiffness and strength to resist lateral forces and remain stable, so these dampers can replace this additional stiffness to reduce the structural responses by absorbing vibration energy so that other structural members remain within the elastic range.

Types of damping

I. External viscous damping (bare)

II. Internal viscous damping (bare)

III. Frictional damping

IV. Hysteresis damping

V. Radiation damping

9 | Study of Relative Displacement of Ten-Story Structures with Steel Frame Systems

In this study, after designing the structures under study, we define seismic isolators using link elements in SAP software. And we examine the outputs by performing dynamic time history analysis. According to the results, it is observed that in a five-story structure with steel convergent bracing under the Erzican earthquake record, the relative displacement of the structure is reduced by 56% by using a rubber base isolator with a damper in the steel structure. Also, under the Duzce and Imperial Valley earthquake records, the relative displacement of the structure has decreased by 3 and 72%, respectively.

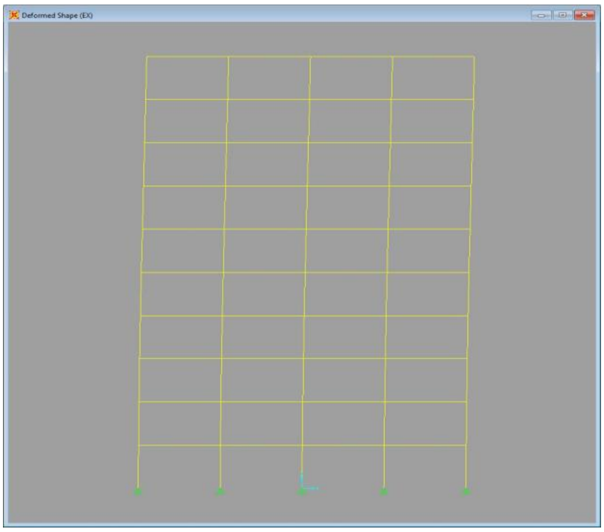

Fig. 5. Mechanism of plastic joint formation in a ten-story structure with a steel frame system.

Regarding the mechanism of plastic joint formation in a ten-story structure with a steel frame system, it is observed that in the usual case, plastic joints are first formed in the bracing members, and then in the beams and finally the columns, yielding and the structure reaching failure. This is despite the fact that in the presence of the vibration isolation system, no plastic joints have formed in any of the members, and the presence of the vibration isolation system has caused the system to remain in the linear phase.

10 | Conclusion

According to the results obtained from this research, the use of a seismic isolation system of natural rubber type with a lead center and a yielding damper is recommended in the improvement of irregular structures. Because by comparing the results obtained in short-story structures, it is possible to prevent the displacement of floors under the effect of the accelerograms obtained from real earthquakes of different earthquakes by more than 80%. And in mid-rise structures, up to more than 75%, the displacement of floors under the effect of the acceleration map obtained from real earthquakes of various earthquakes can be prevented.

According to the results of this research, the use of seismic isolators is recommended to further improve the performance of the structure in short-story structures.

Considering the mechanism of member deformation and displacements, the use of a natural rubber-type seismic isolator with a lead center and a yielding damper has been able to greatly reduce the negative effects of irregularities and control floor drift.

In general, the use of a base isolator with a damper in a steel structure in buildings can have a significant effect on reducing the maximum displacement of the structures and therefore prevent excessive displacements and stress concentration at the base of the columns.

According to the results, the type of lateral load-bearing system of the structure has an effect on the response of structures reinforced with a seismic base isolation system with a damper in a steel structure, in such a way that in a steel frame structure, due to the integrated stiffness in different floors, it has performed more appropriately than the other two cases.

The height of the structure in all three cases studied in this study had a significant impact on the response of structures reinforced with rubber isolators with dampers in steel structures. In all cases examined in this study, as the height of the structure increases, the effect of using a rubber base isolator system with a damper in a steel structure decreases, and the reason for this can be attributed to the dependence of the vertical and horizontal stiffness of the rubber isolators.

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