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Seismic Performance of a Steel Building Braced with Vertical Links in a Rocking Motion System

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Abstract

In recent years, greater emphasis has been placed on developing effective means of dissipating seismic energy in structures that keep structural response within the elastic region. In this case, using a link member in divergent bracing components is one of the solutions used in connecting to structures. In the usual process of structural design, the displacement of supports is often ignored, and supports are assumed to be rigid. However, during an earthquake, the structure usually experiences rocking motion, and the assumption of the foundation's rigidity, which is used for analysis and design, is called into question. The method of doing the work is as follows: first, using a selected laboratory sample, the results were validated in SAP software. Next, by modeling a 12-story steel frame system with divergent bracing with a vertical link member without rocking motion and with rocking motion in different cases, the effect of the presence of the vertical link member and the presence of rocking motion has been investigated using nonlinear static analysis to obtain a capacity diagram. In each case, the relevant behavior curves have been presented. According to the results of the nonlinear analysis, it is observed that by using divergent bracing with a vertical link member, we see a 5.2-fold increase in energy absorption compared to the convergent sample, but the presence of rocking motion has reduced the energy absorption of the buildings examined in the study, in a way that has limited this increase in energy absorption to 78 percent.

Keywords: Vertical links in braced frame (EBF), Rocking motion, Pushover analysis, Finite element method.

1 | Introduction

There are three seismic regions in Iran, namely Zagros, Alborz, and Central Iran. The Arabian plate from the southwest, India from the east and southeast, and Siberia from the northeast exert pressure on Iran. The maximum tolerable force of the building, simulated numerically before the Iranian structure collapsed under applied pressures, led to numerous faults and fractures, and the activity of these faults has made Iran one of the most essential seismic regions in the world. Energy from pressures stored in fault areas, released as

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destructive earthquake waves, causes the destruction and devastation of cities. Earthquakes in Iran are primarily due to the activity of these faults. The conclusion is that because the Iranian ruggedness is young and is located in the heart of the last orogenic belt of the planet (Alpine) and is located between tectonic plates, it has not calmed down in terms of tectonics and consequently seismic movements, and is still active in achieving its isostatic equilibrium [1].

Iran is located on one of the world's seismic belts and has numerous small and large faults; therefore, it has a higher seismic capacity than neighboring countries. Consequently, the location of cities and the construction of buildings examined in the research must be more accurate. In this regard, the people of our country must first believe in earthquakes and take them seriously; secondly, recognize them; and thirdly, cope with them by retrofitting the buildings studied in the research (as the people of Japan and Italy have done).

Some of Iran's faults are active, and others are inactive, but they may become active again. The movement of these faults will continue in the future. Therefore, it is necessary to prohibit the establishment of cities and settlements along the margins of the primary and active faults [2].

During severe earthquakes, significant damage is caused to the buildings studied in the research due to their inelastic behavior. According to the force-displacement curves, the buildings studied in the research enter the inelastic range after passing through the elastic range. In this region, the changes in the maximum load-bearing capacity of the numerically simulated building are negligible before the structure fails, and plastic deformations, which are more closely related to damage, occur. Therefore, in the performance-based design method, the nonlinear performance of the building components studied in the research is examined, and displacement rather than force is proposed as the most appropriate behavior indicator [3].

Knowledge of the earthquake phenomenon is increasing day by day, and the building codes examined in the study are evolving in response to these advances. In previous years, engineers knew only gravity loads, which were treated as forces in calculations. This orientation led early seismic calculation codes to focus on earthquake forces, assuming that during an earthquake an acceleration from the ground is applied to the buildings under study.

Which generate forces by reaching the masses in the buildings studied in the research ($F=m\ddot{x}$) and then by considering these forces as lateral static forces and using numerical analysis based on finite element theory using the linear matrix method and along with controlling the displacement of the buildings studied In the research, numerical analysis was performed based on finite element theory using the matrix and design methods. An R coefficient was used to consider the nonlinear behavior of the buildings studied in the research during earthquakes.

This method encountered many problems because the coefficient exhibited significant error in some cases. Also, even if seismic forces could be estimated realistically by applying this coefficient, it was not possible to precisely control the behavior of the building components examined in the study or the failure mechanisms during the earthquake.

The failure mechanisms of the building components studied are often defined in terms of displacement and strain. However, since conventional numerical analysis methods are based on finite element theory using the matrix method and force-based design, this creates a major weakness in estimating the damage to the buildings studied. In other words, within the range where the buildings studied in the research behave linearly (that is, the mathematically simulated samples numerically generated using the finite element metho) the displacement force is linear.

The force criterion can be used to control members without any problems. Still, since most of the buildings examined in research enter the nonlinear phase during earthquakes, Other mathematically simulated samples using the finite element method and numerically simulated samples do not follow linear force-displacement relationships, so the force criterion is not suitable for controlling failure mechanisms that are based on displacement and strain. Since most of the buildings studied in the research enter the nonlinear range during earthquakes due to economic considerations, in this range, the force changes (the maximum force the building can withstand before it fails, simulated numerically) are insignificant and cause significant deformations (displacements).

Therefore, the displacement criterion is proposed as the most appropriate behavioral indicator. Research on the behavior of buildings studied in recent earthquake research showed that the maximum tolerable force of a building, simulated numerically before structural failure, cannot be a suitable design criterion. In the new regulations, instead of the criterion of the maximum force that a building can withstand, simulated numerically before the structure fails, the behavior criterion is used for the design of the buildings studied in the research [4].

Geographically, Iran lies along the "Alps-Himalayan" seismic belt, which extends from Southeast Asia through India, Pakistan, Iran, and Turkey, and ends in the Mediterranean Sea and Spain. Statistical data and observations show that our relative human losses in the last century, compared to the total population, are about 5 to 6 times the figure reported for the world. Therefore, in our country, it is of great importance to pay attention to the methods for strengthening buildings studied in earthquake research and their proper implementation. The purpose of observing the regulations and rules of the earthquake code in the design of the buildings studied in the research is to create conditions that will allow the buildings studied in the research to withstand mild and moderate earthquakes without significant damage, and to withstand severe earthquakes without collapse, with the maximum force that the building simulated numerically can withstand before the structure fails [5].

In the revised Japanese code, except for buildings studied in small-scale studies with regular configurations, all buildings studied in elastically designed studies must also be controlled for compatibility with the lateral load-carrying capacity in the nonlinear limit [5].

Therefore, in the capacity design method for the maximum force that the building can tolerate simulated numerically until the seismic structure of the buildings studied in the research fails, specific members of the central system resistant to lateral force are selected and then designed with sufficient accuracy for the necessary details to dissipate the energy resulting from severe displacements And other members of the buildings studied in the study are strengthened against movements that could cause their destruction by providing the maximum tolerable force of the numerically simulated building before the structural failure in excess of the maximum tolerable force of the numerically simulated building before the structural failure in the areas of plastic joints.

Thus, it is possible to achieve optimal buildings with desirable seismic response through the design, presentation, and accurate and complete implementation of details at critical points of the structural system. Based on studies of the effects of recent earthquakes, such as the Northridge earthquake in the United States in 1996 and others, researchers observed that buildings designed to common codes performed well in terms of safety and health. However, the damage to the buildings studied in the research (especially those critical for efficiency, such as hospitals and medical centers) is very high, and their repair and restoration are not economically justified [6].

In designing with these regulations, it can be seen that the buildings studied in the research do not suffer significant damage from minor earthquakes, sustain compensable damage from moderate earthquakes, and that the building systems studied in the research remain intact during major earthquakes without collapse. In fact, these regulations include the minimum criteria necessary to ensure the safety of the buildings examined in the study during an earthquake. These regulations lack the necessary mechanism to control the buildings examined in the research at different performance levels. In other words, if the owner of the buildings examined in the research intends a specific behavioral and performance level for a specific risk level, the prescriptive methods of these regulations are ineffective. The basis for designing buildings studied in research worldwide is changing, and unlike older design regulations, specific criteria are used to achieve the desired user performance of the buildings, taking into account the level of seismicity.

In these quasi-regulations, the buildings studied in the research are expected to be designed according to the performance of the elements of the buildings studied in the research and the non-buildings in the research. For example, in the FEMA regulation, the performance goals include preventing destruction—life safety, immediate deployment, and usability after an earthquake [7].

Therefore, considering the above, it must first be determined what is expected from the buildings examined in the earthquake research. Then, considering the location of the construction site of the buildings studied in the earthquake research, the design of the buildings studied in the research is determined, and then, for this earthquake, the design of the buildings studied in the research is carried out in a way that can meet the user's performance expectations.

So it should be said that the buildings studied in the study were designed based on the principles of design, based on the performance of the buildings studied in the economic study, in such a way that the performance of the buildings studied in the study and the non-buildings studied in the study has the required performance, considering the location and seismicity of the construction site. Users of buildings studied in these studies are expected to experience certain levels of earthquake activity.

Regarding the buildings studied in the research that were designed and constructed in accordance with current regulations, such as Standard 2800 and UBC, it should be noted that the safety performance of these buildings will be compromised. However, using a design method based on the actual damage performance of the buildings studied at specific levels of ground shaking, the amount of damage to the buildings is evaluated in the analysis and interpretation against established acceptable criteria.

This method provides the owner of the buildings studied with detailed information on the expected damage at specific earthquake levels. This information then serves as a logical basis for cost-optimized decision-making. From the above, it can be concluded that the maximum load-bearing capacity of the numerically simulated building before structural failure and the performance of the buildings studied differ greatly [8] . Much work has been done in the field of performance-based design across different countries, underscoring the importance of this issue in earthquake-prone regions worldwide.

2 | Earthquake Resistant Systems

For the maximum load-bearing capacity of a numerically simulated building before the failure of the structure against lateral loads caused by wind and earthquakes, the building systems studied have been proposed and applied in various studies, which Examples include the flexural frame system, various wind-retaining systems, shear walls (including concrete, metal, and composite), and active and passive control systems using dampers.

The stiffness and maximum load-bearing capacity of the numerically simulated building before structural failure, the ductility, and, finally, the appropriate behavior of the system during an earthquake are among the most important parameters for selecting a building system studied in this study. The systems will be briefly described below [9].

3 | Mechanical Frame System (MRF)

Buildings studied in studies with complete bending frames, and buildings studied in studies with bending frames around or in part of the plan, belong to this group. In this system, concrete and metal bending frames can be used in normal, medium, or special forms. The way its energy absorption is provided by the formation of plastic joints in the beam is one of its disadvantages.

The repair of the main beam of the buildings examined in the research is complex due to its use and exploitation. In addition, despite its high ductility, this system does not behave appropriately in terms of stiffness and displacement control. Also, this system has a hysteresis curve without loss of stiffness; the maximum force that the building can withstand is numerically simulated before the structure fails, and it exhibits high energy absorption. Also, in each cycle, the numerically simulated building's maximum tolerable force increases until its structure fails, resulting in ductile behavior (*Fig. 1*).

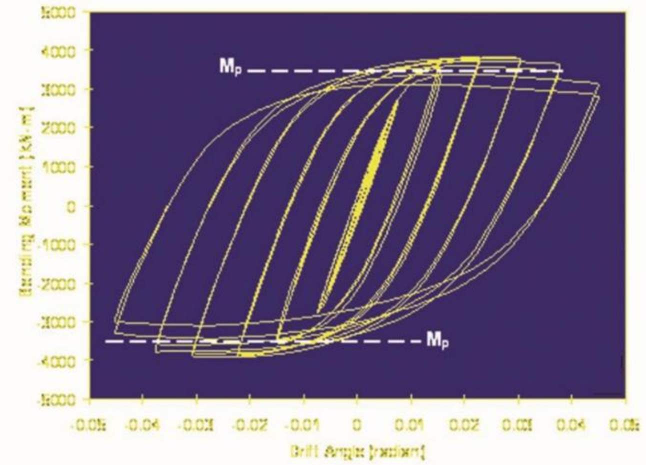

Fig. 1. Hysteresis curve of a bending frame.

4 | Windproof Systems

Convergent Bracing System (CBF)

The most common bracing system in buildings studied in metal research is the concentric cross bracing, which, despite adequate stiffness in terms of ductility and energy absorption, has generally poor performance.

The main characteristic of this system is that the axes of the different members intersect at a common point. Crossed concentric braces have two basic forms:

I. Architectural restrictions arise regarding doors and windows.

II. They have very low ductility and energy absorption capacity, mainly due to general or local buckling of the strut's compression member.

It is also observed that the hysteresis loops of this type of bracing are very unstable and irregular, and especially under alternating loads, it has been observed that after several cycles, due to buckling of the compressive members of the bracing system, the maximum load-bearing force of the numerically simulated building is lost, even up to (50%) before the structure fails *Fig. 2*.

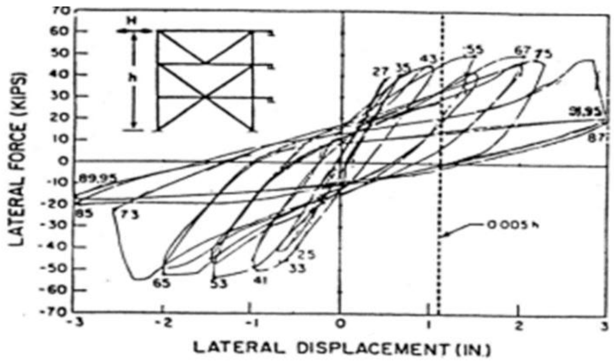

Fig. 2. Hysteresis curve of a convergent windbreak.

Types of Convergent Restraints

Types of converging braces include: one-way Z braces, 7 and 8 braces (chevron), K braces, and diamond braces, which are shown in *Fig. 3*.

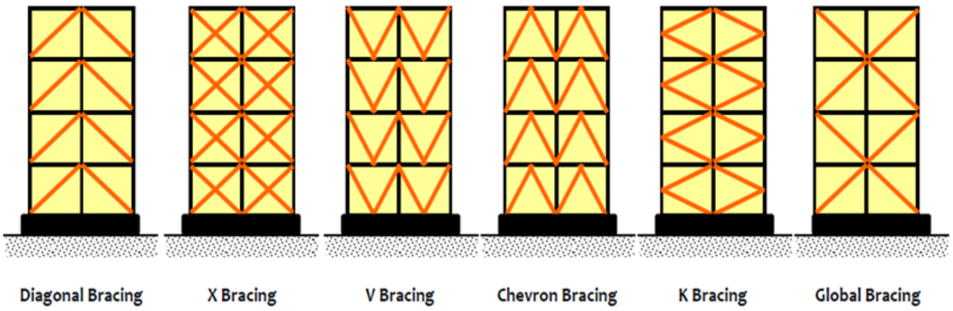

Fig. 3 . Types of convergent windbreaks.

Eccentric, Divergent Wind System (EBF)

This windbreak was first proposed and introduced in 1977 by Professor Popov at the University of Berkeley. Despite its excellent ductility, relatively good stiffness, and the convenience it provides for creating openings in architectural form and facade, the EBF system has some weaknesses due to the difficulty of repairing the bonded beam after a severe earthquake and the challenges of designing and implementing the bond itself. In the design process, determining the optimal bond length (shear bond) or (flexural bond) and providing suitable stiffeners for the beam web are the most essential points. Also, the hysteresis curve of this system (as shown in *Fig. 4*) indicates stable, regular loops with an excellent area under the curve [12].

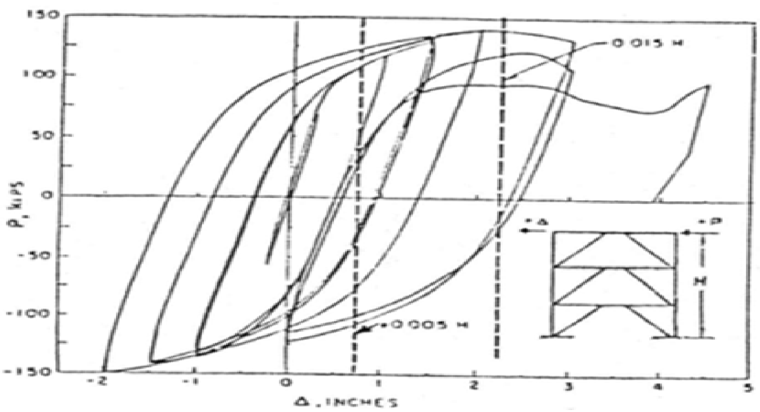

Fig. 4. Hysteresis curve of divergent windbreak.

5 | Buckling-Resistant Bracing System (BRB)

BRB wind-braced frames dissipate energy through tensile yielding of diagonal members and post-buckling behavior of the wind brace. The non-buckling windbreak has high stiffness and high energy absorption capacity. The results of mathematically simulated samples using the finite element method and numerical analysis of the buildings studied in the study show that the stiffness of the buildings with a conventional brace is approximately 3 times that of a non-buckling brace. The weight of steel used is higher than that of a non-buckling brace, and the behavior coefficient is about half that of a non-buckling brace. In this system, the windbreaks are impregnated with grease, then covered with a concrete layer and placed inside a steel sheath.

By doing this, the windbreaks become inflexible under lateral loads and will rupture only under tension and compression (F*ig. 5)*.

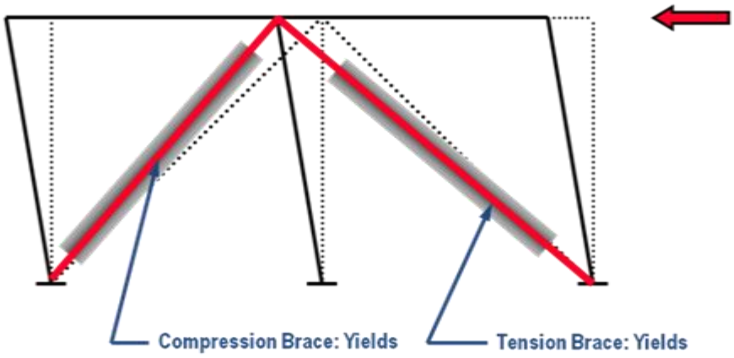

Fig. 5. Behavior of the BRB windbreak.

Knee Bracing System (KBF)

This is the latest wind-braking system introduced worldwide. In the KBF system, the energy-dissipating element is the knee member, which acts as a ductile fuse, and plastic joint formation is limited to it. Replacing this member (for the re-use of the buildings examined in the study) will be more practical after a severe earthquake. One of the most critical behavioral characteristics of the KBF system is that, in small earthquakes, stiffness and resistance to vibration loads are provided by diagonal elements. In contrast, in severe earthquakes, the knee elements come into play, providing a mechanism for energy dissipation and ductility (F*ig. 6)*.

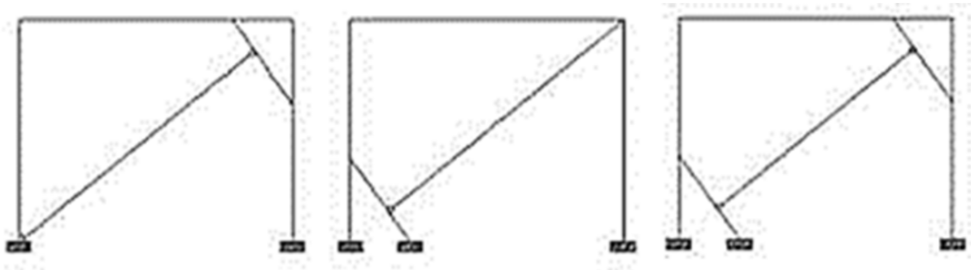

Fig. 6. Types of knee braces.

Examination of mathematically simulated examples using the finite element method. The buildings studied were converted into divergent windbreaks using vertical links and were examined in two normal states and in supported conditions with rocking motion. The results of a numerical analysis based on the finite element method using the static matrix method were examined. The additional load of the mathematically simulated samples was examined numerically using the finite element method.

6 | Conclusion

According to the results, plastic joints form first in the braces. Gradually, with the onset of buckling of an area or part of the members of the mathematically simulated sample using the finite element method, we witness the transformation of the performance of the buildings studied in the research into a mechanism. Finally, the buildings studied in the research have collapsed. The presence of divergent windbreaks and vertical link members greatly increases the energy absorption of the buildings studied, resulting in a 5.2-fold increase compared to the convergent sample. Still, the presence of rocking motion reduces the energy absorption of the buildings studied, limiting the increase to 78 percent. The presence of divergent wind bracing and vertical link members reduces the maximum force that the numerically simulated building can tolerate before the final structure fails in the buildings studied, so that in these studies, we witness a 41%

reduction in the maximum force that the numerically simulated building can tolerate before the final structure fails compared to the convergent model.

However, the presence of rocking motion increased this effect and reduced the maximum tolerable force of the numerically simulated building before the final structure failed by 55%. The presence of divergent wind bracing and vertical link members greatly increases the ductility of the buildings studied, resulting in a 1.22-fold increase in ductility compared to the convergent sample. Still, the presence of rocking motion reduces the ductility of the buildings studied, limiting the increase in energy absorption to 10 percent. The presence of rocking motion in the structure has called into question the assumption of a solid connection to the ground in design and analysis and has removed a structural rigidity constraint. The absence of this constraint has reduced the structure's initial stiffness, delaying its entry into the yield phase. Regarding the mechanism of initiation of plastic joints, it is observed that in a divergent bracing system with a vertical link member, the initiation and sequence of yielding occur entirely in the vertical link member, and practically, the bracing members have not entered the yielding phase. Therefore, more care must be taken in the design of the vertical link member. Due to the vertical link member's high sensitivity, especially during reciprocating motion, the author suggests using stiffeners at regular intervals. The vertical link member can also be designed with bolted connections, allowing them to be replaced after an earthquake and significantly reducing costs.

Conflict of Interest

The authors declare no conflict of interest.

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