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Seismic Assessment of Combined Effects of Knee Bracing and Dog-bone Connections in Dual Moment Frame Systems for Tall Steel Structures

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Abstract

The growing population and urbanization have led to an increasing interest in constructing tall buildings, particularly in large cities. However, the frequent occurrence of earthquakes worldwide has necessitated the development of systems with high ductility and sufficient lateral stiffness. The special dual system of moment frame with bone connections and knee bracing systems are two examples of such systems. In this study, the seismic behavior of these two systems in combination with tall structures was investigated. Ten, thirteen, and sixteen-story frames with four different combinations of bone joints and knee bracing were analyzed using ETABS software. Linear and nonlinear static (pushover) analyses, as well as linear and nonlinear dynamic (time history) analyses, were conducted. Seismic parameters were then calculated for each case and compared. The results emphasized the importance of considering multiple factors and coefficients when evaluating the seismic performance of structures. (DOI:**https//doi.org/10.52547/JCER.5.1.46**)

Keywords: Behavior coefficient; Special dual system of moment frame; Dog-bone connections; Knee bracing; Tall steel structures, Seismic behavior

1. Introduction

The concept of using behavior factor to calculate earthquake forces was first introduced in 1957, and since then, it has become widely used in seismic design codes. Researchers from different nationalities have proposed various methods to calculate the behavior factor, which can be broadly divided into two groups: American and European methods. While American methods are simpler and more practical, European methods are more complex and difficult to use in practice [1].

Bone joints are an innovative design solution for improving the flexibility and seismic resistance of frames exposed to severe vibrational loads. The

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concept of weak arrow-strong column was the driving force behind the development of these joints. Essentially, a reduced section along a limited length of the arrow near the connection site is used, similar to a bone muscle. This reduction is applied at the top width of the arrow, hence the name "Reduced Beam Sections" (RBS) [2].

The use of bone connections offers several advantages, including preventing stress concentration at the node, redistributing stress around the connection of the arrow to the column, and limiting the amount of stress redistributed and made uniform at the top width of the arrow. These connections also increase the flexibility of the joint, forming a hardened post-plastic joint, which can warn the residents before damage occurs due to excessive flexibility. Additionally, bone connections increase the frequency period and behavior coefficient of the special bending frame system, and the bone fuse prevents unwanted forces from passing through the hardened joint, thereby ensuring the connection of the arrow to the column is not threatened. Moreover, bone connections change the type of failure from sudden and brittle to flexible and adaptable. They also reduce the costs of connection and structure implementation, reduce implementation time, and increase the reliability of the structure. Overall, bone joints are a promising solution for enhancing the seismic performance of structures.

Fig1. shows a Dog-bone connection. Based on Engelhardt et al [2], the following ranges and values are suggested for selecting dimensions a, b, and c in knee braced frames:

$$a \cong (0.5\sim0.75)b_f \quad (1)$$

$$\mathrm{b} \cong (0.65\sim0.85)d \quad (2)$$

$$c = 0.25b_f \quad (3)$$

$$\mathrm{R} = \frac{4\mathrm{c}^2 + \mathrm{b}^2}{8\mathrm{c}} \quad (4)$$

A knee braced frame system uses the knee member as a secondary structural member, acting like a "fuse" that creates suitable ductility. In addition, the diagonal bracing member provides excellent lateral stiffness to the frame. This combination results in a system that has both sufficient ductility and lateral stiffness, with the knee member acting as a structural fuse during severe earthquakes to prevent damage to the main structural members.

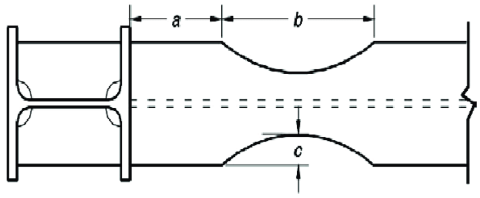

Fig1. Dog-bone connection

The advantages of knee braced frames include their ability to create suitable ductility and lateral stiffness, prevent damage to main structural members during earthquakes, and allow for simple and economical repair and reconstruction of knee members as structural fuses. Strengthening the diagonal bracing member does not affect the lateral performance of the frame and increasing the cross-sectional area of beams and columns can improve the lateral performance, with the effect of increasing the cross-sectional area of the column being greater than that of the beam. However, architectural limitations may restrict changes to beam length or column height, making knee members a valuable option for improving lateral performance by adjusting their own cross-sectional area and length. [3].

Various researchers have investigated the behavior factor Knee bracing and Dog-bone [4-11]. The objective of this study is to evaluate the behavior of steel structures under earthquake loads. Specifically, the effect of factors such as building height (low-rise, mid-rise, and high-rise), the use of dual systems of moment-resisting frames with bone joints and knee braces on the static response of the structure under earthquake loads is investigated. The results of these analyses are compared to provide useful information about the behavior factor of structures, from its fundamental definition to determining it for different types of structures.

2. Modelling

Frames have been designed with three different heights: 30 meters (10-story frame), 39 meters (13-story frame), and 48 meters (16-story frame), all with an equal floor height of 3 meters. The distribution of bone joints in these structures at different heights is presented in the table 1.

Table1. Position of plastic joints in diffrent frame

	Tape af frame	Stories in which plastic joints are used
1	Brace	Without plastic joints
2	Fail	5, 6, 7
3	Middle	3, 4, 5, 6, 7
4	All	All Stories

Previous studies have indicated that "most damages in tall structures occur between half to two-thirds of their height." Therefore, four different conditions were considered for the distribution of bone joints in height. The first condition involved no bone joints. The second condition placed bone joints between half to two-thirds of the height of the structure. The third condition placed bone joints between one-third to two-thirds of the height of the structure. Finally, in the fourth condition, bone joints were distributed throughout the entire height of the structure. The fourth condition was added based on the author's engineering sense, which stated that in braced structures, the effect of bone joints would be less due to the bracing system's presence and power in controlling lateral deformation compared to non-braced structures. Therefore, adding bone joints would have a better effect.

It should be noted that there are several differences in the structural models, which will be discussed shortly. For example, in the 10-story buildings, a 5-meter span is placed between the span containing the bone joints and the span containing the knee braces. This is done to prevent the knee members and bone joints from being located near each other and around a connection (beam to column) that could potentially impact their performance. In contrast to the 10-story buildings, in 13-story structures, the 5-meter span is placed next to the 6-meter span containing the bone joints. The 4-meter span containing the knee braces is placed next to the 5-meter span to examine the effects of knee members, bone joints, and braced frame on the behavior coefficient of the structures. In 10-story buildings, the 6-meter span is used as the side span, and in 13-story buildings, it is used as the middle span. However, since the placement of bone joints in the side span may affect their performance, in 16-story structures, another 4-meter span is added to the right side of the frame to examine the frame stiffness simultaneously and to study the new distance from the braced frame. The earthquake motions used are summarized in Table 2.

Table2. Earthquake motions used

Motion	Time(Sec)	a_{max}	Predominant period (sec)
Bam	50	0.799g	0.70
El Centro	16	0.463g	0.74
Tabas	25	0.852g	0.20
Northridge	10	0.843g	0.34
Naghan	10	0.730g	0.08
Mexico City	12	0.621g	0.22

3. Results and Discussion

According to research conducted by scholars from Berkeley University, the behavior factor of a structure is composed of four coefficients, as mentioned in equation (5) [12]:

$$R_U = R_S \times R_\mu \times R_R \times R_\zeta \quad (5)$$

where RS is the Overstrength factor, Rμ is the ductility factor, RR is the uncertainty coefficient, and R_ζ is the damping coefficient. While RR is significant for analyzing structures against wind loads, and R_ζ is important when dampers are employed in the structure, they are not considered in this study.

The first step in this study was to conduct linear and nonlinear dynamic analyses (Time History) on sample frames subjected to scaled seismic excitations

Table3. Ductility factor (R_μ) in different system

Number of storis	Braced	Fail	Middle	All
10	4.4403	4.4379	4.4335	4.4409
13	4.4299	4.4306	4.4307	4.4407
16	4.0115	4.0138	4.0145	4.0169
average	4.2939	4.2941	4.2926	4.2995

Table 4. Overstrength factor in different system

Number of storis	Braced	Fail	Middle	All
10	2.1892	2.1877	2.2053	2.2087
13	2.1892	2.1877	2.2053	2.2087
16	1.7678	1.7655	1.7668	1.7851
average	2.0487	2.0469	2.0591	2.0675

Table 5. behavior coefficient in different system

Number of storis	Braced	Fail	Middle	All
R_μ	4.2939	4.2941	4.2929	4.2995
R_S	2.0084	2.0071	2.0165	2.0282
R_U	8.6239	8.6187	8.6566	8.7202

using the graphical software ETABS v2018. The ductility factor (R_μ) was then calculated by dividing the linear base shear to the nonlinear base shear. Table 3 illustrates ductility factors in diffrent frames.The results of the study showed that the rate of increase in the ductility factor is higher in the All type frames compared to other types. This finding indicates that braced frames should maintain a better distribution of skeletal joints throughout the structure's height, and concentrating these joints within the lower half or two-thirds of the height will not be significantly effective.

The overstrength factor is defined as the ratio of the maximum base shear to the base shear at the first plastic hinge formation. The values of base shear at the first plastic hinge formation and during structural damage with cracking, as well as the calculated values of overstrength factor for each frame, can be found in columns 2, 3, and 4 of tables 6 to 8, respectively. Table 4 shows the overstrength factors in lateral-resistant systems for frames.

The reduction coefficient due to ductility was also assessed, and it was found that as the number of stories in the frames increased, this coefficient improved relatively in Fail and Middle systems. However, as seen in Table4, the Fail and Middle systems decrease with an increase in the number of stories and become equal or lower in comparison to the Brace system. This is consistent with the inverse relationship between the reduction coefficients due to ductility and increased resistance, which was mentioned earlier. Despite the superiority of the All system in the reduction coefficient due to ductility, this system also showed superiority in the increase resistance coefficient, which is noteworthy. This indicates that the combination of knee braces and distributed bone joints throughout the structure's height is superior to other configurations.

Comparing similar peripheral systems at levels 15 to 18, it was observed that the added resistance coefficient decreases with height, consistent with the results obtained by other researchers. This trend can be predicted for different numbers of stories. The final values of these coefficients were calculated by averaging the values of the added resistance coefficients in each type of the four peripheral systems, and the results are shown in Table 4. Note the relative superiority of the all system type.

The Overstrength factor R_S was calculated and evaluated in the previous sections, and the reduction coefficient of shape deformation Rμ was calculated by dividing the linear base shear to the nonlinear base shear. In order to calculate the overall behavior coefficient of the frames, the average of RS and Rμ were calculated for each frame type. The values for the four peripheral systems can be seen in Table 5. The values for the middle system were calculated for 10-story and 13-story frames. According to the results, the All system has the highest overall behavior coefficient among the peripheral systems, indicating its superior performance in resisting lateral loads. Moreover, the behavior coefficient increased with the height of the structure, which is consistent with the findings of other researchers. The obtained results can be used as a reference in the design of high-rise structures with similar characteristics.

4. Conclusions

• The findings of this study suggest that the use of bone joints and knee braces in the lateral-resistant system of high-rise buildings can lead to significant improvements in their seismic performance. The all state, which combines both knee braces and distributed bone joints, has been shown to have the best performance in terms of both deformation and resistance coefficients. It also has the highest behavior coefficient, indicating its superior overall performance compared to other states.

• The results of this study also emphasize the importance of considering multiple factors and coefficients when evaluating the seismic performance of structures. The behavior factor, which consists of four coefficients, provides a comprehensive measure of a structure's ability to resist seismic forces. R_R and R_ζ, which were not used in this study, may also be important in certain situations, such as wind loads or the use of dampers.

• Finally, it should be noted that the behavior and performance of structures under seismic loads is a complex and multi-dimensional topic that requires careful consideration of various factors, including the design and construction of the structure, the characteristics of the site and soil, and the nature of the seismic hazard. The findings of this study contribute to our understanding of the behavior of high-rise buildings under seismic loads and provide useful insights for future research and design.

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