Future Generation of Communication and Internet of Things (FGCIOT)

Journal homepage: https://sanad.iau.ir/journal/fgciot

PAPER TYPE (Research paper)

Seismic behavior of knee bracing frame, buckling-restrained brace, and eccentrically braced frame using nonlinear dynamic analysis

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Article Info

Article History:
Received: 15 December 2024
Revised 14 January 2025
Accepted 27January 2025

Keywords:
Dynamic analysis, IDA, Energy dissipation and absorption capacity

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Abstract

In this study, the seismic performance of three bracing systems including knee bracing frame (KBF), buckling-restrained brace (BRB), and eccentrically braced frame (EBF) for steel moment-resisting structures with varying heights (5, 10, and 15 stories) were investigated using nonlinear time-history analysis and incremental dynamic analysis (IDA). The structural models were first designed in ETABS and analyzed under the influence of different earthquakes, including El Centro, Kobe, and Tabas, using nonlinear time-history analysis. The seismic response and optimal bracing system for each scenario were assessed. To further evaluate of the failure conditions and the ductility capacity of the frames, IDA was conducted in Seismostruct. The results indicated that the 5-story frame with a BRB system, the 10-story and the 15-story with a KBF system exhibited the best seismic performance. The IDA curves revealed that the 5-story BRB-braced structure demonstrated limited ductility and experienced brittle failure, with a large number of failed elements. As the building height increased, the structural ductility improved, particularly in the 10-story frame where the use of KBF significantly enhanced the results. For the 15-story frame, combining high ductility and the KBF system resulted in a highly effective seismic response, as evidenced by smooth IDA curve development, indicating a soft and stable structural behavior. Therefore, the KBF system is proposed as a highly suitable option for high-rise buildings to enhance ductility, energy absorption, and dissipation capacity, and to control the yielding and failure of structural members.

Introduction

In designing buildings in earthquake-prone areas, two fundamental aspects must be considered: First, ensuring sufficient stiffness and strength in the structure to control lateral displacements and prevent damage to structural and non-structural elements during an earthquake. Second, ensuring adequate ductility and energy absorption capacity to prevent total collapse of the structure during a severe earthquake. In braced frame systems, it is expected that only a small percentage of lateral forces will be resisted through the moment and flexibility of the frame connections. Diagonal members directly convert shear forces into axial compressive and tensile forces, transferring them to the vertical system.

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Studies have shown that eccentrically braced frames (EBFs) provide elastic stiffness comparable to special concentrically braced frames (SCBFs), especially when short link beams are used. In such systems, braces are expected to yield and buckle at inter-story drift ratios of approximately 0.3% to 0.5%. During severe earthquakes, braces may undergo post-buckling axial deformations up to 10 to 20 times the yield deformation. To accommodate such large cyclic deformations without premature failure, braces and connections must be carefully designed. The lack of confinement in braces leads to local buckling and high bending strain concentrations, reducing ductility. To overcome these shortcomings, buckling-restrained braces (BRBs) have been developed and extensively studied. BRB frames, a subclass of concentrically braced frames, offer improved ductility and energy absorption due to the prevention of global brace buckling and the resulting loss of resistance during large displacements [1-3].

The moment-resisting frame system is one of the most widely used seismic-resistant structural systems worldwide. A major problem with buildings constructed using this system is the significant lateral displacement of the structure, which leads to damage in both structural and non-structural components. Bracing systems offer an effective method for seismic strengthening of such moment-resisting structures. A newer type of brace, known as the buckling-restrained brace (BRB), addresses the key issue of traditional braces buckling under compressive forces by providing symmetrical behavior in both tension and compression. Due to the yielding of BRBs in both tension and compression, they can absorb substantial energy and are recognized as hysteretic dampers. Their behavior is enhanced by the combination of a steel core and the confining effect of concrete and steel casing, which results in improved energy dissipation and ductility compared to conventional braces [4]. Since the core principle behind hysteretic dampers lies in the plastic deformation of steel, the design methodology for structures with BRBs is similar to that of eccentrically braced frames (EBFs). Therefore, the equivalent static method provided in the Iranian standard 2800 for EBF systems can also be used to estimate design forces for structures equipped with BRBs [5]. Fang et al. investigated BRBs and introduced a method for restoring residual inter-story drifts using shape memory alloys (SMAs) in the brace core. Their results indicated that SMAs could effectively reduce residual deformations and allow for smaller brace sizes [6]. Nazarimofrad and Shokrgozar studied the re-centering capability of BRBs using metallic and SMA cores, finding that these systems reduce residual inter-story drifts and construction costs [7]. Asgarkhani et al. examined BRBs in 2 to 12-story buildings, challenging previous methods of estimating residual drifts and introducing a more accurate, less conservative approach [8]. Yakhchalian et al. proposed a seismic intensity measure to more efficiently assess residual drifts in BRBs, reducing analysis time and improving the quality and quantity of required ground motion records [9]. Hu et al. evaluated seismic economic losses in mid-rise steel buildings equipped with different lateral-force resisting systems: a moment-resisting frame (MRF), a BRB frame (BRBF), and a system with non-buckling braces (RNBF). These systems were designed using the equivalent lateral force method, and the study converted the IDA results into corresponding fragility curves [10-11].

This study compares key seismic parameters such as period, story drift, base shear, and energy response between BRB, KBF, and EBF bracing systems for frames of various heights. The 5, 10, and 15-story steel frames are modeled and analyzed using ETABS for design, and then subjected to incremental dynamic analysis (IDA) in Seismostruct using three selected ground motions. These records are chosen to differ in intensity, nature, and duration to reflect a range of seismic impacts on the structures.

Methods

This section introduces the design and modeling process of steel frames equipped with knee bracing frames (KBF), buckling-restrained braces (BRB), and eccentrically braced frames (EBF). The models are developed using ETABS software. Subsequently, using the incremental dynamic analysis (IDA) method in Seismostruct, the structures are evaluated, and the results for each sample building are extracted and analyzed. To this end, three two-dimensional residential buildings of 5, 10, and 15 stories are designed based on the fourth edition of the Iranian code 2800 [5] and chapter 6 of the Iranian national building regulations for load application [12]. The structural design follows chapter 10 of the Iranian national building regulations [13] using ETABS. Time-history analysis is then performed in ETABS to extract base shear, displacement, and energy-time curves for the selected earthquakes. The objective at this stage is to compare lateral displacement at the top floor, evaluate base shear and absorbed energy, and assess the capacity of each bracing system in energy absorption and base shear resistance. Subsequently, the structures are modeled and analyzed again in Seismostruct using IDA to evaluate the performance of different bracing systems and extract their corresponding IDA curves.

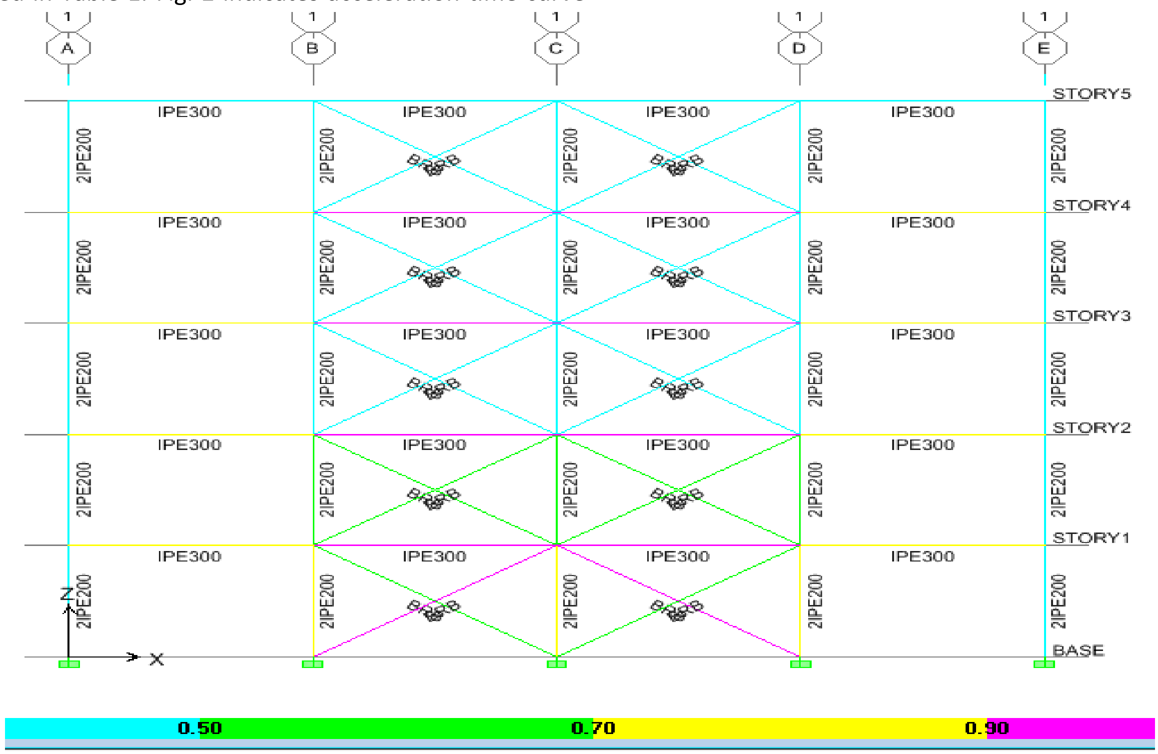
All the considered frames are residential in function and located in Tehran, categorized as a high seismic hazard zone. The lateral load-resisting system is a simple steel frame combined with KBF, BRB, or EBF. The floor system consists of composite beams (chromite). The soil type is classified as type II, with an allowable bearing pressure of 1.2 kg/cm^2. The height of all stories, including the ground floor, is 3.1 meters. The structural design follows either the equivalent static or response spectrum method. The building has four spans, each 5 meters wide. Fig. 1 shows the results of static analysis and frame design in ETABS software for a 5-story frame with BRB, EBF, and KBF braces. Ground motions used in the nonlinear dynamic analysis must be consistent with the expected seismic hazard of the site in terms of frequency content, response spectrum, and duration of strong ground shaking. Records should reflect the tectonic characteristics of the region and the proximity to active faults. Paired ground motions are applied simultaneously in orthogonal directions along the primary axes of the building. The final structural response at any time is considered as the maximum among those obtained from all input records. In this study, three earthquakes El Centro, Tabas, and Kobe were used to assess structural response under varying seismic intensities, frequencies, and durations. The earthquake records used in this study and their characteristics are listed in Table 1. Fig. 2 indicates acceleration-time curve of the El Centro, Kobe, and Tabas earthquakes for time history analysis.

Table 1: Earthquake records used in this research and their characteristics

Earthquake name	Date	Station	Frequency	PGA(g)
Elsentro	17/05/1976	ELC	High-Mid.Frequency	**0.644**
Tabas	16/09/1978	TAB	High-Mid.Frequency	**0.836**
Kobe	16/01/1995	KJM	Low.Frequency	**0.707**

Results and Discussion

The results showed that the maximum base shear for the 5-story frame with BRB, EBF, and KBF systems was 270, 160, and 165 tons, respectively. The maximum roof displacement was 15 mm for BRB, 60 mm for EBF, and 100 mm for KBF. The maximum energy absorption was 5500, 8400, and 25000 ton-mm, respectively. Accordingly, the BRB-braced frame exhibited the most optimal seismic behavior. Under the Kobe earthquake, the maximum base shear for the same frame configurations was 160, 380, and 180



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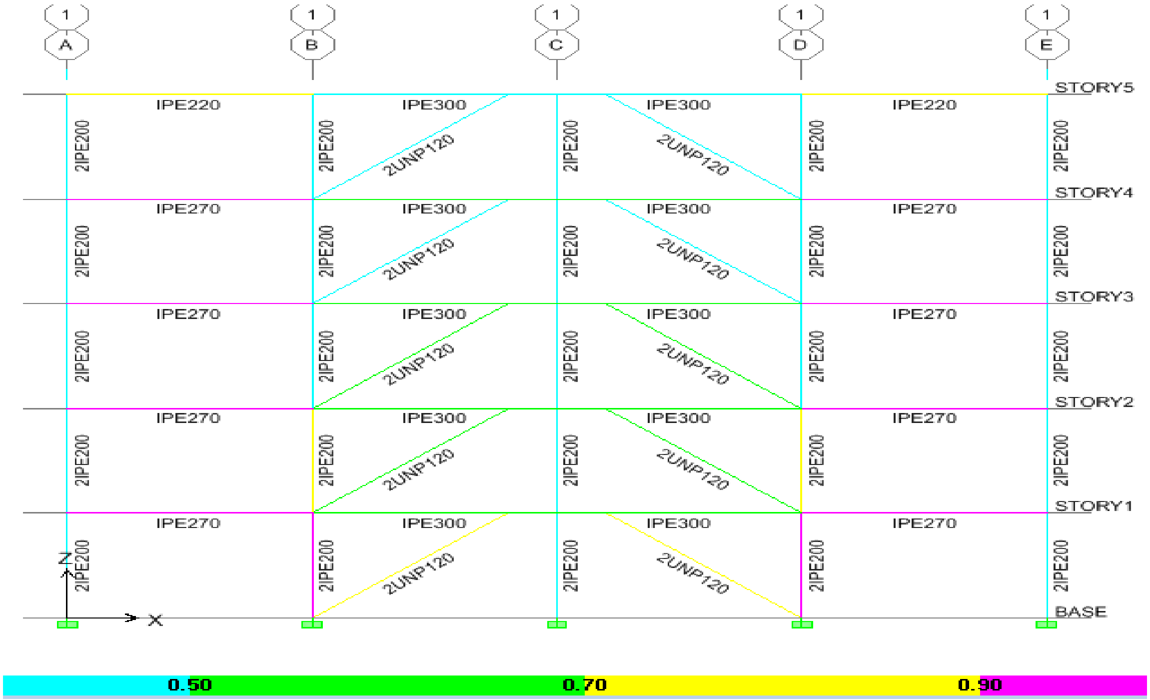

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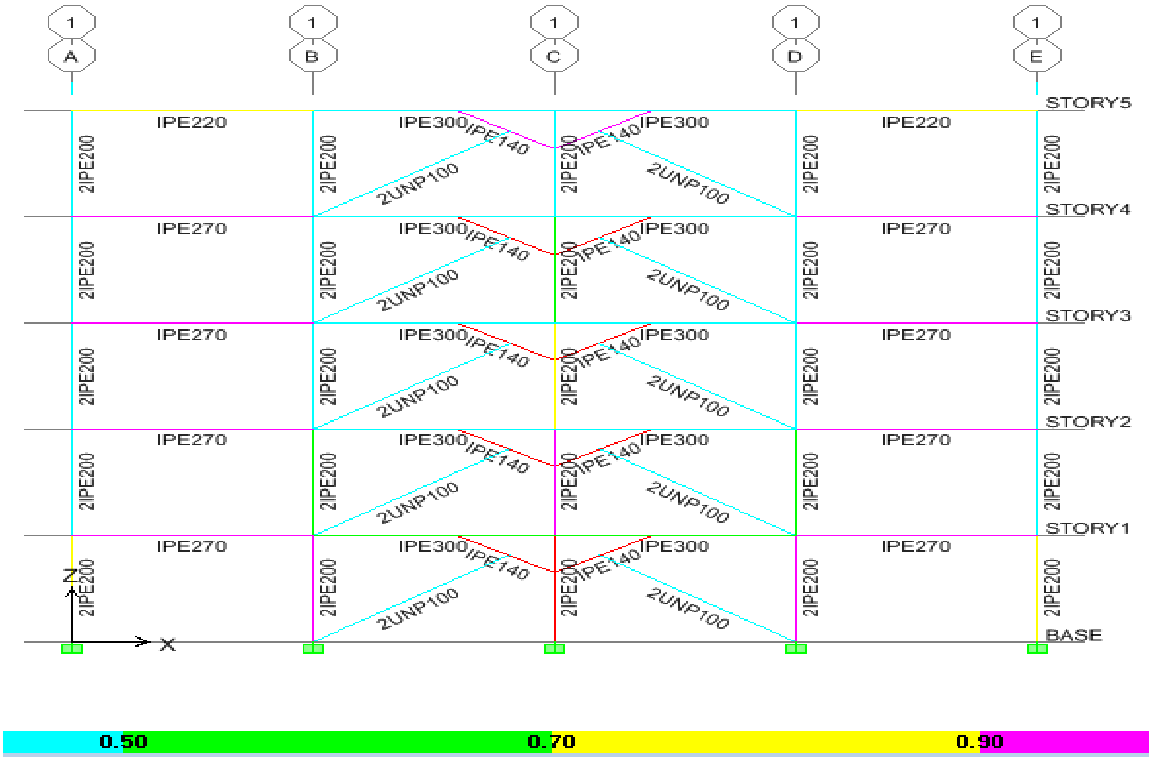

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Fig. 1: Results of static analysis and frame design in ETABS for a 5-story frame with a) BRB, b) EBF, and c) KBF braces

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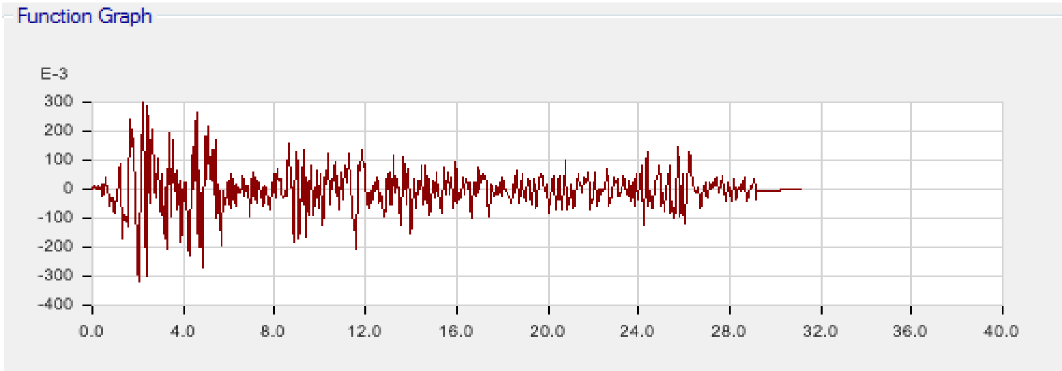

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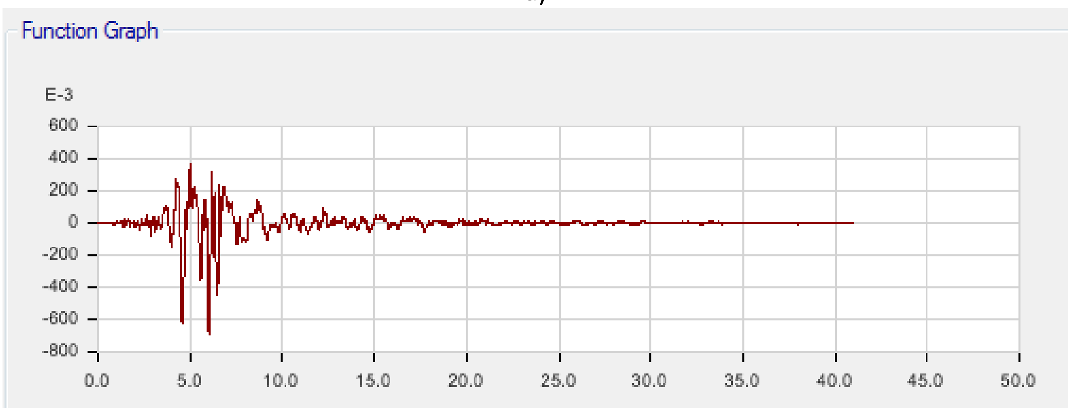

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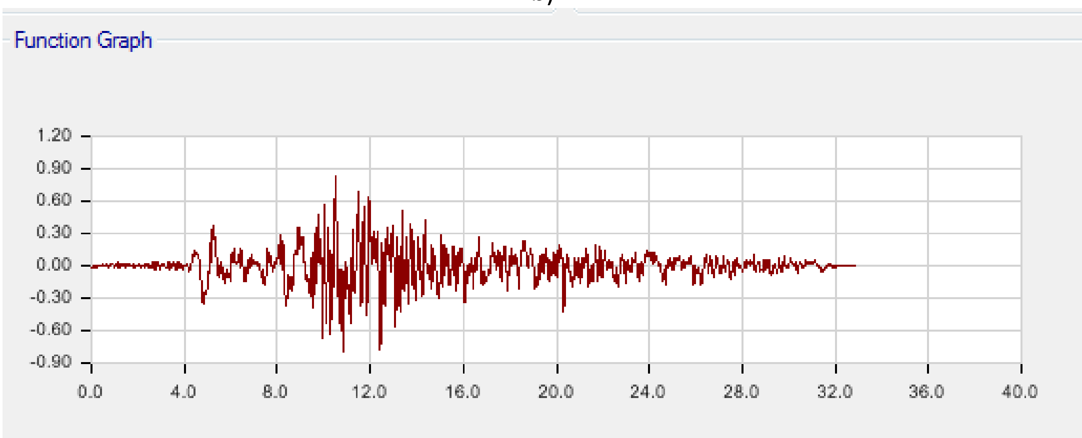

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Fig. 2: Acceleration-time curve of the a) El Centro, b) Kobe, and c) Tabas earthquakes for time history analysis

tons. Roof displacements were 10 mm (BRB), 75 mm (EBF), and 120 mm (KBF). Energy absorption values were 1500, 37000, and 30000 ton-mm. Again, BRB showed the most favorable behavior. Under the Tabas earthquake, the maximum base shear was 390 (BRB), 320 (EBF), and 300 tons (KBF). Roof displacements were 50, 90, and 120 mm, and energy absorption was 13000, 30000, and 72000 ton-mm, respectively. Thus, BRB was considered optimal. For the 10-story frame under El Centro, maximum base shear was 560 (BRB), 130 (EBF), and 200 tons (KBF). Roof displacements were 100, 60, and 120 mm. Energy absorption was 34000, 8500, and 22000 ton-mm. Here, EBF was optimal. Under the Kobe earthquake, the base shear increased to 720 (BRB), 380 (EBF), and 270 tons (KBF). Roof displacements were 85, 150, and 200 mm, and energy absorption reached 80000, 75000, and 64000 ton-mm, respectively. This time, KBF showed superior performance. Under Tabas, base shear was 1100 (BRB),

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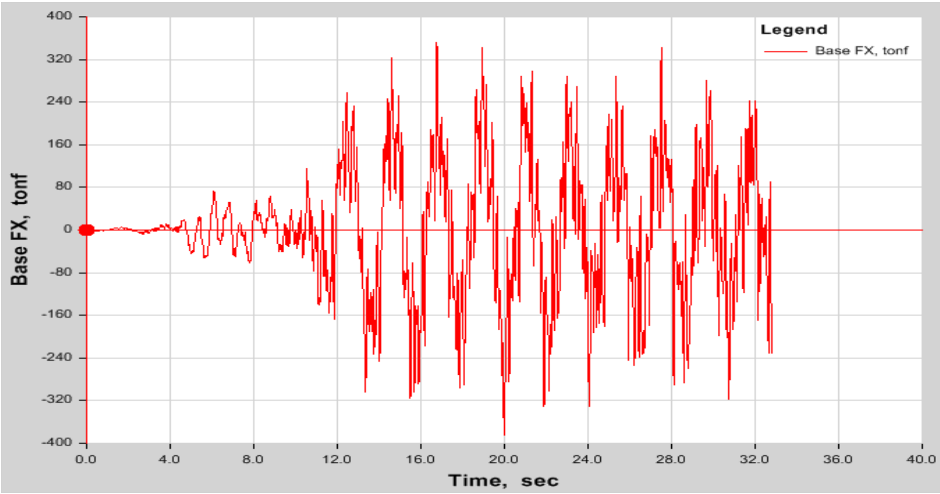
800 (EBF), and 360 tons (KBF). Roof displacements were 100, 120, and 130 mm. Energy values were 217000, 260000, and 105000 ton-mm. KBF was identified as the best system. Fig. 3 presents the time-history curves of base shear, lateral displacement, and energy for the 10-story frame with KBF under the Tabas earthquake. For the 15-story frame under El Centro, base shear was 410 (BRB), 300 (EBF), and 74 tons (KBF). Roof displacements were 100, 120, and 130 mm, and energy absorption was 27000, 28000, and 15000 ton-mm, with KBF again showing superior behavior. Under the Kobe earthquake, base shear increased to 620, 400, and 140 tons, with roof displacements of 120, 150, and 160 mm, and energy absorption of 108000, 97000, and 39000 ton-mm, respectively. KBF was the best. Under Tabas, the values were 1050, 450, and 240 tons for base shear, 150, 60, and 170 mm for roof displacement, and 230000, 148000, and 105000 ton-mm for energy, confirming KBF's effectiveness.



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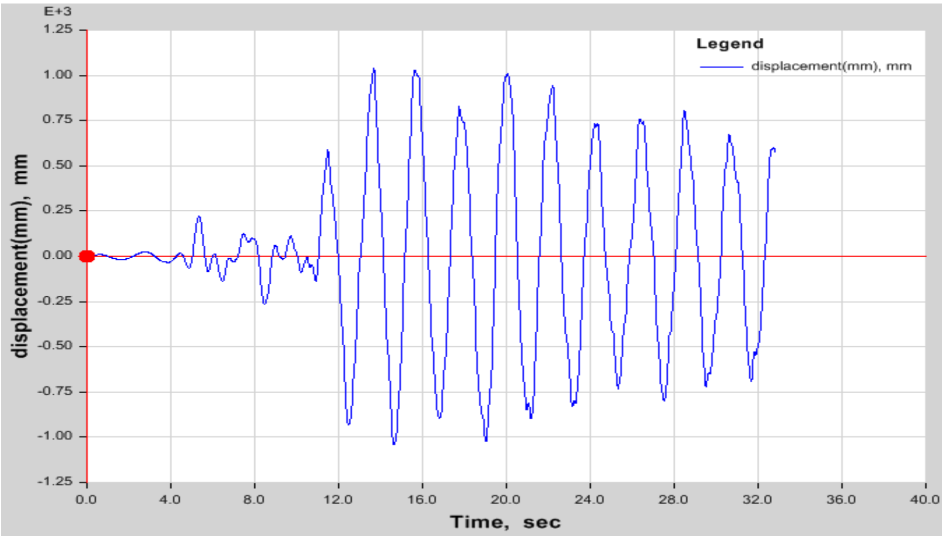

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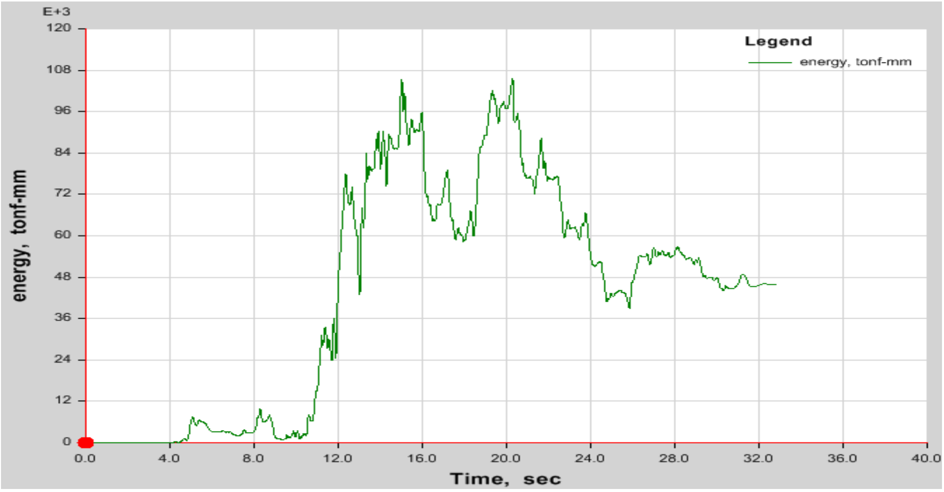

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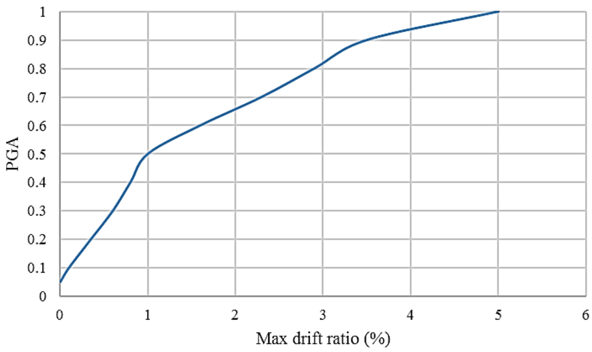
Fig. 3: a) Base Shear, b) Lateral Displacement and c) energy curves for a 10-story frame with KBF bracing under the Tabas earthquake

Fig. 4 shows IDA curves for the Tabas earthquake for 5, 10, and 15-story frames with BRB. The results clearly indicate that the 5-story frame with BRB experienced brittle failure and widespread element damage under seismic loads. As building height increased, ductility improved, particularly in the 10-story frame with KBF. The use of diagonal link beams in KBF systems helps prevent damage to braces and connections, significantly increasing capacity and avoiding brittle failures. In the 15-story frame, combining high ductility with KBF resulted in smooth IDA curve development and soft, desirable structural behavior, highlighting KBF as an optimal system for tall buildings.

In order to evaluate the fragility curves, four damage states namely slight, moderate, extensive, and complete were considered. Subsequently, the fragility curves were plotted as PGA versus the probability of failure for the aforementioned damage states. It should be noted that the fragility curves are based on the most critical earthquake scenario considered in the study. The results obtained from the analysis of fragility curves for the 5-story frame with different bracing systems clearly indicate that the frame equipped with a BRB system demonstrates superior performance compared to the other two configurations.



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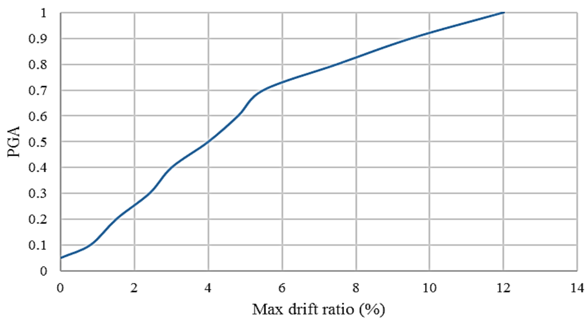

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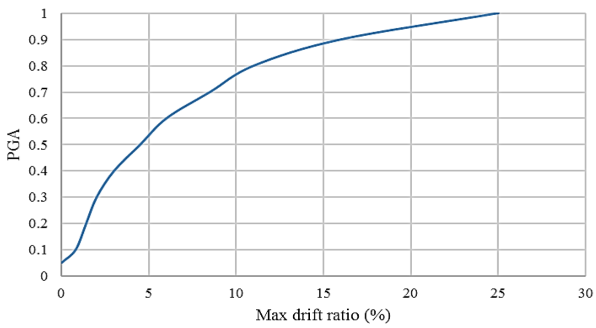

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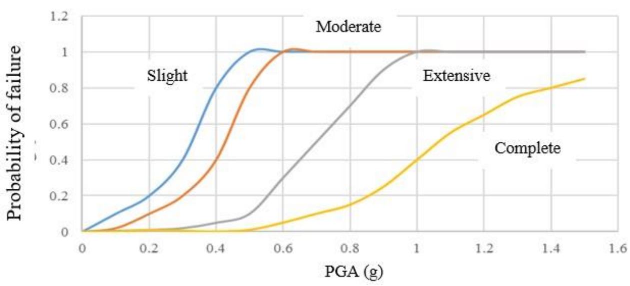
Fig. 4: IDA curve for Tabas earthquake with BRB bracing: a) 5-story frame, b) 10-story frame and c) 15-story frame

In this regard, and according to the fragility curves shown in Fig. 5 for the BRB system, the curves corresponding to slight and moderate damage states are closely spaced. This trend is also observed for the other two bracing types. However, for the BRB and EBF systems, the fragility curves associated with extensive and complete damage states are significantly separated from those of slight and moderate states, which is highly desirable. This indicates that the implementation of the aforementioned bracing systems notably enhances the frame’s ductility and energy dissipation capacity due to nonlinear behavior. Therefore, the probability of failure and complete damage is low and is only significant at high PGA levels with very low occurrence probability. It is important to note that, in the case of using KBF, the fragility curves for slight, moderate, and extensive damage states are relatively close, which at first glance may appear unfavorable. However, the use of a link element in this bracing system can significantly improve its performance. By yielding this element, not only can the yield and damage zones be controlled and improved, but the curve for extensive damage will also shift considerably away from the moderate and slight damage states, leading to more favorable performance for the structure. It is also worth noting that in such cases, the bracing system itself remains undamaged, and only the knee or link element sustains damage, which can be easily replaced. Based on the fragility curve results, it was found that using the EBF system increases the probability of slight, moderate, extensive, and complete damage by approximately 10%, 15%, 20%, and 25%, respectively, compared to the BRB system. Additionally, the use of the KBF system results in an increase of approximately 25%, 35%, 50%, and 60% in the probability of slight, moderate, extensive, and complete damage, respectively, compared to the BRB system.



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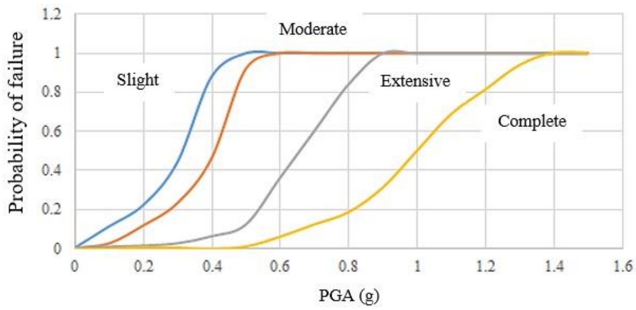

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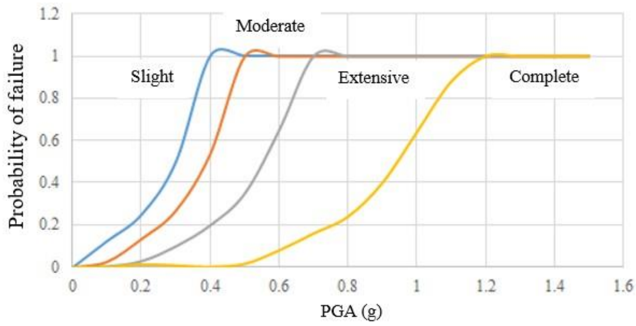

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Fig. 5: Fragility curves of a 5-story frame with a a) BRB b) EBF and c) KBF braces

Conclusion

The findings of this study clearly demonstrate that the development of IDA curves closely related to structural ductility was suboptimal for the 5-story BRB-braced frame. This structure experienced brittle failure with widespread element yielding under seismic loading. As building height and thus ductility increased, the 10-story frame showed improved behavior, particularly when utilizing the KBF system. In the 15-story frame, the combination of high ductility and the KBF system resulted in a highly favorable seismic performance, with a smooth and progressive IDA curve indicating soft and stable behavior. Therefore, the KBF bracing system is proposed as a highly logical and efficient solution for tall buildings to enhance ductility, capacity, energy absorption, and dissipation. It also serves as an effective tool for controlling member yielding and failure under seismic loads.

Author Contributions

Each author role in the research participation must be mentioned clearly.

M. H. Eslami: Investigation, validation, writing - original draft. M.R. Mostakhdemin Hosseini: Methodology, supervision, writing - review & editing.

Acknowledgment

The author gratefully acknowledges the referee and managing editors of FGCIOT for their work on the original version of this document.

Conflict of Interest

The author declares that there is no conflict of interests regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy have been completely observed by the authors.

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