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Comparison of Seismic Behavior of Eccentrically Braced Frames with Vertical and Knee Links in Retrofitting the Reinforced-Concrete Buildings with Intermediate Moment-Resisting Frame Systems

Farzad SAGHAFI [1], Ali SEYEDKAZEMI [2], Hossein MEHRABIAN [3], Morteza Hosseinali BEYGI [4]
[1] M.Sc. in Civil Engineering – Structure, Islamic Azad University, Ayatollah Amoli Branch, Amol, Iran
farzad.s.46@gmail.com
[2] Lecturer, Department of Civil Engineering, Ayatollah Amoli Branch, Islamic Azad University, Amol, Iran
[3] M.Sc ,in Civil Engineering – Structure, Islamic Azad University, Islamshahr Branch, Tehran, Iran
[4] Assistant Professor in Civil Engineering Dept., Nooshirvani Industrial University, Babol, Iran

Abstract

Given the fact that some reinforced-concrete (RC) buildings have not met resistance against seismic loads, it is mandatory to adopt a suitable and economically cost-efficient method to retrofit them. One appropriate method is application of steel Eccentrically Braced Frames (EBFs). This article is aimed at evaluation of seismic performance of retrofitted reinforce-concrete buildings by EBFs with single and knee links. For evaluation of modeled buildings, different editions of the Iranian Seismic Code (Standard No. 2800) were reviewed. To this end, three Moment-Resisting Frames (MRF) of four-, eight-, and twelve-story buildings with medium ductility were modeled where they were designed for seismic loads based on Standard 2800, 2nd edition. In order to evaluate buildings under modified seismic loads, models were seismically reloaded based on the Standard 2800, 3rd edition. Reanalysis showed that the stress ratios exceeded 1 in most columns. Therefore, buildings were retrofitted using EBFs with knee and single vertical links and their seismic performance were evaluated using nonlinear static analysis. Results indicate that knee bracing systems are more efficient than bracing systems with vertical link in increasing rigidity and controlling displacements, while they significantly reduce ductility. For example, application of knee bracing system in the twelve-story building can cause an 11% reduction in displacement in comparison to bracing systems with vertical links.

Keywords : Seismic performance evaluation; retrofitting , Eccentrically Braced Frames (EBFs) , single link beams , knee links

1. Introduction

Taking a quick look at the buildings constructed in Iran in the past shows that a huge percentage of reinforced concrete buildings are not adequately resistant against seismic forces. They are not also essentially designed, constructed and analyzed properly to remain in stable conditions under forces caused by earthquake. Design standards and building codes are changing constantly, and lack of spaces and resources on the one hand, and deterioration and reconstruction expenses on the other, have brought a serious attention to be paid in recent years to the evaluation of current status of the buildings' conditions according to new standards. Extensive researches have been also conducted to devise new methods of retrofitting the current buildings. Knee bracing systems are preferred to those with single vertical links because of the use of two knee links at each span, so they provide following advantages:

1. A reduction in the number of bracing spans which results in a reduction of the number of bracing members and their joints;
2. A reduction in architectural limitations;
3. A decrease in implementation speed via reducing the amount of executive operations;
4. Reducing the concentrated moment applied on beam and controlling spring joint adjacent to vertical link in story beam;
5. A reduction in design forces of connection devices of vertical links, story beam and bracing members.Many scholars have presented analytical models for link beams including both horizontal and vertical types, each of which with their own advantages and disadvantages. It will be briefly referred to hereunder. Shayanfar et al. [1] (2009) evaluated seismic behavior of EBFs with composite vertical links both experimentally and analytically. Mozaffari et al. [2] (2012) examined retrofitted reinforced-concrete buildings with EBFs using single vertical link. They concluded that addition of V-EBF braces into concrete buildings can change the flexural loads applied to the columns into axial, thereby stress ratio in columns is reduced to even less than 1. Moreover, changing the seismic loads into axial forms can transfer plastic hinges from columns to beams; therefore, more than 90 percent of columns are kept safe from failure. Veter [3] (1998) utilized shear link defined by Ricler and Popov to describe shear links in V-EBFs. The model generated in Drain 2DX was used in nonlinear static and dynamic analyses of V-EBFs. This model was defined as a combination of beam-column elements and non-elastic joints. All non-elastic behaviors were attributed to joints. Based on previous studies, they admitted kinematic and isotropic hardening in links on which shear yielding is dominant, and they used non-isotropic hardening rule. In this case, shear yielding complies with a modified isotropic hardening, while flexural yielding only complies

with a kinematic hardening rule. Popov and Halmstad [4] (1983) suggested a finite-element model using the stress formulation. The main defect of this model is consideration of strain hardening. In dynamic analysis, strain hardening is a key factor due to cyclic behavior of link beam. Another weakness of this method is division of link into a large number of elements in order to minimize errors which results in the inefficiency of this model in nonlinear analyses of EBFs. Ghobara and Abul-Fath [5] (2000) investigated seismic performance of non-ductile reinforced-concrete buildings which were strengthened using steel EBFs with vertical link. In order to analyze the nonlinear behavior of link beam, three lines model proposed by Ghobara and Radman was adopted. This model was prepared to be used in DRAIN-DX2 software. Finally, the results were indicative of the great impact of such bracing in reduction of damage index compared to other systems.This article is specifically aimed at retrofitting four-, eight-, and twelve-story reinforced-concrete buildings by EBFs with both single and knee links. At the end, a comparison is made between two systems.

2. Modeling

One of the methods which has recently attracted academic attention is application of EBFs with vertical link beam and knee-bracing systems in order to retrofit the buildings. In this study, three medium-ductility reinforced-concrete buildings with four-, eight-, and twelve-stories have been modeled in SAP2000[6]. The selected plan is a square of 15*15 m2 area and 5m spans (Fig. 1). All stories have 3.2 meters height. Length of vertical link beam in EBFs was considered to be 50 centimeters. The dead and live loads of stories were 600 and 200 kg/m2 respectively. In addition, the dead and live loads of roof were respectively regarded to be 500 and 150 kg/m2. Beams and columns sections of reinforced concrete were designed to be 250 kg/cm2 for the concrete compressive strength and 4,000 kg/cm2 for the yielding strength of bending bars, according to ACI 318-99[7]. For link beams, ST37 typical mild steel was used. The desired buildings were designed according to Iranian Seismic Code (Standard No-2800, the 2nd edition). Dimension of beams and columns are designed in a way to make stress ratio more than 1, for it is desired to take into account the uncertainties generated in the concrete resistance as a result of time pass. Afterwards, seismic coefficients were calculated and applied according to Standard 2800[8], the 3rd edition, to enable us to control and examine designed buildings based on newer codes. Results showed that in new conditions, columns cannot meet the seismic needs cited in the Standard 2800, the 3rd edition, and stress ratios have exceeded 1 in most columns, i.e. they have to be retrofitted. For doing so, EBFs with single vertical and knee links were added to buildings according to Fig. 2. ST37 typical mild steel were utilized for link beams in both systems. The best stress ratios were regarded for link beams, and stress ratios in columns were reduced to a permissible amount (less than 1) after completion of design. Then, by changing seismic coefficients from the 3rd edition of Standard 2800 to the 4th edition, nonlinear static analyses were conducted for existing buildings, and results were examined.

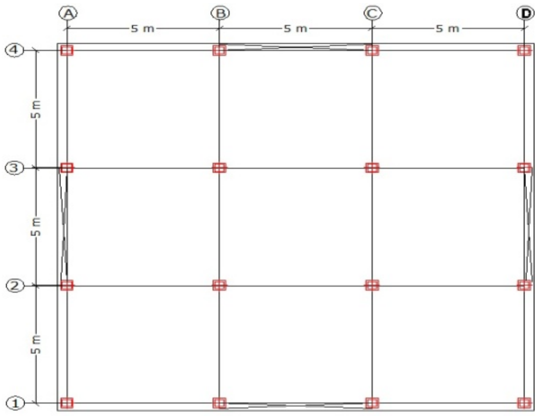


Fig. 1: plan of investigated and retrofitted buildings

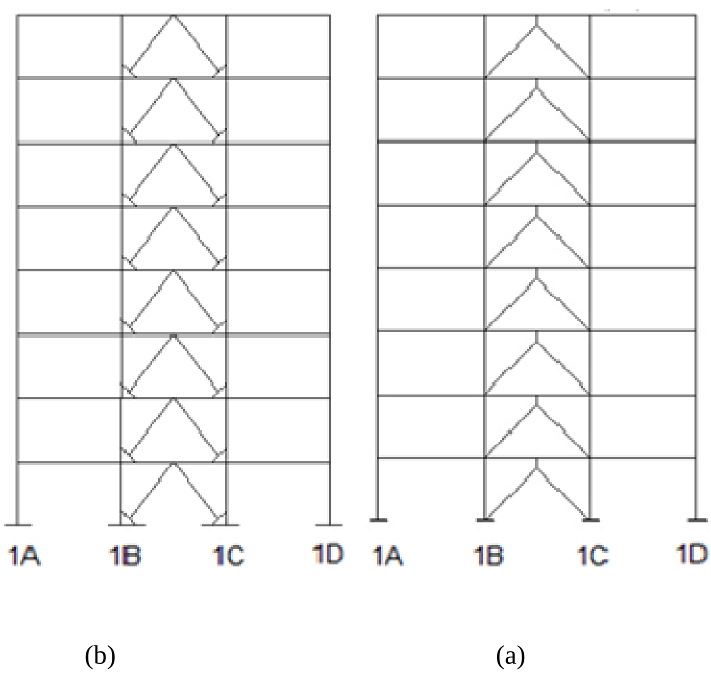


Fig. 2: (a) the eight-story building with single vertical link beam
(b) The eight-story building with knee link beam

3. Analysis of EBF Behavior with vertical and Knee links

Behavior of EBFs depends on the length of their links. Basically, short-length EBFs show shear behaviors and those with lengthy links have flexural behaviors. The shorter the length of the link, the higher the rigidity of frame would be. Experiments carried out on this system are expressing the good behavior of this system with short-length links rather than with longer lengths in dynamic loads. Therefore, it is suggested to select short-length links in designs.

EBFs are designed in a way that they don't buckle even under severe lateral loads. In newer seismic codes, there are more controls on designed models. The main objective in determination of seismic regulations is categorized as follows:

a. Each building should be resistant against minor earthquakes without being damaged;

b. Some non-structural damages are allowed in average earthquakes;

c. buildings should not be overturned during severe earthquakes, however some structural and non-structural damages are permitted.To achieve these purposes under general conditions, each structure should have adequate rigidness and resistance. If a building is designed to resist severe seismic loads elastically and considering the fact that such severe earthquakes happen only once in a century or more, this design cannot be economical. Consequently, each structure should be able to attract and depreciate energy in severe seismic loads. This requires that each structure should be resistant against a proportionate amount of lateral alternative forces and be able to endure severe elastic deformations. In other words, structures should be ductile.

For EBFs, design concepts are used based on capacity of braces, columns and components of beams outside links in order to make sure that yielding just happens only in ductile links disregarding magnitude or distribution of lateral loads.EBFs with single vertical link beam are beneficial compared to EBFs with horizontal link in that they prevent damages to the floor of stories when an earthquake happens. They can also be repaired and substituted easily after earthquakes due to the fact that links are engaged with basic load bearing system. They can also be applied in seismic retrofitting of structures especially in critical structures such as power plants.

In application of vertical link in structure retrofitting, there are limitations such as dimension fit among floor beams and link size, reinforcement of floor beam due to generation of concentrated moment at the end of link, etc. These limitations are more serious in concrete structures as shear forces are transferred into concrete beams. EBFs with knee link are proposed to be applied in order to eliminate mentioned limitations.

4. Nonlinear Static Analysis

In nonlinear static analysis, the performance of structure is evaluated only in its maximum response under design earthquake. To reach this situation, first, the relationship of base shear is determined. This relation is appeared as a curve that is referred to as capacity curve or pushover curve. The relevant static analysis is called pushover analysis. After capacity curve is obtained, a point on this curve is determined that this point should be compatible with demand displacement of earthquake design. This point is called Performance Point (PP) and its corresponding displacement is demand displacement or target displacement. In nonlinear static method, lateral load is gradually applied until displacement exceeds an expected amount in a determined point. When lateral load is increased, displacements and internal forces are taken into account constantly. This method is quite similar to linear static analysis with some differences as follows:

Table 1: Approximate target displacement of buildings with KBF and VEBF

	4 story		8-story		12 story		Note
	2800-v3						
	V-EBF	KBF	V-EBF	KBF	V-EBF	KBF	
C0	1.4154	1.4018	1.4161	1.4416	1.4553	1.5466	Any Load Pattern
C1	1	1	1	1	1	1	Te>Ts
C2	1	1	1	1	1	1	LS, Type II
C3	1	1	1	1	1	1	a > 0
Sa	0.5733	0.6017	0.3852	0.3995	0.2882	0.2927	A×B
Ts	0.5	0.5	0.5	0.5	0.5	0.5	Soil, Type II
Te	0.5855	0.5465	1.0613	1.0036	1.6387	1.5725	Mode 1
St (cm)	6.92	6.267	15.28	14.429	28.015	27.844	$\delta_t = C_0 C_1 C_2 C_3 S_a \frac{T_e^2}{4\pi^2} g$

•Nonlinear behavior of all members and components of structure are entered into analyses;

•The effect of earthquake is evaluated in terms of deformations rather than application of certain loads. In nonlinear static analysis, the model of nonlinear behavior should be determined in multi-linear or simplified two-linear form for each element of structure. In analyses, when lateral loads are gradually increased, deformations and internal forces of all components are calculated and compared with their capacities. This is more complex than linear static analysis, but its results can represent real behavior of structure better and present more useful information for designing. Unlike linear analysis methods, internal forces would be almost equal to expected values under design earthquake as it considers the nonlinear behavior of materials. In performance-based designing and retrofitting, structures are subjected to a set of lateral forces. As lateral displacements increases, forces existing in members also increase to the extent that lateral forces exceed yielding limits in some points of the structure and result in generating plastic hinges. Displacement value is specified for a certain performance level. This displacement is called target displacement in FEMA-356[9]. In

ATC 40, however, this is called demand displacement. In Table 1, target displacement values for building using EBFs with single vertical and knee links are exhibited.

5. Analysis of Results

As mentioned before, this article addressed reinforced-concrete moment frame buildings designed under Standard 2800, the 2nd edition. They were reassessed based on the 3rd edition of this code. Since some members of these buildings were weak, they were retrofitted by single and double vertical bracings. Weak members and retrofitting-caused stress reduction percentage are shown in the Table 2.

Table 2: column stress ratio values in (a) a four-story building, (b) an eight-story building, and (c) a twelve-story building , the percentage of decrease in stress with single link beam

Column ID	Initial Stress Ratio before Retrofitting	Stress Ratio after Retrofitting	
		EBF with Single Link	KBF
	St No 2800,Version3		
1B-4	1.122	0.705	0.536
1B-3	1.119	0.647	0.431
1B-2	1.157	0.802	0.768
1B-1	1.151	0.707	0.813

(a)

Column ID	Initial Stress Ratio before Retrofitting	Stress Ratio after Retrofitting	
		EBF with Single Link	KBF
	St No 2800, Version3		
1B-8	1.022	0.674	0.596
1B-7	1.116	0.564	0.442
1B-6	1.2	0.567	0.422
1B-5	1.237	0.637	0.57
1B-4	1.225	0.848	0.804

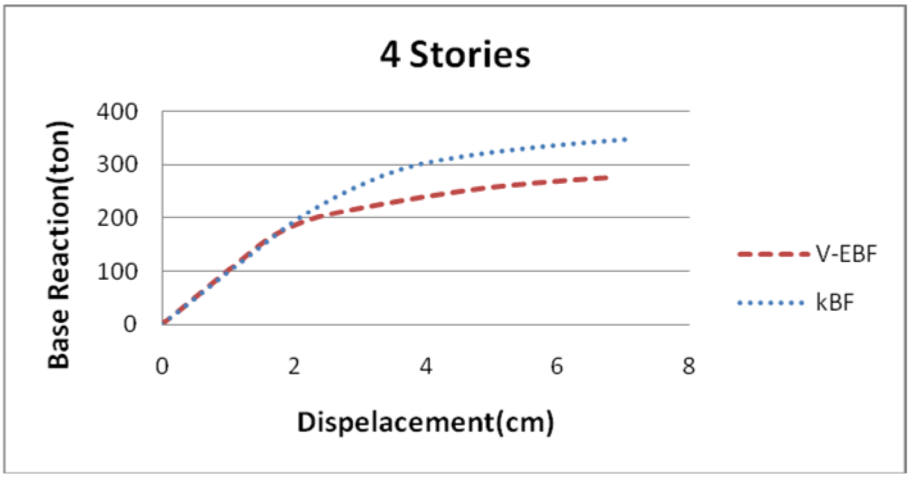
1B-3	1.142	0.927	0.907
1B-2	1.09	0.827	0.862
1B-1	0.957	0.949	0.947

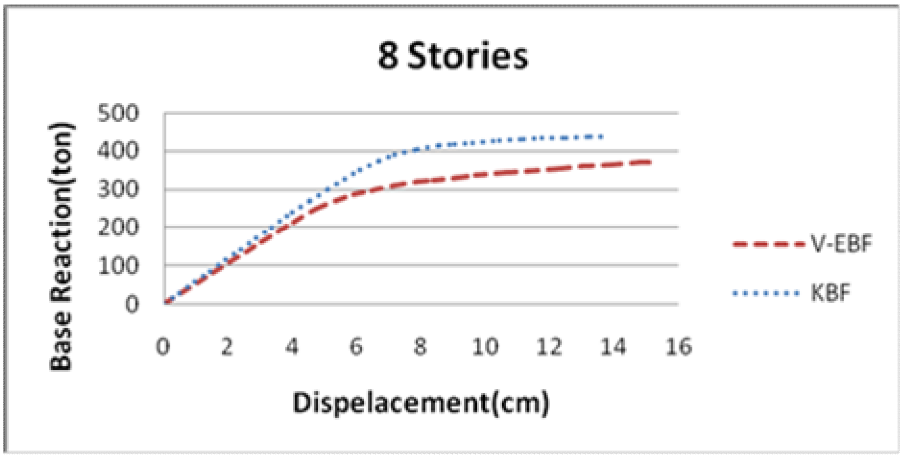
(b)

Column ID	Initial Stress Ratio before Retrofitting	Stress Ratio after Retrofitting	
		EBF with Single Link	KBF
	St No 2800, Version3		
1B-12	1.09	0.824	0.806
1B-11	0.99	0.698	0.415
1B-10	1.13	0.635	0.397
1B-9	0.995	0.574	0.494
1B-8	1.24	0.683	0.596
1B-7	1.106	0.665	0.605
1B-6	1.168	0.833	0.775
1B-5	1.171	0.864	0.807
1B-4	1.06	0.953	0.955
1B-3	1.04	0.91	0.960
1B-2	0.979	0.932	0.971
1B-1	0.994	0.959	0.998

(c)

Fig. 3: Base shear obtained from nonlinear static analysis of selected models





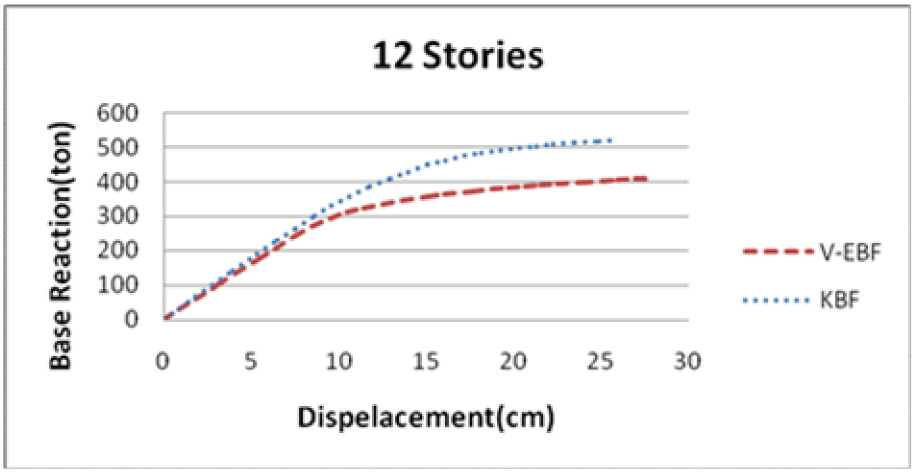


Fig. 4: Base shear curve – displacement of modeled 4-, 8-, and 12-story buildings

5.1. Lateral drift evaluation of stories

Table 3 mentions some limitations for controlling lateral drift of concrete frames. These limitations should not be considered as acceptance criteria for retrofitted structures, since these values can be only thought as approximate and qualitative behavior of structure in a performance level. Lateral drift of retrofitted structures often depends on the demands of non-structural components. In figures 5 and 6, Transient Drift is maximum lateral displacement of stories that is predicted to occur during design earthquake in the building. Permanent Drift is maximum lateral displacement of stories that remain in the building after earthquake due to plastic behavior or fractions.

Table 3: drift limitations based on FEMA-356

Elements	Type	Immediate Occupancy (IO)	Life Safety (LS)	Collapse Prevention (CP)
Concrete Frames	Drift	1% transient; negligible permanent	2% transient; 1% permanent	4% transient or permanent

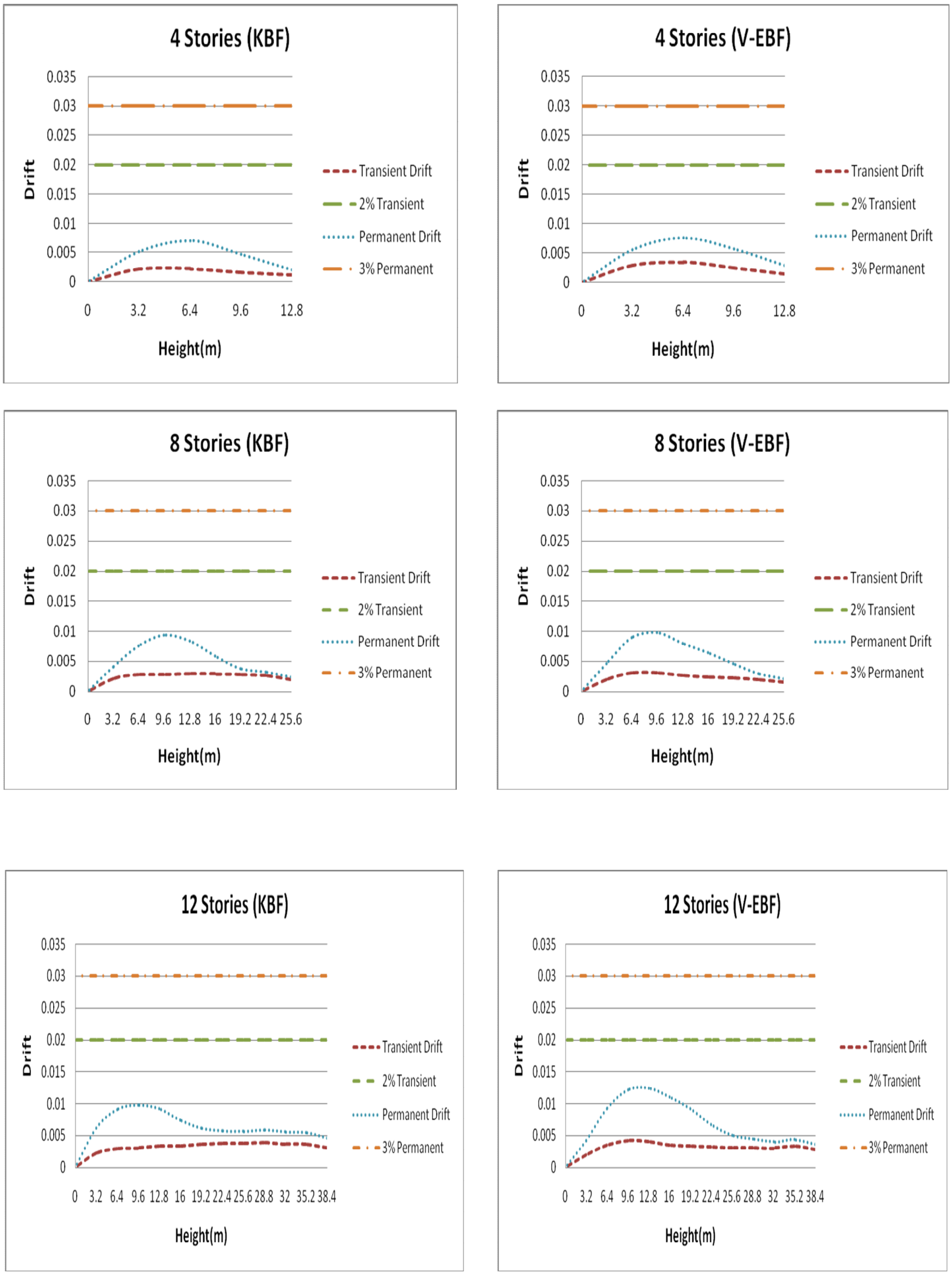


Fig. 5: drift curve of 4-, 8-, and 12-storey buildings with single link vertical connection and knee-

6. Conclusions

This study evaluated seismic performance of EBF-retrofitted reinforced-concrete buildings with single and knee links, and its results are briefly enumerated hereunder:

1. Retrofitting reinforced-concrete four-, eight-, and twelve-story buildings using EBFs with single vertical links can reduce stress ratio in columns by 38, 33, and 25% respectively compared to non-retrofitted reinforced-concrete buildings. These reductions are 57, 46, and 30% respectively for EBF-retrofitted buildings with knee links. Therefore, EBF-retrofitted buildings with knee links can reduce the stress ratio in columns more than EBF-retrofitted buildings with single links. In addition, reduction in stress ratio in retrofitted buildings decreases as the height of building increases.

2. Nonlinear static analysis indicated that if link beam is designed in a way that shows shear behavior, then our seismic needs are met.

3. Nonlinear static analysis carried out on EBF-retrofitted buildings with single vertical and knee links show that lateral displacement in four-story buildings retrofitted by knee EBFs is about 8% higher compared to four-story buildings retrofitted by single EBFs. This value is reduced in eight- and twelve-story buildings by 10 and 11%, respectively. Base shear in 4-, 8-, and 12-story buildings retrofitted by knee EBFs is respectively increased by 19, 15, and 27% compared to those retrofitted by single EBFs.

4. Application of vertical links in EBFs can massively prevent main beam from rotating which results in a reduction in the amount of structure destruction. Knee-bracing systems are much better in preventing main beams from rotating. Rotation of main beam causes a disruption to performance of some certain structures such as industrial structures and power plants whose heavy equipments are braced by floor beams.

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