



Effect of near-field earthquake excitation on seismic behavior of knee-braced moment frames

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Abstract

Inelastic behavioral characteristics of knee-braced moment-resisting frames having 3, 8 or, 12 stories were investigated under near-source earthquake excitation using initially pinned frames that were subsequently substituted with rigid knee elements. These frames were designed so that the knee braces would yield and buckle under seismic loading. Inelastic time-history analysis was carried out to assess the structural performance of the buildings by evaluating the maximum axial forces of the columns, vertical displacement of internal beams, roof horizontal displacement, and maximum base shear of columns in the building members using PERFORM-3D software. The nonlinear behavior of the frames was investigated by comparing the results of pinned and rigid knee elements subjected to near-field earthquakes. The results indicate that rigid-to-pinned connections for knee elements can increase the axial forces of columns by nearly 15% for a 3-story building and about 7% for 8- and 12-story buildings. The vertical displacement of the beams was noticeable, especially for the three-story building. The horizontal displacement of the roof and base shear of columns using pinned connections for knee elements were generally greater than for the rigid connections.

Keywords Near-field earthquake · Knee elements · Steel structures · Knee-braced moment frames

Introduction

Bracing is a very effective upgrading strategy to increase the global stiffness and strength of steel and composite frames. It can increase the energy absorption of structures and/or decrease the demand imposed by earthquake loading. Structures with augmented energy dissipation may safely resist forces and deformations caused by strong ground motion. The attainment of global structural ductility is achieved within the design capacity by forcing inelasticity to occur within dissipative zones and ensuring that all other members and connections behave linearly (Di Sarno and Elnashai 2002). Bracing may be inefficient if the

braces are not adequately capacity-designed and braces can be esthetically unpleasant where they change the original architectural features of the building (Bruneau et al. 1998). Several configurations of braced frames may be used for seismic rehabilitation. The most common are concentric braced frames (CBFs), eccentric braced frames (EBFs), and the novel knee-braced frames (KBFs) recently proposed for earthquake loading (Sam et al. 1995). Moment-resisting frames (MRFs) and concentrically braced frames (CBF) have been widely used for earthquake-resistant steel frames. However, neither of these structural systems alone can efficiently provide the required stiffness and ductility simultaneously which are required for structures subjected to severe seismic excitation (Sam et al. 1995).

Combining the positive features of KBF and MRF frames (stiffness and ductility) into an economical seismic-resistant structural system, Roeder and Popov (1978) proposed the eccentrically braced frame (EBF) where the brace is placed eccentrically into the beam–column joint (Maheri and Akbari 2003). Aristizabal-Ochoa (1986) proposed the KBF as an alternative system which acts like a ductile fuse to prevent structural collapse under extreme

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seismic exposure by dissipating energy through flexural yielding. A diagonal brace with at least one end attached to the knee element affords the most elastic lateral stiffness. A knee-braced frame with a shear yielding knee is being investigated for possible applications in earthquake-resistant design (Balendra et al. 1994). The experimental results reveal that when the knee is designed with web stiffener to prevent tearing of the web, it can dissipate a large amount of energy during a severe earthquake. Maheri et al. (2003) indicated that knee bracing can be employed to provide the desired ductility level for a ductile design and is a more effective system than the x-bracing system. This shows that the knee elements can be designed to yield under small earthquakes or early in a strong one (maximizing their energy dissipation) while still being able to withstand a large event without collapse (Clément and Williams 2004).

Mofid and Lotfollahi (2006) developed a nonlinear analytical knee element model. The actual behavior of this new system, optimal shape, and position of the knee elements presented were tested under nonlinear static and dynamic analyses on two structural systems where the knee element is in the moment and/or shear yielding mode. A modified structural form which effectively restrains relative joint deformation by applying knee braces improves design efficiency in the corner regions of beams and columns. This type is called the knee-braced moment-resisting frame (KBMF) in which the stress at the beam-to-column regions is significantly reduced, effectively alleviating the demand for connections (Lehman et al. 2008). Conti et al. (2009) presented development of a collapse mechanism of global type for seismic-resistant knee-braced frames where the brace connections can be either continuous or pinned. The procedure which is proposed can control both the collapse mechanism typology and the local ductility demands.

Leelataviwat et al. (2011) showed that knee braces provide much less obstruction than the braces in conventional systems, making this structural system architecturally attractive. Moreover, the load deformation characteristics obtained from their results indicate that the newly developed KBMF system can be a viable alternative to conventional structural systems.

A series of cyclic loading tests were performed on a special moment-resisting frame (SMRF) and KBRF systems with in-plane and out-of-plane controlled buckling mechanisms in the knee braces. It was recommended that braces with in-plane buckling modes can be adopted for greater earthquake resistance in KBRF structure designs (Hsu and Li 2015). Reports of destructive past earthquakes and investigations of near-field strong ground motions show that, in many cases, analysis of structures is performed by considering far-field earthquakes and may lead to nonconservative responses. The seismologic

characteristics and importance of near-field ground motion necessitates that more attention be paid to seismic design of structures in these areas (Papazoglou and Elnashai 1996, Collier and Elnashai 2001).

This study aims to determine whether or not the rigid and pinned connections for knee elements constitute a significant proportion of the stiffness, toughness, and ductility that must be resisted by a building subjected to near-source ground excitation. To account for uncertainty, the inelastic seismic response has been quantified in terms of the axial forces of the columns, vertical displacement of the beams, base shear force, horizontal displacement of the roof for 3-, 8-, and 12-story KBMFs, and the base shear of columns was derived using nonlinear time-history analysis.

Structure model and properties

There is an urgent need for studies on seismic evaluation of large-scale buildings because under design-based earthquake loadings in the seismic code, there is potential for great loss of life and economic damage. The responses of structures to earthquake ground motion, whether elastic or inelastic, are highly uncertain. PERFORM-3D software is designed to overcome the difficulties involved in the evaluation of the seismic performance and identify weak points in the designs (CSI 2011). In the present study, 3-, 8-, and 12-story KBMFs were analytically modeled in PERFORM-3D to consider the geometric nonlinearity and material inelasticity of large inelastic deformation of the individual members and structures against seismic loading (10). Figure 1 shows the KBMF systems having 3-, 8-, and 12-stories. They feature a story height of 3.2 m and three spans having widths of 5 m. The live loads were assumed to be 200 kg/m² and dead loads were assumed to be 600 kg/m² in compliance with Iranian loading standards (BHRC 2005). European IPE standards were used for the beams and box sections for the columns and knee elements of the frames to be evaluated under seismic loads.

In this framing system, the steel KBMFs offers exceptional lateral stiffness and for energy dissipation one end of the diagonal brace in the KBF is attached to the knee element instead of connecting to the beam-column joint. The knee element as a structural fuse is designed to sustain controlled inelastic deformation as well as dissipate seismic energy while other parts and connections remain elastic (Balendra et al. 1997). Figure 2 shows the details of the knee elements schematically. During a moderate event, the energy dissipating within the knee elements should be sufficient to reduce the loads on the main frame and protect it from damage. Afterwards, the damaged knee elements can be replaced, returning the structure to its original state.

Fig. 1 Schematic of 3-, 8-, and 12-story KBMF buildings

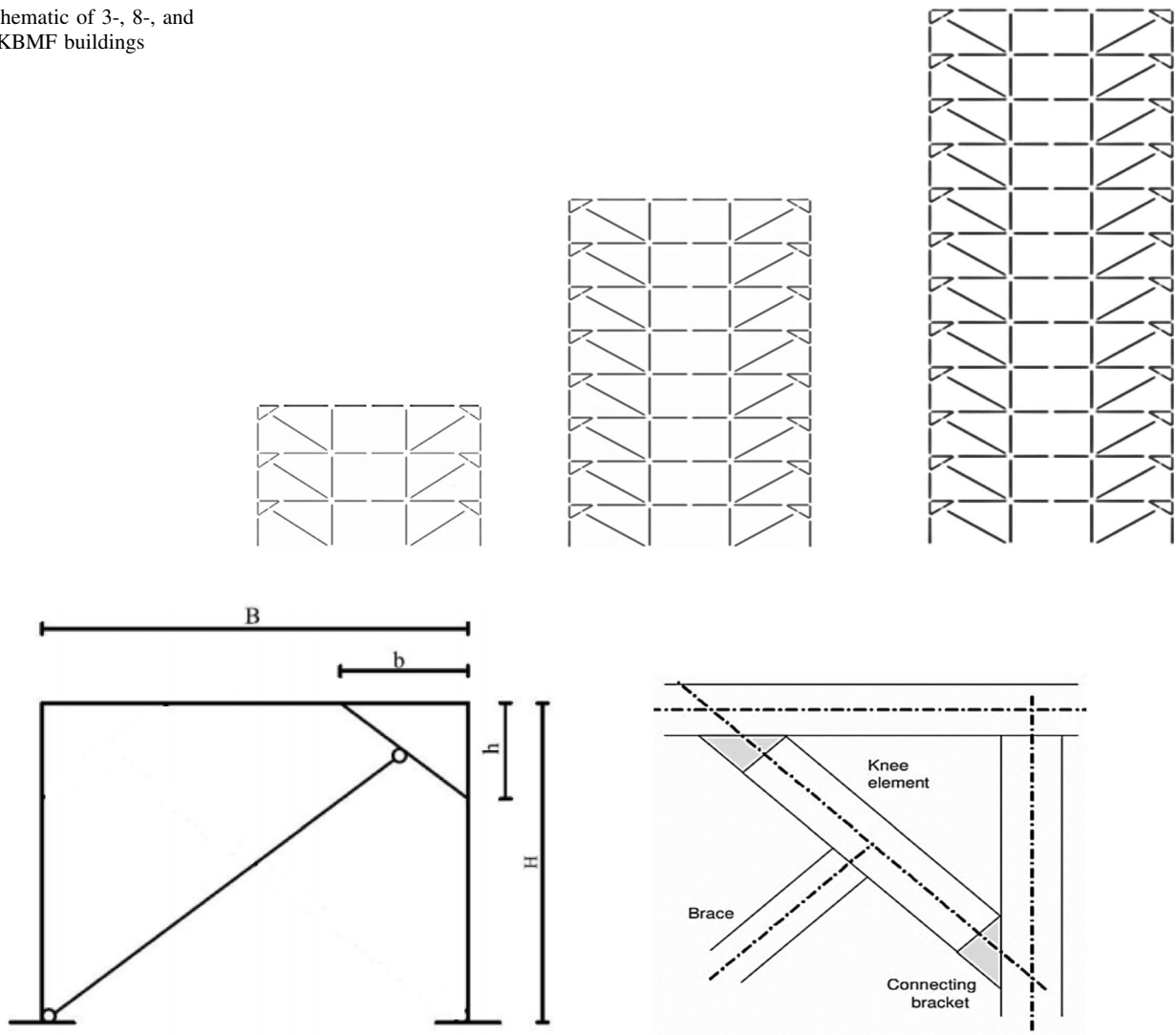


Fig. 2 Location and details of knee elements in KBMFs

Table 1 Data for all fault normal ground motions identified

Earthquake	PGA (g) horizontal	PGA (g) vertical	V/H
Loma Prita, 1989	0.529	0.541	0.652
Kobe, 1995	0.509	0.371	0.729
Northridge (Sylmar), 1994	0.843	0.535	0.64

The knee is a hysteretic damper designed to dissipate energy by the formation of plastic flexural and/or shear hinges at its ends and mid-span when the building is subjected to severe lateral loads. The diagonal brace component remains in the elastic range without buckling at any time, providing the required level of lateral stiffness. In this framing system, the optimal shape was chosen according to the elastic analysis results. When the tangential ratio of $(b/h)/(B/H)$ approaches 1 (Mofid and Lotfollahi 2006), the

optimal angle of the knee element is achieved in which the frame has maximum stiffness. This means that the diagonal element passes through the mid-point of the knee element and the beam-column intersection and the knee element should be parallel to the diagonal of the other direction of the frame, as shown in Fig. 2. In this investigation, it is assumed that $b = 1.5$ m and $h = 1$ m to be compatible for the requirements for both kinds of connections (rigid and pinned) at each side of the knee links.

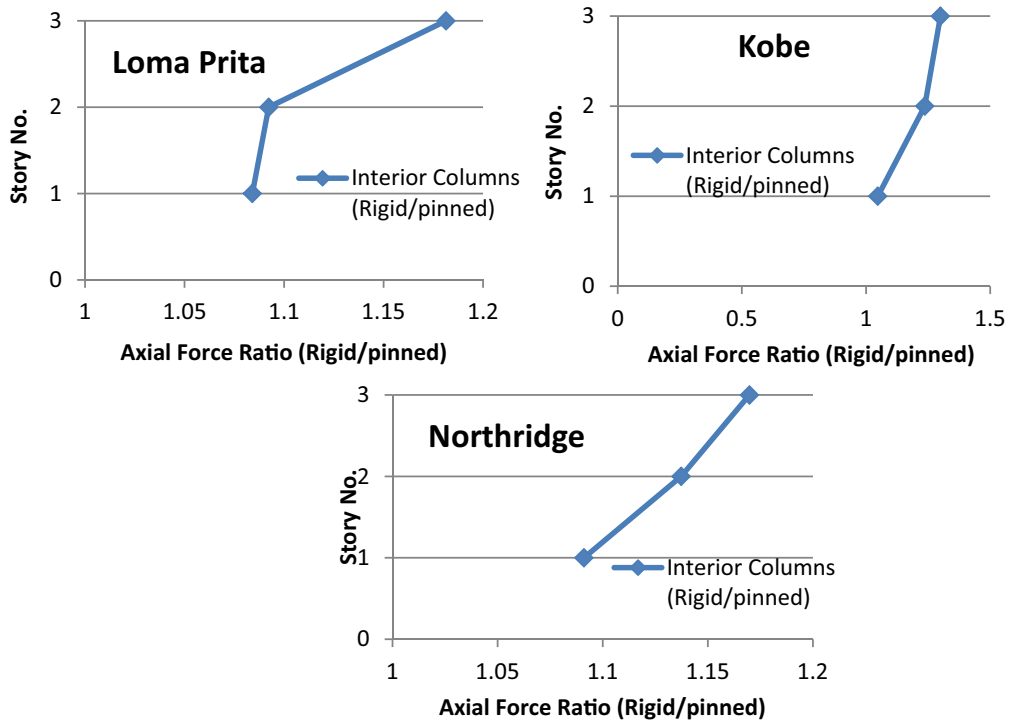


Fig. 3 Axial force ratio of knee joints (rigid/pinned) on interior columns of three-story frame under different earthquakes

Fig. 4 Axial force ratio of knee joints (rigid/pinned) on interior columns in eight-story frame under different earthquakes

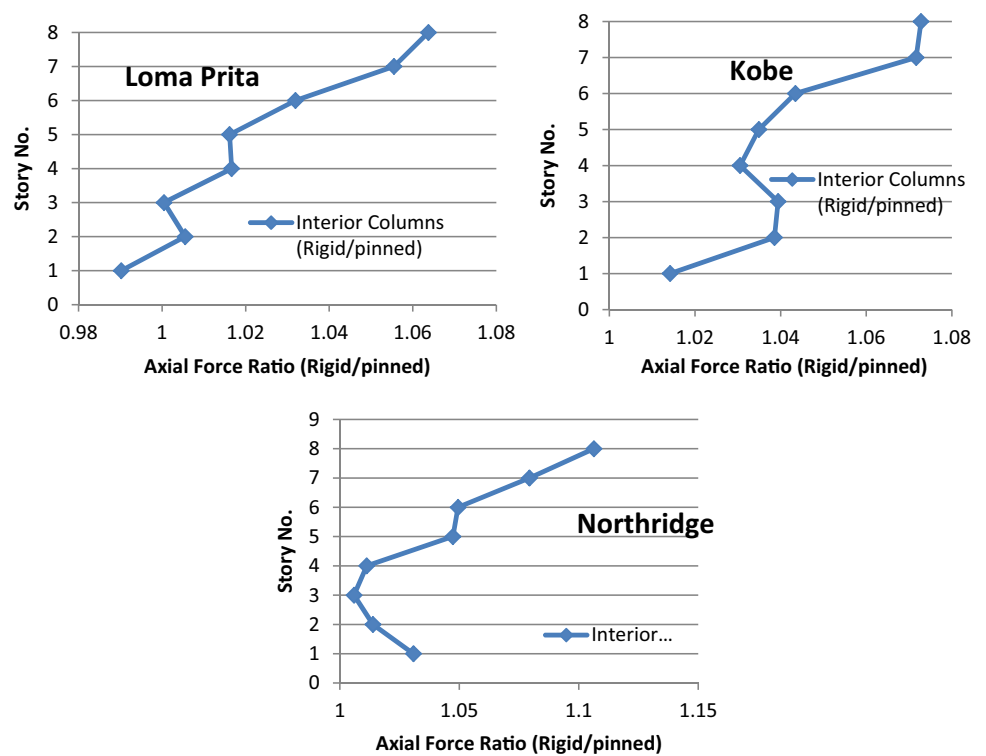
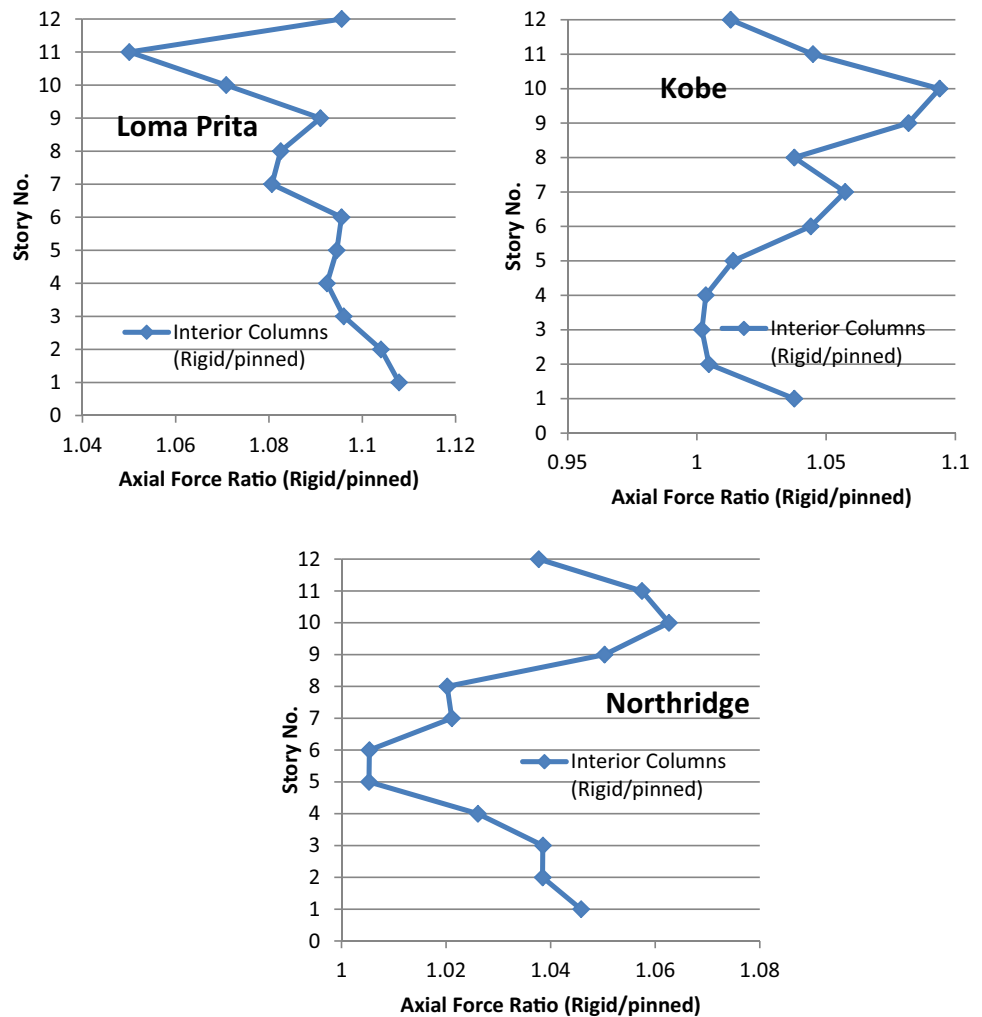


Fig. 5 Axial force ratio of knee joints (rigid/pinned) on interior columns in 12-story frame under different earthquakes



Near-fault ground motion

Near-fault ground motions containing strong velocity pulses caused by forward-directivity in the near-fault region are of interest in seismology and earthquake engineering. These ground motions have been identified as imposing extreme demands on structures to an extent not predicted by typical measures such as response spectra. Baker et al. (2007) proposed a wavelet-based signal processing approach for use on a large ground motion library to empirically identify these pulses in ground motions to reduce conservatism associated with using “worst case” directivity scenarios for engineering design. Table 1 shows the records proposed by Baker et al. (2007).

Seismic response evaluation of structures to near-fault ground motion

The objective of the study was to compare responses, including the load axial force of internal columns, vertical displacement of mid-point of beams, roof horizontal displacement, and base shear of internal and external columns of different joints (rigid and pinned joints on each side of the ends) of KBMFs to propose suitable joint (rigid or pinned) forms of knee elements for different seismic design and performance needs.

Axial force

Figures 3, 4, and 5 show that the axial force ratio of the columns was strongly affected by the use of rigid and pinned joints in KBMFs subjected to near-source excitations. This was an increase of 15% for a 3-story frame and 7% for 8- and 12-story frames. The increased gravity load of internal columns over that of exterior columns changed

Fig. 6 Vertical displacement at mid-points of beams of three-story frame for different earthquakes

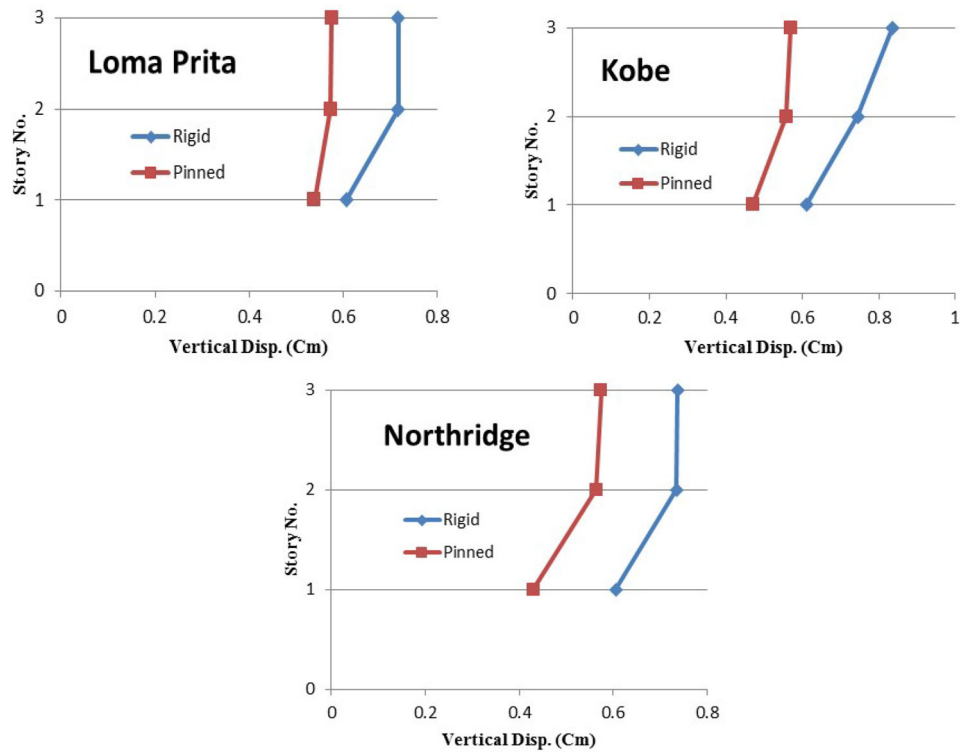


Fig. 7 Vertical displacement at mid-points of beams of eight-story frame for different earthquakes

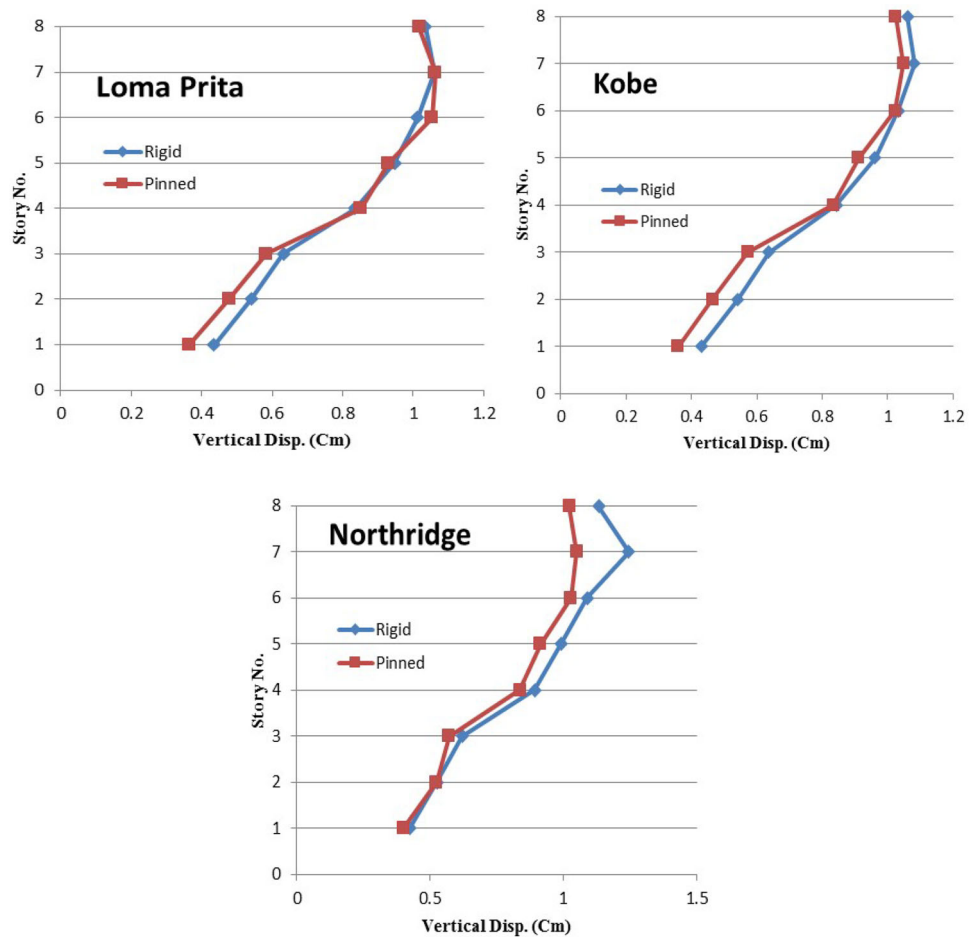


Fig. 8 Vertical displacement at mid-points of beams of 12-story frame for different earthquakes

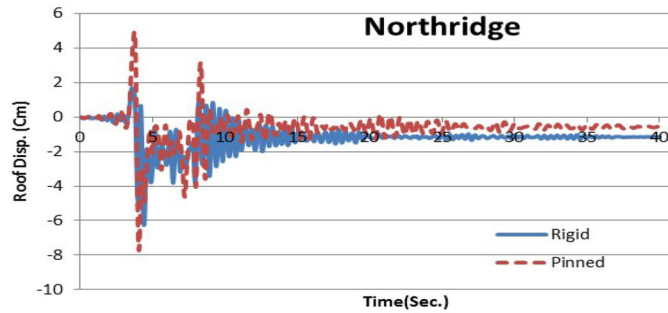
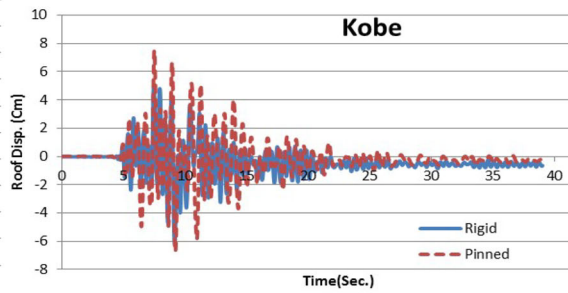
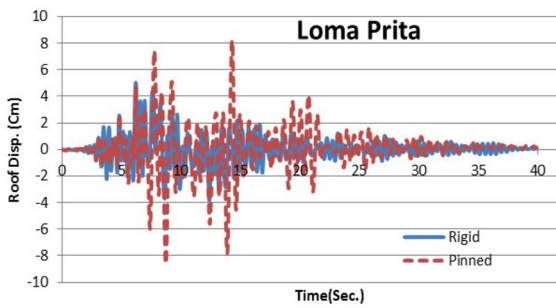
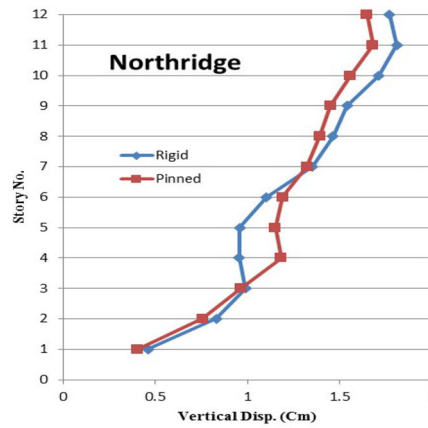
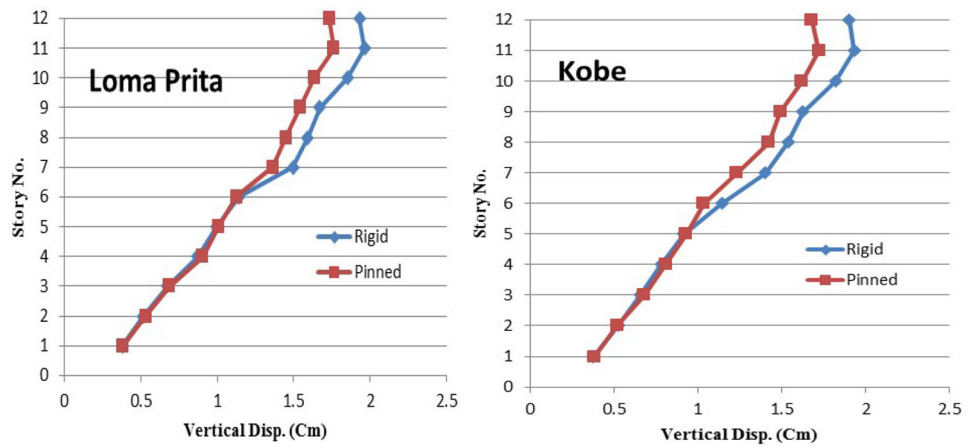


Fig. 9 Roof horizontal displacements of three-story frame for different earthquakes

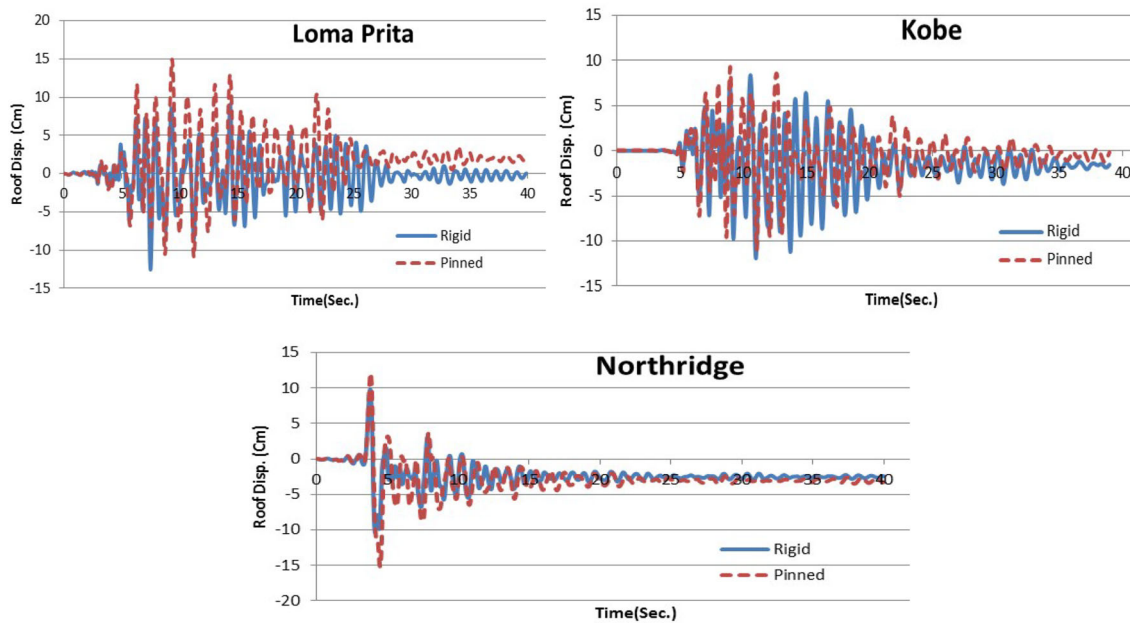


Fig. 10 Roof horizontal displacement of eight-story frame for different earthquakes

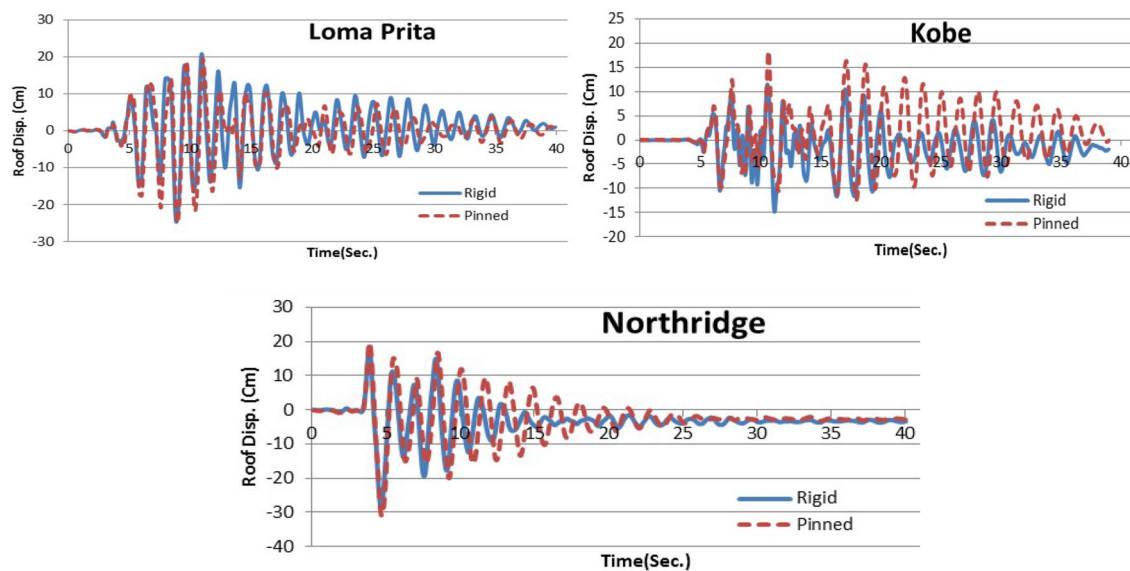


Fig. 11 Roof horizontal displacement of 12-story frame with rigid and pinned joints for different earthquakes

the axial forces. As the number of stories increased, the axial force of the columns increased in all cases of near-field excitation. This illustrates the importance of the placement and condition of the columns in the structures.

Vertical displacement of mid-point of beams

Figures 6, 7, and 8 show the vertical displacement of the mid-points of beams that undergo significant change in the presence of rigid or pinned connections of knee elements for different earthquakes. As the height of the stories

increased, vertical deformation of the beams having rigid joints was greater than for beams having pinned joints. The difference amount of vertical deformation of beams was negligible for the 8- and 12-story frame.

Roof horizontal displacement

Figures 9, 10, and 11 show that using pinned joints in the KBMFs rather than rigid joints, the horizontal displacement increased significantly when subjected to near-source earthquakes. Clearly, pinned connections should not be

Fig. 12 Base shear ratio (pinned/rigid knee joint elements) of columns of three-story frame for different earthquakes

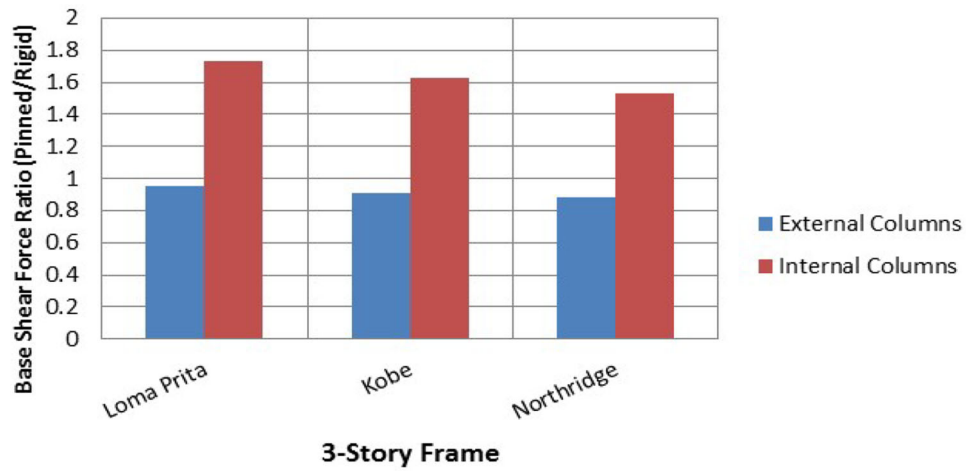


Fig. 13 Base shear ratio (pinned/rigid knee joint elements) of columns of eight-story frame for different earthquakes

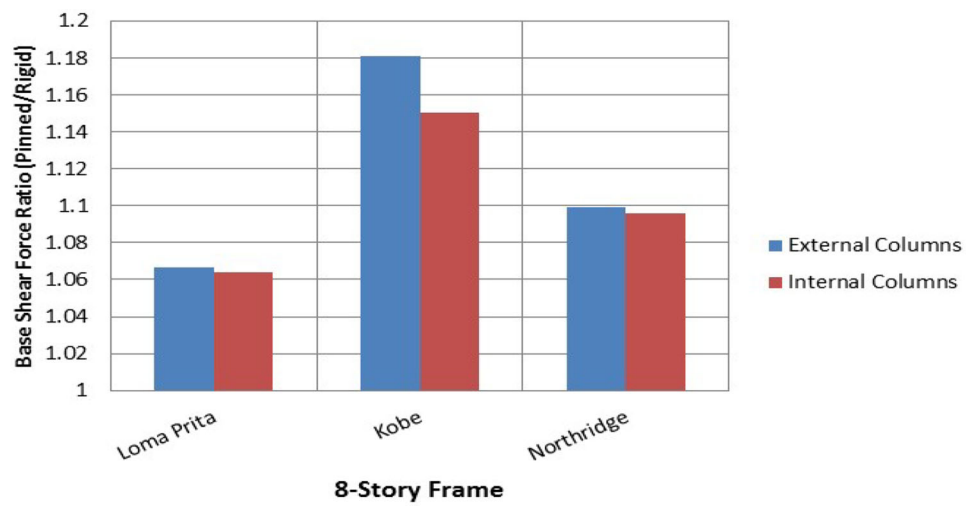
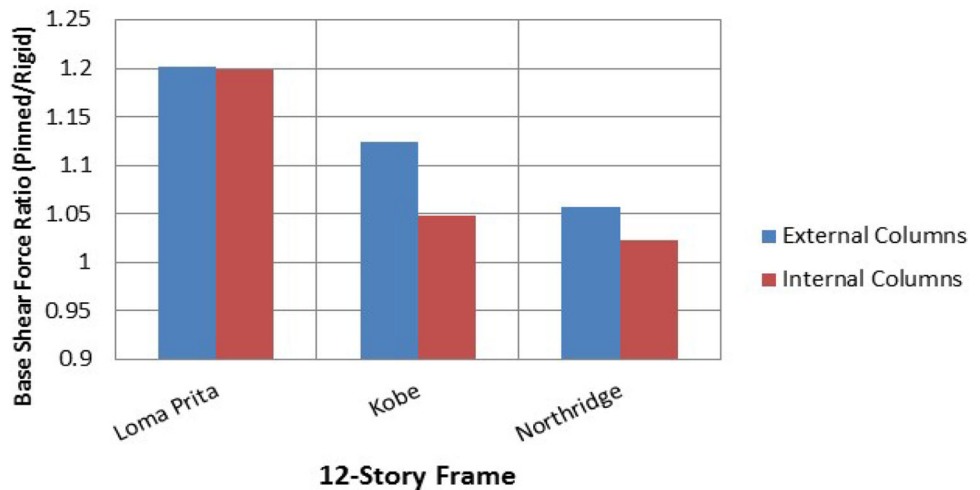


Fig. 14 Base shear ratio (pinned/rigid knee joint elements) of columns of 12-story frame for different earthquakes



applied for the knee connection in the KBMFs because less drift is required for the stories to reduce damage to structural members.

Base shear of columns

Figures 12, 13, and 14 show the base share ratio of the internal and external columns of the KBMFs initially

applied to pinned joints which were then replaced with rigid joints under near-source earthquake excitation. In this response, the base shear ratio for the 3-story frame increased nearly 40% and 8- and 12-story frames increased about 15%. This demonstrates the need to use rigid instead of pinned connections to elicit appropriate structural behavior and reduce performance demand.

Conclusions

This paper discusses and compares the responses of frames incorporating knee elements with rigid and pinned joints under excitation by near-source earthquakes. The degree of fixity of the knee connections at the beam–column joint was found to be critical during seismic behavior and performance of the KBMFs system because:

- The ability of the proposed system to dissipate energy using rigid and pinned joints is shown to increase the axial force of columns. The difference amount of vertical displacement of the mid-points of beams decreased from 3-story frame through 12-story frame.
- The roof horizontal displacement and base shear of the columns ceased, which suggest that when the frames are subjected to a strong near-field excitation, the system can dissipate a large amount of energy before failure by utilizing rigid joints rather than pinned joints for knee connections.
- The use of rigid joints is recommended for the design and construction of knee element connections with columns and beams to guarantee a high level of fixity and maintain structural integrity. Further analytical and experimental research is needed to corroborate the findings presented and to establish the merits of the KBMFs system.

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