Seismic evaluation of RC moment frames with knee braces in the near-fault region

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Abstract

Reinforced concrete Moment resistant frame is one of the structural systems used to resist earthquake loads in buildings. Many existing concrete structures with this system need retrofitting to overcome deficiencies and to resist seismic loads. In the present study, the seismic behavior of rigid frames with knee-type braces was investigated and their response parameters, such as maximum strain in concrete cover, reinforcement and concrete core were evaluated and hysteretic behavior of frames were discussed. Two types of structures, including moment frames and braced frames with knee-type braces in beam to column joints were designed per the Iranian Seismic Design Code and the Iranian Concrete Structures Design Code. Also knee elements were designed per a trial and error method depending on columns maximum axial force. Dynamic analysis using 5 earthquake records for moment frames and braced frames were carried out to obtain dynamic responses and compute seismic parameters. According to the analysis results, concrete core and cover strain in beams and columns are decreased when knee braces with different cross sectional area are used. Also the maximum reinforcement strain in beams and columns sections is decreased as knee braces are utilized. As braced frames enters in plastic range with larger story shears therefore the plastic capacity of structures increases. Also in braced frames, the maximum displacements of the structure increases so the stiffness of the structure increases and the seismic behavior of moment frames is improved.

Keywords: concrete moment frame, knee brace, near-fault region, seismic design.

Introduction

Reinforced concrete moment resisting frames (RC MRFs) have been used as the main structural resisting systems for over 30 years in many countries all over the World. Thanks to rather high capacity in strength, stiffness and low cost of construction, this structural system is capable of resisting both gravity loads and lateral forces like winds or earthquakes. Many buildings using RC MRFs as the main resistance component still have been building expansively. However, there have been still many existing RC MRFs or even new ones, which have not been designed based on the modern seismic codes. This may lead to some undesired failures under a rather low intensity earthquake. This has been experienced in Turkey, Iran and southeast Asian, In addition, in many regions like Turkey, Iran or Taiwan which are high seismic activity with frequently earthquake having probability of occurrence with large magnitude and intensity, this may leads to the increase of seismic hazards of those zones.

The main purpose of seismically retrofitting and/or upgrading a structure is to make it possible to succeed the intended seismic performance under a design earthquake. The retrofit has been required since the structure has not been designed according to a modern seismic code. On the other hand, the upgrading becomes necessary if the recent seismic activities have led to the modification of the seismic hazards. However, the retrofitting or upgrading of the existing buildings is a difficult task for engineers because of technical reasons and retrofitting costs. There are several existing retrofitting systems available for seismically retrofitting or upgrading RC MRFs, such as conventional braces, eccentric braces, steel plate or reinforced concrete shear walls, base isolators or damper systems. In these systems, some are able to increase the stiffness, strength, deformation and energy absorbing capacity of the structures and some are able to reduce the influence of the seismic actions on the structure. The application in reality of these retrofitting systems is dependent on their effectiveness on the structures in both aspects: technique and construction costs [7].

In spite of having much advantage in increasing the stiffness and strength for the buildings, the use of bulky systems such as reinforced concrete shear walls to retrofit buildings under seismic actions becomes more and more limited due to its complication in erection and very high costs for foundation system because of high seismic forces acting on the walls. Therefore, the use of lighter retrofitting systems such as concentric braces, shear walls made from steel, low yield stress steel or aluminums have been becoming more favorable. These retrofitting systems are able to increase the strength and stiffness of the structures. Also, they can provide an effective passive means to absorb the seismic energy during the earthquakes.

In steel structures, moment resisting steel frame possesses good ductility through flexural yielding beam elements, but it has limited stiffness. The concentrically braced frame on the other hand is stiff, however, because of buckling of the diagonal brace its ductility is limited. Kim et al. (2003) [9] have proposed the Knee Braced Frame system for steel moment resisting frames to overcome the deficiencies in these and concentrically braced frames, where the brace is installed in the beam to column joint and is placed above and below the beams. By a suitable choice of knee element length, a sufficient amount of stiffness from the brace is retained while ductility is achieved through the flexural and/or shear yielding of a segment of the beam, which is called the link, created by the eccentrically placed brace member. Also Azizi (2013) [1] have carried out dynamic analysis using 5 earthquake records for steel moment frames with knee braces to obtain dynamic responses and compute seismic parameters of steel moment and braced frames. He achieved plastic hinges formation pattern, displacement and drift of stories and internal forces in moment frames elements and compared them with braced frames responses.

Even with the structural efficiency and cost effectiveness, shear walls and braces are not always favored by architects and building owners because the diagonal braces and shear walls obstruct the flow planning and block the interior view. These shortcomings can be overcome, with some sacrifice in efficiency, by employing knee braces instead of diagonal braces.

This paper presents the seismic performance of RC MRFs with knee-type elements that acted as energy dissipation parts through the loading in the near-fault region. Numerical response analysis for the models with and without braces has been carried out for the purpose of comparison.

RC MRFs seismic behavior

In order to well behave under an earthquake, a building should possess adequate strength, redundancy and ductility. The response of a RC MRFs building subjected to severe seismic forces depends primarily on those properties of its members and on detailing of its individual component and of connections between the components. Many RC MRFs constructed and designed not according to seismic modern design codes or before the development of rigorous seismic design codes and of detailing provisions may not have enough conditions for resisting the seismic actions. It has been clearly observed that many non-ductile RC MRFs structures are severely damaged or collapsed during small earthquakes with undesirable failure modes as shown in Figure 1.

Figure 1: moment resistant frame failure

To ensure ductile behavior during a major earthquake, current design provisions require special detailing of frame members and connections, In addition, code provisions are oriented towards the design of structural systems capable of resisting large inelastic deformation without collapse. Figure 2 shows two possible failure mechanisms for frame buildings, often referred to as the strong-beam, weak-column mechanism and the weak-beam, strong-column mechanism. The former mechanism (strong-beam weak column) is an undesirable collapse mechanism for several reasons, but mainly because yielding of columns in a given story means increased likelihood of collapse of the entire building, In contrast, the weak-beam strong-column mechanism enforces yielding of beams in flexure prior to hinging of columns which allows energy dissipation with less likelihood of collapse of the building [11].

Utilizing knee type braces in the beam to column joints reduce the frame elements internal forces and prevent the formation of plastic hinges at the end of beams and columns that cause a desirable reduction in beam to column joint forces [1].

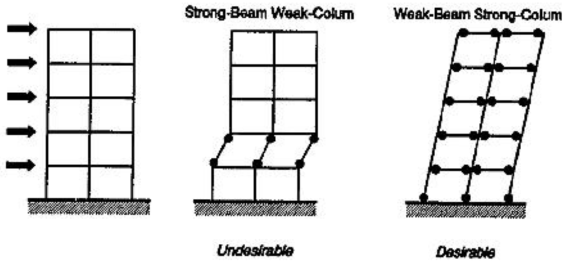

Figure 2: possible failure mechanisms for frame structures under lateral loads [11]

Structural models

Knee braces can be installed above and/or below the beams. The braces above the beams can be placed inside of curtain walls or partition walls, and those below the beams can be hidden above the ceiling. Fig.3 shows the moment frame and design parameters of elements with knee braces placed below the floor beams.

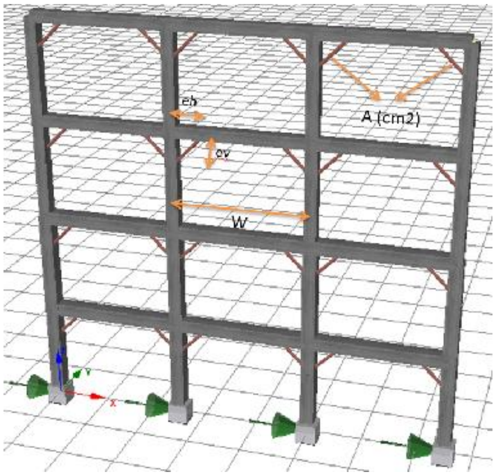

Figure 3: Structure with knee braces

In this paper, the performance of moment frame using knee bracing system with respect to the similar moment frame system is discussed. Therefore, we consider 4-story frame for both systems with equal height and bays. The height of all stories is considered 3 m. There are also 3 bays and length of each bay is 4m. Also according to Azizi [1], the knee elements design parameters were chosen as follows:

$$\frac{e_h}{e_v}=1,\quad \frac{e_h}{W}=0.25 \qquad (1)$$

The only variable in this study is cross sectional area of knee-type elements and it was chosen to help us in achieving design provisions. In this study, circular solid sections with three different cross sectional areas were chosen as follows; so the total number of frames under study is 4.

$$A=15cm^2,35cm^2,55cm^2 \qquad (2)$$

It should be noticed that the braces cross sectional area were determined by a trial and error method and the values in equation 2 were chosen from 17 different values for braces area. In this method, we designed braces as tension members under 10, 50 and 80 percent of maximum axial forces in columns. It also can be mentioned that the braces should remain in elastic range during the earthquake to absorb sufficient energy and help main structure to withstand severe excitations.

According to the Iranian loading code [4], the rate of live and dead force have been considered 200 kg/m2 and 700 kg/m2 respectively and then, structures are analyzed and designed by ETABS V.9.7 . Assuming the conditions of area with much relative danger, the type of usage for residential buildings and lands will be of type III and the loading of frames will be done according to Iranian Seismic Code [8]. The type of the concrete utilized in frames has compressive strength of 250 kg/cm2. Yield strength and ultimate strength of rebar is 2400 kg/cm2 and 4000 kg/cm2, and for concrete, Poison factor is 0.2 and modulus of elasticity is 2.34x105 kg/cm2. After statically analyzing of the structure, it has been designed and specified sections to members in the design have been determined according to Iranian concrete structures design code [5]. Time history analysis of models is considered by SeismoStruct software.

Near-fault ground motion

Near-fault ground motions, which have caused much of the damage in recent major earthquakes (Northridge 1994, Kobe 1995), are characterized by a short-duration impulsive motion that exposes the structure to high input energy at the beginning of the record. This pulse-type motion is particularly prevalent in the “forward” direction, where the fault rupture propagates towards a site at a velocity close to the shear wave velocity. The radiation pattern of the shear dislocation of the fault causes the pulse to be mostly oriented perpendicular to the fault, causing the fault-normal component of the motion to be more severe than the fault parallel component. The need exists to incorporate this special effect in the design process for structures located in the near-fault region. The near-source factors incorporated in recent codes cannot solve the problem consistently, because design procedures should pay attention to the special frequency characteristics of near-fault ground motions. Moreover, the emerging concepts of performance-based design require a quantitative understanding of response to different types of ground motion at different performance levels, ranging from nearly elastic to highly inelastic behavior.

It is recognized that the characteristics of near-fault earthquake ground motions are different from those records in the far-field. The fault normal component is of higher peak ground acceleration than the fault parallel component at the same recording station. In the forward directivity zone, the velocity record is characterized by pulse type motion of long duration. The effect of this pulse type motion on the response is important in the design of structures for near-fault events. In the near-fault region, the short travel distance of the seismic waves does not allow enough time for the high frequency content to be damped out of the record as is normally observed in far field records. Near fault effects were observed in failures during the 1994 Northridge and 1995 Kobe earthquake events. Figure 4 presents the pulse type motion in velocity time history for Kobe earthquake.

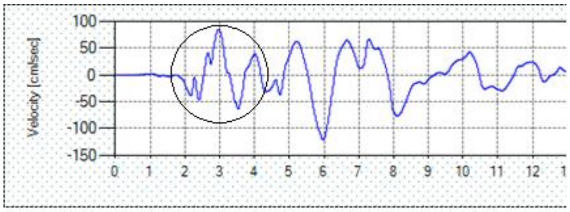

Figure 4: pulse type motion in velocity time history for Kobe earthquake

The designed moment resisting frames are subjected to a set of selected near-fault earthquakes. The selected earthquakes are shown in Table 1. All the earthquakes are larger than magnitude 6 with short epicentral distances of 1 to 12 km. The peak ground acceleration PGA, peak ground velocity PGV and peak ground displacement PGD of each record are listed in Table 1. For near-fault records in forward directivity zone, the ratio of the PGV (in cm/s) to the PGA (in g) is calculated for comparing reasons.

Table 1: Near-fault records

Earthquake	Station	Distance (KM)	PGA (g)	PGV (cm/s2)	PGD (cm)	PGV/PGA
KOBE 1995	TAK-090	1.47	0.616	120.72	37.73	195.97
TABAS 1978	TABAS-L	2.05	0.836	97.75	38.65	116.92
NORTHRIDGE 1995	NW-090	5.92	0.583	74.9	17.74	128.47
DUZCE 1999	DZC-270	6.58	0.535	83.5	51.6	156.07
MANGIL 1990	ABAR-L	12.56	0.635	42.46	14.91	66.86

Performance criteria

Stability of structural models during and after the earthquake is the most important factor in seismic performance of moment frames and braced frames. In spite of plastic hinges formation in frame elements, distribution of internal forces in frames should change to keep total and local stability and prevent frames immediate collapse. In this regard, performance criterions are chosen as follows:

Spalling of cover concrete. It can be recognized by checking for negative cover concrete strains larger than the ultimate crushing strain of unconfined concrete material. (Assumed value: -0.002) [10, 12].

Crushing of core concrete. It can be verified by checking for negative core concrete strains larger than the ultimate crushing strain of confined concrete material. (Assumed value: -0.006) [10, 12].

Yielding of steel. It can be identified by checking for positive steel strains larger than the ratio between yield strength and modulus of elasticity of the steel material. (Assumed value: +0.0025) [10, 12].

Fracture of steel. It can be established by checking for positive steel strains larger than the fracture strain. (Assumed value: +0.06) [10, 12].

In figure 5, the strain output stations in frame elements are shown. Also discretization in the cross sectional area of frame elements and braces with fiber-based modeling method [14] are shown in figure 6.

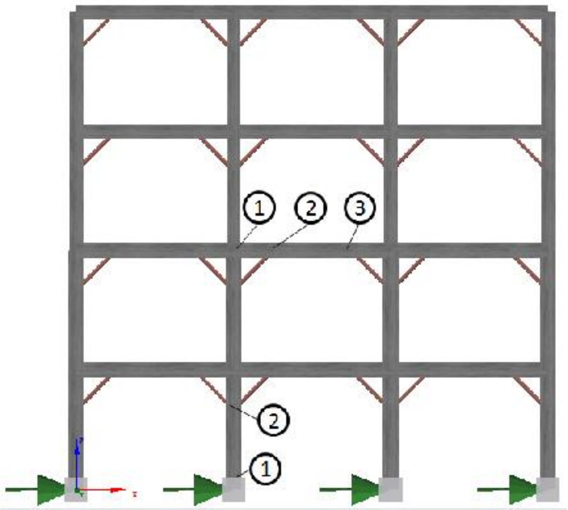

Figure 5 : strain output station for beams and columns in each story

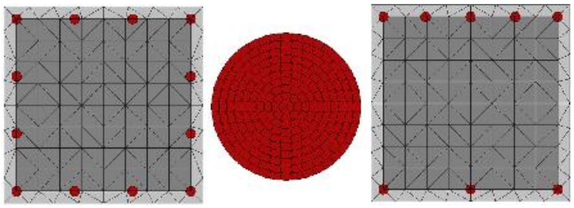

Figure 6 : columns, braces and beams cross sectional area

Sections cover strain

In this section, spalling of concrete cover in beams and columns are considered for comparing reasons. The cover strain in first story columns and second story beams (as shown in figure 5) are derived and sketched in figures 7 and 8.

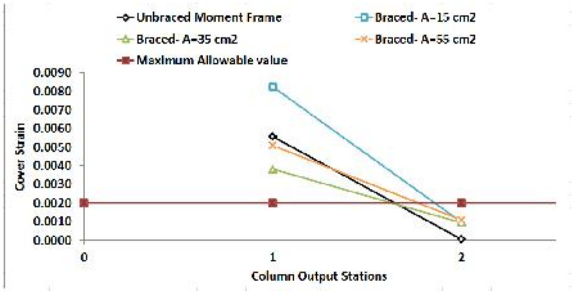

Figure 7: Section cover strain in column output stations

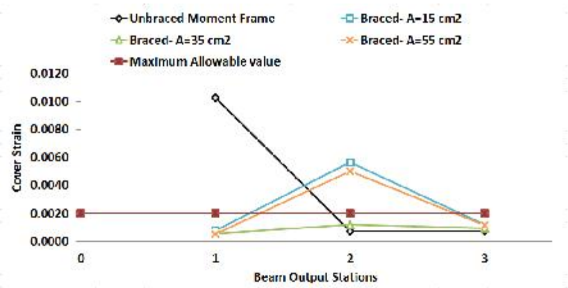

Figure 8: Section cover strain in beam output stations

It can be seen in the figures that with utilizing appropriate cross sectional area for braces cover strain in beams and columns are decreased. With choosing A=35 cm2 , cover strain in critical points such as station 1 in beams and columns decreases to allowable value (green and red line).

Sections Core strain

In this section, crushing of concrete core in beams and columns are considered for comparing reasons. The core strain in first story columns and second story beams (as shown in figure 5) are derived and sketched in figures 9 and 10.

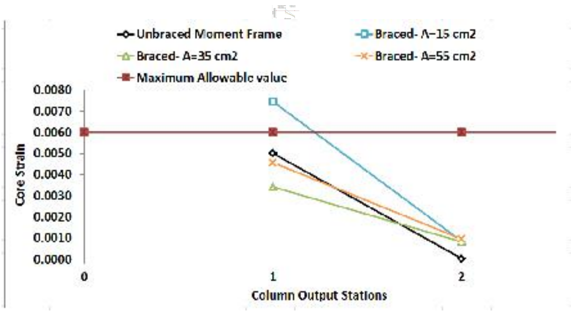

Figure 9 : Section core strain in column output stations

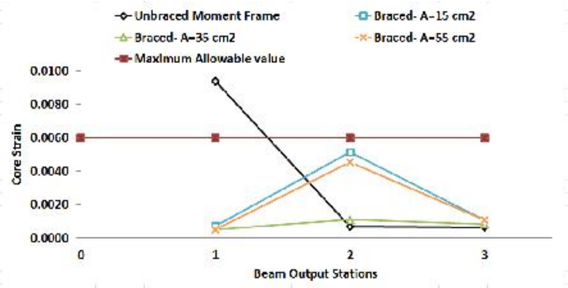

Figure 10 : Section core strain in beam output stations

It can be observed in the figures that in most cases, sections core strain are decreased when knee braces with different cross sectional area are used, while there are noticeable difference when braces with A=35 cm2 are used. It also can be seen that at station 1 in beams, the section core strain for un-braced moment frame is above the allowable line that causes great effect in section bearing capacity so with utilizing knee braces, it is been reduced to allowable range.

Reinforcement strain

In this section, yielding and fracture of reinforcements in beams and columns are considered for comparing reasons. The reinforcement strain in first story columns and second story beams (as shown in figure 5) are derived and sketched in figures 11 and 12.

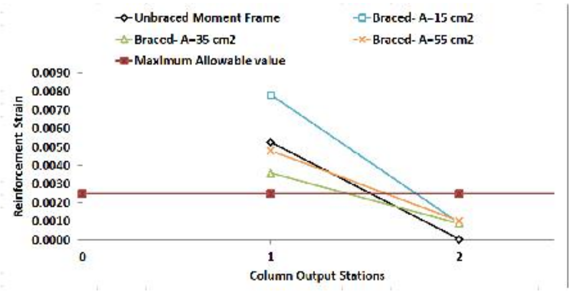

Figure 11 : Section reinforcement strain in column output stations

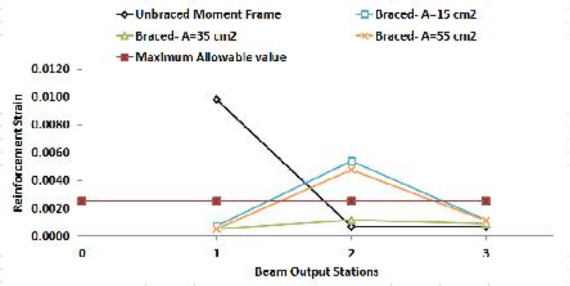

Figure 12 : Section reinforcement strain in beam output stations

It can be concluded from the figures that using knee type braces with inappropriate cross sectional area cause reinforcement strain to increase (station 2 at beams) while with using A=35 cm2, reinforcement strain in beams and columns are decreased.

Frames hysteretic curve

One of the major characteristics of buildings is their hysteresis loops. In structural engineering, hysteresis refers to the path-dependence of the structure's restoring force versus deformation. The adjective pinching describes the shapes of hysteresis loops in concrete structures that appear to be pinched in the middle compared to the hysteresis loops of steel and other materials. The hysteresis loops of structure offer vital information about the forces that act upon it and the resulting deformations. It is imperative to accurately map hysteresis curves since they play a pivotal role in creating a better nonlinear model. Fortunately, many of the commercial products that provide nonlinear analyses have the option to input a hysteresis model. The hysteretic behavior of a structure plays a crucial role in many current approaches to seismic performance-based analysis and design.

Extraction of hysteretic characteristics of concrete moment frame components can lead to an understanding of the structure's degradation and nonlinear response range. The process involves the construction of a hysteresis curve by plotting time history pairs of restoring force across the component (on the vertical axis), and relative displacement across the component (on the horizontal axis). The hysteresis curves for moment frame and braced frames are shown in figure 13.

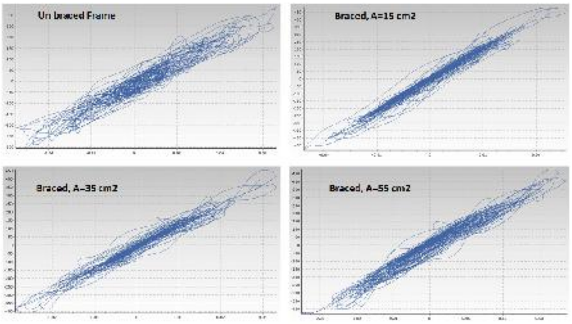

Figure 13 : Frames hysteretic curve for different cross sectional area of braces

Comparing hysteretic curves of moment frames (un-braced frames) and braced frames shows that utilizing knee-type braces for retrofitting moment frames has great effect on plastic behavior of structure. It can be noticed that braced frames enters in plastic range with larger story shears therefore the plastic capacity of structures increase. It also can be seen that in braced frames, the maximum displacements of the structure increases so the stiffness of the structure increases.

Conclusion

This study presents the seismic behavior of concrete moment resistant structures with knee braces. The beams and columns in rigid frames were designed mainly to resist gravity and lateral load, and the knee braces cross sectional area were determined by a trial and error method. The seismic performance of the structure was evaluated using the Iranian steel structures design code and the Iranian instruction for Seismic Rehabilitation of Existing Buildings. Time–history analysis of a 4-story model structure designed following the proposed procedure showed that, although depending on the braces cross sectional area, the structures retrofitted by the proposed method generally satisfied the performance stability criterions.

It can be concluded that in columns, the maximum strain in concrete core decreases to 32 percent of similar values in moment frames while strain of concrete cover and reinforcement decreases to 31 percent. It also can be mentioned that in beams, the maximum strain in concrete core decreases to 90 percent of similar values in moment frames while strain of concrete cover and reinforcement decreases to 94 percent.

With utilizing knee type elements, the formation time of first plastic hinge increase and the number of plastic hinges after the earthquake decrease. This means that when knee elements for retrofitting moment frames are used, the frames are became more stable. Using knee type elements has great effects on decreasing moments at supports and rotations in stories that controlling overturning forces of frames could be possible.

According to the discussions, the optimum value for braces cross sectional area for retrofitting concrete moment resistant frames in the near-fault region is 35 cm2.

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