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Numerical and experimental performance evaluation of upgraded knee braces under cyclic load

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Abstract

In this paper, the seismic performance of the structure is analyzed by introducing a new angular knee element. Cyclic loads are applied to determine the seismic performance. The result is compared with a vertical knee element. The angular knee element showed better seismic performance as compared to the vertical knee element. The new short knee element studied in two positions including 1- a vertical knee element perpendicular to cross-brace is called VSKE 2- An angular knee element that is called ASKE. Using reduced knee section specimens for better performance. Effect of Angular knee element in knee-braced frames (KBFs) under Cyclic Loading was investigated by testing using a half scale specimen mounted on a reaction frame at two positions including horizontally for VSKE and inclined for ASKE. For experimental tests, specimens were loaded by using a hydraulic actuator. Finite element modelling was used for the simulation of detailed behavior using a verified experiment base model. It has been shown that the performance of knee element fuses can improve the ductile behavior of knee braced frames. Based on the results of vertical and angular cases, it has been shown that an increase of angle between main cross brace and short knee element (incline specimen) can reduce maximum equivalent plastic strain (EPEQ) in the web of knee element fuse.

Keywords: Knee element, Fuse, Cyclic-Loading, Plastic Deformation, brace, Numerical Modelling.

1. Introduction

Since stiffness and ductility are generally two opposing properties, it is desirable to devise a structural system that combines these properties in the most effective manner without an excessive

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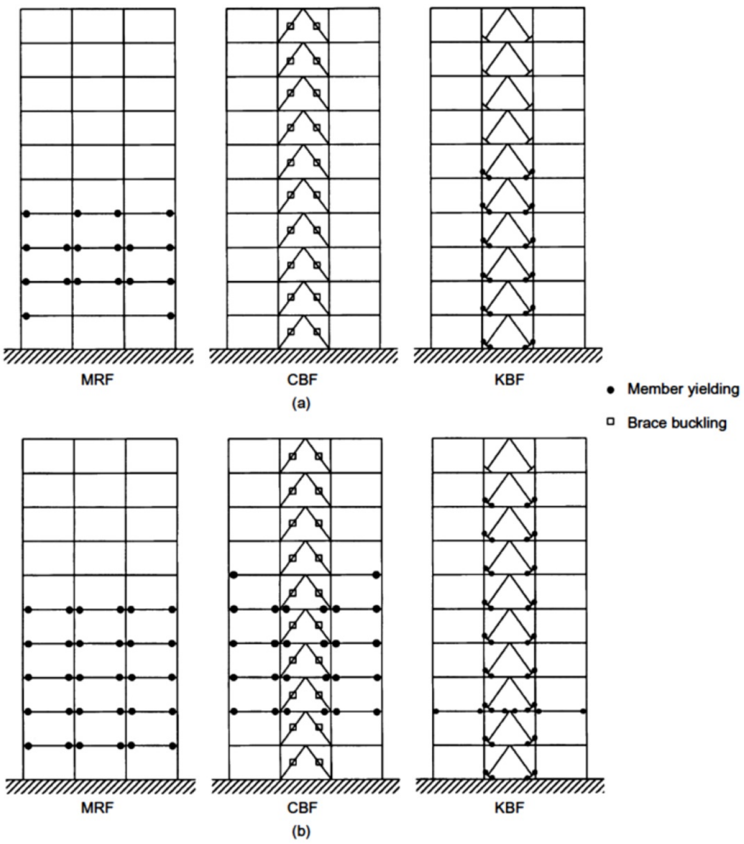


Figure 1: Structural damage to MRF, CBF and KBF under the El Centro earthquake:(a) PGA=0.35g; (b) PGA=0.7g

increase in the cost. In the Moment Resist Frames (MRF), lateral stiffness is limited to control deflections and in the Concentrically Braced Frames (CBF), are stiff, and their ductility is limited because of buckling of the diagonal brace. Eccentrically Braced Frames (EBF) system has proposed by Roeder and Popov [7] to overcome the deficiencies in CBF and MRF. In the main beam of the frame, the repair is very costly. Many types of these devices, utilizing friction, have been studied in many kinds of research. Therefore, many methods are not applicable in engineering practice. The distribution of peak horizontal deflections, story shear, column bending moments and beam ductility for three structures subjected to a PGA of 0.53g shows in Fig 1. Clearly, the knee bracing has been effective in reducing all these parameters. At this level of the earthquake, the KBF has suffered no yielding in any of the main structural members.

The distribution of structural damage for MRF, CBF and KBF frames when subjected to PGAs of 0.35g and 0.7g shows in Fig. 1. The MRF suffer flexural hinging of the beam elements over several of the lower stories at 0.35g. The CBF suffers no yielding, but the braces buckle throughout the height of the structures, negating their ability to control deflections. The KBF shows yielding of the knee elements over the lower six stories and no yielding in the main structural elements. At 0.7g both the MRF and CBF suffer very extensive yielding of beams while the KBF suffer only very limited beam yielding with almost all of the knee elements contributing to the energy dissipation. These studies show the potential of knee bracing to absorb substantial amounts of energy and so protect the main structural members [10]).

Aristizabel-Ochoa [1] has proposed a steel brace frame; with the use of diagonal brace stiffness and the ductile behavior of a knee element together. This system was not suitable for earthquake loading because the brace was designed to be slender. Therefore, the brace leads to pinching of

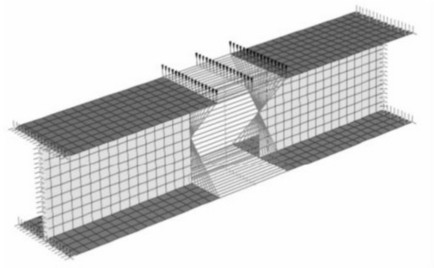


Figure 2: STRAUS7 FEM Model

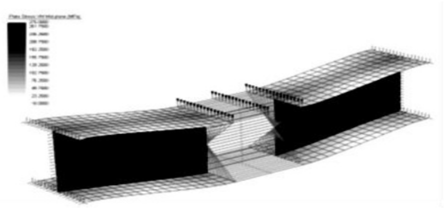


Figure 3: STRAUS7 stress Map at the first yielding

the hysteresis, which is not effective for energy dissipation. Subsequently, Balendra et al. [3, 4], have modified this system. The modified system is called the Knee Braced Frame (KBF). In a knee braced frame (KBF) the main cross-braces are connected to short knee elements which span diagonally across the beam-column connections. The knee elements are designed to yield before the main structural members in earthquake loading. In the KBF system, the energy is dissipated through the shear yielding of the knee while the brace is designed to buckle. The numerical model used for the analysis of the proposed system is confirmed by comparing the results with Huang Zhen et al [11] research. They studied the position and stiffness of the knee anchor and its yielding moment compared to other members. Mofid and Khosravi [6] proposed the flexural and shear yielding mode and the nonlinear behavior of the knee bracing under lateral loading.

Recently, Junda et al. [5] presented an effective brace system for structural steel called buckling restrained knee-braced frame (BRKBF). Fig 2, 3.

Behaviour of Steel Tubular Knee Joint in Aluminum Frames with Tension-Tie Element studied (Davor Skeji'c et al [9]). In their research laboratory tests of three identical steel knee joints with a tension tie element were conducted as well as a parametric numerical study with a variation of tie element stiffness. It was concluded that different stiffnesses of the tie element have little influence on the moment-rotation behavior of the knee joint, but greatly affect overall frame resistance to vertical loads. It was also concluded that different stiffnesses of the tie element can lead to different failure modes of the knee joint as well. In fact, the scatters between the two curves are very small, both in elastic and plastic ranges.

In this paper, the seismic performance of the structure is analyzed by introducing a new short knee element. The knee element was loaded dynamically in a way that simulated its behavior within a structure subjected to an earthquake. This was achieved using a technique known as real-time substructure testing, 13 illustrated in Fig. 4.

Initially, base model analysis was performed and in the next step, cyclic loading was applied on the knee fuse specimens. The model calculated the displacement at the interface with the tested element, and this displacement was imposed on the test specimen. The resulting resistance forces were then fed back into the base model as part of the input for the next calculation step.

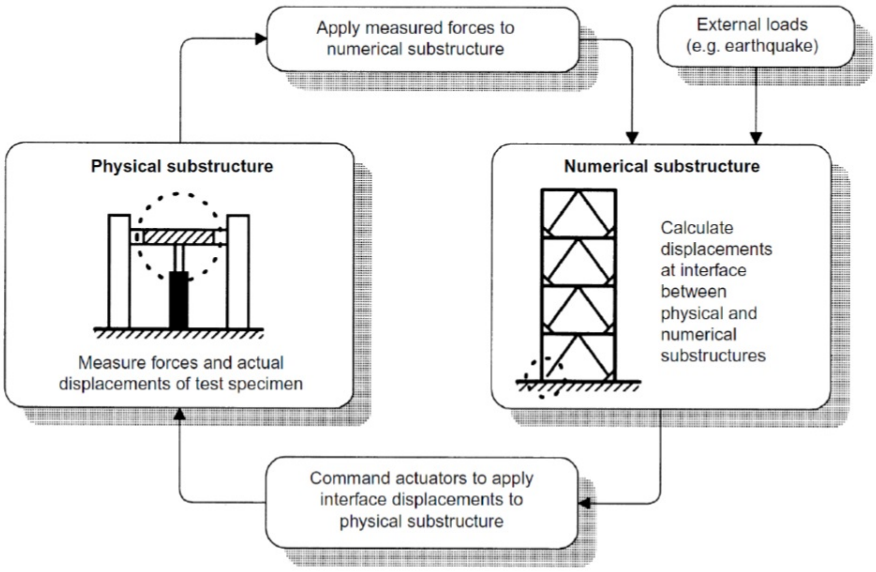


Figure 4: Real-time substructure test control loop

2. Mathematical Formulation

Usually, additional characteristics of parameters, such as rupture index and EPEQ are determined by use of some indices to monitor stress concentration and the crack initiation. These parameters related to experimental investigation and results around holes in the web of element and critical points. In this study, Rupture Index (RI) employed by Atashzaban et al. [2] adopted to evaluate the fracture potential and it demonstrated by Eq. (2.1).

$$RI = \frac{\frac{\varepsilon^{pl}_{eqv}}{\varepsilon_y}}{exp(-1.5\frac{\sigma_m}{\sigma_{eff}})} \tag{2.1}$$

Where:
σ_m: Hydrostatic stress
σ_{eff}:Equivalent stress (also known as the Von Mises stress)
ε_y: Yield strain of the metal
ε^{pl}_{eqv}: Equivalent plastic strain (EPEQ) demonstrated by Eq. (2.2).

$$\varepsilon^{pl}_{eqv} = \frac{1}{\sqrt{2}(1+v')}[(\varepsilon^{pl}_x - \varepsilon^{pl}_y)^2 + (\varepsilon^{pl}_y - \varepsilon^{pl}_z)^2 + (\varepsilon^{pl}_z - \varepsilon^{pl}_x)^2 + \frac{2}{3}(\gamma^{pl^2}_{xy} - \gamma^{pl^2}_{yz} - \gamma^{pl^2}_{zx})]^{\frac{1}{2}} \tag{2.2}$$

Triaxiality Ratio (TR) is the ratio of hydrostatic stress to Von Mises stress and it demonstrated by Eq. (2.3).

$$TR = \frac{\sigma_m}{\sigma_{eff}} \tag{2.3}$$

$TR < -1.5$ Metal is prone to brittle fracture
$-0.75 < TR < -1.5$ Reduction in the metal rupture strain
RI and TR used to compare the likelihood of rupture between different numerical modelling.
Where, ε^{pl}_i and $i = x, y, z$: The appropriate components of plastic strain

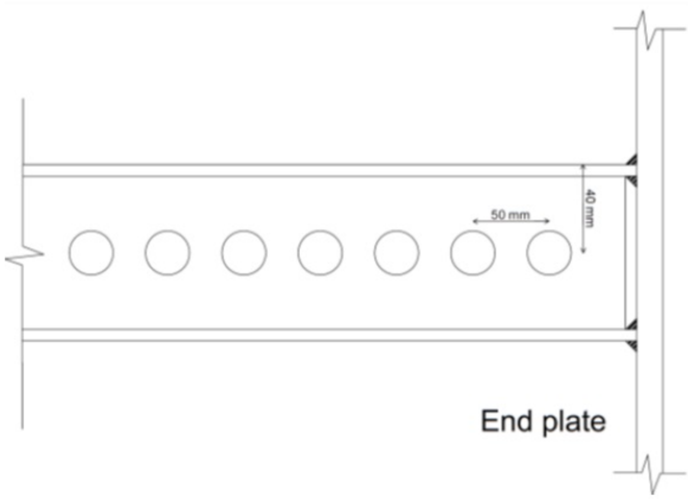


Figure 5: perforated specimen

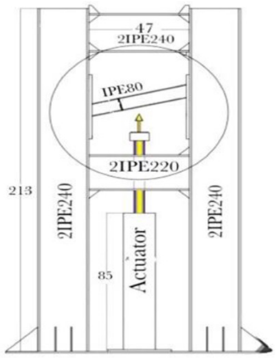


Figure 6: Experimental setup

γ_{ij}^{pl}. And $ij = xy, yz, zx$: The appropriate components of plastic shear strain
v': The effective poison's ratio

3. Material Property And Experimental Setup

Laboratory testing was conducted at the Faculty of Civil Engineering, University of Shahid Beheshti. The figure 5 shows the reference figure of a knee fuse (perforated specimen).

Two identical steel knee elements (marked with VSKE and ASKE) were tested under cyclic loading to induce bending in the specimens. Figure 6 shows the geometry of experimental setup. The boundary condition used is fixed boundary condition that is the two ends of the specimen are restricted.

The material used for knee specimen is low yield point steel because in hysteric knee fuse, steel must become plastic in an earthquake prior to other structural members.

Low yield point steel reduces yield strain also. Material Property of the steel material is shown in table 1.

Cyclic loading is adopted to find the seismic resistance knee element. Cyclic load is applied on the knee middle by hydraulic loading actuator on both positive and negative directions by applying displacement on the knee middle. 24 cycles of loading are done. Fig 7 shows the loading regime graph obtained from SAC-AISC, Steel, 1997 [8].

Table 1: Parameters of TTCIS

Steel Material	Steel Grade	Yield Strength	Ultimate Strength	Elastic Modulus
Frame	St44	315	445	2.1×10^5
All Specimens	St37	240	370	2×10^5

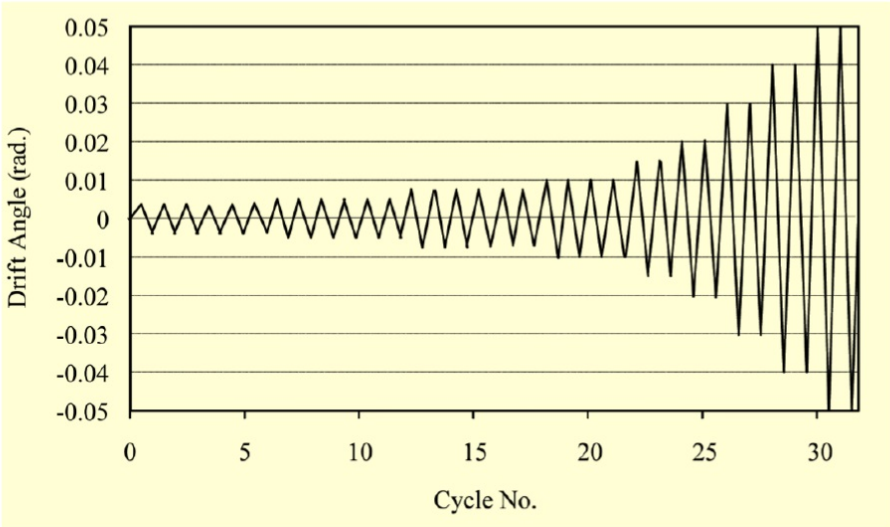


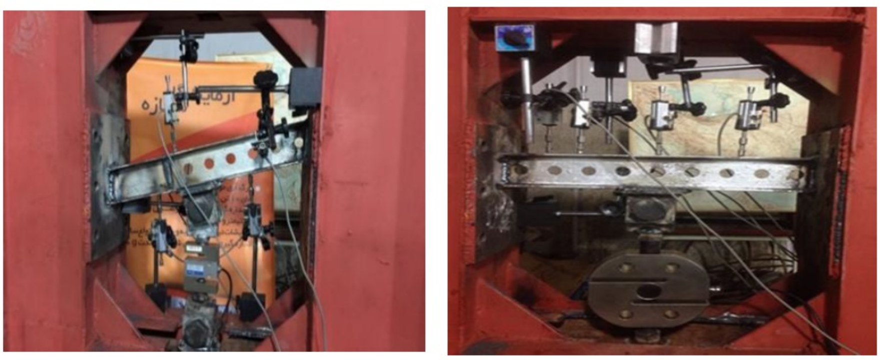
Figure 7: Loading regime

Specimens before experimental loading are shown in Fig. 8

Cracks developed at edge of the holes on the top and bottom lines of holes and quickly grew to join the holes together, as shown in Fig.9.

4. Simulations And Results

Twenty four cycles of loading are applied. Two cycles are performed for each displacement except for the fourth displacement where four cycles are performed. The strategy is to use shell elements (typical modelling of the steel structure elements). The figure 10 shows the stress distribution of the angular and vertical knee fuse obtained after the cyclic load, which indicates that a large part of the web is yielding and so contributing to the energy dissipation.

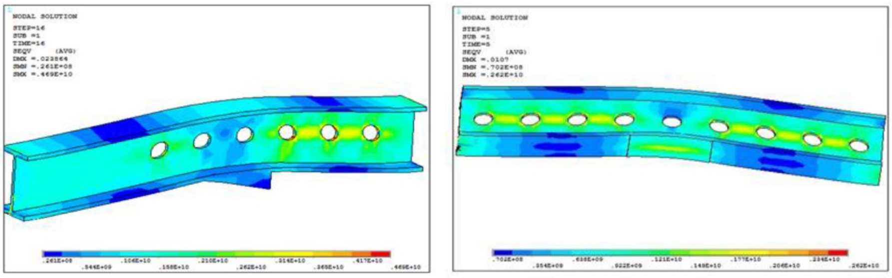


a) angular knee fuse **b)** vertical knee fuse

Figure 8: Specimens before loading

a) angular knee fuse **b)** vertical knee fuse

Figure 9: Specimens after cyclic loading



a) angular knee fuse **b)** vertical knee fuse

Figure 10: Stress distribution in specimens

The hysteretic curve obtained after the analysis is compared with the experimental result. The figure 11 shows the hysteretic curves of the angular knee fuse obtained after the cyclic load.

The figure 12 shows the experimental result obtained by using vertical knee fuse in place of angular knee fuse. The numerical result was carried out using ANSYS software.

Even though both results show a stable hysteretic curve, the angular knee fuse shows a much better result.

Figure 13 shows the Energy dissipation distribution obtained from ANSYS for angular knee fuse and the three specimens with square, horizontal rectangular, and vertical rectangular holes.

Table 2 shows maximum stress and energy dissipation obtained from ANSYS as per loading protocol.

In a conventional square-cut knee element there is relatively significant yielding in the knee

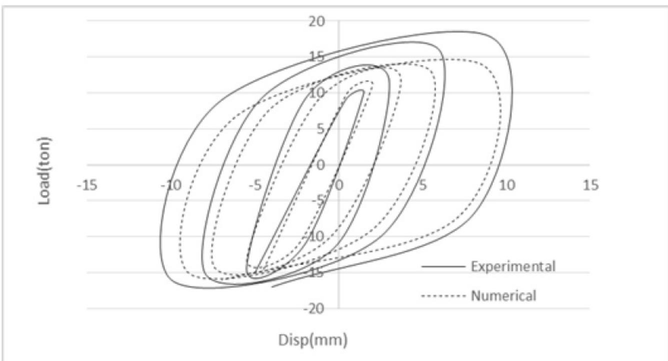


Figure 11: Hysteretic curve of angular knee fuse

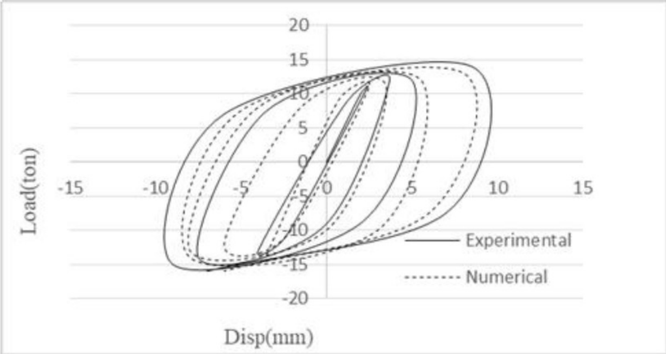
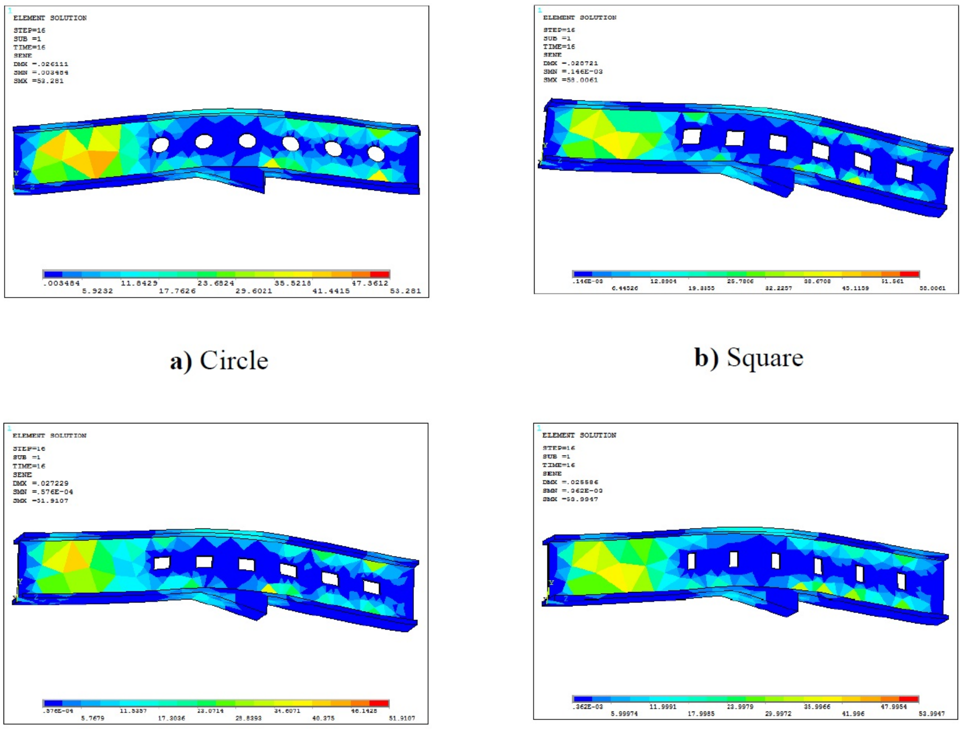


Figure 12: Hysteretic curve of vertical knee fuse



a) Circle

b) Square

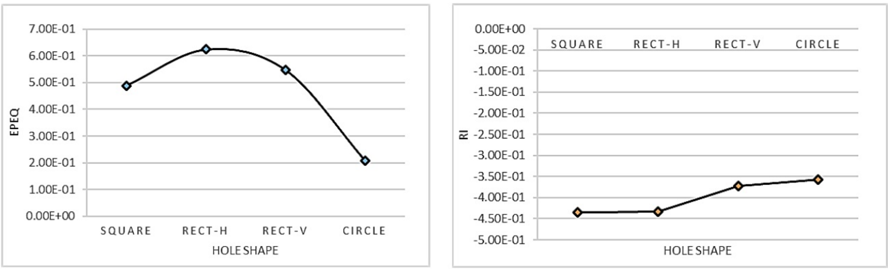
c) Horizontal Rectangular

d) Vertical Rectangular

Figure 13: Energy dissipation in various configuration of holes at angular knee fuse

Table 2: Max Stress and Energy dissipation

Specimen Shape	Energy Dissipate	Stress
S(a=20)	58.0061	$0.662E + 10$
RH2(w=25, h=15)	51.9107	$0.588E + 10$
RV2(w=10, h=20)	53.9947	$0.542E + 10$
C(D=20)	53.281	$0.469E + 10$



a) EPEQ b) RI

Figure 14: Variation of EPEQ and RI in various configuration

Table 3: Reduction factors of test specimens

Loading Situation	Specimens			
	VSKE		ASKE	Diff(%)
Yielding Load (Ton)	Test	7.42	12.5	68.5
	FEM	7.93	12.1	52.6
Ultimate Load (Ton)	Test	10.6	18	69.8
	FEM	10.6	17	60.4

element near the column face. Figure 14 shows the variation of maximum equivalent plastic strain (EPEQ) and rupture index (RI) in the various configuration of holes at angular knee fuse was carried out using ANSYS software.

The results of these numerical and experimental tests has been summarized in table 3.

5. Conclusion

This research reveals the ability of drilled knee fuses to resist earthquakes. The stipulated knee fuse system was designed by taking into account the yield strength of the beam and by this means, while the beam and column were in the elastic range, the plastic deformations were concentrated in the knee fuse, and damage to the beam and column was prevented. The hysteretic curve plotted after test and FE validation of vertical knee fuse is given above the value ranges from 12 to 15ton. The hysteretic curve plotted after test and FE validation of angular knee fuse is given above the value ranges from 14 to 18 tons. Even though both the knee elements give a stable hysteretic curve, the angular knee fuse gives a much better hysteretic curve. Also by comparing the area of two curves, the angular knee fuse has more area which means it has better efficiency for energy dissipation than the vertical knee fuse. Increasing the angle in the ASKE fuse will cause more equivalent plastic strain (EPEQ). According to the test observation and FE numerical results, the difference between the result of VSKE and ASKE for yielding load was equal to 68.5%, 52.6% and for ultimate load equal to 69.8, 60.4 respectively. Therefore, the angular knee fuse showed more load transfer from the column face to the knee element. The application of an angular knee fuse is a better option for earthquake resistance. Also as the angular knee fuse is replaceable, it is more economical.

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