Analytical Study of Simple Replaceable Fuse (SRF) in Eccentrically Braced Frames

Soroush Soltani[1], Mohammad Reza Javaheri-Tafti[2*], Mohammad Qasem Vetr[3]

Abstract:

The lateral bracing frames are one of the common and earthquake-resistant systems. These frames were originally used to withstand wind forces, and were later developed to withstand lateral forces caused by earthquakes. One of the most important lateral bracing systems are eccentric braced frames (EBF). In this investigation, the behavior of eccentrically braced frames with Interchangeable link beam has been studied. Unlike other past researches, in addition to paying attention to the proper function of the fuse in the structure, the researchers have put the simplicity of its construction and easy replacement on the agenda. In this system, the link beam is connected to the out-of-link beam using a pin connection, so that it can be easily interchanged while exhibiting a fully shear behavior. In order to achieve the desired results, eccentric frame design has been done by ETABS V15 software and analysis by ABAQUS V6.14 software. The results of the research show that the use of pinned link beam, in addition to its impressive performance against lateral force, due to its simple interchangeability, the reconstruction time of the structure after the earthquake has been greatly reduced and the structure can be restored in the shortest possible time to the usable state.

Keywords:

Eccentric Bracing, EBF System, Structural Fuse, Link Beam, Joint Connection

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1- Introduction

This is necessary to enter the behavior of the structure into the non-linear region, in structures that are designed according to modern seismic regulations. Obviously, if the behavior of the structure enters the non-linear area, the occurrence of damage and permanent changes in some elements of the structure is inevitable. Experience has shown that after moderate and strong earthquakes, it is necessary to repair and replace the damaged elements of the structure for reuse. So, it is very important to use structural systems that concentrate many sublation in a specific element and at the same time are easily interchangeable. In this investigation, the behavior of eccentrically braced frames with Interchangeable link beam has been studied. The results show that the system that leads to the submission of the horizontal link beam between the eccentric brace has high ductility and energy dissipation against seismic loads. In these systems, severe inelastic deformation occurs in the shear panel (link beam) and the internal energy is lost by this member. Yielding and plastic joint formation in eccentric braced frames (EBF) are shown in Fig.1.

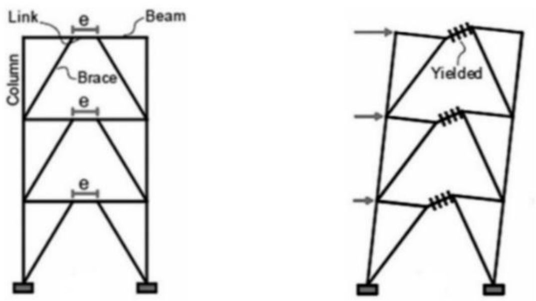


Fig. 1. The process of yielding and plastic joint formation in horizontal shear connection beams

The main frame members are not damaged, since all inelastic deformation occurs in the shear panel (horizontal link beam). Of course, despite the high seismic energy loss, eccentrically braced frames with horizontal link beam (H-EBF[1]) also have disadvantages. The main weakness of this system is that it is very difficult and time-consuming to repair or replace the link beam after an earthquake [1]. A new system called eccentric bracing frame with Interchangeable pinned link beam (SRF[2]) is proposed, to solve this problem in the (H-EBF) system. In this system, the link beam is connected to the beam outside the link area with a full joint connection, in the form of a tongue and

1- EBF with horizontal link

2- Simple replaceable fuse

groove, and using a pair of pins. As shown in, Fig.2.

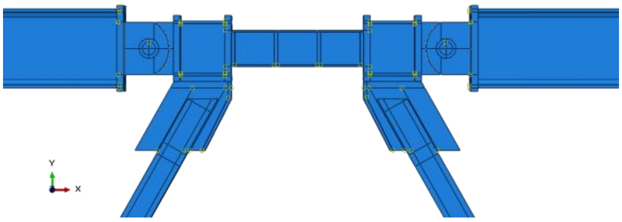


Fig. 2. Joint connection of the link beam to the out-of-link beam

Several studies have been conducted by researchers on this system to prevent buckling and yielding of other members. The results show that with proper design, yielding and energy loss occur only in the link beam, and this member, as a flexible fuse, prevents out-of-plane yielding and buckling of other members of this frame. This is possible to use exchangeable link beams for seismic reconstruction of existing buildings, with changes in the main structure of the frames as well. The link beam should be designed in such a way that by yielding and losing energy, as a flexible fuse, it prevents the occurrence of yielding and buckling in other members, including braces, columns and beams outside the link, according to AISC 360-10[3] regulations. Also, the length of the link beam should be determined in such a way that the possibility of shear yielding is provided without buckling in its web [2]. The inelastic response of a link beam is strongly influenced by the length, and the ratio $\frac{M_p}{V_p}$, in the cross section of the link beam. Using plastic analysis, plastic shear strength V_p and plastic bending strength M_p can be determined:

$$V_p = \frac{F_{yw}}{\sqrt{3}} t_w (d - 2t_f) = 0.6 F_y A_w \tag{1}$$

$$M_p = F_{yf} t_f (b - t_w)(d - t_f) + \frac{F_{yw} t_w d^2}{4} = Z F_y \tag{2}$$

where F_{yw} and F_{yf} are the yield stress in web and flange respectively, t_w web thickness, d beam depth, t_f flange thickness, b flange width, A_w web area, F_y yield stress and Z is the base of the plastic section. The shear link beam has very good ductility and energy dissipation, Popov et al. [3-8]. In fact, the high effect of isotropic strain hardening and the combination of bending and shear leads to an increase in the bending strength and plastic shear capacity. In the final state, the shear capacity and bending strength will

3- American Institute of Steel Construction reach $1.5V_p$ and $1.2M_p$ respectively. Also, in order that shear failure occur before the bending failure of the horizontal link beam, the length of the link beam (e) should be limited to the following:

$$e \leq \frac{2 \times 1.2M_p}{1.5V_p} = 1.6\frac{M_p}{V_p} \qquad (3)$$

Especially, the classification is based on the normalized link beam length (ρ), which is

$$\rho = V_p.e/M_p \qquad (4)$$

The capacity-based design method seeks to limit shear link beams in the inelastic region, so that all other frame members are designed to behave elastically. According to the AISC 360-10 seismic rules, link beams with the following properties

$$\rho \leq 1.6 \quad or \quad e \leq 1.6\frac{M_p}{V_p} \qquad (5)$$

are shear link beams that mainly yield in shear and have a maximum rotation of 0.08 radians under seismic load in the link beam. The relative displacement angle of the frame (θ) can be calculated according to the rotation angle of the link beam (γ), as shown in (Fig.3).

$$\theta_p = \gamma_p\frac{e}{L} \qquad (6)$$

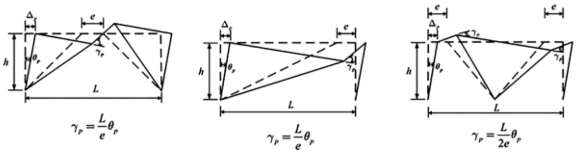


Fig. 3. Rotation of the link beam in the eccentrically braced frames [9]

Also as discussed above, under the base shear applied to the frame, when the link beam enters the inelastic region, the other members of the frame meanwhile outside the link beam, must be designed to remain elastic. The members outside the link beam are designed to resist the forces caused by the complete yielding of the link beam and entering its strain hardening region. For short link beams ($\rho \leq 1.6$), the generated forces can be calculated as in reference [2], (link beam section $= 1.25R_yV_p$), (link beam end bending in beam $= R_yV_p$, link beam end bending in brace

$$\left(1.25R_yV_p.e - R_yM_p\right) \geq 0.75R_yM_p \qquad (7)$$

where R_y is the ratio of the expected yield strength to the minimum yield strength F_y. This ratio is used to define the strength of the material. It is based on the results of 16 link beams, made of A992 steel, the average strain hardening has reached 1.28 with variations from 1.17 to 1.44 [10]. Other studies [4-8, 11-17] generally set the link beam strength factor to 1.5 For this purpose, the members outside the link beam are designed to resist the forces caused by the complete submission of the link beam and entering its strain hardening region [18]. In recent years, many studies have been conducted in this field (see [19-26]).

2- Simple Replaceable Fuse

In the present research, theoretically the nonlinear behavior of the SRF system has been investigated. Also, due to the favorable performance of the link beam in shear yielding, as well as easier replacement, the short link beam with purely shear behavior ($e \,\square\, 1.6 \frac{M_p}{V_p}$) has been studied as a fuse. Considering the influence of the shear panel on the behavior of SRF braces as a lateral load resisting system, this is very important to improve the performance of the shear panel. This research is a part of the SRF project, and in other stages of this project, the construction and laboratory investigation of the full-scale sample is done, hence all the members are modeled and analyzed with real size in the software. In other words, all the members are modeled with full scale (1:1), and finally verified with the laboratory results of the sample in real dimensions.

In this research, the first step is with modeling. It is started through ETABS V15 software. The selected frame is a span of a 10-story building with educational application, which is located on a type II ground and in an area with high seismic risk. The lateral load resistant system of this structure is a special eccentrically braced frame in one direction and a special moment resistant frame in the other direction. The direction of roofs beaming has been considered in a way that the main beams are placed on the moment resistant frame and the special eccentric frame only plays a role to resist against the lateral load. This assumption has been considered in order to investigate more closely the behavior of the system under the lateral load, as well as the easier replacing of the fuse.

In this project, European-type sections have been selected, and the analysis and design in the software has been done according to the AISC 360-10 steel structure code, and using the limit state method (LRFD) [2]. The length of the link beam, which is precisely the distance between the two braces, is 40 cm, the frame opening or span (which is the distance from the axis to the axis of the columns) is 300 cm, and the height of the frame is 240 cm, shown in (Fig.4). The dimensions and details of the sections are given in Table.3.

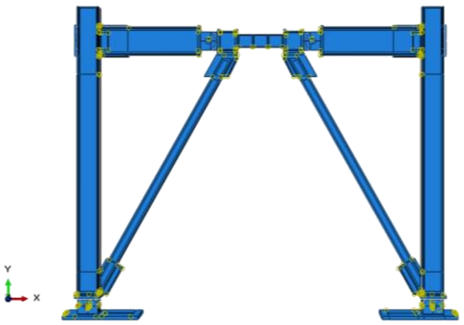


Fig. 4. General view of eccentrically braced frame

In the past researches, the connection of the link beam to the out-of-link beam was in the form of end plates or bolting of channel sections. After the earthquake and at the time of replacing the fuse due to the distortions in these sheets, it was difficult to match all the screw holes with each other, and sometimes some of the screw holes had to be made wider than the specified condition in phase design. However, in the present study, joint connection is used to connect the link beam to the out-of-link beam. This connection consists of 3 steel sheets that connect the link beam with a full joint connection to the out-of-link beam in the form of groove and tongue by pin. Due to the jointness of the connection area, the fuse element only exhibits a shearing behavior, and there is no need to align several screw holes with each other or widen the screw holes during replacement. The fuse can be removed or installed easily by removing or inserting a pair of pins.

The second point is the practicality of this replaceability. In the past studies, replaceability was only mentioned as an advantage and its details were not discussed. In the past examples, for example Figure-1, to remove the damaged fuse after the earthquake, how to replace the fuse that is buried inside the roof? But in this study, taking into account the system main beams (which was in the perpendicular to EBF), gravity load is not applied on the fuse. Also, the connection of the braces to the fuse is made with screws and embedded inside the wall. (Not in the corner of the roof). Therefore, by removing the joinery layer on the wall and temporary opening the braces and removing the pins of the connection area, in a completely practical and effective way, the fuse is moved down and it simply comes out of its place. It is done in the same way for installation. All these steps of installing and replacing the fuse have been practically done in the lab.

3- Finite element modeling (ABAQUS)

3-1- Modeling details

A frame with one floor and one span is subjected to cyclic horizontal displacement, for modeling in ABAQUS V6.14 software. Although the application of gravity load may affect the shear link beam behavior, but since the axial load reduces the capacity of the shear link beam, the researchers decided not to apply any vertical force to the shear link beam.

3-1-1- Mechanical properties of materials

The material of the sections is ST37 steel with a density of $\rho = 7.85 \times 10^{-9} \frac{ton}{mm^3}$ and other elastic and plastic properties present in Tables.1 and 2, based on DIN 17100 St37-2 Steel.

Table 1. Elastic Properties

Poisson's ratio	Young's modulus
0.3	20×10^5 Mpa

Table 2. Stress and strains

Stress (Mpa)	235.359	265.934	277.528	300.083	324.600	353.039	353.039	353.039
strain	0	0.05	0.05	0.018	0.033	0.056	0.088	0.13

3-1-2- Specifications of frame members

As mentioned above, the structure is designed using AISC 360-10 Based on that, the length of the link beam has been chosen in such a way that the web of the link beam will yield in shear. According to the regulation, to ensure the elastic performance of the members outside the link in the dual systems of special eccentric frames and bending frame, the resistance increase factor (Ω_0), 2.5 is suggested. Therefore, other members of the eccentric frame, except for the link beam, have been designed for a force 2.5 times what was created in them from a static analysis. Also, a pair of stiffeners are installed at the beginning and end of the link beam and on both sides of the beam, and two stiffeners are installed along the length of the link beam on one side of the beam. The design result of SRF is presented in Table.3.

Table 3. specifications of frame members

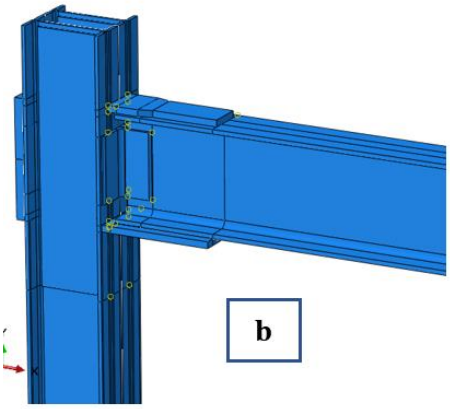
Location	Section type	length (mm)
Link Beam	* PG 100□3-80□5	**400**
out-of-link beam	IPE240	**1300**
out-of-link beam is the distance between the link beam and the joint	IPE240	**250**
column	2IPE180	**2400**
brace	UNP100	**2730**
pin	⌀25	**100**
Link beam stiffeners	** PL 100□40□10	**100**

* h_w □ *100* mm t_w □ *3* mm b_f □ *80* mm t_f □ *5* mm

** *h* □ *100* mm *t* □ *10* mm *b* □ *40* mm

3-1-3- Connections

The link beam is connected to the out-of-link beam with the help of a series of curved sheets and pins as shown in (Fig.5a) and the connection of the out-of-link beam to the column as rigid-type is ensured by embedding the sheet in the joist and seat sheet (Fig.5b). Also, the braces connection is joint connected.



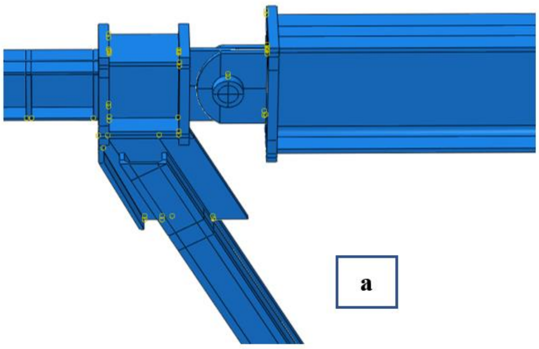


Fig. 5a. The joint connection of the link beam to out-of-link beam, Fig. 5b. Rigid connection of out-of-link beam to column

In view of that the type of connections is not the subject of this research, for the simulation of the welded connections of the Tie, and for the curved sheets and pins connecting the link beam to the beam outside the link, which are in direct contact with each other, Contact limit and two types of vertical and tangential contact are used. In vertical contact, a Lagrangian equation is used to solve the equations; and tangential contact models the friction between two surfaces using a coefficient of friction, which is defined by the user and is about 0.4 for steel. Also, the baseplates are fixed in place and have no movement, which is intended to better convey the concept of the baseplates being stable on the foundation.

3-1-4- Overall stability of the sample

Fundamentally, the out-of-plane lateral stiffness at the lower end of the shear link beam affects the placement of braces. Based on the analytical studies on the lateral stability conditions, to control the lateral torsional buckling, at the beginning and end of the link beam, a lateral brace is installed.

3-1-5- Loading

The loading method used in this research is based on method B of ASTM [27] regulations. In this loading method, the range of motion is a percentage of the target displacement, which is shown in Table .4. These cycles will continue until failure occurs or a significant drop in resistance is observed.

Table 4. Loading protocol by method B of ASTM [27]

Minimum Number of Cycles	1	1	1	1	1	3	3	3	3	3	3	3	3
Amplitude, λ_m %	1.25	2.5	5	7.5	10	20	40	60	80	100	120	140	160
Displacement (mm)	0.6	1.2	2.4	3.6	4.8	9.6	19.2	28.8	38.4	48	57.6	67.2	76.8

The load application steps are based on the percentage of target displacement, according to Table 4. But because each sample has its own final displacement, the loading protocol is different for different samples. But since the purpose of this research is to investigate and compare the behavior of eccentric bracing frame with Interchangeable link beam, in this research, instead of changing the location of the target, the maximum real relative displacement (λ_m) or Drift has been used. The value of λ_m, which is obtained by considering the effects of $P \square \lambda$, in the calculation of λ_m, should not exceed the permissible value of λ_a to do in the following relations. Height of the floor is h.

$$\lambda_a \square 0.020h \quad \leftarrow \textit{in buildings with more than five floors} \tag{8}$$

Accepting that the desired frame is located in a building with more than 5 floors, so the maximum real relative displacement will be equal to:

$$\lambda_m = \lambda_a = 0.020h = 0.02 \times 2400 = 48 \text{ mm} \quad (9)$$

With a displacement of ±0.6 mm in the first stage of initiation and growth, loading continues according to the third column of Table .4 for the next stages. The first five stages of loading are repeated once each and the subsequent stages are repeated three times each (Fig. 6)

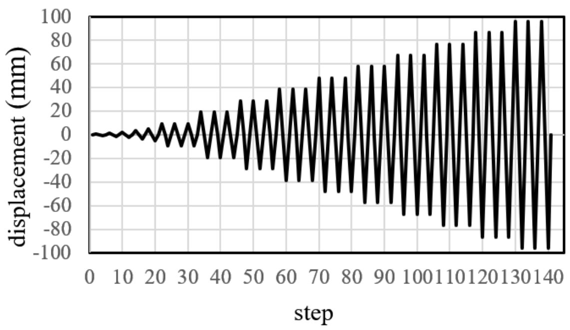


Fig. 6. Loading protocol by method B of ASTM [27]

3-1-6- Meshing

The method and element used for meshing is the Structure technique and the solid element called C3D8R, which is an 8-node cubic or brick-shaped, three-dimensional, linear element with a reduced formulation. The reduced formulation is chosen in order to reduce the calculation time, because in the case of higher order elements, the calculation time becomes very high. At least three members are used in the thickness of the steel flanges, plates and stiffeners in order to properly redistribute the bending behavior. In order to reach the appropriate mesh size, the analysis was performed with different mesh dimensions until the analysis results converged. In the parts of the model where higher stress concentration is expected, the meshing is finer as well. (Fig. 7).

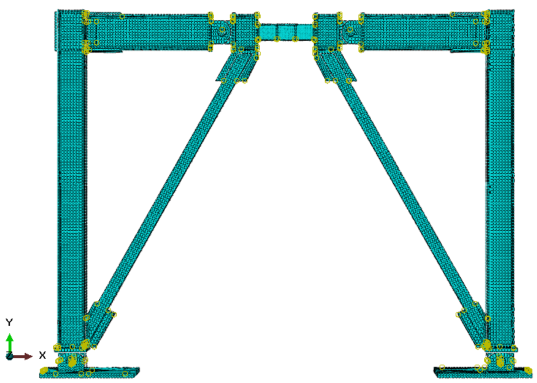


Fig. 7. Frame meshing

4- Numerical results

4-1- Cyclic displacement results

From the finite element modeling, the results which obtained are caused by applying horizontal cyclic displacement to the outer faces of the columns at a distance of about 1510 mm from the center of the link beam, at the level of the floor ceiling. (Fig. 8). Fig. 9 show the deformed form of the target frame under the applied displacement.

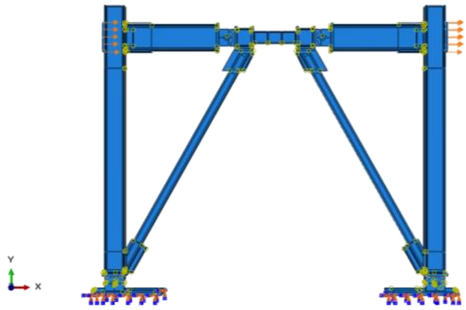


Fig. 8. The location of the lateral load at the level of the floor ceiling

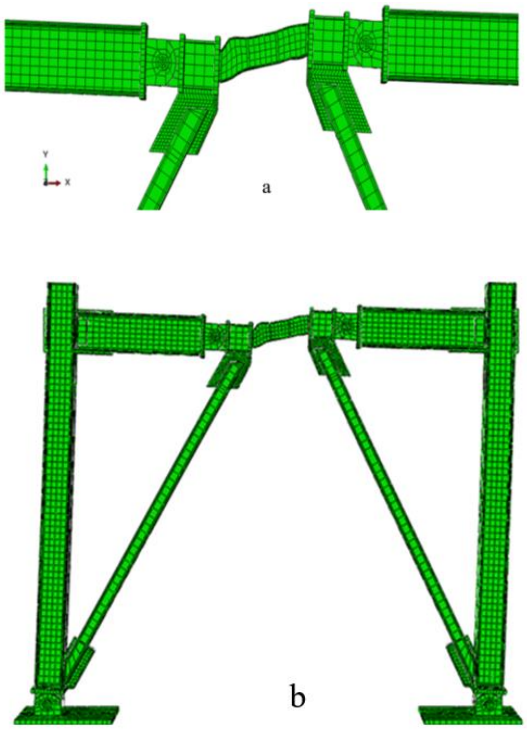


Fig. 9. Deformed, a. link beam, b. frame

Based on the results obtained from the analysis of the frame under cyclic displacement, the main concentration of stresses has occurred in the link beam and while other parts of the structure remain in the elastic region, the link beam undergoes many deformations upon entering the nonlinear region, which has suffered and has caused significant consumption of energy. In Fig. 10, colored graphs of Von Mises stress (s, mises), resulting from cyclic displacement, are presented.

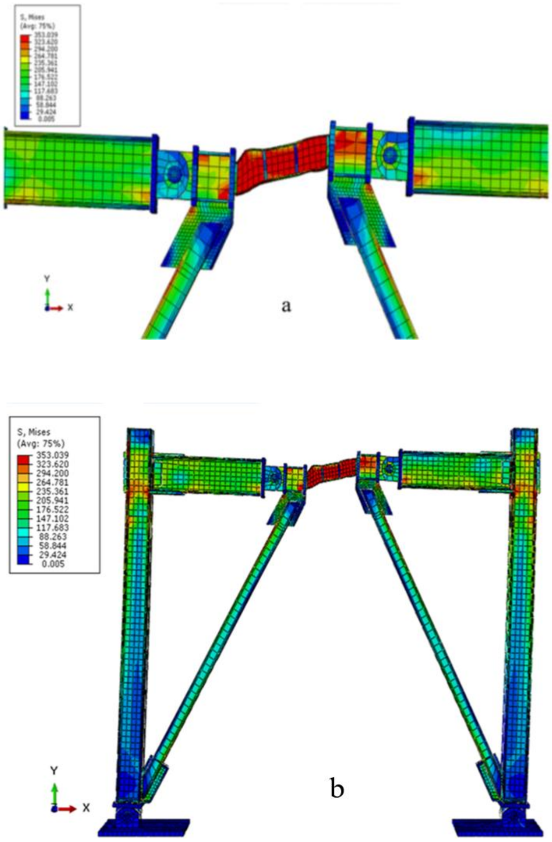


Fig. 10. Colored diagram of von Mises stress, a. in the link beam, b. in the frame

For the purpose of specifying more precisely the behavior of the link beam with joint connection in the frame (SRF), the colored graphs of shear stress (S, S12) are presented in fig. 11.

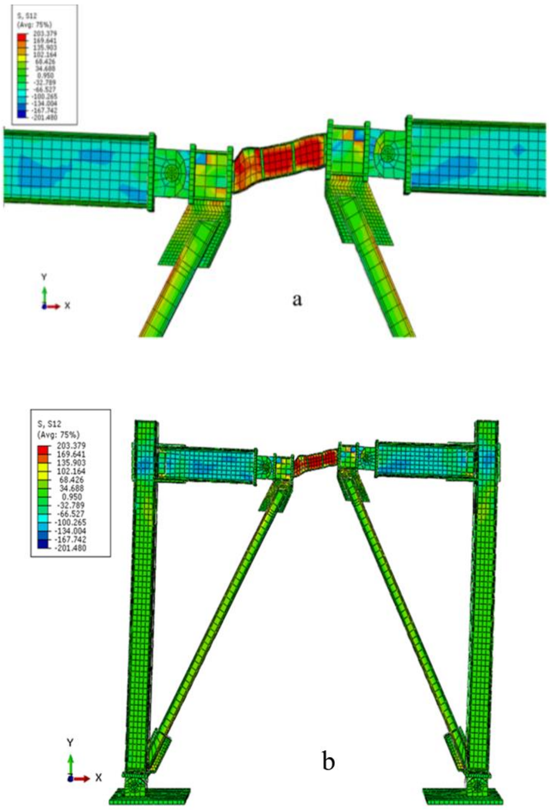
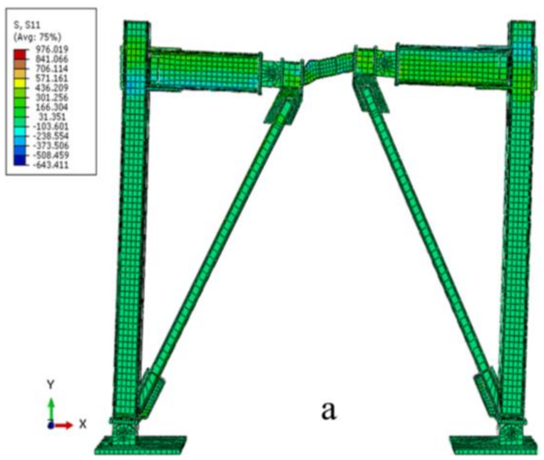


Fig. 11. Colored diagram of shear stress, a. in the link beam, b. in the frame

In the link beam and other frame members the axial force is negligible. Fig. 12, show the more critical points of these stresses for the X, Y and Z directions, respectively.



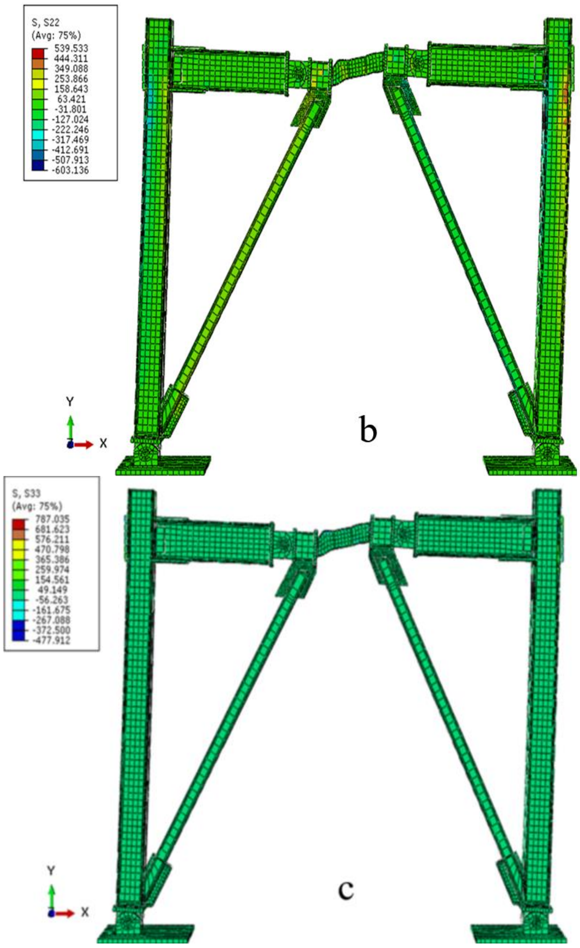


Fig. 12. Color diagram of frame axial stresses, a. X direction, b. Y direction, c. Z direction

5- Analysis of the results

In order to reach forces such as displacement, the forces applied to both columns at each stage of displacement should be added together according to the direction of the forces due to the fact that in this modeling displacement has been introduced to the frame columns. According to the results obtained from the ABAQUS V6.14 software, the sum of forces and displacements applied in the X direction leads to draw a hysteresis diagram as shown in Fig. 13.

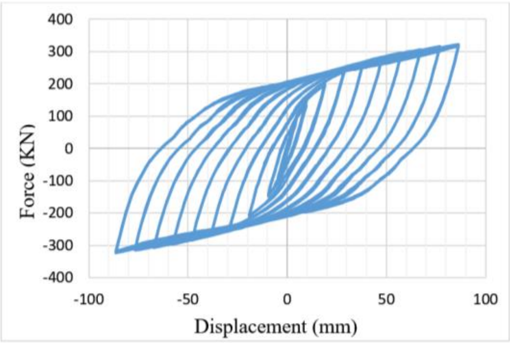


Fig. 13. Hysteresis diagram of the frame under cyclic displacement

Moreover, as it is illustrated in Fig .11, if the points presented in the design section are followed, and the design is done correctly, we will see the concentration of shear force in the link beam, which means the occurrence of shear yielding in the link beam. According to the main idea of the design, that for Interchangeable, were initially two bending joints on both sides of the link beam, we should never have allowed the formation of a third bending joint in the link beam. Because with the formation of the third bending joint, the failure mechanism was formed in the beam and the frame collapsed without bearing an acceptable amount of shear force. Yielding has occurred in the link beam and is of a shear type consequently.

The colored graphs of the equivalent plastic strain (PEEQ) in the change of the maximum location are depicted in fig. 14, as well.

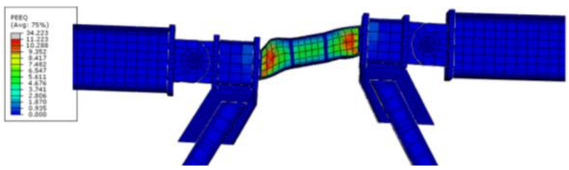


Fig. 14. diagram of PEEQ in maximum displacement

5-1- Verification

In general, the purpose of this research is to investigate the behavior of the introduced fuse and to determine the design parameters and behavior coefficient for the eccentrically braced frame equipped with SRF.

In another part of this project, which includes full-scale experimental modeling, the experimental tests prove the claim of the researchers that the fuse enters the non-linear area and the rest of the frame members are protected during the earthquake. The behavior of the frame in the experimental test is consistent with the numerical studies and the correctness of the behavior of the fuse has been confirmed. As an example, the final images of the experimental test (number-1), the eccentrically braced frame system equipped with SRF is presented to determine the correctness of the model (Fig. 15).

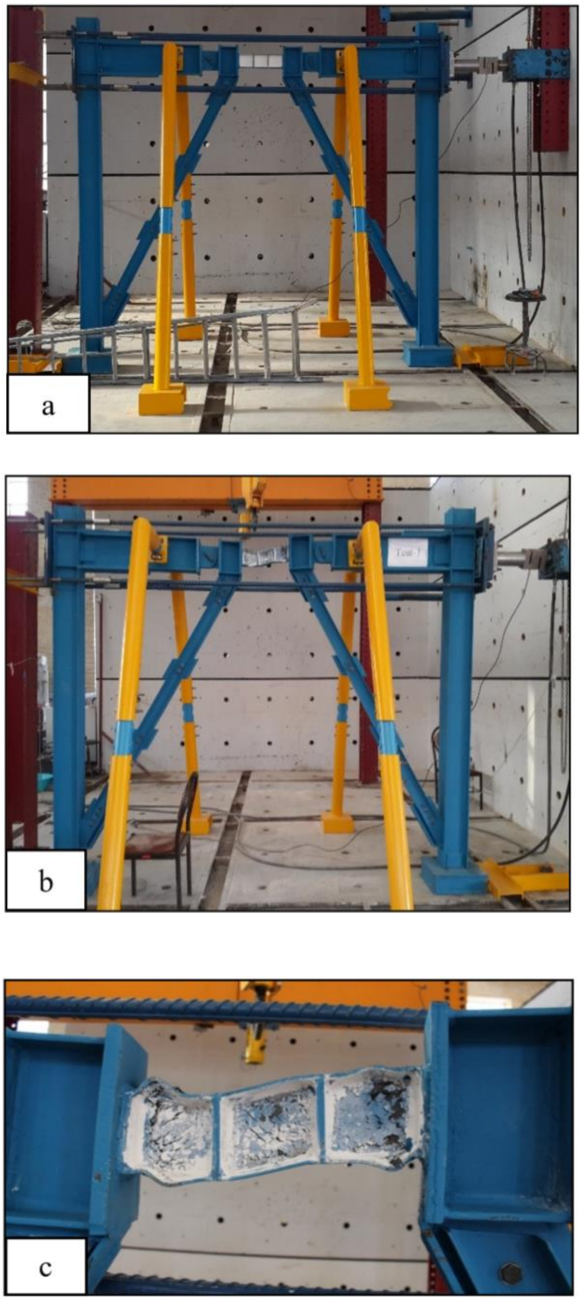


Fig. 15. Verification by experimentally tests. (a) Before Test, (b) After Test, (c) Close ups fuse after test

5-2- Frame design parameters

To idealize the cover curve and determine the design parameters of the frame, Young's method has been used. In this method, a two-line curve is obtained by continuing the elastic range and obtaining the yield base shear and then connecting it to the maximum base shear so that the stored strain energy does not change. The area under the cover diagram is assumed to be equal to the area under the bilinear curve diagram in this case, [28].

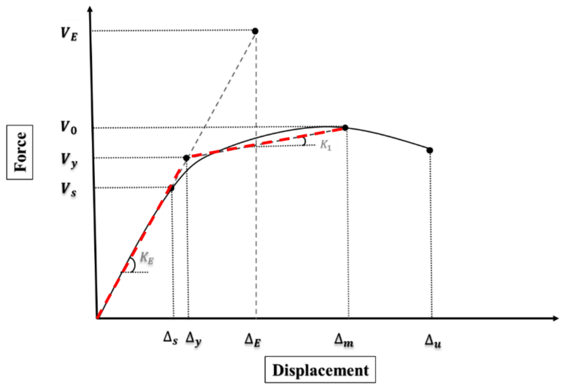


Fig. 16. Bilinearization of Pushover diagram by Young's method [28]

The components of the behavior coefficient consist of four parameters, which are mentioned in Eq. (10) is shown in the research of Berkeley University researchers, [29].

$$R = R_s R_\mu R_R R_\xi \quad (10)$$

In above relation, R_s: additional resistance coefficient, R_μ: coefficient due to ductility, R_R: uncertain coefficient and R_ξ: damping coefficient of the system, which is described in detail in the reference [28], and the results of each are shown in the table below. The desired frame is presented.

Table 5. design parameters of eccentrically braced frame with interchangeable link beam

parameter	value	parameter	value
V_s	90.5628	V_E	**893.87**
$\square_s$	4.8000	$\square_E$	**47.3769**
K_E	18.8672	R_s	**2.3068**
V_0	322.576	$R_{\mp}$	**4.2786**
$\square_m$	86.4000	R_R	**1.00**
V_y	208.912	$R_{\square}$	**1.00**
$\square_y$	11.0727	$\mp$	**7.8029**
K_1	1.5089	R	**9.8701**

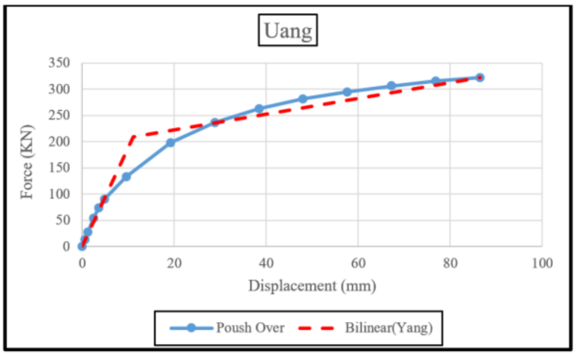


Fig 17. bilinearization of pushover diagram of eccentrically braced frame is introduced

6- Conclusion

As discussed in this investigation, the analytical study of Interchangeable fuse in eccentrically braced frames has been discussed. In this research, the amount of energy consumption in the Interchangeable link beam was investigated by drawing the hysteresis diagram/force-displacement. In order to achieve the desired results, the design of the steel frame has been done by ETABS V15 software and modeling - analysis by ABAQUS V6.14 software.

Totally, against lateral loads caused by earthquakes, the eccentric bracing frame is a reliable system. This system, which with its high hardness and ductility, behaves very well during an earthquake, requires proper design and implementation without defects for its proper operation during an earthquake. The results of the system, especially the coefficient of behavior and the coefficient of plasticity, showed that, in case of accurate design and flawless implementation, during an earthquake, a significant portion of the force enters the link beam and is used to change its shape. In other words, Interchangeable link beam, by accepting a significant shear deformation, enters the nonlinear area and with its damage, other parts of the structure remain immune. The important point of this research is that the joint connection of the link beam to the beam outside the link and the braces makes the fuse or link beam easily and quickly interchangeable after the destruction caused by the earthquake and they come back and can be used as the structures with this system quickly return to operational mode.

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