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Evaluating the performance of OBS-C-O in steel frames under monotonic load

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Abstract. Bracing structures with off-centre bracing system is one of the new resistant systems that frequently used in the frame with pin connections. High ductility, high-energy dissipation and decrease of base shear are advantages of this bracing system. However, beside these advantages, reconstruction and hard repair of off-centre bracing system cause inappropriate performance in the earthquake. Therefore, in this paper, the goal is investigating the behavior of this type of bracing system with ductile element (circular dissipater), in order to providing replacement of damaged member without needing repair or reconstruction of the general system. To achieve this purpose, some numerical studies have been performed using ANSYS software, a frame with off-centre bracing system and optimum eccentricity (OBS-C-O) and another frame with the same identifications without ductile element (OBS) has been created. In order to investigate precisely on the optimum placement of circular elements under monotonic load again three steal frames were modeled. Furthermore, the behavior of this general system investigated for the first time, linear and nonlinear behavior of these two steel frames compared to each other, to achieve the benefit of using the circular element in an off-centre bracing system. Eventually, the analytical results revealed that the performance of steel ring at the end of off-centre braces system illustrating as a first defensive line and buckling fuse in the off-centre bracing system.

Keywords: finite elements; structural control; braces; dampers; ductility factor; energy dissipation; steel structure

1. Introduction

Bending members compared to axial members have more ductility. Hence, adding one bending member to off-centre bracing system lead to increase in ductility of such frames (Moghaddam *et al*. 1999). The geometry of steel ring would be changed provided that bending were applied. Eventually, these changing cause dissipation of energy from bending operation. Embedding steal rings in the off-centre brace in the member AO in Fig. 1 result in loading such as shown in Fig. 2. As a result, bending operation of steel ring in the off-centre bracing system lead to increase in ductility of bracing frame (Moghaddam *et al*. 1995).

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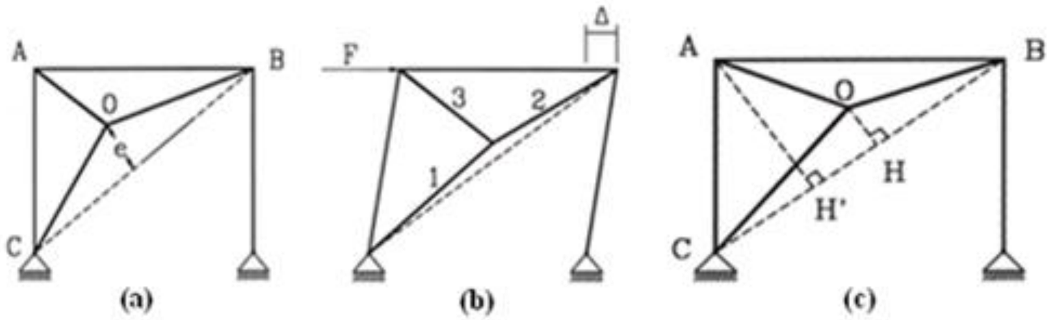


Fig. 1 Off-centre bracing system (Andalib *et al*. 2010, 2014) (a) Undeformed, (b) Deformed, (c) Eccentricity parameters e_1=OH/AH' and e_2=CH/CB

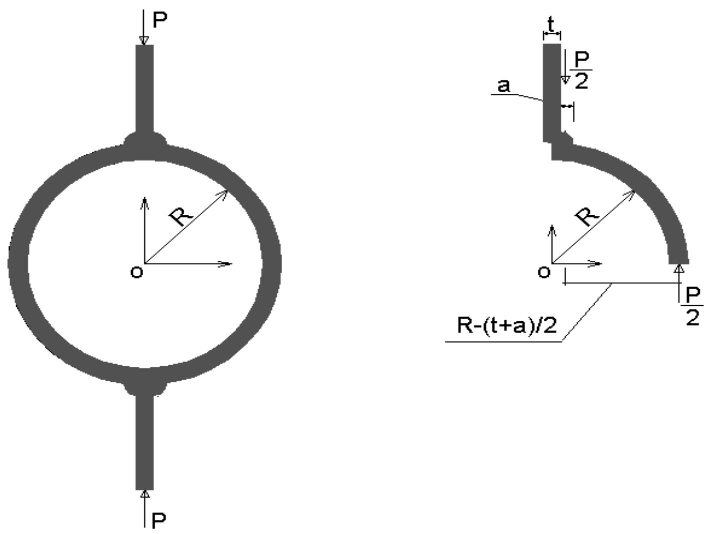


Fig. 2 The load path from connection plate to steel ring

An off-centre bracing system consists basically of the non-straight tension strut BOC with an eccentricity designated as "*e*" is shown in Fig. 1. The midpoint O is connected to the corner by the third member AO. Once the load is applied, all these three members are stretched and, therefore, act in tension. As the load increases, the original geometry changes and a new formulation of equilibrium equations, based on the new geometry, is required. Hence, the characteristics of such an off-centre system are geometrically nonlinear (Moghaddam *et al*. 1999). Additionally, another investigation revealed the degree of nonlinearity depends mainly on the amount of eccentricity and the relative stiffness of the third bracing member. In this paper, ductile element embedded in the third member of off-centre bracing systems (AO), and it is clear that stiffness of this system is lower than that of the system without ductile element. The purpose of this system is mainly on the dissipation of energy to achieve stiffness results of previous research.

In reality, eccentric diagonal of off-centre bracing lead to nonlinear behavior even in elastic zone. The results of analysis and investigation on the load-displacement behavior of off-centre brace system result in nonlinear hardening of such systems (Bazzaz *et al*. 2012, 2011). Although this hardening has decreased and reached to balance by applying circular element, the off-centre system has a suitable bending strength to resist against instability caused by earthquake collapse. This system increased ductility with circular element and dissipation of energy. The optimum circular element has been achieved by previous research (Bazzaz *et al*. 2012, Abbasnia *et al*. 2008).

Energy dissipation in a structure can be achieved in two possible ways, the first being in the form of specially detailed plastic hinges regions of beams and columns which dissipate energy due to inelastic behavior. These, however, cause permanent damage to the lateral force resisting system and prevent its subsequent reuse, which is undesirable. The other viable mechanism involves the introduction of additional energy dissipation systems in the structure which are not part of the gravity load carrying frame (Murthy *et al*. 2005).

As the magnitude of seismic forces applied to a structure depends partly on the characteristics of the structure itself, there is a growing trend to investigate and identify effective methods of enhancing the seismic behaviour of structures by controlling their deformation rather than strength characteristics (Marshall *et al*. 2010, 2010). The impact of this on seismic design has been the emergence of a variety of new structural forms. Eccentric and off-centre bracing may be regarded as examples of such new forms (Constantinou *et al*. 2001).

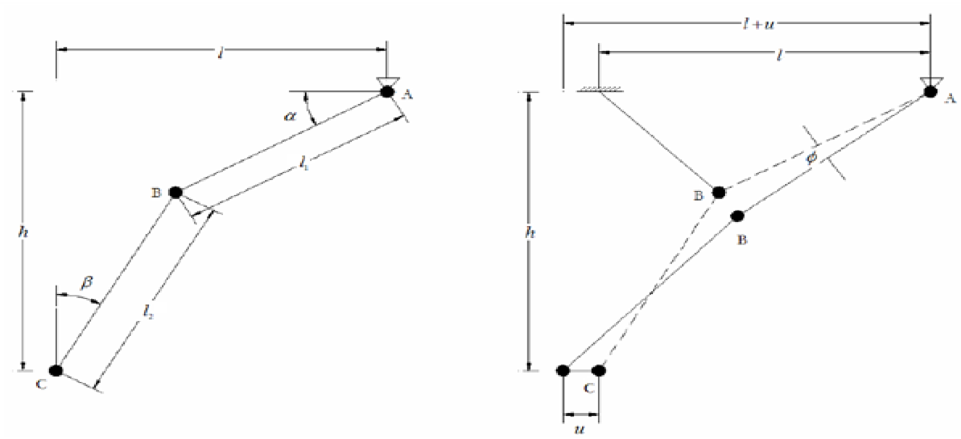
2. Literature review: recent studies

There are methods to reduce the effect of ground motion, such as viscous dampers (Murthy *et al*. 2005), base isolators and other types of passive, active (Marshall *et al*. 2010) and semi-active control devices. The passive control devices were the earliest to be developed and have been used extensively in seismic protection systems because they require relatively less maintenance and need no external power to operate. The most commonly used passive control devices in structural systems are base isolators, tuned mass dampers, and energy absorbing elements (Mahmoudi *et al*. 2010).

In the base isolation approach, the building is decoupled from the horizontal component of the ground motion by introducing a layer of a low horizontal stiffness between the structure and the foundation (Moghaddam *et al*. 2006). The first dynamic mode of the isolated structure produces deformation only in the isolation system. The higher modes, however, cause deformation in the structure, but are not usually of great significance in short to medium height structures (Asgarian *et al*. 2009). The passive energy dissipation systems work by absorbing the dynamic energy through discrete elements called dampers. Therefore, reducing the energy dissipation demands of the primary structural members and minimizing possible structural damage (Davaran *et al*. 2009). The most commonly used passive energy dissipation systems include friction dampers, metallic yielding devices, viscous fluid dampers and viscoelastic solid dampers. However, the load carrying efficiency of such designs is limited when an earthquake induces large story drift because of the lower structural stiffness of the steel frames (Hsu *et al*. 2011).

3. Off-centre brace theory

Several configurations have been proposed for amplifying displacements, and can be used in energy dissipation systems. One of them is a lever mechanism (Hibino *et al*. 1989) and the other is



(a) Deformed toggle configuration (b) Undeformed toggle configuration

Fig. 3 Deformed Off-centre configuration

based on a slider-crank mechanism (Constantinou *et al*. 1997). The system consists of toggles ABC, which are configured as a shallow truss.

When the frame sways to the right (in the u^+ direction), the point B displaces to the bottom, causing a rotation in the toggles. The resulting rotation causes displacements in the device. The displacements in the device are related to the inter-story drift through simple equations. The connection at point B is to be designed as a true pin, and hence there is no bending in the system. Fig. 3 shows the undeformed and deformed configurations of the toggle.

Under the displaced configuration of the toggle, point B moves downward and assuming inextensible members would result in the following equation (Murthy *et al*. 2005)

$$\mathbf{l}_2^2 = \mathbf{h}^2 + \mathbf{l}_1^2 + (\mathbf{l}+\mathbf{u})^2 - 2\mathbf{h}l_1 \sin(\alpha+\phi) - 2(l+u)l_1 \cos(\alpha+\phi) \quad (1)$$

The displacement in the device, which would be equal to the movement of the point B to the deformed configuration, is given by the following equation.

$$\mathbf{u}_{\mathbf{D}=\pm l_1}\left[\sqrt{1+\left[\frac{\sin^2(\alpha+\theta)}{\sin^2\theta}\right]} - \frac{2\sin(\alpha+\theta)\cos(\alpha\pm\phi)}{\sin\theta}\right] - \frac{\sin\alpha}{\sin\theta} \quad (2)$$

Eqs. (1) and (2) reveal a complex nonlinear relationship between the story drift u and the device displacement (δ). However, they can be simplified further as the rotation angle φ and the displacement u are small compared to the structural dimensions. Based on this simplification, the device displacement and the inter-story drift are related to one another by the following relation

$$\delta = \mathbf{fu} \quad (3)$$

The quantity 'f' is the displacement amplification factor, and depends only on the inclination of the toggles and is independent of its dimensions. Extensive research on the toggle-brace-damper system has been conducted by (Constantinou *et al*. 1997, 2001) including the study of the position of these dampers and the effect of the inclination of the toggles on the amplification factor.

The toggle brace configuration can be used for frames where the inter-story drift is less than the

Table 1 Sections specification of hinged frame with off-centre bracing system and ductile element

Specification	Members	Column	Beam	Brace OA	Brace OB	Brace OC
Common in all models	Kind of profile	2UNP14	IPE22	2UNP12	2UNP12	2UNP12
	A(mm^2)	4080	3950	3400	3400	3400
	I_x(mm^4)	12100000	30600000	7280000	7280000	7280000
	I_y(mm^4)	4339500	1620000	3162400	3162400	3162400
	r_x(mm)	54.5	88	46.27	46.27	46.27
	r_y(mm)	32.6	20.2	30.5	30.5	30.5
Model OBS-C-O	l(mm)	1500	2750	330	2000	1060
Model OBS	l(mm)	1500	2750	850	2000	1060
Model OBS-C0.2	l(mm)	1500	2750	-	1800	950
Model OBS-C0.3	l(mm)	1500	2750	-	1830	980
Model OBS-C0.4	l(mm)	1500	2750	-	1890	1070

displacement in the toggles at which their 'straighten out', or in other words $\alpha+\beta=90°$ in the deformed configuration. The limit on the frame displacement is given by the following relation

$$\mathbf{u}=\left[\sqrt{(\mathbf{l}_1+\mathbf{l}_2)-\mathbf{h}^2}\right]-\mathbf{l} \tag{4}$$

4. Geometrical specification of models

4.1 Geometrical specification of frame with off-centre brace and ductile element

In order to investigate the optimum position of ductile element in an off-centre brace frame, a single-story, single-bay hinged frame with off-centre figuration and ductile element in member AO (member AO shown in Fig. 1) has been analyzed and studied. The model for simplification has been named (OBS-C). From this model three different figurations have been created. The variation of these three models is in value of e_1, So that three models were called OBS-C0.2, OBS-C0.3 and OBS-C0.4. The numerals revealed the value of eccentricity e_1 by taking e_2=0.5 in all of them. Concerning the geometry of the models, the length of three members of off-centre brace frame calculated and the specifications of frames are shown in Table 1. The sections of profiles are two channels at a distance of 20 mm from each other. The space between column filler and brace member is 380 mm and the thickness of fillers and plates of corner connections are 20 mm. Connections modeled as pin assuming that pin joint is more conservative.

Circular element is modeled taking external diameter 220 mm, thickness 12 mm and a length of 200 mm.

4.2 Geometrical specification of frame with off-centre braced frame and ductile element in the optimum place

The goal of embedding circular element in the concentric bracing system is increasing in ductility with buckling control. However, the bearing capacity of circular element is limited and

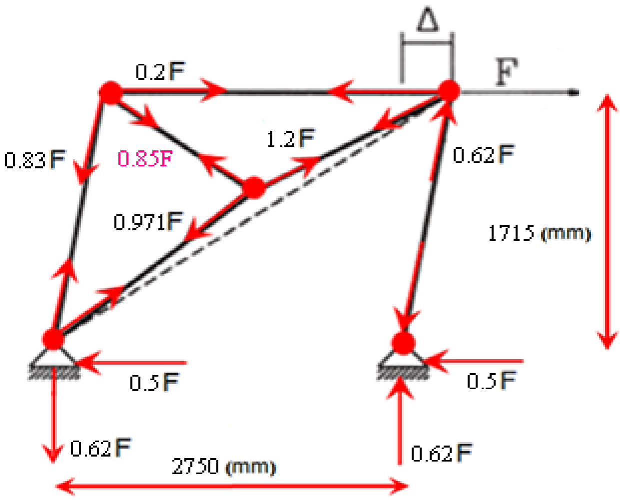


Fig. 4 Preliminary configuration of bracing connection

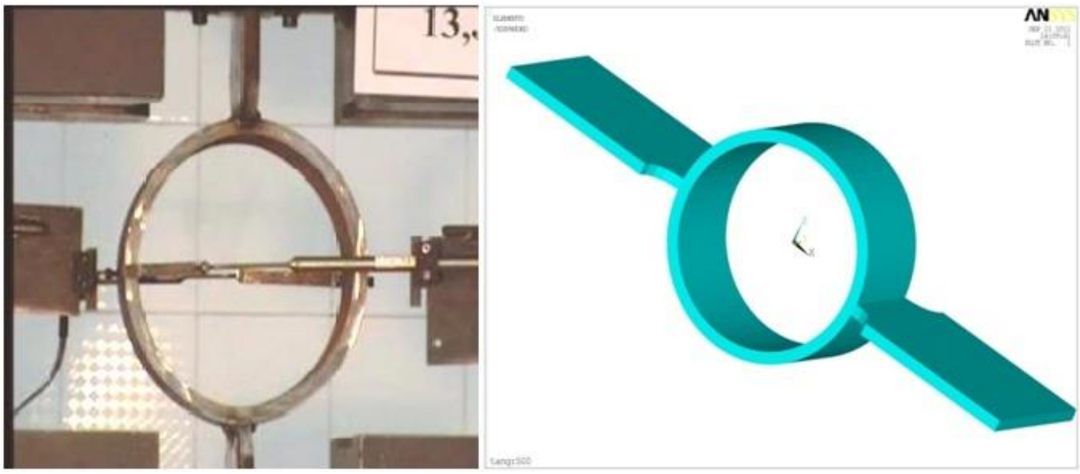


Fig. 5 General view of steel ring in universal jack and ANSYS software

with increasing in diameter, ductility decreased. Also, with considering architectural limitation, circular element has been used in an off-centre bracing system as shown in Fig. 4. Hence, that entering lower force to ductile element and tolerated greater force with suitable ductility.

Bearing capacity of ductile element embedded at the end of bracing members should be less than buckling force of braces. Hence, that before designing dimensions of circular element determination of buckling forces of bracing members is necessary. The sections of profiles are 2 channels with 20 mm distance from each other. The space between column filler and brace member is 380 mm and the thickness of fillers and plates of corner connection are 20 mm. The specification of frame is shown in Table 1. Design of frame sections except circular element is based on elastic behavior and low strain. As shown in Fig. 5, connections modeled as a pin by assuming that pin joint is more conservative.

The goal of investigating on these models is optimum using of circular element. Additionally, bearing capacity of steel ring with correct safety factor should be less than buckling load. Therefore, circular element is modeled by taking outside diameter 220 mm, thickness 12 mm and a length of 200 mm. In order to design steel elements, AISC-ASD 2005 (American Institute of Steel Construction 2005) code is used and to calculating the seismic load ATC-24 (Applied Technology Council 1996) and FEMA-356 (Federal Emergency Management Agency 2000) codes are used.

4.3 Geometrical specification of frames with off-centre bracing system

In order to comparison between off-centre bracing system with circular energy dissipater and off-centre bracing system without circular energy dissipater a hinged frame with off-centre bracing system in a single story and single bay has been created, the model for simplification has been named (OBS). The sections of profiles are 2 channels with 20 mm distance from each other. The space between column filler and brace member is 380 mm and the thickness of fillers and plates of corner connection are 20 mm. The specification of frame is shown in Table 1. Design of frame sections except circular element is based on elastic behavior and low strain. As shown in Fig. 5, connections modeled as a pin by assuming that pin joint is more conservative.

5. Method of model analysis

In order to investigate on the hysteresis behavior of models, nonlinear static analysis is used. The displacement-central criterion is induced for loading of models. The goal of embedding ductile element at the end of bracing member is to increase ductility considering buckling control. To achieve this purpose, it is necessary that bearing capacity of ductile element at the end of brace member should be less than buckling force of braces. This fact was considered in the experimental investigation (Abbasnia *et al*. 2008, Bazzaz *et al*. 2014), and the bearing capacity of this element was considered half of the buckling force of diagonal braced members. Considering the above-mentioned conditions, in this case before designing dimensions of ductile element, buckling load is determined. The capacity design method is used to determine bearing capacity of ductile element. As shown in Fig. 4, induced forces to ductile element need to be less than 0.85 F. In other words, the other members designing are based on this fact that they would be stable before general failure of ductile element.

Therefore, the selected ductile element reaches to inelastic zone and collapsed much earlier before buckling of bracing members. Basically, there is no buckling in this system. Furthermore, this item consists of all types of buckling such as inelastic buckling, buckling load and post buckling stiffness. Buckling is controlled in the experimental research (Abbasnia *et al*. 2008), where the ductile element embedded in the diagonal bracing replaces easily after failure with another element, without any buckling or failure in the other bracing members.

Finally, concerning all above-mentioned reasons, the Eigen buckling analysis is conducted to investigate on the brace members buckling in order to prove the accuracy of modeling at the end of numerical analysis.

6. Validation of numerical analysis with experimental data

To validate analytical results, steel ring is considered as a ductile element and for simplification

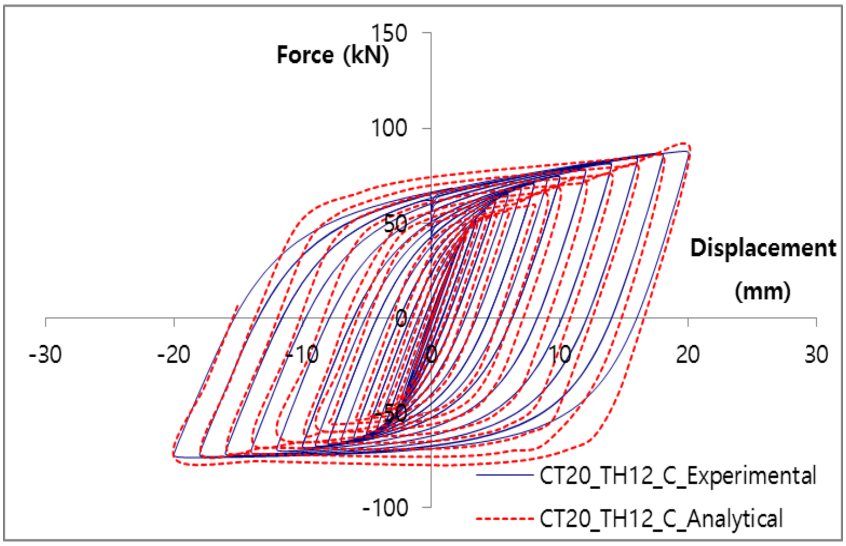


Fig. 6 Comparative hysteresis plots of experimental and analytical results for CT20_TH12_C

Table 2 Behavioral parameters

Models	Q_y (kN)	Δ_y (mm)	Δ_{Max} (mm)	K_e (kN)	K' (kN)	$Q_{y\,0.03}$ (kN)	$E_{Monotonic}$ (J)	μ
Model OBS-C0.2	180.4	6.7	100	27.23	0.502	227.26	19719	10.42
Model OBS-C0.3	231.74	14.45	100	16.03	0.28	255.36	22430	6.92
Model OBS-C0.4	93	14.9	100	6.24	0.263	115.34	9690	6.7
Model OBS-C-O	150	6.7	100	44.64	0.495	196.19	16821	14.93
Model OBS	164.27	7.82	59.5	21.10	0.841	207.75	10278	7.61

has been named (CT20_TH12_C). Attention to modeling in the International Institute Earthquake Engineering and Seismology (Abbasnia *et al*. 2008) another ring with external diameter 220 mm, thickness 12 mm and a length of 100 mm with two connections plate 200×170×12 mm with 7 mm fillet weld is taken, as shown in Fig. 5.

As shown in Fig. 6, the achieved hysteresis plots of experimental and analytical data showed very good superposition.

7. Monotonic load

7.1 Off-centre bracing system with ductile element

Frame with specifications in Table 1 and definition geometry according to Fig. 7 under monotonic load have been analyzed. The result has been studied as a force-displacement curve. In order to investigate the value of stiffness (elastic and inelastic), force and yielding displacement bilinear curve is drawn, as shown in Fig. 8. The obtained value is shown in Table 2 and regarding to maximum displacement and displacement at the end of elastic limit the ductility factor (μ) is calculated.

Fig. 7 shows Von Misses distributions and in plane strain distributions of hinged frame with circular elements with 0.2, 0.3 and 0.4 eccentricities.

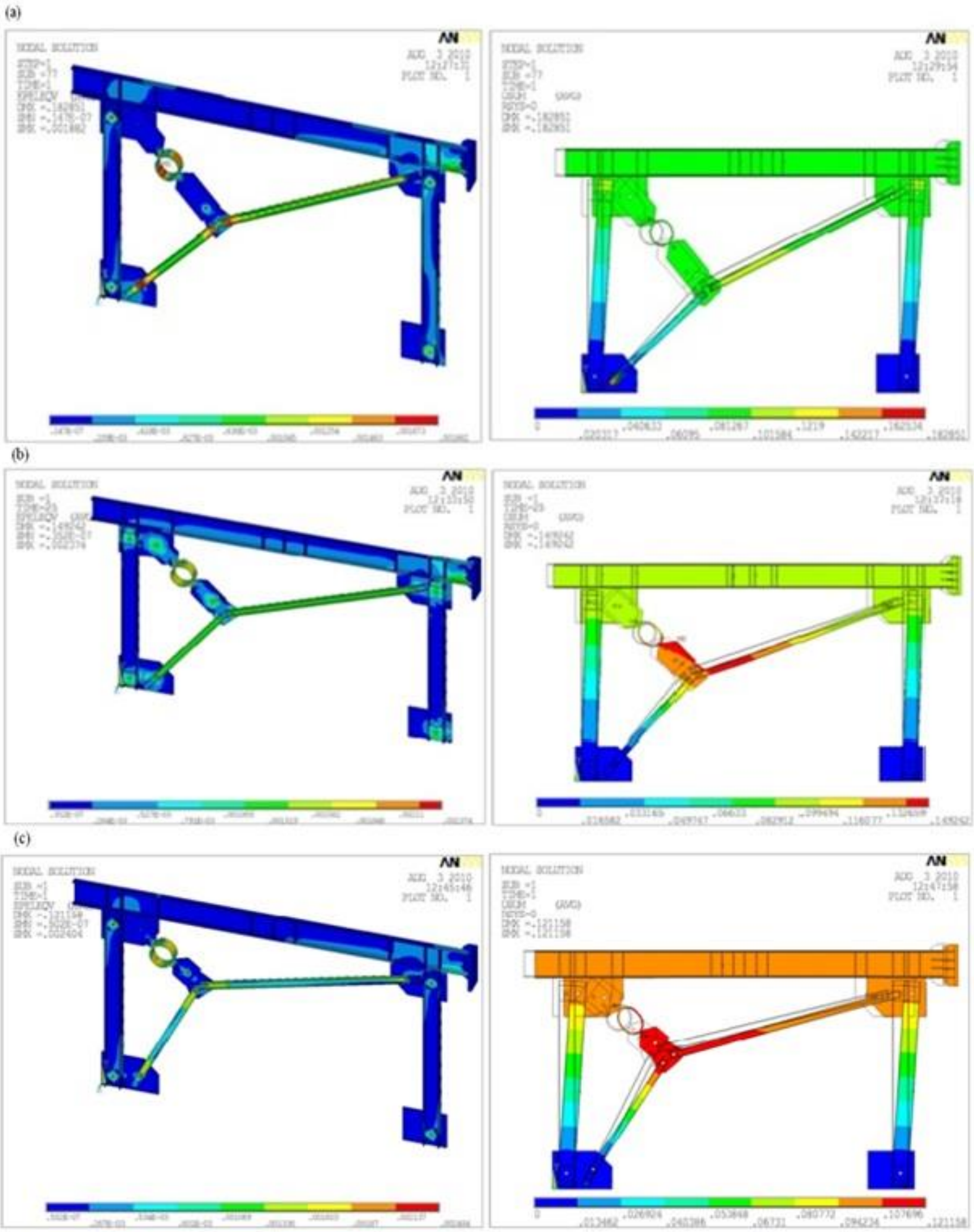


Fig. 7 Von Misses distributions and in plane strain distributions of hinged frame with circular elements (a) OBS-C0.2 Model, (b) OBS-C0.3 Model, (c) OBS-C0.4 Model

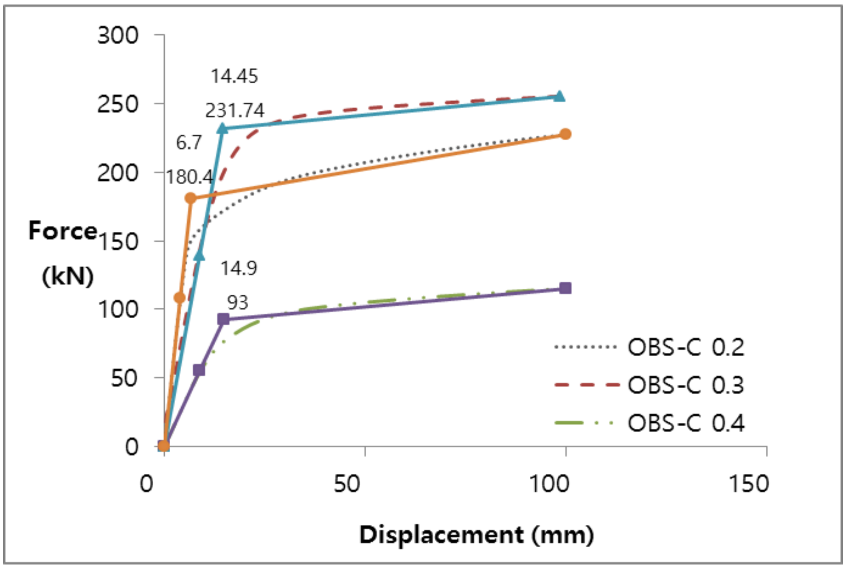


Fig. 8 The comparison between bilinear force-displacement curve of hinged frame with circular elements (a) OBS-C0.2 Model, (b) OBS-C0.3 Model, (c) OBS-C0.4 Model

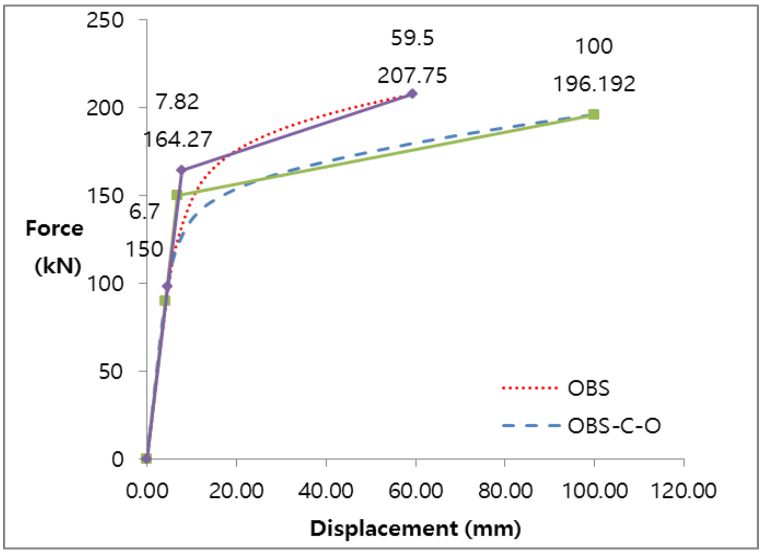


Fig. 9 The comparison between bilinear force-displacement curve of OBS and OBS-C-O Models

7.2 Off-centre bracing system with ductile element in optimum place and without ductile element

Frame with specifications in Table 1 and definition geometry according to Fig. 5 under monotonic load have been analyzed. The result has been studied as a force-displacement curve. In order to investigate the value of stiffness (elastic and inelastic), force and yielding displacement bilinear curve is drawn, as shown in Fig 9. The obtained value is shown in Table 2 and regarding

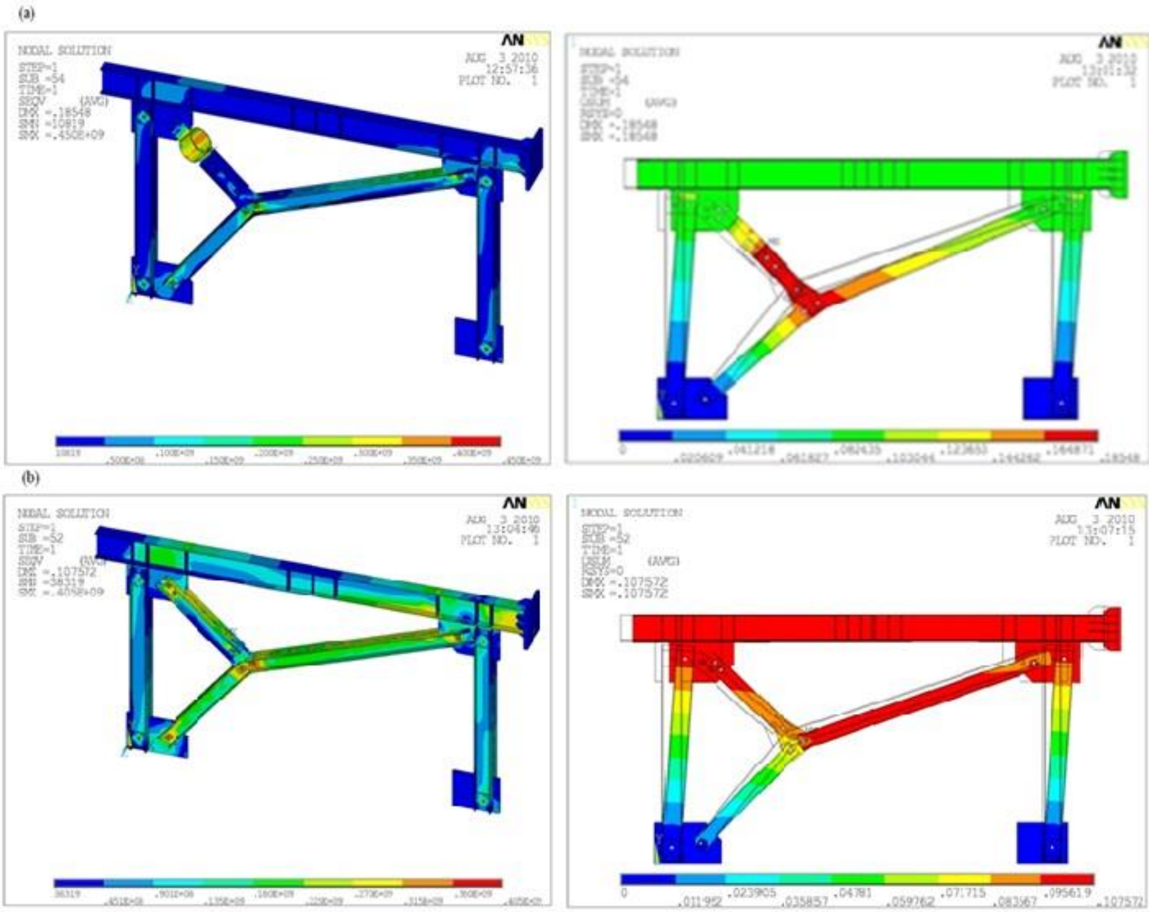


Fig. 10 Von Misses distributions and in plane strain distributions of hinged frame (a) OBS-C-O Model, (b) OBS Model

to maximum displacement and displacement at the end of elastic limit the ductility factor (μ) is calculated.

Fig. 10 shows Von Misses distributions and in plane strain distributions of hinged frame with off-centre bracing system with and without ductile element.

8. Evaluating and comparing the obtained results from models

Push Over and bilinear curve of hinged frame with off-centre bracing system and circular element and various eccentricities of e_1=0.2, e_1=0.3 and e_1=0.4 by taking e_2=0.5 in all of them. Also, bilinear force-displacement curve of hinged frame with off-centre bracing system with and without ductile element, are shown in Figs. 8 and 9.

The push-over curve shows OBS-C0.2 model has the highest elastic stiffness, secondary hardness and ductility factor while the OBS-C0.3 model has the highest value of base shear in elastic displacement, story drift (approximately 0.03 hight of storey) and dissipated energy. Furthermore, in OBS-C0.4 model elastic displacement has the highest value among the models. On the other hand, the OBS-C0.2 model has the lowest elastic displacement value among the models. In addition, OBS-C0.4 model has the lowest value of elastic stiffness, secondary hardness, base shear, story drift, ductility factor and dissipated energy.

The push-over curve shows OBS-C-O model in comparison of OBS model has the higher elastic stiffness, ductility factor and dissipated energy. Additionally, OBS model has higher secondary hardness, base shear in elastic displacement, base shear, story drift (approximately 0.03 hight of storey) and elastic displacement.

As shown in Table 2, by variation of eccentricity, in OBS-C0.3 model base shear in story drift (10 cm) is decreased and led to a reduction of stiffness in OBS-C0.2 model and in OBS-C0.4 model. This reduction lead to reducing of force in these two frames, 11% and 54.8% respectively. Also, the base shear reduced, 22.15% and 59.87% respectively. Furthermore, the energy absorption of these two frames has been reduced, 12.1% and 56.8% respectively.

In OBS frame, base shear value in storey drift is 5.56% higher than OBS-C-O model. In addition, the base shear inelastic displacement in OBS frame is 8.7% higher than OBS-C-O model. However, the absorption energy in OBS-C-O model is 39% higher than OBS. Eventually, the reason of this difference is reduction in frame stiffness with embedding circular element into it.

9. Conclusions

The goal of this paper is increasing in ductility of off-centre brace by using ductile member and also highlighting the role of braces with circular element. Such braces have a suitable workability, ease of maintenance, as well as ductility and stability, preparing and installing with available material in the market and also replacing the system after damaging by hazardous earthquakes with low cost and high rate. Hence, it can make use of steel's properties, while reducing the construction costs.

The research reveals that the idea of using a circular element, as suggested in this paper, supplying the mentioned goals. Furthermore, steel ring has been provided by industrial pipe and preparing of it in order to install in different braces would easily be created by contractors.

The result of the analysis of hinged frames with off-centre brace and steel ring of OBS-C0.2, OBS-C0.3 and OBS-C0.4 models under monotonic load show that the OBS-C0.3 model considering ductility and the dissipation of energy is the best model. Hence, the OBS-C0.3 model as mentioned in previous research has been regarded as an optimal place of steel ring.

In conclusion, the investigation on the hinged frame of off-centre bracing system with steel ring in optimum place and without a steel ring OBS-C-O and OBS models revealed that the OBS-C-O model has high ductility and the dissipation of energy. Also, it is the best among the models. It would be possible to use it as a new bracing system if experimental investigation is performed on this system.

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Abbreviation

Q_y : Yielding force
Δ_y : Yielding displacement
K_e : Elastic stiffness
K' : Secondary hardness
$Q_{y\,0.03}$: Yielding force while displacement is 0.03H
$E_{Monotonic}$: Absorbed energy under monotonic load
μ : Ductility Factor