COMPARING NONLINEAR BEHAVIOR OF TRF AND EBF LATERAL RESISTANT SYSTEMS UNDER CYCLIC LOADING

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ABSTRACT

Selecting a proper lateral seismic resistant system is an essential part ofany structural design. There are many parameters for assessment of structures such as strength, stiffness, ductility and energy dissipation. Nonlinear behaviour of a seismic resistant system is a determinant parameter in strongearthquakes. Each lateral seismic resistant system has some advantages and disadvantages that help engineers to select the best one for the specific project situation. There are many systems which are used as resisting system against earthquake excitation. The most common systems are moment resisting frame (MRF), concentrically brace frame (CBF) and eccentrically brace frame (EBF). EBF has shown better behaviour in the past earthquakes in accordance with the other mentioned systems. T-shaped resisting frame (TRF) has been proposed recently as a ductile lateral resistant system. In this paper, nonlinear behaviour of TRF under cyclic loading is compared with EBF system. Effects of vertical member's web thickness of TRFs and its stiffeners distances are studied. Comparison parameters are Vonmises stress distribution, hysteresis curves, dissipated energy, viscous damping ratio and side column axial forces. Two dimensional single story steel frames are designed using EBF and TRF in the same condition. Then, a standard cyclic loading is applied to the models and the results are extracted and compared. Results show that vertical member's web of the TRFs play a role as link beams in EBFs. Maximum energy dissipation is damped by vertical member's web. Side columns forces of the EBF are more than the TRF ones because of components of the diagonal bracing in EBF systems. Investigations on hysteretic curves demonstrate that energy dissipation of TRFs are appropriate in accordance with EBF one and confirm stability of the TRF hysteretic curves.

INTRODUCTION

Improving computers and simulation abilities paved the way for novel ideas analysis in modifying seismic behaviour with high precision and less cost.Structures should have appropriate stiffness and strength to resist earthquake excitements and prevent major structural damages. Selecting a suitable lateral resistant system requires to know seismic behaviour of different systems. A well-designed system has enough strength, stiffness and ductility simultaneously and has a cost effective structure. Moment resisting system and bracing systems are most popular structural systems among all the structuresdue to their advantages. Moment resisting frames (MRFs) contain beams and columns which are connected to each other such that moment can be transferred from element to element bytheir connections components. This system has high ductility but its lateral stiffness is less than other systems especially in high rise buildings. Braced frames have diagonal elements placed in bays. Concentrically braced frames (CBFs) and eccentrically braced frames (EBFs) are two common types of braced frames. CBFs have great lateral stiffness but their ductility is cheaper than other mentioned systems because of their diagonal elements are susceptible to buckling. Moreover, CBFs almost generate some architectural limitations for improvising windows and doors in buildings. EBFs have advantages of MRF and CBF systems such as high stiffness and ductility. Its diagonal elements supply lateral stiffness and its link beams greatly dissipate earthquake energy applied to structures and supply ductility of structures. Past researches on EBF systems has shown appropriate behaviour and ductility of this system in strong earthquakes. In spite of the proper performance of this system, some architectural limitations and particularly designing difficulties reduce relish for using in Iran.

Another system which hasbeen proposed recently is called T-shaped resisting frame (TRF). Investigations show that it has a suitable behaviour and ductility which can be compared with EBFs (Ashtari and Gorzin (2011)), (Ashtari and Ghassemi (2011)). In addition, this system can be used for retrofitting of steel structures with less interferencein structural elements. TRFs are flexible when architectural limitations emerge. This system can be favourable for architects because of convenience of putting windows and doors on it. In this paper, TRF system is compared with EBF in the same condition such as loading and dimensions. This research can give a true judgement about TRF performance.

TRF SYSTEM

T-shaped resisting frame (TRF) is a lateral seismic resistant system recently proposed by Ashtari (Ashtari and bandehzadeh (2010)). Some investigations have been performed on this system in the past research and satisfied results have been gained. TRF system consists of vertical and horizontal members connected to each other by fixed connections. The members are fabricated by deep I shaped cross section. In order to prevent local buckling of their webs, they are equipped with stiffener steel plates. This system can have 1, 2, 3 or more vertical members in a bay depending on frame dimensions, lateral loads, needs for lateral stiffness, architectural limitations and other parameters related to specification of a project. Horizontal members are placed in each story level in the bay. Schematic layout of TRF systems in a bay are exhibited in Figure 1. In this figure, TRF systems are determined by hatched element. In this paper, columns which placed adjacent of the TRF or EBF system arecalled side columns.

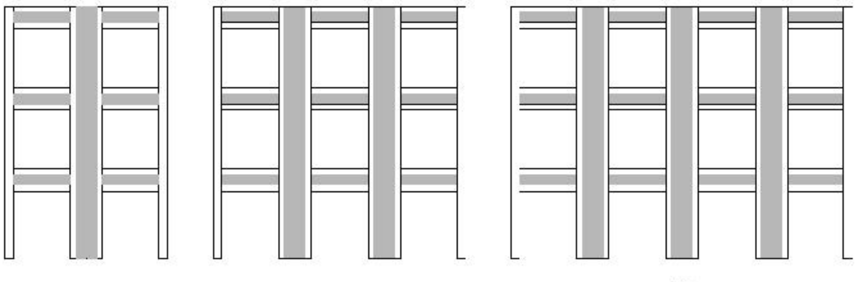

Figure 1. Types of TRF frames with one, two and three vertical members

The horizontal members of the TRF systems can be prismatic or nonprismatic members. All of connections between horizontal and vertical members are fixed but connections of horizontal memberto side columns can be pinned or fixed. On the basis of past researches, most of energy dissipations are happened in the vertical member’s web by its shear yielding ability. Proposed response modification factor for TRF systems is 9. So, in this paper, response modification factor of 9 is used for designing the TRF elements. With growing in length of bays, primary lateral stiffness of the system is increased and response modification factor is slightly decreased.

MODELLING AND ANALYSIS

TRF and EBF systems are used in 2D frames which have one bay and one story for comparing the systems in the same condition. General dimensional properties are illustrated in Figure 2. Bay length of the frames is4.5 meters and their story heights are 3.15 meters. Vertical members of the TRF frames are located in the middle of the span. Link beams in EBF systems are 80 centimetreswhich are located in the middle of the span.

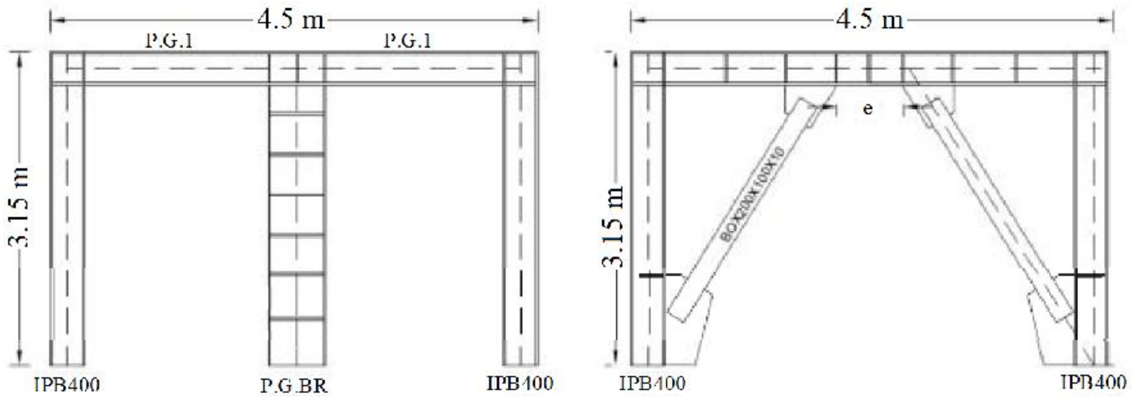

Figure 2. Typical T-shape resistant frame (at left) and eccentrically braced frame (at right)

Some details of sections of the frames are listed in Table 1 and Table 2. As can be seen in these tables, different properties for TRF frames have been considered. In these frames all connections between vertical to horizontal members and also horizontal to side columns are fixed. For vertical members two sections which are called P.G.BR.1 and P.G.BR.2 are used and defined in Table 3. In all the TRF frames, horizontal members are called P.G.1. As can be seen in table 1, vertical member stiffeners with different distances are considered to study their effects. These distances are placed at 20, 40 and 60 centimetres from each other and the S1 frame has not any stiffener. Side columns cross sections are IPB400 in the both systems to create an identical condition for comparing. Length of the link beams in the EBF frames are 80 centimeters. In order to considering different behaviour of the link beams,their cross sections are changed without changing in link beams length. These behaviours are shearing (V), bending (M) and bending-shearing (M-V). Also, diagonal members of EBF frames have box cross section.

Table 1. Some general properties of TRF frames

Frame name	**Vertical member**	**Horizontal member**	**Side columns**	**Stiffeners distances (cm)**
S1	P.G.BR.1	P.G.1	IPB400	-
S2	P.G.BR.1	P.G.1	IPB400	20
S3	P.G.BR.1	P.G.1	IPB400	40
S4	P.G.BR.1	P.G.1	IPB400	60
S5	P.G.BR.2	P.G.1	IPB400	20
S6	P.G.BR.2	P.G.1	IPB400	40
S7	P.G.BR.2	P.G.1	IPB400	60

Table 2. Some general properties of EBF frames

Frame name	**Beam**	**Link beam length (cm)**	**Link beam behavior**	**Side columns**	**Bracing element (mm)**
S8	P.G.2	80	V	IPB400	BOX200×100×10
S9	P.G.3	80	M	IPB400	BOX200×100×10
S10	P.G.4	80	M-V	IPB400	BOX200×100×10

Dimensional properties of P.G.BR.1, P.G.BR.2, P.G.1, P.G.2 and P.G.3 are tabulated in table 3. These elements all have I-shaped cross section. In this table, section depth, flange width, flange thickness and web thickness are summarized by d, bf, tf and tw, respectively.

Table 3. Cross section properties of TRF and EBF frames elements

Element name	**d (mm)**	**bf (mm)**	**tf (mm)**	**tw (mm)**
P.G.BR.1	550	250	20	2
P.G.BR.2	550	250	20	4
P.G.1	330	200	15	6
P.G.2	330	200	15	12
P.G.3	320	150	10	16
P.G.4	330	150	15	14

In order to simulatesteel material behaviour, a nonlinear material with ideal bilinear modelwhich has 3 percent strain hardening is considered for all the frames. Yielding stress (Fy), ultimate stress (Fu), strain in yielding stress (εy), strain in ultimate stress (εu), modules of elasticity (E) and are listed in Table 4.

Table 4. Material properties of steel used in the models

Material	Fy (kg/cm^2)	Fy (kg/cm^2)	ε_y	ε_u	E (kg/cm^2)
steel	2400	3700	0.002	0.1	2100000

A cyclic loading protocol which is proposed by SAC-ATC24 is used and applied as displacement in story level in order to studding on cyclic behaviour of the models. This protocol is shown in Figure 3.

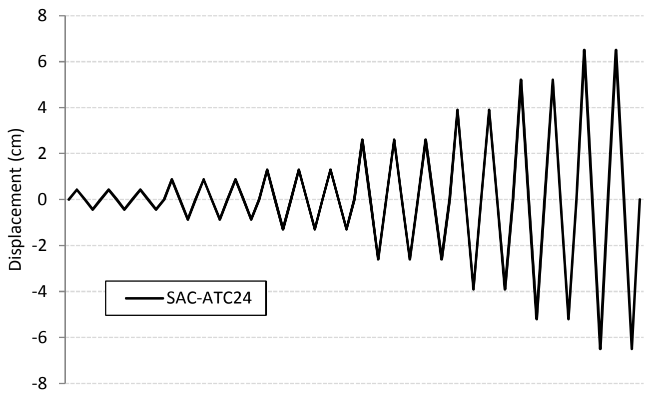

Figure 3. Cyclic loading protocol applied as displacement (SAC-ATC24)

The frames are simulated and analyzedby ABAQUS finite element software. In this software, frames are meshed by FREE pattern and solid element is used to model the members.

COMPARATIVE STRUDY

In this paper, comparison parameters are Vonmises stress distribution, hysteresis curves, dissipated energy, viscous damping ratio and side column axial forces.In this research, impact of the vertical member stiffenersand its web thickness are investigated. Moreover, different behaviors of link beams in EBF system are studied considering its cross section. Figure 4 ShowsVonmises stress distributions in the frames elements. As can be seen in this figure, after ending the cyclic loading applied on the S1 model, whole of the vertical member's web of S1 frame is yielded due to absence of stiffeners. Yielding is also happened in horizontal to side columns connection regions adjacent top and bottom flanges because of stress concentration. It is not seen in other regions of the frame. In this frame, yielding in side columns is only occurred at the base connections and negligible regions of their flanges. It can be inferred that vertical member's web yielding causes to prevent entering other members to nonlinear domain. With respect to the figure, in all TRF frames, vertical member's web isperfectly yielded. Therefore, this member plays a fuse role like link beams in EBF system. Yielded regions in horizontal beams increase with increasing in P.G.BR's web thicknesses. The main mission of TRF systems is to preventetering other members to nonlinear domain.So, this increment is adverse a good performance of this system. Moreover, presence of web stiffeners in vertical members plays an important role to behave appropriately.Lack of the stiffeners or wrong using them lead to diagonal buckling in web of vertical members under shearing loads. This event causes undesirable behaviour of the lateral seismic resistant system in strong ground motions.

As mentioned before, link beams have the same length but for considering different behaviour of the link beams, their cross section are designed by different profiles. In the Figure 4,Vonmises stress distribution in EBF models is also illustrated. As can be expected, steel materials are yielded in whole of the link beams.

Side columns forces are plotted in Figure 5 for the S2 and S8 frames. This figure shows that EBF side columns forces are more than the EBF under cyclic loading applied as displacement in all cycles. In Figure 5, maximum side columns forces are illustrated for all frames. This figure shows that in all EBF models with different link beam behaviour, side columns forces are more than all of the TRF frames. Moreover, with increasing in vertical member web thickness and reduction in stiffeners distance, side columns forces are amplified. Furthermore, unlike the TRF frames, side columns forces in the EBF frames are not depended on link beams behaviour. Therefore, it can be concluded that in buildings with weak columns, TRF system can help to reduce columns axial loads especially in moment resisting frames and dual systems which their columns contribute in bearing lateral loads such as wind and earthquakes loads.

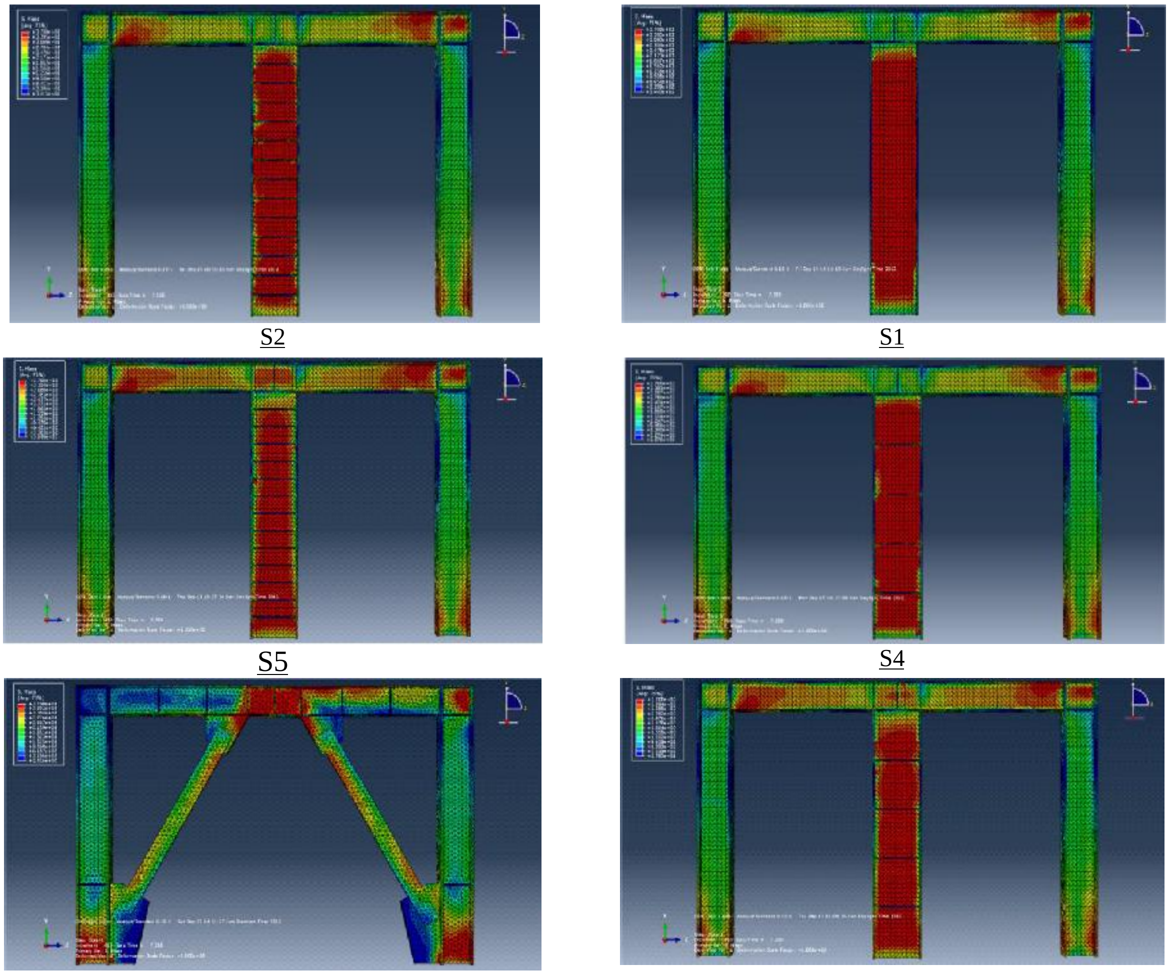

Figure 4.Vonmises stress distribution in the S1, S2, S4, S5, S7 and S8 frames

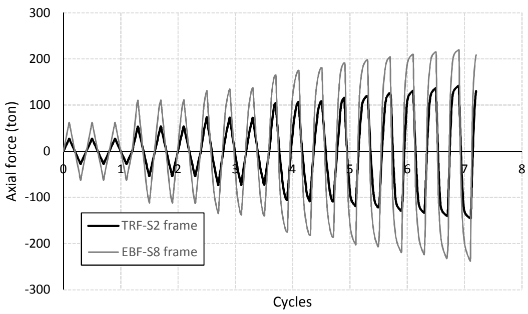

Figure 5. Side columns axial load responses of TRF and EBF frames along cyclic loading

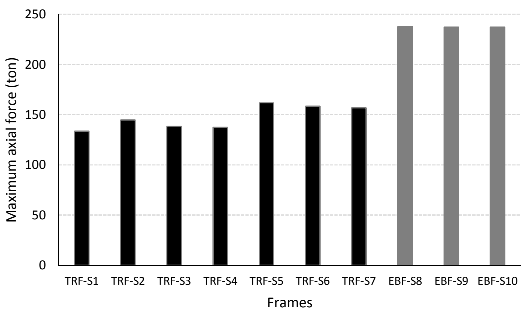

Figure 6. Maximum side columns axial load responses of all TRF and EBF frames

Figure 7 compares hysteretic curves of S2 and S8 frames which are equipped by TRF and EBF lateral seismic resistant systems, respectively, under cyclic loading. These curves show relationship between base shear versus displacement of the centre of the beams. Ductility and energy dissipation parameters and seismic behaviour of the frames can be extracted from these curves.

The two frames have wide and stable curves which demonstrate appropriate behaviour of the two systems. However, the EBF curves are wider than TRFs. it shows that energy dissipation capability of the EBF frames are more than the TRF frames. It can be inferred that both of them have high ductility and energy dissipation capability. Study on the other frames proves that it is true for the other. Moreover, base shear of the TRF frames are increased by lessening distance of the web stiffeners of vertical members which cause to enhance of shearing stiffness of this element. Putting enough stiffeners prevents the web local buckling under shear stresses. The most energy dissipation in TRF and EBF are happened in vertical member's web and link beams, respectively. It shows that this members have direct effects on ductility of the systems and are play an important role to prevent the yielding of other members. It is the main factor of the stability of the frames.

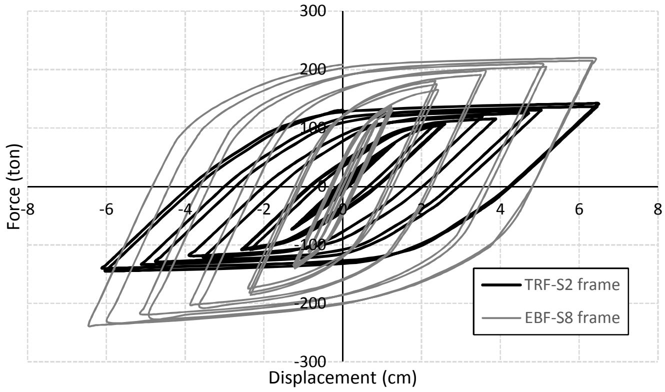

Figure 7. Hysteretic curve of one TRF and one EBF frame

Viscous damping of the frames is shown in Figure 8. This figure shows that both systems have high damping capability. However, the EBF frames have the higher value than TRFs, whereas the damping in common steel and concrete buildings are about 5 percent. With respect to this figure, the maximum value is resulted 40.5 percent for EBF system and 37.8 for TRF system. Reduction in stiffener distances causes high damping in the TRF frames. Having high damping capability results reduction of demands which are needed for linear structural design.

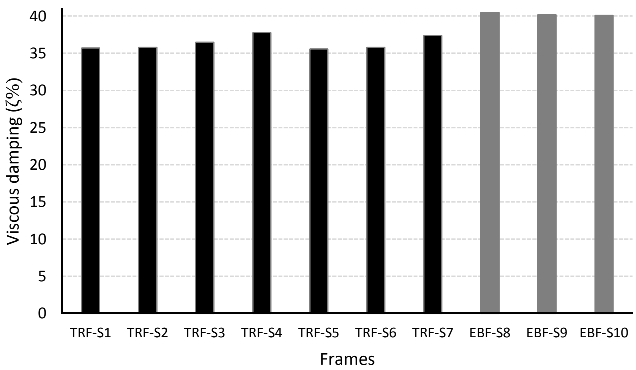

Figure 8. Viscous damping of TRF and EBF frames

CONCLUSIONS

In this paper, behaviour of TRF system and eccentrically braced frame (EBF) system are studied and compared in nonlinear domain in cyclic loading.

From the results obtained in this paper, vertical member in TRF systems operates like a fuse as the link beam in EBF systems. It prevents other members from entering nonlinear zone significantly by its yielding. Consequently, global stability of frame is achieved in strong earthquakes. Hysteresis curves of studied frames illustrate that both systems have stable curves but hysteretic curves in EBF system are wider than TRF's. It can be inferred by investigating the frames dissipated energy that most of dissipated energy in TRF system is due to yielding of vertical member web which operate as EBF's link beam. Viscous damping ratios are close to each other in two systems so that in EBF system is 40.5 percent and in TRF system is 37.8 percent. Referring to the results of this paper and the other past investigations, it can be concluded that TRF system is a proper supersede of EBF system considering architectural and construction limitations. Reduction in stiffener spacing of TRF vertical member leads to increase shearing stiffness of the member. Consequently, in connection region of vertical and horizontal parts of the TRF members Vonmises stresses are amplified. Moreover, the results depict that web thickness increase of TRF system vertical member, escalate the stress values in three regions namely: a) connection region of vertical and horizontal members of TRF, b) connection between side columns to horizontal member and c) bottom area of the side columns. The probability of Web diagonal buckling of TRF vertical member increases by increase stiffener spacing under shearing stresses. Side column's Axial forces in all studied frames by the writer have higher values in EBF model in comparison with TRF ones. In TRF system, axial forces in side columns are increased due to using more stiffeners and thicker web of the vertical member. Viscous damping of the TRF system is also decreased by making use of thicker web of vertical member.

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