Analytical approach of buckling strength of yielding damped braced core (YDBC)

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Abstract:

Previous research on bracing members show that the ductility of bracing members is compromised due to the buckling phenomena. Therefore, many researchers have tried to use special considerations to increase the fracture life of bracing members. Some of these recommendations such as increasing the slenderness ratio, using lower width to thickness ratio, increasing the out-of-plane stiffness of middle connection to increase the fracture life of the bracing members can be used in seismic upgrading of bracing members. In this paper, the buckling behavior of a special type of concentrically braced frame termed as yielding damped braced core is investigated for different percentage of central core. Empirical studies shows that separation of X-braces by central frame, influence the buckling behavior of the system and leads to occurrence of buckling in second mode shape in accordance with two half-sine wave. The theoretical studies shows that the buckling strength of the system increases in proportion to increase in central core rigidity. Using more flexible central core, results in increase the possibility of instability and vice versa. Hence, to enhance the buckling behavior of the system, it is strongly recommended to use a central core with proper rigidity
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1. Introduction

Over the past few decades, buckling is known as an instability phenomenon that has a highly destructive effect on the seismic performance of structures. The ductility of bracing members is limited because of the buckling of its diagonal members. Therfore, many researchers have studied the buckling behavior of the concentrically braced frame to increase the fracture life of braces as a function of width to thickness ratio of their cross section, type of end conditions and slenderness ratio. Dewolf & Pelliccione (1979)[1], El-Tayem & Goel (1986)[2], Kitipornchai & Finch (1986)[3], Stoman (1988 & 1989)[4,5] and Wang & Boresi (1992)[6] investigate the buckling behavior of the concentrically braced frames using a gusset plate to connect braces at their intersection.

These studies demonstrate that due to insignificant out-of-plane stiffness of a gusset plate, such connections tend to behave as simple connections. Dewolf and Pellicione shows that the effective length factor is sensitive to the end conditions of braces[1]. Also, Segal et al. (1994) evaluate the buckling capacity of the X-braced frame by changing the thickness of its end connections[7]. Davaran (2001)[8] concludes that by increasing the out-of-plane stiffness of middle connection via cutting one of the angles at the intersection of braces in double angle sections, the buckling strength of the braces can be improved. Moon et al (2007)[9] investigate the effects of middle connection type on the effective length factor of the concentrically braced frames. They propose a formulation that approximates the critical buckling load of concentrically braced frames using discontinuous diagonal members. Tremblay (2003)[10] concludes that even for bracing members with compact sections, local buckling is more significant in braces with lower slenderness ratio.

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The negative effect of buckling on energy absorption of the system is investigated by Sabouri-Ghomi & Ebadi (2005 & 2006)[11,12]. For their empirical studies [13, 14], they use a connection of special types of concentrically braced frame termed as Yielding Damped Braced Core (YDBC)[15]. They conclude that the middle connection is one of the most important factors that influence the buckling capacity of the concentrically braced frame. Their investigations indicate that the propagation of large compressive strains at middle length of the concentrically braced frame can significantly decrease lifespan of the structure.

In this paper, the buckling behavior of bracing members in which the braces are separated by a central core is investigated. In this investigation, the out-of-plane effective length factor of the system for different central core percentage is obtained based on two half-sine wave attained from empirical studies of Sabouri-Ghomi & Ebadi[13,14]. The theoretical studies shows that the buckling strength of the system increases in proportion to central core rigidity. Depending on the central core percentage and ratio of moment of inertia of the central core to X-braces, the out-of-plane effective length factor of system is varied between 0.2 to 0.9 of its actual length. Using a more rigid central core than the X-braces, results in an increase in the buckling strength of the system. Therefore, it is strongly recommended to use a rigid central core to enhance the buckling performance of X-braces.

2. Theoretical Study of Out-of-Plane Buckling Strength

In order to calculate the out-of-plane buckling strength of yielding damped braced core, the analysis is formulated according to the deformed configuration of the braces. The deformed configuration is considered as the two half-sine wave based on previous empirical studies (Fig.1). Therefore, the effective length factor is considered based on equation 1.

$$y = A\sin\frac{2\pi x}{a} \qquad (1)$$
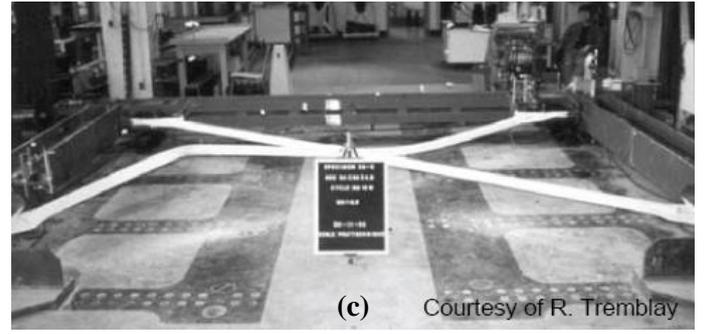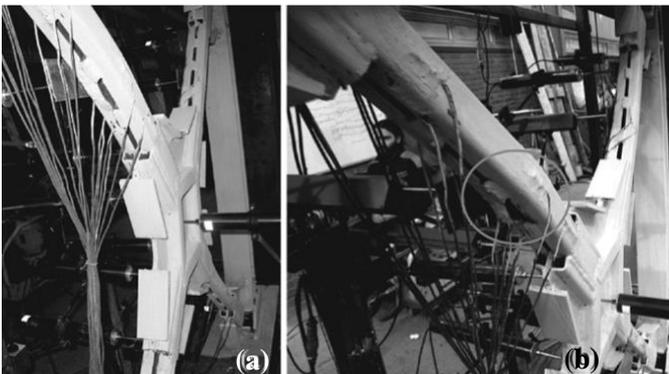
Fig. 1: X-braced frame; (a) Buckling in accordance with two half-sine wave [13]; (b) Generation of global and local buckling [13]; (c) Buckling in accordance with two half-sine wave [16]

Where z is longitudinal axis and x, y are principle axes, A is constant that is determined from the boundary conditions and a, is the total length of bracing member. A free body diagram of compression member is illustrated in Fig.2. As shown in this figure, the positive axial load deals with tension braces. The out-of-plane buckling strength of the YDBC system can be found by equalizing internal energy and external energy of the system. The internal energy is calculated in accordance with equation 2.

$$U = \frac{EI}{2}\int y''^2 dz = \frac{4E\pi^2 A^2}{a^3}\Big[(1-n)I_{x(x-x)} + 2nI_{cc}\Big] \quad (2)$$

Where E is the modulus of elasticity, I is the moment of inertia, y'' is the second derivative of the deflected shape, n is the ratio of central core to the main frame, $I_{x(x-x)}$ is the out-of-plane moment of inertia of X-braces and I_{cc} is the out-of-plane moment of inertia of central core normal to its longitudinal axis. As can be seen in Fig.2, the out-of-plane stiffness of tension braces is neglected in order to have a lower limit of critical buckling strength.
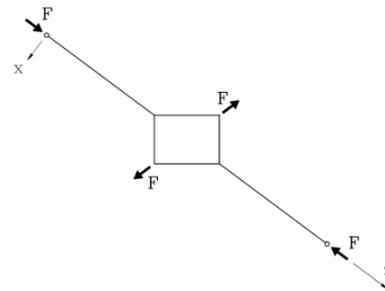
Fig.2: Free body diagram of YDBC system

The external energy of the system is calculated based on equation 3.

$$V = -\frac{F}{2}\int y'^2 dz = -\frac{4\pi^2 A^2}{a}(1+n) \qquad (3)$$

In which y' is the derivative of the deflected shape. By setting equations 2, and 3 equal to each other, the buckling strength of the system is obtained according to equation 4.

$$F_{cr(x-x)} = \frac{4\pi^2 A^2}{a^2}\left[\frac{1-n}{1+n}I_{x(x-x)} + \frac{2n}{1+n}I_{cc}\right] \quad (4)$$

If $\alpha = I_{cc}/I_{x(x-x)}$ and the out-of-plane buckling strength of the system is considered to be equal to the buckling strength of the concentrically brace frame $\left(F_{cr(x-x)} = \frac{\pi^2 E I_{x(x-x)}}{(ka)^2}\right)$, the effective length factor can be calculated based on equation 5.

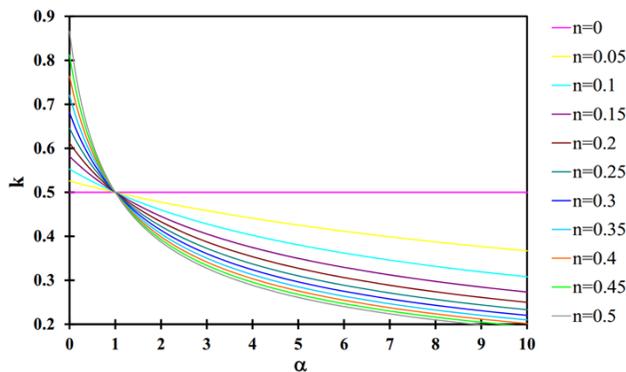$$k = \frac{1}{2}\sqrt{\frac{1+n}{1-n+2n\alpha}} \quad (5)$$

Fig.3: Effective length factor for different ratio of central core to the main frame

As can be seen in Fig.3:

- For $\alpha=1$, all-system with different dimensions of central core have the same out-of-plane effective length factor ($k=0.5$), because the moment of inertia of member along its length is constant and the system acts as a concentrically braced frame.

- In concentrically brace frame ($n=0$), the effective length factor is constant and is equal to 0.5. When the out-of-plane moment of inertia of central core normal to its longitudinal axis is considered equal to out-of-plane moment of inertia of X-braces, the effective length factor is constant ($k=0.5$) and is independent from the dimensions of central core to the main frame.

- When the out-of-plane stiffness of the central core is considered lower than the out-of-plane stiffness of X-braces, the system is exposed to instability and the buckling strength of the system decreases rapidly, and vice versa. For α less than 1, the effective length factor varied between 0.5 and 0.8 whereas, for α

between 1 and 10, the effective length factor varied between 0.2 and 0.5.

- The buckling strength of the system increases in compatibility with increase in the ratio of central core to the main frame.

3. Theoretical Study of In-Plane Buckling Strength

To calculate the in-plane buckling strength of the yielding damped braced core, the internal force distribution should be determined first. The internal force distribution of bracing member is calculated using the classic slope-deflection method besides considering symmetric conditions (Fig.4). Some of the assumptions made during this process are:

- The bending moment induced by the applied load in X-braces is neglected due to its negligible effects.

- In beam and columns, only the axial force induced by the applied load is considered.

- The self weight of the members of frame is neglected.

It is worth mentioning that for its simplicity the use of steel plate at the central core is eliminated.
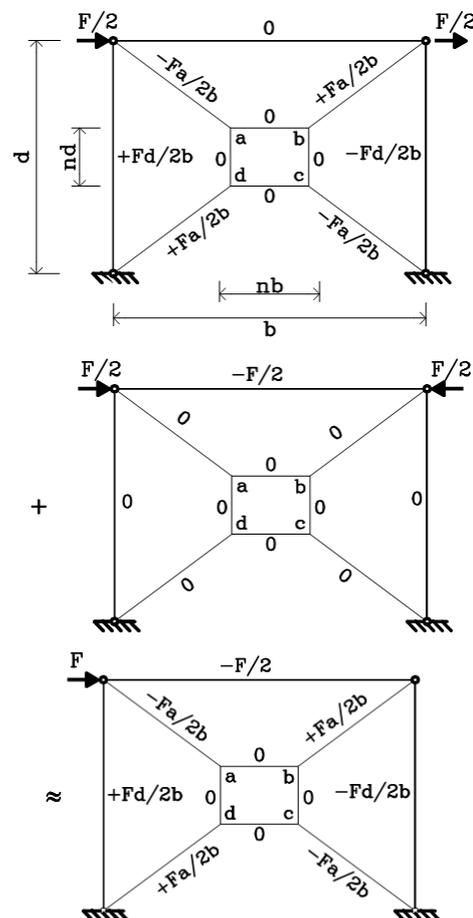
By using slope-deflection method, the internal forces distribution of the central frame is determined as

$$M_{ab} = M_{ba} = M_{dc} = M_{cd} = \frac{Fnd}{4} \qquad (6)$$

$$M_{ad} = M_{da} = M_{cb} = M_{bc} = -\frac{Fnd}{4} \qquad (7)$$

$$V_{ab} = V_{dc} = \frac{M_{ab} + M_{ba}}{nb} = \frac{Fd}{2b} \qquad (8)$$

$$V_{ad} = V_{bc} = \frac{M_{ad} + M_{da}}{nd} = -\frac{F}{2} \qquad (9)$$

The internal moments of the central frame (Equation 6) can be determined by applying the slope-deflection equation and decomposition the frame into symmetric and anti-symmetric parts as shown in Fig.4.

Then, by applying moment equilibrium equation on each element of the central frame, the members shear force can be calculated as in Equations.7, 8.

As can be seen, there isn't any induced axial force in the central frame and hence, buckling of the central frame is not a matter of concern for the designer. As a consequence, the in-plane effective length factor of X-brace can be determined based on their actual length and end support conditions. The in-plane buckling strength of X-braces is calculated in accordance with equation 10 and regarding the boundary conditions of columns with pinned-fixed ends.

$$F_{cr(y-y)} = \frac{\pi^2 E I_{x(y-y)}}{(kl_x)^2} = \frac{\pi^2 E I_{x(y-y)}}{\left(0.7 \frac{(1-n)a}{2}\right)^2} \qquad (10)$$

$I_{x(y-y)}$ is the in-plane moment of inertia of X-braces and l_x is the actual length of X-braces. The in-plane effective length factor is calculated similarly to the out-of-plane effective length factor and equalizing equation 10 to buckling strength of the concentrically braced frame.

$$k = 0.35(1-n) \qquad (11)$$

The coefficient of α versus effective length factor of both principle axis are illustrated in Fig.5.
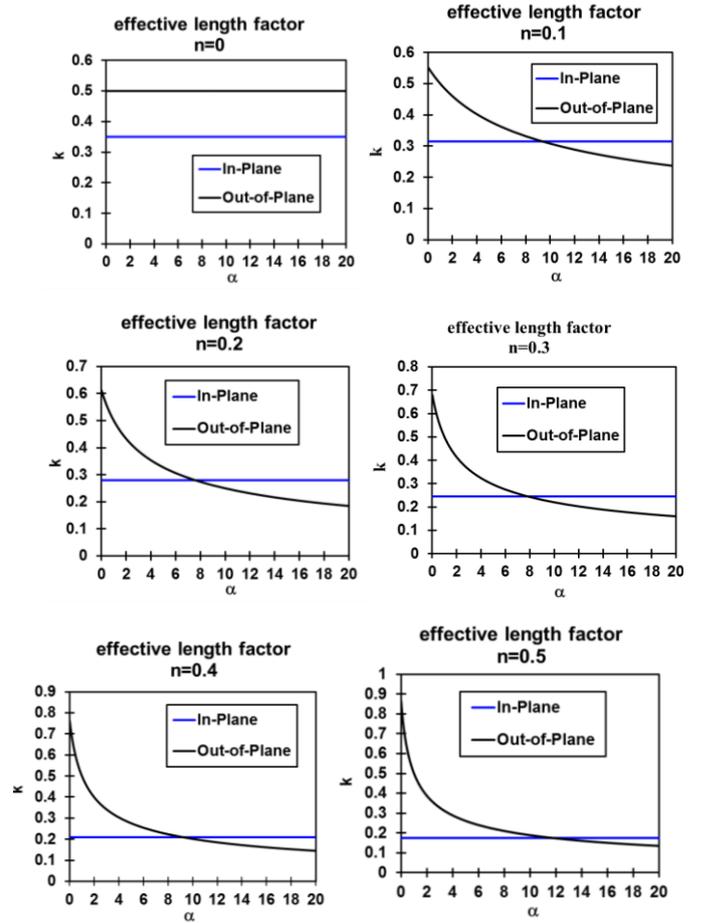
Fig.5: Effective length factor of YDBC system

As can be seen in this figure:

• The out-of-plane effective length factor is more than the in-plane effective length factor for a more common α coefficient. Therefore, the out-of-plane buckling load of the system is almost always smaller than the in-plane buckling load of the system, as expected.

• For α greater than 1, the buckling strength of YDBC system is considered more than the critical buckling strength of the concentrically braced frame and the system would behave in a more stable manner.

• The buckling strength of the system can be directly calculated from equations 4 and 10 or by using graphs, which is defined in Fig.5.

It is noteworthy to mention that, both the buckling out-of-plane and in-plane formulas presented in this paper is the general formula that can be used for buckling calculation of all three systems namely; YDBF system, YDBC system and X-shaped DBS systems. The difference is that the moment of inertia of each part should be selected in accordance with the relevant part.

35

4. Experimental Verification and Results

In this section, the results of experimental work that was carried out initially by Sabouri and Ebadi [13] are used to verify the analytical method. Some important mechanical properties that were used in the test is defined in Table 1.

Table.1: Mechanical properties of tested specimen [13]

| Member		Cross Section	Yield Stress (kN/mm²)	E (kN/mm²)
Diagonal Braces		2U50x27x4	372.65	210
Columns	Flanges	HEB-120	262	210
	Web		338.5	210
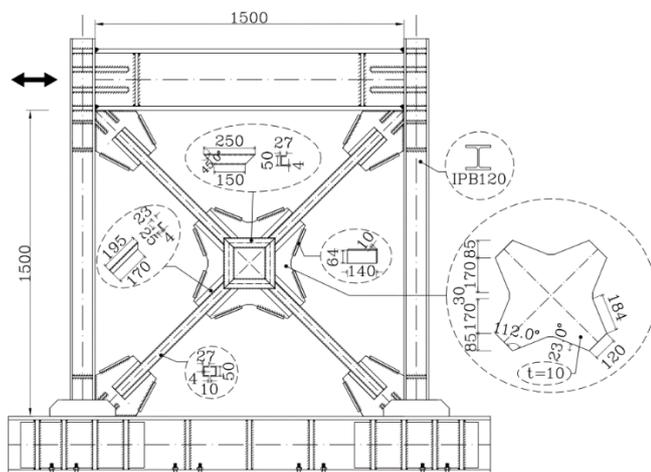
Fig.6: Dimensions of half-scale test specimens

Dimensions of half-scale test specimen is illustrated in Fig.6. Applied Technology Council ATC-24 loading protocol was used for investigation of system's seismic performance [17]. Test results shows that plastic hinges were formed at the middle length of each X-braces when they were subjected to compression. At about 1.1% drift, necking developed through the plastic hinges area, brittle fracture occurred at one of the diagonals and the brace lost its ability to resist further forces. Subsequently, as expected, the load bearing capacity of the system dropped considerably and the frame by itself withstood cyclic loading to approximately 3.8% drift. The distribution of these events is shown in Fig.7.
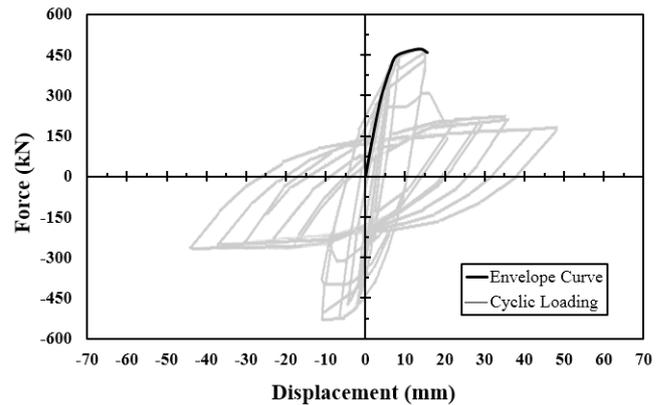
Fig.7: Force-displacement curve of half-scale test specimens

According to this figure, the lateral load bearing capacity of the system and frame is 450kN and 175kN respectively. Therefore, the buckling strength of the system derived is 275kN, which is equal to the load bearing capacity of each brace multiplied by the cosine of angle (Fig.8). Thus, based on tension strength of X-braces, the buckling strength of the X-brace obtained is equal to 128.9. But since the buckling strength of the X-braces according to equation 4 is approximately equal to 1305.4kN, which is much greater than the yield strength of the system, it can be concluded that the buckling occurred in an in-elastic range and the buckling strength of the system dropped rapidly due to stiffness losses in the system shortly afterward. Based on equation 5, the out-of-plane effective length factor of the system is equal to 0.34. As can be seen, due to in-elastic buckling behavior of braces, this test is not a very good example for validation of elastic buckling strength of braces, but it can be helpful in the absence of other experiments in this area.

$$\Sigma F_x = 0$$
$$F_u = (F_{cr} + F_y) \cos \theta$$
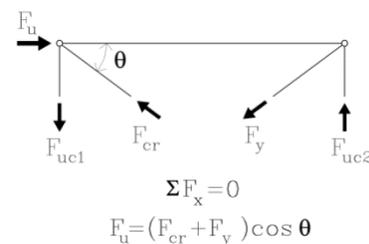
Fig.8: Lateral load bearing capacity of X-braces

5. Conclusions

The following conclusions can be derived:

- Due to the fact that, in YDBC system, the energy absorbed by the central core and the coefficient α is almost always less than 8, it can be concluded that the

buckling capacity of the system is almost always governed by the out-of-plane buckling strength. As a results, using a more rigid central core, could enhance the buckling behavior of system and help the system to behave in a more stable manner.

- The buckling strength of the system is highly dependent on the initial deformation of the system. For two half-sine wave, all-systems intersect each other at k while for one half-sine wave this convergence occurs at $k=1.0$.

- The out-of-plane buckling capacity of the system decreases correspondingly to α increment while the in-plane buckling capacity of the system is independent from this coefficient. By using proposed formula, the buckling capacity of all three systems; YDBF system, YDBC system and DBS system can be calculated easily and thus the seismic performance of braces during an earthquake can be predicted in a very close manner.

References

[1] Dewolf J, Pelliccione J. 1979. "Cross-bracing design", J StructDiv ASCE, 105(7), 1379-1391.

[2] El-Tayem AA and Goel SC. 1986. (First Quarter), "Effective Length Factor for the Design of X-bracing Systems", AISC Engineering Journal, 41–45.

[3] Kitipornchai S and Finch D. 1986. "Stiffness Requirements for Cross Bracing. J Struct Eng, ASCE, 112(12): 2702–2707.

[4] Stoman S. 1988. "Stability Criteria for X-bracing System" J Eng. Mech., ASCE, 114(8): 1426–1434.

[5] Stoman S. 1989. "Effective Length Spectra for Cross Bracing", J Struct. Eng., ASCE, 115(12): 3112–3122. No.3

[6] Wang D and Boresi A. 1992. "Theoretical Study of Stability Ncriteria for X-bracing System", J Eng Mech., ASCE, 118(7): 1357–1364.

[7] Segal F, Levy R, Rutenberg A. 1994. "Design of Imperfect Cross-Bracing", J. Eng. Mech. 120(5), 1057-1075. DOI: 10.1061/(ASCE)0733-9399(1994)120:5(1057).

[8] Davaran A. 2001. "Effective Length Factor for Discontinuous X-Bracing Systems", Journal of Engineering Mechanics, 127(2): 106–112.

[9] Moon, J., Yoon, K. Y., Han, T. S., & Lee, H. E. 2007. "Out-of-Plane Buckling and Design of X-bracing Systems with Discontinuous Diagonals", Journal of Constructional Steel Research, 285-294.

[10] Tremblay R. 2003. "Achieving a Stable Inelastic Seismic Response for Multi-story Concentrically Braced Steel Frame", Engineering Journal, AISC, Second Quarter, pp. 111–129.

[11] Sabouri-Ghomi S, Ebadi P. 2005. "Nonlinear Shear Behavior of Columns in X-braced High-rise Steel Buildings", 7th International Conference on Multipurpose High-rise Towers and Tall Buildings, Dubai- UAE, Dec. 11-12.

[12] Sabouri-Ghomi S, Ebadi P. 2006. "The Role of Columns in Energy Dissipation of X-braced Frames in Steel Structures", The Tenth East Asia-Pacifi Conference on Structural Engineering and Construction, Bangkok - Thailand, Aug. 3-5.

[13] Ebadi P, Sabouri-Ghomi S. 2012a. "Conceptual Study of X-Braced Frames with Different Steel Grades using Cyclic Half-Scale Tests", Earthquake Engineering and Engineering Vibration, Springer, Volume 11, Number 3, pp. 313-329, DOI: 10.1007/s11803-012-0124-2.

[14] Ebadi P, Sabouri-Ghomi S. 2012b. "Guided Local Buckling (GLB) Theory for Braces. International Journal of Steel Structures", Springer, Volume 12, Number 2, pp. 175-189, DOI: 10.1007/s13296-012-2003-0.

[15] Sabouri-Ghomi S, Payandehjoo B. 2009. "Investigating the Effect of Stiffness and Strength of Each Component on Overall Stiffness and Strength of Yield Damped Braced Core (YDBC)", The Structural Design of Tall and Special Buildings. DOI: 10.1002/tal.526.

[16] Rafael Sabelli, July 2006. "Seismic Braced Frames design concepts and connections. AISC.

[17] Applied Technology Council, ATC-24. 1992. "Guidelines for cyclic seismic testing of components of steel structures", Redwood City, CA, USA.