Concept improvement of behavior of X-Bracing systems by using Easy-Going Steel

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ABSTRACT:
The lateral deflections of buildings include bending and shear deflections. The bending deflection can be effectively controlled by combination of various types of coupled systems. But the shear deflection is controlled by increasing the shear stiffness of buildings. In this research, the new idea is introduced and application of Easy-Going steel (EGS) theory for improvement of behavior of X-bracing systems is discussed. The use of this theory for design of X-Braces can increase the lateral stiffness of buildings and decrease the lateral displacements. Moreover, the stability of this system increases and the P-Delta effects decline. So, the columns will be protected against reaching nonlinear state and most of the energy dissipates by braces. The area under hysteresis curves augments and the energy dissipation capacity of this system enhances considerably.
Also in this research comparison between general designed braced frames using structural steel and braced frames with Easy-Going steel concept is performed using harmonic Analysis to verify benefits of using this theory to decrease earthquake response of the structure during resonance.

KEYWORDS:
Easy-Going Steel, X-Brace, Hysteresis, stability, Nonlinear, Harmonic, Earthquake

1. Introduction

Easy-Going Steel theory is a new idea for design of main lateral load resisting systems which highlights new aspects about design of buildings, safely. In this theory, the stiffness of the system is increased while the energy absorption capacity of the system is also increased.

One of the best ways to verify the behavior of building systems is monitoring their situations under harmonic forces. In this research, two frames were designed with Structural steel and also with lower strength steel according to the Easy-Going steel theory and compared their behavior under harmonic loads, especially the resonance conditions. Also, for completeness of our discussion, another analysis under a real earthquake time history is done.

2. Introduction of Easy-Going Steel theory for X-Braced frames

One story-single span frame is depicted in Figure 1 (a). Two frames with similar X-bracing configuration and different made-in materials can be considered. It means that the braces material in one of the frames is lower strength steel which is called here **EGS** and the other one is Structural Steel. The columns and beams and all of connections are made of Structural Steel in both of above mentioned frames.
Now, if both of these frames where designed under a constant lateral force, the following relation between the cross section of braces and related yield point would be considered in Equation 1.

$$A_{bs}\sigma_{ys} = A_{be}\sigma_{ye} \tag{1}$$

Where:

A_{bs} : Cross section of braces made of Structural Steel.

A_{be} : Cross section of braces made of EGS

σ_{ys} : The yield point of Structural Steel

σ_{ye} : The yield point of EGS

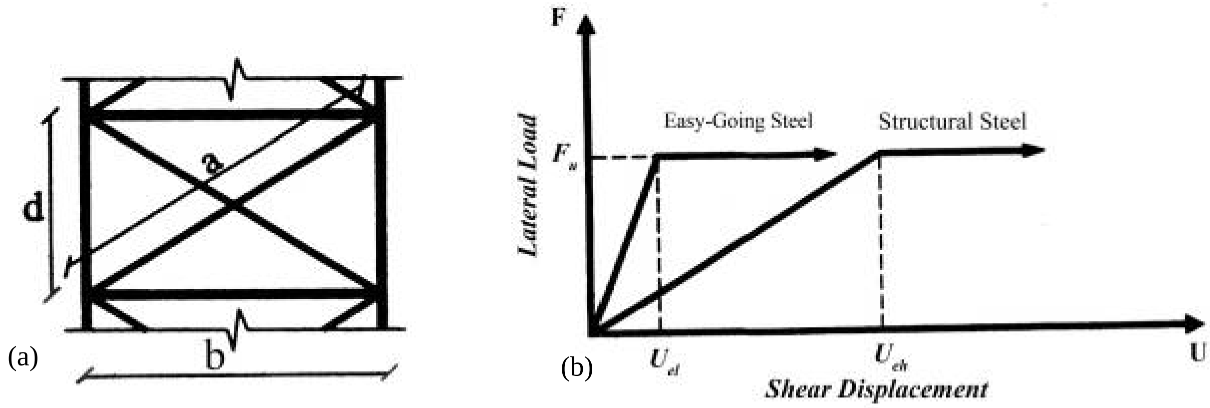

Figure 1: a) dimensions of an X-braced frame, b) behavior of X-braces with EGS and Structural Steel

It can be verified that the capacity design of braces were considered in this relation. So, the braces where designed according their tensile and compressive strength without considering buckling effects. The shear stiffness of X-braced frames can be approximated using equation 2. The used parameters in this equation are shown in Figure 1 (a).

$$K = \frac{2Eb^2A_b}{a^3} \qquad (2)$$

Where:

E: The modulus elasticity of steel

b : Span width

A_b : The cross section area of each brace

a : Length of each brace

K : The shear stiffness of frame

The stiffness of X-Braced frames can be rewritten in more popular form as follows:

$$K = \frac{2E.A_b}{b}(\cos\alpha)^3 \qquad (3)$$

Where

α : The angle between each brace and the horizontal axis.

Using equations 1 and 2, it can be seen that the shear stiffness of frame with EGS is more than the similar frame with Structural Steel. This ratio is obtained by dividing the yield stress of Structural Steel by yield stress of EGS. Since the lateral design force (F) is considered constant and has a linear relation with lateral displacement (U=F/K), using equation 2, it can be understood that the corresponding Elastic-limit displacement of the frame with EGS is much less than the frame with Structural Steel by the ratio which is equal to yield stress of EGS divided by yield stress of Structural Steel. The Force-displacement diagram for each type of frames is depicted in Figure 1 (b).

3. Design of Frames

In order to be able to compare the behavior of frames designed using Structural Steel and Easy-Going steel, two frames were selected with two different types of materials for their braces. The structural steel and Easy-Going Steel with minimum tensile stresses equal to 250 and 90 MPa were used in these frames, respectively. In each case, the columns and braces are the same and are made from Structural Steel and just the materials of braces differ.

The braced framings from the first story of a building with depicted loads in Figure 2 were designed and it is assumed that these frames work in shear.

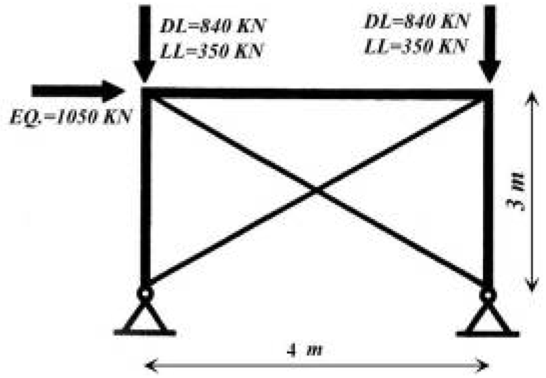

Figure 2: Design Loads

The columns were designed according to the dead load and live load of top floors and also the vertical component of axial forces attached braces. The columns should be able to transfer total loads with elastic behavior and they assumed not to enter to plastic region.

The beams were designed for flexural effects from direct transverse loading of that floor plus the axial forces induced from horizontal component of braces forces. Since the beams are part of roof diaphragm, the appropriate constraints were applied on it.

Since the Easy-Going Steel theory was used to determine the capacity of braces, which was based on non-buckling capacity of braces, tried to apply the latest provisions about limiting the buckling of braces. In this purpose, the provisions of AISC360-05 and the seismic provisions of AISC341-05 for seismically compact elements to limit the local buckling in bracing members and also the restrictive limitations for global buckling of braces was considered. It should be emphasized that the global slenderness of designed frames covers the specifications provisions and we can expect to be in good approximation between the theory and actual behavior of frames during lateral loading. According to designed sections, the slenderness of designed braces using Easy-Going Steel and Structural Steel is equal to 53 and 114, respectively. The design sections and other required design parameters are presented in Table 1.

Table 1: Design sections of X-Bracing Frames

Member Type	Easy- Going Steel $F_y = 90 \quad MPa$	Structural Steel $F_y = 250 \quad MPa$	Slenderness $\lambda = KL/r$
Columns*		BOX 165x165x12	47
Beams*		HEB280	---
Braces (Frame 1)	BOX 270x115x10		53
Braces (Frame 2)		BOX 129x56x8	114

- Columns and Beams in both types of frames were designed using Structural Steel and just the type of braces material differs.

4. Modeling

4.1. Mass-Spring-Damper System

We have introduced the SDF[1] system by idealizing a one-story X-Braced structure. The classic SDF system is the mass-spring-Damper system which is shown in Figure 3. The dynamics of this system is developed here considering the linear and nonlinear material properties. The solution of this system under harmonic loading is discussed and developed. If we consider the spring and damper to be massless and the only motion to be in x-direction, we have a SDF system [Chupra, 1997]. In the other words, the X-Bracing frame was converted to a simple model with concentrated mass of building as m and stiffness of braces as k.

[1] Single Degree of Freedom

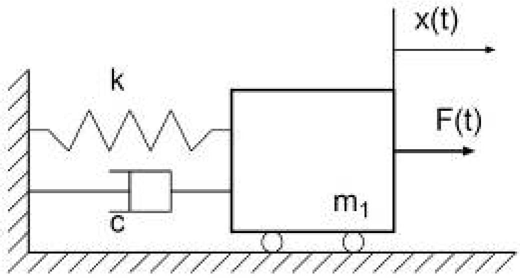

Figure 3: Mass-Spring-Damper system

4.2. Modeling Characteristics

The stiffness of each frame is calculated by using equation (3). Also, according to Easy-Going Steel Theory, the ultimate force capacities of the frames were calculated by formula $F_u = 2.A_b.F_y.\cos\alpha$. So, the yield displacement can be obtained using $\Delta_y = \frac{F_u}{K}$. The natural frequency of each frame was calculated by $\omega = \sqrt{\frac{K}{m}}$. According to these relations, the characteristics of each frame are calculated in Table 2.

Table 2: Force Displacement characteristics and frequency of frames

Frame ID	**m (kg)**	**K** (N/mm)	F_y (MPa)	A_b (mm^2)	P_y (N)	Δ_y (mm)	**T** (sec.)	ω (rad/Sec)
EGS	1270000	373663	90	7300	1051200	2.81	0.366	17.17
SS		138409	250	2704	1081600	7.81	0.602	10.44

It can be seen that according to EGS theory, the relation $A_{b(EGS)}.F_{y(EGS)} = A_{b(SS)}.F_{y(SS)}$ is established. The ratio of $\frac{A_{b(EGS)}}{A_{b(SS)}} = \frac{F_{y(SS)}}{F_{y(EGS)}}$ is obtained equal to 2.78. A similar ratio is established between stiffness of frames ($\frac{K_{EGS}}{K_{SS}} = 2.7$).So, the time of yielding of EGS system is considerably less than SS system ($\frac{\Delta_{y(EGS)}}{\Delta_{y(SS)}} = 0.36$). In the other words, the energy absorption process in EGS system was started in much less displacements and therefore, the energy absorption capacity of the EGS system is more than SS system.

4.3. Load Application Format

Since the earthquake is generally defined by acceleration of the base of the structure, the loads were applied as support accelerations. The support acceleration is defined as $a = a_0.\sin(\Omega.t)$ which a_0 is the acceleration amplitude and Ω is the acceleration frequency.

The analyses were done according to the ratio of $\frac{\Omega}{\omega}$ in order to see the behavior of system in various situations, especially under resonance conditions. In harmonic analyses, the damping effects were not considered. As though, from comparative view, the same relations can be expected.

The EGS-1 and SS-1 analyses were considered with $\frac{\Omega}{\omega} = 1.0$. In these cases, the initial amplitude of the earthquake has a small value and increases gradually under resonance conditions.

The EGS-2 and SS-2 analyses were related to quasi-static response of the systems under $\frac{\Omega}{\omega} = 0.2$ conditions. The amplitude of support acceleration is considered equal to 0.35g in each case.

Another analysis was accomplished under Tabas earthquake record to compare the behavior of systems. Here, the damping of the system is considered equal to 5 percent.

5. Results Summary

5.1. Resonance conditions

As discussed previously, the stiffness of EGS system is 2.7 times greater than SS system. So, we expect to have much less lateral displacements in EGS system relative to SS System. With EGS-1 and SS-1 analysis types under resonance conditions, it can be seen that at each time, the lateral displacement of frame-1 is less than lateral displacement of frame-2 because of its higher stiffness. These graphs are depicted in Figure 4.

The significant reduction in shear displacement of the stories not even causes the main vertical load-bearing members of the structure – like the columns – to be safe from serious damage due to the smaller lateral displacements and noticeable moment reduction in them, but broadly reduce the undesirable effects of the $P-\Delta$ phenomenon.

The other definitive parameter in behavior of EGS system is related to start of nonlinear behavior. The Figure 4 shows that the braces of EGS system, as the lateral load bearing components, became non-linear in very small lateral displacements and absorb most of the energy. In this way, the main vertical load-bearing members – like the columns – commonly remain linear and unaffected from any damage caused by nonlinearity.

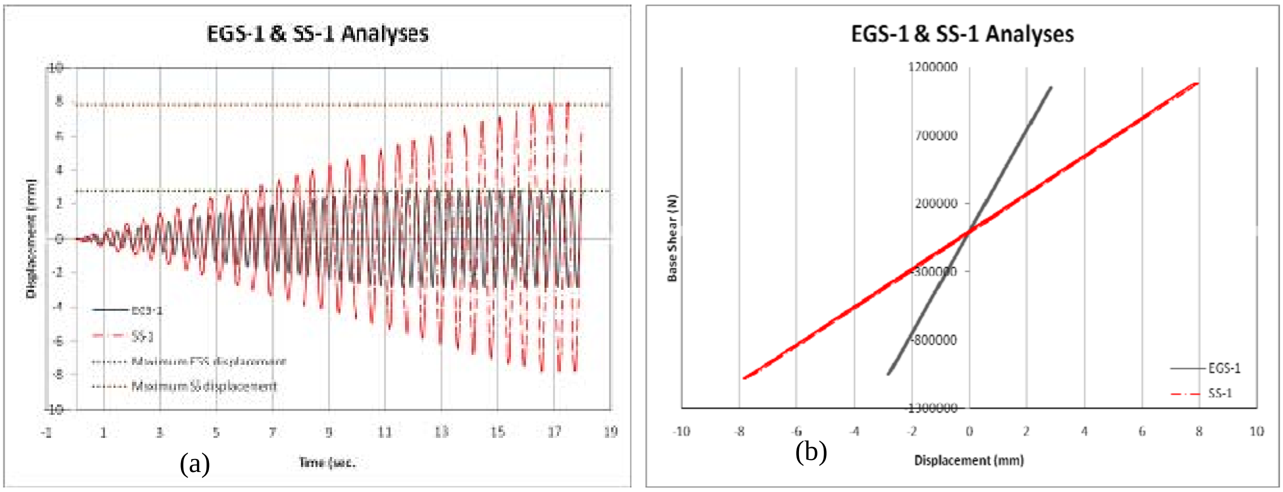

Figure 4: a) Lateral displacements of frames under Harmonic analyses with EGS-1 and SS-1 analysis types
b) Base Shear - Displacement diagram of frames under Harmonic analyses with EGS-1 and SS-1 analysis types

With comparing graphs in Figure 4 (a), it is evident that the EGS system with much less lateral displacements prevents from increasing the lateral displacements and therefore the transferred forces to structural members such as beams, columns and connections, decreases the risk of earthquake for the building. We can see that with time increasing, the applied forces to the frames is also increasing incrementally because of resonance, but the maximum displacements and also the transferred forces to columns would be limited to constant values. These values in EGS system are much less than SS system.

The diagrams of base shear-displacement of these analyses are traced simultaneously in Figure 4 (b). It can be seen that the stiffness of the frame-1 is much more than frame-2.

5.2. The Quasi-Static Response

In order to compare the behavior of two systems under harmonic loading, the ratio of earthquake frequency divided by natural frequency of each system is selected equal to 0.2. The graphs are shown in Figure 5.

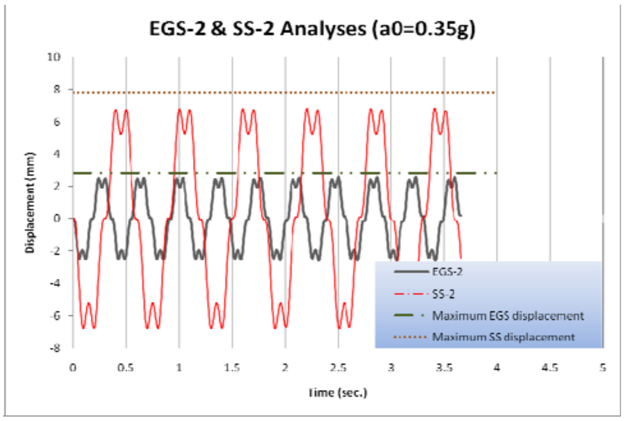

Figure 5: Lateral displacements of frames under Harmonic analyses with EGS-2 and SS-2 analysis types

It can be understood that, as though we don't have resonance anymore and these systems remain in elastic range, but the displacement of EGS system is much less than SS system and it has better behavior and stability because of less transferred loads to other structural members.

5.3. Earthquakes Response

The Tabas earthquake is selected for this analysis. The base acceleration is scaled to 0.28g. The response of two above mentioned frames were monitored under application of earthquake time history according to Figure 6.

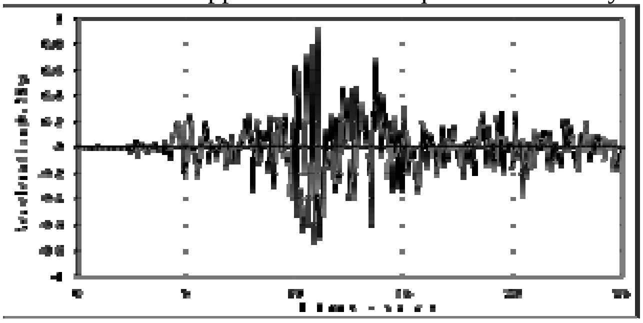

Figure 6: Time history of Tabas earthquake

The response of EGS system and SS-system are shown in Figure 7 in order to be able to comprise their behavior.

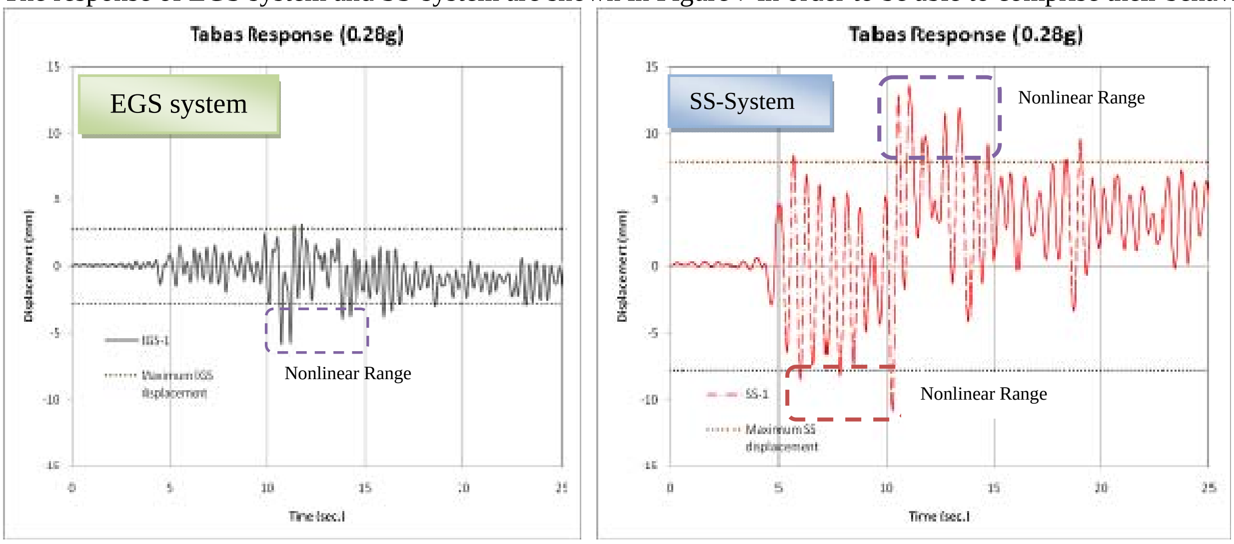

Figure 7: lateral displacement of frame-1 under tabas earthquake

It can be seen that maximum displacement of EGS system is equal to 5.6 mm at time 10.7 sec. and maximum displacement of SS system is equal to 13.48 mm at time 11.1 sec. So, as mentioned before, it is evident that the displacements of EGS system are much less than SS system.

Base Shear –Displacement diagram for each frame under Tabas Earthquake is shown in Figure 8. It can be seen that the EGS system has more stable behavior than SS system and in spite of its more ductility and more energy absorption capacity, its lateral displacements are much less than SS system. In fact for tall buildings the shear deflections will be controlled successfully and the ductility of the system is also increased. This quality in behavior and control of shear displacements of the system in tall buildings can be easily obtained using Easy-Going Steel.

Figure 8: Base Shear – Displacements of frames under Tabas Earthquake

6. Conclusions

By applying Easy Going Theory for design of Lateral Load resisting systems the following benefits can be obtained:

1. The lateral stiffness of the system increases and the lateral drifts decreases significantly.
2. The ductility and energy absorption capacity of the system increases.
3. The $P-\Delta$ effects reduce.
4. The stability of the system growths.

Briefly, it should be emphasized that in spite of general systems that when increasing stiffness, the ductility of the system decreases, by using Easy-Going Steel Theory and its application for design of buildings; the ductility and stiffness of the system as well as its Energy absorption capacity increased significantly.

Invention Registration

The Easy-Going Steel general concepts and theory with its various implications were registered by Dr. Saeid Sabouri-Ghomi. So, using this theory and related applications copyrighted and is the sole property of his respective billet.

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