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The Investigation of Permanent Displacement in Structures with Buckling-Resistant Braces under Impact Loading in Two Joint Bracing Systems of BF and Dual

M. Ali Lotfollahi Yaghin[1], M. Reza Bagerzadeh Karimi[2,*], R. Mehdi Nezhad[3], V. Sadeghi Balkanlou[2]

[1]Prof. of Faculty of Civil Engineering, University of Tabriz, Iran
[2]Young Researchers and Elite Club, Tabriz Branch, Islamic Azad University‹Tabriz‹, Iran
[3]Department of Civil Engineering, Islamic Azad University, Maraghe Branch, Iran

Abstract Repeated damage to frames with concentric bracings in recent earthquakes such as the 1984 Mexico City earthquake, 1989 Loma Prieta, and 1994 Northridge intensified the concerns about the ultimate ductility capacity of this class of structures. Several categories were mentioned for the poor performance of this class of braced frames. In this paper, a three-story steel structure in three dimensions is raced with buckling-resistant braces and then a dynamic analysis was applied to it. Then the results of application of buckling-resistant braces to dual system for reducing permanent deformation under impact loading have been investigated. Finally, the impact of imperfection in protective cover upon the performance of brace is studied. The results are indicated in tables and figures, hence being compared.

Keywords Buckling-resistant brace, Dual system frame (Dual), Impact loading, Dynamic load

1. Introduction

Repeated damage to frames with concentric bracings in recent earthquakes such as the 1984 Mexico City earthquake, 1989 Loma Prieta, and 1994 Northridge intensified the concerns about the ultimate ductility capacity of this class of structures. Several categories were mentioned for the poor performance of this class of braced frames. For example, the typical braces often have ductility with limited energy dissipation capacity under cyclic load. Therefore, a new system resistant to lateral_ a system of frame with buckling-resistant brace was studied in the U.S. in 1994. The buckling-resistant braces show good energy dissipation characteristics. However, the low re-indurations of these braces make the system vulnerable to damage and unfavorable behavioral characteristics such as large displacement.

As noted above, the use of low-strength steel in the core of buckling-resistant braces has some advantages compared to other types of steels. This advantage for low-strength steel is due to the following main reasons:

1- High energy waste (high CPD)
2- High ductility
3-The low stress of bracing components in the columns

* Corresponding author:
mrbkarimi@gmail.com (M. Reza Bagerzadeh Karimi)
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Although the above factors are very desirable advantages for buckling-resistant brace made of soft steel core, the use of soft steel causes a very important undesirable behavior in the structure which is permanent displacement in the structure. According to the research conducted by Sabelli, this permanent displacement is about 40% to 60% of the maximum displacement [1]. One of the proposed mechanisms to reduce this permanent displacement is by adding the previously mentioned supporting bending frame. In this study, the permanent displacement in a steel joint structure with buckling-resistant bracing whose core is made of soft steel (yield stress 100 Mpa) under impact loading is investigated and the effect of adding supporting moment frame on the rate of permanent displacement under impact load is assessed. The impact of support moment frame upon ductility of structure will be investigated as well. Because, adding bending frame should not have a great effect on ductility of the main structure.

Testing of metal brace covered with mortar inside the metal tube was carried out by Kimureat. The tube filled with mortar proved to be effective against the buckling of the core. In the subsequent investigation, 4 samples were tested with the actual sizes under seismic load. They indicated that if the ratio between the buckling strength of elastic outer shield and the yield strength of the core brace is greater than 1.9, no buckling occurs in the core of brace and that testing sample did not show good hysteresis. Iwata et al, in 2004 [2], studied the periodic performance of some of the existing anti-buckling braces in Japan. Three large-sized braces were tested by BRB at University of Berkely to help design and construct buildings.

Black et al, in 2002 [3], did a different analysis on actualization of internal core stability in the great earthquakes and elastic torsional buckling of core. Chen found out that application of metal with low resistance makes possible the yield of the brace with low flexural deformation, hence more ductility is achieved. In a study conducted by Uang, the advantage of application of BRB in the dual system for reducing the permanent deformation was investigated [4].

Tsai and Lai, in 2005, studied the impact of friction reducers on the periodic response of braces [5]. Sabelli increased the seismic absorption of frames by coating bracing system. Kim et al, [6-8], provided a seismic design process for BRBF based on energy waste and a direct displacement design process.

In this paper, behaviour of the lateral load resistance systems such as bracing systems have been studied under buckling, and also its behaviour have been studied under the impact of loading. Then, designing method has been investigated under the impact loading. The results gained from dynamic analysis can be observed in the diagrams of displacement of stores and the displacements between stores which have been illustrated in figures.

2. Modeling and Analysis

In order to check the accuracy and precision of the modeling and comparing the results with designing goals, dynamic analysis using finite element software ABAQUS was carried out [9]. A three-story steel structure in three dimensions is raced with buckling-resistant braces and then a dynamic analysis was applied to it.

Since the design of these types of structures, namely the metal frames braced with buckling resistant braces, is based on the principle that the beams and columns remain absolutely elastic in earthquake and seismic load is wasted by braces and dual system, thus the design of structure is limited only to the design of braces and the beams and columns which are designed for gravity load and the component load of braces, will be the same in all samples, and the only difference between the four different models is the size of braces with other elements and structural characteristics being the same in all aspects.

2.1. Introduction of Structure

The structure under study is a three-storey structure, once modelled as a simple building frame with buckling-resistant brace and once as a dual system meaning a simple building frame with buckling-resistant brace by adding moment frame. In this study, a three-dimensional structure has been modeled. Cross-Sections of beams, columns and braces are represented in Table (1) and (2).

The figure (1) indicates the placement of braces and moment frame. As it can be observed, in each plan there are 4 braced spans and also, in dual system (Figure 1-B) there are 4 braced spans with a moment frame. Regards that the stress caused in the structural members is within the acceptable limit, the members of the moment frame are selected as similar to the members of joint frame. Since the software used (ABAQUS) is not a designing-software, the ratio between the number of moment frames with that of joint frames and the number of buckling-resistant braces is not very ideal. But, by using suitable design software it can be achieved with an optimal ratio between them so that adding moment frame would have the least impact ductility of structural and the highest impact upon reducing permanent displacement. Thus, this study merely deals with the impact of adding supporting moment frame to the structures with buckling-resistant braces under the impact load, while the aim of this study is not to provide a proper ratio between the number of joint frames with buckling-resistant braces and the number of moment frames.

Table 1. Section of beams and columns (mm)

Story	Columns	Beams
1-2	H 250 x 250 x 9 x 14	H 400 x 200 x 8 x 13
3	H 200 x 200 x 8 x 12	

Table 2. Cross-sectional area of the brace

Story	S (cm^2)
1	1.09
2	0.91
3	0.54

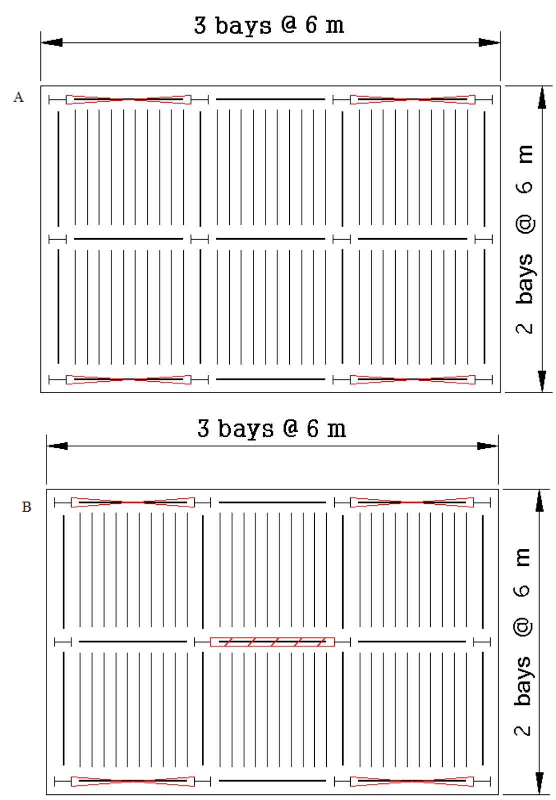

Figure 1. Plan of Structures A) Joint frame with buckling-resistant brace (BF), B) Dual system frame (Dual)

2.2. Introduction of Impact Loading for the 3D Structure

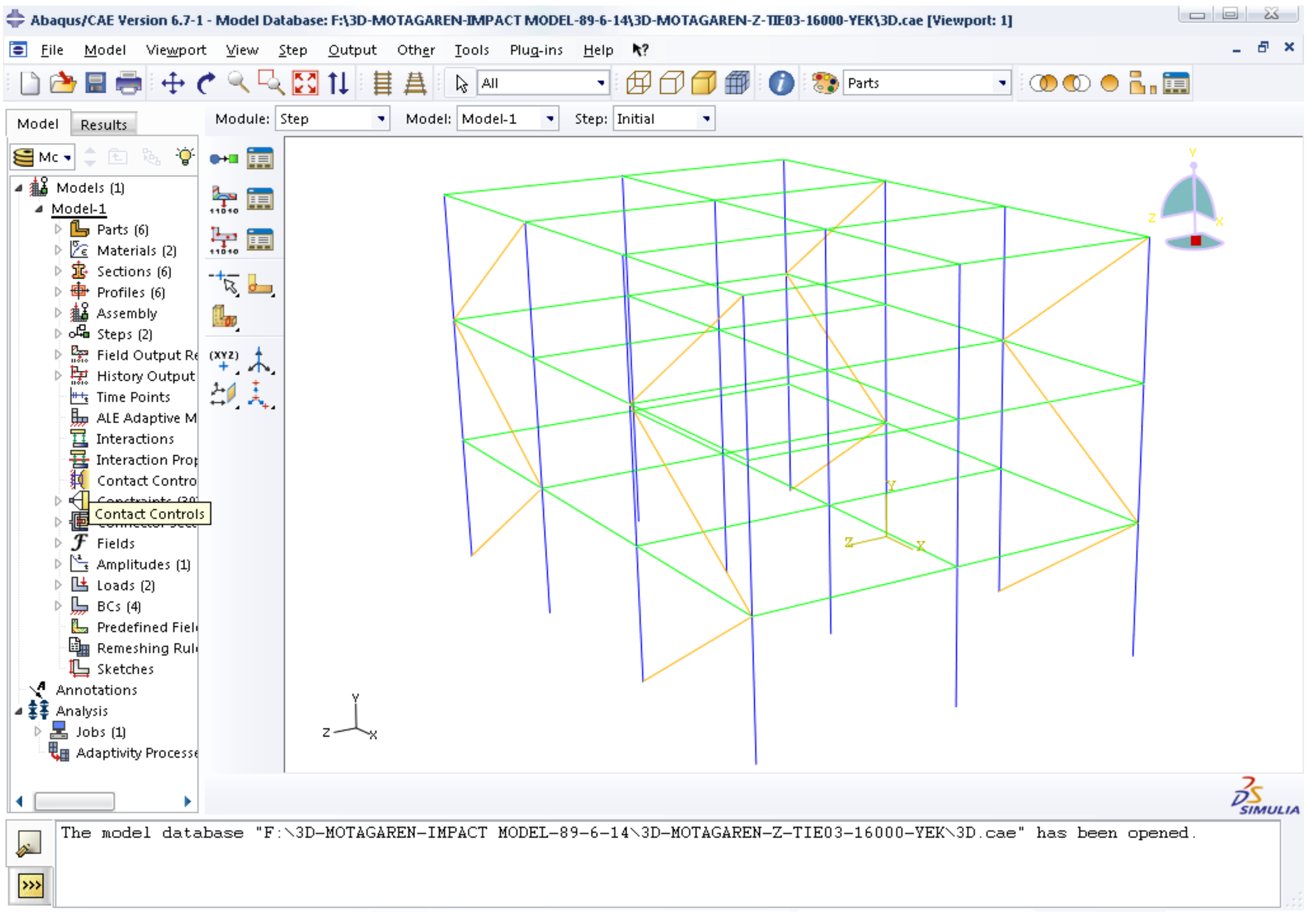

Figure 2. The 3D Image of Structure

Figure (2) shows a 3-D image of the structure modeled by ABAQUS. The altitude of all stories equals 4 meters. Impact load was applied to the structure in two triangular and rectangular forms so that each had a different intensity. In this section, the load values were chosen so that all the elements of the area under diagram of load-time are constant. The load values for both triangular and rectangular shapes are observed in tables (3) and (4).

As can be observed in the following tables, the load values is the same for triangular and rectangular loads whereas the values of impact force time for rectangular load is half of that of triangular load.

Table 3. The Values of Triangular Impact Load

Story	Case 1	Case 2	Case 3
T (s)	0.5	0.4	0.3
P (N)	9600	12000	16000

Table 4. The Values of Rectangular Impact Load

Story	Case 1	Case 2	Case 3
T (s)	0.25	0.2	0.15
P (N)	9600	12000	16000

This has been done due to the fact that in addition to the unification of the area under the diagram of load-time, we can investigate the impact of increasing the intensity of the momentary load upon maximum displacement and permanent displacement. The point worth mentioning about loading is that firstly according to the tables (3) and (4), the value of momentary load at the time of related impact was applied to the structure. Then, after stoping of momentary load, simultaneously for rectangular load and gradually for triangular load, the analysis was continued. In other words, the structure was allowed free vibration until it reached quiescent state and the values of maximum displacement and permanent displacement were determined.

2.3. The Results of Analysis and Comparison of Results

By modelling 3D structure and application of impact load and after vibration of structure, the values of maximum displacement and permanent displacement for Case 1 are presented in Figure (3).

As observed, the structures under impact load after reaching maximum displacement is vibrated and eventually the structure reaches quiescent state. Since the members of structure are connected to each other through joints, and the whole length of core brace yields entering in the plastic phase, the structure has permanent displacement after reaching quiescent state which is indicated in the figure (3). To fix this defect, supporting moment frame has been used. In the following, the impact of adding supporting moment frame on the performance of braces is shown in the diagram.

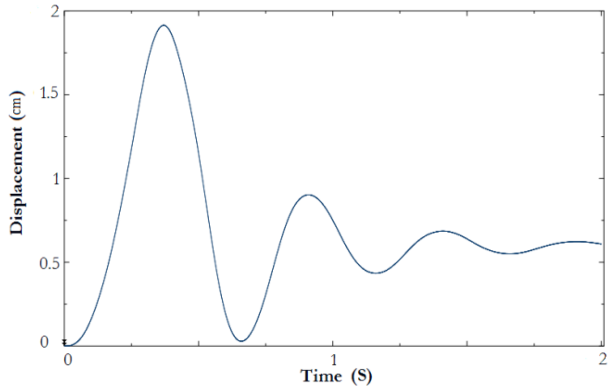

Figure 3. The Diagram of Displacement Level of Three Stories under impact loading (BF)

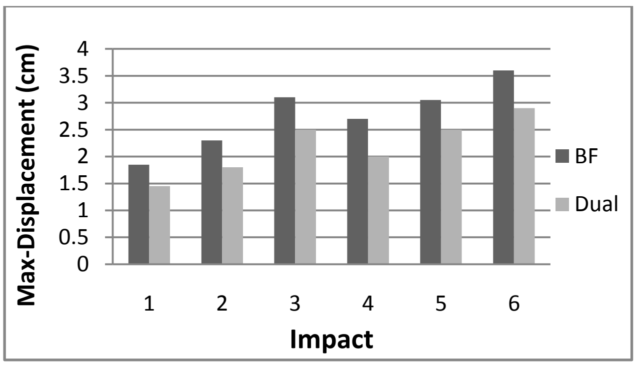

Figure 4. The Diagram of Ratio of Maximum Displacement

As indicated in figure (4), adding supporting moment frame to the structure has little impact upon ductility of the structure for all values of load and with various intensities. Figure (4) shows that the average of maximum displacement for BF and Dual systems is respectively 2.75 and 2.2 cm. Thus, the average of reducing these values is calculated as 20%. The figure (5) shows that maximum permanent displacement is more in BF system than is in Dual system for all cases.

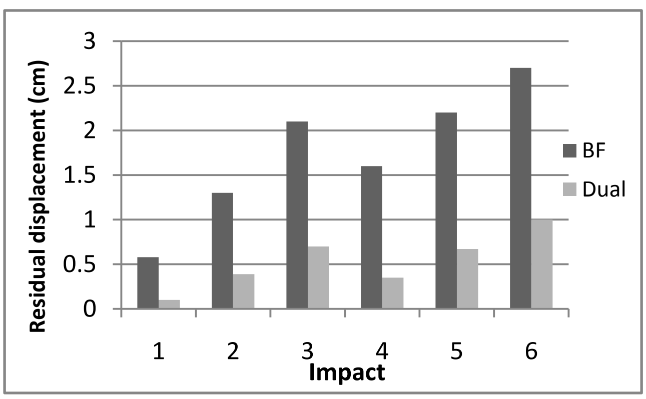

Figure 5. The Diagram of Ratio of Permanent Displacement

The average of permanent displacement for BF system and Dual system is respectively 1.75 and 0.54 cm. Thus, the average reduction of these values is calculated as 69%. Thus it can be observed that adding a moment frame to the structure with buckling-resistant brace which might be faced with impact loading results in significant reduction of permanent displacement.

Also, the figures (4) and (5) indicate that rectangular impact loading causes more maximum displacement and permanent displacement than does triangular impact loading. This event is due to the intensity of the load impact because in rectangular loading, the value of impact suddenly reaches its maximum and can have a greater effect on the structure. It can be observed that the same is true for the 3 triangular loads applied to the structure with different intensities by increasing the intensity of impact loading from CASE 1 to CASE 3.

Another important aspect of this study is determining the ratio between the load-impact intensity and increasing permanent displacement for BF and Dual systems. This relationship or ratio is indicated in a diagram of load-impact intensity-permanent displacement in Figure (6).

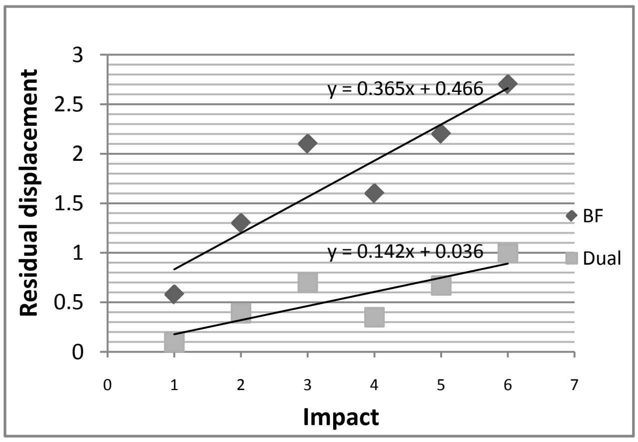

Figure 6. The Diagram of the Ratio between impact Intensity and Permanent displacement

As Figure (6) indicates, the impact with more intensity is more prone to cause a greater permanent displacement, and this inclination is more in BF system than in Dual system. In other words, if the curves fitted are considered, it is indicated that the slope of these diagrams for the system BF is greater than that of Dual system. Thus, under the impact load with more intensity the behavior of the structure is more desirable with Dual system than with BF system. For the evaluation of the effect of adding supporting moment frame upon maximum displacement and permanent displacement along the height of the frame, these changes were drawn for one of the samples (CASE 3) in the diagram of Figure (7).

As it is observed in the diagram of Figure (7), the extents of maximum displacement for the systems BF and Dual along the height of the structure are close, whereas, the extent of permanent displacement for the Dual system shows a considerable reduction.

According to the above results, it can be stated that adding supporting moment frame to the structure with buckling-resistant brace improves the performance of the structure under impact load and reduced the repairs costs.

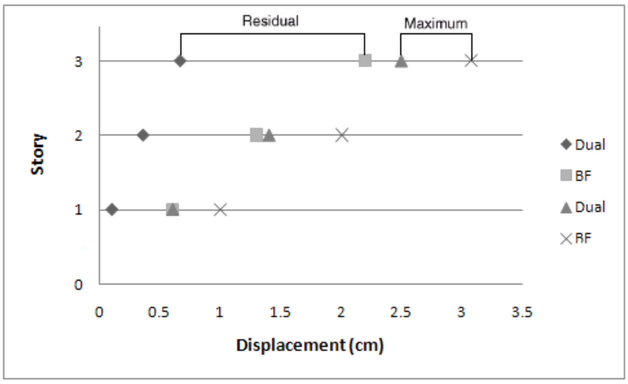

Figure 7. The Ratio of Maximum Displacement and Permanent Displacement along the Height of Building

3. The Impact of Geometric Imperfection upon the Behavior of Buckling-Resistant Braces

As previously mentioned, the core of buckling-resistant braces is considered as one of the most important and critical parts of this type of braces. It was previously observed that the core of buckling-resistant braces bears the entire axial load and outer shield prevents buckling of the core and it should not share a part of the endurance of axial load. But, the point which merits investigation is as to what will be the behavior of the brace with geometric imperfection in the coating of the brace and what will be the impact of behavior of core of brace and resistant-buckling cover upon one another's performance. The geometric imperfection in the cover of buckling-resistant braces is perhaps due to the slow set mortar being curved. In fact, the necessity of study is this point that as to what extent we can rely on the outer shield as a mechanism for the same behavior of brace in tension and compression and as to how much we should be careful in making the cover of buckling-resistant braces.

To investigate this point, a brace with a strong outer shield but with geometric imperfection is modeled and the behavior of brace under dynamic load is analyzed. At first, a kind of buckling-resistant brace is modeled and put under dynamic load, and after determining the behavior and making sure of modeling by creating geometric imperfection on the cover, the behavior of brace is investigated again.

3.1. Modeling of Buckling-Resistant Brace

Here the characteristics of a type of buckling-resistant brace are introduced. This brace is made up of the main parts of core, protective cover, separating material, and connector. The figure (8) shows a cross section of the brace.

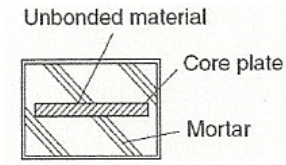

Figure 8. Cross Section of Buckling-Resistant Brace

The length of brace is 1000 mm and the core cross section 8 x 60 square mm and the yield stress of core of brace is considered 100 MPA [10]. The thickness of the protective is 5 mm and its dimensions 100 x 100 mm. The yield stress and breaking of protective cover are 240 and 420 MPA, respectively. The compressive strength of mortar was considered 24 MPA, its density 23.6 Kilo Newton / Square Meter, and its elasticity modulus 23 GPA. For the behavior of brace to be close to the reality, the core brace must have an imperfection so that the core under dynamic load begins to buckle and the outer cover prevents buckling. For this purpose, first the brace was applied to buckle analysis and the first five modes of buckling were determined and then according to the figure (9), the first mode of buckling was entered into the core as imperfection and then it was applied to dynamic analysis [11]. The important point in modeling, which is of high importance, is the way of interaction between the core and the protective cover. It is briefly explained here. As previously mentioned, the frictional contact between core and protective cover must reach its minimum value.

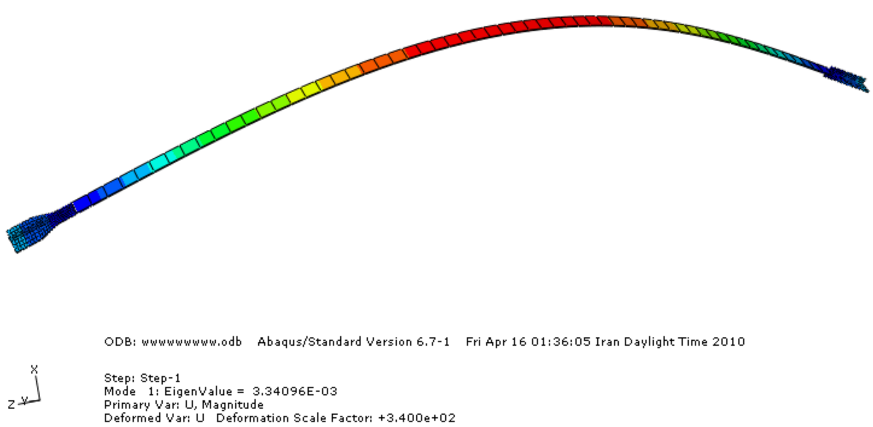

Figure 9. The First Mode of Buckling

This is done by using materials whose friction coefficient is very little. The purpose of this is that the core move easily inside the cover and be able to easily reduce and increase the length so that its hysteresis curve be regular and the transfer of stress between the core and the protective cover be prevented, and as such, the cover would not have to endure the axial force and be buckled. In this modeling, in order to provide this situation, a 2 mm empty space or gap was placed between the core and the protective cover. In this way, given the existing distance, the contact interaction was used between the core and protective cover according to figure (10). In this type of connection, according to figure (11), and (12), we have considered the contact from the type of hard contact with the friction coefficient of 0.1 [11].

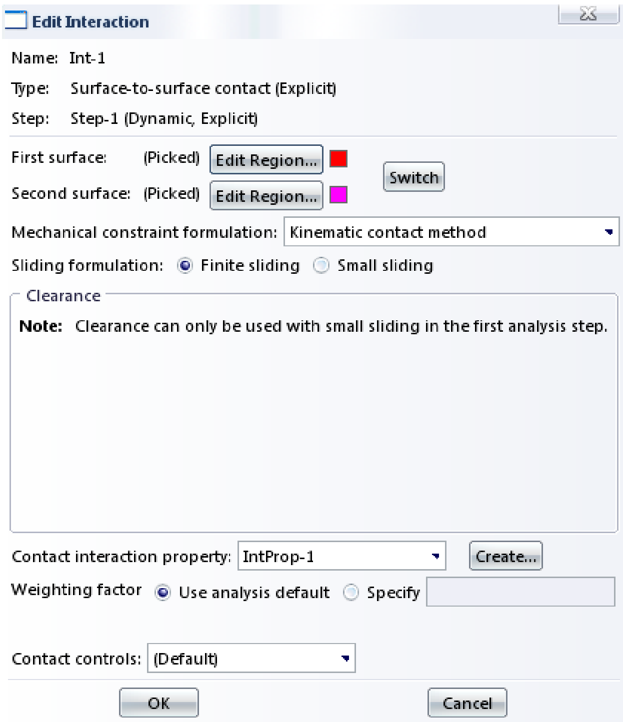

Figure 10. The Way of Contact between Core and Cover

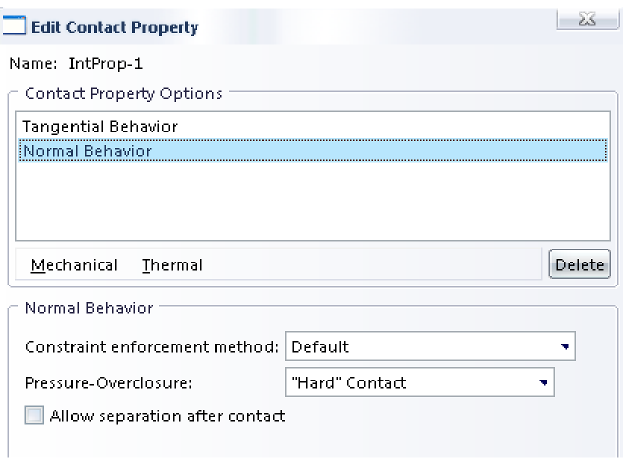

Figure 11. The Characteristics of Contact between Core and Cover

The connection of protective metal cover to mortar was considered as Tie type because no slippage was allowed between them. In order to be assured of modeling and to study the behavior of brace, loading was considered as the axial displacement of the core, according to the figure (13). After applying load and completing the analysis, the stress–strain curve of buckling-resistant brace was achieved according to figure (14). As the figure (14) indicates, the stress–strain curve of brace is regular, and the behavior of brace is the same in tension and pressure. Thus, it can be said that the modeling of buckling-resistant brace has been done properly.

After being assured of modeling, next the effectiveness of geometric imperfection in brace upon the behavior of buckling-resistant brace is investigated. The shape of geometric imperfection is considered in a way which would result in reduction of cover strength.

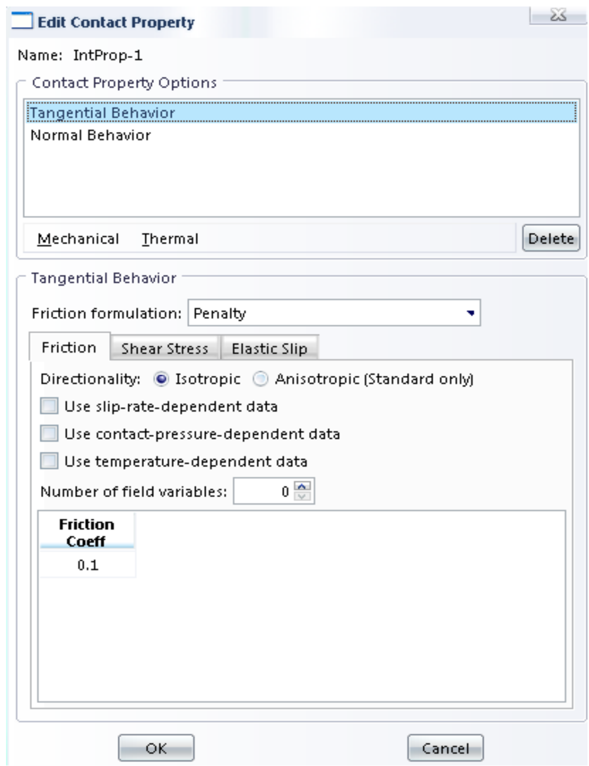

Figure 12. The Friction Coefficient Related to the Areas in Contact

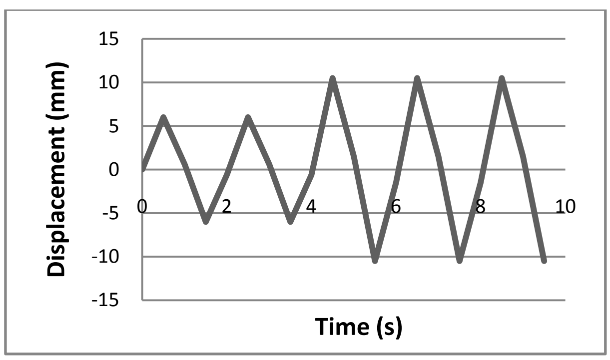

Figure 13. The Time Record of Axial Displacement of Core

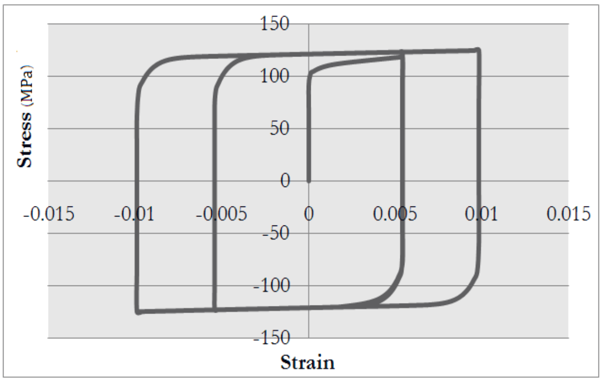

Figure 14. The Stress-Strain Curve of Brace

3.2. Introduction of the Shape of Geometric Imperfection

As is observed in Figure (15), it is assumed that the mortar inside protective cover is curved toward and the empty space or gap between the core and the mortar has decreased.

We assume the length of this arc is 100 mm and its depth 0.9, 0.85, and 0.8 mmfor Case A, Case B, and Case C, respectively. By applying this geometric imperfection between the core and the cover, the gap is reduced, but the type of contact does not change. And for this state also the friction coefficient is considered 0.1.

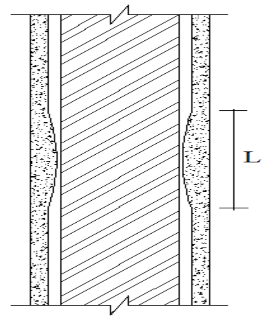

Figure 15. The Details of Geometric Imperfection

3.3. The Results of Analysis

By doing a dynamic analysis for all cases A, B, and C, the values of compressive and tensile strain were obtained. The values related to the stress in the members of brace can be observed too. As indicated in the figure (16) which has been developed for the Case A, in the region of geometric imperfection, the stress of protective mortar was highly increased and the mortar was ruptured because of transfer of stress from the core of brace to protective mortar.

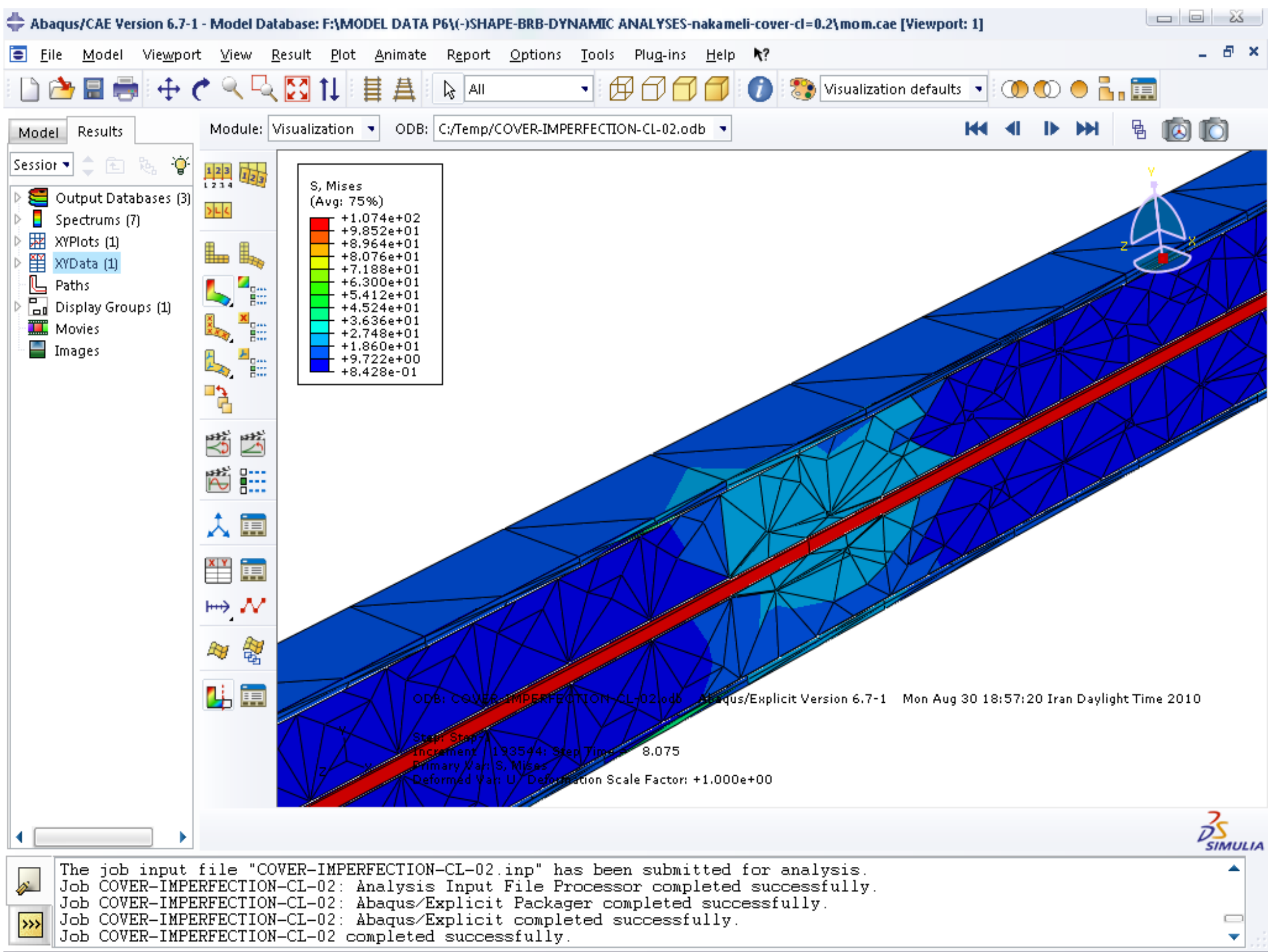

Figure 16. Stress in Members of Brace

For other cases (B and C) also there is an almost the same situation and the stress in the region of imperfection has been highly increased which represents the transfer of stress from the core to the outer cover. The transfer of stress from core to outer cover is an adverse event which can disrupt the performance of brace. A number of these undesirable cases are mentioned in the following:

1- Cracks and rupture of protective mortar

2- Creating a fictitious resistance in the brace, and thus stress transfer between the core and cover

3- Non-uniform performance of brace in tension and compression

4- The general buckling of brace with anti-buckling cover under high stresses

For example, figure (17) indicates the difference between strain in tension and strain in compression for the cases. The Case D is the same case without imperfection which had been previously modeled and here brought for comparison.

As the figure (17) indicates, for a situation imperfect arch depth has highest value (Case A), we are observing the greatest difference between the strains. Also as it is observed in Figure (18), by increasing the depth of geometrically imperfect arch, the ratio of strain in tension to strain in pressure strain increases and this is due to the decrease of strain in pressure, thus creating a fictitious resistance in the core of the brace, it owing to stress transfer between the core and the buckling-resistant cover.

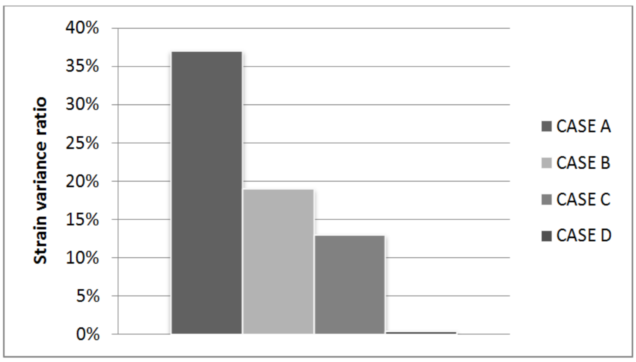

Figure 17. Ratio of Difference between Strains in Tension and Compression

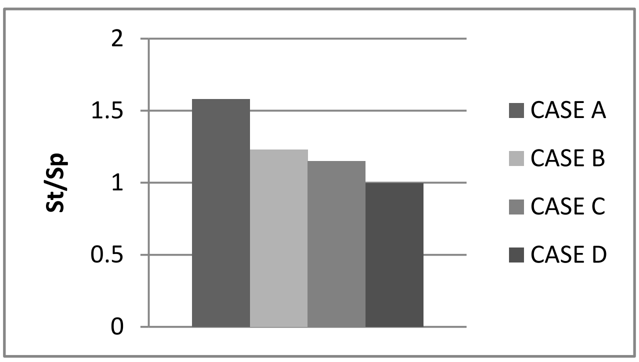

Figure 18. Ratio of Maximum Tensile Strain to Compression Strain

As it can be seen in figure (18), the Case D, which corresponds to the healthy brace, has the best performance, and the ratio of strain in tension to strain in compression is close to number 1. Therefore it can be concluded that for non-transfer of stress between core and outer cover, mere use of materials with low friction coefficient and negligible thickness between them is not enough. And, materials with suitable thickness and low friction coefficient must be used which provide the space suitable for the expansion of the core under pressure.

4. Conclusions

In this study, the process of seismic design based on performance was investigated for structures with buckling-resistant braces by joint connection of the beam to column. The proposed design process, assumes a straight line for the shape of storey displacement, the type of cutting, and the shape of main mode. The performance of structure of the model designed to displace the target was evaluated under impact loading by dynamic analysis in order to check as to whether or not the objective of the operation has been achieved.

According to the numerical results, the diagram of maximum displacement diagram is close to the line and the displacement between stories under impact loading is the same.

1- Adding supporting moment frame to the joint system with buckling-resistant brace, or in other words, using Dual system, greatly helps to reduce permanent under impact loading and has less impact upon ductility of structure.

2- The geometric imperfection has a significantly undesirable impact upon the performance of brace.

3- The use of separators with negligible thickness for buckling-resistant braces is not appropriate and the thickness of the separator must be so much that it would provide the sufficient distance for the expansion of the core of brace as a result of compressive load, and the core would easily increase and decrease its length inside protective mortar in a way that the stress transfer does not take place between them.

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