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Comparative study on the seismic behavior of steel structure in Afghanistan retrofitted with buckling-restrained braces and base isolation system

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Abstract –*Afghanistan is located in a geologically active part of the world and every year a strong earthquake occurs. With recent development, there has been many middle rise and high rise buildings built but none of them are designed based on international code requirements. These structures are subjected to collapse or large lateral displacements due to strong earthquake ground motions. The need for evaluating the seismic adequacy of the existing structures has come into focus. Therefore this paper discuss about the steel special moment frame structure which was retrofitted with a two resistance system (base isolation and buckling restrain brace). Moreover, the effectiveness of both system as a passive device control in a high seismic hazard area is also considered. The investigation was conducted based on a nonlinear static analysis, time history analysis, and the capacity spectrum method procedure. Simulated earthquake ground motion was generated for Parwan province of Afghanistan which has a high level of seismicity. The Seismic design category base on spectral design response is D with site class soft soil. The model was analyzed for gravity, and seismic load using Afghan structure code referring to ASC 302.3.1. The design generated according to the specification for structural steel buildings in the Afghan structure code refers to ASC 604.2.2.*

Key Words: buckling bracing system, Base isolation system, capacity spectrum method, the effectiveness of both system as a passive devices

1. INTRODUCTION

Parts of Afghanistan lies within a relatively stable, southward-projection promontory of the Eurasian tectonic plate. Meanwhile, the country is surrounded on the east, south, and west by active plate boundaries that are associated with deformation, faults, and earthquakes. The greatest hazard is in the east, where the Indian plate moves northward with respect to Eurasia at a rate of about 4 cm/yr. A broad zone deformation along the plate boundary lies partly within eastern Afghanistan, through Kabul, and along the Afghanistan-Pakistan border. The zone is characterized by abundant earthquakes and major faults. The result of historical data shows that the seismic hazard is high in northeastern Afghanistan and much lower in the western half of the country. Recently on 26 October, 2015 an earthquake occurred in the Hindu Kush range at a magnitude of 7.5. As a result, more than 399 people were killed and a further 2,342 injured. Based on historical earthquakes and tectonic mapping of Afghanistan, which has been investigated by the US Geological Survey (USGS), several faults that are possibly active inside the country are shown in Figure-1.

Fig-1: Map of Afghanistan showing the locations of modeled fault sources (DZ, Darvaz, HR, Hari Rod, CH, Chaman, CB, Central of Badakhsan fault) [1].

Potentially, four active large faults such as the Chaman fault, Herat fault, central Badakhshan fault and the Darvaz fault are those most likely to contribute to a seismic hazard. These faults have dimensions and surface expressions that are similar to major continent-scale strike-slip fault systems worldwide. After the invasion of Afghanistan by the United States in 2001 the major cities in Afghanistan have expanded rapidly and many new structures in the form of middle rise and high rise buildings have been built. But none of these building are designed based on international code requirements to resist the earthquake load. These structures are subjected to collapse or large lateral displacements due to strong earthquake ground motions. Therefore with the recent building development, it is an urgent need to increase the seismic capacity of existing structures.

2. NUMERICAL MODEL

The targeted building was six-story steel special moment frame office building designed for the Parwan province of Afghanistan. A 2D frame model from the middle of the six story office building in X direction has been chosen and analyzed. The first story is 500 cm tall and the upper stories dimensions are set respectively the same. The building has a span of 500 cm in the X direction and 600 cm in the Y direction as shown in the following Figure-2.

The analysis of the building is carried out by three-dimensional frame elements in which six nodal displacements per one node are considered. In this model, each beam is divided into three elements and each column is divided into one element.

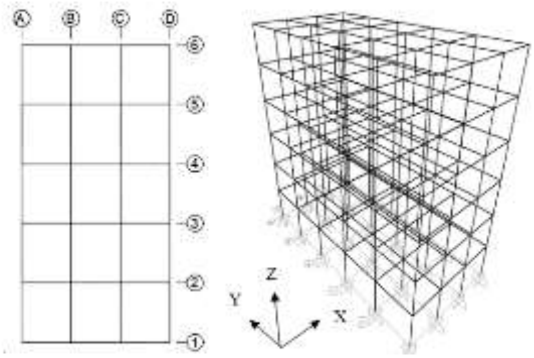

Fig-2: The 6th story structure model

For the structural analysis, ASTM A992 grade 50 has been used as the steel material for beams and columns with having a tensile yield strength of 345 MPa (50ksi), tensile ultimate strength 450 MPa (65ksi) and strain to rupture (elongation) 18% as shown in Table -1. Hollow square section and Wide flange section were selected for column and beam elements [2], [3].

Table -1: Summarize of section property

No	Description	Type	Fy (Mpa)	Fu (Mpa)	Material standard
1	column	HSS.500.500.20.10	345	450	A 992
2	Beam	WF.300.300.1.5.1	345	450	A 992

3. RESPONSE SPECTRUM AND GROUND MOTION

It is assumed that the building is located in the Parwan province of Afghanistan which has a high level of seismicity and ground acceleration. Seismic design categories based on design spectral response is D. The spectral acceleration at a short period of 0.2 second SS=1.4g and spectral acceleration at the period of 1 second S1=0.7g has been chosen according to the Afghan structure code. The design response spectrum is expressed according to ASC with 5% damping as follows [4],

$$S_a(T) = \begin{Bmatrix} \mathrm{S_{SD}}\left(0.4 + 0.6\frac{\mathrm{T}}{T}\right), & if\ T\ \leq T_0 \\ \mathrm{S_{SD}}\ , & if\ T_0 \leq T \leq T_s \\ \mathrm{S_{SD}}/T\ , & if\ \ T\ \leq T \end{Bmatrix}$$

4. ANALYSIS PROCEDURE AND RESULT

The analysis is conducted by Dynate software. Nonlinear static and dynamic type's analysis were performed [5]. In pushover analysis or nonlinear static analysis of the frame, two patterns of load and one pattern of displacement are considered. Firstly, the structure is loaded within its demand limits with 10 steps of vertical load and 100 steps of horizontal load both of which have magnitudes of 0.1 and 0.01 respectively. This loading is the same loading as the building is designed for and the response of the building is within its elastic range. Secondly, to find out the full capacity of the building, 200 steps of horizontal displacement in X direction with a magnitude of 0.1 cm at top of the structure is added to the vertical and horizontal loads. With the above-mentioned number of steps, the largest displacement that occurs at the top of the frame is within the allowable limit of displacement which was targeted and equal to H/100 based on Afghan structure code. From the result of pushover analysis Maximum story drift and story drift angle appear in the second, 3rd and 4th stories as shown in figure-3

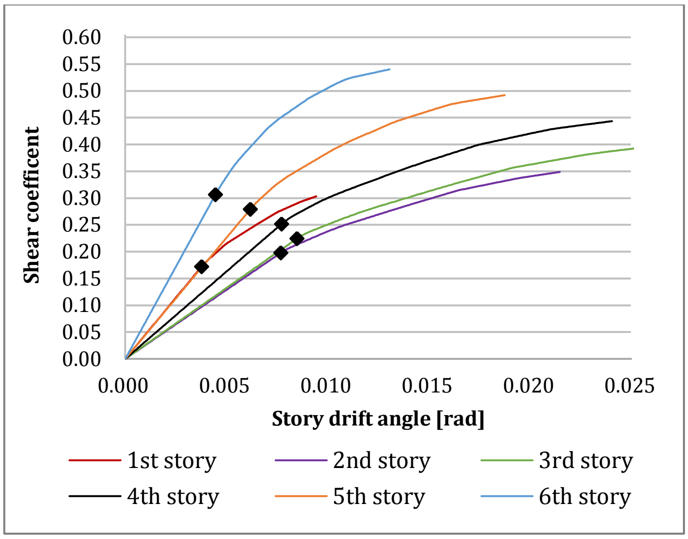

Fig-3: Relationship between shear coefficient and story drift angle

As a result, first plastic hinge appears for the second story with a displacement of 19.63 cm. When the load is gradually increased the yield appears for the 1st up to the 6th stories. In order to evaluate seismic performance, a dynamic response analysis was carried out for the simulated ground acceleration by having an intensity of 437.2972 cm/sec2 in the X direction. The result of simulated earthquake ground motion was used to the input of seismic loads for numerical analysis where the original data of ground motion input was EI Centro EW. A Newmark-β scheme with β=1/4 is used for numerical integration, and the time interval for response calculation Δt is 0.002s. The mass matrix of the structure is calculated by dividing the weight of each node to the gravitational acceleration. Further, the stiffness matrix of the structure is calculated by finite element method. The Raleigh damping matrix is adopted with 2%.

Table-2: Maximum response of building according to the dynamic response analysis.

Story	δ story [cm]	δ allowed [cm]	ϒ story [rad]	ϒ allowed [rad]	Stats
1	4.13	5	0.008	0.01	ok
2	8.38	5	0.017	0.01	not ok
3	8.57	5	0.017	0.01	not ok
4	7.12	5	0.014	0.01	not ok
5	5.87	5	0.012	0.01	not ok
6	4.44	5	0.009	0.01	ok

From the result of time history analysis as shown in Table-2, from the second up to 5th stories cross the allowable limits of story drift which was targeted. As a result, the maximum displacement of overall structure for simulated earthquake ground motion was around 34.14 cm; although the allowable limit of displacement for the structure which was targeted is 30cm. In order to decrease the story drift and overall maximum displacement, it is required to increase the horizontal stiffness of the structure by the installation of a passive device controlling system.

5. BUCKLING BRACING SYSTEM

In order to evaluate structure performance, an inverted V type buckling restrain brace has been selected as a passive device controlling system as shown in Figure-4.

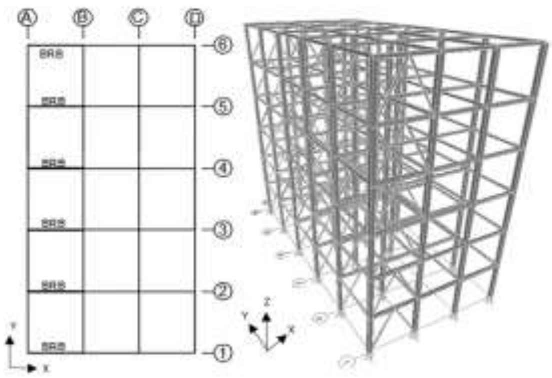

Fig-4: Location of inverted V type BRB in SMF building

The concept of a buckling restrained brace was developed in Japan at the end of the 1980's and was first used in the United States in 1999. Basically, the system has the suitable lateral stiffness to prevent relative drift due to lateral load impacts resulting from an earthquake. Meanwhile, a significant amount of kinetic energy is distributed into the structure and the level of damage sustained by the building depends on the dissipation of this energy. Therefore, the BRB system develops a balanced hysteresis loop when subjected to cyclic loading, with its compression yielding response similar to its tension yielding response. The system consists of four parts being the inner yielding steel core, mortar, debonding material, and surrounding steel tube. An inner yielding steel core, being the primary load-bearing component of the system, resists both tension and compression axial force subjected to the system by lateral forces [6].

In order to control the displacement and inter-story drift of a structure the section properties which were designed and selected for the steel core area of the buckling brace can be seen in Table-3.

Table-3: Properties of buckling bracing system

No	Description	Area cm2	Fy (Mpa)	Fu (Mpa)
1	1st -4th Stories	70	250	400
2	5th -6th Stories	30	250	400

From the result of pushover analysis first plastic hinge appears for the BRB of the second story where displacement reaches 13.25 cm. As load and displacement are gradually increased, plastic hinges appear for BRB in all stories except the 6th story. After BRB lost its capacity then the structure starts its performance. From the result of time history analysis,

inter-story drift, story drift angle and overall displacement of the structure is reduced up to the targeted allowable limit. On the other hand, due to horizontal stiffness, acceleration of the structure is increased. Table-4 describes that story drift and story drift angle are below the targeted allowable limit. Meanwhile, time period of the structure is reduced from 1.6 to 0.76 second.

Table-4 Maximum response of SMF building according to time history analysis

Story	δ story [cm]	δ allowed [cm]	ϒ story [rad]	ϒ allowed [rad]	Stats
1	1.75	5	0.004	0.01	ok
2	3.35	5	0.007	0.01	ok

3	3.64	5	0.007	0.01	ok
4	3.61	5	0.007	0.01	ok
5	4.24	5	0.008	0.01	ok
6	3.36	5	0.007	0.01	ok

6. BASE ISOLATION SYSTEM

The base isolation system is one of the most popular means of protecting a structure against earthquake forces. It is a collection of structural elements which should substantially decouple a superstructure from its substructure resting on a shaking ground [7].

Table-5: Properties of base isolation system

Outer diameter [mm]	1300	Total weigh [tonf]	3.01
Total rubber thickness [mm]	252	Compressive stiffness [kN/mm]	2.06E03
Total height [mm]	445.5	Equivalent shear stiffness [kN/m]	2.06E03
Critical stress [N/mm2]	52	Initial stiffness [kN/m]	12.2E03
Thick ness of reinforce steel plate [mm]	4.4	Equivalent damping ration	0.240

For decreasing the inter-story drift and high acceleration of special moment frame structure, a base isolation system was proposed. In order to fulfill the requirements specified on the IBC 2000 for Preliminary design, the time period for a basic earthquake level was assumed to be 2.5 seconds and for a maximum considered earthquake level was assumed to be 3 seconds. The type of base isolation system which was considered and chosen is a high damping rubber bearing with a post yielding stiffness of 10% (k2/k1). The properties of the designed base isolation system can be seen in Table 5.

Table-6 Maximum response of building according to the time history analysis.

Story	δ story [cm]	δ allowed [cm]	ϒ story [rad]	ϒ allowed [rad]	Stats
1	3.72	5	0.007	0.01	ok
2	4.21	5	0.008	0.01	ok
3	4.07	5	0.008	0.01	ok
4	3.56	5	0.007	0.01	ok
5	3.02	5	0.006	0.01	ok
6	2.37	5	0.005	0.01	ok

From the result of time history analysis, the time period of the structure is increased from 1.6 to 2.17 seconds. The maximum displacement of the structure at the base is 25.3 cm and at the top structure, it is 41.1cm. On the other hand, acceleration of the structure is reduced significantly which was the main and important characteristic of the base isolation system. With regard to story drift, all stories were within the targeted allowable limits as shown in Table-6.

7. Evaluation of maximum deformation by using the Capacity spectrum method

The capacity spectrum method [8] is a procedure that can be applied in performance-based seismic design. The purpose of performance-based seismic design is to give a realistic assessment of how a structure will perform when subjected to either particular or generalized earthquake ground motion. Essentially the procedure compares the capacity of the structure in the form of a capacity curve with the demand on the structure in the form of a demand spectrum curve. The graphical intersection of the two curves approximates the maximum responses of the structure due to the earthquake.

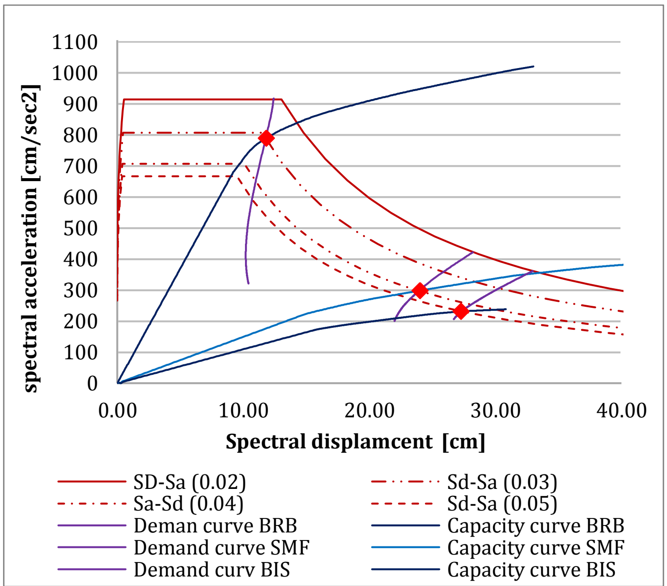

Fig-5: Demand curve and capacity curve in ADRS format

In order to find out the performance point of both systems, the multi-degree of freedom system has been changed (MODF) to the equivalent single degree of freedom (ESDOF) system. By installing the BRB system in the structure, the capacity of the building exceeds the demand. Meanwhile, the elastic strength of the structure is significantly increased. Both capacity curve and the demand curve structure intersect each other in nonlinear state or elastic plastic range. The maximum displacement of the structure in both the linear and nonlinear state is significantly reduced but the acceleration of structure is increased as shown in Figure-5. On the other hand, the structure with the base isolation system works in an opposite approach to that of the BRB system, instead of increasing the capacity it reduces the seismic demand of the structure. As a result, the capacity and the demand curve of the base-isolated structure intersect each other at the point where the maximum displacement of the structure is increased in both linear and nonlinear states. Considering the acceleration of the structure, it is completely reduced which mitigates the earthquake hazard.

8. Discussion

There are two primary mechanisms that cause structural and nonstructural damage. The first is related to inter-story drift between floors, and second-floor accelerations. From the result of time history analysis, both systems were really effective for controlling the inter-story drift as shown in the following Figure 6. The target limit for story drift is assumed to be h/100 as shown in the vertical line in mentioned figure.

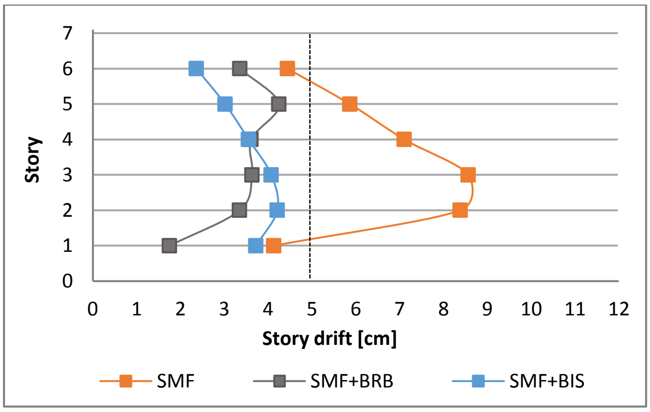

Fig-6: Story drift of SMF, BRB, and BIS system

On the other hand, considering the maximum displacement, special moment frame structure has 34.14 cm, structure with buckling bracing system has 19.2 cm and the base isolation structure has a displacement of 25.3 cm at the base and 41.1 cm at the top as shown in Figure 7.

Giving priority to the structure acceleration, the buckling bracing system has high acceleration at the top of the building which produces high resonance in the building but the structure with the base isolation system has less acceleration at the top but maximum acceleration at the bottom of the building as shown in the following Figure 8.

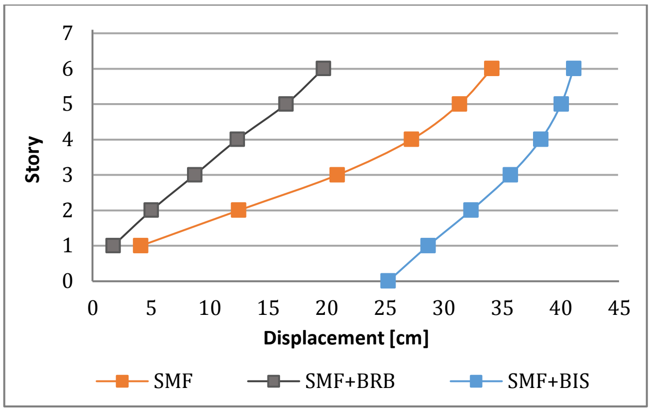

Fig-7: Maximum displacement of SMF, BRB, and BIS system

In addition, installation of both resistance systems for the SMF building was really effective and working perfectly in order to control lateral displacement of structure and story drift. But in the case of acceleration, the BRB structure has high acceleration due to the reduction of the time period. Comparing to the base isolation system, acceleration is very low mainly because of the long time period at the top of the building which has the ability to eliminate or reduce structure or non-structure damage in a significant manner.

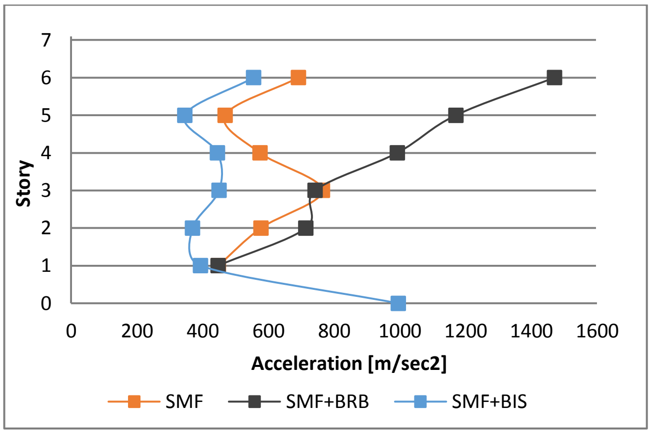

Fig-8: Story drift of SMF, BRB, and BIS system

9. Conclusion

In this research, the horizontal seismic capacity of a six stories special moment frame structure is increased based on two resistance systems; buckling-restrained brace (BRB) and base isolation system (BIS). The main purpose for installation of both systems is to control the primary mechanism of damage to the structural components such us horizontal displacement, inter-story drift and high acceleration. From the result of time history analysis, the BRB system is really effective for controlling the inter-story drift and maximum displacement of the structure but the acceleration of structure is increased due to high horizontal stiffness. In order to modify the demand on the structure by preventing or reducing the motions being transferred to the structure from foundations a base isolation system has been proposed. As the system works in an opposite approach to that of a BRB system, instead of increasing the capacity it reduces the seismic demand. The maximum displacement of the structure is increased in both linear and nonlinear states. On the other hand, acceleration of the structure reduced significantly which was the main and important characteristic of the base isolation system in order to mitigate earthquake damage.

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