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STRUCTURAL SEISMIC ISOLATION METHOD FOR SEISMIC PROTECTION OF HIGHLY RELIABLE STRUCTURES

A. A. Kasimzade(1), G. Atmaca(2), M. Kuruoglu(3), R. A. Mukimov(4), K. S. Pfidze(5)

(1) Professor, Department of Civil Engineering, Ondokuz Mayis University, Samsun 55100, Turkey, azer@omu.edu.tr
(2) Civil Engineer, Provincial Directorate of Disaster and Emergency, Samsun 55200, Turkey, gencayatmaca@hotmail.com
(3) Dr., Department of Civil Engineering, Dokuz Eylul University, İzmir 35160, Turkey, mehmet.kuruoglu@deu.edu.tr
(4) Chief Engineer, Azerbaijan National Academy of Sciences, Oil and Gas Institute, Baku, Azerbaijan, mukimov-rauf@mail.ru
(5) MSc Student, Department of Civil Engineering, Ondokuz MayisUniversity, Samsun, 55100, Turkey, kudakwashepfidze@gmail.com

Abstract

The aim of this study is to provide protection to Highly Reliable Structures (HRS)*1 from the effects of strong and long period ground motions by using the Structural Seismic Isolation Method (SSIM). The Conventional Application Method of Seismic Base Isolation Devices (CAMSBID) such as the use of LRB and LCRB does not solve the problem caused by effects of strong and long period ground motions on Highly Reliable Structures (HRS)*1.

In order to ensure that the structure does not resonate from the effects of long period ground motion and it's base moment will be less than that of a structure seismically isolated by the CAMSBID method, the structure was converted to a Structural Seismic Isolation System (SSIS) by using the SSIM method. The Structural Seismic Isolation System (SSIS) exhibited inverse pendulum behaviour. Using this method, the structure's foot base and foundation contact surface was generally designed as a curved surface (spherical, elliptical, etc.) dependant on the earthquake-soil-superstructure parameters with the contact surfaces separated by elastomeric bearings (i.e. laminated rubber bearings-LRB, lead core rubber bearing-LCRB etc.).

The dominant period of the SSIS system obtained by application of the SSIM method can be set above the ground motion period (i.e. above 11 seconds) of long period earthquakes. In contrast structures seismically isolated by the CAMSBID method (i.e. with LRB, LCRB etc) are usually isolated for periods of ground motion of up to 4 seconds. If required, various other seismic isolation devices and systems (SID) such as lead core rubber bearing (LCRB), friction pendulum isolation (FPI) devices, dampers, active control systems, etc. can be used to keep the response of SSIS system under control. The benefits offered by the SSIS system under these conditions in comparison to the structures seismically isolated by the CAMSBID method are that the structure does not resonate, structural element cross-sections and building mass decrease, column openings and building height increase in proportion to the decrease of the building base moment.

The SSIS system's performance for the Highly Reliable Structures (HRS)*1 was compared to a structure seismically isolated by the CAMSBID method with LRB, LCRB used as base isolation devices in both instances. The top, base accelerations, base shear and base moment responses of the SSIS building structure were 23.24% , 63.74% and 77.50% on average lower than CAMSBID building structure respectively. It is also shown that the application of the SSIM method results in significantly lower response of the structure which leads to the possibility of designing lighter structures. The ratio of the substructure depth (hf) to superstructure height which is about Hs/hf = 3-13.62 in existing high-rise buildings is thus effectively and economically utilised.

Another important point is that, the application of the SSIM method, allows the efficient use of today's manufactured seismic isolation devices (LRB, LCRB) which have periods of up to 4 seconds. The objective of the research is to prove the earthquake-resistance of HRS*1 structures seismically isolated through the implementation of the SSIM method, which exhibits inverse pendulum behaviour thus reaching a high level of reliability.

Keywords: Structural Seismic Isolation Method-SSIM; Strong and Long-period earthquake; FE modeling by LS-DYNA

Note*1: The SSIM method presented in this study is aimed at protecting Highly Reliable Structures (HRS) from the effects of strong and long period ground motions. Highly Reliable Structures (HRS) are classified as follows:

1) Nuclear Containment Structures; 2) High-rise buildings that contain information, operating systems, sensitive instruments, communication systems, routing systems, bank operating systems, data bases, management systems and other such features that are linked to the security and economy of the country; 3) High-rise hospitals etc.

1. Introduction

Seismic isolation separates the structure from the harmful motions of the ground by providing the flexibility and energy dissipation capability through the insertion of isolation devices, called isolators, between the foundation and the superstructure. Conventional Application Method of the Seismic Base Isolation Devices for Building (CAMSBID-Bg) leads to the shifting of the superstructure's dominant period. The seismic base isolation device's dominant period becomes the superstructure's dominant period, which in the available isolation devices is about 2-4 seconds. Therefore, the acceleration of the superstructure is significantly reduced in comparison to the earthquake acceleration. Several reports indicate the vulnerability of base-isolated structures against near-fault pulse and long-period earthquakes (i.e. earthquakes with a dominant period of more than 2-4 seconds). For instance, during the 2011 Tohoku earthquake in Japan seismically isolated buildings suffered serious damages to their seismic isolation layers due to large displacements. In other words, in CAMSBID-Bg structures, the resonance of the upper structure is inevitable under long-period earthquakes (more than 2-4 second). This leads to structural damage and rendering the structure out of service.

There are several studies on enhancing the performance of seismic base-isolated structures against near-fault and far-source long-period earthquakes. However, these studies include solutions for specific situations and are difficult to generalize like conventional seismic isolation methods (CAMSBID).

Kasimzade et al. [1, 2, 3, 4] proposed and developed new Structural Seismic Isolation Method (SSIM) for protection of structures against strong and long-period ground motions. This method aims to eliminate the limitation and vulnerability of the conventional elastomeric (lead rubber or laminated rubber bearing) base-isolated structures [5]. On the bases of this method, the structure in this study is converted to a Structural Seismic Isolation System (SSIS) by the SSIM method thus exhibiting inverse pendulum behaviour. SSIS system provides the possibility of keeping the natural-period of the structure in a larger interval, which is greater than the predominant-period of most earthquakes (including near-fault pulse) using currently existing conventional elastomeric isolators that have a period of up to 4 seconds. SSIS system developed by the SSIM method do not cause resonant vibrations under long-period earthquakes.

Using the SSIM method to seismically protect structures was found to be an original idea and a patent application was made [4]. Detailed applications and performance of the new Structural Seismic Isolation Method (SSIM) for the high-rise building structures (SSIS-Bg) and for the nuclear containment structures (SSIS-NC) was researched by Kasimzade et al. [6, 7]. Results indicate that the base and top accelerations, base shear, and base moment responses of the SSIS-Bg structure is 23.21%, 75.47% and 85.74% on average lower than the structures that use the Conventional Application Method of Seismic Base Isolation Devices for Building (CAMSBID-Bg) respectively. SSIS-Bg structures are not prone to resonant vibrations under long-period earthquakes which result in excessive deformation in the isolation layers as is with the case of using CAMSBID-Bg structures. According to Kasimzade et al. [7] in relation to containment structures the base and top accelerations, effective stress and critical shear stress responses of the SSIS-NC structure are 48.67 %, 36.70% and 32.60% on average lower than CAMSBID-NC structures respectively. The result also confirms that the SSIS-NC structure did not cause resonant vibrations under long-period earthquakes. On the other hand, there is excessive deformation in the isolation layers of CAMSBID-NC structure.

In this study, the dynamic performance of a a high-rise steel building under 3 scenarios is incestigated. The SSIM method was applied to the high-rise steel building to form a SSIS system (SSIS-Bg) this was then compared with the conventional application method of the seismic base isolation devices for the building (CAMSBID-Bg) and a fixed base building (FB-Bg) using finite element simulation under the world's strongest - Tohoku earthquake.

2. Fundamentals and Advantages of SSIM Method

As mentioned, Structural Seismic Isolation Method (SSIM) aims to provide high safety for Highly Reliable Structures (HRS) against strong earthquakes including near-fault and long-period ground motions. Using the

SSIM method Highly Reliable Structures (HRS) can be converted to a Structural Seismic Isolation System (SSIS) which exhibits inverse pendulum behaviour. Using the proposed method the structure's foot base (Fig.1a, part 2) and foundation contact surfaces (Fig.1a, part 4) can be designed as any curved surface (spherical, elliptical, etc) depending on the earthquake-soil-superstructure parameters. The contact surfaces are separated by elastomeric seismic isolation devices (lead core rubber or laminated rubber bearings) (Fig.1a, part 3). This allows the structure's foot base to turn around the gyration centre through contact with the rubber bearings and maintain similar behaviour to the superstructure (Fig.1a, part 1). SSIS systems provide the possibility of providing a larger interval for the natural-period of the structure, which is usually greater than the predominant-period of most earthquakes (including near-fault pulse) using available conventional elastomeric isolators with periods of up to 4 second. In the case of using the CAMSBID-Bg structure (Fig.1c), superstructure's vibration dominant period will be approximately equal to the elastomeric isolator's dominant period (2-4 second). CAMSBID-Bg structures are prone to resonant vibrations under long-period earthquakes resulting in excessive deformation in the isolation layers. Consequently, CAMSBID-Bg structures are vulnerable under near-fault and long-period ground motions. Due to this problem, the conventional application of the currently available seismic base isolation elastomeric devices is limited. SSIS systems provide the opportunity of controlled rotation to the superstructure resulting in less bending moment and shear force formation in the superstructure base, in comparison with CAMSBID-Bg structures.

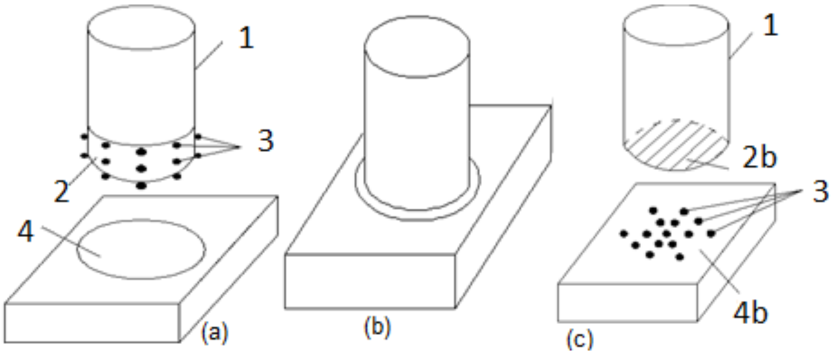


Fig. 1 – Schematic illustration of the SSIS system obtained by SSIM method (a) and completed SSIS-Bg structure (b) and CAMSBID-Bg structure (c): 1- Superstructure, 2- Curved surface superstructure foot base, 3- Elastomeric seismic isolation devices, 4- Foundation contact curved surface, 2b- Plane surface CAMSBID-Bg superstructure foot base, 4b- Foundation contact plane surface of CAMSBID-Bg structure [4,6]

The major advantages of SSIS system obtained by using the SSIM method over the CAMSBID method and other methods can be noted as follows:

- SSIS systems are applicable for highly reliable structures including high-rise buildings while the majority of studies focus on low-rise or medium-rise structures.
- Some of the seismic isolation methods require extra energy to function which may be inconvenient in some cases. On the other hand, the SSIS system is a totally passive seismic isolation system which does not require any extra energy to function.
- The usage of friction pendulum isolator for the purpose of seismic isolation could be problematic due to stick-slip and non-uniform pressure distribution of the pendulum on steel plate, while the SSIS system uses elastomeric isolators.
- SSIS system is more reliable than CAMSBID-Bg systems under the effect of long-period and near-fault earthquakes due to the fact that the period of seismic isolators used in CAMSBID-Bg structures is between 2-4 seconds. The SSIS system does not cause resonant vibrations despite the fact the SSIS system's period is much higher thanks to the rotating gyration center.

The governing equation, the mathematical model of the SSIS system and assessment of the SSIS-Bg structure was carried out using MATLAB and Simulink programming tools by Kasimzade et al. [1, 2, 3], Kasimzade [8] and the summary of the work is presented in the following section.

3. Assessment of SSIS System for High-Rice Building Structure

A numerical verification of the SSIS -Bg structure is presented with an example of 26 storey steel framed structure. For comparability, the storey height, column spacing of the SSIS-Bg, FB-Bg and CAMSBID-Bg structures were considered as the same including an equal total mass of 3.04894E+7 kg as presented by Kasimzade et al. [3]. Pre-sizing of the SSIS-Bg (26-storey, 104 m), CAMSBID-Bg (24-storey, 96 m) and FB-Bg (24-storey, 96 m) steel superstructures were designed so that the maximum story angle is lower than 1/200. A steel grade of SN-490 (with 357.0 MPa yield strength) is used for the superstructure members and reinforced concrete is used for the base as shown in Table 1. Total floor load (per meter square) containing the dead load of the columns and beams is 7840.0 N/m^2. Storey height, column spacing are accepted 4 m, 8 m respectively. Pre-sizing results for beams and columns were presented in Table 2. The floor mass distribution for FB-Bg, CAMSBID-Bg and SSIS-Bg structures are presented by Kasimzade et al. [3]. The total superstructure mass is given as follows:

($M_{totalsuperstore}$) of CAMSBID-Bg and FB-Bg is presented according to the total mass of SSIS-Bg as following:

$$M_{totalsuperstore(FB\text{-}Bg\&CAMSBID\text{-}Bg)} = M_{total(SSIS\text{-}Bg)} - M_{IsolationLayer(CAMSBID\text{-}Bg)} \tag{1}$$

$$(3.17750E + 7 - 0.12858E + 7)\ \text{kg} = 3.04894E + 7\ \text{kg} \tag{2}$$

Table 1 – Material properties of steel for superstructure and reinforced concrete for the base part of SSIS-Bg

Material properties	**Steel**	**Reinforced concrete**
Elasticity modulus[N/m^2]	2.05E + 11	3.80E+10
Density [kg/m^3]	7860	2400
Poisson's ratio	0.3	0.2

Table 2 – The dimension of the storey column and beams

Stories	**Column (box-section)**		**Beam (I-section)**			
	width x breadth [m]	**Thickness [m]**	**H* [m]**	**W [m]**	**FT [m]**	**WT [m]**
1-10th	0.8x0.8	0.02	0.8	0.3	0.03	0.015
11-20th	0.65x0.65	0.016	0.8	0.3	0.03	0.015
21-26th	0.47x0.47	0.012	0.8	0.3	0.03	0.015

* H (Height), W (Flange width), FT (Flange thickness) and WT (Web thickness)

Assuming that the predominant period of the earthquakes in the area where FB-Bg, CAMSBID-Bg and SSIS-Bg structures will be built is about 11 s . The required total elastomeric isolator horizontal stiffness for the first approximation for the SSIS system in case of free vibration is equal to $k_b = 8.2455E + 7$ N/m according to Kasimzade et al. [3]. Other parameters of the elastomeric isolator such as period, damping coefficient and damping ratio were defined as $T_b = 4$ s, $c_b = 1.5182E + 7$ Ns/m^2, $\xi_b = 0.15$ respectively.

Based on the above parameters of the SSIS-Bg structure and using governing equations for SSIS system from the previous section, the SSIS-Bg structure's performance was preliminary assessed using the

Tohoku 2011 Earthquake's Y-direction acceleration as the excitation and it was observed that the acceleration in the SSIS-Bg structure's base was significantly (about four times) reduced. Based on the preliminary design parameters and assessments results presented in this section, a comparative and detailed finite element modelling of the SSIS-Bg, FB-Bg and CAMSBID-Bg structures was performed in the following section.

4. Finite Element Structural Model of Steel Building with SSIS system

Finite element modelling of the steel building with the SSIS system has been prepared in the LS-DYNA software, tetrahedron solid, beam and isolator link finite elements were used (Fig.2). The material properties, section properties, and mass distribution of the finite elements as presented by Kasimzade et al. [3] are in shown in Table 1 and Table 2 respectively. The isolator links (discrete beam isolator) are modelled based on bi-directional coupled plasticity theory and the finite element parameter definitions, pre-sizing and finalization design results are based on appropriate design codes. The Tohoku earthquake spectrum, was presented in the Table 3. The positions of seismic isolators in the SSIS–Bg structure are shown in Fig.2.

Table 3 – Properties of seismic LCRB isolators for SSIS-Bg and CAMSBID-Bg structures

Parameters	SSIS-Bg	CAMSBID-Bg
K_v (Vertical stiffness) [N/m]	2.2800E + 09	2.8330E + 09
F_y (Yield force) [N]	4.550E + 05	6.520E + 05
K_h (Horizontal stiffness)	1.560E + 06	2.230E + 06
Damping ratio [%]	1.50E - 01	1.50E - 01
u_y (Yield displacement) [m]	4.50E - 02	4.50E - 02
Φ (Diameter) [m]	9.70E - 01	9.70E - 01
R_T (Rubber thickness) [m]	5.00E - 01	5.00E -01
Number of Isolators	53	37

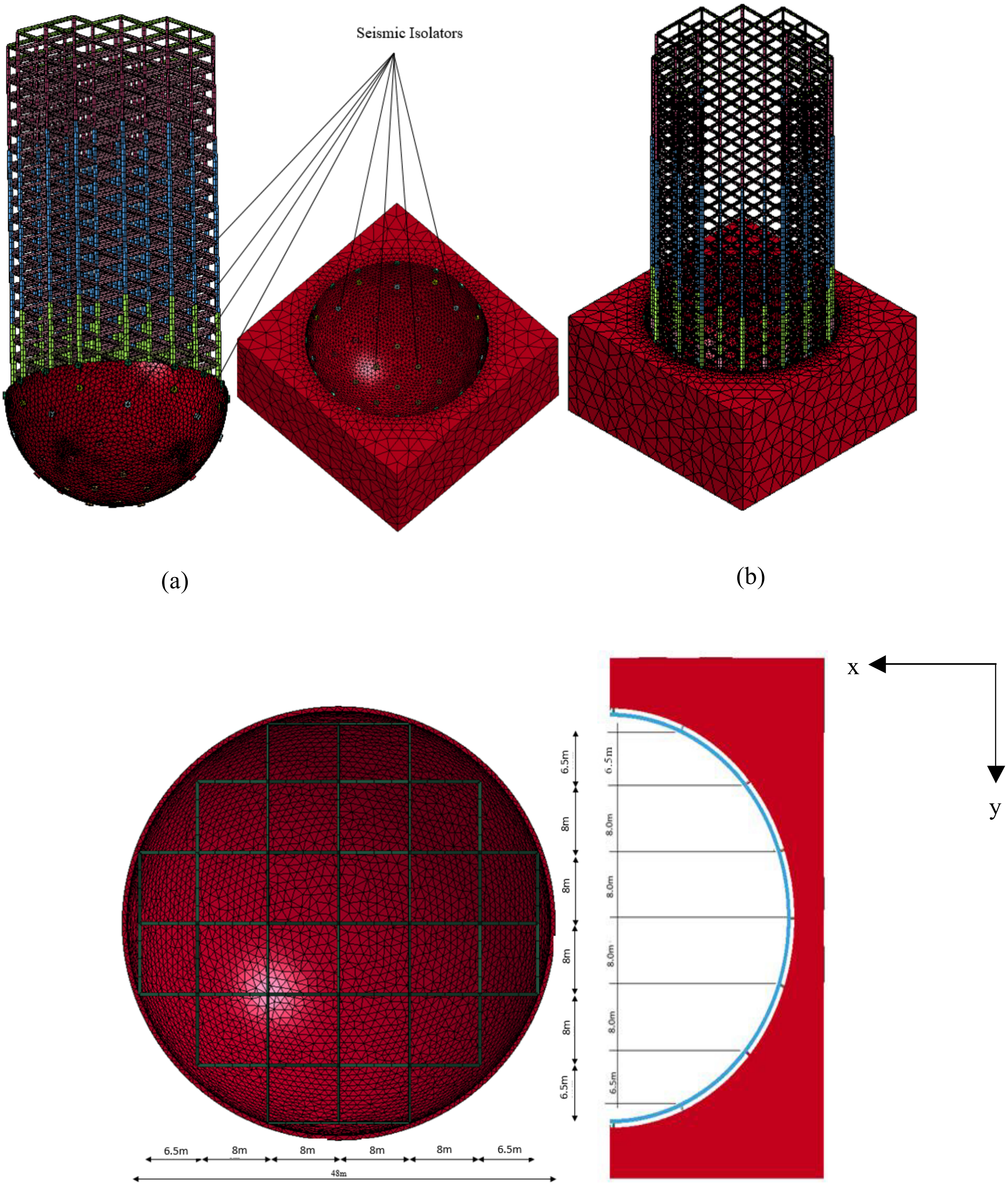
5. Numerical Study

Nonlinear dynamic analysis of the presented finite element model (Fig.2) has been analysed using world's strongest - Tohoku earthquake excitation. General characteristics of this earthquake are presented in Table 4. Time-history data of the ground motions are obtained from PEER Berkeley Strong Ground Motion database.

Table 4 – Tohoku earthquake ground motion characteristics

Earthquake	Year	Station	PGA-X	PGA-Y	Type
Tohoku	2011	FKS012	8.31	9.31	Near fault

The dynamic analyses of SSIS-Bg, CAMSBID-Bg and FB-Bg structures are conducted using LS-DYNA explicit solver in the high-speed computers of 12 CPU cores with 18 GBs of RAM. Total CPU time for each analysis are 21 hours 47 minutes 30 second, 28 hours 31 minutes 9 second, and 32 hours 16 minutes 20 second respectively. Base, top, base shear and base moment responses SSIS-Bg, CAMSBID-Bg and FB-Bg structures under effect of 2011 Tohoku earthquake is provided in Fig. 3-7.



(a)

(b)

(c)

Fig. 2 – The positions of deployed seismic isolators in SSIS–Bg structure (a), the overall view and illustration of the finite element model of 26 storey structure SSIS-Bg equipped with SSIS system (b), and the general floor plan including the position of isolators of the structure (c)

6. Results and discussion

As presented in Fig.3 and Fig.4 the base and top acceleration response for SSIS-Bg is tangibly lower than CAMSBID-Bg and FB-Bg structure in both X and Y directions. The top storey displacements of SSIS-Bg and CAMSBID-Bg are lower than FB-Bg structure while being alike as shown in Fig.5.

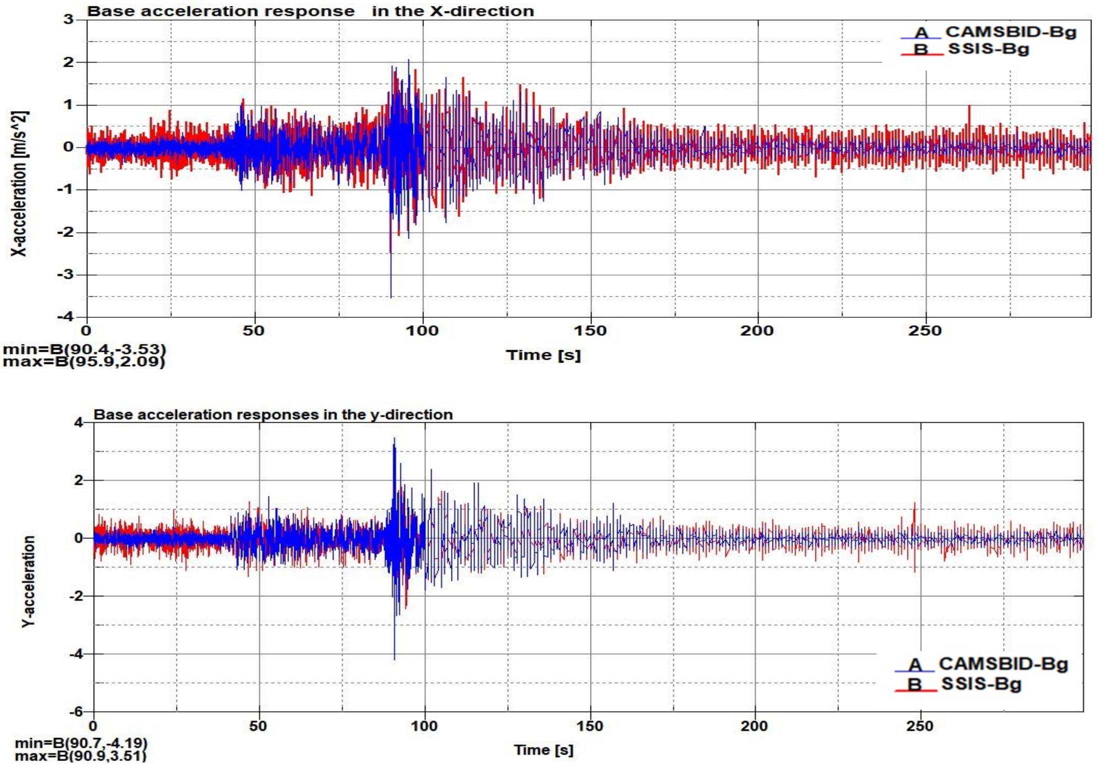


Fig. 3 – Base acceleration response of SSIS-Bg and CAMSBID-Bg structures in X and Y directions

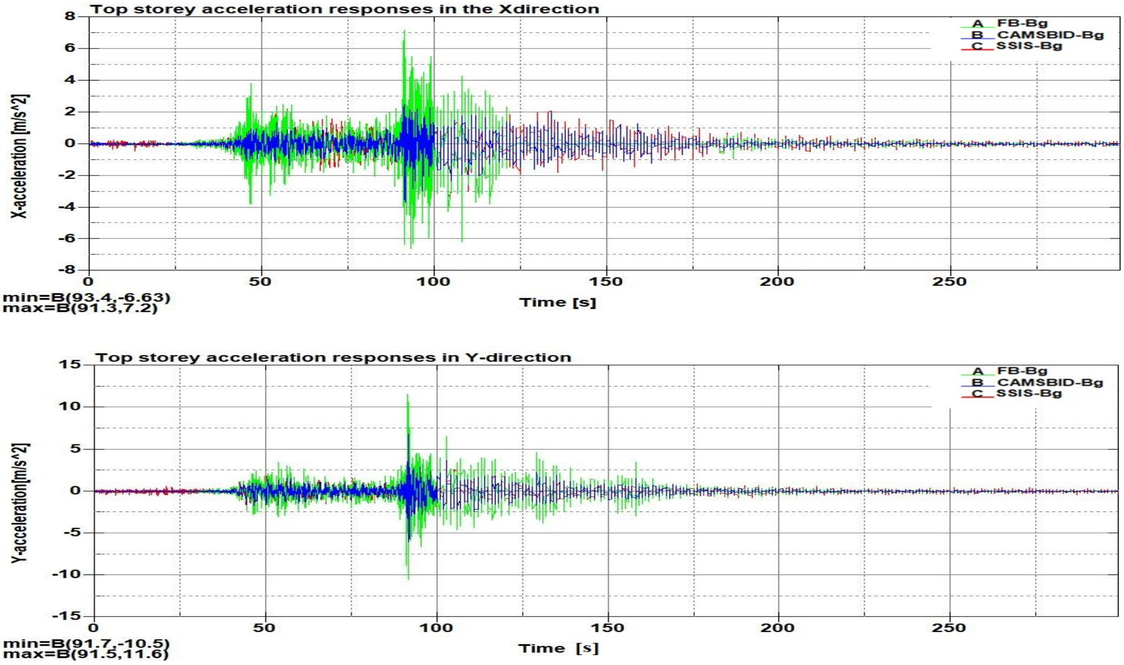


Fig. 4 – Top storey acceleration response of SSIS-Bg, CAMSBID-Bg and FB-Bg in X and Y directions

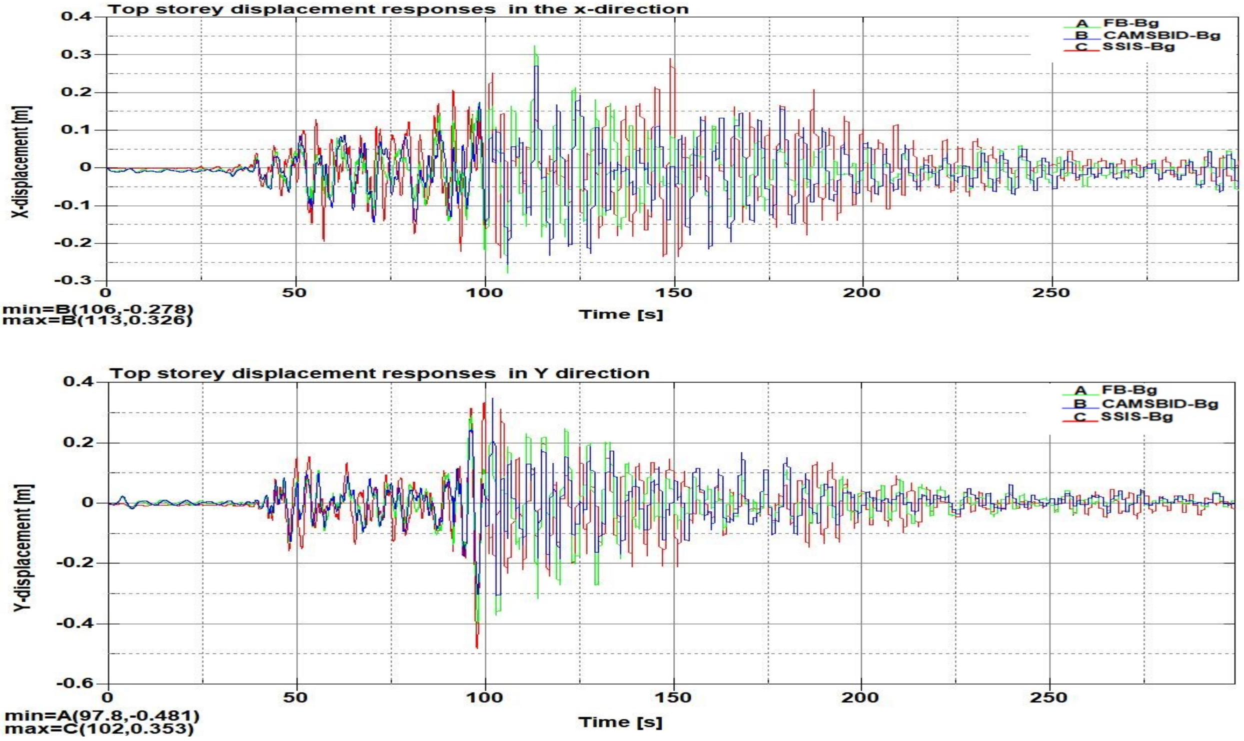


Fig. 5 – Top storey displacement response of SSIS-Bg, CAMSBID-Bg and FB-Bg in X and Y directions

While the acceleration response of SSIS-Bg is considerably lower than the CAMSBID-Bg and FB-Bg structures, the reduction of the base shear and base moment response of SSIS-Bg is significantly lower than CAMSBID-Bg and FB-Bg structures as well. It is achieved due to turning effect of the gyration centre of the SSIS-Bg structure. The base shear and base moment responses of SSIS-Bg, CAMSBID-Bg and FB-Bg structures due to the effect of the 2011 Tohoku earthquake are presented in Fig.6 and Fig.7.

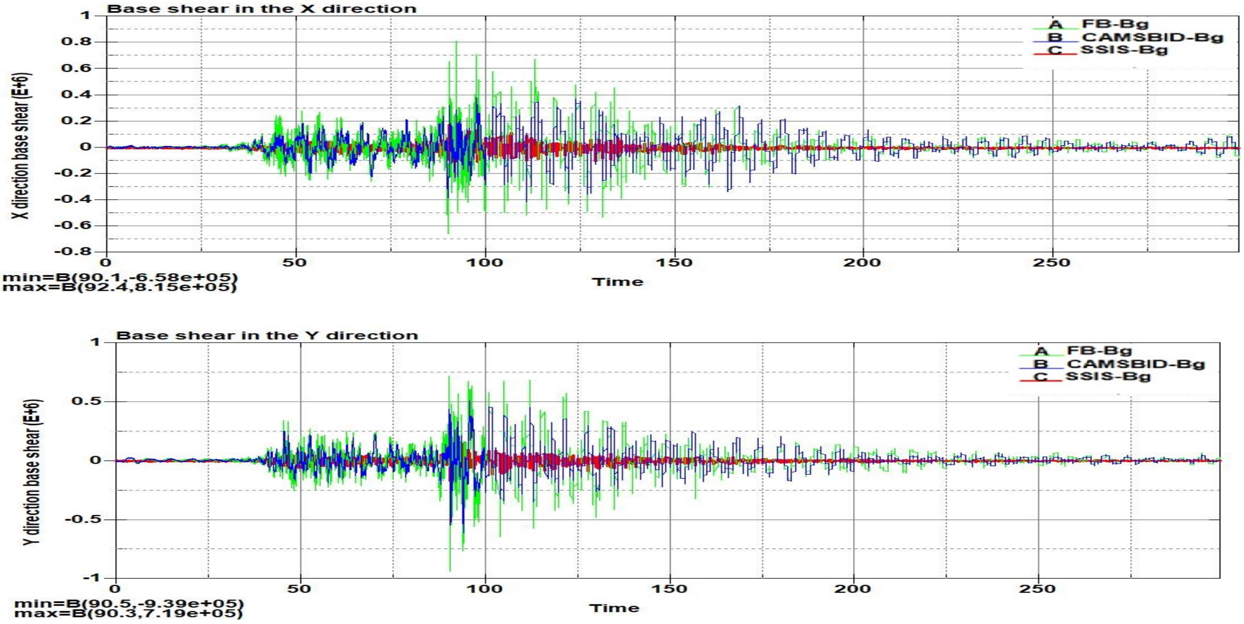


Fig. 6 – Base shear response of SSIS-Bg, CAMSBID-Bg and FB-Bg structures in X and Y directions

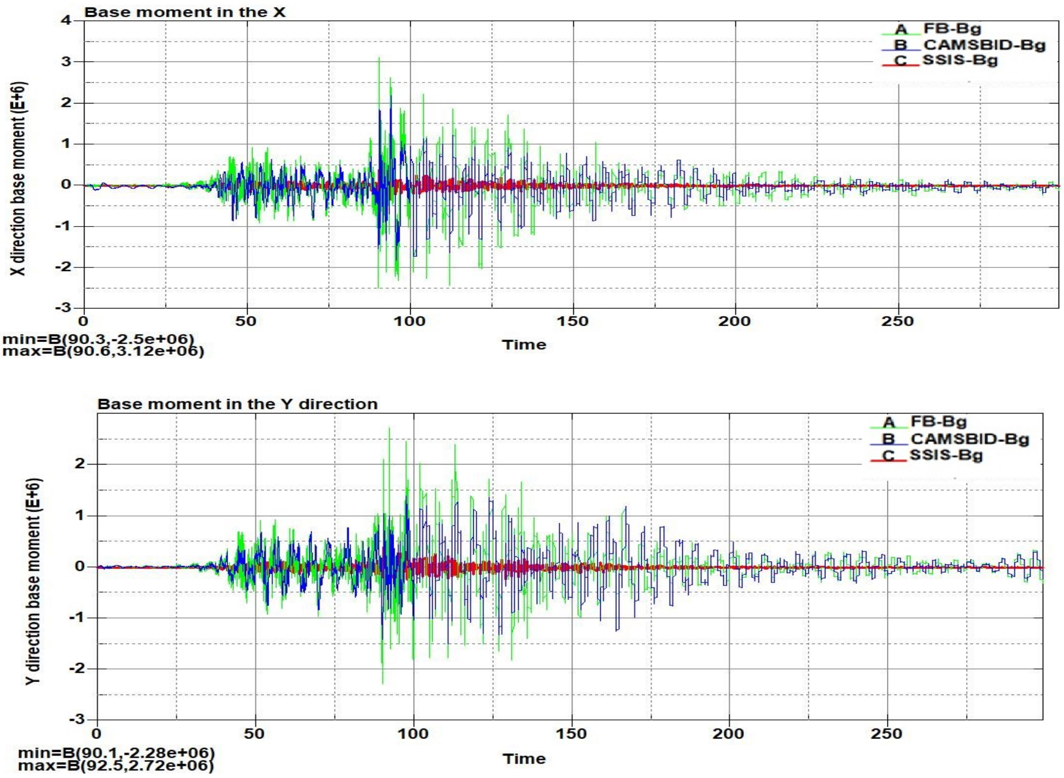
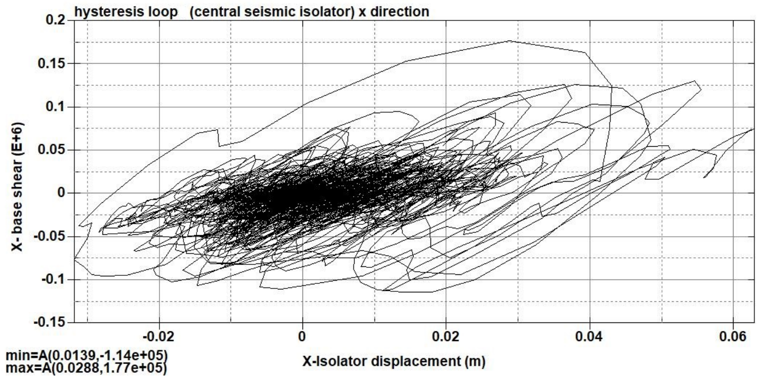
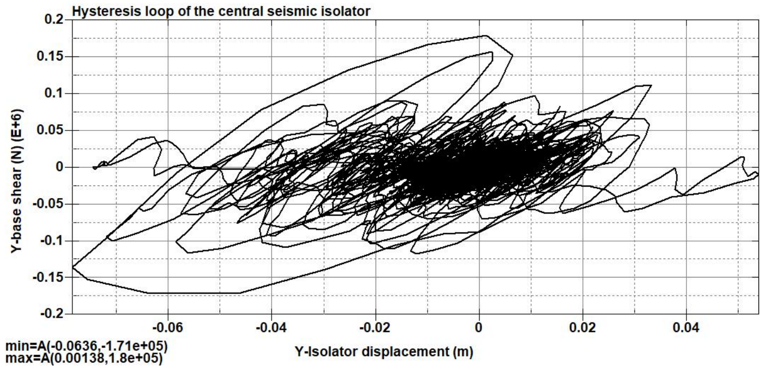


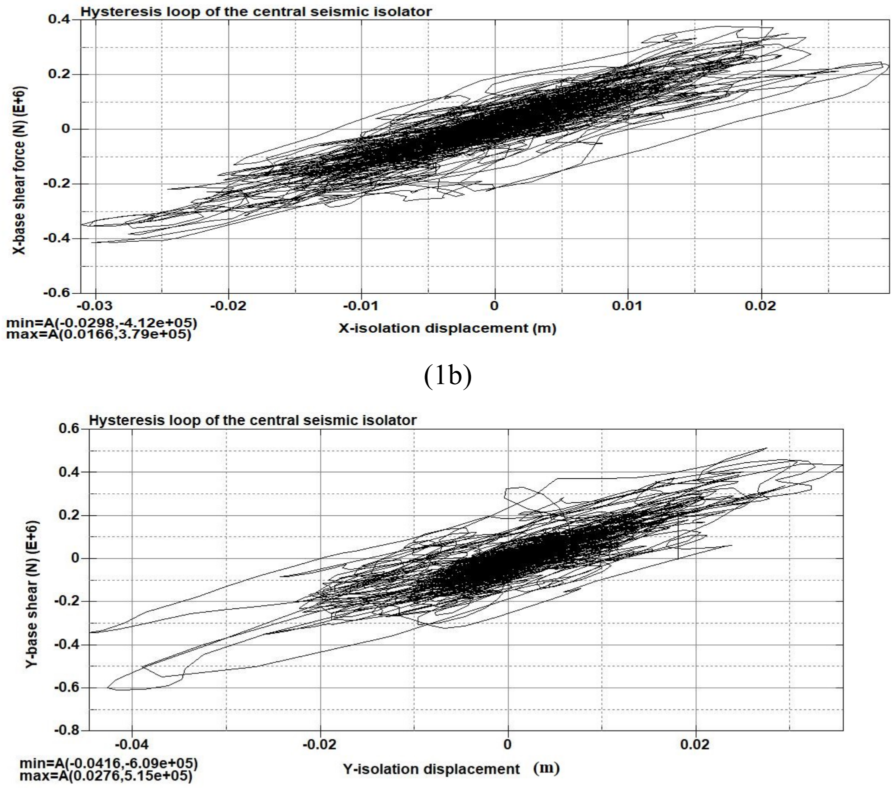
Fig. 7 – Base moment response of SSIS-Bg, CAMSBID-Bg and FB-Bg structures in X and Y directions respectively



(1a)



(2a)



(1b)

(2b)

Fig. 8 – Comparison of the hysteresis loops of the central seismic isolator of SSIS-Bg (1a and 2a), CAMSBID-Bg (1b and 2b) structures

All peak top acceleration, top displacement (Table 5), base shear and base moment responses (Table 6), base acceleration, base displacement (Table 7) of SSIS-Bg, CAMSBID-Bg and FB-Bg are presented as follows.

Table 5 – Top level acceleration and displacement peak responses of SSIS-Bg, CAMSBID-Bg and FB-Bg structures

Ground Motions	**X-direction**						**Y-direction**					
	Top storey acc. [m/s^2]			**Top storey disp. [m]**			**Top storey acc. [m/s^2]**			**Top storey disp. [m]**		
	SSIS-Bg	**CAMSBID-Bg**	**FB-Bg**	**SSIS-Bg**	**CAMSBID-Bg**	**FB-Bg**	**SSIS-Bg**	**CAMSBID-Bg**	**FB-Bg**	**SSIS-Bg**	**CAMSBID-Bg**	**FB-Bg**
Tohoku	3.85	3.68	7.2	0.29	0.27	0.32	5.16	6.8	11.6	0.48	0.35	0.39

Table 6 – Base shear and base moment peak responses of SSIS-Bg, CAMSBID-Bg and FB-Bg structures

Ground Motions	X-direction						Y-direction					
	Base shear [N] x 10^5			Base mom. [N.m] x 10^5			Base shear [N] x 10^5			Base mom. [N.m] x10^5		
	SSIS-Bg	CAMSBID-Bg	FB-Bg	SSIS-Bg	CAMSBID-Bg	FB-Bg	SSIS-Bg	CAMSBID-Bg	FB-Bg	SSIS-Bg	CAMSBID-Bg	FB-Bg
Tohoku	1.77	4.12	8.15	4.06	21.9	31.2	1.8	6.09	9.39	3.97	15	27.2

Table 7 - Base level acceleration and displacement responses of SSIS-Bg, CAMSBID-Bg

Ground Motions	X-direction				Y-direction			
	Base acc. [m/s^2]		Base disp. [m]		Base acc. [m/s^2]		Base disp. [m]	
	SSIS-Bg	CAMSBID-Bg	SSIS-Bg	CAMSBID-Bg	SSIS-Bg	CAMSBID-Bg	SSIS-Bg	CAMSBID-Bg
Tohoku	2.46	3.53	0.13	0.09	2.77	4.19	0.16	0.17

The base acceleration response of the SSIS-Bg structure is 30.31% and 33.89% lower than the CAMSBID-Bg structure in X and Y directions respectively as shown in Table 7. Similarly, there was 4.62% and 24.12% difference between the top storey acceleration response of the SSIS-Bg and CAMSBID-Bg structures as shown in Table 5. The response of FB-Bg structure clearly indicates the extreme vulnerability of fixed base structures under effect of strong and long-period earthquakes.

While the acceleration response of the SSIS-Bg structure is considerably lower compared to CAMSBID-Bg and FB-Bg structures, there is a tremendous difference between base shear and base moment responses of the SSIS-Bg, CAMSBID-Bg and FB-Bg structures. As presented in Table 6 the base shear response of SSIS-Bg structure is 57.04% and 70.44% lower than CAMSBID-Bg structure in X and Y directions respectively. On the other hand, higher differences are observed between the base moment response of SSIS-Bg and CAMSBID-Bg structures which are 81.46% and 73.53% in X and Y directions respectively (Table 6).

8. Conclusions

The SSIS system obtained by the SSIM method for the seismic isolation of building structures (SSIS-Bg) has shown the following when compared with the conventional application method of seismic base isolation devices for building (CAMSBID-Bg) structures presented by Naeim and Kelly [9] and fixed base building structures (FB-Bg):

- Due to the fact that the SSIS systems provide the opportunity of controlled rotation to the superstructure, bending moment and shear forces formed in the SSIS-Bg superstructure base was less in comparison with those formed in the CAMSBID-Bg structures.The base, top accelerations, base shear and base moment responses of the SSIS-Bg structure were 23.24% , 63.74% and 77.50% on average lower than CAMSBID-Bg structure respectively.
- The SSIS-Bg structure is not prone to resonant vibrations under long-period earthquakes that is usually related to the excessive deformation in the isolation layers.
- The significantly lower response of the SSIS-Bg structure compared with CAMSBID-Bg and FB-Bg structures can lead to the design of an even lighter structure (in this study approximately the same total

mass was used for SSIS-Bg, CAMSBID-Bg, FB-Bg structures only for comparability of the responses);

- Generally, in CAMSBID-Bg and FB-Bg high-rise buildings, approximately 1/3.1 -1/13.62 of the height of the superstructures mostly is considered as foundation. Hence, a considerable part of the structure cannot be used effectively. On the other hand, in CAMSBID-Bg system besides the feasibility of the usage of the underground part, all the mentioned system will be included in a curved surface foundation. Thus, in terms of total useful area of the buildings, the SSIS-Bg is much more efficient than CAMSBID-Bg and FB-Bg structures.
- SSIS system allows the efficient use of today's manufactured seismic protection devices (LRB, LCRB, etc.). As shown in this study, structures with the conventional application of the seismic base isolation devices for Building (CAMSBID-Bg) are vulnerable under long-period earthquake excitation.

In Summary, the application of structural seismic protection SSIS systems obtained by using the SSIM method on highly reliable structures as presented in this research solves certain known shortcomings of the conventional application of the seismic base isolation devices thus making it an attractive and very productive option. The feasibility of the usage of the SSIM method is not limited to high-rise buildings, it could be used as a seismic protection system for other important structures such as nuclear power plants, offshore oil platform, high-rise hospitals etc.The feasibility of the usage structure foot base and foundation contact curved surfaces' types (spherical, elliptical, etc.) depends on the earthquake-soil-superstructure parameters is the subject of future research.

9. Acknowledgements

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