



Retrofitting Existing Masonry Structures by Using Seismic Base Isolation System

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Abstract

Historical masonry structures are the most important features that distinguish our cultural heritage, from here comes the importance of protection this type of masonry structures from collapse under earthquakes effect or other dynamic loading such as blast loading. Therefore, Seismic Base Isolation is used to reduce earthquakes damages and protect structures from collapse. This paper aims to study the Effect of Seismic Base Isolation, using High Damping Rubber Bearing (HDRB) on Existing Masonry Structures subjected to dynamic loads such as earthquakes, through utilizing numerical modeling of masonry structures. This paper includes definition of seismic base isolation mechanical characteristics, and definition of numerical modeling approaches for structural masonry analysis. The studied masonry structure is the old AWQAF Directorate Building in Aleppo, which is islamic government building affiliated to the Syrian Ministry of AWQAF; In order to perform the numerical modeling, equivalent masonry properties used for this structure were also determined. This structure was analyzed applying nonlinear dynamic analysis-time history method, and reanalyzing it by using seismic base isolation, type HDRB applying the same method. The results of the two analyses were discussed and compared, and the conclusions of this paper showed reduction in shear force when using seismic base isolation, and reduction in stresses that appear in structure because the stresses are located in the level of base isolation system.

Keywords Numerical modeling · Masonry structures · Heritage structures · Dynamic analysis · Isolated structure · Hysteresis loops

1 Introduction

Seismic base isolation systems are considered one of the most important techniques that be used to design seismic resistant structures, and retrofitting existing structures to resist earthquakes, because they reduce the damages of earthquakes and protect structures from collapse.

Historic/heritage structures made of masonry are subjected to process of degradation with time, earthquakes constitute a significant cause of degradation. The seismic assessment and retrofitting of heritage structures has become an issue of great importance around the world today. Therefore, the importance of retrofitting this type of structures is vital in order to preserve our architectural heritage [1].

The aim of this paper is retrofitting existing masonry structures that are not designed to resist seismic loads, to resist these loads by using seismic base isolation system, as a result the ground beneath the building can move without transmitting these motions into the structure, therefore reducing its deformations and stresses [2].

Some types of Seismic base isolation systems are High Damping Rubber Bearing, HDRB, is only composed of rubber and steel shims, and it possesses necessary flexibility as well as energy-dissipation capabilities [3].

Several studies have been done for masonry and heritage structures under the effect of earthquakes, where researcher Jäger et al. (2009) did research at the University of Dresden in Germany. In this research, Takiyya Sulaymaniyah Mosque in Damascus was modeled using the LS-DYNA program to study the behavior of the heritage masonry structure under the effect of earthquakes, and each calculation was performed using parallel 40 Intel Itanium processors “SGI Altix 4700” at the center of High-Performance Computing of TU-Dresden. The calculation for the model was carried out along 7 days

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for only 20 s of loading. The results of the analysis showed the collapse of the portico and parts of the structure; hence, the importance of providing this type of important structures with seismic base isolation system to protect these structures from collapse [4].

And there are many studies in masonry structures under the effect of earthquakes in Syrian Arab Republic such as the research in 2007 of the minaret of Great Umayyad Mosque in Aleppo which was subjected to severe atmospheric conditions and many strong earthquakes. The recent one occurred near Aleppo was on 13/8/1822 with magnitude of 7.4 on Richter scale, and the other one was on 3/4/1872 with magnitude of 7.2 on Richter scale. These earthquakes had major effects on the minaret such as tilting, twisting, in addition to longitudinal and horizontal cracks in the inner and outer walls of the minaret [5].

Another research was done about a minaret of the ADILIYA Mosque in 2018 in Aleppo which was also subjected to earthquakes; in addition to damages due to wars [6], the study showed that the stresses exceeded the allowed stresses, and a study of the damaged minaret has been done, where practical steps for restoration and reconstruction were taken, [6].

Also, research of the domes of many mosques in Aleppo city was done in 2021, which was also subjected to earthquakes, in addition to damages due to wars [7], the study showed that the tension stresses exceeded the allowed stresses [7].

All previous research showed that the stresses exceeded the allowed stresses especially tension stresses in masonry structures, so the structures had been damaged under the effect of earthquakes, from here comes the importance of protection the masonry structures from the effects of earthquakes by providing them with seismic base isolation system which is considered one of the most important methods used in retrofitting the old historical masonry building.

In the 1995 Hyogoken Nanbu Earthquake in Japan, the many buildings were severely damaged. Especially, the damage was concentrated to the buildings designed by the old seismic design code in Japan. The many seismic evaluation and retrofitting projects were progressing favorably in Japan. In retrofitting construction methods, there are various type of strengthening methods; the most popular one is the newly adding the reinforced concrete wall or the steel brace inside the existing open frame. These methods have the demerits of changing the interior and exterior of buildings. Recently, the base isolation technology has been used to eliminate the above demerits and to increase the high seismic performance [8]. So, the researcher Seki et al. (2000) did research; in this research, the first masonry building in Japan was isolated in 1999, consisting of one floor, a hall with masonry walls and wooden roof, in order to overcome the weak resistance of these structures when exposed to earthquakes [8], and the

researcher Seki et al. (2012) did research to study the behavior of the same building that was isolated in 1999 under the effect of the earthquake that occurred in Japan in 2011. The results showed that the seismically isolated building did not have any damages compared to the traditional buildings near this building, where the importance of using the seismic isolation technology was emphasized to resist earthquakes with preserving the architectural form of those structures [9].

2 Materials and Methodology

This paper was done according to the following steps:

- Explain numerical modeling approaches for structural masonry analysis.
- Definition of seismic base isolator mechanical characteristics.
- Methodology of selection of HDRB isolators.
- Determination of numerical constants used in modeling masonry structure and methods of analysis used in the modeling. The SAP2000V20.2.0 program [10], will be used to model the studied structure in both fixed and isolated cases.
- Description of structure, and modeling fixed structure.
- Modeling isolated structure using HDRB type.
- Studying nonlinear behavior of seismic isolator, where the ABAQUS2019 program [11], will be used to study the nonlinear behavior and draw energy dissipation loops.
- Compare the results of the two cases and reach a set of recommendations and proposals.

2.1 Defining of Numerical Modeling Approaches for Structural Masonry Analysis

Numerical modeling and analysis of masonry structures is one of the greatest challenges faced by structural engineers. This difficulty is attributed to the number of factors such as: dimension and anisotropy of the masonry units, mortar width, material properties of both brick and mortar, and quality of workmanship.

Numerical modeling of masonry structures could be summarized as following [12]:

2.1.1 Macro-Modeling

In this method, masonry units, mortar and masonry unit—mortar interface are modeled as a homogeneous continuum.

This method may be preferred for analysis of large-scale masonry structures, it is not suitable for detailed stress analysis of small masonry units, due to difficulty of capturing all its expected failure modes.

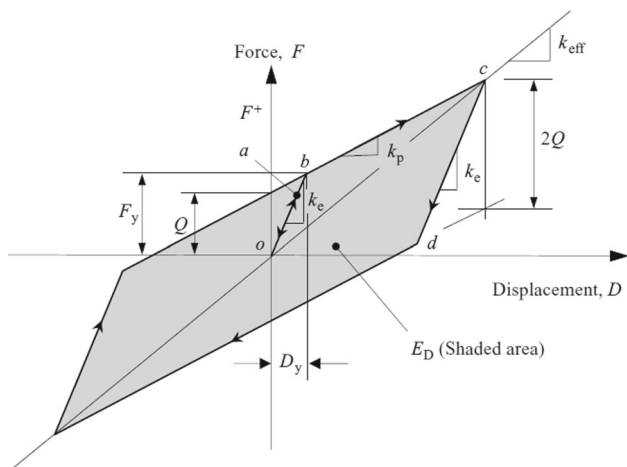


Fig. 1 Bilinear model of isolator unit [13]

2.1.2 Simplified Micro-Modeling

In this method, masonry units are represented as continuum elements with same size of original dimensions plus real joint thickness. The mortar joint is also modeled as an interface with zero thickness.

This method leads to reduction in computational effort and yields a model that is applicable to a wider range of structures.

2.1.3 Detailed Micro-Modeling

In this method, masonry units and mortar in joints are represented by continuum elements whereas masonry unit–mortar interface is represented by discontinued elements. While this modeling leads to more accurate results, it requires complex and intensive calculations using advanced computing devices with very high performance, thus, limiting its application to small-scale laboratory specimens and structural details.

2.2 Defining of Seismic Base Isolator Mechanical Characteristics

Seismically isolated structures are established on assumptions of effective damping and effective stiffness of isolation system, as well as linear stiffness of structure’s seismic force-resisting system.

The bilinear model, used to express the relation between shear force and lateral displacement, can be defined by three parameters: elastic stiffness k_e , post-yield stiffness k_p , and characteristic strength Q , as shown in Fig. 1.

2.2.1 Bilinear Model of High Damping Rubber System

The three parameters used to generate a bilinear model for a high damping rubber bearing are conventionally derived

from tangent shear modulus G , and effective damping β_{eff} . Then, post-yield stiffness is calculated by Eq. (1) [14, 15]:

$$k_p = \frac{G \cdot A}{t_r} \tag{1}$$

where A is bonded area of rubber, and t_r is total rubber thickness. The characteristic strength Q , can be evaluated by Eq. (2) [13]:

$$Q = \frac{\pi \beta_{eff} k_p D_D^2}{(2 - \pi \beta_{eff}) D_D - 2 D_y} \tag{2}$$

where D_D is denoted as design displacement, yield displacement D_y , is unknown until the parameters, k_e , k_p , and Q are determined.

The yield force of the bearing F_y , is easily determined as follows by Eq. (3) [13]:

$$F_y = Q + k_p \cdot D_y \tag{3}$$

Then, the elastic stiffness of high damping rubber bearing becomes as shown by Eq. (4) [13]:

$$k_e = \frac{F_y}{D_y} = k_p + \frac{Q}{D_y} \tag{4}$$

The effective stiffness at design displacement can be derived as follows by Eq. (5) [13]:

$$k_{eff} = \frac{2Q(D_D - D_y)}{\pi \beta_{eff} D_D^2} \tag{5}$$

2.2.2 Vertical stiffness of High Damping Rubber System:

The vertical stiffness of rubber bearing is given by Eq. (6) [14, 16]:

$$K_V = \frac{E_c A}{t_r} \tag{6}$$

where E_c is modulus in compression and is given by Eq. (7) [14]:

$$E_c = \frac{6GS^2 K}{6GS^2 + K} \tag{7}$$

where K is bulk modulus of material, the value of K varies quite widely in reference material, ranging from 1000 to 2500 MPa. The value most commonly used is 2000 MPa as indicated in the reference [13].

where S is shape factor for a circular bearing of diameter \varnothing is given by Eq. (8):

$$S = \frac{\varnothing}{4t_r} \quad (8)$$

2.3 Methodology of Selection of HDRB Isolators

- Assuming an effective design period of isolated structure (T_D) is greater than three times elastic fixed-base period of structure above isolation system [3].
- Determination an initial horizontal effective stiffnesses of seismic base isolators in accordance with actual vertical dead load applied to isolator from Eq. (9) [14]:

$$K_H = \frac{W}{g} \times \left(\frac{2\pi}{T_D} \right)^2 \quad (9)$$

- Determination an initial dimension of isolator from Eq. (10) [14, 17]:

$$K_H = \frac{G \cdot A_r}{t_r} \quad (10)$$

where (G) is effective shear modulus, (t_r) is total rubber thickness and (A_r) is bonded rubber area. Where value of (t_r) and (G) are assumed and (A_r) is calculated, then isolator radius required is determined.

- Selection type of seismic base isolator based on the tables provided by international companies specialized in manufacture of seismic base isolators, as one of international companies is AGOM.

Where type of isolator was selected in accordance with actual vertical dead load applied to isolator and in accordance with isolator radius that was initially calculated in previous step, then the type of rubber isolator that was selected will be checked in subsequent steps.

- After selection suitable seismic base isolator and determination its dimensions from previous step, horizontal effective stiffness is recalculated for each isolator from Eq. (10), and verification that it is within allowed values that exist in the tables.
- Calculation value of minimum horizontal stiffness of isolation system (K_{Dmin}) which is equal to sum of effective horizontal stiffnesses for all isolators which were calculated in previous step.

- Calculation effective period of isolated structure (T_D) at design displacement (D_D), from Eq. (11) [3]:

$$T_D = 2\pi \sqrt{\frac{W}{K_{Dmin}g}} \quad (11)$$

- Calculation design displacement (D_D) of isolated structure, from Eq. (12) [3]:

$$D_D = \frac{\left(\frac{g}{4\pi^2} \right) C_{VD} T_D}{B_D} \quad (12)$$

where C_{VD} seismic coefficient C_V , B_D numerical coefficient related to the effective damping of isolation system at design displacement β_D . Where D_D' is used instead of D_D when Dynamic analysis is used as shown in equation (13) [3]:

$$D_D' = \frac{D_D}{\sqrt{1 + \left(\frac{T}{T_D} \right)^2}} \quad (13)$$

- Calculation value of maximum horizontal stiffness of isolation system (K_{Dmax}), from Eq. (14) [3]:

$$K_{Dmax} = \frac{1.1 \times K_{Dmin}}{0.9} \quad (14)$$

- In all cases, values of all calculated displacements in previous steps should not exceed value of allowed maximum horizontal displacement of rubber isolator as shown in Eq. (15) [14]:

$$D_{max} = \frac{\varnothing}{1 + K_H \times h/w_1} \quad (15)$$

- Calculation the value of vertical stiffness of isolation system (K_v), as shown in Eq. (6).

2.4 Determination of Nonlinear Characteristics of Seismic Isolators

When using equivalent static analysis, linear response spectrum analysis, or linear time-history analysis, effective stiffness (k_{eff}) and effective damping (β_{eff}) of isolator are only used on modeling. In case of using nonlinear time history

analysis, the following properties also are used: elastic stiffness (k_e), yield displacement (D_y), and ratio of post-yield stiffness to elastic stiffness, ($\mu = k_p/k_e$) [3].

These properties are determined according to following steps, after selection used isolators:

- The value of effective horizontal stiffness of isolator (K_{eff}) is equal to value of (K_H), which was calculated in previous paragraph.
- Effective damping (β_{eff}) is determined from tables provided by isolator manufacture companies.
- Calculation yield displacement (D_y), from Eq. (16) [13]:

$$D_y = \frac{Q}{9k_p} \quad (16)$$

where Q was calculated from equation (2), and k_p was calculated from equation (1).

- The yield force (F_y) is calculated from Eq. (3).
- The elastic stiffness (k_e) is calculated from Eq. (4).
- After determining all properties, base isolated structure is modeled and analyzed. Then, story displacements should not exceed allowed values. In addition, tension and compression stresses values should not exceed allowed stresses values.

In addition to, the displacements of all isolators according to all loading conditions should not exceed the value of maximum horizontal displacement allowed for rubber isolator.

2.5 Numerical Constants Used for Studying Masonry Structures

The engineering model that will be studied in this research is a masonry structure; therefore, the structural system is masonry walls. The seismic zone of Aleppo city is (2C), so the seismic zone factor is $Z = 0.25$.

Since bearing of structure foundation soil used is (2.5 kg/cm^2); therefore, the soil profile type is (S_D), thus $C_a = 0.32$, $C_v = 0.47$, for fixed structure [1], and for isolated structures, C_{AD} value is taken as C_a and C_{VD} value is taken as C_v [3].

Nonlinear dynamic analysis- time history method will be used in this paper, where an actual earthquake will be applied to the structure.

2.6 Description of Structure

The studied masonry structure is the old AWQAF directorate structure in Aleppo; the structure is located in Baza Square of old city. Its construction date back to around 1940 AD / 1359 AH by the engineer Hikmat Al-Yaziji.

The structure consists of two floors, ground floor and basement, the height of the ground floor is 5 m, height of first floor 4.5 m, height of second floor is 3.5 m, and height of basement is 4 m. The thickness of masonry walls is 50 cm in each of first floor, ground floor and basement, while its thickness is 40 cm on last floor.

New equivalent material has been defined that represents the material of the masonry unit, taking into account the mortar [5, 18], where the weight per unit volume of masonry is equaled ($\gamma = 27 \text{ kN/m}^3$). The height of masonry unit equals ($L_m = 40 \text{ cm}$), and the thickness of mortar equals ($L_G = 0.3 \text{ cm}$). The masonry modulus value of elasticity equals ($E_m = 18 \text{ GPa}$), the mortar modulus value of elasticity equals ($E_G = 0.1 \text{ GPa}$), so the equivalent modulus of elasticity (E_{eq}) is obtained according to Eq. (17) [19, 20]:

$$E_{\text{eq}} = \frac{E_m \times E_G \times L_{\text{eq}}}{E_m \times L_G + E_G \times L_m} \quad (17)$$

where (L_{eq}) is the equivalent height and it is taken equal to height of masonry unit plus thickness of mortar, substituting in Eq. (17):

$$E_{\text{eq}} = \frac{18 \times 0.1 \times 40.3}{18 \times 0.3 + 0.1 \times 40} = 7.72 \text{ GPa}$$

Thus, ($E_{\text{eq}} = 7.72 \text{ GPa}$) is the equivalent modulus of elasticity will be used in modeling the historical masonry building. In general, the values of the equivalent modulus of elasticity range from (3 GPa) to (9 GPa) [19].

Since the historical masonry structures have high resistance to compression and weak resistance to tension, so according to Syrian Arab Code for unreinforced bearing walls in buildings, the allowable compression stresses were ($1.5 \text{ MPa} = 15 \text{ kg/cm}^2$), and the allowable tension stresses were ($0.15 \text{ MPa} = 1.5 \text{ kg/cm}^2$) [1].

2.7 Modeling the Historical Masonry Building

The idea is to supply the existing building with seismic isolation by gradually separating it from foundation and installing the isolators at the level of upper level of foundation between a two-stage system of R/C beams [21].

In this paper, the whole structure was modeled by using macro-modeling method based on several previous researches such as those mentioned in the references [6, 7, 22]. The structural analysis and design program SAP2000V20.2.0 [10] will be used, where actual studied structure is replaced with a model, and this is done by dividing each masonry unit of structure into small-dimensional elements, and these elements are connected among themselves with virtual points called nodes, which in turn form the ends finite elements [6, 7, 22].



Finite elements of type (Shell-Thick Elements) were used to model structure walls [1].

Figure 2 shows the studied structure, where Fig. 2a shows horizontal plan of studied structure with places of masonry walls system before placing seismic isolators.

Figure 2b shows horizontal plan of studied structure with places of seismic isolators, where lower reinforcement beams were placed under seismic isolators, and bottom base of each isolator is fixed to it. Upper reinforcement beams were placed on seismic isolators, and top base of each isolator is fixed under it.

Dimensions for upper reinforcement beams are (60 × 40), and for lower reinforcement beams are (60 × 30).

Figure 2c shows 3D shape of studied structure after modeling it on SAP2000V20.2.0 program, with finite element used in modeling with local axis on it, where each of local axis1 and 2 are located in the same plane of element and axis3 is located in perpendicular to element plane, and stresses S_{11} represent stresses in direction of local axis1, and stresses S_{22} represent stresses in direction of local axis2, and stresses are positive if they are tension stresses, and negative if they are compression stresses [1].

2.7.1 Using Nonlinear Dynamic Analysis-Time History Method for Modeling Fixed Structure

The Sakarya earthquake was applied, this earthquake occurred in the year 1999 near Sakarya in Turkey, a maximum intensity was 7.2 on the Richter scale.

The applied earthquake data are given as an equation between time of shake and its accelerations in terms of the gravitational acceleration $g = 9.81 \text{ m/sec}^2$, where Fig. 3 shows applied shake data over a period of 20 s, where value of maximum acceleration of applied shake was 0.628 g at $t = 5.92 \text{ s}$.

Scaling of this shake was also done to correspond to expected earthquake intensity for Aleppo city according to Syrian Arab Code, with a maximum acceleration of 0.25 g.

The load combinations used in nonlinear dynamic analysis- time history method are shown in Eqs. (18), (19), (20) [20]:

$$U_1 = 1.4D + 1.7L \tag{18}$$

$$U_{2TH} = 1.32D + 0.55L + 1.1TH \tag{19}$$

$$U_{3TH} = 0.99D + 1.1TH \tag{20}$$

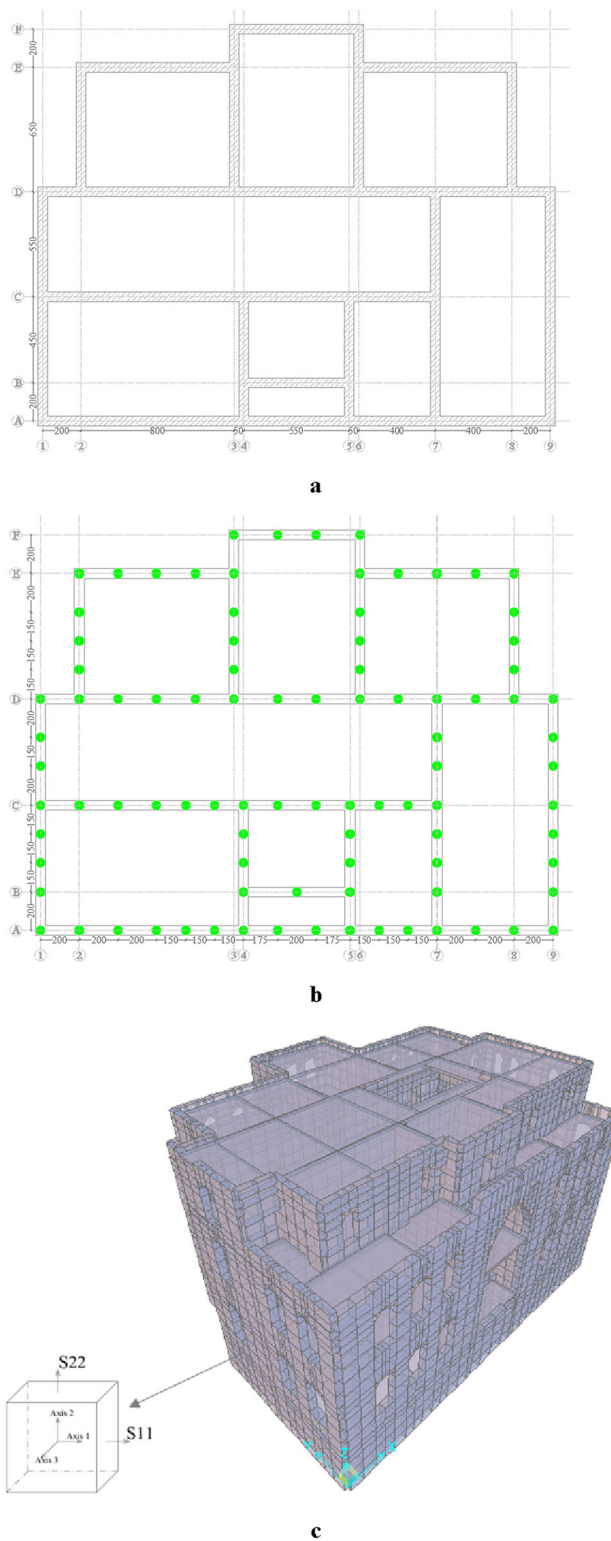


Fig. 2 The Studied historical masonry building. **a** Horizontal plan before placing seismic isolators, **b** Horizontal plan with places of seismic isolators, **c** 3D shape of studied structure with finite element used in modeling

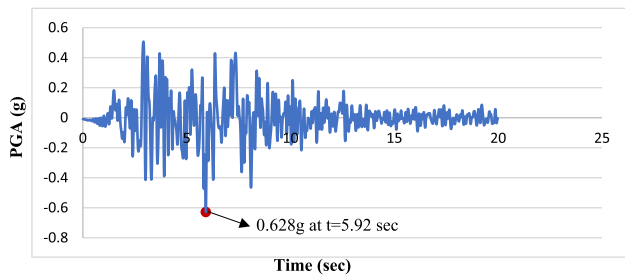


Fig. 3 Chart (acceleration-time) of Sakarya earthquake [20]

After finishing modeling and analysis, values of periods and base shear forces according to each direction are as follows:

$$T_X = 0.143 \text{ sec}, T_Y = 0.173 \text{ sec}$$

$$V_{THX} = 23335 \text{ kN}, V_{THY} = 22512 \text{ kN}$$

2.7.2 Using Nonlinear Dynamic Analysis—Time History Method for Modeling Isolated Structure

The isolators were designed, final specifications of isolators and seismic isolation system were done as shown in paragraph (5), where all equations were programmed using Excel because of overlapping equations and long calculations, and for accuracy and speed in completing these calculations. The type of rubber isolator was chosen based on the tables provided by AGOM company [23], and then, design results were compared with allowed values in these tables. The damping ratio used is $\beta = 10\%$, and value of rubber shear modulus is $G = 0.4 \text{ MPa}$ according to values indicated in the tables provided by AGOM company [23], as shown in Table 1.

Table 2 shows specifications of seismic isolators used in modeling and comparing them with allowed values from tables provided by AGOM [23].

Linear and nonlinear seismic isolator properties that will be used in isolator modeling were also determined, as shown in Table 3.

Table 2 The design values of seismic isolator-type HDRB

Seismic isolator specifications-Type (HDRB)	Design values	Allowed values
Isolator diameter D (mm)	450	450
Isolator height H (mm)	248	248
Thickness of total rubber layers (mm)	114	114
Greatest reaction on isolator (kN)	663	2559
Vertical stiffness (kN/m)	401,912	< 525,000
Horizontal stiffness (kN/m)	558	560
Maximum displacement (mm)	372	> 250

Table 3 Seismic isolator properties used in modeling

Seismic isolator properties used in modeling seismic isolator	Design values
Effective stiffness K_{eff} (kN/m)	558
Effective damping β_{eff}	10%
Vertical stiffness (kN/m)	401,912
Elastic stiffness K_e (kN/m)	4793
Yield force F_y (kN)	21
Ratio of post-yield stiffness to elastic stiffness μ	0.1

After completing modeling and analysis, values of periods and base shear forces of isolated structure according to each direction are as follows:

$$T_{D(x)} = 2.02 \text{ s}, T_{D(y)} = 2.024 \text{ s.}$$

$$V_{THX} = 5954 \text{ kN}, V_{THY} = 5967 \text{ kN.}$$

For displacement, story drift should not exceed value of allowed story drift for isolated structure when using dynamic nonlinear analysis- time history method ($0.02/R_1$) [3].

2.8 Studying Nonlinear Behavior of Seismic Isolator

After completing modeling of structure and confirming feasibility of using seismic isolators in reducing values of shear

Table 1 The allowed values based on the tables provided by AGOM company [23]

HDRB/ S–10% damping, horizontal displacement = 250 mm									
item	D_g	T_q	H_{tot}	K_b	K_v	$N_{ed, max}$	F_{zd}	L	W
E-Safe	(mm)	(mm)	(mm)	(kN/mm)	(kN/mm)	(kN)	(kN)	(mm)	(kG)
HDRB/S Φ 400 × 253	400	110	253	0.45	459	422	2554	450	174
HDRB/S Φ 450 × 248	450	114	248	0.56	525	635	2559	500	209
HDRB/S Φ 500 × 248	500	114	248	0.69	785	1175	4015	550	257
HDRB/S Φ 550 × 237	550	112	23	0.85	904	1693	4847	600	294

Significance of bold is the allowed values of seismic isolator-type HDRB used in modeling

Table 4 Periods and shear forces values for fixed and isolated structure

Studied structure	Periods values (sec)		Shear forces (kN)	
	X Direction	Y Direction	X Direction	Y Direction
Fixed structure	0.143	0.173	23,335	22,512
Isolated structure	2.02	2.024	5954	5967
ψ %	93%	91%	74%	73%

forces and accelerations occurred in structure and thus reducing stresses occurred in structure, that is, ensuring the safety of structure during exposure to earthquakes. It is necessary to study behavior of seismic isolators due to their dissipation of earthquake energy and elastic–plastic behavior which is expressed as hysteresis loops, which are energy dissipation loops.

Hysteresis loops express relation between lateral displacement and applied shear force at every moment in time of earthquake and to ensure safety of these isolators.

The seismic isolator-type HDRB was modeled by using detailed micro modeling method based on several previous researches such as those mentioned in the references [24–26].

To achieve this, ABAQUS 2019 finite element program was relied on modeling seismic isolator- type HDRB, as this program is considered one of the most powerful and most important engineering programs used in micro numerical modeling.

The components of seismic isolator- type HDRB and their geometric dimensions were defined; these components are rubber and steel. Both the rubber layers and steel sheets were modeled. Appropriate finite element was selected for each of rubber layers and steel sheets, in addition to complete bonding between these layers and sheets. Then, applying the vertical load which isolator is exposed to and horizontal displacements which isolator is exposed to at each interval of the earthquake were obtained from the SAP2000 program, where modeling steps were based on the references [24, 25, 27].

After completing the modeling and analysis process using the ABAQUS program, shear forces values that affected on isolator were obtained at each time interval of earthquake. Furthermore, the horizontal displacements values which isolator is exposed to at each time interval of earthquake were obtained. Then, relation between horizontal displacements values and shear forces values was drawn in order to obtain the hysteresis loops that express response of seismic isolator during earthquake.

3 Results and Discussion

The results showed an increase in periods values and a decrease in shear forces values in case of isolated structure

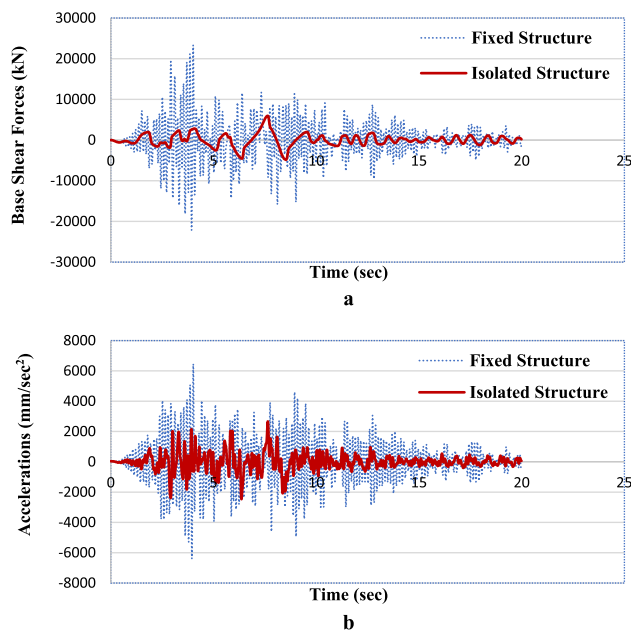


Fig. 4 Comparison between base shear forces and accelerations for fixed and isolated structure. **a** Chart (base shear force–time), **b** Chart (acceleration–time)

than fixed structure, which leads to a reduction in stresses values that occurred in isolated structure, as shown in Table 4.

Seismic isolators worked to raise the seismic efficiency of structure, as these isolators absorbed the energy entered the structure, and thus, reduced the forces transmitted to the upper part of the structure.

Figure 4 shows a comparison between base shear forces and acceleration for fixed and isolated structure.

Figure 4a shows that base shear force in isolated structure is significantly lower than fixed structure when applying Sakarya earthquake, as maximum base shear force in X direction reached in case of fixed structure 23335 kN at time $t = 4.01$ s, while in case of isolated structure it reached 5954 kN at time $t = 7.65$ s. That means that providing structure with isolation system decreases base shear force by (74%), thus reducing stresses generated within structure.

Figure 4b also shows a comparison between variable acceleration values at every interval for fixed and isolated structure when they were subjected to applied earthquake on

Table 5 Maximum story drifts values for fixed and isolated structure

Sakarya earthquake	Maximum story drifts values (mm)				
	Story	First	Second	Third	Fourth
Fixed structure		0.78	1.61	1.05	0.53
Isolated structure		0.3	0.5	0.39	0.2
ψ %		62%	69%	63%	62%

Table 6 Maximum values of stresses (S_{11}) and (S_{22}) for fixed and isolated structure

Sakarya earthquake	S_{11}						S_{22}					
	Compression stresses (-) MPa			Tension stresses (+) MPa			Compression stresses (-) MPa			Tension stresses (+) MPa		
	TH	U_{2TH}	U_{3TH}	TH	U_{2TH}	U_{3TH}	TH	U_{2TH}	U_{3TH}	TH	U_{2TH}	U_{3TH}
Fixed structure	1.1	1.3	1.2	0.9	1.1	1.2	2.1	3.3	3	2.1	1.4	1.7
Isolated structure	0.3	0.4	0.3	0.14	0.12	0.13	0.6	1.5	1.4	0.15	0.12	0.1
ψ %	73%	69%	75%	84%	89%	89%	71%	55%	53%	93%	91%	94%

last floor. The acceleration values are usually maximum on higher floors of structure, where maximum acceleration value in case of fixed structure reached 6458 mm/sec^2 at time $t = 4.01 \text{ s}$, while that value in case of isolated structure reached 2665 mm/sec^2 at time $t = 7.64 \text{ s}$, therefore providing structure with isolation system contributed to decrease the value of acceleration on last floor by (59%).

As a result of the important role of seismic isolation system in reducing the base shear forces, this means a decreasing in the forces affected the structure, and thus a decreasing in the story drifts, which means the protection of the structural elements in the building.

By checking story drifts of structure, the story drifts are within allowed values for all seismic loads and combinations, as Table 5 shows a comparison between values of maximum story drifts when applying Sakarya earthquake for fixed and isolated structure.

Table 5 shows that maximum story drifts values in isolated structure are lower than fixed one, which leads to a reduction in values of stresses in isolated structure.

The results also show that tension stresses exceeded allowed values in case of fixed structure, but became within allowed values in case of the isolated structure, thus the structure became safe and stable against seismic loads.

Where Table 6 shows a comparison between maximum values of compression and tension stresses for both directions (S_{11}) and (S_{22}) when applying the Sakarya earthquake in case of fixed and isolated structure for seismic forces.

It is noted from Table 6 that values of compression and tension stresses that occurred in isolated structure were lower than that of fixed one, it is also noted that unverified values of compression and tension stresses in fixed structure have

become verified in isolated structure; thus, the effectiveness of using seismic isolation in this type of structure appears here.

Figure 5 shows the compression, tension and shear stresses distribution diagram for both directions (S_{11}) and (S_{22}) under effect of seismic combination (U_{2TH}). The whole structure is stable, there are local zones occurred where tension stresses are above allowable stresses this lead to local damage; however, when we provide structure with seismic base isolation system the tension stresses almost diminished and the behavior of the structure is representing the rigid body motion.

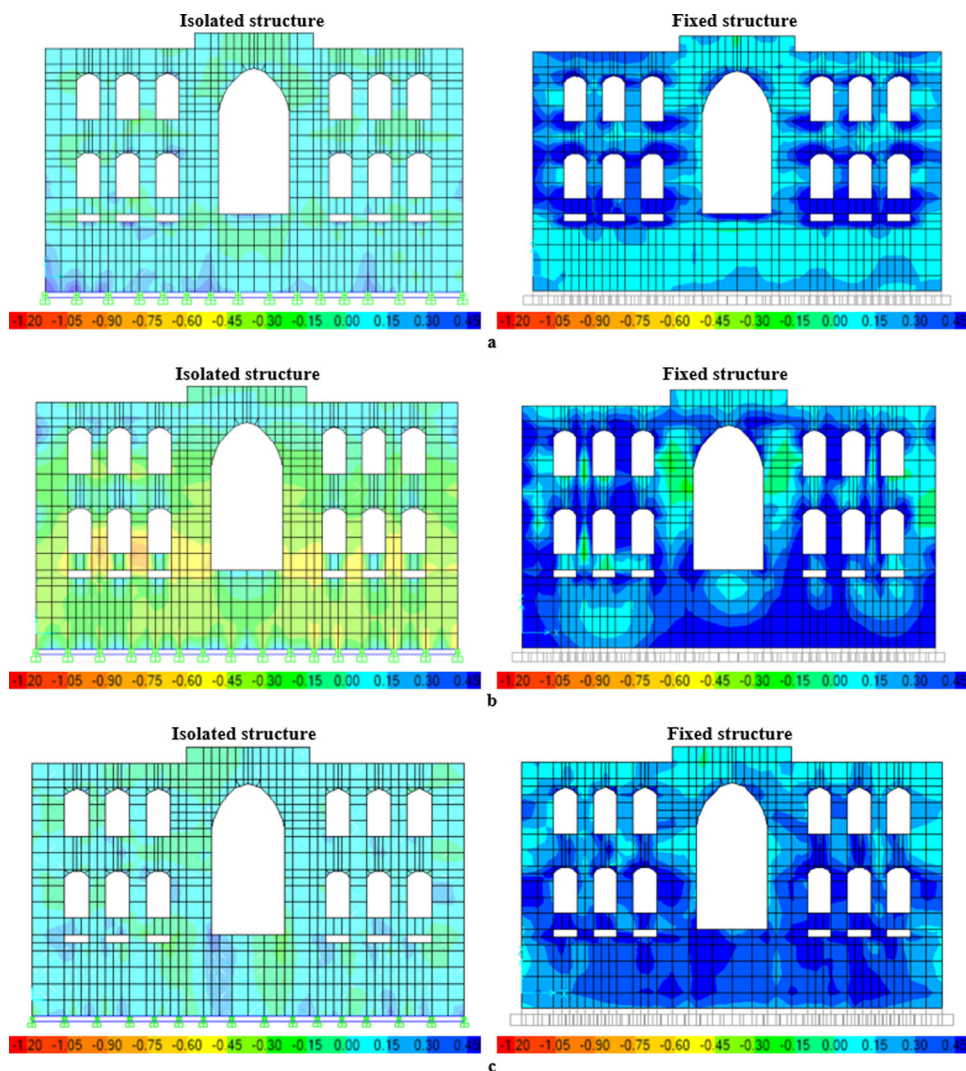
Figure 5a shows compression and tension stresses distribution diagram (S_{11}) for fixed and isolated structure, it is noted that unverified tension stresses in fixed structure are highly concentrated in places of openings, while values of tension stresses in the isolated structure are significantly decreased and become within allowed values.

Figure 5b also shows compression and tension stresses distribution diagram (S_{22}) for fixed and isolated structure, it is noted that unverified tension stresses in fixed structure are highly concentrated in places of openings, while values of tension stresses in isolated structure are significantly decreased and become within allowed values.

Figure 5c also shows shear stresses distribution diagram (S_{12}) for fixed and isolated structure, it is noted that unverified shear stresses in fixed structure are highly concentrated in places of openings, while values of shear stresses in isolated structure are significantly decreased and become within allowed values.

Thus, when the base seismic isolation is used, the structure remains safe, stable and not subject to collapse in the event of exposure to earthquakes.

Fig. 5 stresses distribution diagram under the effect of seismic combination (U_{2TH}). **a** Compression and tension Stresses distribution diagram (S_{11}), **b** Compression and tension Stresses distribution diagram (S_{22}), **c** Shear Stresses distribution diagram (S_{12}).



The relation between horizontal displacements values and shear forces values was drawn in order to obtain hysteresis loops that express the response of seismic isolator during earthquake.

Figure 6 shows model of seismic isolator- type HDRB used in ABAQUS with the resulting hysteresis loops under the effect of the applied earthquake.

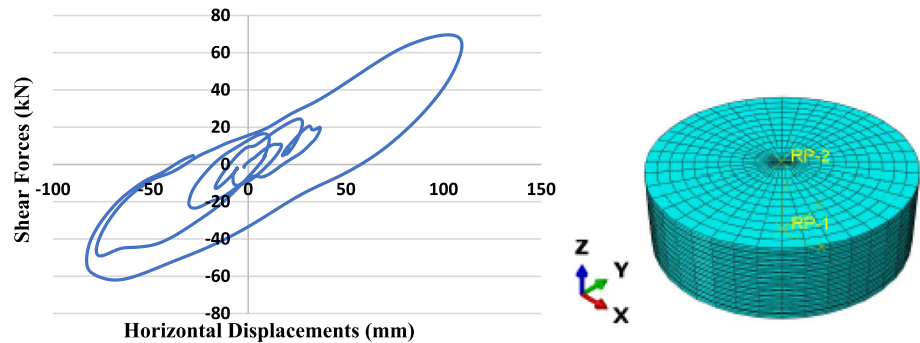
Figure 6 shows the hysteresis loops that express the response of the seismic isolator during earthquake, which are several loading and unloading cycles in the positive and negative directions, where the seismic isolator dissipates the energy of the earthquake.

It is noted from Fig. 6 that the value of the maximum positive displacement which the isolator is exposed reached 109 mm, which is within the allowable design values. The force, which the isolator is exposed, reached 63.64 kN, and the value of the maximum negative displacement which the isolator is exposed was 83 mm, which is within the allowed design values.

From the foregoing, providing structure with base seismic isolation system contributed to reducing base shear forces, and thus reducing values of stresses occurring in structure, thus the structure remains safe and stable under effect of earthquakes.

For the considered building, which has historical and architectural value the technique of installation of seismic isolators has especially important meaning. First of all, an infringement of the external view of the building should not take place under any circumstances. Secondly, no one stone of the facade should fall down during implementation [21]. The Methodology of constructing seismic base isolation in masonry structures to resist earthquakes is done according to steps in the reference [21].

Fig. 6 Model of seismic isolator-type HDRB with hysteresis loops



4 Conclusion

In this research, the effect of providing the base seismic isolation system on an existing masonry structure was studied when an actual earthquake was applied to the structure. The study showed the effectiveness of this system significantly in reducing the shear forces, and decreasing the accelerations occurred at the structure. Hence, results lead to reduce in the stresses occurred in the structure, especially tension stresses, that have decreased significantly. Moreover, these stresses are almost non-existent in large areas of the masonry structure. Consequently, maintaining this type of important structure and keeping them safe and stable under the effect of earthquakes.

5 Recommendations:

- Using the dynamic nonlinear analysis-time history method which studies the dynamic response of the structure during each interval of the specified time intervals from the response chart drawn in terms of time, where it is characterized by the accuracy of the calculation and the reliability of the results.
- Using the base seismic isolation system in the retrofitting of important masonry and historical structures that are not designed to resist earthquake loads, where the study showed the effectiveness of this technique in resistance of earthquake loads for this type of structures.
- Studying the possibility of manufacturing seismic isolators locally in accordance with the requirements of the region, whereas materials required for the manufacture of this type of isolators are available at acceptable prices.

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