The 12th ISAV2022 International Conference on Acoustics and Vibration
14-15 Dec 2022 Tehran - Iran
Iranian Society of Acoustics and Vibration
Amirkabir University of Technology

Investigating the Effect of Dimensions of Circular Opening on Seismic Behavior of Steel Plate Shear Walls Using Time History Analysis

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Abstract

Retrofitting buildings against lateral load in the shelf life of buildings is always one of the determinative concerns and factors for designers. In addition to the use of systems like moment frames and braces, applying shear walls as one of the main options in designs is raised. This article investigates the effect of dimensions of circular opening on the center of steel shear walls. In the steel shear walls system, circular openings with different shapes and sizes can be used if needed. Steel shear walls act like cantilevered plate girders in which the columns serve as their flanges, the floor beams as their stiffener, and steel sheets as their web. The basis of the idea of shear walls, which has been seriously considered in the last three decades, is the use of a diagonal tensile field in which a steel sheet is created after buckling. In order to investigate the effect of the size of the circular opening on six types of frames with different dimensions, the displacement of the upper level of the frame was investigated. According to these investigations, it was found that the wall stiffness decreases linearly with an increasing circular opening. In general, it can be concluded that the shear panel with or without the circular opening has a better function than the frame without a shear wall.

Keywords: vibration control; steel shear wall; circular opening; analysis of temporal history

1. Introduction

Steel shear walls are resistance elements to lateral loads, especially earthquakes. These structures can absorb high seismic energy and therefore their use in buildings has increased. In the design of structures, the provision of suitable interior spaces and architectural considerations is one of the most important purposes. The design engineer will be bound to create a suitable structure within the framework of the designated spaces. Applying such architectural and beautification needs can be considered as one of the factors that create a circular opening in steel shear walls. Also, non-structural considerations such as the position and direction of facility systems can be other effective factors in creating a circular opening in steel shear walls. One of the first laboratory studies performed on steel shear walls with circular opening samples was researched in the structural laboratory of the University of Cardiff, England. In these studies, a series of experiments were performed by applying quasi-static cycle loads on steel shear wall samples without reinforcement and with a circular opening in the centre of the sheet. It was observed that the samples have sufficient ductility and s-shaped hysteresis rings and the energy absorption capacity of them in each load cycle increased with the maximum shear deformation amplitude and it was found that the strength and stiffness of the panels decreased with increasing opening diameter. In 2004, a sample of thin sheet steel shear wall with twenty circular holes and another sample with a quarter-circular circular opening in the corner of the sheet, using low flow resistance steel sheet in the National Structural Laboratory of the Earthquake Engineering Research Centre at Taiwan National University was tested. Based on the results of these experiments, it was found that steel with low flow resistance can be a very suitable alternative for use in the manufacture of energy-absorbing elements in lateral bearing systems. In all tested samples which have a circular opening, a decrease in hardness and strength was observed compared to the samples without a circular opening. In the lattice pattern, the sheet began to flow at narrow intervals between the circular openings and expanded in these areas. The sample performed very well at the beginning of the test. This sample had elastic behaviour in the small displacement range and stable hysteresis behaviour in the inelastic range. The sample, with a quarter-circle circular opening to 2.5% drift, showed a stable elastic behaviour while applying load cycles. In 2008, a variety of laboratory studies were conducted at the Central Laboratory of Evaluation and Planning of the Construction and Transportation Industry of South Korea to investigate changes in the bearing capacity of steel shear walls made of steel sheets with different construction details. One of the experiments was performed on a 3-floored sample with 2 sheets with a width of less than half of the opening and having a welded connection with the frame elements, which are placed side by side in the middle of the opening of the circular opening.

2. Scaling Accelerometers

Each of the records obtained from accelerometers harvesting has been entered into Abacus software after scaling, matching, and normalizing to g in the x and y axes by SeismoSignal software. By applying the scale factor, which is obtained from the average square root of normal squares in the x and y axes, observing damping of 5%, the range in the requirements outlined in The Fourth Edition of the 2800 Standard Regulations for Soil Type II for pairs of accelerometers is obtained. Fig. 1 is the spectrum diagram of the 2800 Standard Regulations for Soil Type II in comparison with the spectrum obtained from applying the scale factor for the accelerometer pair. After entering the obtained scale factor for time history records, we apply damping in Abacus software by the Riley method. In this method, using mass, we take two consecutive modes and determine the damping on this basis, and finally, The HHT method, which is based on the letters of three scientists (Hilber-Hughes-Taylor), apply the history of temporal analysis to the structure.

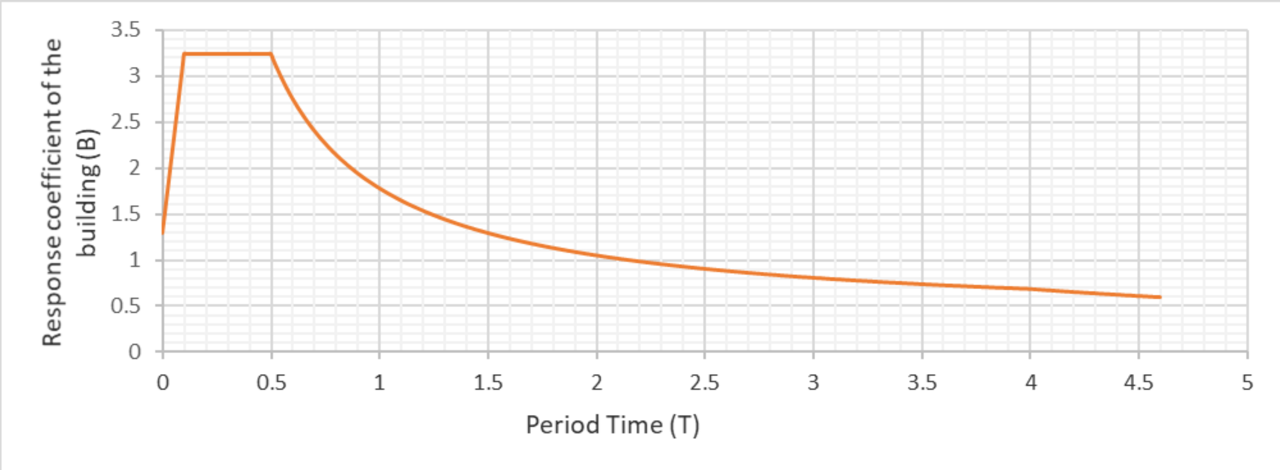


Figure 1. The spectrum of the fourth edition of The 2800 Standard Regulations for Soil Type II

Recommended Method of The 2800 Standard Regulations (R4) in which each accelerometer pair is scaled so that for each period in the range of 0.2T to 1.5T the average value of the range of the square root of the total squares for all pairs of components is more than ten percent of 1.3 times won't be less than the corresponding value of the standard design range.

3. Investigating Models

In this article, a steel frame surrounded by a shear wall with variable opening width and height with specific steel materials is considered by the table below.

Table 1. Geometric characteristics of the investigating frames

Beam Section	Column Section	Opening Width (m)	Frame Height (m)	Frame No.
IPE220	IPB240	4	4	4
IPE220	IPB240	6	5	2
IPE220	IPB240	5	4	3
IPE220	IPB240	6.5	5	4
IPE220	IPB240	7	5	5
IPE220	IPB240	6	4	6

Table 2. Specifications of consumed steel in the investigating frames

Steel Grade	E (GPa)	F_Y (Mpa)	F_U (Mpa)
St37	210	235	370

Circular openings in the above frames are installed inside a steel shear wall with a thickness of 8 mm. The loads on the intended frame are divided into two categories of gravity and lateral.

Gravitational loads including dead and live loads equal to 8500 kg/m length and lateral loads are also applied to the frame in the form of Tabas, Manjil, and Bam earthquakes analysis.

3.1 Used Accelerators

In this study, three accelerometers were examined. Bam earthquake in 2003 with a magnitude of 6.6 occurred in the east of Kerman province.

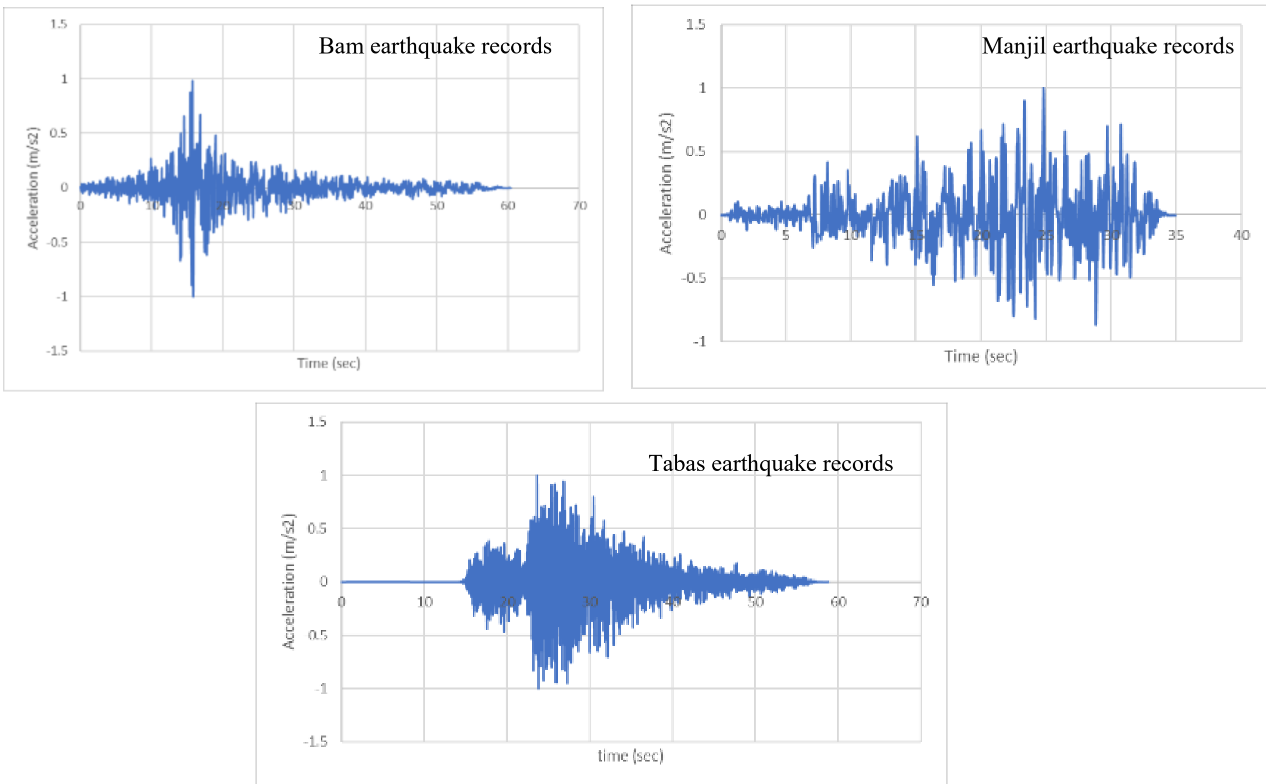


Figure 2. Bam, Manjil, and Tabas earthquake records

In addition to the Bam earthquake, the record of the Manjil earthquake, which shook Gilan province and the west of Zanjan province in 1990 with a magnitude of 7.4, has also been used.in addition to the above, the record of the Tabas earthquake, which occurred in 1978 with a magnitude of 7.8 in the west of South Khorasan province, has been included in the analysis. After applying the above accelerators, the time history of the mentioned frames has been analysed. Then, by examining the displacement of the structure, the best size for circular openings is given.

4. Circular Opening

First, circular openings in the centre of the shear wall are modelled, for which openings with the following dimensions have been studied:

$$D = n \times h \tag{1}$$

$$n = (0.4, 0.3, 0.2, 0.1) \tag{2}$$

n: The ratio of the opening dimensions to the corresponding dimensions of the frame
D: Circular opening diameter
h: Frame height

Table 3. Dimensions of frames modelled with thecircular opening

Frame No.	L (m)	h (m)	L/h
Frame No. 1	4	4	4/4=1
Frame No. 2	6	5	6/5=1.20
Frame No. 3	5	4	5/4=1.25
Frame No. 4	6.5	5	6.5/5=1.3
Frame No. 5	7	5	7/5=1.4
Frame No. 6	6	4	6/4=1.5

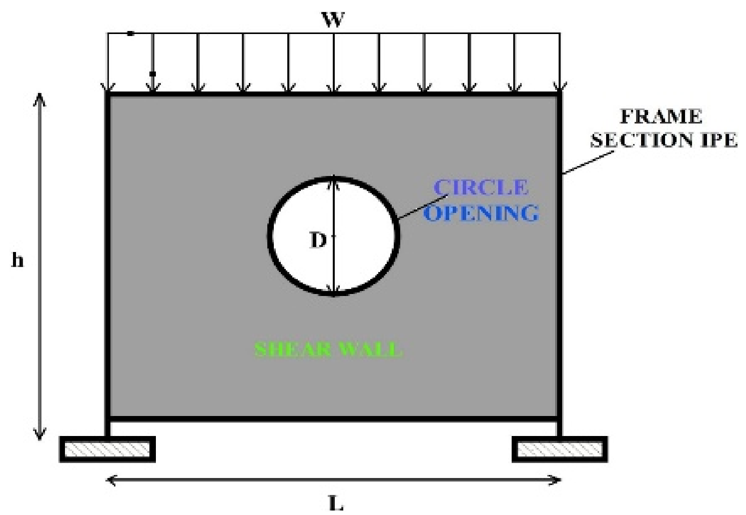


Figure 3. Schematic circular opening embedded in a steel shear wall

After analysing the time history, we examine the changes in the amount of displacement of the upper level of the frame to extract the optimal opening dimensions.

5. Analysis of models

5.1 Study the frame with a width of 4 meters and a height of 4 meters (Frame No. 1)

The best place to place the openings in the steel shear wall has been investigated by placing openings with different dimensions in the shear wall. The followings are the details of the openings under consideration:

The results of the displacement resulting from the analysis of time history with three acceleration maps are as follows:

Table 4. Frame displacement with dimensions of 4×4 meters due to the accelerated mappings

Displacement						
Model With Circular Opening	Opening Dimensions			Bam Earthquake Record	Manjil Earthquake Record	Tabas Earthquake Record
	H (m)	L (m)	n			
1	4	4	0.4	0.03912	0.06194	0.03816
2	4	4	0.3	0.036793	0.05759	0.03653
3	4	4	0.2	0.033914	0.053865	0.034848
4	4	4	0.1	0.031221	0.049954	0.031471

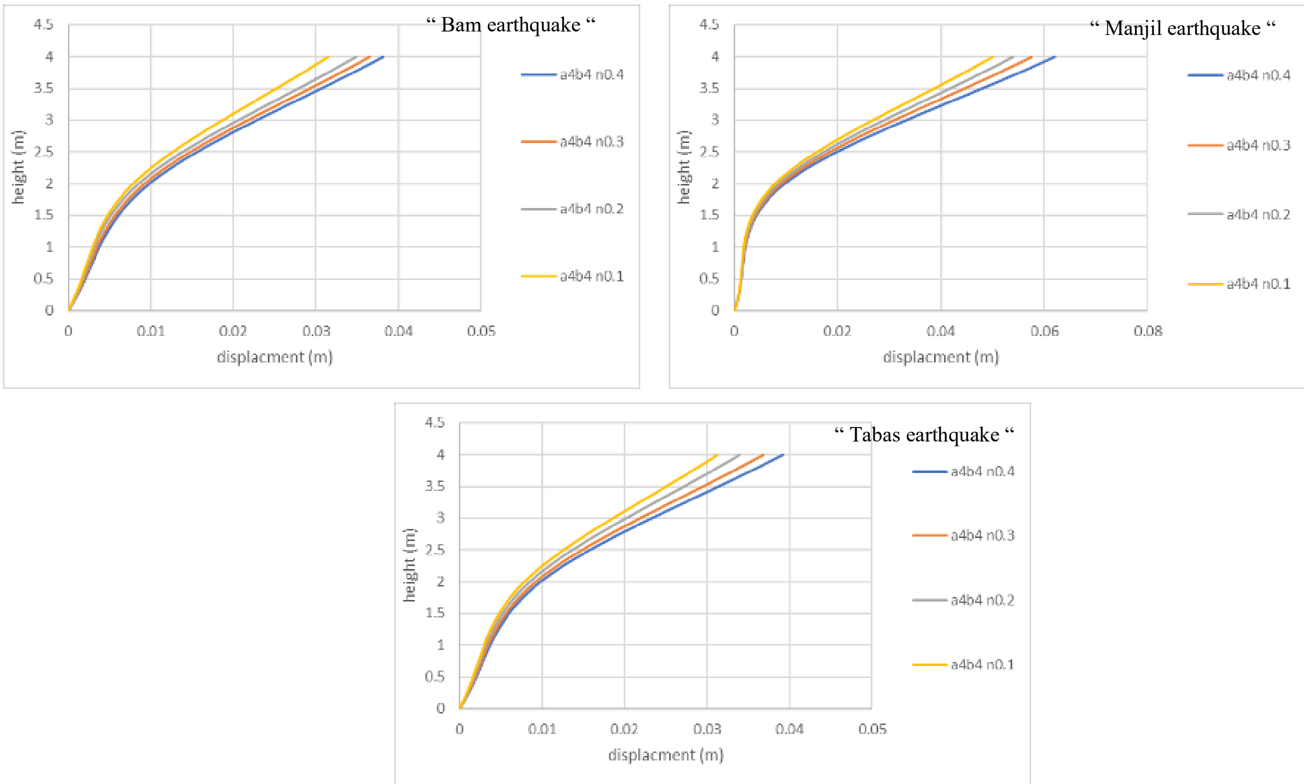


Figure 4. Investigation of frame displacement with dimensions of 4×4 meters due to the Bam, Manjil, and Tabas earthquakes

Due to the Bam accelerometers, the least amount of displacement is observed in the frame with an opening width of 4 meters and a height of 4 meters is 0.031221 meters, which has an opening with a coefficient of n = 0.1 (diameter of 0.4 meters). Also, the frame with Basho with a diameter of 1.6 meters had the highest amount of displacement.

Due to the Manjil accelerometers, the least amount of displacement is observed in the frame with an opening width of 4 meters and a height of 4 meters is 0.049954 meters, which has an opening with a diameter of 0.4 meters. Also, the opening frame with a diameter of 1.6 meters had the highest amount of displacement.

Due to the Tabas accelerometers, the least amount of displacement is observed in the frame with an opening width of 4 meters and a height of 4 meters is 0.031471 meters, which has an opening with a diameter of 0.4 meters. Also, the opening frame with a diameter of 1.6 meters had the highest amount of displacement.

5.2 Study the frame with a width of 5 meters and a height of 4 meters (Frame No. 2)

The results of the displacement resulting from the analysis of time history with three acceleration maps are as follows:

Table 5. Frame displacement with dimensions of 4×5 meters due to the accelerated mappings

Displacement						
Model With Circular Opening	Opening Dimensions			Bam Earthquake Record	Manjil Earthquake Record	Tabas Earthquake Record
	H (m)	L (m)	n			
1	4	5	0.4	0.042123	0.05894	0.039897
2	4	5	0.3	0.038244	0.053983	0.034561
3	4	5	0.2	0.036244	0.051095	0.032095
4	4	5	0.1	0.031239	0.049983	0.031489

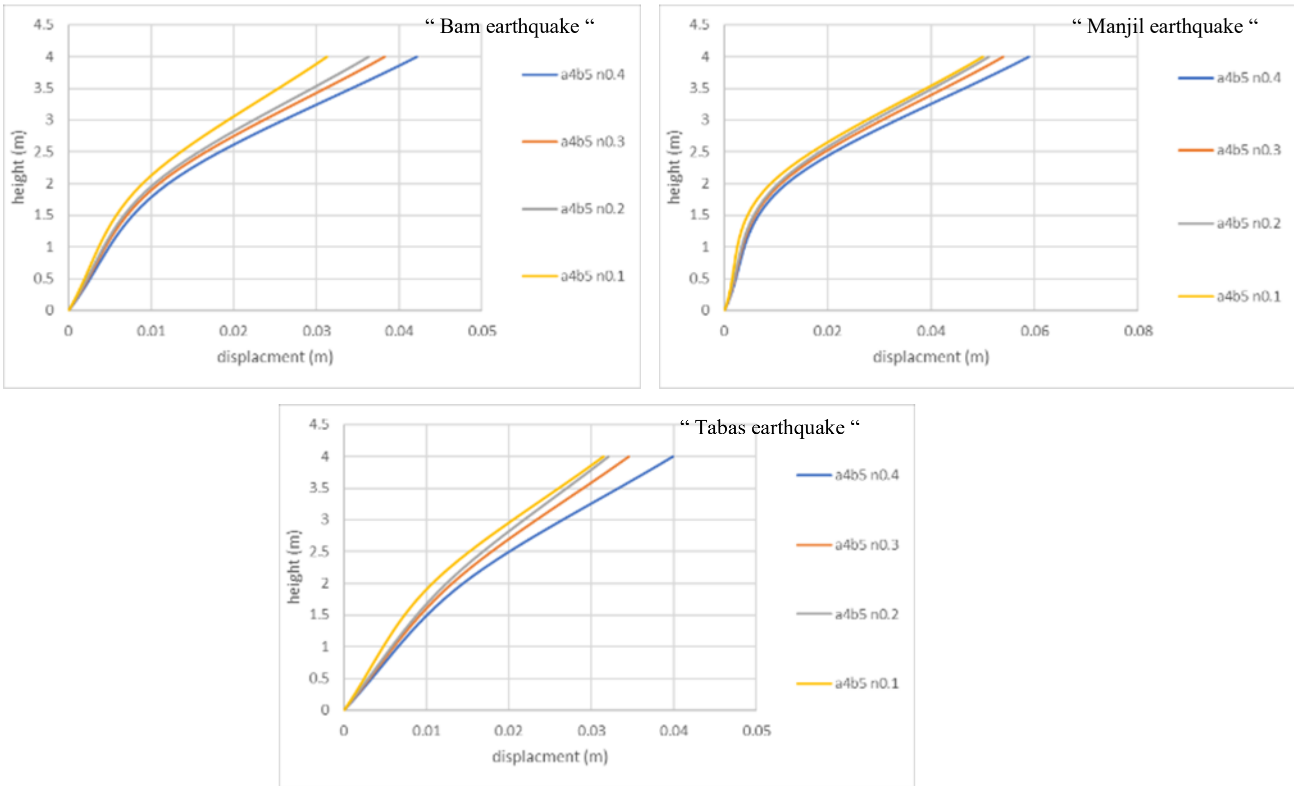


Figure 5. Investigation of frame displacement with dimensions of 4×5 meters due to the Bam, Manjil, and Tabas earthquakes

Due to the Bam accelerometers, the least amount of displacement is observed in the frame with an opening width of 5 meters and a height of 4 meters is 0.031239 meters, which has an opening with a dimension factor of n = 0.1 and an opening with a diameter of 0.4 meters. Also, the opening frame with a diameter of 1.6 meters had the highest amount of displacement.

Due to the Manjil accelerometers, the least amount of displacement is observed in the frame with an opening width of 5 meters and a height of 4 meters is 0.0499 meters, which has an opening with a diameter of 0.4 meters. Also, the opening frame with a diameter of 1.6 meters had the highest amount of displacement. Due to the Tabas accelerometers, the least amount of displacement is observed in the frame with an opening width of 5 meters and a height of 4 meters is 0.031489 meters, which has an opening with a diameter of 0.4 meters. Also, the opening frame with a diameter of 1.6 meters had the highest amount of displacement.

5.3 Study the frame with a width of 6 meters and a height of 4 meters (Frame No. 3)

The results of the displacement resulting from the analysis of time history with three acceleration maps are as follows:

Table 6. Frame displacement with dimensions of 4×6 meters due to the accelerated mappings

Displacement						
Model With Circular Opening	Opening Dimensions			Bam Earthquake Record	Manjil Earthquake Record	Tabas Earthquake Record
	H (m)	L (m)	n			
1	4	6	0.4	0.042096	0.064568	0.038975
2	4	6	0.3	0.039909	0.057654	0.037496
3	4	6	0.2	0.032135	0.055674	0.033508
4	4	6	0.1	0.03124	0.049984	0.03149

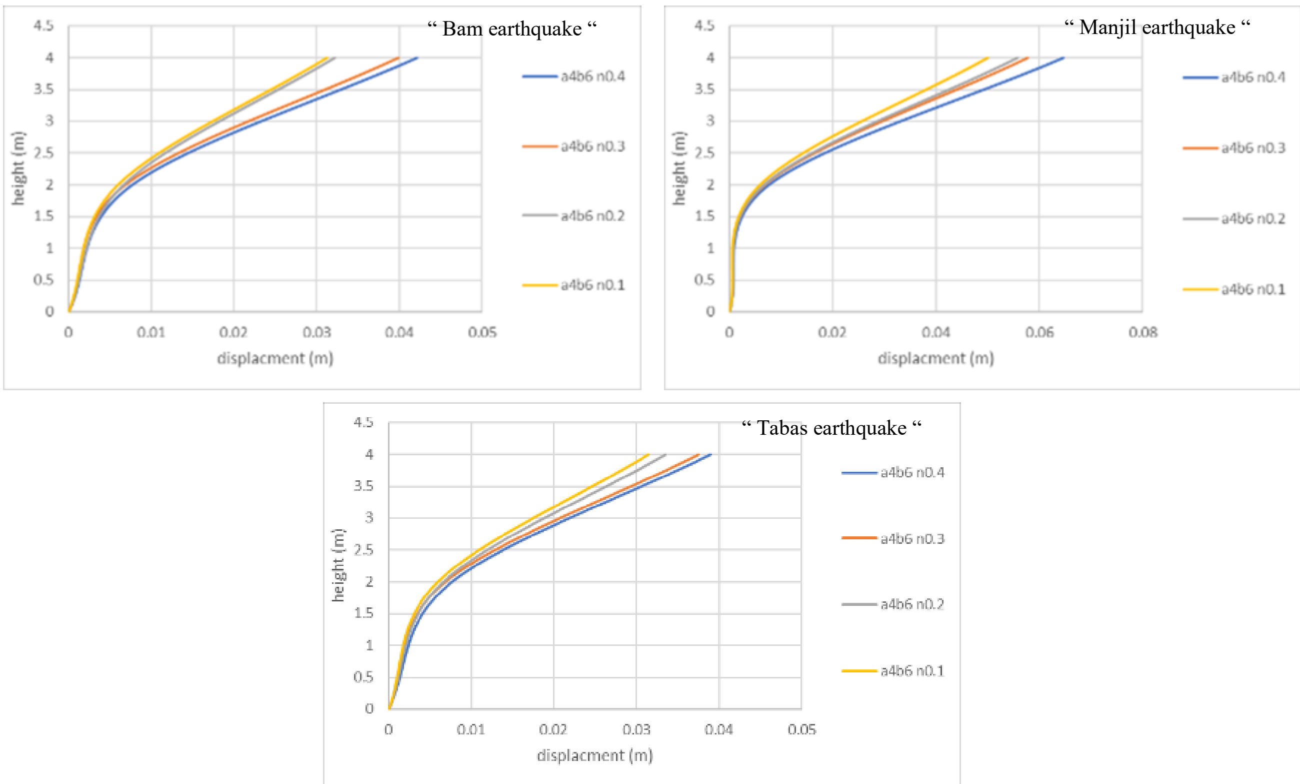


Figure 6. Investigation of frame displacement with dimensions of 4×6 meters due to the Bam, Manjil, and Tabas earthquakes

Due to the Bam accelerometers, the least amount of displacement is observed in the frame with an opening width of 6 meters and a height of 4 meters is 0.03124 meters, which has an opening with a diameter of 0.4 meters. Also, the opening frame with a diameter of 1.6 meters had the highest amount of displacement.

Due to the Manjil accelerometers, the least amount of displacement is observed in the frame with an opening width of 6 meters and a height of 4 meters is 0.049984 meters, which has an opening with a diameter of 0.4 meters. Also, the opening frame with a diameter of 1.6 meters had the highest amount of displacement.

5.4 Study the frame with a width of 6 meters and a height of 5 meters (Frame No. 4)

The results of the displacement resulting from the analysis of time history with three acceleration maps are as follows:

Table 7. Frame displacement with dimensions of 5×6 meters due to the accelerated mappings

Displacement						
Model With Circular Opening	Opening Dimensions			Bam Earthquake Record	Manjil Earthquake Record	Tabas Earthquake Record
	H (m)	L (m)	n			
1	5	6	0.4	0.045298	0.059808	0.038955
2	5	6	0.3	0.038314	0.056103	0.036456
3	5	6	0.2	0.034311	0.052098	0.032561
4	5	6	0.1	0.031299	0.050078	0.031549

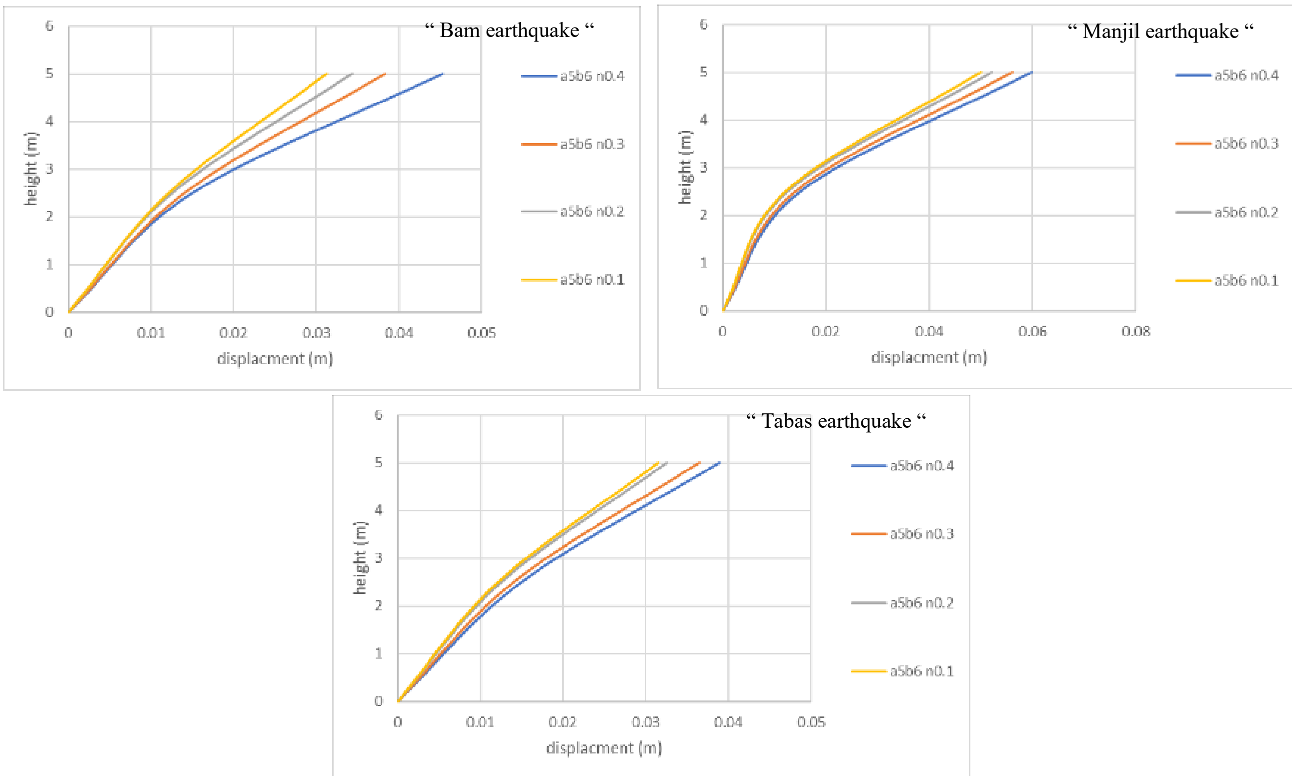


Figure 7. Investigation of frame displacement with dimensions of 5×6 meters due to the Bam, Manjil, and Tabas earthquakes

Due to the Bam accelerometers, the least amount of displacement is observed in the frame with an opening width of 6 meters and a height of 5 meters is 0.031299 meters, which has an opening with a diameter of 0.5 meters. Also, the opening frame with a diameter of 2 meters had the highest amount of displacement.

Due to the Manjil accelerometers, the least amount of displacement is observed in the frame with an opening width of 6 meters and a height of 5 meters is 0.050078 meters, which has an opening with a diameter of 0.5 meters. Also, the opening frame with a diameter of 2 meters had the highest amount of displacement.

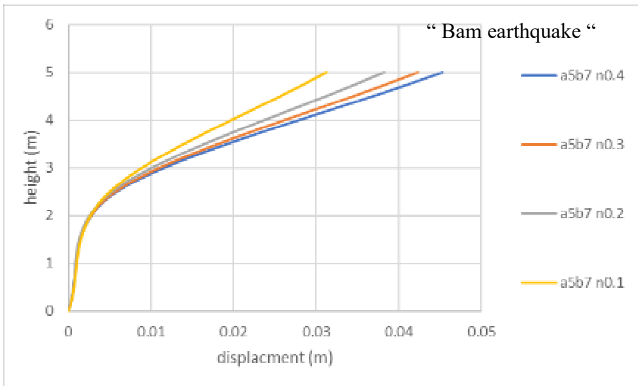
Due to the Tabas accelerometers, the least amount of displacement is observed in the frame with an opening width of 6 meters and a height of 5 meters is 0.031549 meters, which has an opening with a diameter of 0.5 meters. Also, the opening frame with a diameter of 2 meters had the highest amount of displacement.

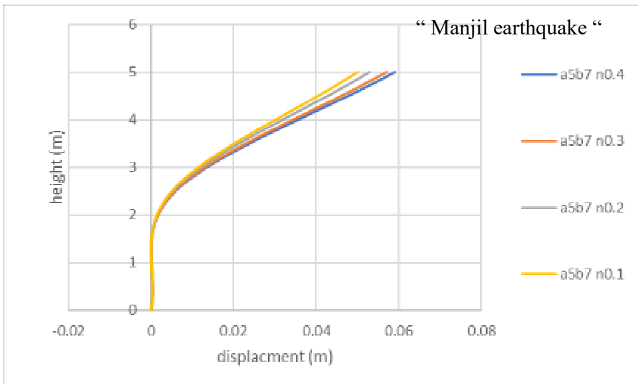
5.5 Study the frame with a width of 7 meters and a height of 5 meters (Frame No. 5)

The results of the displacement resulting from the analysis of time history with three acceleration maps are as follows:

Table 8. Frame displacement with dimensions of 5×7 meters due to the accelerated mappings

Displacement						
Model With Circular Opening	Opening Dimensions			Bam Earthquake Record	Manjil Earthquake Record	Tabas Earthquake Record
	H (m)	L (m)	n			
1	5	7	0.4	0.045343	0.059149	0.039859
2	5	7	0.3	0.042301	0.057082	0.033551
3	5	7	0.2	0.03828	0.053048	0.03253
4	5	7	0.1	0.031298	0.050077	0.031549





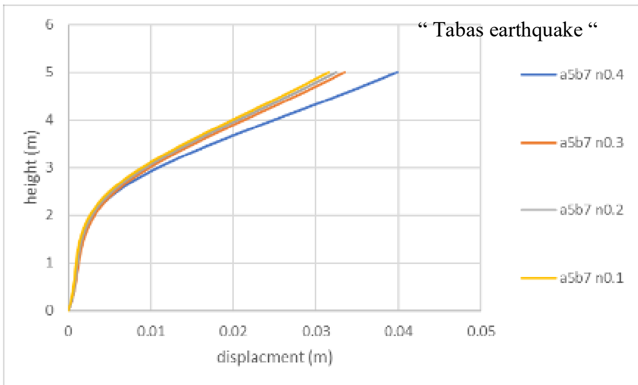


Figure 8. Investigation of frame displacement with dimensions of 5×7 meters due to the Bam and Manjil earthquakes

Due to the Bam accelerometers, the least amount of displacement is observed in the frame with an opening width of 7 meters and a height of 5 meters is 0.031298 meters, which has an opening with a diameter of 0.5 meters. Also, the opening frame with a diameter of 2 meters had the highest amount of displacement. Due to the Manjil accelerometers, the least amount of displacement is observed in the frame with an opening width of 7 meters and a height of 5 meters is 0.050077 meters, which has an opening with a diameter of 0.5 meters. Also, the opening frame with a diameter of 2 meters had the highest amount of displacement. Due to the Tabas accelerometers, the least amount of displacement is observed in the frame with an opening width of 6 meters and a height of 5 meters is 0.031549 meters, which has an opening with a diameter of 0.5 meters. Also, the opening frame with a diameter of 2 meters had the highest amount of displacement.

5.6 Study the frame with a width of 6.5 meters and a height of 5 meters (Frame No.6)

The results of the displacement resulting from the analysis of time history with three acceleration maps are as follows:

Table 9. Frame displacement with dimensions of 5×6.5 meters due to the accelerated mappings

Displacement						
Model With Circular Opening	Opening Dimensions			Bam Earthquake Record	Manjil Earthquake Record	Tabas Earthquake Record
	H (m)	L (m)	n			
1	5	6.5	0.4	0.045443	0.059749	0.039859
2	5	6.5	0.3	0.042301	0.057982	0.033551
3	5	6.5	0.2	0.03818	0.053648	0.03253
4	5	6.5	0.1	0.0321298	0.0506777	0.031549

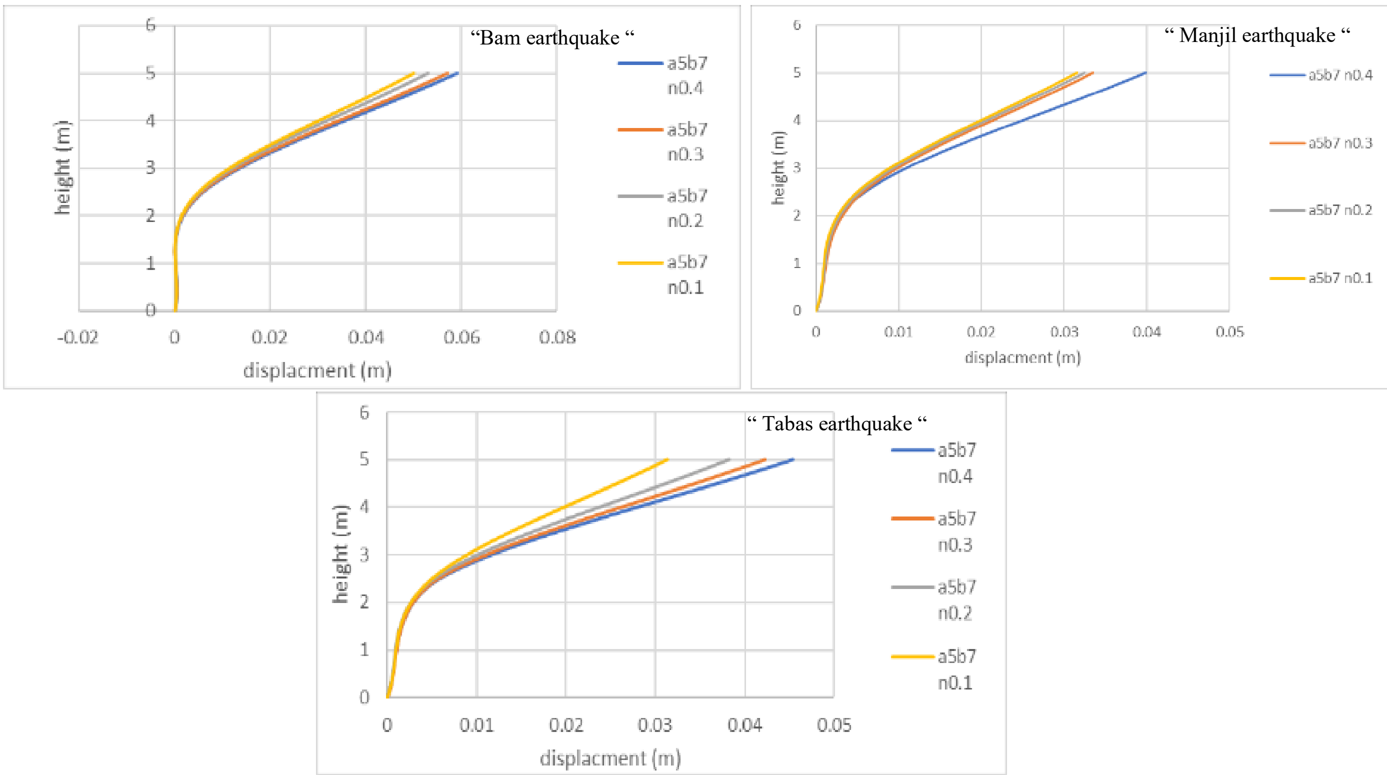


Figure 9. Investigation of frame displacement with dimensions of 5×6.5 meters due to the Bam, Manjil, and Tabas earthquakes

Due to the Bam accelerometers, the least amount of displacement is observed in the frame with an opening width of 6.5 meters and a height of 5 meters is 0.0321298 meters, which has an opening with a diameter of 0.5 meters. Also, the opening frame with a diameter of 2 meters had the highest amount of displacement.

Due to the Manjil accelerometers, the least amount of displacement is observed in the frame with an opening width of 6.5 meters and a height of 5 meters is 0.050677 meters, which has an opening with a diameter of 0.5 meters. Also, the opening frame with a diameter of 2 meters had the highest amount of displacement.

Due to the Tabas accelerometers, the least amount of displacement is observed in the frame with an opening width of 6.5 meters and a height of 5 meters is 0.031549 meters, which has an opening with a diameter of 0.5 meters. Also, the opening frame with a diameter of 2 meters had the highest amount of displacement.

6. Conclusion

Steel shear walls are an effective and economical way to withstand the lateral forces of earthquakes and wind in buildings. Steel shear walls are a very simple system in terms of operation and there is no special complexity in it. Using those saves about 50% in steel consumption compared to bending frames. It can be implemented without the need to acquire new skills, and due to the simplicity and possibility of manufacturing in the factory and on-site installation, the system's speed is high and reduces the operating cost to a great extent. Shear walls not only in steel structures but also in concrete structures are faster replacement in terms of performance, and safer in terms of strength and behaviour than concrete shear walls. The plastic behaviour of this system is significant and its energy absorption rate is much higher than bracing systems. In addition to the high stiffness and shear strength of steel shear walls, this system in terms of the width of the connection (sheet with the surrounding frame) and the lack of a centralized connection such as a bracing system and gradual and uniform stress formation in steel sheet and good ability to adjust stresses until the final load, it is more reliable than other conventional systems and its energy absorption is gradual and with the least general and local weakness. In steel shear walls, using steel sheets the post-buckling phenomenon, similar to sheet beams, can be used without any disturbance in stability. Research from the University of California, Berkeley in 2000 shows that the capacity of steel shear walls to withstand earthquakes, hurricanes, and explosions is at least 25% higher than other systems such as flexural frames [12]. In this study, the seismic behaviour of the steel shear wall system with the concrete shear wall system and the cross-bracing system is compared. After scaling the three accelerations and modelling, these three systems are the result of the success of the steel shear wall system in reducing the displacement of the roof level and the base shear. This factor can help designers and engineers save materials and make the design more economical overall.

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