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Research Article

Use of Geopolymer Mortars in Structural Systems for Earthquake Resistance

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Keywords

Earthquake resistance structure, Geopolymer mortar, Sustainable environment, Shake table test.

Abstract

The high concrete consumption in the construction industry contributes significantly to global CO_2 emissions and energy consumption. Recently, geopolymer concretes have been studied as an alternative to traditional concrete. Studies have shown that geopolymer concretes can contribute to the formation of a sustainable construction environment by reducing energy consumption and C02 emissions. In this study, the use of geopolymer concrete mortars for both sustainable and earthquake-resistant structures was investigated. It is well established that, the first damaged element under the effect of an earthquake is the infill walls. It is thought that making infill walls more resistant to earthquakes will improve the performance of load-bearing elements such as columns and beams. It is known that connecting infill walls to columns with flexible joints will increase the relative story drift capacity of the structure. In the current study, it is aimed to investigate the effect of using traditional and geopolymer mortars on seismic behavior in infill walls connected to columns and beams with flexible joints. In this context, the effect of geopolymer mortars was investigated in the time and frequency domains with shaking table tests applied to two steel frame models produced in a laboratory environment. It was observed that the use of geopolymer mortars reduced both the peak displacement and peak acceleration values of the frame decreased and the dominant frequency values of the structure increased.

1. Introduction

Earthquakes in recent years have shown that infill walls increase the seismic capacity of structural systems [1]. The fact that the first elements of damage during an earthquake are infill walls and that the earthquake energy is consumed at this stage is an important parameter. Earthquake-induced damage and cracking in infill walls can absorb seismic energy, thereby limiting or preventing damage to load-bearing elements such as columns and beams [2,3]. In order for this situation to occur, infill walls have been strengthened [3]. It was observed that the basement and ground floor walls that were not reinforced suffered heavy damage [4]. The importance of strengthening the walls was especially seen in the earthquakes centered in Southern Türkiye [5]. Sakr et al. (2017) modeled a reinforced concrete frame with CFRP reinforced masonry infill walls using the finite element method. The results showed that the CFRP and infill walls showed compatibility and increased the energy absorption and load carrying capacity of the reinforced concrete frame [6]. Liu et al. (2020) used steel fiber reinforced recycled concrete mortars to improve the seismic performance of infill walls. An incremental load test was applied in a laboratory environment. At the end of the study, it was determined that it increased the energy dissipation capacity and the rigidity of the infill wall frame [7].

Borsaikia et al. (2021) applied shaking table experiments to structures at different scales to investigate the effects of infill walls designed with traditional mortars on the earthquake behavior of model reinforced concrete buildings. In model buildings where earthquake data with different characteristics were used, dominant frequency values and acceleration values corresponding to these frequency values were obtained [8]. Wang et al. (2023) investigated the collapse mechanism of reinforced concrete frame with concrete filled steel pipe and infill walls. Experimental and numerical data showed that infill walls increased the lateral load carrying capacity by approximately 55%. It was determined that the load carrying capacity increased by 21% as a result of strengthening the infill walls with CFRP [9]. Kusonkhum et al. (2024) covered the infill wall with expanded metal in diagonal, vertical and horizontal forms to improve the seismic performance of

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the infill walls. The study results showed that the displacement values decreased despite the increase in the base shear force of the frame [10].

However, it is well established that, concrete mortars used in the reinforcement of infill walls cause the depletion of natural resources and the increase in energy consumption. Therefore, concrete consumption harms the environment by producing too much carbon dioxide [11,12]. In addition to preventing this damage to the environment, geopolymer concrete is also an important issue in providing resistance to dynamic or static loads that may affect the structure from outside. Geopolymer concrete is considered a sustainable alternative to traditional Portland cement, offering the potential to mitigate these global issues while also achieving rapid strength gain [13]. Generally, aluminosilicate-based materials such as fly ash and metakaolin are used in geopolymer production. Metakaolin is a 97% kaolin-based binder material that can be adjusted between 20°C and 120°C [14]. Metakaolin SiO_2+Al_2O_3 has high pozzolanic properties [15]. This pozzolanic material exhibits high strength when activated with alkaline solutions. The reason why metakaolin is preferred as the main binder in geopolymers is due to its early strength gain and good compatibility with alkaline activators [16]. Metakaolin is used in geopolymerization reactions due to its high reactivity, Al_2O_3 and SiO_2, and specific surface area. In addition, geopolymer concrete is the result of the chemical reaction between alumino silicate oxides, sodium hydroxide and sodium silicate. It also occurs by activating dusts such as fly ash (FA) and ground granulated blast furnace slag (GGBFS) with sodium hydroxide and sodium silicates [17]. Geopolymer mortars with a pressure value of approximately 160 MPa have been produced in the literature [18].

In this context, a series of studies have been carried out to counter the seismic effects of geopolymer mortars. Maraş and Köse (2021) applied compressive tests in a laboratory environment to the panels produced by reinforcing infill walls with geopolymer composites. It has been determined that geopolymer mortars delay the collapse of the panels and at the same time increase the ductility capacity [19]. Maraş (2021) used latex-added geopolymer mortars for the reinforcement of infill walls. Compressive strength and load-displacement curves were obtained from the test samples subjected to compressive tests. At the end of the study, it was determined that the ductility and compressive strength capacity of geopolymer mortars increased [20]. Geopolymer mortars were used as the main load-bearingmaterial in the construction systems. The seismic behavior of the reinforced concrete frame formed with geopolymer recycled mortars was investigated [21]. In addition, geopolymer mortars were used as reinforcement materials in reinforced concrete column beam joints. The applicability of geopolymer mortars for reinforcement purposes in construction structures was tested with dynamic tests by adding steel fiber reinforcement [8].

Building on this research this study aims to determine use of geopolymer mortars to improve the seismic behavior of infill walls connected to reinforced concrete columns and beams with flexible joints. The aim is to determine the seismic behavior of steel frames with geopolymer mortar and traditional concrete mortar infill walls in a laboratory environment by using the acceleration data of the earthquakes centered in Southern Türkiye.

2. Testing Process

2.1. Test specimens and properties

In the experimental system, single-span and single-story infill wall steel frames were produced by connecting the infill walls to the columns with flexible joints as defined in the Turkish Building Earthquake Code 2018 (TBEC 2018) in Figure 1 [26]. The steel frames were designed to have a span of 1.50 m and a height of 1.50 m. Infill walls were used in accordance with the standard with the dimensions of 19x8.5x19 cm [22]. The columns and beams used in the infill wall steel frame were used with the dimensions of 80x5 mm and S235 N/NL quality [23]. The infill wall steel frames produced with flexible joint connections with geopolymer and traditional cement mortar are shown in Figure 2. Wet concrete tests were carried out using 200 g of water, 350 g of cement and 1750 g of stream aggregate and sand in 1 cm^3 in the traditional cement mortar mixture shown in Figure 2a [25]. In the geopolymer mortar mixtures shown in Figure 2b, wet concrete tests were completed using 150 g water, 64.35 g NaOH (Sodium Hydroxide), 160.65 g Na_2SiO_3 (Sodium Silicate) and 1121 g limestone per 1 cm^3 [24]. Hardened concrete tests were performed on 15x15x15 cm cube samples and 10x20 cm cylinder samples [25]. The hardened concrete test results showed that the average compressive strengths of both mixtures were approximately 12-13 MPa.

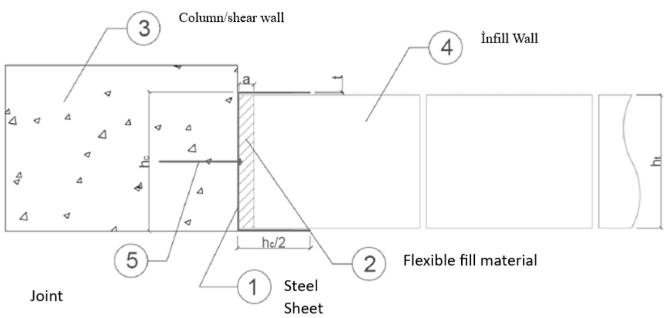

Figure 1. Connection of infill walls to steel columns by leaving a flexible joint (TBEC 2018)

(a) (b)

Figure 2. Steel frames with infill walls; a) traditional mortar (TM), b) geopolymer mortar (GM)

The infill wall steel frame models shown in Figure 2 were planned to be placed in the shaking table test setup shown in Figure 3. A shaking table with servo-electric actuator, 2000 mm x 2000 mm dimensions, 1.5-ton vertical load capacity, 200 mm movement length, maximum empty table acceleration of 4 g, maximum speed of 500 mm/s and 1 g earthquake acceleration loading capacity was used in the experimental setup. The frequency range of the shaking table is between 0-1000 Hz. A two-axis analog accelerometer with ±8 g acceleration capacity and analog output was used to measure the peak acceleration values formed in the frames and transfer them to the 16-channel data acquisition unit. In addition, displacement meters (LVDT) that can measure 200 mm displacement were used to measure the peak displacement values.

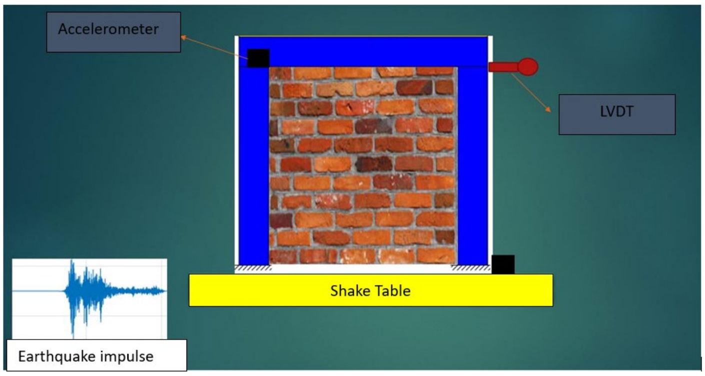

Figure 3. Experimental setup

The experimental setup planned in Figure 3 was created in the laboratory environment as shown in Figure 4. The acceleration and displacement values occurring at the top of the model steel frame due to the earthquake effect were transferred to the data collection unit. The infill walls are rigidly connected to each other with mortar. They are also placed in a way that they can withstand pressure under the effect of earthquake load.

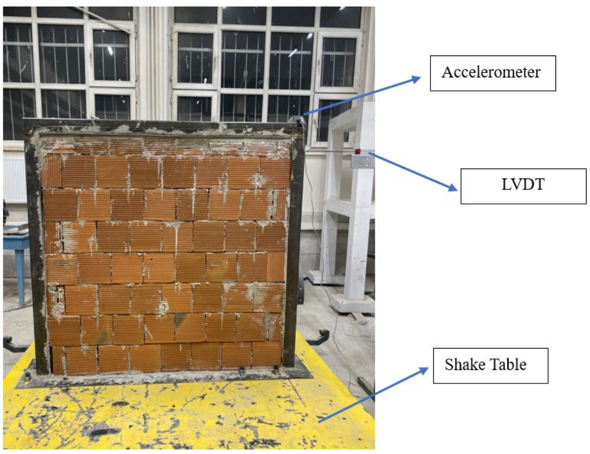

Figure 4. Measuring devices used in experiments

2.2. Earthquake records

In the shaking table experiments, the earthquake records of Elbistan (Mw=7.6), Pazarcık (Mw=7.7) and Nurdağı (Mw=6.6) centered in Southern Türkiye on February 06, 2023 were used. The characteristic features of the earthquakes are given in Table 1.

Table 1. Characteristics of the earthquake records used in the study

Earthquake's	Date	Station	Latitude	Longitude	PGA (g)	Magnitude (Mw)
Elbistan	06.02.2023	Göksun	38.089	37.239	0.648	7.6
Pazarcık	06.02.2023	Pazarcık	37.288	37.043	2.07	7.7
Nurdağı	06.02.2023	Nurdağı	37.304	36.92	0.454	6.6

Three different earthquake records with peak ground acceleration (PGA) ranging from 0.45 to 2.07g were used in shaking table experiments. Assuming that the steel frames with infill walls are located at 39.9026 Latitude and 41.2498 Longitude locations and the soil class is ZD, the earthquake records were scaled according to TBEC 2018 [26]. In the horizontal elastic acceleration spectrum drawn specifically for the structure within the scope of TBEC 2018, the acceleration values between 0.2 Tp and 1.5 Tp were matched with the earthquake spectrum acceleration values in the same range. Figure 5 shows unscaled and scaled earthquake acceleration graphs. Figure 6 presents the spectrum curves matched with the horizontal elastic acceleration spectrum of the structure.

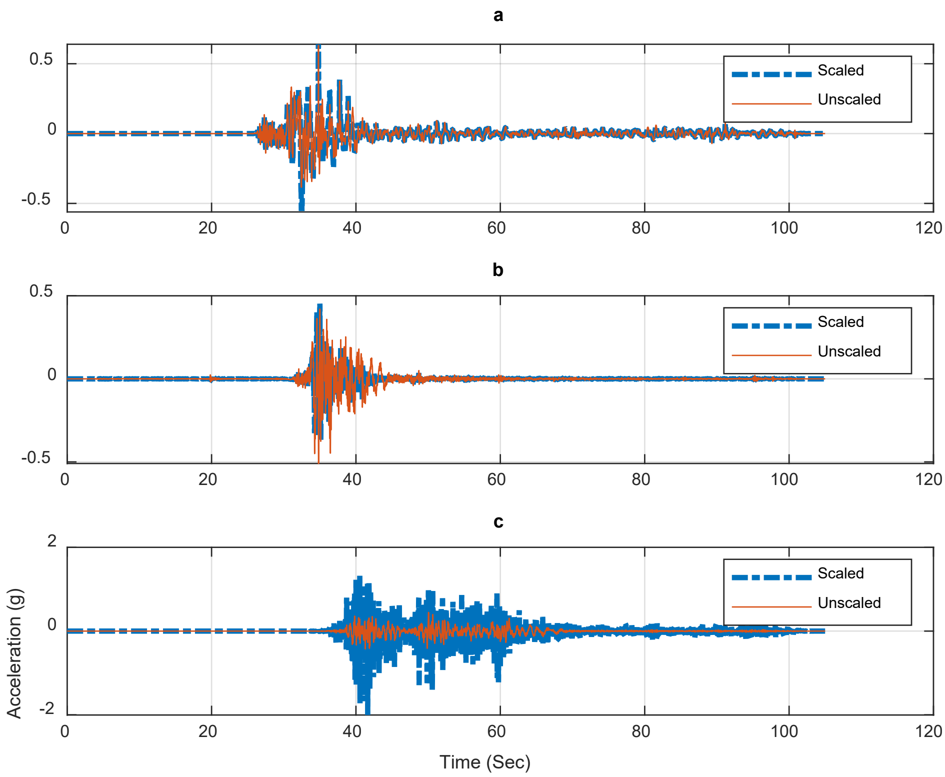

Figure 5. Time-acceleration in the time domain

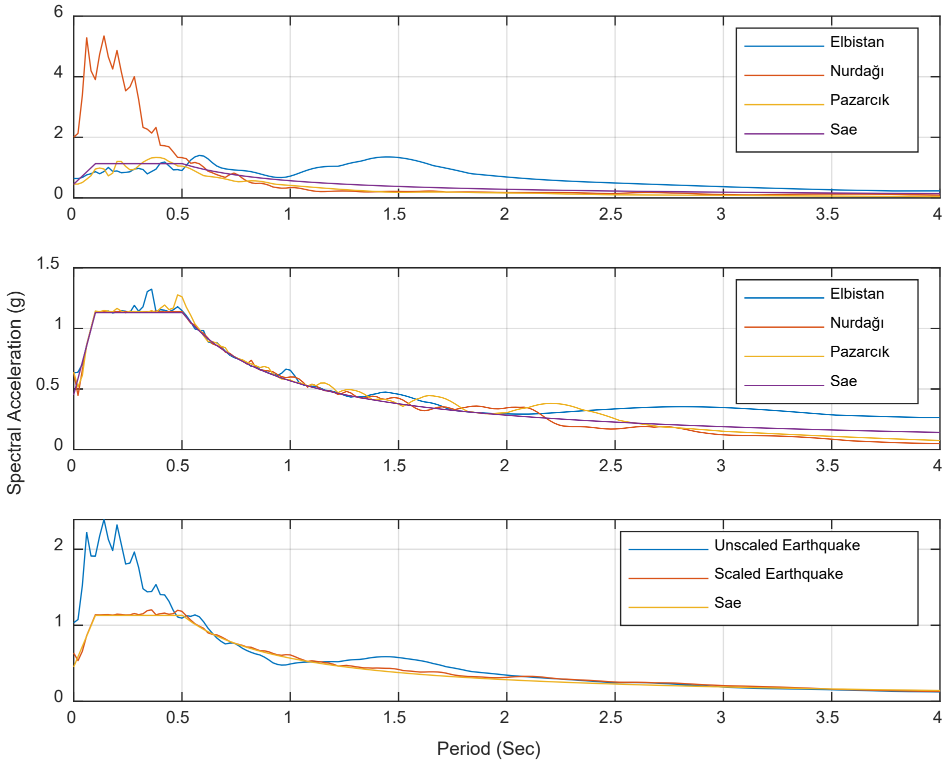

Figure 6. Earthquake spectrum

It is understood from Figure 5 and Figure 6 that the shaking table experiments were carried out on a scale with an average earthquake ground acceleration of approximately 0.5 g and a spectral acceleration of 1.20 g.

3. Experimental results

Shaking table tests were applied on two model steel frames produced as a result of using traditional cement mortar(TM) and geopolymer concrete (GM) mortars in the infill wall joints of the flexible jointed infill wall steel frame. In the shaking table tests, acceleration data belonging to the Pazarcık (Mw=7.7), Elbistan (Mw=7.6) and Nurdağı (Mw=6.6) earthquakes that occurred in the south of Türkiye on February 06, 2023 and whose epicenter was Maraş were used. Acceleration values were scaled specifically for model steel frames and taken into account in the experiments. Average acceleration values of 0.5 g in terms of peak ground acceleration and 1.20 g in terms of spectral acceleration were designed and used. In the experiments, peak acceleration values, peak displacement values and analyses in the frequency domain were taken into account.

The peak acceleration values, measured in g, were obtained. The acceleration values at the top of the traditional cement mortar model are given in Figure 7.

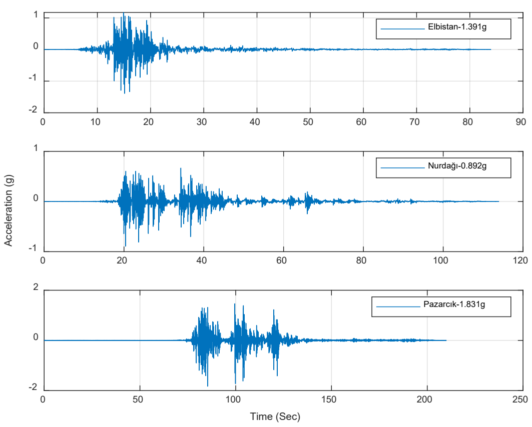

Figure 7. Peak acceleration values in the TM

For the TM model, the Pazarcık earthquake created the highest acceleration value (1.831g). It was determined that the Pazarcık earthquake created 24.03% and 51.28% more acceleration datas than the Elbistan and Nurdağı earthquakes, respectively. It was observed that the Pazarcık and Nurdağı earthquakes created higher acceleration valuesin the -X direction, while the Elbistan earthquake created higher acceleration valuesin the +X direction. The acceleration values at the top of the geopolymer mortar model (GM) are given in Figure 8. For the GM model, the Pazarcık earthquake created the highest peak acceleration value (1.464 g). In the GM model, it was determined that the Pazarcık earthquake created 57.58% and 64.95% more acceleration values than the Elbistan and Nurdağı earthquakes, respectively. It was determined that the earthquakes affecting the frames created effective acceleration values in both directions.

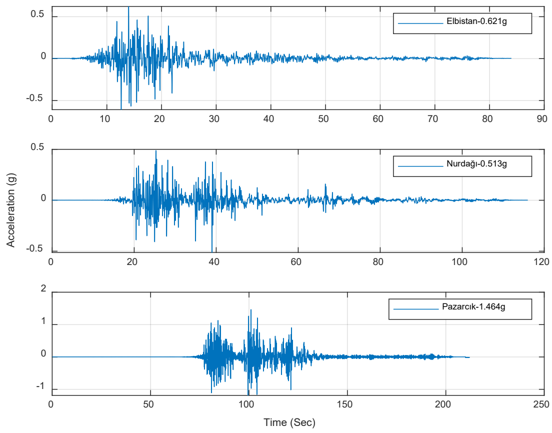

Figure 8. Peak acceleration values in the GM

The peak acceleration values resulting from earthquakes in the GM model and the TM model are given comparatively in Figure 9. The peak acceleration values in the TM model were 56.01%, 23.08%, and 20.04% lower than those in the GM model for the Elbistan, Nurdağı, and Pazarcık earthquakes, respectively. The effectiveness of geopolymer mortars in reducing peak acceleration values decreased with increasing earthquake moment magnitude.

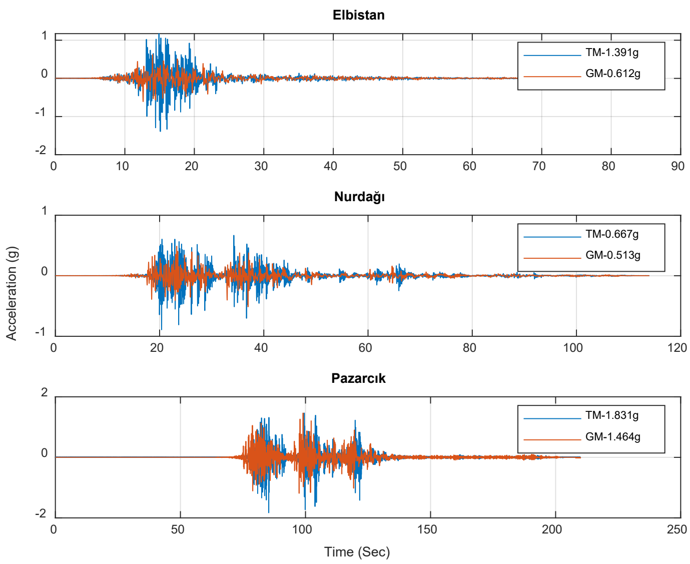

Figure 9. Peak acceleration values in the GM and TM model

Another result obtained in the shaking table tests is the dynamic peak displacement values. Dynamic displacement values caused by earthquakes in the TM model are given in Figure 10. It was determined that the Elbistan earthquake created the largest displacement value with a value of 128.45 mm. It was determined that the peak dynamic displacement values created by the Elbistan earthquake in the model were approximately 60.02% and 64.86% higher than the peak dynamic displacement values of the Pazarcık and Nurdağı earthquakes, respectively.

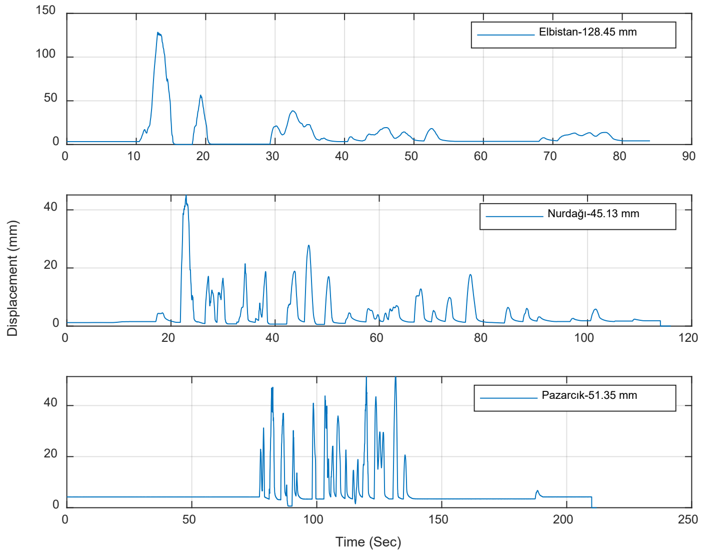

Figure 10. Dynamic displacement values in the TM model

Dynamic displacement values caused by earthquakes in the GM model are given in Figure 11. It was determined that the Elbistan earthquake created the largest displacement value with a value of 115.44 mm. It was determined that the peak dynamic displacement values created by the Elbistan earthquake in the model were approximately 44.22% and 234.60% higher than the peak dynamic displacement values of the Pazarcık and Nurdağı earthquakes, respectively in the GM model.

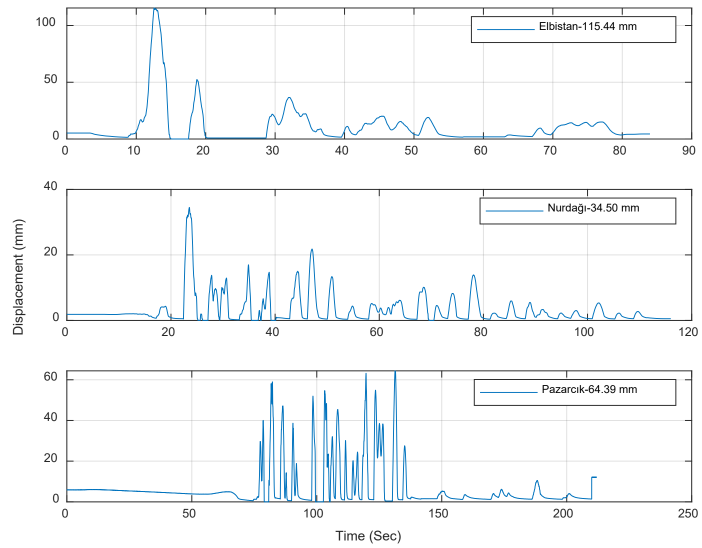

Figure 11. Dynamic displacement values in the GM model

A comparison of dynamic displacements between TM and GM models reveals are compared separately for each earthquake in Figure 12. It was determined that the peak acceleration values generated by the Elbistan and Nurdağı earthquakes in the TM model were 10.12% and 23.55% less than the peak acceleration values generated in the GM model, respectively. However, the use of geopolymer mortars caused the dynamic displacement values caused by the Pazarcık earthquake to increase by 20.25%. This outcome may be attributed to the relative distance of the Pazarcık earthquake being more distant from the structure compared to other earthquakes or to the energy that the earthquake generated relative to the structure.

Frequency domain analyses were performed in GM and TM models. The dominant frequency values and corresponding amplitude values of the structure in response to each earthquake effect were compared. Fast Fourier transforms (FFT) resulting from the Pazarcık earthquake in the GM and TM models are shown as semi-logarithmic plots in Figure 13. The dominant frequency value of the TM model was calculated as 7.29 Hz and the corresponding amplitude value was 2.146 g. It was determined that the GM model reached an amplitude value of 1.52 g at 3.44 Hz.

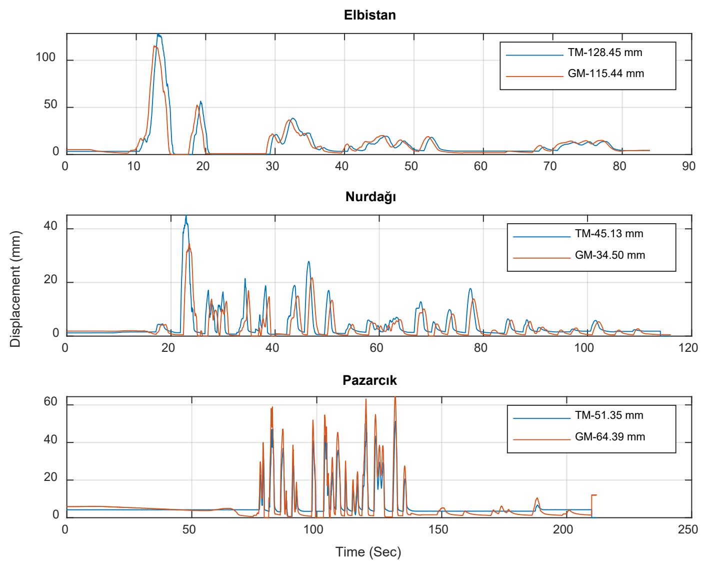

Figure 12. Dynamic displacement values in the GM and TM model

In Figure 13, it is concluded that the GM model oscillates less against the Pazarcık earthquake at the dominant frequency values, but the TM model behaves more rigidly against the GM model. This statement has been added to the relevant section.

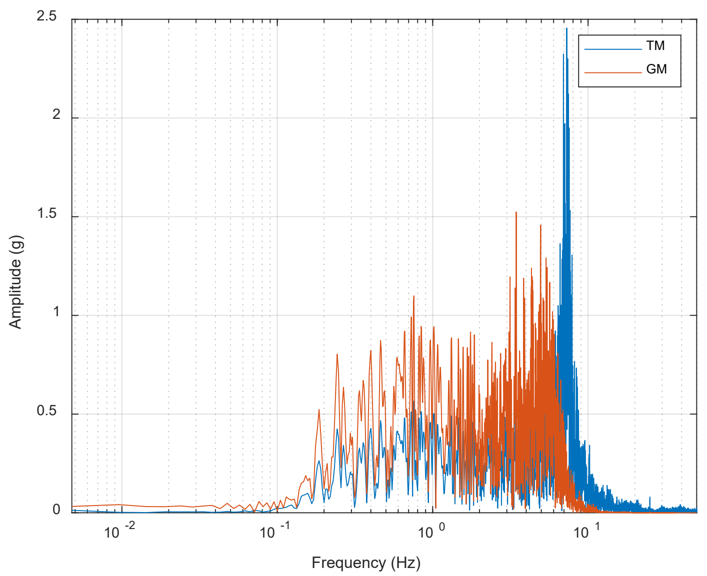

Figure 13. Frequency domain response of TM and GM models during Pazarcık earthquake (FFT analysis)

The frequency values and corresponding amplitude values resulting from the Elbistan earthquake in the GM and TM models are given in Figure 14. It was determined that the TM and GM models reached amplitude values of 1.84g and 0.36g at the dominant frequency values of 7.29 Hz and 4.53 Hz, respectively. It was concluded that the TM model reached high acceleration values with a more rigid behavior, while the GM model reached lower acceleration values with a more flexible behavior. In Figure 15, the frequency and corresponding amplitude values occurring in the GM and TM models are given for the Nurdağı earthquake. It was calculated that the amplitude value of 0.90 g occurred in the TM model with a dominant frequency value of 6.96 Hz and that it reached an amplitude value of 0.523 g with a dominant frequency value of 5.22 Hz in the GM model. It was concluded that the effect of the Nurdağı earthquake produced similar results to the effects of the Pazarcık and Elbistan earthquakes.

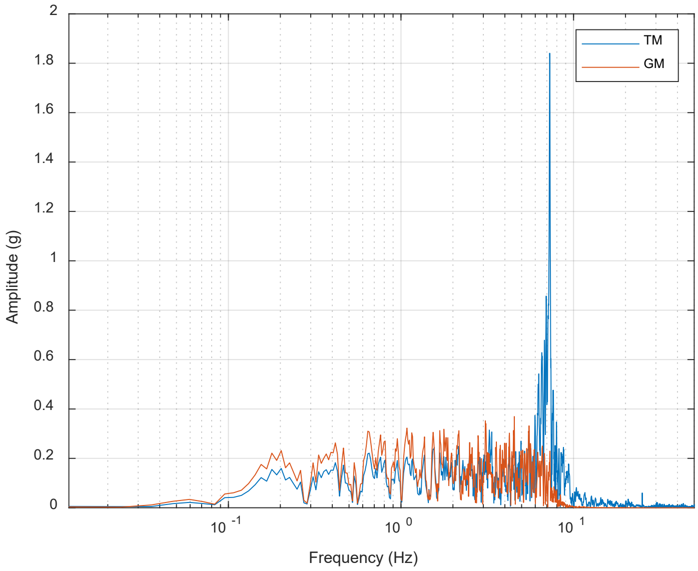

Figure 14. Frequency domain response of TM and GM models during Elbistan earthquake (FFT analysis)

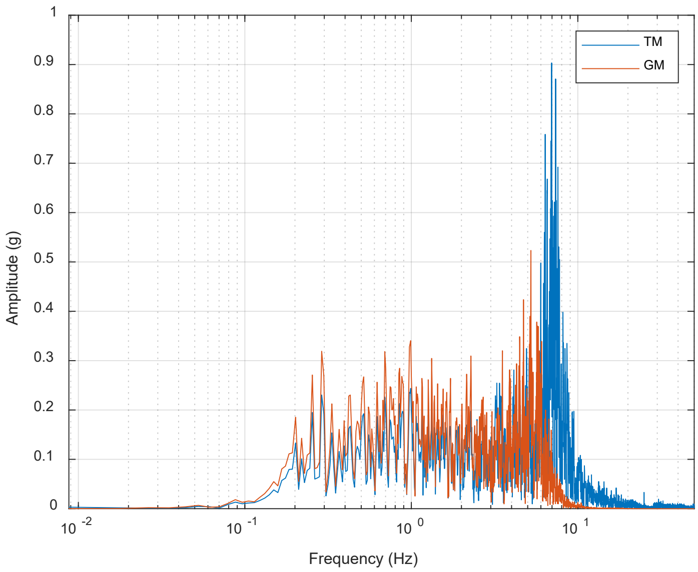

Figure 15. Frequency domain response of TM and GM models during Nurdağı earthquake (FFT analysis)

4. Conclusion

This study aims to investigate the effect of geopolymer mortars on the seismic behavior of infill wall structural systems. It is aimed to determine the changes that may occur in terms of peak displacement, peak acceleration and frequency contents when geopolymer mortar is used instead of traditional concrete mortar in model frames where infill walls are flexibly connected to columns and beams. For this purpose, model steel frames with infill walls and traditional concrete mortar were produced and subjected to shaking table tests. In shaking table tests, Pazarcık (Mw=7.7), Elbistan (Mw=7.6) and Nurdağı (Mw=7.6) earthquake data were used by scaling them specifically for model frames. The results of the study are summarized below. The results summarized below are given by averaging three earthquakes affecting infilled wall frames.

- The use of geopolymer mortars in the model steel frame resulted in average reductions of 36.83% in peak acceleration values and 14.28% in dynamic displacement values.
- Geopolymer mortars reduced the average dominant frequency of the structure by 38.85% and the average amplitude by 50.85%, indicating a significant reduction in earthquake-induced oscillations. It has been concluded that geopolymer mortars significantly reduce the oscillations that will occur in the structure against earthquake effects.
- The experimental results showed that the improvement of the seismic performance of the structure by geopolymer mortars decreased as the earthquake moment magnitude increased. This means that the improvement percentage decreases.

- The use of geopolymer mortars reduced the peak acceleration and displacement values at very different rates. The experimental results showed that the use of geopolymer mortar was approximately 60% more effective in reducing displacements than reducing the peak acceleration values. This is due to the early setting of the geopolymer mortar and the fact that it is an impermeable mortar.
- The experimental results showed that the use of geopolymer mortars was effective in reducing the dynamic displacement values in the Elbistan and Nurdağı earthquakes, but was ineffective in the Pazarcık earthquake. This situation was thought to be due to the directional effect of the earthquake. The directional effect of the earthquake on the building is a common situation in far-field earthquakes. The dynamic behavior similarities of some far-field earthquakes with the structure reveal these results.
- At the end of the study, it was found that some innovative studies should be tried in order for geopolymer mortars to be fully effective in reducing dynamic parameters such as peak displacement, peak acceleration values and oscillation values. It was suggested that the mixing ratios of geopolymer mortars that could reduce the displacement effect may need to be changed. Or, it was thought that fiber-reinforced geopolymer mortars that could absorb more earthquake energy by increasing the ductility capacity could be tried.

In the study, it was concluded that geopolymer mortars, which provide sustainable construction better than traditional concrete, can be used as reinforcement material in earthquake-resistant building design, in addition to reducing $C0_2$ emissions and energy consumption. In the future, geopolymer mortars can be studied more under earthquake effects in model frames with different types of connections.

Nomenclature

FFT: Fast Fourier transform
g: Gravitational Acceleration
GM: Model Frame with Geopolymer Mortar
LVDT: Linear Derivation Displacement Transducer
Mm: Millimeter
Mw: Magnitude of Moment in the Earthquake
N: Newton
PGA: Peak Ground Acceleration
Sae: Horizontal Elastic Acceleration Spectra for TBEC 2018
S235 N/NL: Steel Material Class with a Yield Strength of 235 N/mm^2
TBEC 2018: Turkish Building Earthquake Code 2018
TM: Model Frame with Conventional Mortar

Declaration of Conflict of Interests

The authors declare that there is no conflict of interest. They have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. This article was written within the scope of the master's thesis titled "Investigation of The Effects of Infill Walls Reinforced with Geopolymers on The Seismic Behavior of Steel Frames".

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