Konya Mühendislik Bilimleri Dergisi, c. 11, Özel Sayı, 42-54, 2023
Konya Journal of Engineering Sciences, v. 11, Sprecial Issue, 42-54, 2023
ISSN: 2667-8055 (Electronic)
DOI: 10.36306/konjes.1386827

COMPARISON OF NUMERICAL ANALYSIS OF A SINGLE-SPAN STEEL PROTOTYPE STRUCTURE AND A SCALE MODEL STRUCTURE UNDER THE EFFECT OF SEISMIC LOADS

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Highlights

- In this study, a scaling factor (λ=10), which is widely accepted in the literature, was used to design a scaled model to represent a three-storey single-span life-size structure.
- In the analysis of the prototype and scaled structure with the Sap2000 program, time history analyzes were made using the real and scaled earthquake records of El Centro (1940), Kobe (1995) and Northridge (1994).
- The time history analyses of the prototype and the scaled structure were compared by looking at the acceleration and displacement values of each floor and it was seen that the results were close to each other when scaled according to the scaling factor (λ).

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(Received: 06.11.2023; Accepted in Revised Form: 03.12.2023)

ABSTRACT: One of the biggest problems encountered in many experimental studies is examining a real-size structure in the field or in a laboratory environment. With today's technological opportunities, it is possible to experimentally examine a real-sized structure in the field or in a laboratory environment. However, to do this, the manufacture of a large, real-size structure, experimental setup and measuring devices are required, which are costly. For this reason, it is not always possible to reach such a laboratory environment. It is very difficult to experimentally examine large-scale structures both economically and in terms of time saving. In this context, in this study, a scaling factor (λ) widely accepted in the literature was used to design a scaled model to represent a real-size structure. λ=10 was used in this scaling approach. A real-size three-story single-span steel prototype building was scaled to a laboratory-scale model structure and analyzed digitally with the Sap2000 program. The natural period/frequency values of the real-size prototype structure and the scaled model modeled in the Sap2000 program were examined. Later, Time history analyzes were performed using real earthquake records from El Centro (1940), Kobe (1995) and Northridge (1994). While real earthquake records were used as they were in the analysis of the prototype structure, these real earthquake records were used by scaling them depending on the scaling factor λ in the analysis of the scaled model. Subsequently, the digital analyzes of the prototype and scaled structure were compared by looking at the acceleration and displacement values of each floor. It was observed that the results were close to each other when scaled according to the scaling factor (λ). This situation demonstrated the accuracy of the scaling rates applied within the scope of the study. Thus, it has been shown that a real-size structure can be scaled to a model in a laboratory environment with correct scaling methods and that this prototype structure can be analyzed with more economical and simple methods.

Keywords: *Prototype model, Structure ccaling, Seismic loads, Earthquakes, Time history analysis*

1. INTRODUCTION

Within the scope of this study, although the studies presented in the literature related to scaling are generally on the structure-soil-pile interaction, scaling of the superstructure has also been done. Conducting a systematic study on scaling, Hokmabadi et al. [1] developed a scaling method in their study by taking into account all structure and ground-related parameters. This method, which pioneered many studies in the literature, made it possible to scale a prototype structure, ground or pile to represent the prototype structure, ground or pile in a laboratory environment. Meymand et al. [2] pointed out that, using this method, the natural frequency of the prototype should be scaled with an appropriate scaling relationship. It has been shown that by defining scaling conditions for density and acceleration, mass, length and time scale factors can be expressed in terms of the geometric scaling factor (λ) and a complete dimensional scaling relations can be derived for all variables examined.

Thejaswini et al. Experiments were carried out in a laboratory environment by scaling two five-storey and three-span buildings. Similarly, they scaled the model representing the prototype structure according to scaling laws. Shaking table tests of scale building models were carried out. The results obtained in

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experimental and numerical studies have been compared [3,4]. They scaled the scaled model representing the 15-storey prototype building. They carried out single-axis shaking table tests of the superstructure model along with the ground model [5]. Shaking table experiments were carried out in a laboratory environment to better understand the dynamic behavior of a 10-storey scaled model representing a prototype structure. The scaling method was analyzed numerically and the period and frequency values obtained experimentally were compared. The values obtained from the results were found to be compatible and results close to the desired results were found according to the scaling method [6].

What is planned in this study is to scale the prototype structure and check whether the designed model structure's behavior in the digital environment is compatible. In addition, time history analysis under the influence of seismic loads was performed and the results obtained were checked with the scaling method and similar results were tried to be obtained. It will be a guide in terms of having the opportunity to observe the behavior of the planned prototype structure in advance and helping us determine the design criteria.

2. METHOD AND NUMERICAL ANALYSIS

2.1. Scaling Method

The purpose of using the scaling method is that it is not always possible to carry out real-scale experiments in terms of physical and infrastructure. Even if it were done, this would be very costly in economic terms. Instead of working at real scale, it is possible to reach an approximate conclusion by examining the laboratory experiments of the model structure, which is scaled with the λ scaling factor according to Table 1, which represents the prototype structure in the laboratory. In order to design the scaled model, the first step to be followed is to scale the model structures by taking into account the natural period/frequency, mass density, material properties and dimensions of the prototype structure, using the relations given in Table 1, with the help of scaling factors. While scaling within the scope of this study, the scaling factor was determined to be λ=10. This scale ratio was used to scale the parameters given in Table 1 below.

Table 1. Scaling relationships in terms of the geometric scaling factor (λ) [1]

Parameters	Scaling relationship
Mass density	1
Force	λ^3
Stiffness	λ^2
Modulus	λ
Acceleration	1
Shear-wave velocity	$\lambda^{1/2}$
Time	$\lambda^{1/2}$
Frequency	$\lambda^{-1/2}$
Length	λ
Stress	λ
Strain	1
EI	λ^5

2.2. Prototype Structure and Scaled Model

The features of the prototype structure and scaled model used in numerical analysis are given below. As can be clearly seen from Figure 1, the prototype building has three floors and a single span. The floor heights and floor spans of the steel prototype building are designed as 3 m. Material properties and cross-

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sections of the column, beam and floor of the prototype are shown in Table 2.

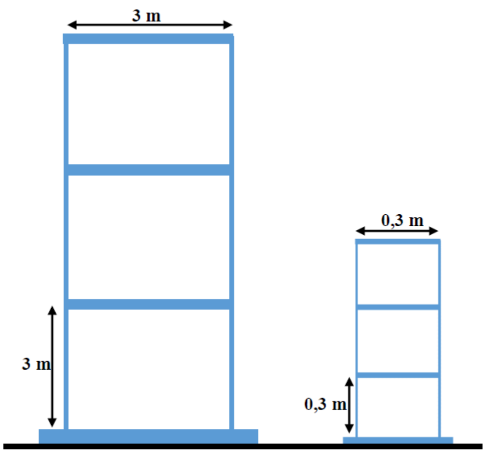
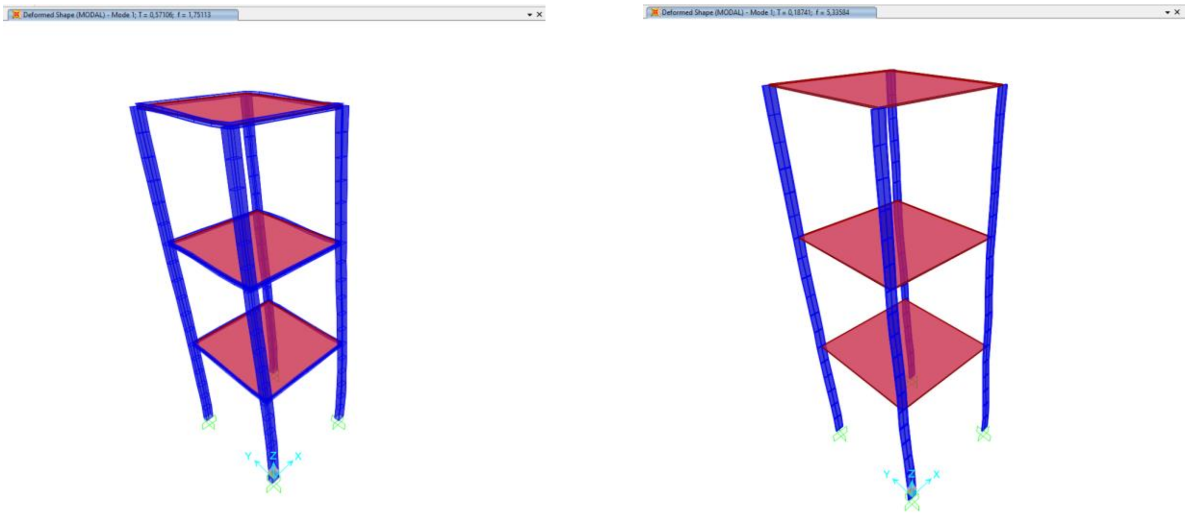


Figure 1. Designed prototype structure and scaled model

In scaling the prototype structure, which is a three-storey sliding frame, to the laboratory environment, the scaling ratio was chosen as λ=10. The parameters and their values that we will consider only in scaling the superstructure are given in Table 2 below. As can be clearly seen in Figure 1 above, the scaled building is scaled according to the prototype structure as a three-storey and single-span building. The floor heights and floor spans of the model building are determined as 0.3 m. The scaled model is designed as a steel structure. The material properties and cross-sections of the column and floor of the model building are shown in Table 2.

As can be seen in Figure 1, the prototype structure was first scaled by taking into account mass density, natural vibration frequency and geometric ratios. The mass densities of the prototype structure and model structure were kept constant as the scaling ratio was "1". Floor heights and floor openings were reduced by 10 times by λ. It is not correct to only do geometric scaling when scaling the column sections and material properties of the building. For the cross-sections and material elasticity modulus to be designed for the scaled model structure, the columns of the prototype structure must be scaled according to the flexural stiffness. From here, the column sections and material elasticity module of the model were determined. The flexural stiffness (EI) of the prototype was divided by λ^5 to obtain the flexural stiffness of the model structure depending on the geometric scaling factor (λ). Modal analyzes of the prototype and scaled model, whose column cross-sections and material properties were determined, were performed in the Sap2000 program. From these analyses, the natural vibration periods/frequencies of the structure were calculated. While the natural period of the prototype structure (T_n=0.57106 sec) was adjusted to be $\lambda^{1/2}$ times the natural period of the scaled model structure (T_n=0.18741 sec), the natural frequency of the prototype structure (f_n=1.75113 Hz) was adjusted to be $\lambda^{-1/2}$ times the natural frequency of the scaled model structure (f_n=5.33584 Hz). These period/frequency values were determined by trial and error using modal analysis in the Sap2000 program. Figure 2 shows the visuals of the structures whose modal analysis was performed in the Sap2000 program.



(a) (b)

Figure 2. (a)Designed prototype structure; (b)Scaled model Modal analysis in Sap2000 program

The data of the prototype structure and the scaled structure are given in detail in Table 2 below. A model building design was made by scaling the created prototype structure. By analyzing the prototype and scaled model in the Sap2000 program, period/frequency values expressing the dynamic behaviors of the structures were also obtained.

Table 2. Features of the prototype and model structure

Parameters	**Prototype structure**		**Model structure**	
Number of floors	3		3	
Total height of the structure (m)	9		0.9	
Each floor height(m)	3		0.3	
Material type	Steel		Steel	
Material modulus of elasticity, *E* (MPa)	210000		210000	
Moment of inertia, *I* (m^4)	$2.339\ 10^{-5}$		$2.25\ 10^{-10}$	
Flexural stiffness of columns, *EI* (Nm^2)	4912.629		$4.725\ 10^{-2}$	
Column dimensions (m)	h	0.25	h	0.025
	b	0.15	b	0.003
	t	0.008		
Beam dimensions (m)	h	0.1	-	
	b	0.055		
	t_f	0.0057		
	t_w	0.0041		
Slab thickness (m)	0.03		0.003	
Natural period, T_n (sec)	0.57106		0.18741	
Natural frequency, f_n (Hz)	1.75113		5.33584	
Mass density, ρ (kg/m^3)	105.336		106.667	

Sap2000 analysis of the created prototype structure was performed. Using the scaling method, the same values of the scaled model were calculated, taking into account the mass density of the prototype structure, period/frequency and flexural stiffness of the columns. The mass density of the designed scaled model and the flexural stiffness of the columns were modeled in the Sap2000 program and natural period/frequency values were obtained by performing modal analysis. The parameters obtained from the properties of the prototype structure according to the scaling method and the results obtained from the analysis of the scaled model are given in Table 3 below. When these values are compared, they are quite close to each other.

Table 3. Features of the prototype and model structure

Parameters	Prototype structure (Sap2000)	Model structure (Scaled)	Model structure (Sap2000)
Mass density, ρ (kg/m^3)	105.336	105.336	106.667
Natural period, T_n (sec)	0.57106	0.18058	0.18741
Natural frequency, f_n (Hz)	1.75113	5.53756	5.33584
Flexural stiffness of columns, EI (Nm^2)	4912.629	4.913 10^{-2}	4.725 10^{-2}

2.3. Scaling of earthquakes

Three real earthquake records were selected as the earthquake ground motion to be applied to the structure. El Centro (1940), Kobe (1995) and Northridge (1994) earthquake records were used. Some features of these earthquake records are seen in Table 4.

Table 4. Earthquake records and some reference features to be used in analysis

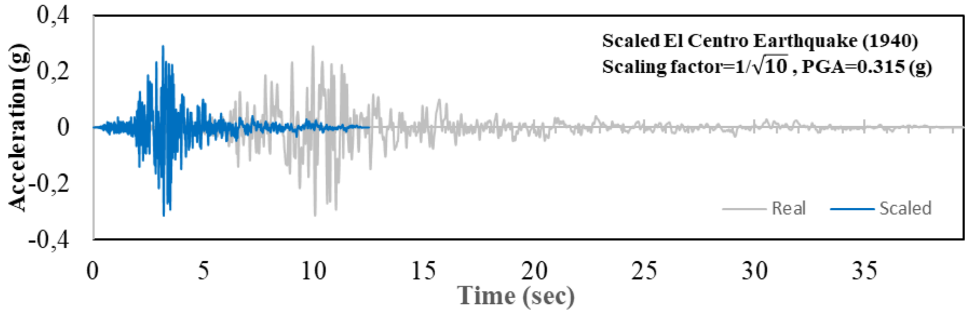
Earthquake	Country	Year	Peak ground acceleration (g)	Magnitude (Mw)	Duration (sec)
El Centro	ABD	1940	0.315	6.95	39.49
Kobe	Japonya	1995	0.345	6.9	40.9
Northridge	ABD	1994	0.568	6.69	39.89

Selected real earthquake records are based on Hokmabadi et al. [1] and was scaled to the laboratory environment using a systematic method. The purpose of using this scaling method is that it is not always possible to conduct real-scale experiments physically . Even if it were possible, it would be very costly in economic terms. Instead of working on a real scale, it is possible to reach an approximate conclusion by examining the experiments of the scaled model that represents the real structure in the laboratory. Likewise, real earthquake records must be scaled and applied to the model in the laboratory environment. Within the scope of the current study, real earthquake records were scaled by taking into account the scaling rates given in Table 1. When scaling in this study, the scaling factor was determined to be λ=10. While the acceleration values of the selected earthquakes remained the same, they were only scaled in time and these values were used.

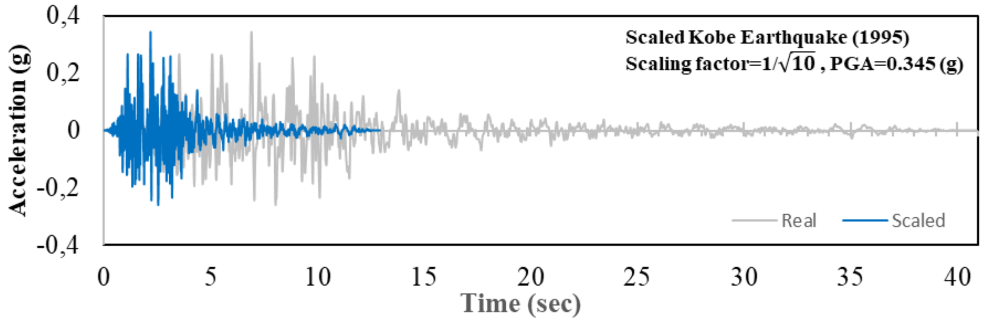
In the figure above, real earthquake records with time-dependent acceleration values are scaled with the mentioned method. While real earthquake records were used in the Sap2000 analyzes of the prototype building, scaled earthquake records were used in the Sap2000 analyzes of the model building.

3. ANALYSIS RESULTS AND DISCUSSIONS

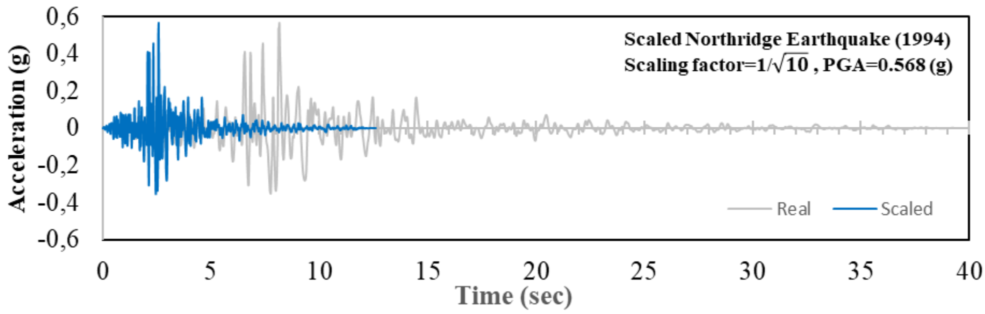
Time history analyzes of the prototype structure and the scaled model structure were made in the Sap2000 program. In these analyses, real and scaled earthquake ground motions given in Figure 3 above were used. As a result of numerical analysis, time-dependent displacement and acceleration values on each floor of the prototype and model are obtained graphically below.



(a)



(b)



(c)

Figure 3. Real and scaled (a) El Centro earthquake; (b) Kobe earthquake; (c) Northridge earthquake

Figure 4 below shows the displacement values at each floor of the real prototype building and the scaled model under the influence of the real and scaled El Centro (1940), Kobe (1995) and Northridge (1994) earthquakes, respectively. If each displacement value on the same floor is scaled by dividing by λ=10 according to the geometric scaling factor by looking at the parameter in Table 1, it can be seen that these are acceptable values.

As in the displacement graphs, Figure 5 below shows the acceleration values at each floor of the real prototype building and the scaled model under the influence of the real and scaled El Centro (1940), Kobe (1995) and Northridge (1994) earthquakes, respectively. These values are considered as "1" in the scaling method. In other words, the acceleration values of the same floors of the prototype and the model must be the same. The results obtained here show that if the acceleration values on the same floors are scaled, they are acceptable values.

Figure 4. Time-dependent displacement values of each floor of the prototype and model structure, respectively, under the influence of the following earthquakes: (a,b) El Centro (1940); (c,d) Kobe (1995); (e,f) Northridge (1994)

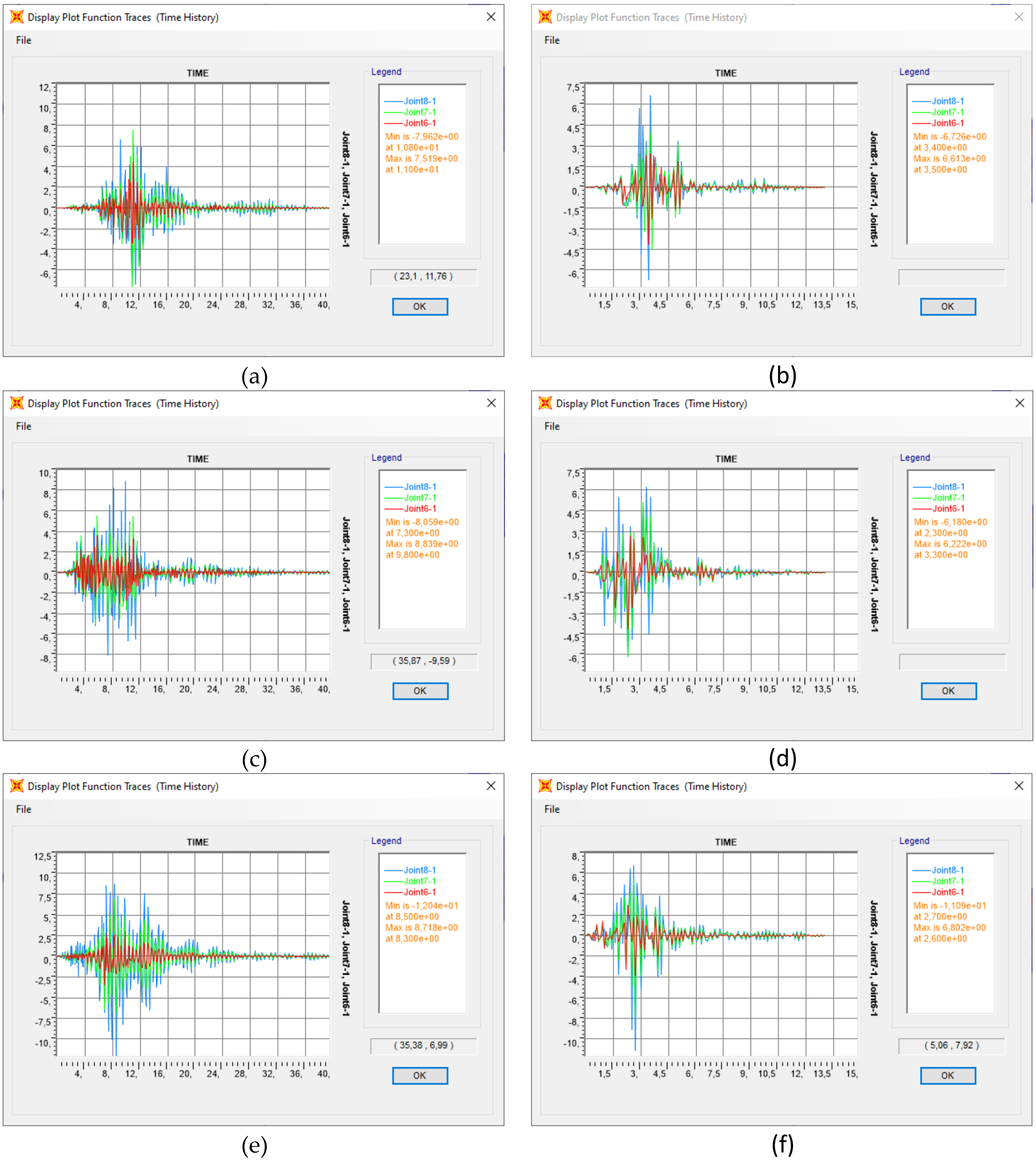


Figure 5. Time-dependent acceleration values of each floor of the prototype and model structure, respectively, under the influence of the following earthquakes: (a,b) El Centro (1940); (c,d) Kobe (1995); (e,f) Northridge (1994)

Generally, the most dominant mode in structures is the first mode. In other words, it is the situation where the top floor experiences peak displacement. As a result of the time history analysis obtained, the displacement and acceleration values on the top floor of the prototype and model building will be examined and when these results are compared according to the scaling method, very close results are obtained. Figures 6 and 7 below show the time-dependent displacement and acceleration values at the top floor of the prototype and model building under the influence of three earthquakes, respectively. When these displacement and acceleration values are scaled and compared, the results are quite close.

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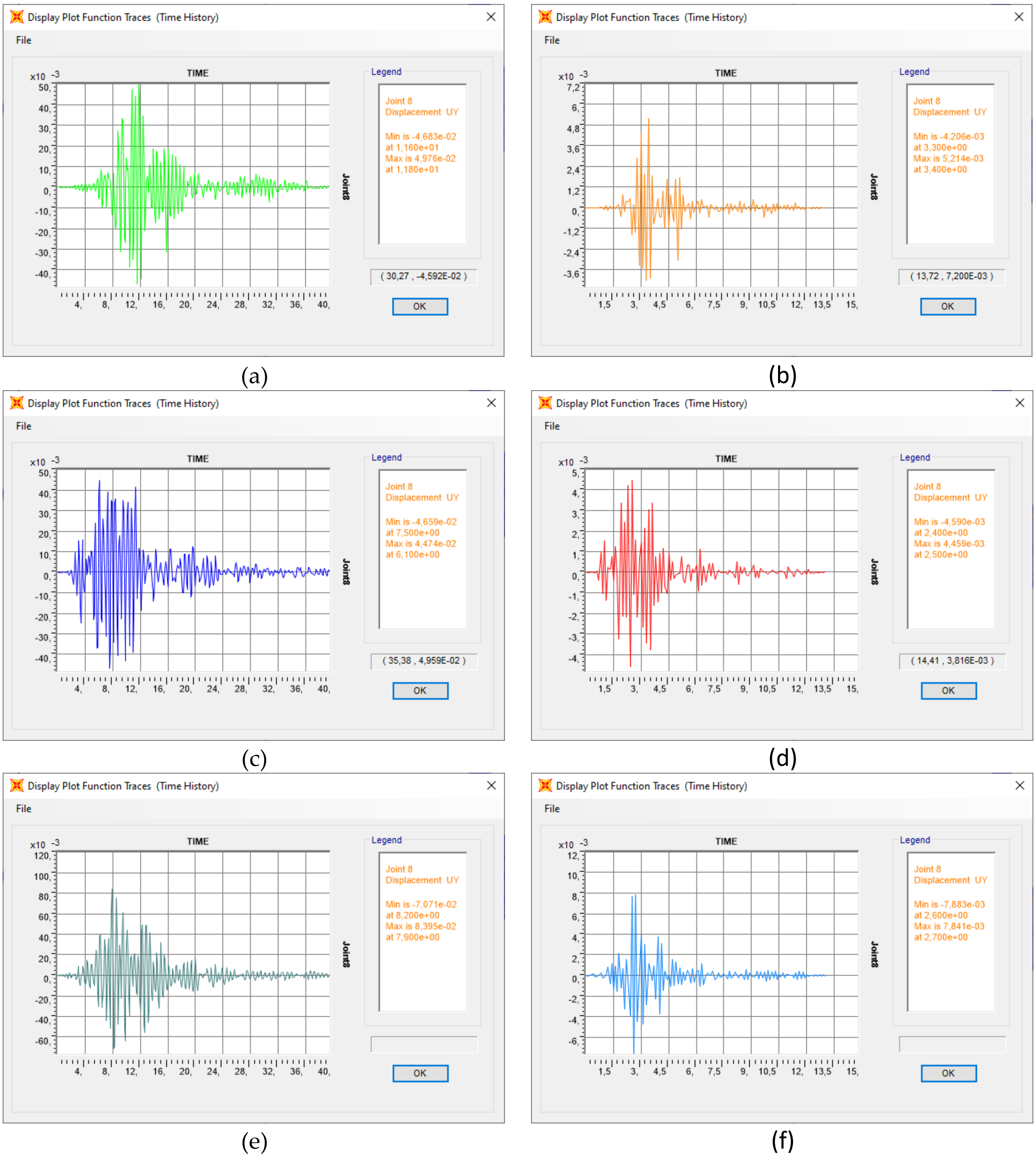

Figure 6. Time-dependent displacement values of the top floor of the prototype and model structure, respectively, under the influence of the following earthquakes: (a,b) El Centro (1940); (c,d) Kobe (1995); (e,f) Northridge (1994)

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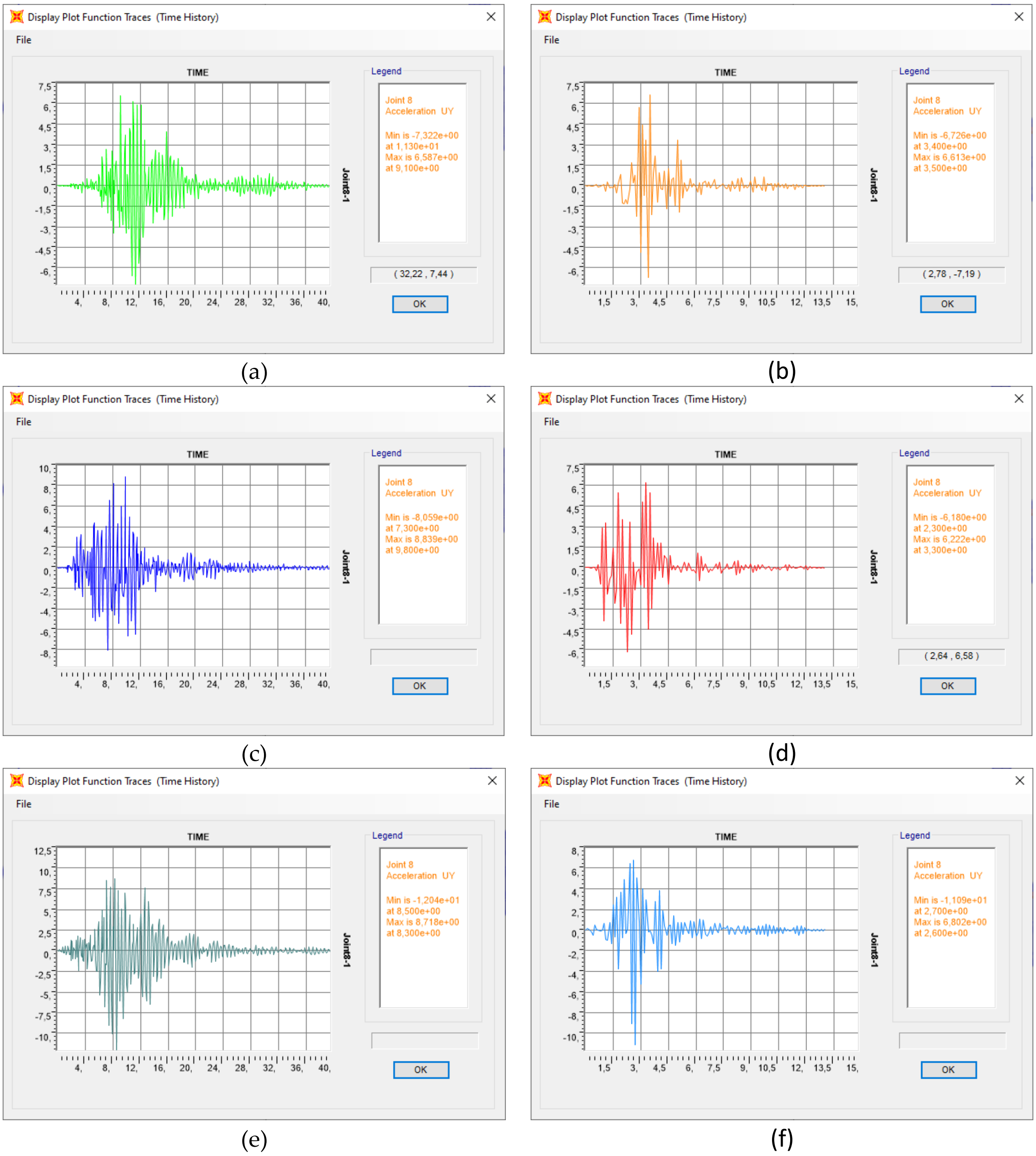

Figure 7. Time-dependent acceleration values of the top floor of the prototype and model structure, respectively, under the influence of the following earthquakes: (a,b) El Centro (1940); (c,d) Kobe (1995); (e,f) Northridge (1994)

In Figures 8-10 below, the peak displacement and acceleration values of each floor of the earthquakes used in time history analyzes for the prototype and model building are given respectively. When the displacement and acceleration values are scaled according to the scaling method based on the geometric scaling factor, it is seen that the results are quite close to each other.

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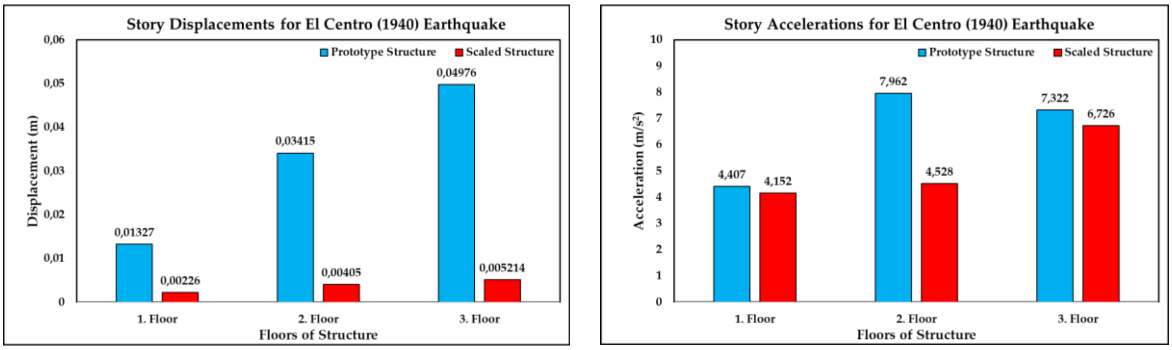
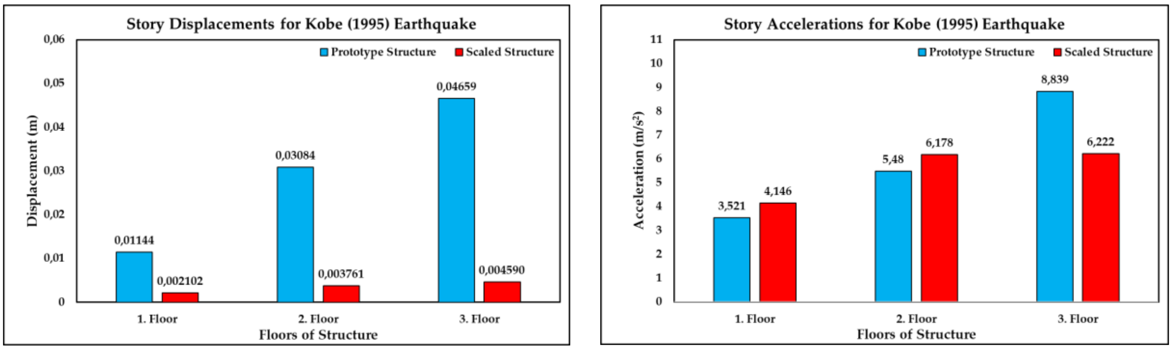


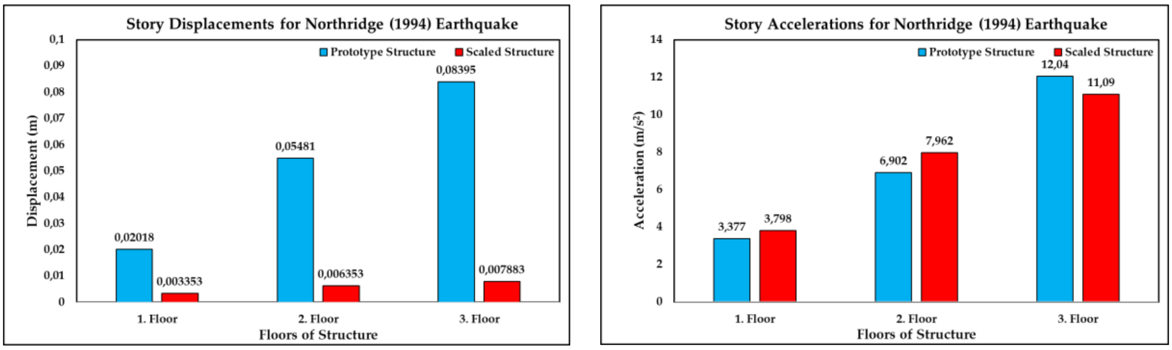
(a) (b)

Figure 8. (a) Displacement; (b) Acceleration; of each floor of the prototype and model structure under the influence of the Kobe (1995) earthquake



(a) (b)

Figure 9. (a) Displacement; (b) Acceleration; of each floor of the prototype and model structure under the influence of the El Centro (1940) earthquake



(a) (b)

Figure 10. (a) Displacement; (b) Acceleration; of each floor of the prototype and model structure under the influence of the Northridge (1994) earthquake

Parameters such as displacement and acceleration values of each floor of the building give us an idea about how the structure behaves. As can be clearly seen from the displacement and acceleration graphs of each floor above, it can be said that the behaviors of the prototypes and models are similar, although the characteristics of the earthquakes used in the numerical analyzes are different. This shows that the scaling method is quite successful.

4. CONCLUSIONS

The aim of this study is to create a model structure by accurately scaling a prototype structure and to examine the behavior of these two structures under the influence of seismic loads. First, a prototype

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structure was created in the digital environment and the model structure was obtained by scaling the created prototype. A superstructure was scaled by taking into account the scaling parameters so that it could be used experimentally in the laboratory environment. In this scaling, the mass density of the prototype (ϱ=105.336 kg/m^3) and the mass density of the scaled model (ϱ=106.667 kg/m^3) were very close to each other, as seen from the results obtained. When scaling the columns of the prototype building, it is not correct to only do geometric scaling. Here, along with the rigidity of the columns, the elastic modulus of the material is also important. These two parameters express the flexural stiffness (EI) and the design must be made accordingly. It is aimed to obtain the flexural stiffness of the model structure, EI=4.913 10^{-2} Nm^2, by dividing the flexural stiffness of the prototype structure, EI=4912.629 Nm^2, by λ^5, depending on the geometric scaling factor (λ). The flexural stiffness of the scaled model was found to be EI=4.725 10^{-2} Nm^2 and was very close to the value found by the scaling method. According to the data obtained, the prototype and scaled model were modeled in the Sap2000 program and modal analyzes were performed. As a result of the analyses, the natural period and frequency values of the prototype structure were found to be T_n=0.57106 sec and f_n=1.75113 Hz. By dividing the natural period of the prototype structure by $\lambda^{1/2}$ and its natural frequency by $\lambda^{-1/2}$ with the scaling method, it is aimed to find the natural period and frequency values of the model as T_n=0.18058 sec and f_n=5.53756 Hz. The results obtained from the digital analysis of the scaled model Natural period and frequency values were obtained as T_n=0.18741 sec and f_n=5.33584 Hz. By looking at these parameters, it was concluded that the scaled model would successfully represent the prototype structure.

Afterwards, the displacement and acceleration values of the prototype and scaled model structure under the influence of dynamic loads were examined. The values of these parameters, which express the dynamic behavior of the building, on all floors and on the top floor, where the first mode of the building is dominant, were examined and compared according to the scaling method. In this comparison, it was aimed to find the displacement values corresponding to that floor of the model building by dividing the displacement values of the floors of the prototype by the scaling factor λ. Similarly, with the scaling method, it is aimed to find the acceleration values of the floors of the prototype equal to the acceleration values corresponding to that floor of the model building. According to the results of the displacement and acceleration graphs obtained, although these displacement and acceleration values did not approach our target values on some floors, in most cases they were quite close. As a result, this study shows that the dynamic behaviors of a scaled prototype and a scaled model are compatible in digital analysis. According to the results obtained, it has been observed that when a prototype structure is scaled correctly, this scaled model will represent a prototype structure in the digital environment. This study was carried out using only digital analysis and three real earthquake records. However, it is planned to use more real earthquake records with different characteristics in future studies and to compare the scaled model with shaking table experiments in a laboratory environment with numerical analyses.

Declaration of Ethical Standards

The author declares that all ethical guidelines including authorship, citation, data reporting, and publishing original research are followed.

Declaration of Competing Interest

The author declares that there is no conflict of interest.

Funding / Acknowledgements

This study did not receive funding from any provider.

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