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Comparative Dynamic Seismic Analyses of RC Minarets Strengthened with FRP and Buttresses

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Abstract

In recent earthquakes occurred in Turkey, an unexpected number of reinforced concrete (RC) minarets were heavily damaged or collapsed causing loss of lives and economic damages. These structures can be counted as the most common constructed slender structures in Turkey. Therefore, the detailed behavior of these slender structures should be determined in order to strengthen the existing ones and construct safer and stronger RC minarets. In this study, the most common constructed types of RC minarets were analyzed under 17 August 1999 Mw 7.4 Kocaeli Earthquake for the determination of the effectiveness of strengthening techniques namely fiber reinforced polymers (FRP) and buttresses. Also, soil-structure interaction (SSI) is included in the dynamic seismic analyses of the minarets as proposed by Burman et al. (2012). At the end of the analyses performed, it was determined that FRP strengthening is more effective in enhancing the seismic response of RC minarets as the height of the minaret increases when compared with the buttress strengthening. Also, the stress demand locations predicted from the dynamic seismic analyses of the representative minarets were found to be consistent with the damages observed in recent earthquakes.

Keywords
Reinforced Concrete, Minaret, Seismic, Soil-structure Interaction, Viscous Boundary, Dynamic

Payanda ve FRP ile Güçlendirilmiş Betonarme Minarelerin Karşılaştırmalı Sismik Analizi

Özet

Türkiye'de son zamanlarda meydana gelen depremlerde, beklenmeyen sayıda betonarme minare, can ve ekonomi kaybına neden olarak ağır hasar görmüş veya tamamen yıkılmıştır. Bu yapılar, Türkiye'deki en yaygın inşa edilmiş narin yapılar olarak sayılabilir. Bu nedenle, bu narin yapıların ayrıntılı davranışı, mevcut yapıların güçlendirilmesi ve daha güvenli ve güçlü betonarme minarelerin inşa edilmesi için belirlenmelidir. Bu çalışmada, en yaygın inşa edilmiş betonarme minare tipleri, 17 Ağustos 1999 M_w 7.4 Kocaeli Depremi etkisi altında, güçlendirme tekniklerinin, yani lifli polimerlerin (LP) ve payandaların etkinliğinin tespiti için analiz edilmiştir. Ayrıca, Burman vd. (2012) tarafından önerilen zemin-yapı etkileşimi, minarelerin dinamik sismik analizlerine dahil edilmiştir. Yapılan analizlerin sonunda, LP güçlendirmesinin, yükseklik artışı oldukça payanda takviyesiyle güçlendirmeye kıyasla betonarme minarelerin sismik davranışında daha etkili olduğu tespit edilmiştir. Ayrıca, temsili minarelerin dinamik sismik analizlerinden tahmin edilen gerilme talep bölgelerinin son depremlerde gözlemlenen hasarlarla tutarlı olduğu tespit edilmiştir.

Anahtar Sözcükler
Betonarme, Minare, Sismik, Zemin-yapı Etkileşimi, Viskoz Sınır, Dinamik

1. Introduction

RC minarets, reflecting the traces of Islamic architecture, are the most common constructed slender and tall structures in Turkey (Fig.1). In almost every district, there are two or three mosques that include RC minarets with different heights in different geometry. In early days, minarets were utilized to announce the arrival of prayer times to people that are far from the mosques. However, when time passes and with the development of technology, the task for the announcement of azan from the minarets diminishes. But, they were also used for completing the magnificence and impressiveness of the mosques in terms of visuality. Therefore, designers prefer to construct higher and slender ones which makes these special structures more vulnerable to earthquake forces.

Turkey is reported to be in a very active seismic region of the world with a long and well documented history of earthquakes (Erdik et al. 1999). So many destructive and severe seismic actions occurred that cause the loss of lives and economy. Some of them are (Gülkan and Kalkan 2002, Tan et al. 2008, Ersoy and Gürüm 2011, Şanlı et al. 2017): 13.03.1992 Erzincan M_w 6.8, 17.08.1999 Kocaeli M_w 7.4, 12.11.1999 Düzce M_w 7.1, 23.10.2011 Van M_w 7.2.

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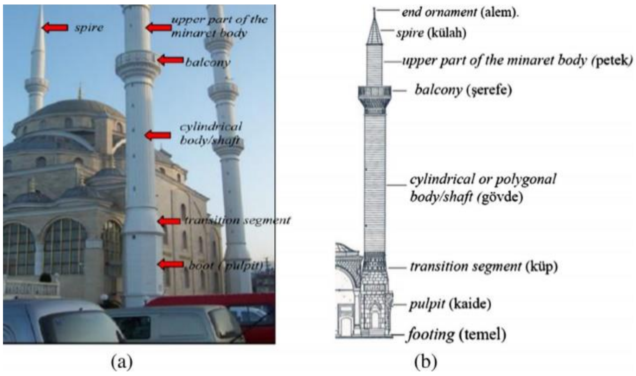

Figure 1: The parts of a typical RC minaret (Doğangün et al. 2006a, Sezen et al. 2008, Türkeli et al. 2015)

Also, in these severe actions of nature, there are so many RC minarets are reported to be heavily damaged or collapsed (Sezen et al. 2003, Doğangün et al. 2006b, Acar et al. 2007, Doğangün et al. 2007a, Doğangün et al. 2008, Doğangün and Sezen 2012, Sezen and Doğangün 2012, Oliveira et al. 2012, Türk 2013). Some of the heavily damaged or collapsed RC minarets are given in Fig.2.

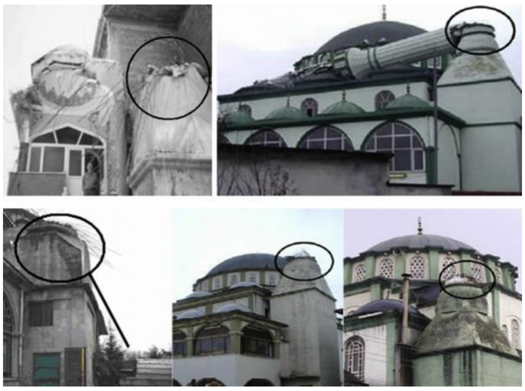

Figure 2: Failures or damaged RC minarets (Sezen et al. 2008)

Also, one of the most crucial matter about the most constructed RC minarets is that they are mostly constructed from experienced contractors or workers without using any application projects and without engineering knowledge (Sezen et al. 2008). Therefore, the vulnerability of these tall and slender structures against earthquakes increases.

Moreover, soil-structure interaction (SSI) is an important subject that should be considered in the dynamic analysis of the structures (Yazdchi et al. 1999, Pak and Guzina 1999, Mylonakis and Gazetas 2000, Tabatabaiefar and Massumi 2010). Also, SSI effect is very important when determining the dynamic seismic response of RC minarets. Therefore, the dynamic response of the representative minarets considered in this study was determined by considering the effect of SSI. Other than these, generally, the dynamic seismic response of RC minarets is studied without considering SSI effect (Örmecioğlu et al. 2011, Türk and Coşgun 2012, Mortezaei et al. 2012, Pekgökgöz et al. 2013, Türkeli 2014, Ural and Fırat 2015, Clemente et al. 2015, Basaran et al. 2016, Erdoğan et al. 2017).

In the technical literature, there are some strengthening techniques proposed for enhancing the overall response of RC minarets against seismic actions. One of these strengthening techniques is wrapping FRP to the cylindirical body of the minarets. In the search of the technical literature, the author coincided with only one study (Altunışık 2013) about the FRP strengthening of RC minarets without considering SSI effect (The other study is about FRP strengthening of masonry minarets from Altunışık 2011). According to this study (Altunışık 2013), using FRP is determined to enhance the overall seismic responses of the minaret. The other strengthening technique is the assembly of buttresses on the minaret. In the technical literature, there are some studies dealing with the effect of buttresses (Doğangün 2007b, Türkeli et al. 2015).

Mortezaei et al. (2012) studied about earthquake and structural behavior of the 'Masjed-e-Jame' of Semnan. Ganesan et al. (2013) tested and compared the engineering properties of geo polymer concrete and steel fiber reinforced geopolymer concrete obtained from standard tests. Ural et al. (2013) provided general information about the suggestions of restoring of crooked minaret by considering finite element model (FEM). Ural (2013) dealt with the seismic analyses of Halil Ağa Mosque by response spectrum analyses considering the investigation of a site survey of masonry damages. Hosseinpour and Abbasnia (2014) identified the effects of corner radius and aspect ratio on different aspects of stress-strain behavior of FRP confined concrete specimens.

Al-Tamimia et al. (2014) experimentally evaluated the effects of environment on the bond between ribbed Glass Fiber Reinforced Polymer (GFRP) reinforcing bars and concrete. Karaca et al. (2015) determined that FRP material can be used on chimneys which are very high and slender when compared with RC minarets. Hosseinpour and Abdelnaby (2015) statistically evaluated the monotonic models for FRP confined concrete prisms. Razavi et al. 2015 investigated the load-deflection analysis of the Carbon Fiber Reinforced Polymer (CFRP) strengthened Reinforced Concrete (RC) slab using Recurrent Neural Network (RNN). Basaran et al. (2016) utilized destructive and non-destructive tests for the seismic performance of historical masonry minaret of Hacı Mahmut Mosque.

The objective of this paper is to determine the effectiveness of strengthening techniques on the earthquake responses of representative RC minarets by considering SSI that is based on the method proposed from Burman et al. (2012). For this purpose, three representative minarets were selected as application. The destructive seismic time history records of 1999 M_w 7.4 Kocaeli Earthquake (so many RC structures are heavily damaged) were applied to the representative minarets. Also, in the strengthening process of representative minarets, four layers of FRP and buttresses were applied to separately to the representative minarets to determine the effect of these cited strengthening techniques. SAP2000 structural analysis program (Wilson 2000) was utilized in developing the three-dimensional (3D) FEM of the representative minarets. At the end of the study, the seismic response of FRP and buttress strengthened representative minarets were compared with each other as first mode periods, displacements and maximum-minimum principal stresses and some general conclusions and suggestions were reached.

2. Description of the Finite Element Models (FEM) of Representative Minarets

SAP2000 structural analysis program was utilized in constructing the FEM of three representative minarets. The FEM of these three representative minarets without strengthening were given in Fig.3. Also, as an example, the FEM of the strengthened Model 1 was given in the following part of this study.

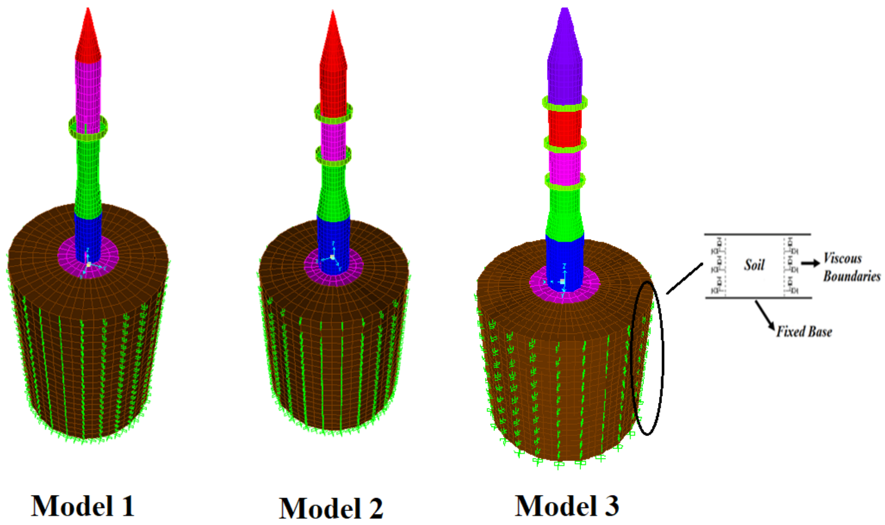

Figure 3: FEM of the representative minarets

The main body of the representative minarets were modelled by using shell elements. Also, the foundation and the underlying soil of the chimneys were developed by using solid finite elements that is called as "Direct Method" for SSI in the technical literature (Güllü and Pala 2014). Also, buttresses were modelled as frames which are starting from the base of the minaret (ground) and ending at the level of first balcony. As can be seen from Fig.3, Model 1, Model 2 and Model 3 has one, two and three balconies, respectively. Also, there are two, three and four door openings in Model 1, Model 2 and Model 3, respectively. The location of the openings are at the base and at the level of the balconies that are used for entrance purposes. The height of door openings for all models are 1.50 m in height whose shapes are rectangular. Moreover, the width of door openings is approximately an arch that have an angle of 30° at the level of base and the balconies. As clear from Fig.3, all models have foundations embedded to the underlying soil. The dimensions of foundations for Model 1, Model 2 and Model 3 are 5.00-1.00 m, 6.00-3.00 m, 8.00-2.00 m. in radius-depth, respectively. For all representative models, it is assumed that the thickness of the soil is 20 m. and after this height the soil is anchored to the main rock that it can be accepted as rigid. The underlying soil is also assumed as homogeneous in itself. RC was used for the production of the superstructures, foundations and buttresses of the representative models. The material properties like unit weight, the Young's Modulus, Poisson's ratio and concrete compressive (which is generally used in practice) strength of used material were assumed as 23.5 kN/m^3, 30,000 MPa, 0.2 and 16 MPa, respectively.

Also, ø12 (12 mm. in diameter) and ø10 steel reinforcements (S420 type steel-yield strength of the reinforcement is 420 MPa) in two layers are considered (which is generally used in practice) in the dynamic analyses for longitudinal and horizontal directions, respectively. In site surveys and in practice (Türkeli et al. 2015), the compressive strength of concrete used in this study is observed as typical. Also, in the analytical model considered all analyses and materials are in elastic range. The dimensions of the representative minarets are given in Fig.4.

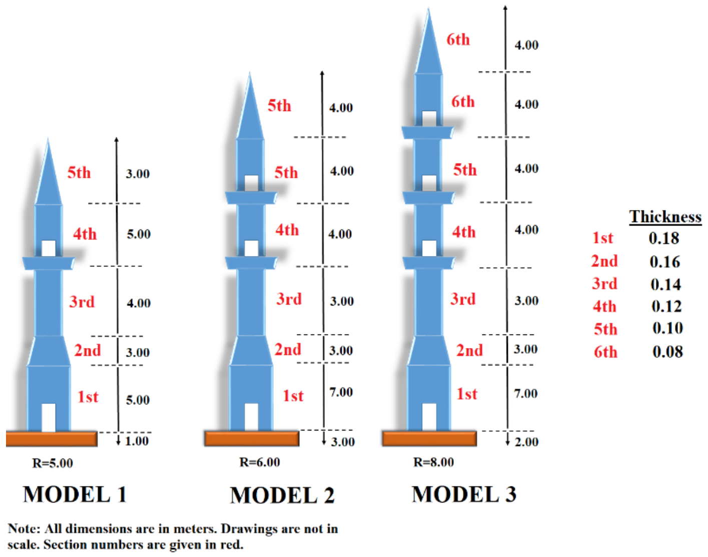

Figure 4: Dimensions of the representative minarets

The current representative models of minarets do not take the relation and minaret-mosque interaction. Also, the effect of wind loads are not dealt in this study. In the dynamic time history analyses of the models, the accelerations produced in 17 August 1999 M_w 7.4 Kocaeli Earthquake was utilized (URL-1 2017). In Fig.5, the time history of the cited ground motion was represented.

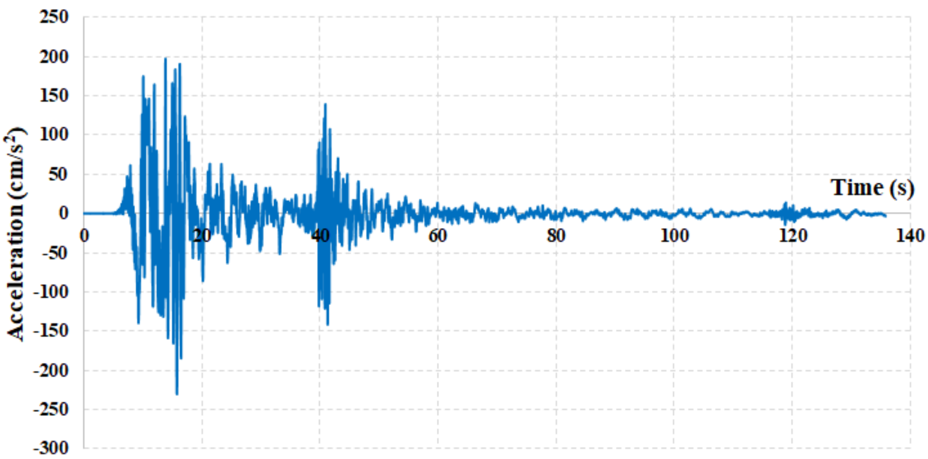

Figure 5: Ground motions recorded at 17 August 1999 Kocaeli Earthquake (East-west component)

The dynamic analysis performed and the results given in this study were in the linear range. 17 August 1999 Kocaeli Earthquake was applied with 0.005 s time intervals and 27163 steps. Although these time history steps were fully applied to all representative models, it is not possible to show all durations for the analysis because of the reasons that the graphs become illegible for full durations and not suitable for comparison purposes. Therefore, the duration intervals that create maximum responses were considered in the analysis. By considering the results of a parametric study performed by the author, the ground motion shown in Fig.5 was applied only in x-direction to all representative models. According to the results of this parametric study, the critical axis for the application of the seismic load is determined to pass through the axis which divided the door openings into two equal arcs. Also, the model names were updated according to the strengthening technique that is applied i.e. after wrapping FRP to Model 1, Model 1 was named as Model 1_frp. After adding buttresses to Model 1, the name of Model 1 was changed as Model 1_buttress. The names of the other models were given in the same manner.

In this study, the soil is selected from the technical literature (Livaoğlu and Doğangün 2007) and basic mechanical properties are provided in Table 1.

Table 1: Properties of the soil considered (Livaoğlu and Doğangün 2007)

Soil Type	E(kN/m^2)	γ(kg/m^3)	v	v_s(m/s)	v_p(m/s)
S1	500000	1900	0.35	309.22	643.68

The difficulty in simulating the infinite underlying soil under the RC minarets can be overcome by modelling the near field soil with solid finite elements and considering the rest of the infinite soil by adding artificial boundaries to the end of near field as shown in Fig.6.These artificial viscous boundaries are modeled by using link elements of SAP2000.

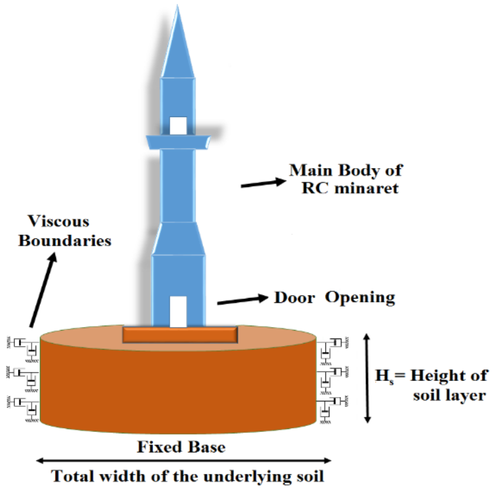

Figure 6: Schematical view of the artificial (viscous) boundaries at the end of soil

By using these types of boundaries, the reflecting and radiation effects of the propagating waves from the structure foundation layer may be avoided (Livaoğlu and Doğangün 2007). In this study, for the viscous boundaries shown in Fig. 3 and Fig.6, the method suggested from Burman et al. 2012 was utilized. According to this method (Burman et al. 2012);
The normal and tangential damping coefficients can be determined by using Eqs. (1) - (2).

$$c_n = A_1 \rho V_p \tag{1}$$

$$c_t = A_2 \rho V_s \tag{2}$$

In these equations given above, the shear and compression wave velocities are,

$$V_s = \sqrt{\frac{G}{\rho}} \tag{3}$$

$$V_p = \sqrt{\frac{E(1-\nu)}{(1+\nu)(1-2\nu)\rho}} \tag{4}$$

where G is the shear modulus of the medium and is expressed as,

$$G = \frac{E}{2(1+\nu)} \tag{5}$$

where E is the Young's Modulus and v is Poisson's Ratio. By assuming that the energy of waves arrives at the boundaries with equal probability from all directions. For an isotropic soil medium, this results in

$$A_1 = \frac{8}{15\pi}\left(5 + 2S - 2S^2\right) \tag{6}$$

$$A_2 = \frac{8}{15\pi}\left(3 + 2S^2\right) \tag{7}$$

where,

$$S^2 = \frac{(1-2\nu)}{2(1-\nu)} \tag{8}$$

The FRP strengthening of the representative minarets were performed by using Tyfo SCH-41-2X that is unidirectional carbon fabric sheets (Karaca et al. 2015). The mechanical properties of the cited FRP material is provided in Table 2.

Table 2: Composite dry typical properties of Tyfo SCH-41-2X

Tensile strength (GPa)	Tensile modulus (GPa)	Ultimate elongation (%)	Density (g/cm^3)
3.79	230	1.7	1.74

Comparison of the thickness of FRP used in the strengthening process with the wall thickness of the representative minarets showed that the thickness of FRP was very small. Therefore, this cited thickness of FRP was selected as 2mm. In the composite strengthening process of the models, the cylindrical body of the representative minarets (above the transition segment and below the spire except at the door openings) was fully wrapped with four layers of FRP (total thickness of FRP is 8 mm). The tensile and compressive element stiffness behavior was considered. FRP is modelled by using the layer property of shells in SAP2000 by constructing shell elements considering perfect bonding between concrete and FRP material (full adherence is assumed). As an example, the FEM of FRP strengthening with SAP2000 interface for Model 1 is provided in Fig.7. The FEM of Model 2 and 3 are in the same manner as Model 1.

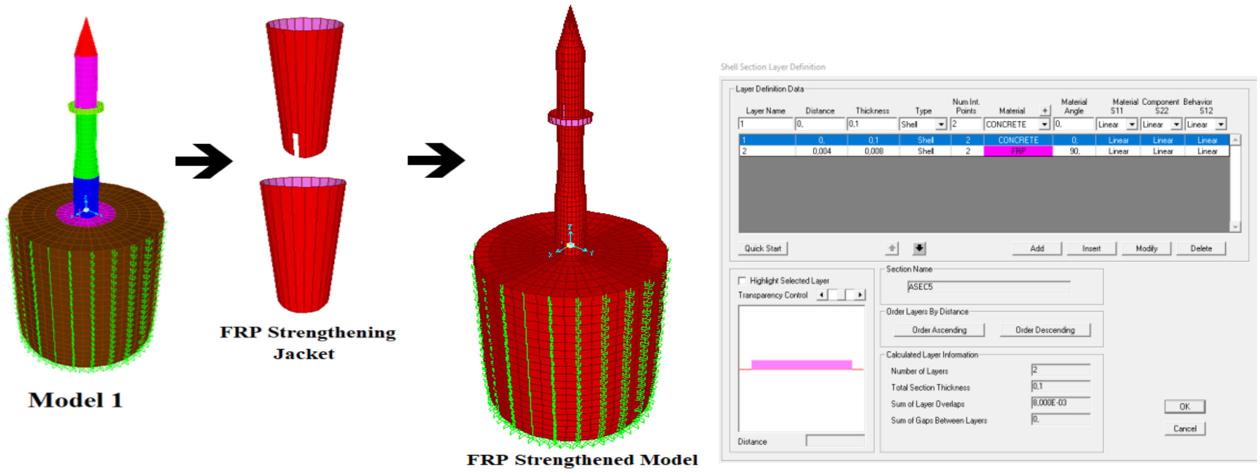

Figure 7: FEM of FRP strengthening for Model 1 with SAP2000 interface

The other strengthening technique for RC minarets is the assembly of buttresses to the body of the minaret under the first balcony. Also, minimum yield strength of f_y = 420 MP was considered in the reinforcement of buttresses whose strain capacity was 0.18. Also, the properties of concrete utilized in the buttresses are same with other concrete members. The detailed information about the assembly of buttresses can be found in the study of Türkeli et al. (2015). Also, Fig.8 is obtained by modifying the figure in Türkeli et al. (2015) provided for buttress strengthening.

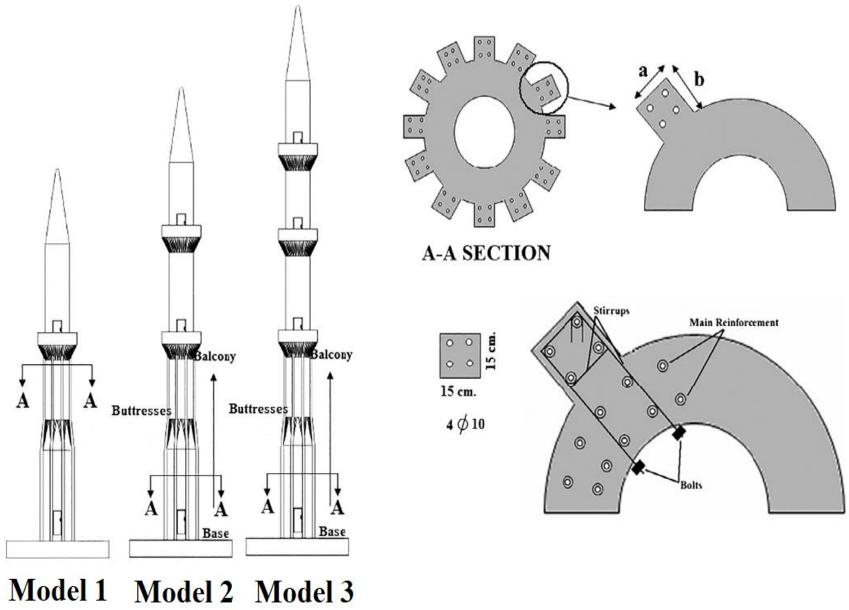

Figure 8: Strengthening of representative minarets by utilizing buttresses

3. Dynamic Seismic Analysis of the Strengthened Representative Minarets with SSI

The three representative minaret models were seismically analyzed under the ground motion cited in the preceding part of this study. In order to see the effect of strengthening techniques on the dynamic response of RC minarets, two strengthening techniques namely FRP wrapping and assembly of buttresses were applied to the representative minarets that consider the effect of SSI also. After all dynamic analyses performed, the obtained results were compared with each other to reach some conclusions. The dynamic response of representative minarets were investigated for various aspects such as first mode periods, maximum and minimum principal tensile and compressive stress distributions and top displacements.

3.1 First Mode Periods

As all other tall and slender structures, the first mode periods of representative RC minarets comprise an important part in the determination of the dynamic response. Although RC minarets are tall and slender structures and higher modes are effective on the dynamic response of these structures, from the preceding studies performed on the subject (Türkeli et al. 2015), the first mode periods are treated as the dominant ones. Therefore, the first mode periods obtained from the dynamic analyses are given in Table 3.

Table 3: First mode periods of the representative minarets

	Model 1	Difference (%)	Model 2	Difference (%)	Model 3	Difference (%)
No SSI	0,21493	-	0,218147	-	0,235511	-
SSI	0,24847	15,61	0,230892	5,84	0,26863	14,06
SSI (Buttress)	0,22041	-11,29	0,211175	-8,54	0,254314	-5,33
SSI (FRP)	0,22992	-7,47	0,205924	-10,81	0,239096	-10,99

As can be deducted from Table 3 that considering SSI in the dynamic analyses of the representative minarets increase the first mode periods. The first mode period of the first minaret changed from 0.21493 to 0.24847 that is 15.61 %. In the same manner, the percentage increase in the first mode periods of the second and third minarets are 5.84 % and 14.06 %, respectively. As a result, as expected, considering SSI in the dynamic analyses of the representative RC minarets changed the dynamic response of the structure. Also, strengthening techniques have adverse effect on the first mode periods of the minarets. From Table 1, it can be clearly identified that adding buttress to first model decreased the first mode period from 0.24847 to 0.22041 which is 11.29 %. Also, wrapping FRP to the first model decreased the first mode period from 0.24847 to 0.22992 which is 7.47 %. For the first representative minaret considered buttress strengthening is found to be more effective when compared with FRP strengthening.

For Model 2 and 3, it can be clearly seen that FRP strengthening is determined to be more effective when compared with buttress strengthening. Also, from Model 1 to Model 3, the percentage decrease of first mode period obtained from buttress strengthening drops from 11.53 % to 5.53 %. However, for FRP strengthening, from Model 1 to Model 3, the percentage decrease of first mode period obtained from FRP strengthening increase from 7.47 % to 10.99 % which shows that as the height of the RC minaret increases, effectiveness of FRP strengthening increases. The graphical representation of the percentages given in Table 3 of first mode periods for FRP and buttress strengthening is given in Fig.9.

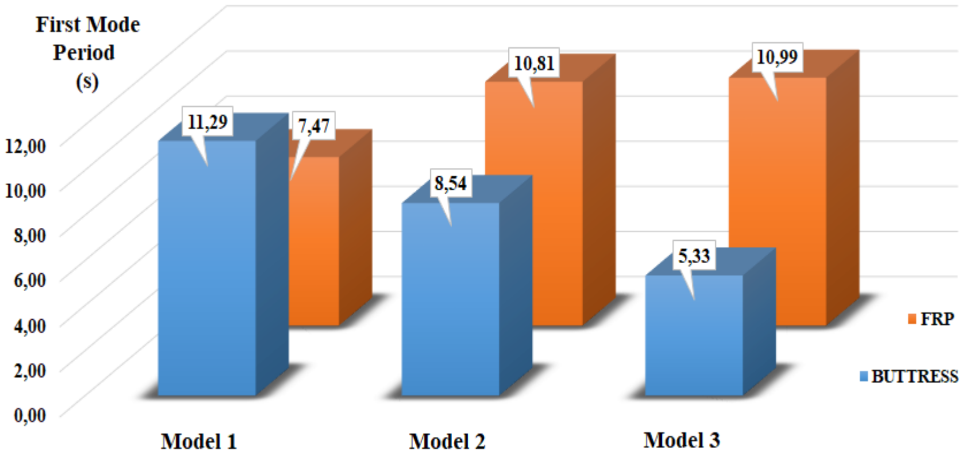

Figure 9: Percentage differences of FRP and buttress strengthening for representative minarets

From Fig.9, it can be clearly seen that the effectiveness of FRP strengthening increases as the height of the minaret increases when compared with buttress strengthening. Also, first five mode shapes of the representative models are provided in Figs.10-12.

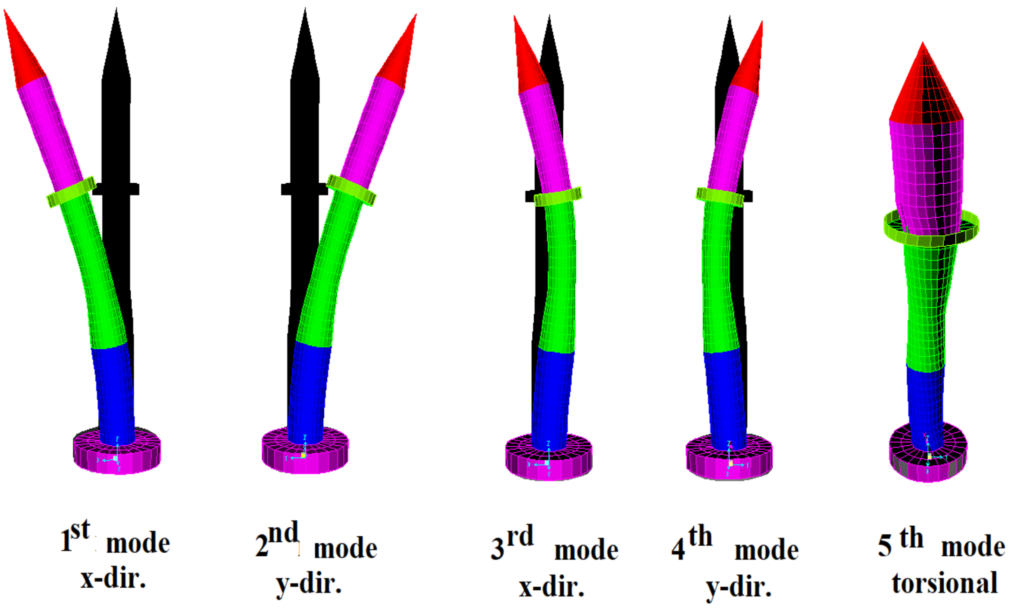

Figure 10: Mode shapes (first five) of Model 1

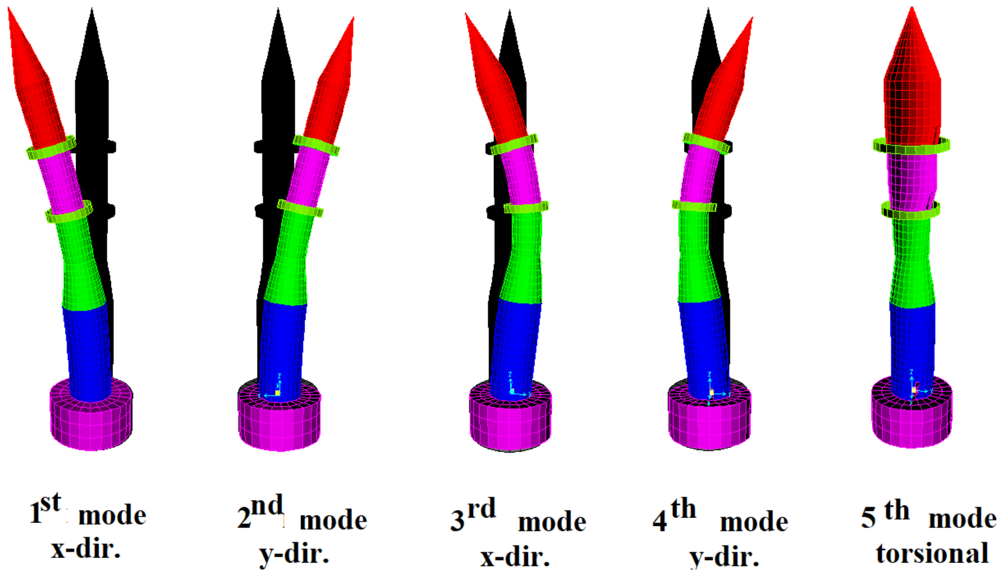

Figure 11: Mode shapes (first five) of Model 2

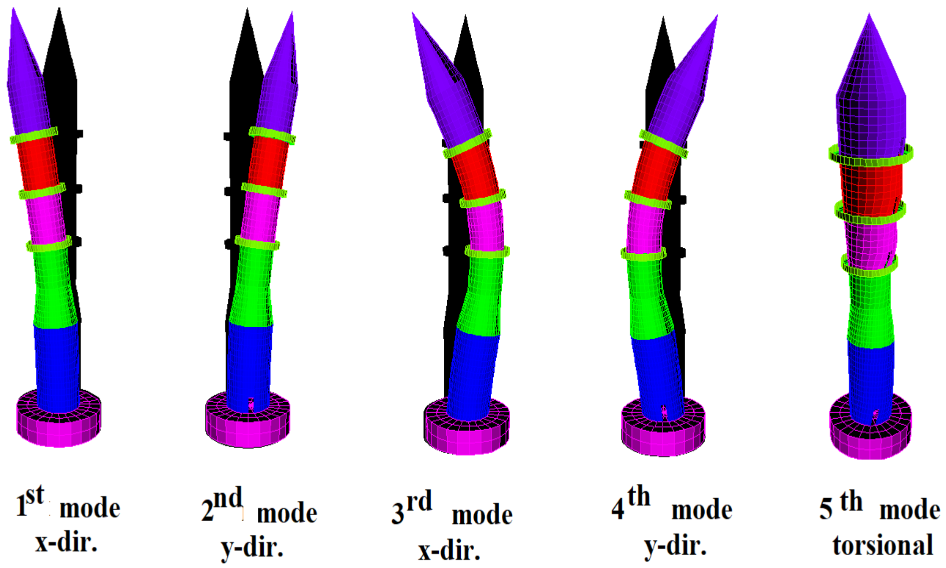

Figure 12: Mode shapes (first five) of Model 3

From Figs.10-12, for the representative minarets considered, the first four mode shapes are in the x and y directions. Also, the fifth one is the torsional mode.

3.2 Top Displacements

The other important parameter that should be taken into account on the dynamic seismic response of representative RC minarets is the top displacement. In this part of the study, the top displacements of the representative minarets under the cited Kocaeli Earthquake by considering SSI are represented. Also, in the following figures given, the full durations of the cited earthquake are not given because of the reason that the comparison of the strengthened models can't be possible and visible with full durations. Therefore, only the intervals of the durations that create maximum response obtained from the dynamic seismic analysis were represented in Figs.13-15.

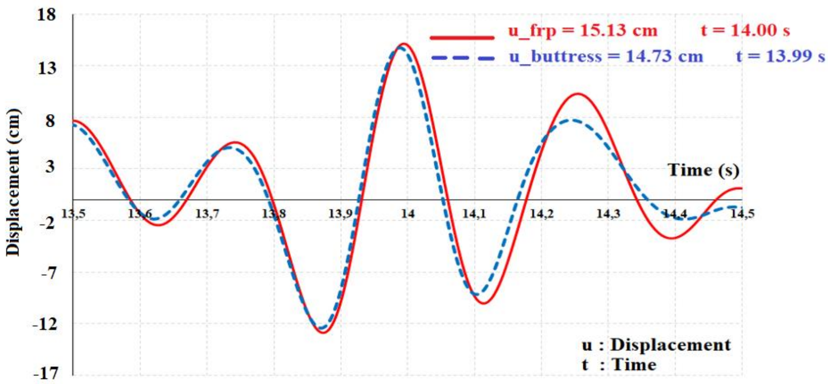

Figure 13: Time histories of maximum top displacements of Model 1 for FRP and buttress strengthening

From Fig.13, it is clear that for Model 1, buttress strengthening is determined to be more effective when compared with FRP strengthening. The representative RC minaret, Model 1, can be classified as squat with respect to its height. Also, in Fig.14, the time histories of maximum top displacements of Model 2 (it is similar for Model 3) is represented. Model 2 and 3 can be classified as mid-height and long with respect to their height, respectively.

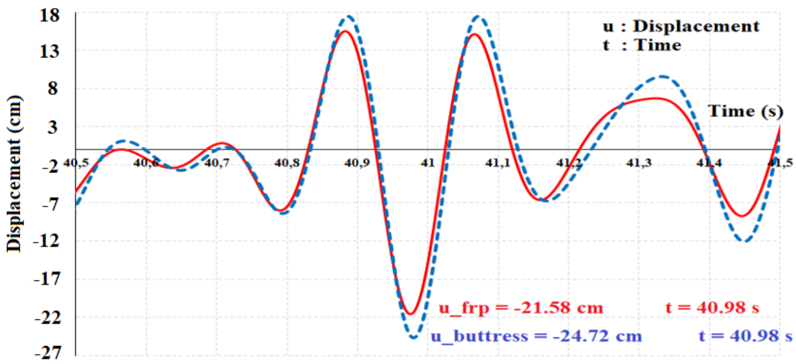

Figure 14: Time histories of maximum top displacements of Model 2 for FRP and buttress strengthening

From Fig.14, FRP strengthening is determined to be more effective when compared with buttress strengthening. Also, it can be deducted from Fig.14 that as the height of the minaret increases, the effectiveness of buttresses decreased whereas the same property of FRP wrapping increased. Also, the percentage differences of the maximum top displacements of the strengthened models with respect to unstrengthened ones are provided in Table 4.

Table 4: Maximum top displacements (in cm) and their relative percentage differences

	Model 1	Difference (%)	Model 2	Difference (%)	Model 3	Difference (%)
No SSI	10,29	…	11,46	…	15,83	…
SSI	19,48	89,31	30,5	166,14	41,04	159,25
SSI (Buttress)	14,73	-24,38	24,72	-18,95	38,02	-7,36
SSI (FRP)	15,13	-22,33	21,58	-29,25	29,76	-27,49

As can be deducted from Table 4 that SSI changed the top displacements considerably. As the height of the representative minarets increased from Model 1 to Model 3, there is an increase in the percentage differences. For Model 1, 2 and 3, these increases are 89.31 %, 166.14 % and 159.25 %, respectively. This shows the importance of considering SSI in the dynamic seismic response of representative RC minarets. Also, from Model 1 to 3, the percentage difference of buttress strengthening decreases from 24.38 % to 7.36 % that shows the decrease in the effectiveness of buttress strengthening. In the same manner, from Model 1 to 3, the percentage difference of FRP strengthening increases from 22.33 % to 27.49 % that shows the increase in the effectiveness of FRP strengthening. Moreover, from Table 4, for Model 1, buttress strengthening is determined to be more effective on dynamic seismic response. However, for Models 2 and 3, FRP strengthening is found to be much more effective when compared with the buttress strengthening.

This shows that as the height of the RC minaret increases, effectiveness of FRP strengthening increases. Also, the maximum horizontal displacement contours of the representative RC minarets are represented in Figs.15-17.

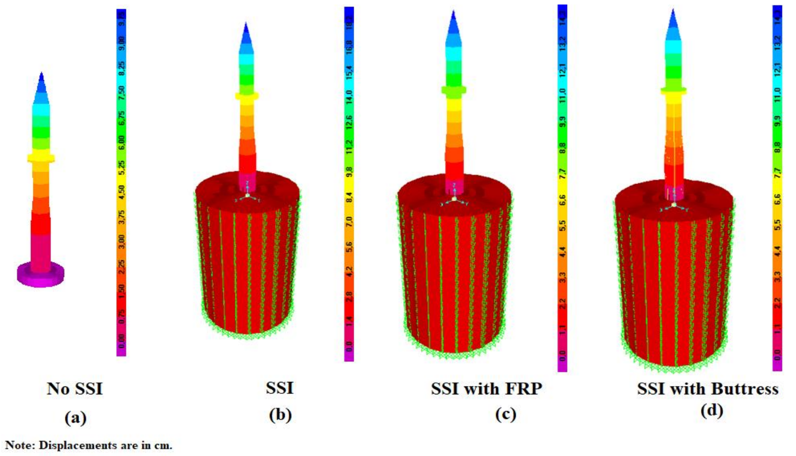

Figure 15: Maximum horizontal displacement contours of Model 1 a) No SSI b) SSI c) SSI with FRP d) SSI with Buttress

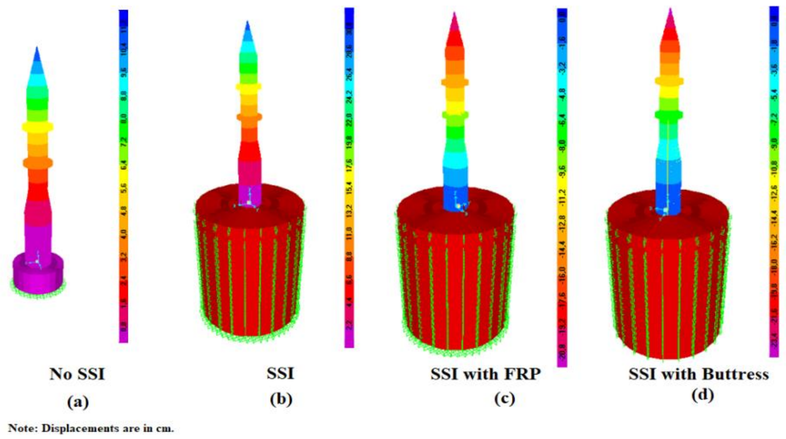

Figure 16: Maximum horizontal displacement contours of Model 2 a) No SSI b) SSI c) SSI with FRP d) SSI with Buttress

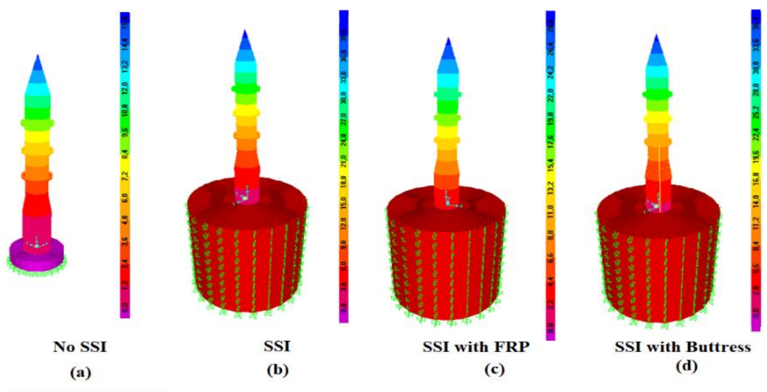

Figure 17: Maximum horizontal displacement contours of Model 3 a) No SSI b) SSI c) SSI with FRP d) SSI with Buttress

In Figs.15-17, the distribution of the peak values of maximum displacement for the representative minarets are provided. These displacements are the ones that are calculated at each point within the section considered. Also, it can be clearly seen that the displacements increase along the height of minaret from bottom to top with maximum values occur at the top.

3.3 Stress Distributions

Under 17 August 1999 Kocaeli Earthquake, the stress histories of the maximum and minimum principal ones of the representative RC minarets are provided in Figs.18-23. Also, for the visibility purposes, it not possible to provide the full durations of the dynamic response of the strengthened models under cited earthquake. Therefore, only the intervals of the durations that create maximum response obtained from the dynamic seismic analysis were represented in Figs.18-23. In Figs.18-23, it is clearly seen that the stress histories of the maximum (tensile) and minimum (compressive) principal ones occurred approximately at the place where transition segment and cylindrical body were attached to each other (at the time of maximum response).

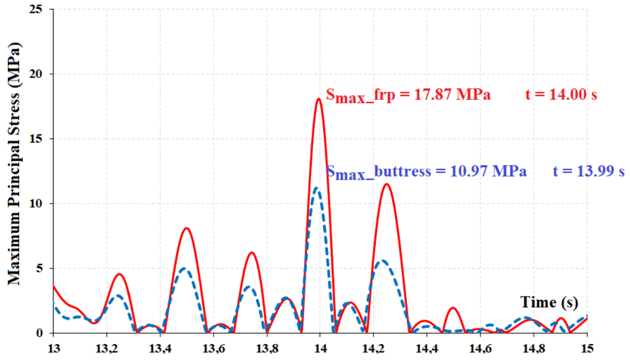

Figure 18: Time histories of maximum principal stresses of Model 1 for FRP and buttress strengthening

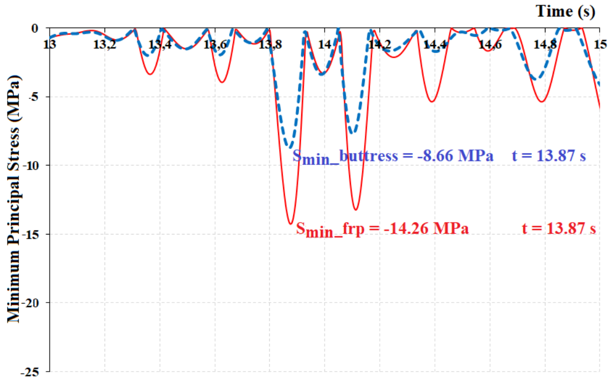

Figure 19: Time histories of minimum principal stresses of Model 1 for FRP and buttress strengthening

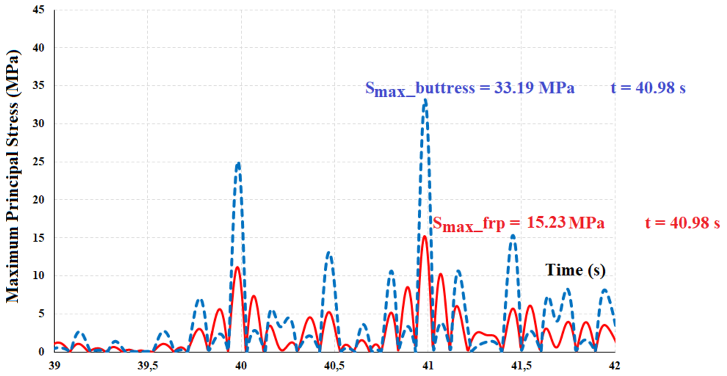

Figure 20: Time histories of maximum principal stresses of Model 2 for FRP and buttress strengthening

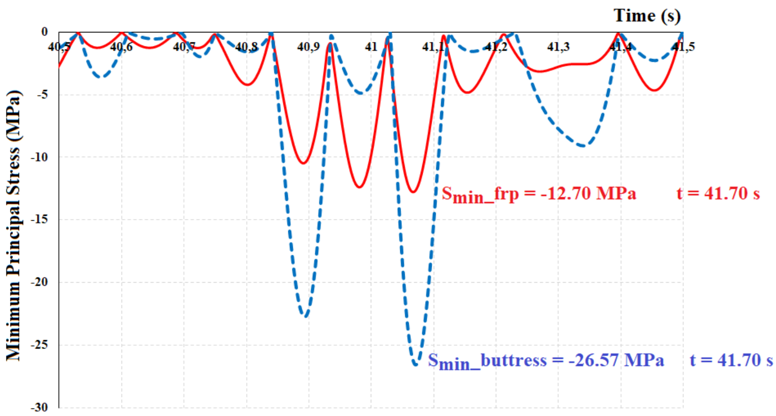

Figure 21: Time histories of minimum principal stresses of Model 2 for FRP and buttress strengthening

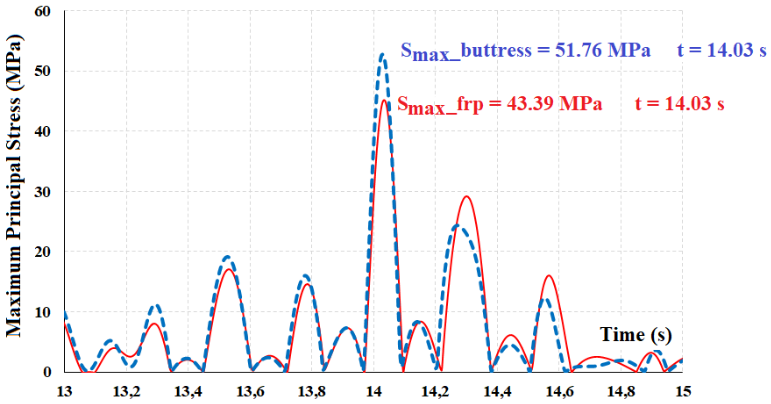

Figure 22: Time histories of maximum principal stresses of Model 3 for FRP and buttress strengthening

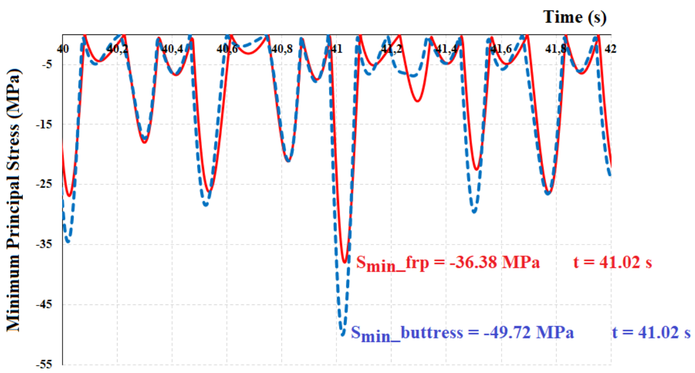

Figure 23: Time histories of minimum principal stresses of Model 3 for FRP and buttress strengthening

From the interpretation of Figs.18-23, for Model 1 i.e. squat minaret, it is clearly identified that buttress strengthening is more effective when limiting maximum and minimum principal stresses occurred at the junction point of transition segment and cylindrical body. For Model 1, the maximum principal stress decreased from 17.87 MPa to 10.97 MPa which is 38.6 % decrease. Also, the decrease in minimum stress is 39.3 % i.e. -14.26 MPa to -8.66 MPa. However, this is not the case for Model 2 and 3. For Model 2 and 3, FRP strengthening is determined to be more effective when compared with buttress strengthening. The percentage decrease of Model 2 for S_{max} and S_{min} are 54.11 % and 52.20 %, respectively. In the same manner, this percentage decrease of Model 3 for S_{max} and S_{min} are 16.17 % and 26.83 %, respectively. It can be deducted that as the height of minaret increases from squat to mid-height, the effectiveness of FRP strengthening increases when compared with buttress strengthening. Moreover, from the comparison of percentage differences, from mid-height to long minaret, the effectiveness of FRP strengthening decreases. Also, the maximum and minimum principal stress contours of the representative minarets are provided in Figs.24-29.

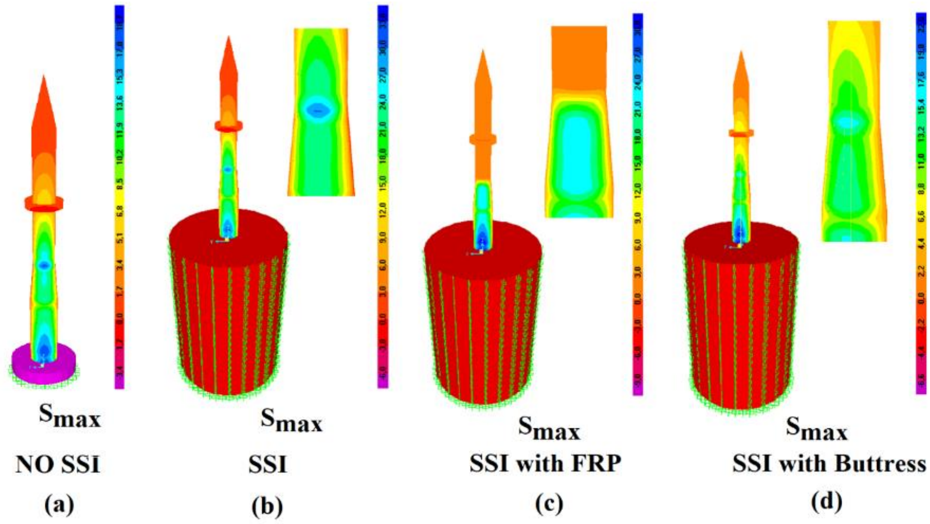

Figure 24: Maximum principal stress contours of Model 1 a) No SSI b) SSI c) SSI with FRP d) SSI with Buttress

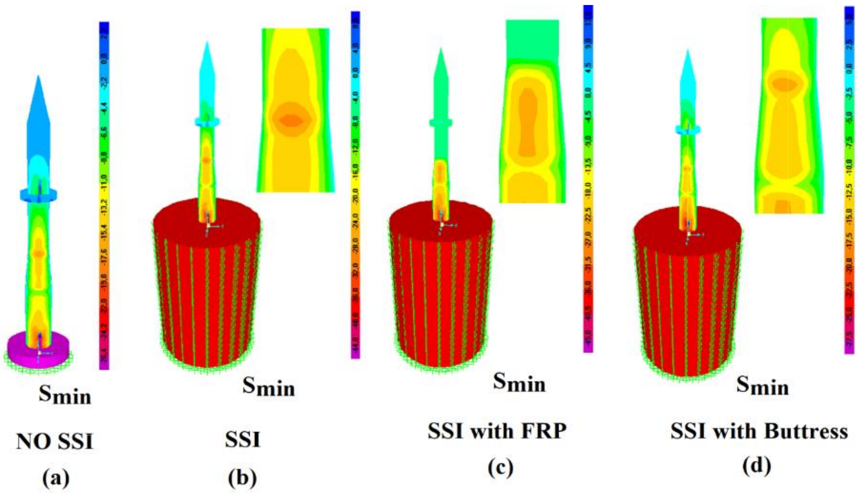

Figure 25: Minimum principal stress contours of Model 1 a) No SSI b) SSI c) SSI with FRP d) SSI with Buttress

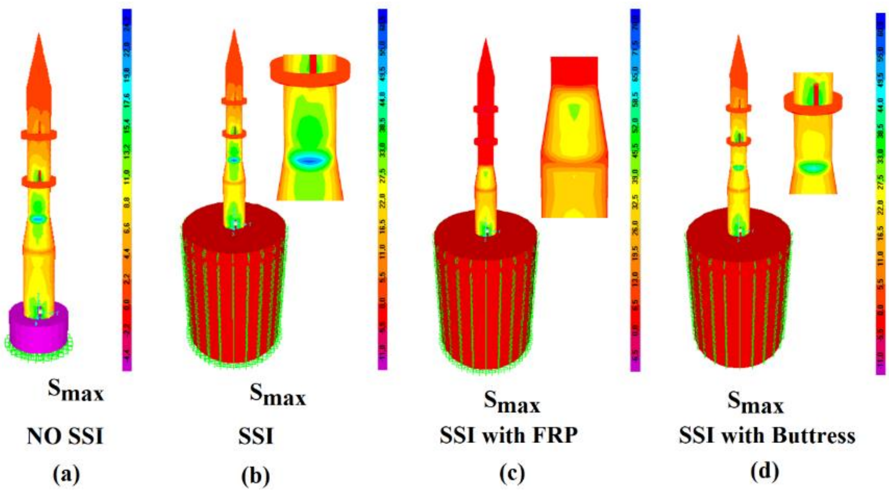

Figure 26: Maximum principal stress contours of Model 2 a) No SSI b) SSI c) SSI with FRP d) SSI with Buttress

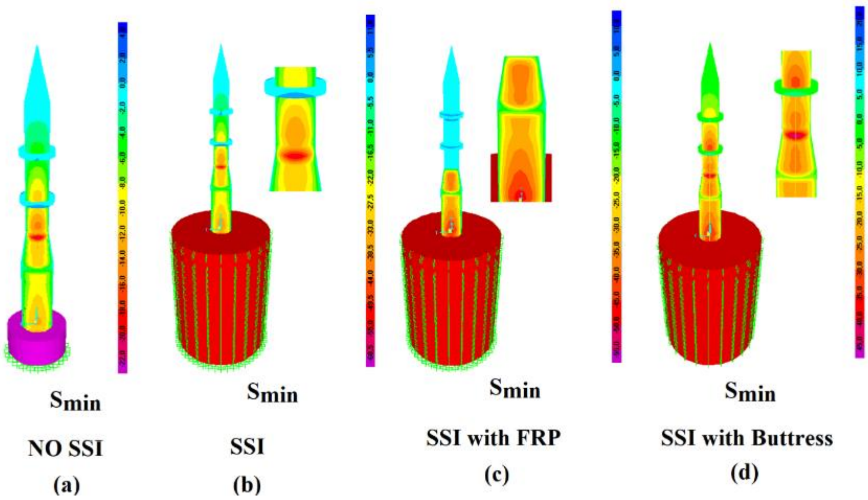

Figure 27: Minimum principal stress contours of Model 2 a) No SSI b) SSI c) SSI with FRP d) SSI with Buttress

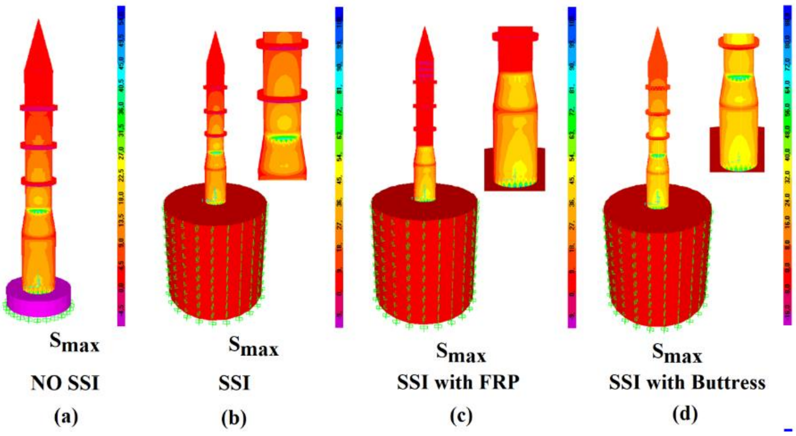

Figure 28: Maximum principal stress contours of Model 3 a) No SSI b) SSI c) SSI with FRP d) SSI with Buttress

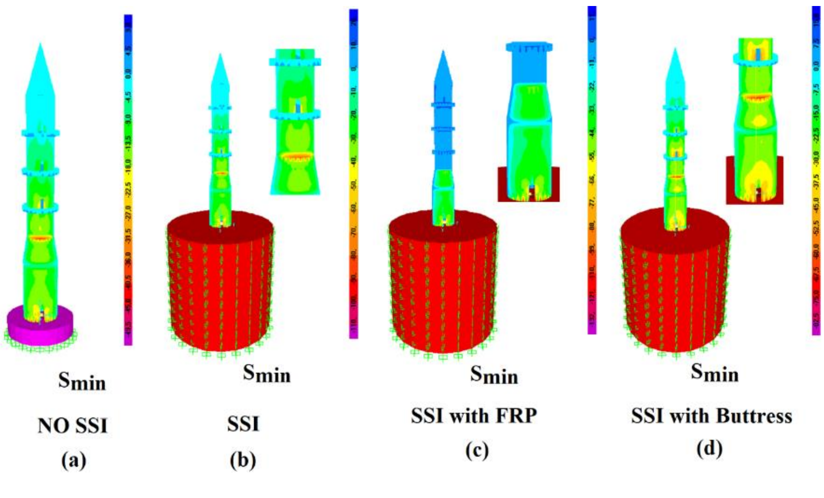

Figure 29: Minimum principal stress contours of Model 3 a) No SSI b) SSI c) SSI with FRP d) SSI with Buttress

From Figs.24-29, S_{max} and S_{min} values were accumulated just a few meters above the transition segment. In another words, S_{max} and S_{min} values were accumulated from the point of attachment i.e. junction point of transition segment and cylindrical body. In real life situations, this cited region of stress accumulation is determined to be the vital place where cylindrical body of the minaret suffered collapse or damage and this accumulation validates the failure of vast majority of RC minarets in the recent earthquakes.

As can be seen from Fig.2, the findings obtained in this study is consistent with the ones suffered in real life situations. Also, it can be identified that considering SSI clearly affected the dynamic seismic response of the representative RC minarets.

4. Conclusions

This study aimed to determine the effectiveness of adding buttresses and FRP wrapping on the dynamic seismic response of RC minarets by considering the effect of underlying soil. Three representative minarets that have different structural characteristics are selected as application. 3D FEM of the representative minarets are produced in SAP2000 software, and linear seismic behavior is determined by using time history records of 1999 M_w 7.4 Kocaeli Earthquake. Also, SSI is considered by using the method of viscous boundaries. Some of the conclusions that can be derived from this study are as follows:

- From the modal analyses of the representative minarets, considering the effect of underlying soil in the dynamic analyses increased the first mode periods of the structure. This increase is around 5%-15% depending on the structural and mechanical properties of the upper structure of the minaret and the soil.
- For the first representative minaret, the percentage decrease in the first mode period of the buttressed and FRP strengthened are 11.29 % and 7.47 %, respectively. The same decrease in the first mode period of the second buttressed and FRP strengthened minaret are 8.54 % and 10.81 %, respectively. This is 5.33 % and 10.99 % for the third minaret, respectively. It is determined that buttress strengthening is losing its effectiveness as the height of the minaret increases. Also, the effectiveness of FRP strengthening is determined to increase as the height of the minaret increases. Briefly, for squat type of minarets, buttresses can be preferred to rehabilitate the overall seismic performance. From mid-height to long type of minarets, FRPs can be utilized for improving the dynamic seismic behavior.
- From the comparison of the top displacements and the corresponding percentage differences, it is concluded that the contribution of buttress strengthening decreases as the height increases from squat to long (24.38 % to 7.36 %). However, this is the reverse for FRP strengthening (22.33 % to 27.49 %). Also, for squat type of minaret, buttresses is found to be more effective when compared with FRP strengthening. However, for mid-height and long minaret, the contribution of FRPs are much more compared with buttresses. Therefore, the type of strengthening should be determined by considering the structural and mechanical properties of the considered minaret.
- Both the buttresses and FRP wrapping can be effectively used on representative RC minarets without interrupting any structural element and architectural point of view.
- From the dynamic analyses of the representative minarets, it is determined that the maximum and minimum principal stresses accumulated at the junction region where transition segment and cylindrical body attaches to each other. Therefore, it is likely that probable cracks and damages occur at this critical region. The real situations occurred at recent earthquakes is consistent with the finding of this study.
- From the stress point of view (occurred at the junction point of transition segment and cylindrical body), FRP strengthening can be counted as more effective for mid-height and long representative minarets. However, this is not the case for squat minarets. For Model 1, the percentage decrease of maximum and minimum principal stresses are 38.6 % and 39.3 % (buttresses are more effective). However, this is not the case for Model 2 and 3. The percentage decrease of Model 2 for S_{max} and S_{min} are 54.11 % and 52.20 %, respectively. In the same manner, this percentage decrease of Model 3 for S_{max} and S_{min} are 16.17 % and 26.83 %, respectively. For Model 2 and 3, FRP strengthening is determined to be more effective when compared with buttress strengthening.

In summary, this study represented the dynamic seismic analysis of the representative minarets strengthened with buttresses and FRP wrappings. Also, the effect of soil is considered in the analyses. It is clearly shown that the selection of the strengthening technique depends on the type of the minaret considered. Therefore, detailed dynamic analyses of the considered minaret should be performed before the application of the strengthening technique.

Acknowledgments

This study is dedicated to the venerable memory of our great teacher Prof. Dr. Ing. Ahmet DURMUŞ whom we lost in 07.03.2017.

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