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ANALYTICAL INVESTIGATION OF EFFECT OF RETROFIT APPLICATION USING CFRP ON SEISMIC BEHAVIOR OF A MONUMENTAL BUILDING AT HISTORICAL CAPPADOCIA REGION OF TURKEY

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ABSTRACT

This study focuses on analytical investigation of effect of seismic retrofit application using carbon fiber (CFRP) plates on seismic behavior of a monumental building constructed in historical Cappadocia region of Turkey. The investigated building is located at the town of Fertek which is two kilometers from the city of Nigde. It has been used as a worshipping temple since it was built in the year 1835. In addition to modal and response spectrum analysis, the building is subjected to ground motion records which were obtained during recent earthquakes in Turkey. These ground motions were recorded during Ceyhan earthquake (1998) which occured close to Nigde, Marmara earthquake (1999) and Duzce earthquake (1999). Furthermore, the building is exposed to static load combinations given in the Turkish Code. Seismic behavior of the monumental building both before and after the application of retrofitting using CFRP plates is investigated analytically. Carbon fiber (CFRP) retrofitting is applied at column and beam elements as surface coating of 0,5 cm and 1,0 cm thickness. The CFRP plates are applied at all convenient and available surfaces of column and beam elements. The analyses are conducted on the monumental building for the cases of with wall and without wall in order to consider the effect of structural walls on the seismic behavior of the building. In the light of the analytical results, expected level of structural damage of the retrofitted monumental building is examined within the scope of displacement based approach. It is observed that there is a stable decrease in maximum lateral drift demand upon application of CFRP retrofitting on the original building model.

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Introduction

In this study analytical investigation of effect of retrofit application using carbon fiber (CFRP) plates on seismic behavior of a monumental building at historical Cappadocia region of Turkey is investigated. The monumental building has been used as a worshipping temple since it was built in the year 1835. It is located at the town of Fertek at Nigde province. It is a good model for similar temples which were built during the same era in the Cappadocia region.

Investigation of seismic behavior of the retrofitted monumental building is conducted using the analytical approaches for modal, response spectrum and static analysis procedures. Ground motion records which were recorded during recent earthquakes in Turkey are used. The indicated ground motions were recorded during Ceyhan earthquake (1998), Marmara earthquake (1999) and Duzce earthquake (1999). The original and the CFRP retrofitted models of the monumental building for two cases of with wall and without wall are analyzed considering the effect of structural walls on the seismic behavior.

Seismic drift response of building structures at seismically active and near-fault regions has been investigated (Ozturk 2003). Furthermore, seismic drift response of this historical building was presented regarding its original model (Ozturk 2008). In this study, seismic behavior of the CFRP retrofitted historical building is evaluated from a perspective of maximum drift ratio. Meanwhile, the effects of CFRP retrofitting on the seismic behavior of the building for different thicknesses are presented and the resulting damage to be observed is assessed.

Building Description

The monumental building was built as a church in 1835. It was converted into a mosque in 1924 and is still being used as a temple. It is located 2 km. away from the city center of Nigde county. It has two storeys which are the entrance floor and the gallery floor, respectively.

In its original form it was built as a basilica type of church. There are three semicircular apses forming the east walls of the building. There is a "U" shaped narthex at the west entrance of the building which has a circular curve outside of the building (Parman 1988). Inside the building, the gallery part is composed of columns which are connected to each other with rounded arches in the east, west, north and south directions, and the main area is surrounded in "U" shape.

Yellow or dark gray colored straight-cut stones are used in all outer walls. Timber is used both in the inner part at the top of the columns and at the entrance hall at the top of the narthex. The front and inside views of the building are shown in Figure 1.

(a) (b)

Figure 1. Front (a) and inside (b) view

Nigde yellowstone was used in its construction which was easily available and commonly used in the Cappadocia region. The stone has a density, γ value of 18 kN/m^3 , modulus of elasticity value of 18 * 10^6 kN/m^2 and Poisson's ratio, ν value of 0,3.

The diameter of inner columns and outer columns are 60 cm (Ø 60) and 50 cm (Ø 50), respectively. The building extends for 34.55 m in the east-west direction while its length is 23.90 m in the north-south direction. Inner walls and outer walls have a thickness of 60 cm and 85 cm, respectively. The plan of the entrance and gallery stories of the building is shown in Figure 2 while its three-dimensional model is given in Figure 3.

The building has seven spans in the east-west direction four of which have lengths of 4.40 m while the remaining three spans have lengths of 5.20 m, 4.70 m and 4.10 m, respectively. There are five spans in the north-south direction: two of them have lengths of 4.00 m, two of them 4.35 m and one of them 6.20 m.

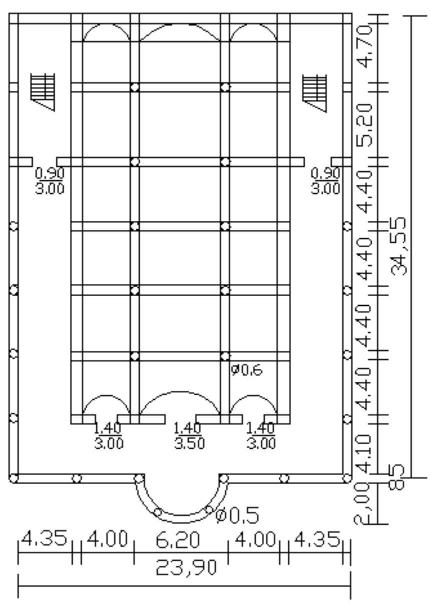

Figure 2. Building plan with all dimensions in m (Celik and Sadak 2007)

The top of the gallery storey elevation is 8.00 m such that while the entrance storey has a height of 4.50 m, the gallery storey has a height of 3.50 m. Finally, the elevation of building roof top is 11.60 m. Total weight of the building is around 9070 kN.

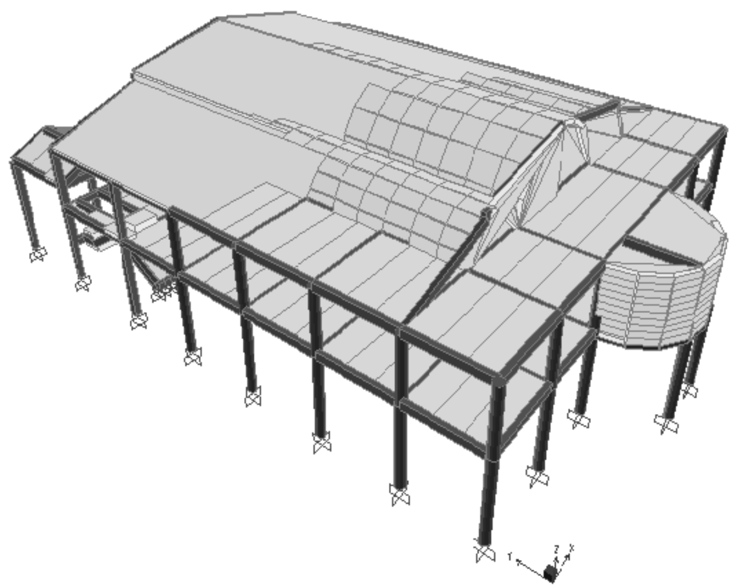

Figure 3. Three-dimensional model (Celik and Sadak 2007)

Retrofitting Material CFRP and Its Application Procedure

Carbon fiber (CFRP) plates are used for retrofitting of the monumental building. The material properties of CFRP are given in Table 1.

Table 1. Material properties of carbon fiber (CFRP)

Strength in tension (MPa)	4’100
Elastic modulus (MPa)	231’000
Ultimate elongation (%)	1.7
Ultimate tension force (kN)	44
Density (g/m^3)	$1.78*10^6$

SAP2000 analysis program (2000) is used for the analyses of the retrofitted structure. The CFRP plates are applied at all convenient and available surfaces of column and beam elements. For beams, CFRP plates are applied at bottom surfaces in order to withstand tension stresses. For columns, CFRP plates are applied at the surface area of columns in order to withstand tension stresses. No retrofitting is applied at structural walls, arches and domes of the building. For analytical investigation of effect of CFRP application on beams and columns, thicknesses of CFRP plates are taken as 0.5 cm and 1.0 cm, respectively. The application of CFRP plates on beam and column elements are shown in Figure 4.

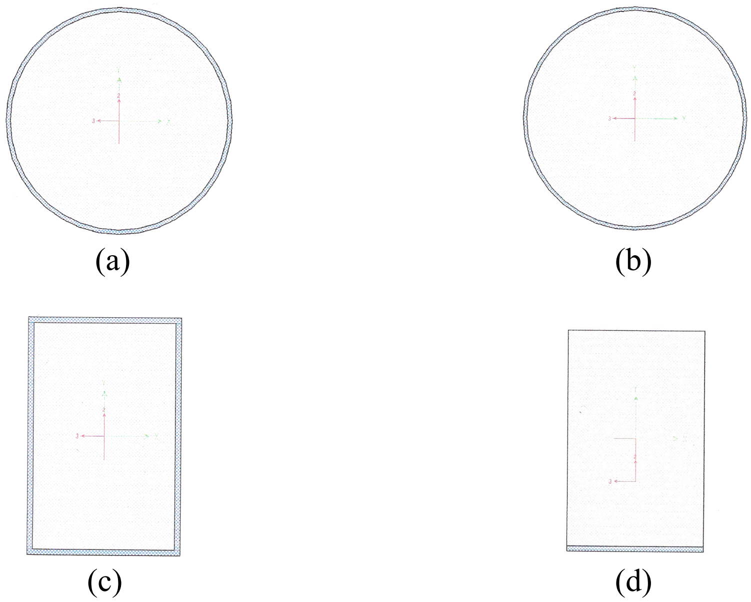

Figure 4. Retrofitting application on column and beam elements
(a) circular column with 50 cm diameter,
(b) circular column with 60 cm diameter,
(c) rectangular column with 25 by 40 cm dimensions,
(d) beam element with 25 by 40 cm dimensions

Analysis of the Monumental Building

There are 1881 nodes defined in the structural system of the building with walls while there are 814 nodes defined for the building without walls. Periods of the first three modes of the original building and its retrofitted versions are obtained as a result of modal analyses (Sap2000 2000). These periods are provided both for the building with walls and the building without walls (Tables 2-4). In the analyses, a damping ratio of 5 % is considered. As carbon fiber (CFRP) retrofitting is applied, a stable drop is observed at the period values of the first three modes of the building (Tables 2-4) both for the building models with walls and the building models without walls.

Table 2. Periods of first three modes of the original building

Modes	**Periods of building with walls (sec)**	**Periods of building without walls (sec)**
1st	0.31	0.63
2nd	0.28	0.46
3rd	0.27	0.44

Table 3. Periods of first three modes of the retrofitted building (CFRP plate thickness is 0.5 cm)

Modes	**Periods of building with walls (sec)**	**Periods of building without walls (sec)**
1st	0.27	0.33
2nd	0.22	0.27
3rd	0.17	0.22

Table 4. Periods of first three modes of the retrofitted building (CFRP plate thickness is 1.0 cm)

Modes	**Periods of building with walls (sec)**	**Periods of building without walls (sec)**
1st	0.26	0.31
2nd	0.21	0.27
3rd	0.17	0.21

The building is located on a soil type of Z3 with T_A=0.15 sec and T_B=0.6 sec, respectively. The corresponding spectrum function is given in Figure 5. Effective ground acceleration constant, A_O value is 0.1 while the building importance constant, I value is 1.0. Ductility constant, R value is taken as 1 regarding the brittleness of the material. Spectrum constant, K, which is evaluated as 0.98 m/sec^2, is calculated using Equation 1.

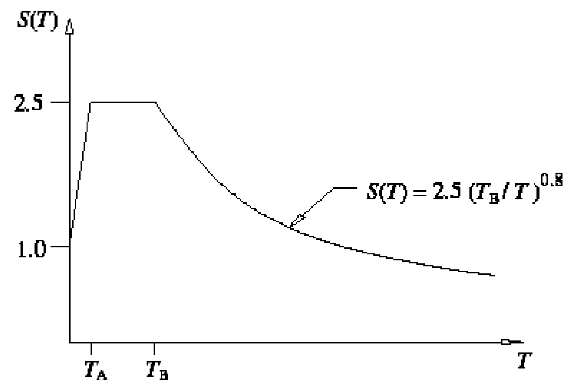

Figure 5. Spectrum function

$$K = \frac{A_O \cdot I \cdot g}{R} \tag{1}$$

Spectrum constant, $S(T)$ which is evaluated according to Equation 2 is calculated to be 4.24 for the building with walls and 2.40 for the building without walls.

$$S(T) = 2.5(\frac{T_B}{T})^{0.8} \tag{2}$$

The analyses are conducted both in X and Y directions for the ground motion records provided in Table 5. The building, soil and seismic region properties of the structure explained above are used. The results of the analyses for the retrofitted building models are compared with the results of the original building model which were evaluated previously (Celik and Sadak 2007).

The ground motion records used are Ceyhan EW and Ceyhan NS records (Adana Ceyhan Earthquake 1998), Izmit EW and Izmit NS records (Marmara Earthquake 1999), and Bolu EW and Bolu NS records (Duzce Earthquake 1999). The maximum ground acceleration values (PGA) are provided in Table 5 for the given earthquake data set.

Table 5. Ground motion records and maximum ground acceleration (PGA) values

Ground motion record	**Maximum ground acceleration (PGA)**
Ceyhan EW (Ceyhan1998)	0.23 g
Ceyhan NS (Ceyhan1998)	0.28 g
Izmit EW (Marmara 1999)	0.23 g
Izmit NS (Marmara 1999)	0.17 g
Bolu EW (Duzce 1999)	0.82 g
Bolu NS (Duzce 1999)	0.75 g

The retrofitted building models are analyzed covering the cases of both with walls and without walls in order to consider that they may be exposed to several severe earthquakes during their lifetimes so that the walls may be destructed and may not function structurally (Senturk, Yilmaz and Yildirim 2008).

Load combinations proposed in the Turkish Code (TS500 2000) are used for the determination of vertical loads and lateral earthquake loads applied on the model buildings. Results of static analyses for different load combinations given in the Turkish Code (TS500 2000) are provided in Tables 6 – 8 both for the original structure and its retrofitted models.

Table 6. Results of analyses for the original structure

Original (with walls)			
Load combination	Structural height (m)	Δ_{imax} (m)	Δ_{imax}/H (%)
1.4G + 1.6Q	11.6	0,0039	0,03
G + Q + Ex	11.6	0,0085	0,07
G + Q - Ex	11.6	0,0086	0,07
G + Q + Ey	11.6	0,0038	0,03
G + Q - Ey	11.6	0,0052	0,05
Original (without walls)			
Load combination	Structural height (m)	Δ_{imax} (m)	Δ_{imax}/H (%)
1.4G + 1.6Q	11.6	0,0094	0,08
G + Q + Ex	11.6	0,0303	0,26
G + Q - Ex	11.6	0,0309	0,27
G + Q + Ey	11.6	0,0180	0,16
G + Q - Ey	11.6	0,0170	0,15

Table 7. Results of analyses for the retrofitted structure (CFRP plate thickness is 0.5 cm)

Retrofitted (with walls)			
Load combination	Structural height (m)	Δ_{imax} (m)	Δ_{imax}/H (%)
1.4G + 1.6Q	11.6	0,0026	0,03
G + Q + Ex	11.6	0,0081	0,07
G + Q - Ex	11.6	0,0082	0,07
G + Q + Ey	11.6	0,0038	0,03
G + Q - Ey	11.6	0,0046	0,04
Retrofitted (without walls)			
Load combination	Structural height (m)	Δ_{imax} (m)	Δ_{imax}/H (%)
1.4G + 1.6Q	11.6	0,0073	0,07
G + Q + Ex	11.6	0,0069	0,06
G + Q - Ex	11.6	0,0070	0,06
G + Q + Ey	11.6	0,0035	0,03
G + Q - Ey	11.6	0,0032	0,03

Table 8. Results of analyses for the retrofitted structure (CFRP plate thickness is 1.0 cm)

Retrofitted (with walls)			
Load combination	Structural height (m)	Δ_{imax} (m)	Δ_{imax}/H (%)
1.4G + 1.6Q	11.6	0,0021	0,02
G + Q + Ex	11.6	0,0063	0,05
G + Q - Ex	11.6	0,0064	0,06
G + Q + Ey	11.6	0,0033	0,03
G + Q - Ey	11.6	0,0031	0,03
Retrofitted (without walls)			
Load combination	Structural height (m)	Δ_{imax} (m)	Δ_{imax}/H (%)
1.4G + 1.6Q	11.6	0,0051	0,05
G + Q + Ex	11.6	0,0043	0,04
G + Q - Ex	11.6	0,0044	0,04
G + Q + Ey	11.6	0,0033	0,03
G + Q - Ey	11.6	0,0028	0,03

The results of static analyses revealed that there is a stable decrease in maximum lateral drift demand, D_{imax} and corresponding drift percentage, D_{imax} /H (%) upon application of CFRP retrofitting on the original building model. Maximum displacement response values are observed at nodes located at the roof top.

Conclusions

The presented study focuses on analytical investigation of effect of retrofit application using carbon fiber (CFRP) plates on seismic behavior of a monumental building located at the town of Fertek which is in historical Cappadocia region of Turkey. The building is suggested to be representative of many similar buildings which were built as worshipping temples during the same era at the Cappadocia region.

As parts of the investigation modal, response spectrum and linear static analysis for different load combinations are applied. The ground motions used in the analyses are introduced in Table 5. The building is analyzed for both with walls and without walls cases in order to consider that it may be exposed to several earthquakes during its lifetime, and the walls may be destructed and may not function structurally.

The CFRP plates are applied at all convenient and available surfaces of column and beam elements. As carbon fiber (CFRP) retrofitting is applied, a stable drop is observed at the period values of the first three modes of the building (Tables 2-4) both for the building models with walls and the building models without walls. In addition, the results of static analyses show that there is a stable decrease in maximum lateral drift demand, D_{imax} and corresponding drift percentage, D_{imax} /H (%) upon application of CFRP retrofitting on the original building model (Tables 6-8).

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