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Strengthening a Historical Building with Carbon Fiber Bands

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Abstract - In general, horizontal stresses that occur during earthquakes cause cracks in masonry walls. In old buildings, usually wooden or iron beams were used as tension members. These beams rotted on the walls of many old buildings examined and lost their tensile properties. This may be riskier, especially where there is more atmospheric pollution, and the increase in this pollution in the next centuries may result in these beams lasting 100 years or less instead of about 300 years. In this study, an exemplary historical building is modeled and analyzed in the SAP2000 program using finite element method, and a mixed system in which carbon fiber bands and carbon fiber meshes are used together is proposed to strengthen the masonry walls. Thus, we can say that these pull elements added to the structure are a system that acts as a stirrup that prevents the masonry walls from opening laterally.

Keywords: *Masonry Wall, Reinforcement, Seismic Performance, Beam, Carbon Fiber Material.*

1. Introduction

The main purpose of strengthening or improvement works is to increase both the ability of the structure to behave better in the case of inelastic deformation and to increase the load carrying capacity and integrity of the structure. One of the most commonly used methods for reinforcing masonry structures consists of applying externally bonded carbon fiber composite materials. The use of this material has become popular due to its lightweight and advantageous mechanical properties. However, the potential of carbon fiber

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material reinforcement techniques is still far from fully utilized when applied to masonry structures due to compatibility issues. In this study, our subject is to make static analysis of a sample structure, to examine the horizontal and vertical load bearing systems, and also to create a mathematical model of the building using the finite element method. In order to determine the structural behavior in the most accurate way, the geometry of the building was largely complied with in modeling studies and modeled in three dimensions. The old pictures of the historical building were selected from engravings and modeled by adhering to the most appropriate building system.

2. Materials and Methods

The creation of the mathematical model of the building started with the creation of a 3D building model in the CAD environment as a result of the architectural studies. The information about the bearing elements and the data obtained from the ground study report were compiled and these collected data were processed on the prepared model. After defining the geometry of the structure in the CAD environment, the prepared geometric model was transferred to the SAP2000 program. The load-bearing walls are defined in the SAP2000 program with the help of solid and wooden roofs and 3 small domes with the help of surface elements. Wooden columns and beams used on the roof are included in the model with the help of frame elements. In modeling studies, it was aimed to divide finite elements into more parts in statically critical sections and to obtain more precise results in these regions [1]. During the finite element decomposition process, it is ensured that the nodal points where different elements intersect with each other are compatible with each other and do not create discontinuities.

In the next step, the boundary conditions, degrees of freedom of the supports and nodal points and the loads affecting the model were determined and entered in the SAP2000 environment in line with the determined geometric conditions of the structure, and thus the model was ready for analysis. In the analysis of the model, the geometrical and material non-linear behavior of the structure and the possibility that the mistakes that can be made may cause wrong results are not taken into account. As a result, the structure has been analyzed according to the linear elastic theory. In linear elastic theory, calculations are made with the assumption that building materials show linear-elastic behavior against tensile and compressive stresses.

For the load-bearing masonry wall of the building, assuming linear elastic behavior under pressure stress is an approach that can give realistic results. Although there is no similar situation for tensile stresses, linear elastic behavior approach is important in determining the areas of the wall subjected to tensile stresses and taking precautions against tensile stresses (against cracks that may occur) in these regions. The loads used on the three-dimensional model in the analysis of the structure are listed below.

- Self (Dead) Loads: In the calculations, the self-weights of the building are taken into account and these loads are automatically included in the calculation by the program.
- Live Loads: In TS 498, a value of q = 5 kN/m^2 is given as live load in residential buildings. This load value is defined as the uniformly distributed load on the floors.
- Earthquake Loads: Both the equivalent earthquake load method and the earthquake spectrum load method were used in the calculation of the earthquake effects of the structure.

Spectral acceleration analysis is used in earthquake analysis of wooden masonry buildings in the Earthquake Code. This was the case when the coefficient R could be taken as 2.5. It has been made using the spectral curve according to the soil class and earthquake zone degree used in spectral analysis. Earthquake loads for both principal directions (X and Y directions) of the building were included in the analyzes separately. The existing load-bearing walls of the building are made of bricks.
The characteristic values given for the walls are given in the table below.

Table 1. Characteristic values given for walls

Physical Size	Value
Specific Weight	18 kN/m^3
Pressure Strength	1.000 kN/m^2
Elasticity Module	2 ile 4.000.000 kN/m^2
Tensile Strength	100 ile 150 kN/m^2

First class pine will be used for the wooden element. The mechanical properties of the material are given below.

Table 2. Mechanical properties of wooden elements

Physical Size	Value
Specific Weight	8 kN/m^3
Pressure Strength	11.000 kN/m^2
Elasticity Module	10.000.000 kN/m^2
Tensile Strength	10.000 kN/m^2

The proposed equations for carbon fiber reinforcement design showed that the design compressive strength f_{mcd} for elements subjected to the lateral confining pressure f_1 can be written as follows:

$$f_{mcd} = f_{md} + k' \cdot f_1' \tag{1}$$

where f_{md} represents the design compressive strength of unconfined masonry, *k'* is a non-dimensional coefficient and f_1' is the effective lateral confining pressure [2]. The coefficient *k'* can assume different values depending on the material and the typology of the applied reinforcement. For carbon fiber reinforcement, the value of *k'* is indicated as $g_m/1250$ where g_m is the specific weight of masonry expressed in kg/m^3. Where k_{eff} is the effectiveness coefficient. This value is the product of two terms: k_H and k_V related to the horizontal and vertical effectiveness [2]. The effective pressure f_1' is expressed in the Standard as:

$$f_1' = k_{eff} \cdot f_1 = k_H k_V f_1 \quad (2)$$

The parameters used are shown below.

- Ground acceleration A = 0.4 g
- Earthquake 1st degree and ground 2nd degree
- Significance factor I = 1.4
- Reduction coefficient = 1

The graphics and other parameters found after these values are entered into the program are shown in Figure 1 and Figure 2.

In the analysis, the regions where tensile and compressive stresses more than the stone wall can carry were determined and spectrum values of the region are given both graphically and numerically. This spectrum has been used to examine the most unfavorable situation for the existing historical building.

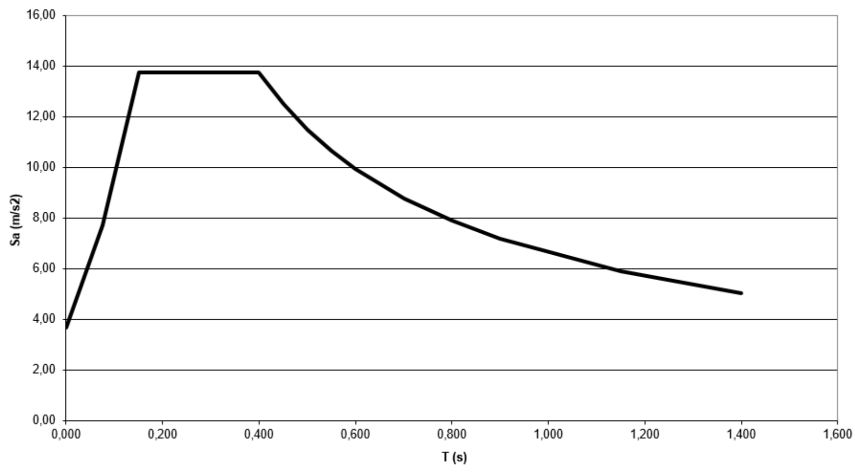

Figure 1. Evaluation response spectrum

Z2-Q1-R1-I4

	Elastic				Inelastic
Period	Spectral Coeff.	Spectral Acc.	Spectral Acc.		Spectral Acc.
(S)		(g)	(m/s2)		(m/s2)
T	S(T)	$A_oIS(T)$	A(T)	Ra(T)	A(T)/Ra(T)
0,000	1,00	0,56	5,494	1,50	3,66
0,075	1,75	0,98	9,614	1,25	7,69
0,150	2,50	1,40	13,734	1,00	13,73
0,400	2,50	1,40	13,734	1,00	13,73
0,450	2,28	1,27	12,499	1,00	12,50
0,500	2,09	1,17	11,489	1,00	11,49
0,550	1,94	1,09	10,645	1,00	10,65
0,600	1,81	1,01	9,929	1,00	9,93
0,700	1,60	0,89	8,777	1,00	8,78
0,800	1,44	0,80	7,888	1,00	7,89
0,900	1,31	0,73	7,179	1,00	7,18
1,150	1,07	0,60	5,900	1,00	5,90
1,400	0,92	0,51	5,041	1,00	5,04
1,900	0,72	0,40	3,949	1,00	3,95
2,400	0,60	0,33	3,275	1,00	3,28
2,900	0,51	0,29	2,815	1,00	2,82
3,400	0,45	0,25	2,479	1,00	2,48
10,000	0,19	0,11	1,046	1,00	1,05
			for R=1	R=	1,00

Input SAP2000		
Freq.	Period	Acc.
(Hz)	(S)	(m/s2)
F	T	A(T)
100,00	0,000	3,662
13,33	0,075	7,691
6,67	0,150	13,734
2,50	0,400	13,734
2,22	0,450	12,499
2,00	0,500	11,489
1,82	0,550	10,645
1,67	0,600	9,929
1,43	0,700	8,777
1,25	0,800	7,888
1,11	0,900	7,179
0,87	1,150	5,900
0,71	1,400	5,041
0,53	1,900	3,949
0,42	2,400	3,275
0,34	2,900	2,815
0,29	3,400	2,479
0,10	10,000	1,046
	R=	1,00

Soil	Z2
A_o=	0,40
I	1,40
T_A	0,15
T_B	0,40
R=	1,00
Gravity=	9,81
T	

Input blue values from table 6.4, 6.2 & 6.5	
Z2	Soil Type (Z)
1	Earthquake Zone Type
1,40	Importance Factor
1,00	Reduction Factor

FORMULAS:		
A(T)= Ao I S(T)=	0,560	S(T)
$S(T)=1+1.5T/T_A$=		(0<T<TA)
S(T)=2.5=		(TA<T<TB)
S(T)=2.5(TB/T)^08=		(T>TB)
Ra(T)=1.5+(R-1.5)T/TA=		(0<T<TA)
Ra(T)=R=	1,00	(T>TA)

Figure 2. Earthquake spectrum

2.1. Finite Element Model

After the three-dimensional model prepared by using technical drawings was transferred to the SAP2000 program, the facade views of the model consisting of 3D shell and bar elements were obtained. Color differences on the model represent elements with different characteristics or features. In the past, there were 4 chimneys in the building and these chimneys were generally destroyed in earthquakes and were built again. Since the rigidity of the structure is higher than these chimneys, problems arise in dynamic analysis. Therefore, during the solution, either the chimneys are removed and analyzed in a separate model or the whole system is analyzed together by giving its mass to zero. Analysis done in this way does not pose a problem.

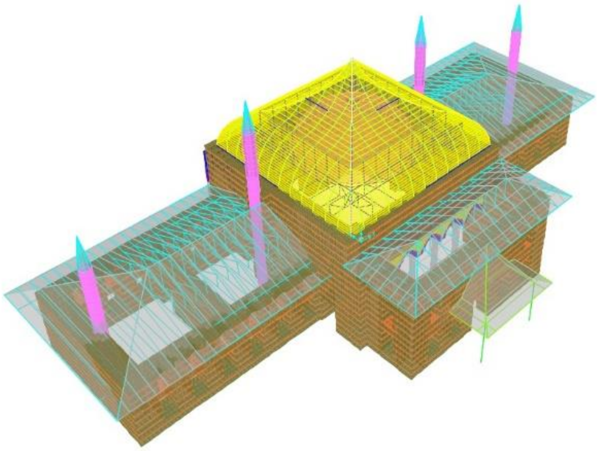

Figure 3. 3D representation of the new structure only, without showing the existing structure

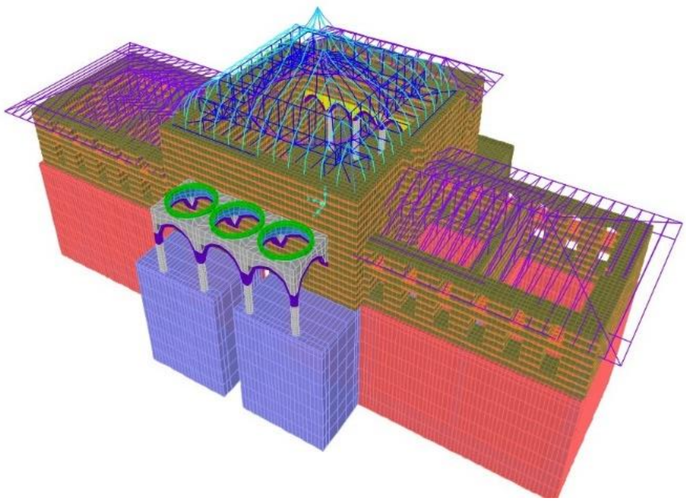

Figure 4. 3D display of the existing building and the new building to be added

In general, the coating and its own weight are given along with the snow load on the roofs. Here the roof weight is 100 kg/m².

2.2. Deformation

Dead, coating, snow, live loads are very little, so it only affects the roof. The general values of the deformations are calculated for the combinations by giving understandable node numbers where desired. Here, the deformation at the top of a roof and the horizontal deformations at the top of the walls are numerically found.

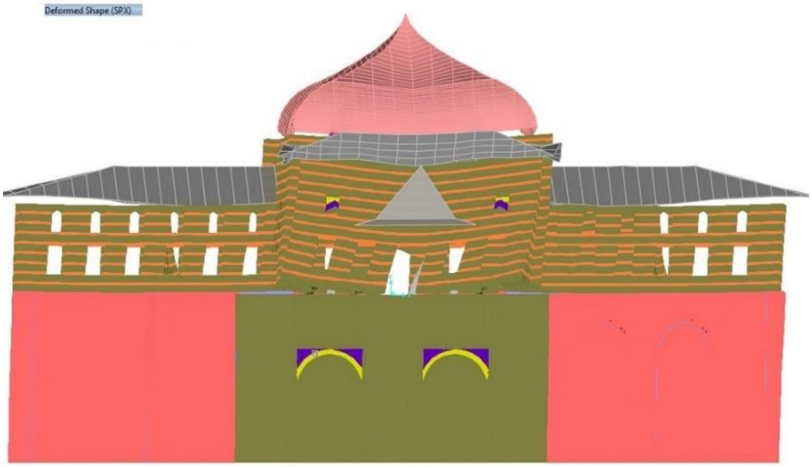

Figure 5. An example form of deformation caused by the structure's own weight and earthquake loads

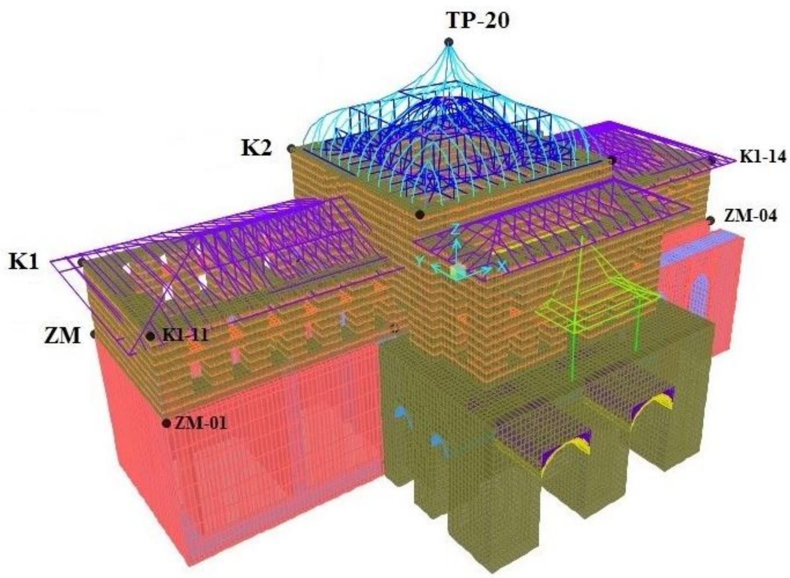

Figure 6: Joint numbers with values shown in the model

2.3. Modal Analysis

Deformations arising from modal analysis were examined. Since the structure is very heavy, the first modes occur on the light roof. But the next modes are given by the building's own mod shapes. In this case, the mass participation factors of the modes do not change, whether in the first or the latter.

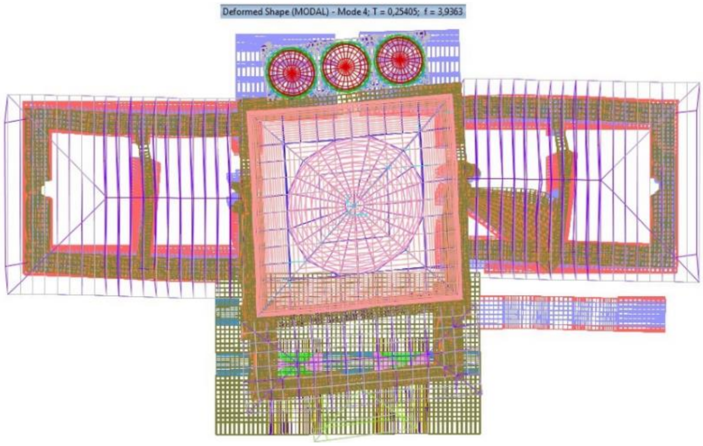

Figure 7. One of the deformed shapes

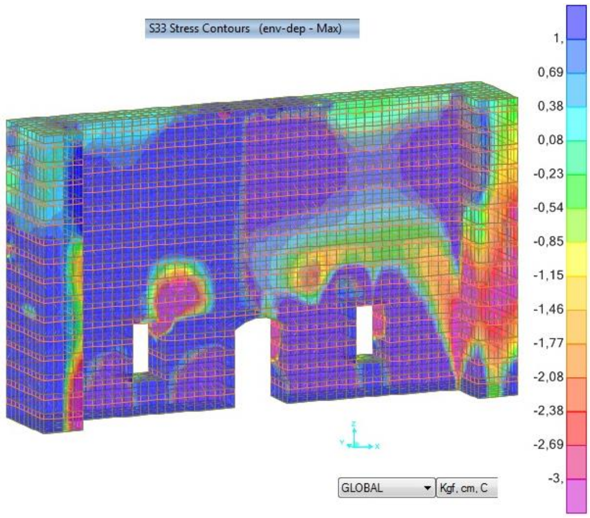

Figure 8. Wall 4 Earthquake loading and S 33 Stress (vertical direction)

In this study, all values of different parameters, which are formed from modal analysis, are calculated. Findings are modal participating mass ratios, modal participation factors, modal periods and frequencies and response spectrum modal information. The walls are modeled as solid (or infill) elements and internal forces are studied in horizontal and vertical directions. In general, vertical stresses are observed in walls under dead and live loads, and the stresses are often far below the capacity of the masonry element. In earthquake situations, these pressures usually increase between 30% and 50%, but the same amount of vertical tension occurs on the other side. If this pull is more than 1-2 kg/cm^2, a slight separation or lift occurs and comes back to its original position depending on the earthquake back and forth movements. If this pull is more than a certain amount in thin and long structures, overturning occurs, which should be examined in such structures. It is necessary to look at the largest negative values (ie min. Contour) to see the maximum pressure and the largest positive values (max. Contour) to see the maximum pull. As an example, one of them is shown in Figure 8.

3. Conclusion and Suggestions

Building strong and earthquake-resistant walls is to build a wall layer by layer. It is the rule of earthquake-resistant wall construction that every 100-150 cm high layers and smooth stone surfaces in the plane of the layer are formed, the horizontal plane of the wall interlocking one to the other, and a framework with tensile members is formed. In general, horizontal stresses cause cracks in the wall. For this reason, beams in old buildings were placed and if there were no beams, openings would occur on the walls. These walls have cut stone on the outer wall and rubble stone on the inside. The lifespan of these tensile members is about 300 years, but in ancient times these walls were rebuilt using the same techniques. In this structure, the walls are modeled as solid elements and internal forces are viewed in horizontal and vertical directions.

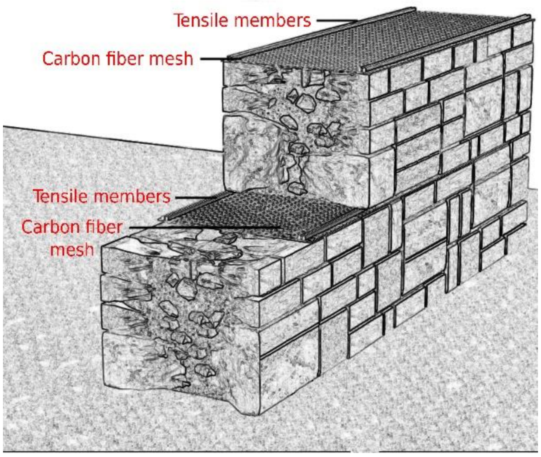

Figure 9: Placement of carbon fiber mesh [3]

In this study, a net is recommended to provide a transverse tensile member between the layers, and this is a system that acts as a stirrup to prevent the wall from opening laterally. Placed wooden beams generally do this task, but opening in case of decay is an inevitable result. Another suggestion is to put a pair of solid beams at the lowest level while constructing the walls. These beams evenly distribute the wall load and prevent cracks if variable settlements occur. In old buildings, wooden beams were generally used as a tensile member. Adhering to the old, these wooden beams were placed in the project. Our recommendation is to place these carbon fiber tensile members together with wooden beams and carbon fiber mesh. These beams rotted on the walls of the old buildings that we have examined in large quantities and lost their tensile properties. The tapes placed are either a material consisting of carbon fiber or glass fiber [4, 5].

The values obtained in the study of the horizontal tensile amounts of masonry walls are used here in the strengthening calculations. A tensile member equivalent to these tensile amounts was placed. On average, the tensile values on the walls are 1-2 or to 1.5 kg/cm^2. Suppose the wall itself carries the 0.5-1.0 kg/cm^2. For the amount of 1 kg/cm^2 remaining here, 2 pieces of 40 cm wall total tensile amount is 5-6 tons. Here, a total of 4 tensile strength bands of 1 tonne will be placed on both sides of the walls.

The structure is located in the first degree earthquake zone, but since the ground type is good, ie it is built on II and also the importance coefficient of the building is 1.4, there will be a small amount of stress in general. For this, cross cracks are very likely to occur in the walls between windows. On the other hand, these strength bands will be placed in the middle of the wall with 50-60 cm intervals, 2 in each.

Properties of the carbon band;

- There is no corrosion problem seen in steel material in carbon strength bands,
- The carbon strength bands used have an average of 7 times more tensile strength than steel,
- Carbon tapes of 1 to 4 mm thickness and 1 to 4 cm width are easily inserted into the wall joints without disturbing the texture of the structure.
- Strength bands help the wall by carrying not only the tensile stresses, but also the shear stresses occurring in that section.

Carbon tape strengths;

- Tensile strength: 3430 N/mm^2
- Elasticity module: 230000 N/mm^2
- Tape tensile strength: 7480 N

Usage of carbon tape;

- The joints to be opened into the wall are cleaned,
- Double-component polymer is applied to the carbon band in the joint prepared by being fed as much as possible,
- Carbon tapes are stretched and placed in the joint,
- The double component polymer is applied again with a brush on the carbon band, which is placed in the joint and is in physical contact with the joint depth.

- In the polymer application process, care should be taken to polymerize the carbon band and the contact points with the joint without gaps,
- The interior of the joints where carbon tape is laid and polymerized, is filled with a special mortar until the outside of the wall,
- The filled mortar is leveled and smoothed on the wall surface.

The railroad passes next to the building, so the vibrations caused by the rails should be measured with precision instruments and its effect should be examined both in a short time and a long time. Our suggestion is to equip a certain length of these rails with anti-vibration insulators.

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