Seismic Vulnerability Analysis and Rehabilitation of Gonbad Kavous Tower (The tallest brick tower in the world)

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SUMMARY:
Gonbad-e-Kavous brick tower which dates back to 10th century, is the remnant of an ancient glorious building and is located in downtown. This massive brick building is known as the world's tallest brick tower. The structure is located on a highly-active seismic region and needs to be retrofitted properly due to its historcial significance. The purpose of this article is to provide some methods for rehabilitaion for the existing brick structure through some common structural analyses. Three-dimensioal finite element models of the tower have been utilized in the nonlinear finite lement program Ansys 13.0. Dynamic modal and time-history analyses were conducted subsequently to give insight into dynamic response of such structures according to which, rehabilitation approaches have been proposed.

Keywords: Seismic, three-dimensional finite element model, dynamic response, rehabilitation.

1. INTRODUCTION

One of the most unique and prominent monuments of Iranian architecture in the Islamic period is the Gonbad-e-Kavous brick tower with national monuments registration number of 86. Gonbad-e-Kavous brick tower dates back to 10th century and was built by "Shams Al Qaboos Ibn-e-Woshmgir" for his tomb (figure 1). It is located three kilometers away, northeast from the ancient city of Gorgan (jorjan) in Golestan province (figure2). Such buildings typically used to celebrate and remember the person who is buried there.

Figure 1. Gonbad-e-Kavous Tower views

Figure 2. Gonbad-e-Kavous Tower location.

The building has a 36.14m height body with a ten-pointed star shaped plan and a 15.93m circular plan dome with the inner radius measuring 4.8m. In its' lower level the dome thickness is measured to be 2.63m (figures 3 and 4).

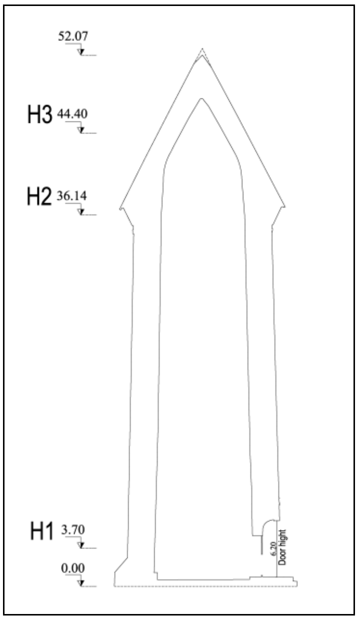

Figure 3. Gonbad-e-Kavous Tower; elevation view

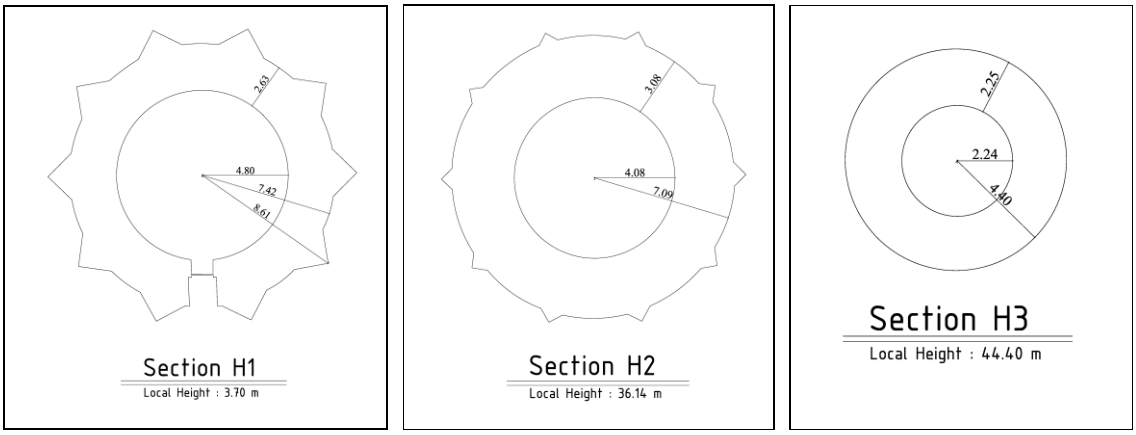

Figure 4. Gonbad-e-Kavous Tower; section view

Also the building has an entrance on its southern side with 6.20 meters height (figure 5).

Figure 5. Gonbad-e-Kavous Tower; entrance view

2. NUMERICAL SIMULATION

2.1. Material Properties

There exist some difficulties in the simulation process regarding materials used in the structure and the construction method. First of all there is not reliable information regarding the materials used in the inner parts of the structure. Secondly large discrepancies in mechanical properties can be observed due to using natural materials. Thirdly determining the mechanical properties of the materials is costly and time consuming. Also unknown construction sequence and existing flaws in the structure are the other factors which add to the uncertainty of the numerical solution.

Mechanical properties of the material used in the simulation process are presented in Table1 and figure 7. These values are determined according the recommended values given in the instructions for seismic rehabilitation of masonry buildings and also qualitative observational studies.

Two methods commonly used in modeling brick walls are:
1-Micromodeling 2-Macromodeling

A brick wall mainly consists of brick, mortar and the interface of brick and mortar (figure 6).

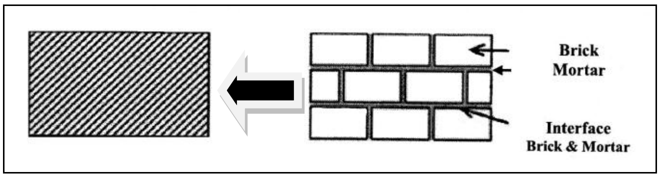

Figure 6. Micro modeling method

In Micro modeling method, each component of the brick wall are separately modeled and then connected to each other. Despite the accuracy of the micro modeling approach, it is not applicable in case of large scale problems, because of the high computational cost due to complexity of the computational framework used. So macro modeling approach are commonly use in case of modeling massive structures.

Table 2.1. Masonry material properties

<table>
<tr><th>material model</th><th>element type</th><th>material properties</th></tr>
<tr><td>1</td><td>Solid 65</td><td>
<table>
<tr><th colspan="2">linear isotropic</th></tr>
<tr><td>Ex</td><td>2.33e6 (KN/m2)</td></tr>
<tr><td>PRXY</td><td>0.25</td></tr>
<tr><td>DENS</td><td>1.8 (ton/m3)</td></tr>
</table>
<table>
<tr><th colspan="3">Multilinear Isotropic</th></tr>
<tr><td></td><td>Strain</td><td>Stress (KN/m2)</td></tr>
<tr><td>Point 1</td><td>0.0004635</td><td>1080</td></tr>
<tr><td>Point 2</td><td>0.0007879</td><td>1674</td></tr>
<tr><td>Point 3</td><td>0.001775</td><td>2988</td></tr>
<tr><td>Point 4</td><td>0.002465</td><td>3492</td></tr>
<tr><td>Point 5</td><td>0.003156</td><td>3600</td></tr>
</table>
<table>
<tr><th colspan="2">Concrete</th></tr>
<tr><td>ShrCf-Op</td><td>0.3</td></tr>
<tr><td>ShrCf-Cl</td><td>1</td></tr>
<tr><td>UnTensSt</td><td>170 (KN/m2)</td></tr>
<tr><td>UnCompSt</td><td>-1</td></tr>
<tr><td>BiCompSt</td><td>0</td></tr>
<tr><td>HydroPrs</td><td>0</td></tr>
<tr><td>BiCompSt</td><td>0</td></tr>
<tr><td>UnTensSt</td><td>0</td></tr>
<tr><td>TenCrFac</td><td>0</td></tr>
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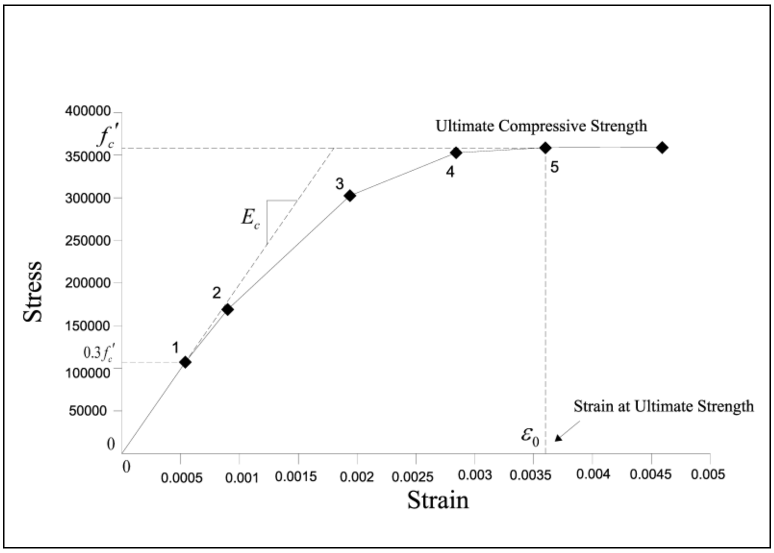


Figure 7. Non-linear stress-strain curve of Solid65 element

2.2. Finite Element Modeling

Three-dimensioal finite element models of the tower have been made with the aid of nonlinear finite element program Ansys 13.0. Three types of elements were used in building the model including Solid65, Conta175, Targe170 elements in which the first element is used for wall and the second and third elements are used for taking into account the interaction between foundation and body of the building and the dome (figure 8)

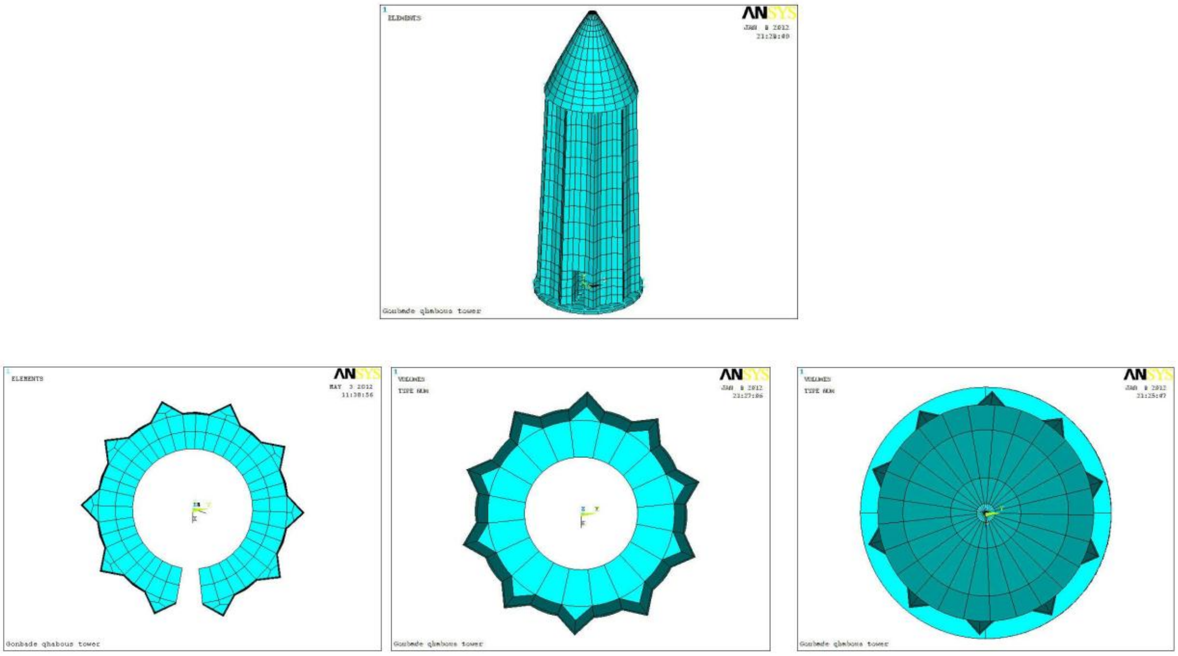
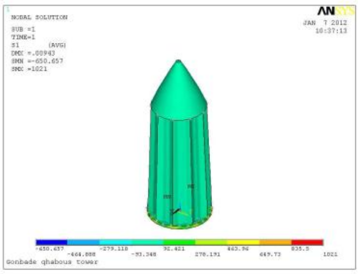


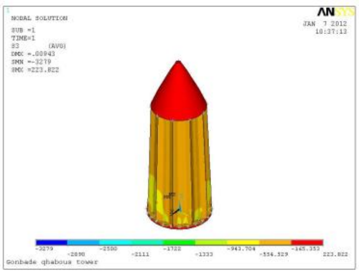
Figure 8. Modeling and meshing views of structure in ANSYS program

2.3. Gravitational Analysis

Studying the behavior of the building under gravity loads is the first step in structural analysis.

In this case load transfer between structural members in static condition determines the accuracy of the numerical model. The acceleration of gravity is set to 9.81 m/s^2 for the analysis and applied to all structural masses. After static analysis it is observed that the structure is in good condition regarding stability and sustainability issues. The structural weight was calculated to be 86400 KN (figure 9-11).





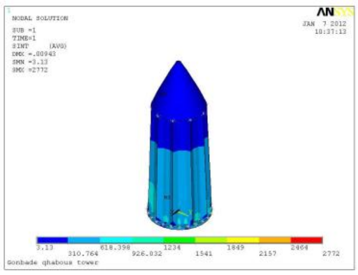


Figure 9. Tensile stress (S1) **Figure 10.** Compressive stress (S3) **Figure 11.** Shear stress (Ssint)

2.4. Modal Analysis

In the modal analysis, natural frequencies and mode shapes were determined in the desired frequency. Modal analysis was performed as Linear and After analysis. The graphical representation of the results for the first 10 vibrational modes have been exhibited in figure 12.

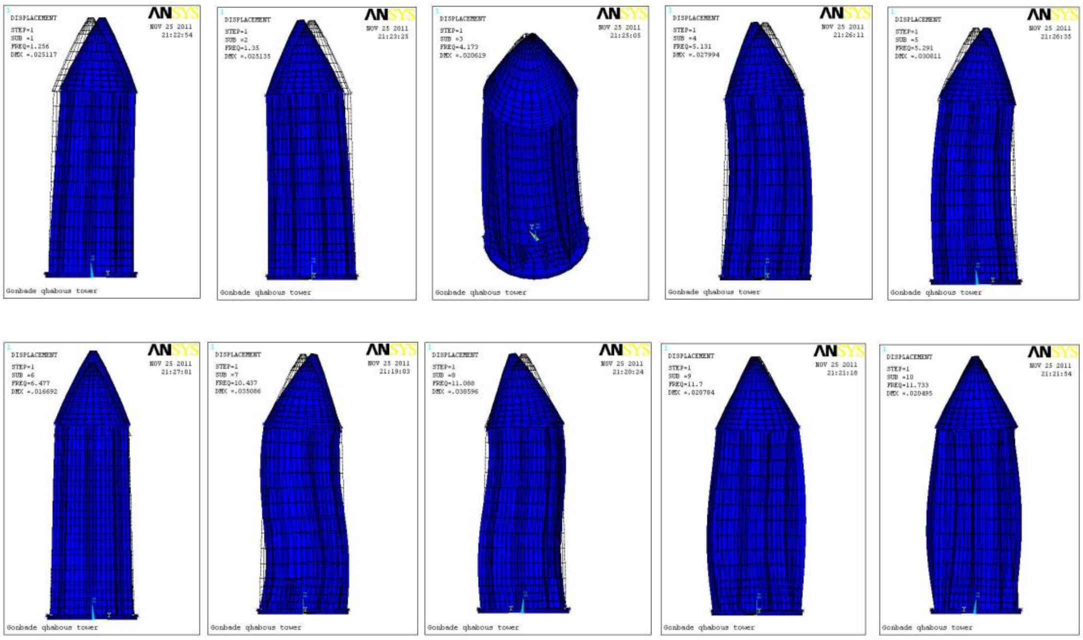


Figure 12. Results of the first 10 vibrational modes

2.5. Non-linear Time History Analysis

A complex method and also the most accurate one to assess non-elastic structural behavior is to impose the real underground motion acceleration to the structure. For structural analysis of the dome Kavous, the Northridge earthquake data is used here (figure 13, 14). All of the earthquake accelerations are multiplied by a scale coefficient. The scale factor is equal to 1/A where A is the base design acceleration and is equal to 4.5. After modification of the two components, we regard each earthquake from Arias a_5% to Arias a_{95}% and we enter the two components as the input into the structure analysis separately.

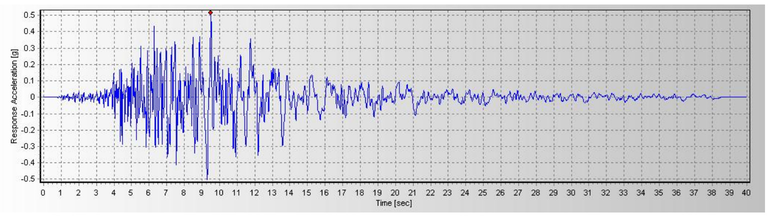


Figure 13. Northridge earthquake accelerations in direction x

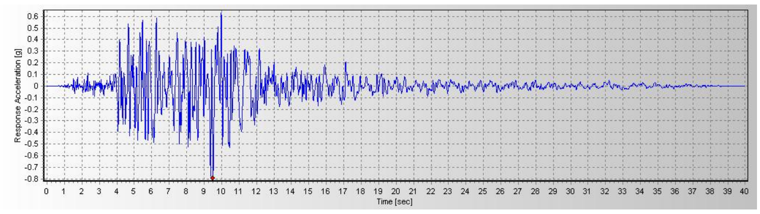


Figure 14. Northridge earthquake accelerations in direction y

The real damping matrix of the structure is hard to determine and since there is no exact formula for it in the literature, approximate methods are commonly used such as those regarded as Riley methods.

$$c = a_0 m + a_1 k \tag{6.1}$$

$$\begin{Bmatrix} a_0 \\ a_1 \end{Bmatrix} = \frac{2\xi}{w_m + w_n} \begin{Bmatrix} w_m w_n \\ 1 \end{Bmatrix} \tag{6.2}$$

In wich, w_n is the frequency of the first mode, w_m is the frequency of the third mode and ξ is assumed to be equal to 0.015. Equations 6.1 and 6.2, results in a_0= 0.03 and a_1= 0.0055. Coefficients a_0 and a_1 are then used in the time history analysis. The structure is analyzed with Northridge earthquake acceleration data. The critical time for the Northridge earthquake in the x direction is 4.28 seconds and at this time the maximum displacement of the structure is obtained as 8.43 cm. The critical time for the direction y is 6.12 seconds for which the maximum displacement is obtained as 12 cm. As can be seen in figures 15- 20, in the critical time, stresses exceeded the allowable stress in the structural elements in both directions from which it can be concluded that the tensile stress is the only critical stress and the building has enough resistance against compressive and shear stresses. The value of the critical stress is 170KN/m^2 for tensile stress, -3600KN/m^2 for compressive stress and 1800KN/m^2 for shear stress.

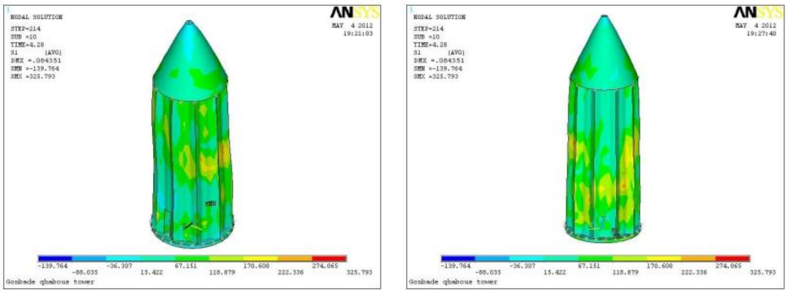


Figure 15. Tensile stress in the front and rear View (S1) (Dir X)

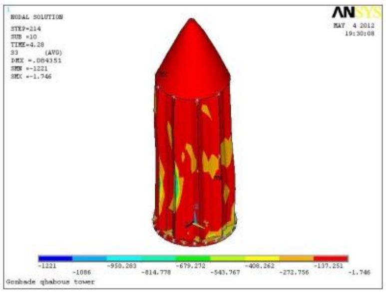


Figure 16. Compressive stress (S3) (Dir X)

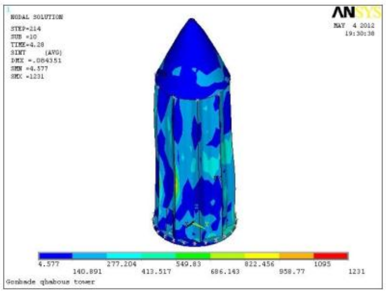


Figure 17. Shear stress (Ssint) (Dir X)

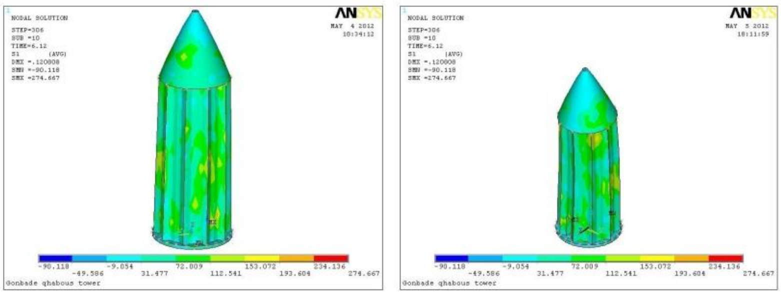
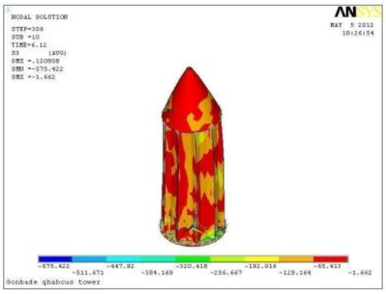


Figure 18. Tensile stress in the front and rear View (S1) (Dir Y)



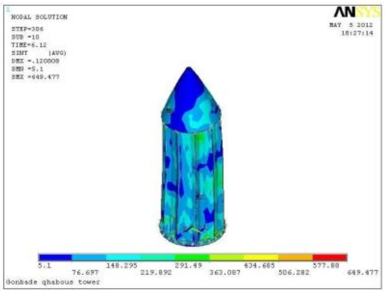


Figure 19. Compressive stress (S3) (Dir Y) **Figure 20.** Shear stress (Ssint) (Dir Y)

3. RETROFITTING USING SEISMIC BASE ISOLATORS

Rubber seismic isolation with lead core is considered for earthquake retrofitting and reducing the earthquake force acting on the Kavous tower (figure21). Rubber isolations are not suitable for providing high damping and energy absorption. The amount of damping that is about 3% of the critical damping in rubber isolations increases to more than10 percent at the time of vibration with the aid of lead-core in rubber isolations with surrender. Also, the lead core supplies Primary adequate stiffness, which provides resistance for isolated structure against lateral mild loads such as wind or weak earthquakes.

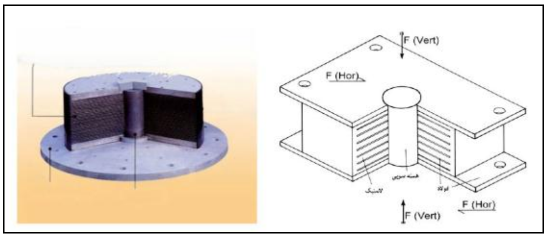


Figure 21. Rubber seismic isolation with lead core

According to the seismic isolation design Instruction and design and performance Guide (523 Publication) for seismic isolation systems in buildings, the mechanical specifications are summarized in Table 3.1 and figure 22.

Table 3.1. Base isolatore with lead core design results table

D_D (Displacement Design) (m)	0.22	(E) (rubber vertical modulus) (KN/m^2)	2000
B_D(Damping Ratio)	%25	(k) (Modified coefficient modulus)	0.5
(n)(number of baseisolator)	57	(G) (rubber shear modulus) (KN/m^2)	500
(kv)(Vertical Stifness) (KN/m^2)	674230	(γ) (maximum shear strain)	%150
(k_H) (Horizontal Stifness) (KN/m^2)	1070	(Ec) (rubber and steel Compressive vertical modulus) (KN/m^2)	314500
(F_{ypb})(stress yeilding lead) (KN/m^2)	12000	(S) (shape factor)	12.5
(σ_{all}) (Compressive stress allowable) (KN/m^2)	10000	(F_y) (Steel ST52)	42000

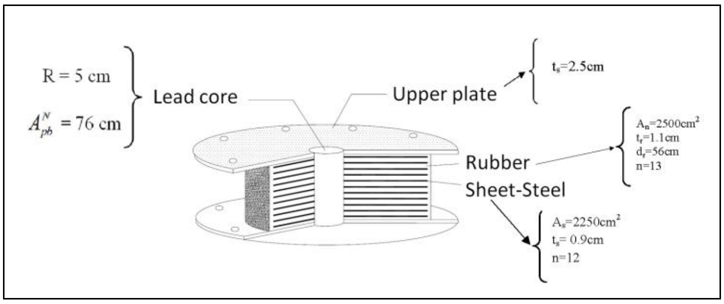


Figure 22. Base isolatore with lead core mechanical specifications

Isolation Modeling in ANSYS is achieved by using three springs in the x and y directions, with different stiffness with COMBIN14 element (figure 23, 24).

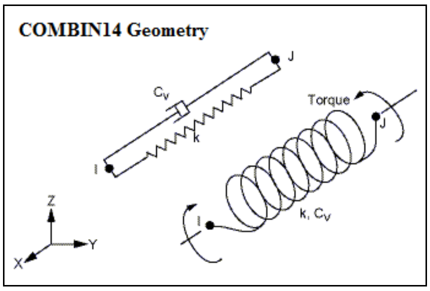


Figure 23. Combin14 element For Modeling isolation

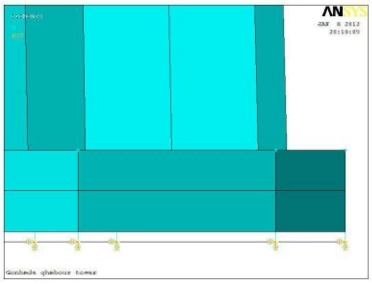


Figure 24. Modeling isolation in ANSYS program

4. TIME HISTORY ANALYSIS RESULTS FOR RETROFITTING BUILDING

Because the tensile stress is the critical stress, which occurs in x direction, retrofitted structure is investigated in the direction of applied force x. After the Time history analysis, the maximum displacement is 20.4 cm which occurs at 10.32 seconds at the highest point of the structure. By comparing the critical values of the tensile stress which happens in the regions of maximum displacement with that of the primary structure without retrofitting, it can be observed that the critical stress is less than the maximum allowable stress (SMX= -179.396 KN/m2) (figure 25, 26).

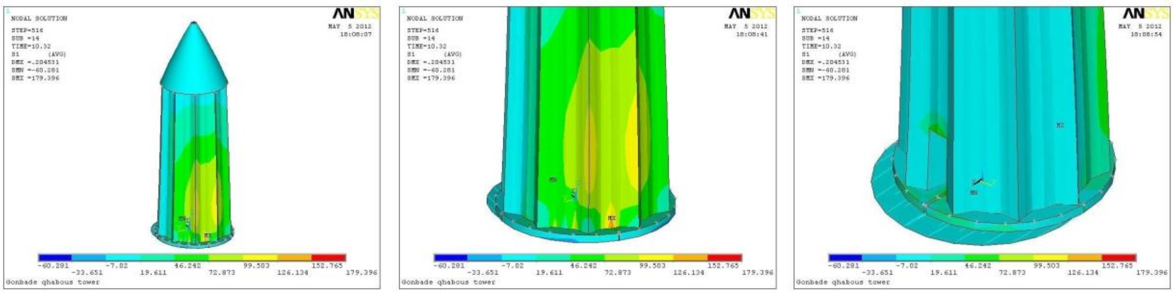


Figure 25. Tensile stress (S1) (Dir X)

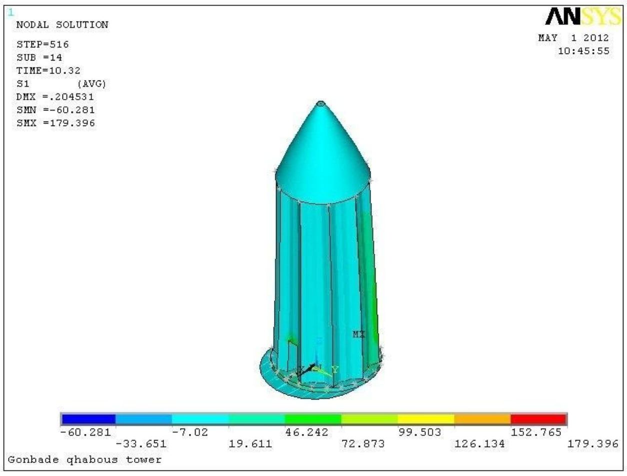


Figure 26. Tensile stress (S1) (Dir X)

5. CONCLUSION

Time history analysis revealed that the stress in the Kavous tower exceeds the allowable value under seismic action and retrofitting methods need to be applied to reduce the earthquake effect on the entire structure. Analysis showed that the tensile stress is the critical stress and so the base isolation method has been utilized and its' robustness has been investigated under Northridge earthquake. It is observed that using such retrofitting method reduces the maximum displacement and leads to values of critical stress within the allowable limit.

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