SECOND EUROPEAN CONFERENCE ON EARTHQUAKE ENGINEERING
AND SEISMOLOGY, ISTANBUL AUG. 25-29, 2014

SEISMIC RETROFITTING OF A 29 STORY HOTEL BUILDING IN A VERY HIGH SEISMIC ZONE IN TEHRAN, IRAN

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ABSTRACT

The 29 story Azadi Hotel building is located in Tehran in a very high seismic zone. It was built in early 1970's with a relatively poor seismic design standard. The main lateral load carrying elements are the concrete cores and shear walls. As many other hotels built in that period, the major deficiency is the existence of a soft story in the lobby.

A major challenge in retrofitting of this building was the inability of the engineers to intervene largely in the lobby. Further challenge was to retrofit the high columns in the lobby, which had very little stirrups and consist of poor quality concrete with average concrete compressive strength of 18 MPa. Moreover, due to the large mass and the 82 meters height, the building would overturn during a major earthquake.

In order to prevent overturning of the structure, and reduce moments and shears at the base, 16 hydraulic dampers were utilized in the lobby and first floor. More than 20,000 Meters of FRP was also used to reinforce the columns and the cores in the lobby and the two basement floors. The dampers were installed with help of inverted V-bracings. Following the seismic retrofit of the building the total shear and overturning forces at the base were reduced by 35 percent.

Total time for the seismic retrofitting of the building took 6 months and the hotel was reopened in 2011. Currently, there are many new projects which are using the same concept as used in this project, and thus the Azadi Hotel project can be seen as a pioneer of its own for large retrofitting projects in Iran.

Soil-structure interaction was well considered in the retrofitting analysis of the building. This paper highlights the analytical and design procedure used in the retrofit of the Azadi Hotel building.

INTRODUCTION

The 29 storey Azadi Hotel was built during the 1970's by a German engineering company from Stuttgart (Figure 1). Figure 2 shows the ground floor plan of the hotel. In order to determine the seismic resistance of the Azadi Hotel, the lateral-force-resisting system was first identified. The building is a made of concrete and the preliminary resisting units for the seismic loads are the shear walls. The building has extensive walls from the 2nd floor to the 28th floor. These walls partition the rooms and are made of reinforced concrete. However, these walls stop at the ground level, introducing a discontinuity to the lateral load resisting system. Additionally, the building has two cores made of reinforced concrete. The seismic load then must be transferred to the foundation via the cores and the two walls which are at the most exterior side of the building plus additional walls which exist between the first floor and the foundation. The flat concrete slabs have continuous steel through the columns and the walls. This is advantageous during an earthquake.

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Additional reinforcements have been provided at the opening of the walls, which shows a good construction detailing and dimensioning. The wall thickness is minimum 20 cm, and thickness of the walls is higher than the 1/25 of the height, which is required in case the building must be operational after a severe earthquake. Examining the diaphragms had no opening immediately adjacent to the shear walls, which were larger than 15 percent of the wall length.

In the lateral-force-resisting system there are more than two walls in each principal direction, thus providing a redundant system. In the floors 2^{nd} and 28^{th} the distance of the shear center to the center of mass is less than 20 percent of the building width, which is very advantageous. However, in the lobby floor, this distance is higher; this causes a torsion effect during a severe earthquake which is disadvantageous. The mass distribution in all the stories is uniform. The shear walls which are present, at floors 2^{nd} and 28^{th}, stop at the ground level, this causes a stiffness discontinuity of 70% or higher, which leads to the soft story problem.

Figure 1. Azadi Hotel before retrofitting

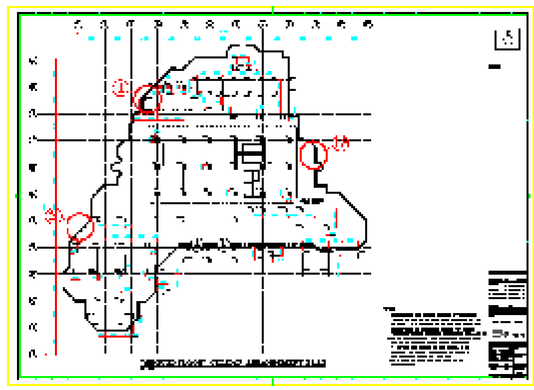

Figure 2. Ground floor plan of Azadi Hotel

REQUIREMENTS OF SEISMIC HAZARD, RETROFITTING AND MODELING

The owner had set the seismic performance level of the building to immediate occupancy for earthquakes with 475 years return period (FEMA 356). This means that the post-earthquake damage state should include very little structural damage. The basic vertical and lateral load resisting systems of the building should retain nearly all of the pre-earthquake strength and stiffness. The risk of life-threatening injury as a result of structural damage should be very low, and although some minor structural repair may be appropriate; this should not be generally required prior to preoccupancy (FEMA 356). The FEMA prescribes the overall damage for the building for immediate occupancy to be light. No permanent drift is to be expected. Minor cracking in the walls, slabs, and cores are allowed for immediate occupancy performance. For structures in which concrete walls carry most of the earthquake loads, the cracking width is limited to 1.6 mm in the walls, and in the beams to 3.2 mm. The drift is limited to 0.5% during the earthquake and should be negligible after the earthquake. The crack width in the concrete diaphragms should be limited to 3.2 mm. The foundation should undergo a minor settlement and negligible tilting.

The seismic hazard due to the ground shaking is defined by the acceleration time history and response spectra. The Iranian code of practice for seismic resistant design of buildings, Standard number 2800, prescribes a response spectrum for all Iran. The building is considered to be in a very high seismic zone. This spectrum is adjusted for four different types of soils; soil classes I, II, III, IV. The site classes depend on the average shear wave velocity of the soil. Soil class II was assumed for the Azadi site in Tehran. However, a local site investigation was performed by IIEES Institute in Tehran, and a site specific spectrum was determined for the hotel site. The spectrum is applied in both translational directions for the calculation of the Azadi hotel. For the final design, nonlinear analyses with acceleration time history were performed. The input time histories were also provided by IIEES. The behavior of the cores is governed by flexures and they tend to form a plastic hinge around the base of the wall under severe earthquake loading. The ductility of the wall is a function of the:

- Vertical reinforcements
- Shear reinforcements
- Level of the axial load

As they carry high axial loads and have little shear reinforcements, they are not very ductile. Some shear walls are introduced from the foundation to the first floor. These walls behave in a mixture mode of shear and flexure; the ductility of these walls, however, is very limited. Due to the above facts, a ductility factor of 2 was assumed for the existing unretrofitted building. Very critical are the columns at the lobby which are introduced to create a commercial space in the first story. Such designs are not allowed in seismic zones, because a high demand is placed on these columns during the earthquake loading. In buildings which are built during the 1970's, the columns have usually only standard vertical and transverse reinforcements. In order for these columns to survive severe earthquake loading, they must have tightly spaced closed ties, which are well anchored.

The Azadi building shows considerable out-of-plane irregularities. The shear walls, at upper stories, discontinue at first floor, resulting a setback in the first story. Additionally, there is an in-plane-discontinuity in the first floor, that is, there are new shear walls in this floor, which do not exist in the upper floors. Due to the irregularity of stiffness, and geometry at the first floor, the equivalent static load method cannot be applied to this building. The response spectrum method and the time history method should be used to evaluate the building's response during an earthquake. Further, because of considerable stiffness and geometrical irregularities, two dimensional models such as equivalent beam model cannot be used to determine the response of the building during a strong earthquake, thus, a three dimensional model must be utilized. An extensive finite element model was prepared for the building with the ADINA program. This model (Figures 3, 4, and 5) includes all the structural elements of the building, without any simplifications. That is, all the load carrying walls from the foundation to the 28th floor, the cores, and the floor slabs have been modeled. The model also includes the foundation mats, the columns in the first floor, and the girders and beams in the lobby. Further, the model uses solid elements for concrete columns and walls. FRP was modeled using shells.

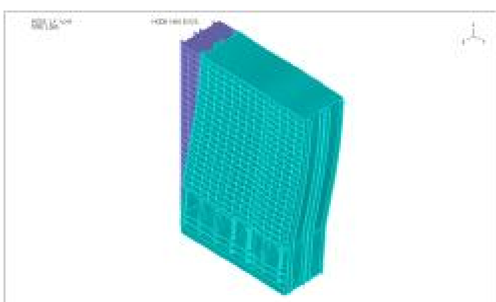

Figure 3. 3-dimentional finite element model of Azadi Hotel

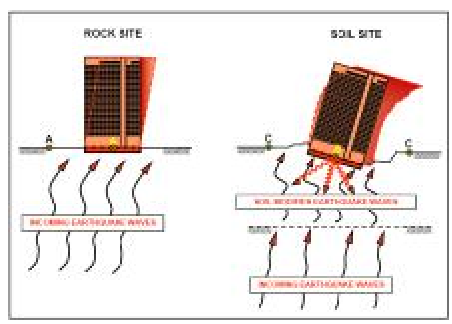

Figure 4. Soil and structure model of Azadi Hotel

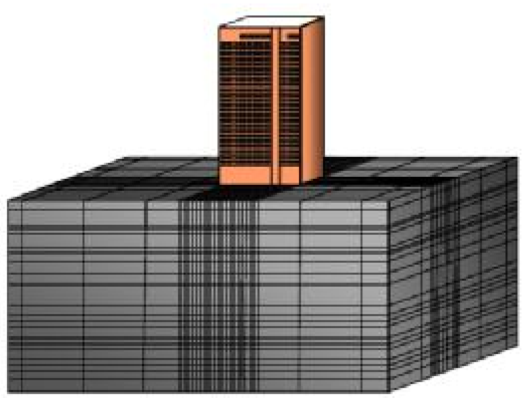

Figure 5. Finit element model of soil and structure system

ANALYSES

Following calculations were performed:

1. Eigen frequency calculations (10 modes)
2. Response spectrum analyses
3. Time history calculations

Multidirectional seismic effects were considered to act concurrently for the Azadi hotel. This is because the building has an in plane discontinuity in the lobby floor. The shear walls which exist in the 2nd to the 28th floor stop at the lobby. The Iranian Seismic Code (Standard 2800) as well as FEMA prescribes for this building to be designed for a concurrent seismic effect. We have applied the seismic motion concurrently. The seismic motion input is the response spectrum defined in the Iranian Seismic Code 2800 for soil class II and the spectrum provided by IIEES. These response spectra are applied as follows:

1. 100% of the spectra in X direction plus 30% of the spectra in Y direction
2. 100% of the spectra in Y direction plus 30% of the spectra in X direction

The maximum values from case one and two were then used for the design. The following parameters were used for the hotel building dynamic calculations.

A: Base Acceleration = 0.35g
I: Importance factor = 1.2
R: Behavior factor: = 2.0

The behavior factor according to the Code 2800 for the reinforced concrete shear wall building is 5. However, in order to apply factor 5, one has to be sure that the building satisfies the latest seismic codes and has enough ductility to undergo the severe seismic loading. Due to the lack of reinforcement of the shear walls in the lobby and the columns, we cannot assume behavior factor of 5 for the hotel building at this stage. Thus, a conservative factor of 2 was applied. For the response spectrum analysis in each direction 10 modes were calculated. The inclusion of these modes was necessary to capture more than 90% of the participating mass of the building according to the Iranian Code 2800 and FEMA. Modal damping ratios were assumed to be 5% for all the modes. The peak stresses, displacements, for each mode of response were combined using CQC (complete quadratic combination) rule. The CQC method has been recommended by the Iranian code 2800 for buildings which demonstrate irregularities in the plan as the Azadi. The following component gravity force Qg was considered for the combination with seismic load according to FEMA:

$$Q_g = 1.1\,(Q_d + Q_l) \qquad (1)$$

where

Q_g = Gravity load
Q_d = Dead load
Q_l = Effective live load, equal to 25% of the unreduced design live load.

Rigorous models to calculate the dynamic stiffness and the effective foundation input motion for the seismic excitations exist. These include the boundary element method, sophisticated finite element methods such as the thin layer method, the scaled boundary finite element method and the Dirichlet-to-Neuman method. These rigorous methods require a considerable amount of computational time and significant data preparations. The mathematical complexity of these methods obscures the physical insights. These methods belong more to the field of computational mechanics as civil engineering. Thus, cone models were used to determine the dynamic stiffness of the soil for the Azadi Hotel building (Figures 5 and 6).

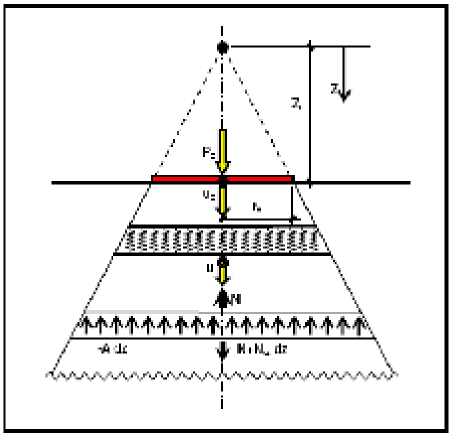

Figure 5. Soil on the basis of cone model simulation

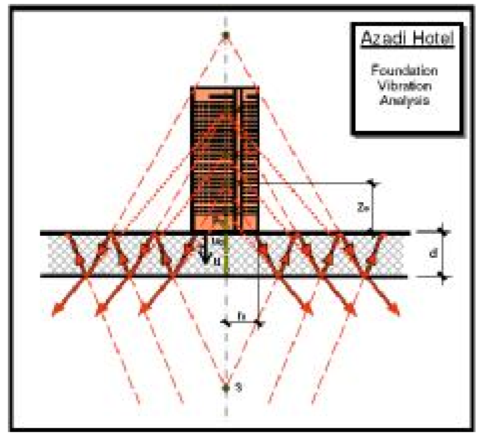

Figure 6. Reflected and refracted earthquake waves

Cone models, the one-dimensional strength-of-materials theory with conical bars and beams have the following advantages:

1. *Conceptual clarity with physical insight*. The wave pattern is clearly postulated. The one-dimensional waves propagate with the dilatational-wave velocity, reflecting back and forth, spreading and decreasing in amplitude and thus radiating energy towards infinity horizontally.

2. *Simplicity in physics and exact mathematical solution as well as in practical application*. Due to the deformation behavior enforced in cones, one-dimensional models arise which can be solved exactly in closed form, and which can in many cases be analyzed with a hand calculator.

3. *Sufficient engineering accuracy layering and embedment for all degrees of freedom and all frequencies.*

4. *Sufficient engineering accuracy*. A deviation of ± 20% of the results of cone models from those of the rigorous methods for one set of input parameters is, in general, sufficient, since many of the uncertainties can never be eliminated.

5. *Satisfaction of physical features*. Certain properties are enforced exactly when constructing the cone model, such as the doubly-asymptotic behavior of the truncated semi-infinite cone. Others are very closely modeled as a consequence of the assumed wave pattern. For instance, no radiation damping occurs in a layer fixed at its base in the frequency range below the so-called cutoff frequency (the fundamental frequency of the layer).

The simplicity and low cost of a single analysis permit parametric studies, varying the parameters with large uncertainty (such as soil properties), to be performed, and the key parameters of the dynamic system to be identified, as well as alternative designs to be investigated.

A well-balanced design, one that is both safe and economical, does not call for rigorous results (of which the accuracy is limited anyway because of the uncertainties that cannot be eliminated) in a standard project. Cone models capture the salient features, and are based on experience gained from rigorous analyses. Cone models are quite dependable; incorporating implicitly much more than meets the eye. Cone models should be applied wherever possible.

The dynamic stiffness of the soils was calculated using CONAN program. CONAN program is based on wave propagation in cone segments and has been developed at the Swiss Federal Institute of Technology. The stiffnesses are frequency dependent; they were input to ADINA as springs and dampers to model the damping effect of the soil and the flexibility of the underlying soil. A mesh sensitivity analysis was performed to determine the optimal mesh length of the detailed finite element model of the Azadi. In order to achieve an accurate result, the final model of the Azadi had over one Million elements. This leads to over three Million equations. Such a model cannot be solved in a conventional computer with Windows operating system as XP, 2000, NT, or ME. A 64 bit computer is required to manage such large files. A LINUX computer using a 64 bit processor from SMTEAM GmbH was utilized for the Azadi Hotel building calculation. This LINUX machine has 3 GB of RAM and over 512 GB disk space.

SEISMIC RETROFITTING

Seismic retrofitting of the Azadi Hotel building was necessary as it was shown through preliminary seismic performance evaluation. The building as existed did not meet the minimum requirements up to the current building code of Iran and would suffer severe damage or even collapse during a major seismic event. The retrofitting of the hotel building required an evaluation of technical aspects, economic an architectural and social aspects as well. Recent changes in hotel construction technology and innovations in retrofitting were applied for the retrofitting of the Azadi Hotel building in Tehran. Conventional methods include addition or strengthening of existing walls, frames and foundations. Adopting these methods leads to time consuming construction works, lengthy occupant relocation of the hotel with further associated direct and indirect costs. The indirect costs of relocating the guests can be very high. Thus, it was decided to utilize, innovative technologies which have been extensively researched and applied in seismic retrofitting projects in recent years.

During the past fifteen years, a significant amount of research has been conducted into developing hazard reduction for building structures such as damping devices, advanced composite FRP, building isolators and external prestressing. In general, the damping devices such as friction dampers and viscous dampers reduce the overall seismic demand upon the structure of the hotel, the use of carbon fiber reinforced plastic FRP improves the performance of individual structural elements such as columns and the beams or walls. Fiber Reinforced Polymer (FRP) is a material consisting of high strength fibers immersed in a structural matrix such as epoxy or other durable resin. The most common fibers used in FRP technology are glass, carbon and aramid. The use of FRP dates back to the first applications of fiberglass in the early 20th century. The marine, aerospace, and automotive industries have made significant use of FRP due to the lightweight, high-strength and non-corrosive properties of these materials. It was not until mid 1980s that the engineers began to realize the potential of FRP for structures in areas prone to seismic activity. Advanced composite materials such as FRP are much stronger and lighter than steel. The non-corrosive characteristic of FRP makes FRP reinforcement a very effective alternative to steel reinforcements for reinforced concrete structures. Analytical and experimental results have shown that, wrapping of structural elements (columns, beams and walls) with FRP sheets improve their strength and ductility without adding stiffness to these elements. Extensive research at EMPA in Switzerland, University of California, has shown that by applying FRP externally to columns the ductility and shear resistance increases considerably.

Column ductility is an important design criterion for seismic retrofitting of the Azadi Hotel building in Tehran. Lack of the ductility results in failure of the columns even in small earthquakes. The use of FRP on test columns has improved column ductility by a factor of eight, meaning that the column is capable of accommodating displacements that are eight times as large as a non-retrofitted column. Additional benefit of FRP is to increase the vertical load capacity of the columns. Testing has shown that a two layer application of glass FRP on standard cylinder increased the axial load capacity by a factor of 35 percent. Ease of installation makes the use of FRP sheets a very cost effective alternative in the seismic retrofit of existing buildings.

DESIGN

The final design was to apply FRP along with hydraulic dampers. This design was calculated using ADINA and response spectra of the Iranian code 2800 and local site spectrum and corresponding time histories.

A thickness of 0.4 mm was assumed for the FRP. These layers were modeled as shell elements applied to all the columns and walls in the lobby and in the first floor. Application of FRP to the columns at the lobby floor of the hotel building is shown in Figures 7 and 8. The response spectrum analyses results of shear forces, normal forces and displacements were calculated. The loading was applied at both axes. The shear resistance of the columns and shear walls adding 0.4 mm of FRP and dampers was enough to withstand the seismic loads.

Figure 7. Strengthening of columns in the lobby floor by FRP

Figure 8. Strengthening of rectangular shape columns by FRP

The bracings were introduced between the columns at the lobby level and their position was discussed with the owner at various visits to the site in Tehran. As in the lobby we could not introduce many bracings due to architectural reasons, only eight bracings in each direction were allowed. Figure 9 shows the strengthening of columns by steel plates and Figure 10 represent a typical executed bracing and damper in the lobby floor. Examining the shear stresses also shows that they reduce up to 25% which is very beneficial. The normal stresses in the columns also reduce 25% to 15 MPa, which is in the allowable range. Concurrent with seismic retrofitting of the hotel building, a renovation of the building also took place. These changes included architectural aspects (like changing the facade), interior design, air conditioning, etc. Figure 11 shows the present hotel building after seismic retrofitting and architectural renovation.

Figure 9. Strengthening of columns by steel plates

Figure 10. Executed bracing and damper

Figure 11. Azadi Hotel building after seismic retrofitting and architectural renovation

CONCLUSIONS

In this paper modern methods of retrofitting were introduced for the seismic retrofitting of the Azadi Hotel building in Tehran. Extensive calculations were performed using the ADINA program, the Iranian seismic code 2800, and the local site spectrum. The preliminary design was to apply FRP to the columns and shear walls at the lobby level and the basement. However, it was clearly demonstrated that applying FRP alone could not be satisfactory. The FRP could solve the shear problem of the columns; however, the bending problems of the columns could not satisfactorily be solved. They drift too much, resulting into high bending moments. It was decided to introduce additional bracings with hydraulic dampers in the lobby level and in the first floor. The retrofitting was as follows:

- Introduction of bracings in the lobby and 1st floor.
- Introduction of hydraulic dampers at the lobby floor and in the 1st floor.
- Strengthening the columns and the walls with FRP sheets (lobby and underground floors).

Running the 475 year earthquake through the retrofitted building shows that the drift at the lobby level shall reduce by 50%. Consequently, the stresses at the columns and walls shall be drastically reduced. The maximum values of shear forces, moments and axial forces for every floor was calculated and compared to the resistance values of members. Also, checking the shear forces, moments and axial loads with the allowable shear forces and moment-axial load capacity diagrams shows that the building can undergo the 475 year earthquake without major damage. The retrofitted solution has following advantages:

1 The drift of the lobby reduces, this solves the soft story problem
2 The shear stresses are reduced up to 50%
3 The bending stresses shall reduce up to 35%
4 The loads in the bracing shall be in order of acceptable levels
5 The dampers allow a seismic health monitoring of the hotel in future

ACKNOWLEDGEMENT

Authors are grateful to Dr. M. Motavali from EMPA, Switzerland and Mr. J. Najafi from Rahyab company for their contribution.

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