13th World Conference on Earthquake Engineering
Vancouver, B.C., Canada
August 1- 6, 2004
Paper No. 1598

REHABILITATION OF HISTORICAL BUILDINGS SUBJECTED TO SEISMIC HAZARDS, A METHODOLOGY

Mansour ZIYAEIFAR[1], Hossein MESHKI [2] and Mohamad RAJAEI [3]

SUMMARY

Survival of historical buildings after earthquakes is the concern of people from many disciplines. Although, everyone advocates safeguarding of these cultural heritages from seismic hazards, the foreseeable inflicted damage to the Archeological, Architectural and Aesthetical values (AAA values) of these monuments (due to retrofitting process) hinders a required decisive consensus on whether or not an action should be taken to save these treasures. This may be due to the lack of a common ground in weighing the added values of seismic risk reduction on the building (due to strengthening of the structure) and the damage to AAA values attributed to any particular retrofitting techniques. In this study a methodology is proposed in which different possible techniques for rehabilitation of any particular historical building can be weighed and compared based on their risk mitigation added value, their reduction on AAA values and their predictable costs. The proposed methodology offers a rational process in which weighing coefficients defined independently by different disciplines (structural engineers, architects, archeologists, financial planners and so on) contribute in a decision making process for rehabilitation of building. Not to much surprise, application of this methodology for valuable historical buildings ends up, mostly, to the fact that none of the envisaged rehabilitation techniques are quite fit for such structures and the best action is to wait for new retrofitting ideas with less damage to the AAA values of these monuments.

INTRODUCTION

The fact is, in every earthquake we are losing a few good historical heritages. Recent quakes in Italy, Turkey and Iran have shown no mercy to these treasures and some of our living histories and memories have gone down into the dust. Along with, there was an inexplicable belief in some people that, these monuments will survive the earthquakes (advocating that these buildings have passed a natural selection process by previous quakes and survived). The Bam 2004 incident, that destroyed a 2000 years huge adobe monument, has shattered this belief and cast doubt on any charismatic speculation on the survival of such structures.

[1] Assistant Prof., IIEES, No.27, Arghavan, Farmanieh, Tehran, Iran. Email: mansour@dena.iiees.ac.ir
[2] Research Associate IIEES
[3] Research Associate IIEES

The cultural importance of these monuments brings people from many disciplines into the decision making process on safeguarding these buildings against earthquakes. Archeologists, architects, artists, historians along with politician, tourism bureau and other parts of the society have their own view regarding the importance and values of these treasures and can not easily share their prospects with each other. The conflict between these views will be more pronounced when strengthening of the monument against earthquakes comes into the picture. Obviously, any strengthening approach encompasses damage to some of the aforementioned values that may pass the red line of one of these pressure groups and bring the retrofitting idea to the halt. Therefore, the main problem in rehabilitation procedure is how to find a solution that brings a consensus among all parties by ensuring them of a seismic risk reduction added value for the building that practically comprises their view into the process.

Seismic retrofit of historical building has, in fact, two main sides. One side is the necessity of seismic risk mitigation for monuments that prompts strengthening of the system and lies on the hand of structural engineering expertise. In the other side, there is a need to look after the originality, consistency and beauty of the system by avoiding any unwise strengthening intrusion. The later puts the structural engineer in check and assures restricting the inflicted damage to the historical values of the monument. These values are mostly attributed to the Archeological, Architectural and Aesthetical aspects of the building (hereinafter, AAA values) and should be defined independently by a wide range of expertise and/or authorities related to these issues.

Mathematically, the above challenge is a classical constrained minimization problem in which, the solution would be a retrofitting technique with maximum risk mitigation added value that does not violate any of the predefined AAA value constraints. To address this problem, the current work offers a simple methodology, similar to those in the building codes, that rationally evaluates (and compares) all the possible rehabilitation techniques for any particular historical building. The evaluation process is based on the seismic risk mitigation added value of each technique in contrast with its adverse affects on AAA values of the building. Among all possible retrofitting techniques, the one which brings the highest positive added value to the monument would be the viable rehabilitation choice. The predictable cost of each technique can also be included in the evaluation procedure to finalize the decision making process.

SEISMIC RETROFIT OF HISTORICAL BUILDINGS, THE MORALS

The main difficulty in seismic rehabilitation of historical monuments is the dominance of ambiguous but compelling AAA values of the structure that comes across with the transparency and ease of structural (and earthquake) engineering techniques in reducing seismic hazard risk on buildings. The gap between these two different classes of problems is similar to the gap between art and science and reconciliation can be achieved only based on morals.

Historical Building Rehabilitation and Seismic Risk

In ordinary buildings, based on the required structural performance at a predefined seismic hazard level, structural engineers prepare their suggestions for rehabilitation purposes. However, in the case of historical buildings the same line of action cannot be directly followed.

While, the desired level of structural performance for historical buildings is typically high (to limit the crack size and other visible damages or unpleasant large deformation features in such buildings), the importance of these monuments requires strengthening of the system up to a high level of seismic risk hazard (to ensure their safety against long-term threats). These aspects prompt a large demand for added strength and stiffness to the building. Considering the scale of envisaged damage to AAA values of the monuments due to such strengthening, structural engineers are not likely to find any feasible rehabilitation plan for historical buildings using this approach. In other words, it would be impractical to have a rehabilitation plan based on a desired structural performance and a preferred seismic hazard risk level.

In an alternative approach, structural engineers should, at first, propose a visionary rehabilitation plan based on the maximum allowed damage to the historical values of the monuments and then calculate the seismic hazard risk level attributed to such plan. In this case, there would be a practical rehabilitation plan that improves the seismic performance of the building (till a particular level of hazard) but it is not providing as much protection as ideally needed.

In here, the moral for structural engineers is to interact with the archaeologists, architects and so on to take their views into the consideration (regarding the AAA damage tolerance) and prepare not to stick to a predefined level of seismic hazard risk for historical monuments.

Historical Values and Seismic Risk

The inherent value of historical buildings is indebted to their originality, matured appearance and the charm of their inhabited artistic impression. None of these values have a real substitute in our contemporary life and any damage to these values cannot be authentically restored. This is, perhaps, the main reason for our nostalgic sentiment toward any change or restoration in these monuments. Accordingly, archeologists, architects, historians and those responsible for cultural aspects of the society have developed a kind of sensitive attitude toward any restoration plan for these treasures. In some cases, this attitude has reached to a zero tolerance level if restoration plan for the building suggests strengthening the whole system beyond its original capacity. They argue that, the great architects of the past have accomplished creation of a perfect building and there is no need for strengthening of such structure. As mentioned earlier, this view does not serve the reality and our precious monuments need dependable plans for seismic retrofit.

Obviously, seismic rehabilitation in historical structures causes damage to the originality, impression and beauty of the building and should be done, only, if there is a real necessity. When these monuments are located in a region prone to earthquake hazards, our duty is not to preserve the historical values of the building only at this time, but to extend these values to a longer time span.

The moral in here is to try to rationalize the concept of historical values. In fact, there is a need to add another dimension to the concept of historical values, their life expectancy regarding the earthquake hazard risk in the region. In other words, if historical values can survive longer (considering the seismic hazard risk) they should be considered more valuable.

In this way, strengthening of the monuments may add to the historical values of the buildings. This requires weighing the current historical values (considering its present life expectancy) together with that after the seismic retrofit (when contemporary historical values are reduced but their life expectancy improved). Such weighing procedure eventually leads us to a consensus on whether the seismic retrofit plan should be recommended or not.

THE METHODOLOGY

Based on the above prospects a methodology is introduced that brings all the possible rehabilitation plans to the point of historical value assessment. In here, the acceptance criteria for any retrofitting idea is the long term AAA value of the monument after rehabilitation. If this value is less than the value of building without retrofit, the rehabilitation plan should be rationally ruled out from the course of action.

Perhaps, the main feature in this methodology is its use of historical value of building as a common ground in decision making process among all the disciplines. This feature puts the structural engineer in a position equivalent to that of the other authorities in charge of cultural aspects of the building (by advocating longer time span for historical values of the monument). Financial planners will also share the same position in rectifying the investment needed for seismic protection of these treasures.

The methodology has three distinct phases in which, each phase focuses on the expertise of a different working group contributing in planning the rehabilitation procedure for the building. In the following sections all these phases will be discussed in details.

Phase 1 - Historical values manifestation

Rehabilitation of historical building may start with a qualitative appreciation of the AAA values of the structure; however, in the case of seismic retrofit these values should be quantified in order to be able to continue the process. This phase has to be done by the experts and the authorities responsible for preserving the cultural values and imperative impressions of the building. To have a simplified guideline, this phase has been broken down into the following steps.

1- Identify the valuable parts of the building (archeological, architectural, aesthetical, etc.)
2- Speculate on the maximum tolerable damage ratio for each historical aspects of the building.
3- Define a damage function and its weighting parameters (or functions) in terms of AAA values. Weighting parameters are representing the equivalent value of total damage per unit area (or volume) for each historical aspects of the building (identified in step 1).

This is the complicated and controversial part of the work (particularly steps 2 and 3) and requires broad expertise and extensive consultancy to be accomplished. Without the above procedure in historical values manifestation, it would be difficult to justify the inevitable retrofitting damage to the AAA value of the monument.

Phase 2 – Rehabilitation plans and damage estimation

In historical building, any attempt for strengthening the system is facing the possibility of damage to one of the AAA values of the building. Therefore, a vigilant agenda for proposing rehabilitation plan for historical building should be adopted. Practically, this phase of the work should be based on the structural engineering visionary expertise in devising retrofitting techniques with damage tolerance constraints. Earthquake engineering knowledge is also required for evaluation the seismic hazard risk level for each rehabilitation technique. This parameter can be, later, converted to the seismic life expectancy of the structure.

Another face of the problem is assessment of damage to the historical values of the building, attributed to each rehabilitation technique. This requires, at first, calculation of damage ratios in each historical aspects of the building. These ratios will be used in damage estimation and, consequently, evaluation of contemporary historical value of the building after retrofit. Following steps explain the above points in more details.

1- Proposing retrofitting techniques that do not violate any of the maximum tolerable damage ratios in any historical aspects of the building. The choice of no retrofit action should also be considered a respectable option.
2- Choose a structural performance level for the building and calculate structural capacity (the strength of building against earthquake) of the monument in all retrofitting plans (including no retrofit option).
3- Investigating on possible changes in dynamic characteristics of the building due to retrofit (e.g. reduction of natural period).

4- Having structural capacity and dynamic characteristics of the building (steps 2 and 3), determine the magnitude of the earthquake that its demand matches the capacity of the structure (e.g. its PGA).
5- Based on information provided in step 4, calculate seismic hazard risk level for each rehabilitation plan using an appropriate hazard curve.
6- Estimate seismic life expectancy of the building for all retrofitting plans. Steps 2 till 6 in the case of a code-type approach can be simplified as shown in Fig. 1.
7- Assessing damage ratios in each type of historical values of the building for all rehabilitation plans (considering retrofit damage to AAA values of the building). In the case of no retrofit option there is no damage ratio attributed to any historical value of the building.

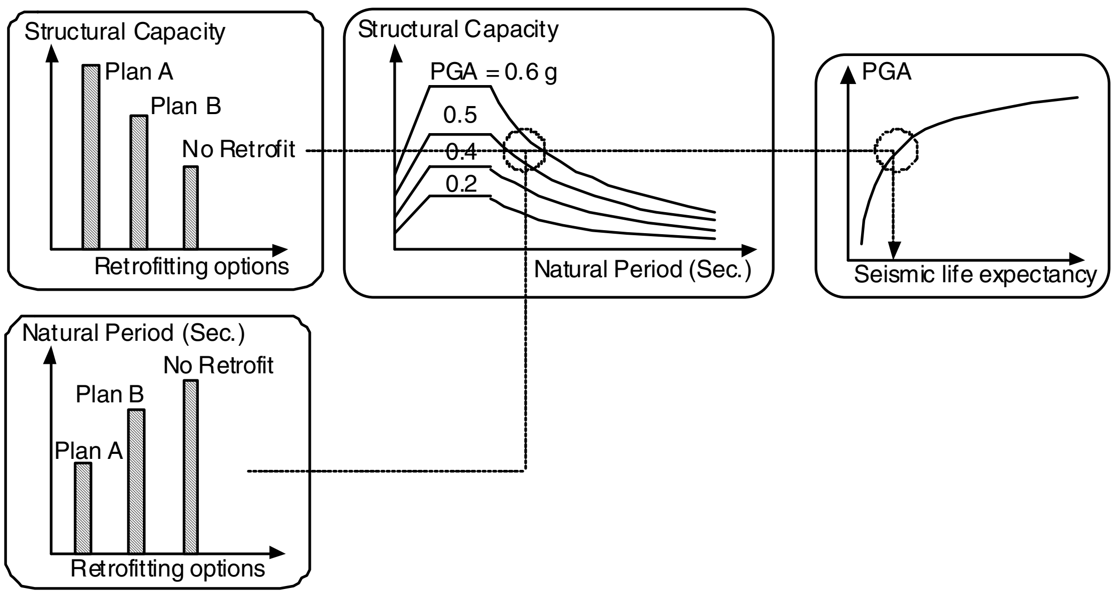

Fig. 1- Life expectancy determination for historical building

The examples of retrofitting plans shown in Fig.1 are indicating the fact that, higher strength (structural capacity) provided by Plan-A, may add to the stiffness of the system and cause shorter natural period for the structure. This could eventually create larger than expected earthquake forces on the structure. In this case, there would be a slim possibility in which strengthening of the building may even reduce the seismic life expectancy of the system.

It should be noted that, the change in natural period of the system in this case is different from the one mentioned by other researchers in which natural period increases by softening the monument during the time [1].

Phase 3 –Seismic retrofit evaluation

The main point of this methodology is to provide a common ground in weighing the added values of seismic risk reduction to the building and damage to its AAA values due to application of retrofitting techniques. As it was mentioned earlier, this common ground is historical value itself. This phase of the work requires an independent panel of proficient authorities to finalize the evaluation process. Following steps describe the above procedure that should be followed for all the proposed seismic rehabilitation techniques.

1- Calculate total damage to AAA values of the building for all rehabilitation plans using appropriate damage ratios and weighing functions (based on step 7 in phase 2 and step 3 in phase 1).
2- Calculate the equivalent contemporary value of the building after deducting the retrofit inflicted damages to the system (known in the previous step).
3- Convert seismic life expectancy to an equivalent life span value for the building.
4- Calculate long term historical value of the building using life span and contemporary values (using steps 3 and 2).
5- To finalize the seismic retrofit evaluation procedure, modify the long term historical value of the building (obtained in step 4) by a function representing the cost of retrofit. The above procedure from step 2 through 5 is depicted in Fig. 2.

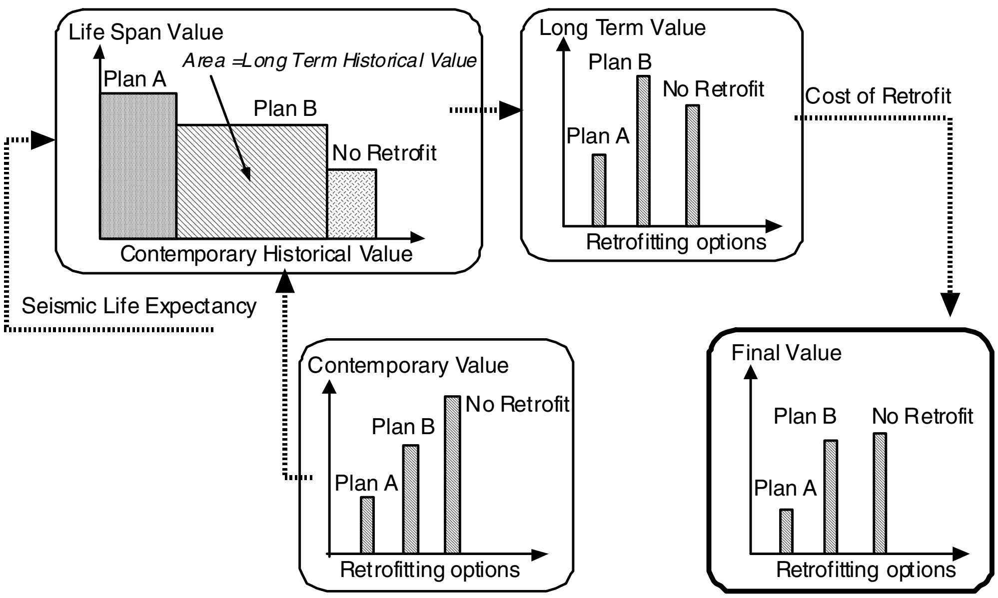

Fig. 2- Seismic retrofit evaluation procedure

As shown by retrofitting examples in Fig. 2, Plan-A provides longer life span for the structure, but its pertinent damage to the historical aspects of the building reduces its contemporary value and results in a very low long term historical value for the monument. At this point Plan-A should be ruled out from further justification. Plan-B, however, has a higher long term value comparing with No-retrofit option but the cost of retrofit reduces its final long term value and No-retrofit option marginally prevails in the screening process.

EXAMPLES

Two examples of application of the above mentioned methodology in seismic retrofit of historical buildings are represented in this work. Examples are both studied at a preliminary level of engineering practice without scrutiny on structural details and historical aspects of the buildings. Most of the required inputs in calculation of seismic life span and damage assessment are only based on speculations.

A simple Minaret

The example is a 700 years old minaret located in the city of Natanz (300 kilometers south of Iranian capital, Tehran). The city is in the zone of high seismic hazard risk but, in last thousand years there have not been any record for major earthquakes in the region. The minaret has about 37 meters free standing height and around 7 meters diameter at its base. The thickness of its surrounding shell is from 0.6 meter at the base to 0.4 at the top. The inner core of the minaret has a diameter around 1.3 meters at its bottom. A general view of this structure is shown in Fig. 3. The minaret is made of good masonry materials (high quality bricks and a local mortar made of limestone, sand and clay).

Minaret is considered valuable mostly for its aesthetical values. The tiles, some calligraphy on bricks and tiles (entirely on the outer surface of the structure) are unique in their style and considered nonreplicable beauties in the contemporary ornamental practice. Archeological and architectural aspects of the building should also be taken into the consideration. Valuable historical aspects of the building subjected to foreseeable damage in the case of seismic retrofit are identified as:

1- Finishing of the outer surface of the minaret.
2- The ancient masonry materials.
3- The inner parts of the minaret

Fig. 3 – General view of the minaret

In the case of first item, removal and/or replacement of a part of outer surface of the building is considered damage to the aesthetical appeals of the minaret. Given the fact that, replacing ancient materials with the new ones reduces the originality of building, the change in volume of the second item is reflected as a loss on archeological value and originality of the monument. In addition alteration of inner parts of the minaret, represented by the third item, is considered a loss on architectural impression of the building.

For simplicity, maximum tolerable damage ratio for each of these values is assumed to be at 20% (of its total value) for all the above items. The reduction on AAA values of the building (due to seismic retrofit) is calculated using a linear damage function and simple weighting constants.

$$D = w_1 D_1 + w_2 D_2 + w_3 D_3 \qquad \Rightarrow \quad D = w_2 (20 D_1 + D_2 + 5 D_3) \qquad (1)$$

In the above relationship w stands for weighting constant and D resembles damage ratio. Subscripts 1, 2 and 3 are referring to the historical value items specified earlier. According to the defined damage function, one percent damage to the finishing of outer surface of minaret is equivalent to 20% damage to the volume of material ($w_1 = 20 w_2$) and 5% damage to the inner surface of the system ($w_3 = 5 w_2$). These proportions are all hypothetical. Instead of such simple weighting constants and the linear damage function in this example, in a realistic approach more complicated weighting and damage functions might be preferred.

Altogether the following six retrofitting techniques are proposed for strengthening the minaret (the work by Penells et al. [2] was consulted in proposing some of these rehabilitation techniques).

1- Substitution (with the original material) of a 150 mm thick reinforced concrete shell around inner surface of the surrounding shell.

2- Adding a reinforced concrete frame system carved into the inner surface of the shell.
3- Replacing the inner core of the minaret with a reinforced concrete core.
4- Adding a steel frame system made of Channels carved into the inner side of the shell
5- Using knife shape Flat Steel Bars pushed into the outer surface of the surrounding shell.
6- Pre-stressing the minaret using Carbon Fiber strands located at outer surface of the shell.

At first, the above techniques are proportioned to not to violate the 20% damage threshold in the three identified historical values of the structure. Later, a structural performance level based on crack size limiting criteria was introduced. Having this limitation, the change in structural capacity (strength) and dynamic characteristics of the monument for each rehabilitation plan was calculated (using a simple structural model for minaret). Following the steps defined in phase 2 and 3, seismic hazard risk level, seismic life expectancy, damage ratios, total damage, contemporary value, seismic life span, long term value and final value for all retrofitting plans (the six proposed method plus No-retrofit option) were determined.

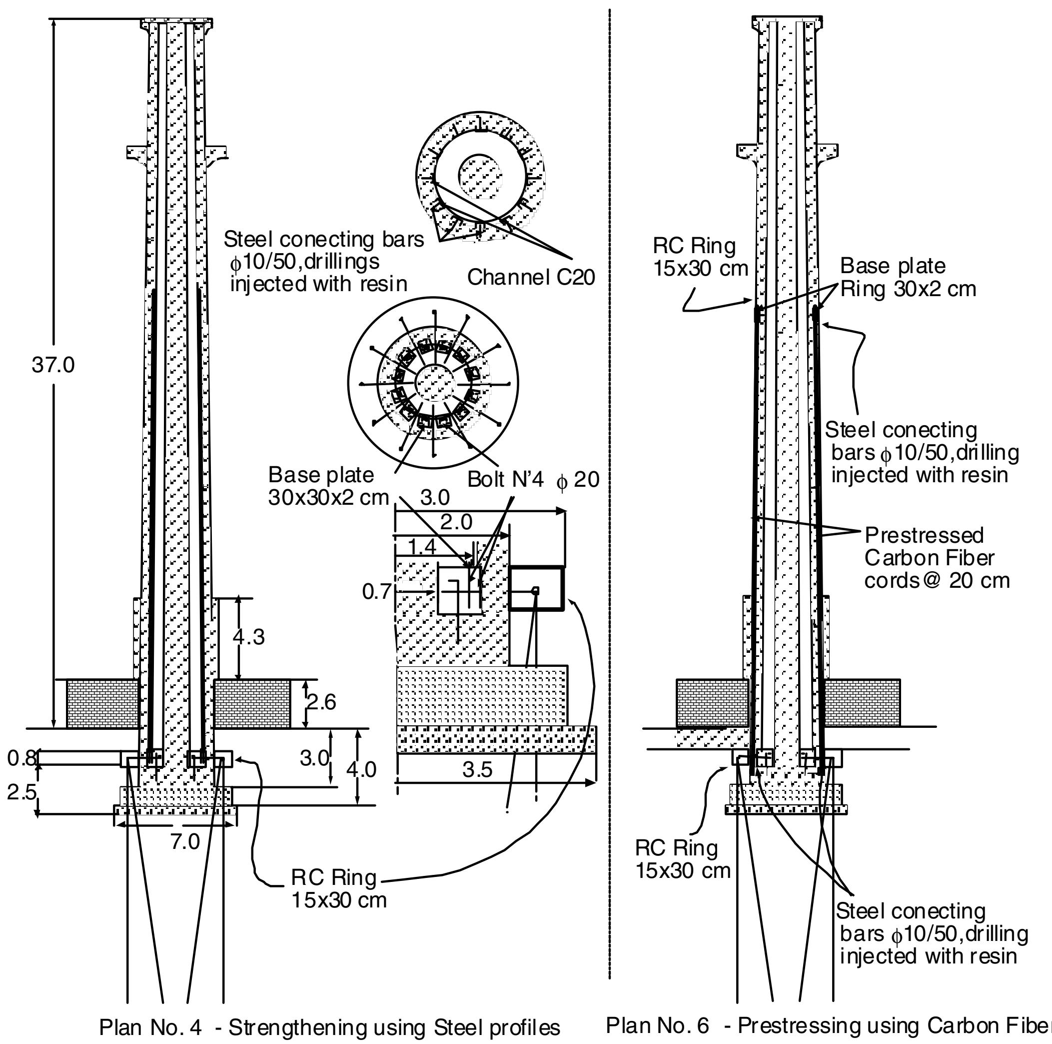

Fig. 4 – Two of the rehabilitation plans for the minaret

The screening process for rehabilitation plans ruled out four of the proposed options (numbered 1,2,3 and 5) because their final value is less than that of the No-retrofit option. Figure 2 shows the only rehabilitation plans that may add to the final value of the minaret. The retrofitting option based on using steel frame inside of the structure (Plan No. 4) has a marginal lead to the pre-stressing option (Plan No. 6) due to the high cost of implementation of Carbon Fiber Strands in the structure. Both of these options have to be studied in details using more accurate structural risk analysis procedure and better damage (and weighting) function(s) for assessing the contemporary value of minaret in each rehabilitation plan.

A masonry building

In this case a valuable and large size building was chosen for further studies (from the value point of view the building in Iran is considered in the same order of value if it compares with those reported by Croci [3] and Robertson [4]). The example is a 140 years old masonry structure located in central part of Tehran. The city is in the zone of high level of seismic hazard risk and building is in the highest intensity region of the most probable earthquake scenario in the city. This monument is a large structure consists of four storeys and one basement with total height of 35 meters. The area of building at basement is about 650 square meters but, reduces along the height. Architecturally, the system is considered irregular in plan and height and quite complicated comparing with ordinary masonry buildings. The thickness of the main walls of the structure is categorically high (about 1.7 in basement till 0.7 meter in the last storey) and they are made of very good masonry materials. Figure 5 shows a general view of the building and Fig. 6 illustrates some of its architectural details.

The structure, called Shams-Al-Emareh (sunshine of buildings), is one of the main symbols of a historical era in the country. From this viewpoint the monument is considered quite valuable. The walls of the building are extensively decorated from inside with paintings, ornamental works on glass, carved stones and other classical eastern artworks. Seismic retrofit on this building not only may cause physical damage to the AAA values of the monument, it may also reduce the historical impression of the building. In other words, any non-proportional visible structural element in the proposed rehabilitation plan is considered both, an aesthetical and an emotional damage to the values of building.

Fig. 5 – The large masonry building

Similar to that of the first example, at the beginning, valuable aspects of the building were identified and their maximum tolerable damage ratios were determined. The procedure was followed by introducing a simple linear damage function along with its weighting constants. This damage function was more complicated than the one in the minaret example and consists of 7 types of damages and their weighting constants. In phase 2 of the procedure four rehabilitation plans were proposed for further studies (considering the no-retrofit option, there were five choices for the screening process). These seismic retrofit plans are as follows.

(a)- Front Elevation (b)- Side Cut

Fig. 6 – Masonry building architectural details

1- Pre-stressing the main walls with high tension steel tendons.
2- Substitution of a reinforced concrete frame system inside of the main walls.
3- Adding a frame system made of heavy tubular elements in the main lobby of the building.
4- Using a tubular truss structure outside of the building for supporting the whole system.

Rehabilitation Plans No. 2,3 and 4 are shown in Figs. 7,8 and 9 respectively. To find the final value of building in any of the above 5 plans (considering the No-retrofit option) the same procedure, introduced earlier, is followed exactly similar to that described in the first example. The only difference in here was the kind of structural performance indicator used in this particular case. In the minaret example, bending dominated behavior of the structure provides enough justification for using a tension based crack size limit criteria in defining the structural performance level in the system. In the case of Shams-Al-Emareh example, structural complexity of the system and contribution of tension, shear and compression stresses in determining local damages in the structure, urged us to use a more complicated criterion based on fracture plasticity model for masonry material in defining the level of structural performance.

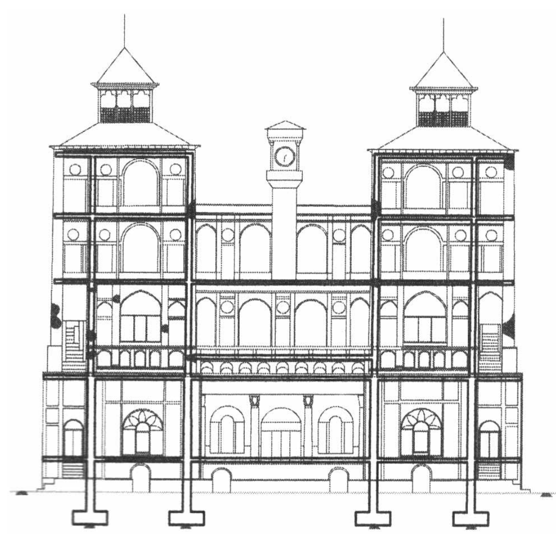

Fig. 7 – Strengthening using concrete frame

Not to much surprise, the evaluation phase of the study ruled out all four rehabilitation plans. In fact none of these plans can really add to the final value of building if they compare with the No-retrofit option. Now there is a good reason to not to take any action for seismic retrofit intervention in this monument unless another rehabilitation idea (or technique) with either less binding damage to the AAA values of the building or more potential in seismic risk mitigation emerges.

Retrofitting Plan No. 4, shown in Fig. 9, has a good potential to considerably improve the seismic life span of the building. This Plan also has the minimal physical damage to the building. In the evaluation procedure, however, the proposed technique is strongly rejected due to its detrimental affects on view and impression of the building.

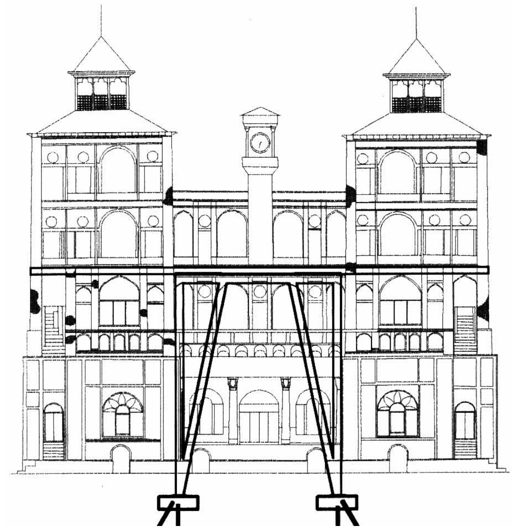

Fig. 8 –Steel frame inside of lobby

CONCLUSION

Using performance based design approach and nonlinear numerical tools; seismic rehabilitation is considered to be in its mature phase of development by offering practical, reliable and cost efficient solutions for seismic risk mitigation in existing structures. In the case of historical buildings, however, there is still a decisive set back in verifying the credibility of typical seismic retrofit approaches. In fact, most of the proposed rehabilitation techniques for such buildings are flatly rejected by the authorities in charge of preserving the historical values of these monuments. Apparently, the engineering part of these typical approaches is not to blame. The fact is, transparency and ease in engineering side of seismic retrofit process faces the ambiguity and complexity in the historical value side of the problem and brings the retrofitting ideas to the halt. To be able to put these two sides together, a methodology is proposed that provides a common ground for weighing different aspects of seismic retrofit in historical buildings. The methodology is supposed to provide consensus among all involved parties dealing with seismic rehabilitation plans in a particular building. Preliminary application of this methodology in two different historical monuments is presented in the current study. The results indicate the potential of this approach in finding convincing solutions for seismic retrofit of monuments satisfying all involved parties in the decision making process. According to these results, in the case of valuable buildings the dominance of historical values rationally blocks all the envisaged rehabilitation plans and leave the No-retrofit option as the only practical solution. This describes two of our known questions in rehabilitation of historical buildings. Why No-retrofit option is commonly the most favorite solution for valuable historical buildings (i.e. due to the dominance of historical values) and why we are always looking for advanced technologies for strengthening our precious monuments (to reduce intervention in the building).

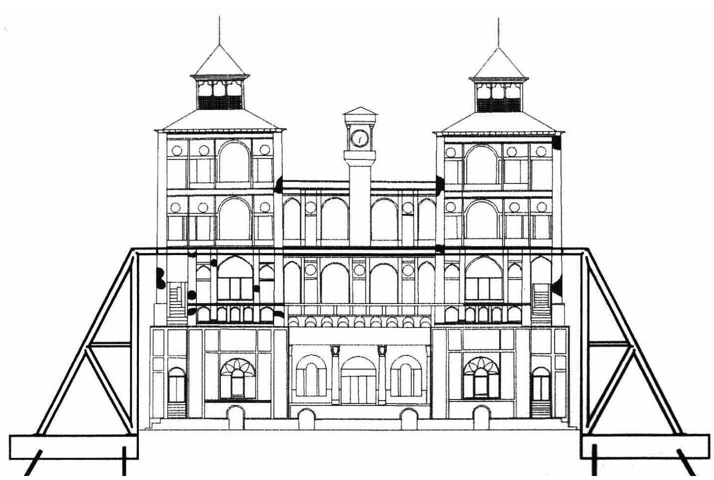

Fig. 9 –Tubular truss system outside of the building

ACKNOWLEDGEMENT

This work has been financially sponsored, in parts, by the ZIYA foundation for scientific excellence. This support is gratefully acknowledged. The first author wishes to express his deep appreciation to Ms. A. L. Familgan for her valuable help on preparation of this manuscript.

REFERENCES

1. Croci G. “The Conservation and Structural Restoration of Architectural Heritage.” WIT Press, 2002: 147-183.
2. Penells G, Papayianni I, Stylianidis K, Ignatakisand C, Athanassidis L. “Strengthening of a 400 years old Ottoman Minaret.” Second Symposium on Conservation and restoration of monuments, Rome, 1992: 629-639.
3. Croci G. “Strengthening the Basilica of St. Francis of Assisi after the September 1997 Earthquake.” Structural Engineering International, 2001: 207-210.
4. Robertson T. “The Strengthening of Auckland Town Hall.” 12th WCEE, Paper no. 1155, 2000.