

Seismic Assessment and Rehabilitation of Historic Structures

P. Gülkan¹ and S. T. Wasti¹

Abstract: The post-earthquake assessment and rehabilitation of damaged structures, as also pre-emptive retrofitting of existing vulnerable buildings to resist a future earthquake, call for a systematic engineering approach, involving phases of detailed examination, computer model analyses, evaluation of material behavior and the development of suitable structural upgrading techniques. The task becomes more difficult when irreplaceable and monumental historic structures of antiquity must be made seismically secure. The present paper investigates the challenges posed by, and solutions needed, to ensure the structural longevity of historic structures. Case studies are described where principles stated in the context of achieving longevity for ancient monuments have been implemented.

Keywords: Seismic assessment, structural retrofit, repair and strengthening, structural intervention, historic structures, structural longevity, seismic effects.

1 Introduction

Buildings and structures may be classified as historic for three main reasons: They are associated with acts of historical importance, they are old and a long time has passed since their construction, and they are monumental and irreplaceable. Old is a relative term, and in practice can be as low as 50-100 years; in more ancient civilizations at least a few centuries are required before a building is regarded as historic. In general, what makes a historic structure precisely that, is its longevity. What makes it an edifice that must be preserved for future generations are one or more of its cultural, architectural, symbolic, social or historic attributes. Not all historic structures are located in seismically active areas, but it may be pointed out that of the seven wonders of the ancient world, only the Pyramids of Egypt have survived and most of the rest have perished due to natural disasters, primarily like earthquakes [Wasti and Ersoy (2003)]. Studies of the seismic vulnerability of historic buildings and attempts to mitigate the associated hazards [whether by

¹ Middle East Technical University, Ankara, Turkey.

retrofitting or other procedures] and improve both the load resisting capacity and the longevity of such structures are therefore of great interest. However, it should be recognized [Feilden (1980)] that the seismic resistance of each historic building depends on its form, materials, workmanship and dynamic performance.

2 Background of Seismic Studies of Historic Structures

We encounter historic structures in many seismically hazardous regions of the world in different states of structural integrity, ranging from intact to near-total ruined. If a structure has experienced an earthquake in the past, then it will certainly experience one in the future, however remote, so in one sense every historic structure is currently in between earthquakes. Should we intervene now to reduce the likelihood of damage or collapse during that next earthquake? What are the proper structural measures that must be enforced to prolong its longevity? What are the characteristics of the next earthquake so that we can design for it rationally? What is more important: preserving the structure with enforcement of modern techniques and materials so that we deliver it to successive generations, even though this may be achieved at the cost of altering those of its very inherent qualities that drove us to conserving it, or should the objective be directed toward preserving its current appearance and load-bearing system? These are only a few of the questions that must be answered before a survey of a preservation program is undertaken on any historic structures.

The systematic development of Earthquake Engineering as an analytical and applied scientific discipline goes back less than 70 years. With sophisticated building codes and specifications in place in many countries, as also the emergence of advanced building materials, techniques for the design as well as construction of new buildings to resist seismic forces are currently well-known and widely used. A greater problem lies in the fact that the vast stock of existing buildings in the world does not conform to the requirements stipulated by current knowledge as necessary for seismic safety. A further complication is that for reasons of poverty a large percentage of the world's population lives in non-engineered sub-standard dwellings of crude brick or mud masonry that are extremely vulnerable to collapsing, usually with loss of life, even in earthquakes of small to moderate magnitude. Damage to historic structures in earthquakes depends on many factors and can be severe, but one reason why scant attention has been paid to the seismic behavior of historic structures in the past is that most such buildings are massive and over-designed, as a result of which they are less likely to fall to bits and create life-threatening situations. What part of the historic building stock has survived until our age owes its existence to the fact that their structural form, material or other physical attributes combined to impart to them the physical capacity to resist ground shaking effects.

In many seismically prone settlements in the world it is possible to record the destructive effects of earthquakes through the changing skyline as captured in old paintings, drawings and even photographs. This is the architectural equivalent of the principle of the survival of the fittest. With increased travel in recent decades, historic buildings have, in many cases, become popular destinations for tourists and the attractiveness of the edifice, or aggregates of edifices becomes the primary driving force of the local economy. The revenue generated provides an incentive for retrofitting such structures and thereby keeping them in seismically safe conditions. We need only to recall that Florence, a city of perhaps half a million in the Tuscany region of Italy, hosts 45 million visitors a year. This, however, should not be confused with regular maintenance and upkeep of the buildings concerned or with cosmetic repairs. Such an attitude to retrofitting of historic structures in advance of their sustaining damage is by no means widespread; in problems of building health it is always tempting to prefer cure to prevention and, in many cases, resources for such retrofitting are highly limited.

Historic structures have generally been constructed with basic building materials such as rock and stone, brick masonry and, in some cases, adobe or wood. In a majority of cases, large traditional structures have been supported by columns and arches, and all walls are load-bearing. A mixture of structural form and materials is also to be found in some historical buildings. Massive buildings made from these traditional materials usually possess strength but lack ductility, i.e. the capacity to undergo deformation without collapsing. Under lateral loads such as those engendered in an earthquake, it is the ductility of elements and structures constructed from modern materials such as steel and reinforced concrete that enables them to suffer deformation and sustain damage without losing integrity or collapsing.

The main challenges that face engineers who wish to conduct seismic upgrading of historic structures as well as some appropriate responses may be summarized as follows:

- No attempt should be made to change the existing load-carrying mechanism of the structure unless the whole or part of the structure is to be base-isolated by means of isolators or friction dampers, etc. Historic buildings tend to be massive and stiff structures made of brittle material. For some old structures, or buildings that may not allow major intervention, the possibility of providing base isolation may be envisaged. Seismic base isolation is a relatively new technique, usually involving the decoupling of the superstructure from the foundation by the interposition of a horizontally flexible layer [or individual isolators of rubber bearings reinforced with steel shims]. The resulting increase in the period of vibration of the system allows the structure to attract less of the horizontal force engendered in the earthquake. Base isolation has

developed with much rapidity and while it has been applied extensively to new buildings, examples of base-isolated older or historic structures are becoming more frequent. For historic structures which are not base-isolated, the necessity and economic feasibility of retrofitting [providing additional strength by using pre-stressed tie-rods, thin plates, buttresses, etc.] for seismic protection and risk reduction needs to be investigated virtually on a case by case basis.

- Any structural intervention must not, if at all possible, create aesthetic conflict. Various forms of plain or reinforced concrete and/or fiber-reinforced polymer wraps and other new materials, if used for repair and strengthening, must be used both efficiently and unobtrusively. Cultural sensitivities as well as a respect for the past mean that a direct technical approach to the rehabilitation or seismic retrofitting of historic or monumental buildings is not encouraged. Furthermore, whereas routine structures may suffer frequent structural interventions, this is not possible for historic structures. An unstated rule is that the retrofitting of historic structures be almost invisible. Guidelines are available in the 1964 Charter of Venice.¹ While structural intervention guidelines are not explicitly addressed in this document, parts of it can be interpreted in the light of structural requirements. For example, modern techniques are admissible where they are adequately proven as being appropriate for the use intended, and adequate strength cannot be ensured by traditional techniques. Where there is no satisfactory alternative to the use of a technique which is not adequately proven, particularly in connection with durability, then the technique should be used in a manner which must permit corrective action at a later date if this is required. The Charter also has articles describing how anastolysis, the process of putting back in their proper place components of structures which have become dismembered, possibly during ground tremors, should be executed.
- The seismic upgrading of historic structures differs from that of more mundane structures in that historic buildings do not have to conform to design codes and specifications which, thereby, are not applicable to such structures. More importantly, all seismic retrofitting must be reversible [Look, Wong and Augustus (1997)]. It should be possible to dismantle it in the future in case a less intrusive or more advanced technique is available. In repairing and strengthening cultural and historical monuments in current or former urban nuclei, a wide range of parameters, both structural and nonstructural,

¹ This is a statement adopted during the Second International Congress of Architects and Technicians of Historic Monuments, Venice, Italy, 25 – 31 May, 1964.

must be considered. During this exercise it is necessary to look ahead into the future, and to eliminate the need for further remedial intervention. The fact that such structures have already existed, perhaps much longer than was envisaged when they were first built, and even survived a few earthquakes, substantially changes the design problem. Customary codes of practice become irrelevant in this new context. There is also cause for respecting such structures which have come through the ages in spite of not having been fortunate enough to receive the level of technical design of today.

- Material properties from the structure to be protected need to be assessed on the basis of accurate experiments. However, obtaining samples or cores is often tantamount to a minor desecration of the monument and may therefore be difficult.
- Adequate as well as realistic computer modeling of complicated historic structures requires expertise. It is probably best to start with the simplest realistic model and then, as necessary, develop the model to reflect the structural complications of the structure.

The above-mentioned Charter of Venice provides the first coherent stipulations adopted at the international level for the overall conservation of historic buildings. It has encouraged a series of other documents dealing with the preservation and conservation of architectural and cultural heritage. Conservation of buildings against the ravages of time, of wear and tear, of deliberate vandalism or the effects of large crowds of visitors is not directly relevant to seismic protection. However, ensuring the safety and usability of the historic structure is common to both approaches – that of architectural preservation and that of imparting pre- or post-earthquake structural strength and integrity.

Accounts of various international conferences, colloquia, symposia and workshops dealing with all aspects of historical structures can be found in the literature, especially among the publications of the International Council on Monuments and Sites (ICOMOS) and the Getty Conservation Institute. State-of-the-art reports on seismic strengthening of historic structures are also available [UNIDO (1984)]. A presentation at the International Colloquium in Quito, Ecuador also sums up the current philosophy regarding seismic protection of historic structures [Gülkan (1995)].

In the present paper, after a survey of procedures for the assessment of historic structures from the seismic point of view in Part 3, a discussion of seismic upgrading of such structures will be given in Part 4, followed by a couple of case studies in Part 5.

3 Assessment of Structural Condition of Historic Structures

Whether it is for the purpose of post-earthquake repair and strengthening, or for the pre-earthquake retrofitting in preparation for a future earthquake, a study has to be made in great detail both of the load-carrying mechanisms of the historic building or structure under consideration. Historic buildings are generally large and possess unique features – both structural as well as ornamental. It is thus by no means as simple to design a seismic assessment form for historic structures as it is for more common or routine buildings. In particular, in many countries of the Old World, the sheer number of historic structures that need to be identified, classified and then assessed can be very high. For an initial assessment, therefore, the amount of effort required should not exceed that necessitated by a simple “walk down” street survey for urban buildings. Only after the inventory has been prepared should relatively vulnerable structures be assessed in greater detail.

As an example, a simple form devised for a “first look” assessment of historic structures for initial damage evaluation or vulnerability assessment is given in Table 1. Apart from providing a snapshot of the condition of the cultural property, information in such a form, if filled in by a qualified professional, provides the first step for the preparation of the analytical or computer model required for an evaluation of the existing strength of the structure as well as the formulation of suitable intervention methodologies for pre-earthquake retrofitting or post-earthquake strengthening, as the case may be.

3.1 Elements of Historic Building Evaluation

After the inventory of historic structures in a given seismic area is completed, structures are assessed on a case by case basis. This is in contrast to the overall seismic assessment of modern building stock, because each historic structure is generally unique in scope, plan, design and execution. The steps to be followed for the assessment may therefore be summarized as follows:

- Identify the structural characteristics of the structure under consideration, that is, the way in which it responds to the seismic excitation, and what its capacity might be.
- Diagnose the evidence of present structural condition, both visible and concealed. Do the necessary investigations for this diagnosis, including assessment of foundation conditions.
- Make complementary assessment of the local seismic hazard.
- Decide whether temporary shoring is needed to safeguard a damaged structure before, during and after rehabilitation.

Table 1: Simple Inspection / Assessment Form for Historic Structures

FORM FILLED IN BY / DATE	
BUILDING CODE / NO. / ADDRESS GPS LOCATION PLAN OF BUILDING & LOCATION PHOTOGRAPH(S) ATTACHED YES / NO	
ROUGH AGE OF BUILDING [YEARS]	
STRUCTURAL SYMMETRY	EXISTS IN PLAN / EXISTS IN ELEVATION / NO SYMMETRY
ROUGH AREA COVERED BY BUILDING STRUCTURE [SQ. METERS]	
NO. OF STORIES	() / NOT APPLICABLE
TOTAL HEIGHT OF BUILDING [M]	
FOUNDATION MATERIAL	STONE MASONRY / BRICK / OTHER
FOUNDATION TYPE (IF OBSERVABLE)	STRIP UNDER WALLS (DEPTH)/PILES
WALL CONSTRUCTION	BRICK / STONE / MUD / OTHER
WALLS ARE LOAD BEARING	YES / NO / EXPLAIN
STRUCTURAL QUALITY OF WALLS	SOLID MASONRY / WEAK / OTHER
TYPICAL WALL THICKNESS [M]	
LATERAL LOAD RESISTING ELEMENTS [BUTTRESSES / RING BEAMS / LINTELS / ETC.]	YES / NO / EXPLAIN
CONNECTIONS [WALLS TO ROOF ETC.]	POOR / ADEQUATE / GOOD / OTHER
ROOF	DOMES / VAULTS / BRICK / OTHER
MINARETS OR OTHER STRUCTURAL APPENDAGES	YES / NO / EXPLAIN
MORTAR / CEMENTING MATERIAL	LIME / CEMENT / MUD / OTHER
DAMAGE LEVEL : FOUNDATIONS	NONE / LIGHT / MODERATE / SEVERE / NEAR COLLAPSE
DAMAGE LEVEL : WALLS	NONE / LIGHT / MODERATE / SEVERE / NEAR COLLAPSE (CRACK WIDTHS)
DAMAGE LEVEL : ROOF	NONE / LIGHT / MODERATE / SEVERE / NEAR COLLAPSE (CRACKING?)
DAMAGE LEVEL : OTHER ELEMENTS	NONE / LIGHT / MODERATE / SEVERE / NEAR COLLAPSE
RECOMMENDATION	RETROFITTING / FURTHER ANALYSIS / DEMOLITION / OTHER
JUSTIFICATION:	

- Propose and justify schemes for final repair and strengthening. Prepare the necessary documentation for the selected scheme, in cooperation with other experts if necessary.

During the above architectural/structural survey, a detailed analysis of structural failures, local or otherwise, a thorough study of cracks, the nature of the soil, faults in the original structure, defects of construction, shifting of the foundations, signs of excessive stresses, defective components, etc. should be carefully investigated. For most important edifices, a photogrammetric survey utilizing laser technology may be appropriate.

With the complete information set comprising structural features such as material properties, wall thicknesses, and state of cracking as opposed to architectural or conservation-relevant, local geology and estimated ground motion, simplified SDOF models need to be developed for each building in the style shown in Figure 1. Ground motion is assumed to act in one of two principal horizontal directions, and separate stress analyses are required for in- and out-of-plane wall capacities. Openings in walls must be taken into account in estimating their stiffness, and roofs or domes are assumed as inert masses in preliminary assessments. Site-specific response spectra adjusted for distance to fault rupture and local soil characteristics were tools for estimation of the spectral acceleration. No force reductions are allowed, so wall stresses or out-of-plane strengths are based on values from limited coupon tests or triple their code allowables. This elementary exercise is found to yield good vulnerability estimates. An account is provided for this type of implementation in the Fatih district of Istanbul in Section 5.

4 Seismic Protection and Rehabilitation of Historic Structures

Methods for the seismic protection of all buildings of value, whether historic or not, may be considered to fall into two separate groups:

- Conventional approaches that involve substantial strengthening intervention in the superstructure and, where necessary, the infrastructure. The conventional approaches themselves may be divided into two as described earlier, i.e., they may be termed ‘retrofitting’ methods if the intervention is conducted in for a vulnerable building in advance of and in preparation for a future earthquake or, if the building has suffered some damage in an earthquake, they may come under the heading of ‘repair and strengthening’ or ‘rehabilitation’. The conventional approaches may, furthermore, be divided into ‘traditional’ strengthening techniques, which recommend the addition of new lateral load resisting structural members [such as shear walls or bracing] to the system or enlargement of member dimensions, and ‘innovative’

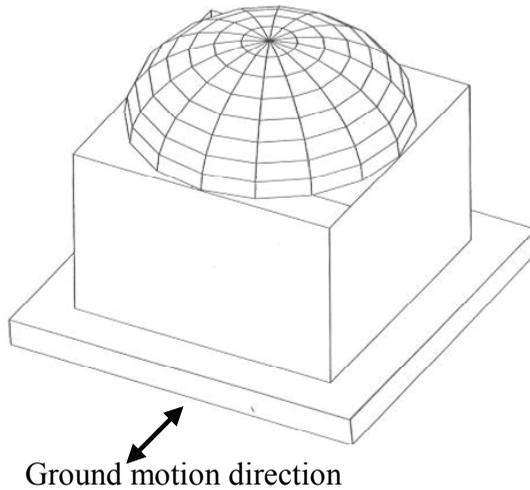


Figure 1: Simplified Model of a Historic Building

techniques making use of fiber-reinforced polymer, epoxy resins and high strength steel and concrete.

- Passive control solutions that involve placing an intermediate flexible interface of some kind between the foundations and the superstructure of the building, which are therefore called ‘base isolation’ techniques. The function of base isolation is to reduce the effect the forces generated by an earthquake have on the superstructure of the building by installing a large number of isolation bearings at points of connection between the foundation and the superstructure. Typical isolation bearings have alternate laminations of high strength steel and rubber resulting in low lateral stiffness but high vertical resistance. The high vertical strength enables the vertical loads from the superstructure to be carried efficiently. The low lateral stiffness of the bearings results in a much higher period of vibration for the superstructure than the value it would have in the absence of the isolation bearings. As a result, while the bearings suffer large deformation in shear in the event of an earthquake, the forces acting on the superstructure are greatly reduced and the superstructure remains virtually undamaged, like a rigid body undergoing lateral motion.
- Isolation techniques which do not use the steel-rubber bearings also exist; these employ energy dissipation devices like friction dampers or sliding iso-

lation elements not necessarily located between the base and the foundation of the structure. The use of friction pendulum bearings for base isolation is on the increase. Sketches of an FPS [Frictional Pendulum System] and a typical LRB [Lead Rubber Bearing] are given in Fig.2 (a) and (b) below.

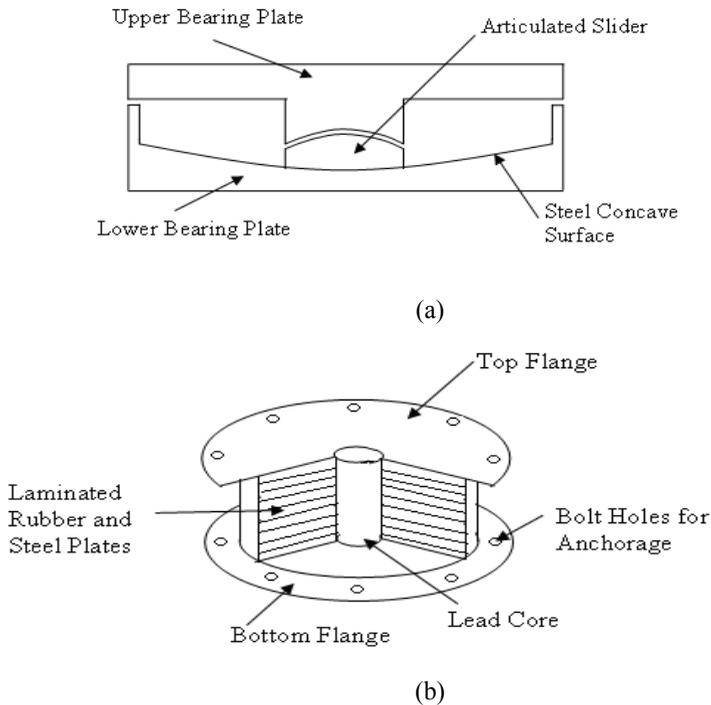


Figure 2: Friction Pendulum System [FPS] and Lead Rubber Bearing

For conventional approaches, repair and strengthening of the historic structure are usually carried out by using modern constructional materials in as unobtrusive a manner as possible. This involves the following inter-related steps:

- Selection of materials for repair and strengthening either the whole or parts of the structure. Steel, whether in the form of light mesh, reinforcing bars or plates provides solutions which are usually adequate. Wrapping of structural elements with carbon fiber polymers and epoxy adhesives is also feasible.
- After re-erection of dismantled or fallen masonry or timber, local repairs (repair of cracks, stone blocks or timber members) may be conducted.

- Local strengthening (strengthening of walls and piers by grouting and reinforcement, strengthening of walls by applying skins of reinforced concrete, strengthening of free-standing columns and minarets by applying steel and/or concrete jackets, strengthening of timber floors, arches and arched vaults, domes and domical vaults) needs to be planned and executed.
- Overall strengthening of the historic structure above ground may consist of all or some of the following operations: removal of excess mass, improvement of the distributions of mass and stiffness, improvement of structural interaction in classical temples and colonnades, in halls with timber roofs, improvement of structural interaction in multistory buildings and in arched, vaulted, and domed structures.
- Strengthening of foundations generally necessitates consolidation of the ground, strengthening of existing footings, and vibration isolation.

A large number of historic structures have now been base-isolated using either rubber bearings [divided into laminated (LRB) or high damping (HDRB) rubber bearings] or friction pendulum systems (FPS). Examples include the City Halls of Oakland and San Francisco in California. The International Terminal at San Francisco Airport and the Los Angeles City Hall have been base-isolated with friction pendulum systems. Friction pendulum systems of various dimensions similar in type to the cross-sectional view shown in Fig. 2(a) were employed.

The applicability of base isolation systems to massive historic structures, especially those which are both huge in scale as well as centuries old, is still a subject for discussion, but the method does hold promise for the future.

5 Case Studies

Two case studies that are in progress, with various stages of implementation, are presented in this section. One is a macro-study of seismic protection in a large district of Istanbul and the other a micro-study of a historical building in south-east Turkey.

5.1 Historic Building Assessment in the Fatih District of Istanbul

In recognition of a possible future earthquake Istanbul Metropolitan Municipality has started an action program that has a component for seismic assessment of historic buildings in Fatih as part of a wider urban renewal undertaking. The total number of cultural heritage buildings and other items in this district amounts to more than four thousand. These buildings are mostly masonry; many serve devotional purposes, with ages often spanning centuries. The categories fall into

mosques, theological schools, tombs, convents for religious orders, libraries, baths, fountains, churches, synagogues, cisterns, historic public kitchens, remains of fortified walls and cemetery appurtenances. The municipal administration developed an inventory with information for location, architectural features, historic or artistic significance, legal ownership status and whether repairs or modifications had been done on them. It was clear that, owing to time and resource limits, only a smaller subset of the thousands of buildings could be considered for seismic assessment. It therefore became desirable to develop an additional information database with regard to the structural features of the load resisting system for each chosen building. This implied a complementary phase of field work following a generic procedure:

- Do survey drawings exist? If not create these with total station or other scanning technology, noting any structural defects or deviations from original state. Use 1/100 or 1/50 scale as necessary.
- Create electronic building-condition forms. Note building materials. Measure GPS coordinates, assess environmental conditions and site geology. Create a GIS database. Define seismic hazard at site. Create a photographic record.

Thus the record for each building contained all of the information required in the ICOMOS Principles for the Recording of Monuments, Groups of Buildings and Sites. Additional information related to the following items is provided:

- Plan areas and total areas
- Section areas for vertical load-carrying members, and information on openings or material losses in them
- Characteristics of the structural walls and diaphragms for horizontal load resistance
- The foundation system

Fatih is a living part of a vibrant metropolis. Ancient, old and modern are inter-mixed, urban functions bustle. Many of the buildings are currently being actively used, or are guarded by their custodians even if they are idle. It was not easy to gain access and do lengthy measurements. Removal of material samples for testing required additional permit so it was not attempted at this stage. Of the original inventory we first developed an 800-building subset, which was finally reduced to 285 entries listed in Table 2. Even with this modest number, the Fatih Seismic Assessment Project represents a comprehensive attempt to assess the earthquake

performance of major buildings in the historic core of Istanbul. The procedure is only a preliminary stage for ranking the buildings. Even detailed and lengthy analyses are beset by uncertainties; the objective was to create two bins, one for buildings that would likely survive and the other for those that would likely fail to achieve that objective. The dividing line can be a vague one.

The seismic assessment of selected buildings was done for an M7.2 earthquake occurring on the Marmara Sea Segment of the North Anatolian Fault closest to the city. For this purpose a building inventory system was developed to record the structural features of the buildings. Each building was carefully surveyed using laser techniques. As detailed stress analysis of each building is unfeasible, a two-tiered rapid survey procedure was developed. In the first stage a simplified model of the building was created from laser scan measurements and wall stresses were computed for comparison with limits. The second stage comprised detailed stress analysis for a typical subset of about 20 buildings. The last stage will incorporate the rehabilitation measurements and typical strengthening details.

5.1.1 Historic Building Stock Characteristics in Fatih

The urbanization in Fatih region goes back to the time of East Roman emperor Constantine (4th century). In the fifth century, by the construction of the Theodosian Wall, the city was enlarged in the western direction. The Theodosian Wall is a 7 km long defensive structure that suffered from several earthquakes and had to be repaired to defend the city through the Middle Ages. Other Byzantine buildings, like the Church of Monastery of Christ of Chora make up a rich legacy of religious architecture. These are monuments of high historical and artistic importance. Due to their exceptional architecture and decoration, they must be protected from further deterioration (Ahunbay, 2006).

The churches from the early Christian and Medieval Periods have alternating wall construction, with brick courses acting as bands uniting the wall structure. Walls were constructed of local limestone, well baked brick and good quality mortar consisting of slaked lime, crushed brick aggregate and powder and sand. Some of the walls also had timber runner beams, providing reinforcement to resist earthquakes. Yet, the fragile sections, such as the tall apse windows suffered from tremors and needed to be repaired many times. Vaults and domes also had structural failures and had to be reinforced or reconstructed.

The Fatih area also has many important Ottoman buildings dating from the second half of the fifteenth century up to the early years of the twentieth. Small size timber and masonry houses do not present serious problems from the point of earthquake risk, but mosques with designs incorporating major domes in their composition have been facing serious problems. Due to their long life span, monu-

Table 2: Breakdown of the Buildings Surveyed in the Program

Mosque (with appurtenances)	112	School	18	Convent	18	Church (with appurtenances)	36
Tomb	30	Seminary	16	Annexes	8	Public Bath	6
Contemplation Room	1	Koran School	2	Private House	8	Institutional	1
Museum	1	Hospital	2	Public Kitchen	1	Fountain	1
Library	1	Timing House	1	Oil Press	1	Cistern	1
Masjid	13	Gate	1	Sundry	6	Total	285

ments in Istanbul have resisted several earthquakes; those of 1509, 1766 and 1894 have caused serious damage to these masonry structures. Vaults are usually made of brick, which is lighter than stone. Here the lack of tie bars or their deterioration has caused failures. Arcades were also the weak parts of the mosques and religious colleges which had small sized domes in their design. Ottoman architects were clever not to build oversized domes that would collapse during strong ground motions. The most vulnerable part of a mosque is the minaret. Their construction was reinforced by using clamps and dowels, aimed at fixing the blocks horizontally and vertically. However, the uppermost part of tall minarets usually suffered from earthquakes and had to be rebuilt.

Public baths were important in Turkish society. Many baths were built to meet the demand in the residential and commercial parts of the town. Some baths stand out with their impressive dressing halls, with domes measuring as big as those of medium sized mosques, reaching 16-18 m in diameter. Such big sized domes suffered severely from earthquakes and the baths had to be restored to continue their service. Otherwise, they were out of service and fell into neglect.

Most of the historic buildings in Fatih are in a poor state of preservation. The expected earthquake will affect these buildings more if they are not retrofitted carefully. Any repairs will demand careful analysis of the vulnerabilities and minimum intervention to maintain the authenticity of the historic buildings.

5.1.2 Elements of Historic Building Analysis

With the complete information set comprising structural (materials, wall thicknesses, and state of cracking as opposed to architectural or conservation-relevant) features, local geology, estimated ground motion we built simplified SDOF models for each building in the inventory in the style shown in Fig. 1. Ground motion was assumed to act in one of two principal horizontal directions, and separate stress analyses were made in- and out-of-plane wall responses. Openings in walls were taken into account in estimating their stiffness, and roofs or domes were assumed as inert masses in the first tier of analysis. Site-specific response spectra adjusted for distance to fault rupture and local soil characteristics were tools for estimation of the spectral acceleration. No force reductions were allowed, so wall stresses or out-of-plane strengths were based on values from limited coupon tests or were assumed as being triple their code allowable values. This elementary exercise, formatted for spreadsheet calculations, yielded good vulnerability estimates. Application of performance criteria to existing masonry buildings is not meaningful. We chose instead to estimate the shear stresses in the in-plane walls of the buildings by modeling them as simple one-degree-of-freedom systems, a further simplification of the concept in Fig. 1. Openings in the walls and translations caused by rota-

tional effects were considered. The strengths of out-of-plane walls were estimated by checking whether cracking was likely to occur under the postulated roof level acceleration (assumed as 2.5 times the ground acceleration) and the gravity loads. The churches in the stock are mostly broad and one-story buildings without any belfries. We estimated that their resistance would be sufficient in many cases. The set of simplified calculations that have been made for the buildings belie the reliability of the fundamental and conservative approach developed for the assessment of these nearly three-hundred buildings. Its accuracy is similar to that of methods developed for street-level surveys for buildings. In many cases the estimates for the gross shear stresses in the walls agreed well with the average stresses in those walls derived from the next tier of analyses. The exception to this was for re-entrant corners and walls with irregular plan views.

A sample evaluation sheet is shown in parts of Figure 3. Only a highly limited excerpt from the evaluation is reproduced here. Part (i) contains the identification attributes, and is reproduced in frame (a) of Fig. 3. In Part (ii) ownership and current function are documented. Part (iii) summarizes field and vicinity information. Part (iv) deals with the conservation and former intervention information, including the epoch to which the building belongs, dates and extent of previous interventions and building/segment elevations. Part (v) is a summarized description of the load carrying system of the building including material characteristics. The only historic earthquakes for which reasonably reliable records exist are the 1766, 1894 and 1999 earthquakes. In Part (vi) all available information concerning these events as they affected the building are entered. This includes any out-of-plumbness of walls, roof inclinations and foundation movements. The cadastral data for locating the edifice are entered under Part (vii) as given in frame (b), and an extensive set of photographs, as in Part (viii), are given for the current outlook as in frame (c).

This body of information serves as the backdrop for spreadsheet calculations where wall stresses are estimated from building masses and site-specific response spectra. An example is provided in Fig. 4(a) for a tomb with an oval plan. Each of the small wall segments resists the lateral force transmitted by the cupola mass and tributary appurtenances in both directions. The stress estimates are summarized in the table in frame (b), and compared with the limiting stresses in the elements are judged not to exceed the critical limits. The table is in Turkish, and presented only for indicative purposes. It contains sections for the total structural weight, seismic parameters such as equivalent static earthquake force components in the x and y directions, the safe normal and shear stresses for the wall material, and calculations for the final normal and shear stresses calculated for each wall [13 in the case considered]. The last column in the table has an entry for whether the wall is adequately safe under the earthquake forces.

GANZANFER AGA TURBESI

(a) Identification Information



(b) Cadastral Location

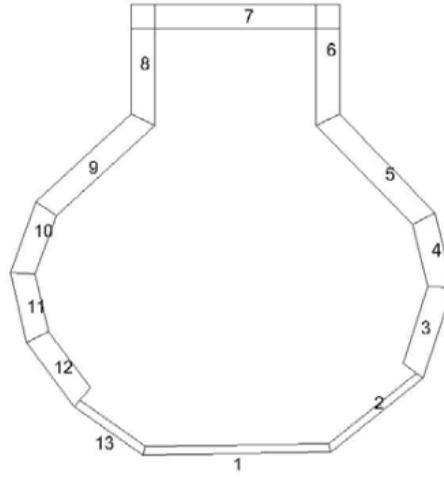


(c) Photographic Information

Figure 3: Historic Building Assessment Form for a Tomb

5.2 The Free-standing Minaret in Diyarbakir

Historic buildings can serve as unwitting but crude seismographs if they have survived earthquakes during their existence. A unique opportunity presented itself for the case of a free-standing minaret that is part of a 500-year old mosque. The four-



(a)

Fatih İşçesinin Depreme Karşı Güvenli Kılınması Projesi - Anıt Eserleri Yapı Stokunun İnceleme ve Değerlendirmesi

KAĞIR YAPILARDA BAŞİTLEŞTİRİLMİŞ HESAP METODU İLE PERFORMANS DEĞERLENDİRMESİ																			
Referans No:	FA020	Anıtın Adı:	Fevziye Küçük Efendi Camii																
Tavan İzdüşüm Alanı(m ²) =	137.08	Döşeme x _{taban} (cm)=	695.7																
Tavan Döşeme Kalınlığı (cm) =	26	Döşeme y _{taban} (cm)=	1362.8																
w _{taban} / h _{taban} (m) =		Kübbe x _{taban} (cm)=																	
Döşeme Özgül Ağırlığı (kN/m ³) =	20	Kübbe y _{taban} (cm)=																	
TOPLAM BİNA AĞIRLIĞI ΣW(kN)=		4545.19																	
DEPREM HESABI PARAMETRELERİ																			
M _{taban} (ton) =	275.55	A _g (m/s ²) =	1.387																
Sax (m/s ²) =	3.26	Tx (sn) =	0.2099																
Say (m/s ²) =	3.26	Ty (sn) =	0.2871																
Deprem Yüku Fx (kN)=	899.6	Deprem Yüku Fy (kN)=	899.6																
Duvar Malzemesi ve Emniyet Gerilmeleri																			
Düşey delikli blok tuğla (delik oranı %33'ten az)																			
σ _{em} (MPa) =	3.0																		
τ _{em} (MPa) =	0.6																		
TAŞIYICI DUVAR HESAPLARI																			
Duvar No	Malzeme Özellikleri		Yükseklik	Duvar Plan Yerleşim Bilgileri					Düşey Yük Hesabı		Rijitlik Hesabı		Kırıktık Duvar Fargası Özellikleri		Düzlem İçi Etikler		Düzlem Dışı Etik ve Dayanım	Eleman Kontrol	
	E _{duvar} MPa	γ _{duvar} kN/m ³		X sol-alt cm	Y sol-alt cm	Lx/Ly cm	Lnet cm	Açı derece	A _{kesit}	EK Yükl (kN)	ΣP kN	kx kN/m	ky kN/m	k kırıktık k kesit	A kırıktık cm ²	τ MPa			σc MPa
1	1500	20	490	415	731	589/25	589		163295	213.7	21272	0	1.44	6000	0.22	0.35	22	77	Yeterli
2	1500	20	490	1003	741	25/365	365	38	113516	148.5	5132	9900	0.98	4500	0.23	0.31	-	-	Yeterli
3	1500	20	490	1291	966	75/293	293	72	97333	127.4	2572	107	0.83	3075	0.03	0.31	-	-	Yeterli
4	1500	20	490	1384	1243	75/232	232	104	75911	99.3	22957	408	1.00	11400	0.08	0.13	-	-	Yeterli
5	1500	20	490	1258	1435	75/483	483	128	113686	148.7	41293	22413	0.60	9225	0.13	0.12	54	690	Yeterli
6	1500	20	490	956	1823	75/256	256		113950	149.1	0	22229	0.96	10425	0.18	0.15	-	-	Yeterli
7	1500	20	490	378	2030	659/75	659		146243	191.3	74517	0	0.44	9000	0.11	0.11	74	1011	Yeterli
8	1500	20	490	378	1769	75/356	356		113950	149.1	0	33482	0.96	10425	0.19	0.15	-	-	Yeterli
9	1500	20	490	80	1504	75/399	399	42	113686	148.7	20910	27477	0.54	9225	0.09	0.13	-	-	Yeterli
10	1500	20	490	0	1287	75/231	231	70	75283	98.5	20798	1128	1.00	11400	0.07	0.13	-	-	Yeterli
11	1500	20	490	49	1073	75/220	220	103	74684	97.7	19573	273	1.00	11700	0.07	0.13	-	-	Yeterli
12	1500	20	490	199	897	75/245	245	128	79148	103.6	15409	7660			0.04	0.10	-	-	Yeterli
13	1500	20	490	415	731	25/262	262	145	81334	106.4	2526	6887			0.03	0.21	-	-	Yeterli

(b)

Figure 4: (a) Stress Analysis Model for a Historic Tomb [shown in plan] (b) Stress Analysis for a Historic Tomb

legged Minaret of Sheikh Mutahhar Mosque has been constructed in the early 16th century. This is a special structure because the minaret is not connected to the body

of the mosque, but is an adjacent and separate component. It is unique because the minaret body has been placed on four cylindrical stone columns (Fig. 5). There is no positive connection between the columns and the minaret. This minaret is seemingly vulnerable though it has survived for five centuries in a city that is subjected to moderately strong earthquakes. In order to investigate the likely seismic performance and strength of the four-legged minaret, the architectural renderings of the minaret have been examined.



Figure 5: Free-standing Minaret

If the minaret has been able to stand without toppling for five centuries, then it is possible to estimate which upper ground motions it must have experienced. The structure measures about 2.0 m square in plan and stands above four 1.75 m tall basalt pillars that are topped with stone lintels supporting the 13 m tall masonry body of the structure to the level of the balcony. Then there is a 4.2 m long cylindrical part followed by a 2 m tall timber cone giving it the familiar architectural profile in Fig. 6.

It is observed that the approximately 22 m tall mosque appurtenance sits freely above the circular, 0.5 m diameter supporting pillars 1.75 m in height (Fig. 7). The top ends of the pillars are free for purposes of analysis, but the conditions below the grade level are not known. The two extreme possibilities are shown in the right frame of Fig.6. If the bottom ends are fixed perfectly into the foundation then the only feasible type of dynamic motion for the minaret would be to rock at the lintel

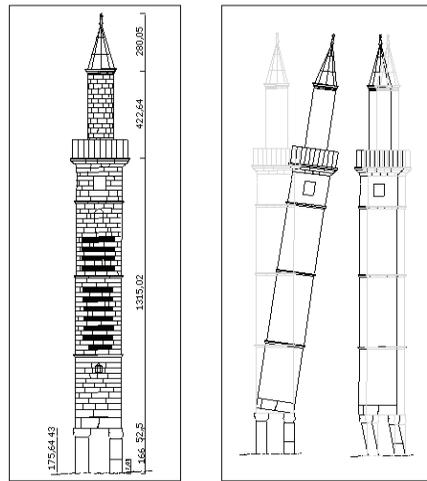


Figure 6: Geometry of the Minaret

level, the situation described in the figure on the left. If the bottom ends of the pillars are similar to their upper ends then it will be the pillars that rock, allowing the rest of minaret to follow their motion as a horizontally translating mass.

The first eventuality is represented as the idealized rocking rigid block of Fig. 8. With sufficient friction developing across the plane of contact the block will move as shown in the sketch, rocking alternatively around its two corners O and O'. The seminal work for the analysis of such blocks has been done by Housner (1963), paving the way for later investigations, e.g., Makris and Roussos (1998) and Anooshehpour et al. (1999).

The fundamental question to be answered is: what is the ground motion pulse that will cause the block in Fig. 8 to topple? This is not a question that has a unique answer because both the amplitude a_p and duration T_p of the pulse determine that response. A series of dynamic response calculations for the minaret indicated the combined response limits illustrated in Fig. 9. Reducing the ground motion to a sinusoidal pulse is a necessary simplification for purposes of the current analysis, but the region to the left and lower side of the curve is the safe region for the minaret. It is seen that long period pulses are more dangerous for the geometry of the structure here.

Whereas a 2-s pulse needs to have a 0.15 g peak, a 1-s pulse must be above 0.5 g and a 0.7-s pulse needs to be above 1 g in amplitude to cause a catastrophic amount of rocking. As the duration of the pulse becomes longer the estimate of the amplitude that leads to toppling approaches the static acceleration of about 0.11



Figure 7: Support Details of the Base of the Minaret

g. The curve is only an approximate estimate of the ground motions that occurred in Diyarbakir during the last half-millennium. The alternative idealization for the fixity of the supporting pillars in Fig. 8 leads to the estimate that the peak ground velocity during the same period cannot have exceeded 0.8 m/s.

6 Conclusions

The threat of future earthquakes and other disasters will ensure that in every country and region attention will be given in coming decades to the retrofitting of historic

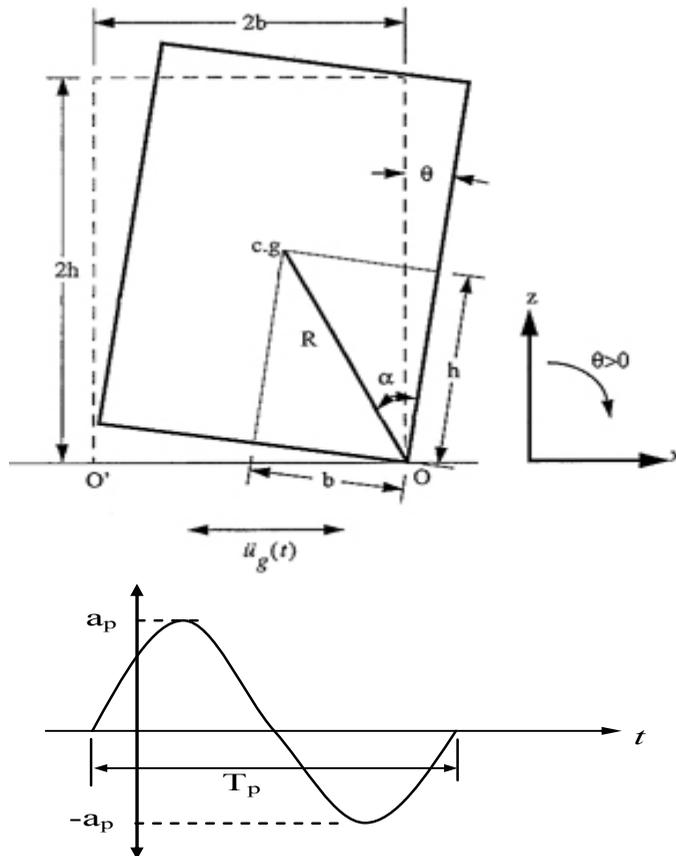


Figure 8: Dynamics of Rigid Blocks

structures. Such monumental structures are a concrete reminder of the glories of the human past in a world that is shrinking in terms of space and time. National pride will, slowly but inevitably, be interpreted as a part of all global achievement. Structural longevity will become a requirement, not just a goal, for outstanding historic buildings, regardless of their current condition or location. The seismic retrofit leading to preservation of historic structures requires the satisfaction of the requirements of aesthetics, architecture, engineering and technology. Attempts are therefore necessary to provide at least a 'code of practice' if not a code of specifications for the assessment, analysis and strengthening aspects of the seismic rehabilitation of historic structures.

Conventional strengthening methods, especially those involving 'invisible' intervention, will continue to play an important part in the seismic protection of historic

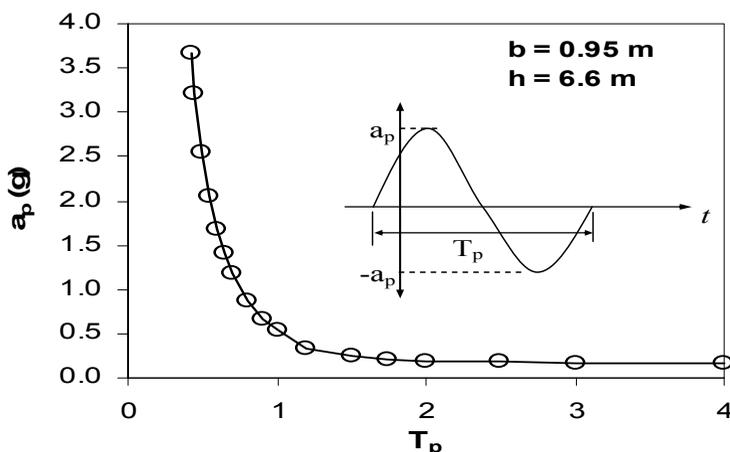


Figure 9: Safe and Unsafe Regions for a 13.2 m tall, 1.90 m Wide Block

[as well as more conventional] structures. However, the development of base isolation technology for wider application at lower cost will result in greater use of friction pendulum interfaces between the superstructure and foundations of historic buildings, and the feasibility of such solutions will be restricted only if the size of the structure is very large.

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