SEISMIC VULNERABILITY AND RISK ASSESSMENT OF CULTURAL HERITAGE BUILDINGS IN ISTANBUL, TURKEY

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ABSTRACT :

The Government of Turkey (GOT) and the International Bank for Reconstruction and Development (World Bank) have agreed upon a loan to implement the Istanbul Seismic Risk Mitigation and Emergency Preparedness Project (ISMEP) objectives of which are to improve the city of Istanbul's preparedness for a potential earthquake. Within the framework of Component B, subcomponent B.3 "Risk Assessment of Cultural Heritage Buildings" funds a technical assistance program to address the vulnerability of building with cultural heritage value. The project has five components, from literature to field survey, to vulnerability and risk assessment of almost 200 buildings and the development of a GIS database. The paper proposed here will provide an overview of the project and specifically discuss the methodology and results of the seismic vulnerability and risk assessment components.

KEYWORDS: seismic vulnerability, historic structures, risk assessment

1. INTRODUCTION

In 2005 the Government of Turkey (GOT) and the International Bank of Reconstruction and Development (World Bank) have agreed upon a loan to implement the Istanbul Seismic Risk Mitigation and Emergency Preparedness Project (ISMEP) for a total of 310 Million Euro over five year. The main objectives of the projects are: Strengthening institutional and technical capacity of emergency management; Increasing emergency preparedness and response awareness Retrofitting/Reconstruction of priority public buildings Vulnerability inventory and sample retrofitting design for cultural and historical heritage assets Taking supportive measures for the efficient implementation of development law and building codes. The Istanbul Project Coordination Unit (IPCU) was established under Istanbul Special Provincial Administration (ISPA) to administrate and oversee the implementation of the project. The second and most substantial component of the ISMEP Project is devoted to the "Seismic risk mitigation for priority public buildings" by means of retrofitting or reconstruction of individual structures such as hospitals, schools and other priority public facilities". This component includes a minor subcomponent B.3 "Risk Assessment of Cultural Heritage Buildings". The implementation of this component in the past 18 months is the subject of this paper. IPCU nominated the Ministry of Culture and Tourism (MoCT), Istanbul Directorate of Surveying and Monuments (IDSM), as the responsible directorate to carry out the activities under the component B.3 of the ISMEP Project.

The main goal of the subcomponent B.3 "Risk Assessment of Cultural Heritage Buildings" is to assist the Government of Turkey in: a) mitigating the seismic risks associated with the cultural and historical property (heritage) in Istanbul; b)strengthen the capacity for pro-active measures in order to mitigate the damaging and devastating effects of future earthquakes on cultural and historical property (heritage buildings) and other historical and cultural structures and assets in Turkey such as, museums and museum displays. To achieve the B.3 (CB4.1) subcomponent goal, the ISMEP Project foresees on one hand the development of an inventory of cultural heritage buildings which are owned or used by the Ministry of Culture and Tourism, and on the other a campaign of vulnerability assessment of such cultural heritage buildings. The Joint Venture (JV) ARS Progetti -SPC, Studio Progettazione e Controlli-Consultancy for Conservation, headed by ARS Progetti, was awarded the contract, after an international tender, for the services related with point (i) and (ii) above. Work started in May 2007 with in five tasks covering: literature survey, field surveys, vulnerability assessment, risk mitigation measures, GIS database. This paper focuses on the methodology developed for the delivery of the vulnerability and risk assessment tasks and their implementation within the GIS Database, by use of examples.

2. METHODOLOGY

Procedures to assess the vulnerability of existing and historic buildings are usually classified in relation to the dimension of the sample for which the vulnerability is considered and the number and detail of the structural parameters used to carry out the analysis (Bernardini, 1999, Coburn & Spence 2002). Typically the larger the size of the sample the smallest the number of parameters and vice versa. Conversely studies move from purely statistical approaches for large samples to detailed structural analysis when a few buildings are considered. The project illustrated here however presented a specific challenge, as the number of buildings to be considered is relatively large, close to 200, while due to the nature of the sample is very difficult to identify common typologies and generalize behaviours within it. At the same time given the time frame of the project and its resources was unconceivable to run specific level 3 or above assessment analysis for each of the buildings. Hence a compromise was struck. On one hand a quantitative level 2 analysis based on failure mechanisms and limit state analysis, called FaMIVE, whose robustness and reliability has already been proven in past studies for more homogeneous samples of historic masonry buildings (D'Ayala, Speranza 2003), was chosen as a quantitative tool for assessment. On the other hand a qualitative vulnerability assessment was also performed. This is based on accurate on site observation of a number of parameters that are known to qualify the seismic performance of historic masonry buildings, leading to an expert judgment of the expected building vulnerability. In the next two sections the two approaches will be presented in turn and the complementarity of the two discussed.

3. QUALITATIVE VULNEARBILITY ASSESSMENT

Qualitative seismic vulnerability assessment of a building is a quick procedure to identify the structural layout and assess its characteristics that can affect its seismic vulnerability. It is a very approximate procedure based on conservative parameters to identify the potential earthquake vulnerability of a building and can be used to screen buildings for detailed evaluation. This preliminary evaluation is a synthesis of a deductive process based on experience and on elaboration of a restricted set of qualitative data. This procedure is based both on in-situ inspection and on a preliminary knowledge of the building history and its architectural and technical features. The survey inspection has the aim to understand the actual morphology of the building, the relationship with its surroundings, the state of damage and decay, the alterations occurred in the structure during the time, including repair and restoration works. The following list summarizes the basic set of the survey data needed to carry out the qualitative seismic vulnerability assessment:

- *Relationship with adjacent buildings:* Buildings are often sited close to each other. During seismic shaking two such adjacent buildings may hit each other due to lateral displacements. Building pounding affects the dynamic response of both buildings and additional inertia loads are induced on both structures.
- *Geometric characteristics of the building*: Plan configuration, number of storeys and dimensions, presence of mezzanines. Geometric irregularity of the overall building shape in plan and elevation affects the seismic response of the structure. Also an irregular shape indicates an irregular mass distribution, and it may also happen that certain parts of building may respond dynamically in an independent manner in respect to the rest of the building. Mezzanines can often lack a lateral force-resistant system. Untied mezzanines pose a potential collapse hazard, and should be checked for stability.
- *Structural system*: Vertical and lateral force-resisting system, floor and roof diaphragm effectiveness, connection in the wall's corners and between walls and floors, basement and foundation system. One of the fundamental attributes required for the proper seismic response of a building during earthquake is that its lateral load resisting members should be properly tied together to act as a 3D unit. This provision is intended to provide a continuous lateral load path to transmit additional seismic forces safely to the ground.

- *Mass irregularity*: for historic buildings this might relate to the difference in structure among floors leading to heavy roofs or part of them causing unexpected dynamic behaviour.
- *Architectural features* that may affect seismic performance, as thrusting structures such as arches, vaults or sloped roof without ties, arcades or pillars alignments that behave as a soft-storey, irregular arrangements of masonry partition walls, etc.
- *General conditions***:** Decay of materials, damages, also due to past earthquakes, alterations and additions that could affect seismic performance.

The in-situ survey data is cross-checked and improved with literature data, which provide for both a preliminary statement about the more relevant structural and seismic history of the building and acknowledgment of peculiar features, construction techniques and materials that can be found in the structure in accordance with the past and present of local building practices. Qualitative data are collected in a simplified model to understand the behaviour of the structure and the possible local and global weakness. Finally the assessment ranking is derived from an assessment of most probable mechanisms of damage and from a qualitative evaluation of the possibility of local or global failure under seismic actions. Therefore the assessment reliability derives from the possibility to analyse and understand the structure and its damages.

4 QUANTITATIVE VULNERABILITY ASSESSMENT

4.1 Categorisation of buildings

The first step in the methodology for the vulnerability assessment by analytical method is to categorise the buildings, by identifying the load bearing structures and horizontal structures systems, as this will determine the analytical method chosen as well as the possibilities of identifying generic characteristics. The categorization is conducted after onsite visit and collection of preliminary information on the buildings. The following categories were identified in the ISMEP sample:

- *Load bearing masonry buildings with a variety of horizontal structures, which are not vaulted*. These buildings are the majority and are assessed with FaMIVE.
- *Load bearing masonry with vaulted structures*: the vaulted structures is first assessed with a separate procedure called VULVAULT, which allows calculating the resultant maximum thrust and position of hinges or levels of sliding within the vault subjected to gravity and horizontal loadings. The results from the assessment of the vaults are input in FaMIVE to assess vulnerability of vertical structures supporting the vaults.
- *Gigantic load bearing masonry as in city walls and defensive constructions:* these structures often lacking a masonry box layout are not suitable for FaMIVE and they have been analysed using a number of global indicators such as total shear base capacity and walls or columns slenderness, following guidelines from EC8.
- *Timber clad timber frames supported on masonry basement walls:* the lower part of the structures is made of masonry and at this level of assessment, without a detailed survey of the connection of the timber superstructure is difficult to quantify reliably the effectiveness of the frame action of the timber portion. It is assumed that the overall structures behave in a manner similar to a masonry building as far as the triggering of the mechanism is concerned, while in the post peak phase the timber structure will be able to show greater ductility than typical masonry structures. Hence FaMIVE has also been applied to these classes of buildings.

Structures made of modern materials for which FaMIVE is not appropriate were not analysed in this phase.

The FaMIVE procedure was developed to be applicable whether drawings information and other cartographic data was or not available. Indeed, the information required to conduct the assessment can mostly be obtained by observation on site once the typological system and construction details are known. In the present application, the use of FaMIVE benefited from direct access to most of the buildings and from the fact that for most of them some drawing documentation is available. A first phase of the data collection requires the identification of construction details, specifically masonry and floors/roof/horizontal elements construction and fabric. This aspect of the data collection was carried out along the field survey, very similar to the observation leading to the qualitative assessment. The second phase is based on completing a survey datasheet containing geometric and structural information.

Irregular and complex buildings are subdivided in simple subunits, and for each of them the most qualifying elevations are then identified and one form is filled for each elevation or homogeneous portion of elevation in the building. For each assessment campaign the form is tailored to best suite the sample. In this case the form has been slightly modified to include data on vaulted structures to be used in the VULVAULT procedure, such as height of springing of the arch/vault/dome, type of vaulting (cross vault, barrel vault, domical vault, dome, etc.), type of support (column, pillar, wall), thickness, rise and span of the vault or arch, and its profile (circular, raised, shallow, parabolic etc.). Numerical data is estimated or measured on site and actual measures are available from reliable drawings.

4.2 Definition of quantitative vulnerability judgement for each building

The FAMIVE procedure is based on the lower bound approach of limit state analysis and identifies all possible mechanisms that can occur for an elevation in a building given its connections to other elevations and horizontal structures and the layout of openings (D'Ayala, Speranza 2003). Among all possible mechanisms for each wall the one that has the worst combination of load factor and damage extension, is considered as defining the vulnerability of the wall. These results can be presented in terms of synthetic plan maps in which the values of collapse factor, type of mechanism and extent of wall failure are plotted, or can be further elaborated to give an overall judgement of the vulnerability of the building as shown in Figure 1. To include the results in the GIS system for each building a *global, prevalent and local vulnerability judgement* are defined as follows:

• *Global vulnerability* refers to weaknesses which are either distributed in various and several parts of the building or characterise a most relevant part/section of it, such as more than one entire façade and involving in their collapse floors and roofs, so that possible damage would affect a large portion of the building. In terms of collapse load factor and class attribution the global vulnerability is calculated as the weighted average of the collapse load factors and class of each of the critical collapse load factor for each elevation, while as far as the mechanism is concerned the most common is chosen as the building mechanism, or the one associated with the highest extension.
• *Prevalent vulnerability* (class, load factor, failure mechanism) is neither the worst nor the average vulnerability, but the most significant i.e. that which best characterises or refers to the possible most significant damage, i.e. is either the most common or the one with the most serious consequences. In this respect in some cases global and prevalent might coincide in terms of class or mechanism, but it is unlikely in terms of collapse load factor.
• *Local vulnerability* refers to the most vulnerable element/section/part of the building where possible damage affects a limited part of the building. It highlights a localised weakness where possible damage can occur for considerably lower collapse load factor than the rest of the building. Also usually these are vulnerability that can be easily identified and mitigated with ordinary, conventional strengthening. For instance, mechanisms G and M (see fig.1) are usually considered as local.

The reliability judgement, relating to the input of the data provides the range of confidence with which the central value of collapse load factor is arrived at. In this respect only one value is given for each building indicative of the overall quality of the assessment. It is worth notice that besides the final values described above and directly implemented in the GIS, for each elevation analysed results are provided for all feasible mechanisms, together with the extension of wall involved in terms of storeys and the consequence for horizontal structures. This allows the operator to compare results for a given elevation and quickly consider what would be the expected collapse load factor if the current most likely mechanism is prevented.

5 CAPACITY ASSESSMENT AND RISK JUDGEMENT

5.1 Definition of capacity

The fundamental assumption of the work developed in this project is that the seismic capacity of masonry walls is highly reliant on the possibility of considering post elastic behaviour, and specifically extensive cracking

under relatively stable loading conditions. (D'Ayala 2005) The frictional model introduced to describe the structural behaviour, at the basis of both FaMIVE and VULVAULT, indeed assumes that any mechanism is stable until the "plastic hinges" needed to define the mechanism are fully developed, i.e for in plane mechanisms, for instance, failure will not occur until the width of the crack is greater than the staggering of the units. This allows considering capacity curves for each wall which are characterised by post peak behaviour. From a mechanical point of view the collapse load factor as calculated in FaMIVE corresponds to the inception of collapse and hence to a condition of "repairable damage", characterised by damage level D2 to D3 depending on the type of building and the mechanisms considered.
The capacity is measured in two ways: a) as ratio of non linear acceleration demand obtained from a NEHRP-like (National Earthquake Hazard Reduction Program) spectrum against acceleration capacity measured as the collapse load factor; b) as a comparison between capacity and demand in spectral displacement terms by checking the performance point on the non linear displacement spectrum obtained starting with the NEHRP equivalent spectrum (Ansal et al. 2006).

The capacity curves are defined for each facade on the basis of 3 parameters. The strength capacity, a_y, is identified on the basis of the limit state analysis and hence coincides for each façade with the collapse load factor obtained with FaMIVE, as illustrated in section 4. This quantity has the dimensions of a spectral acceleration (a/g). The elastic limit displacement, at the top of each façade, is estimated with the following simple relationship:

$$\Delta_y = \frac{a_y}{4\pi^2} T^2 \qquad \text{with} \qquad T = \sqrt{\frac{m_{eff}}{K_{eff}}} \qquad 5.1$$

where T, natural period of the façade, is calculated on the basis of the mass m_{eff} of the façade activated by the failure mechanism, and K_{eff} the elastic stiffness relevant to the specific mechanism (e.i in plane or out of plane stiffness of the façade with specific constraint conditions and cracked cross section). The ultimate displacement Δ_u is defined in a manner coherent to the mechanism approach at the basis of the FaMIVE procedure, and calculated as the displacement that determines the geometric instability of the facade and hence its collapse. Hence for each wall, in relation to its slenderness and its constraint conditions a different value of out-of-plane or maximum lateral displacement can be calculated beyond which equilibrium is not recoverable. Following this method the capacity curve for each façade can be obtained and the available ductility for each one can be calculated (figure 2)

5.2 Seismic risk evaluation

Risk evaluation is the convolution of hazard and vulnerability. In other words is the relative measure between the capacity of the building and the demand of the external hazard considered. In general, this is expressed in terms of a certain level of damage expected compared to a given level of foreseen hazard. In evaluating the risk, the hazard has been quantified assuming a deterministic earthquake scenario for Istanbul (Erdik et al. 2007) and the damage level corresponds to the performance level indicated, as repairable damage for all building considered, according to the Turkish Seismic Code (TEC 20007). With this definition the condition of repairable damage correspond to the onset of collapse mechanisms as calculated with the FaMIVE procedure and hence the collapse load factor can be compared to the spectral non linear acceleration as explained in the previous section. On the basis of the risk evaluation and quantification, mitigation measures can then be identified, ranked and eventually implemented. Following this approach the evaluation of the seismic risk, in the ISMEP project, is based on the comparison between the vulnerabilities of each building (historical, qualitative and quantitative) and the seismic hazard of its site. In other words the vulnerability assessment coming from the qualitative and quantitative method are compared on the basis of their reliability and weighed by the information and data on their seismic performance through history as obtained from the Literature survey. This type of assessment corresponds to a level 2 risk assessment. In other words, the judgment is based on limited knowledge and simplified analytical models and hence represents an initial form of assessment. While this is entirely within the scope of the project in identifying a ranking schedule of relative risk for the set of buildings studied, it cannot be used as a definite measure of a specific building risk on the basis of which mitigation or strengthening measure can be automatically designed. All compounds and buildings have been assessed by using the same methodology considering two different sets of data, in relation to the availability of hazard data and type of seismic assessment conducted. Specifically:

- The vulnerability of buildings which have undergone a qualitative seismic assessment and a quantitative seismic assessment by global indicators has been compared with the level of hazard expressed in terms of European Macroseismic scale for the Istanbul deterministic earthquake.
- The vulnerability of buildings for which both FaMIVE and the qualitative assessment have been applied has first been weighed comparing the relative ranking for each of the two approaches, and then the numerical global collapse load factor has been compared with the non linear spectral acceleration obtained from site specific spectral analysis for the deterministic earthquake.

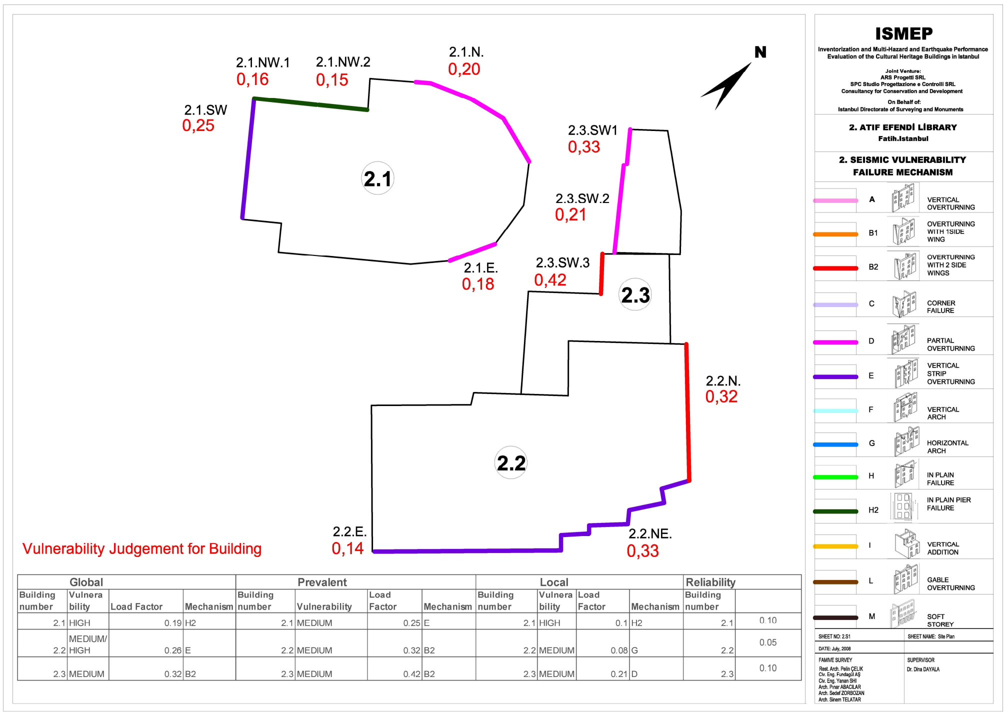
In all cases the risk is expressed in qualitative terms defining classes of risks as follows:

- LOW for buildings of low vulnerability for both judgements which show a safety factor $\Lambda > 1.5$
- MEDIUM/LOW for buildings of either low or medium vulnerability with safety factor $1.15 < \Lambda < 1.5$
- MEDIUM for buildings of medium vulnerability for both judgements with $.85 < \Lambda < 1.15$
- MEDIUM/HIGH for buildings of either medium or high vulnerability with $0.6 < \Lambda < 0.80$
- HIGH for buildings of high vulnerability for both judgements with $0.4 < \Lambda < 0.6$
- VERY HIGH for buildings of very high vulnerability for either judgement with $\Lambda < 0.4$.

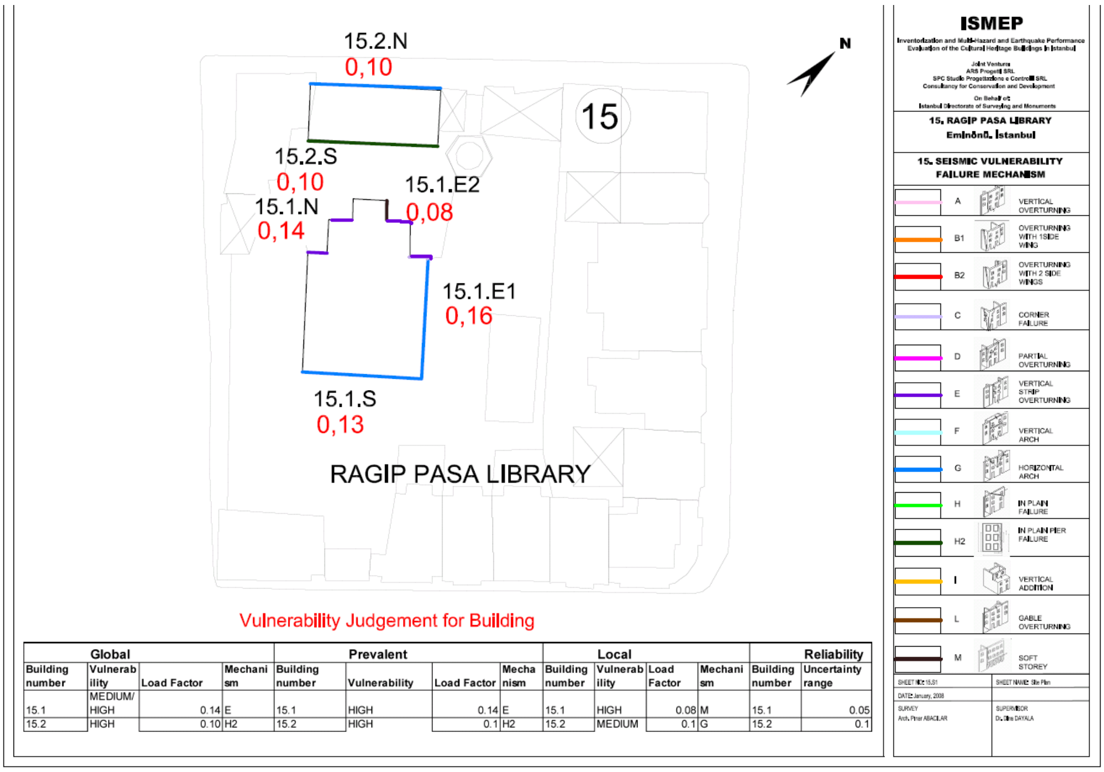
Moreover the judgement is weighted according to the protection level of which the building needs to be endowed. The expected performances of any building is generally diversified according to its importance and use, and therefore to the more or less heavy consequences of damage due to a seismic event. The level of protection depends, therefore, on the historical and architectural value of the building and of its contents, as well as on its strategic importance and its level of use, with the following rating: LOW for buildings of relative recent construction or that have undergone substantial alteration, i.e of low architectural value, whit modest content and function; MEDIUM for buildings of some architectural value with content and function of secondary importance; HIGH for buildings which for either their artistic or architectural value or for their strategic use or for the value of their content are considered of primary importance. The reliability of the risk assessment depends on the reliability of the vulnerability assessments and of the evaluation of on site seismic hazard. As a reliability judgement has been associated to each step of the assessment the risk reliability is the compound value of the reliability of all components. The procedure highlighted above is presented with reference to the case study of Ragip Pasa Complex in the following section.

6 APPLICATION OF THE PROCEDURE AND CONCLUSIONS.

The application of the procedure is presented with respect of two units of assessment: the Atif Efendi Library and the Ragip Pasa Library. Set both on the inner part of the Istanbul Historic Peninsula, relatively close to each other, they were both built in the mid 18th Century. The two units are both constituted by a main library building and secondary buildings hosting other functions. Both libraries have a central plan, not too dissimilar shapes, with Ragip Pasa being more regular and symmetric. Figure 1. presents the results for the collapse load factor and mechanism of each elevation considered, but also the overall vulnerability judgement for each building. It should be noted that for unit 2.1 the GCLF is 0.19 a/g leading to ***high vulnerability*** and for unit 15.1 is 0.14 a/g leading to ***medium/high vulnerability***. This is because, although in the second case the collapse load factor is smaller, this is associated prevalently to relatively localised mechanisms type G, involving the collapse of the upper spandrels above the system of anchors at the springs of the arches supporting the domes, while in the case of Atif Efendi the mechanism identified for all walls are global, i.e. cause the collapse of both walls and floors. However when considering the capacity and the performance against demand, and hence the risk, due to the different local soil conditions but also to different level of ductility associated with the different mechanisms, the results show that Ragip Pasa is overall at greater risk than Atif Efendi as both in terms of non linear spectral acceleration the values are always lower than the demand, but also in terms of ductility the ultimate performance point of the equivalent push over curves are always below the non linear displacement spectra for the site.



Global				Prevalent				Local				Reliability	
Building number	Vulnerability	Load Factor	Mechanism	Building number	Vulnerability	Load Factor	Mechanism	Building number	Vulnerability	Load Factor	Mechanism	Building number	
2.1	HIGH	0.19	H2	2.1	MEDIUM	0.25	E	2.1	HIGH	0.1	H2	2.1	0.10
2.2	MEDIUM/ HIGH	0.26	E	2.2	MEDIUM	0.32	B2	2.2	MEDIUM	0.08	G	2.2	0.05
2.3	MEDIUM	0.32	B2	2.3	MEDIUM	0.42	B2	2.3	MEDIUM	0.21	D	2.3	0.10



Global				Prevalent				Local				Reliability	
Building number	Vulnerability	Load Factor	Mechanism	Building number	Vulnerability	Load Factor	Mechanism	Building number	Vulnerability	Load Factor	Mechanism	Building number	Uncertainty range
15.1	MEDIUM/ HIGH	0.14	E	15.1	HIGH	0.14	E	15.1	HIGH	0.08	M	15.1	0.05
15.2	HIGH	0.10	H2	15.2	HIGH	0.1	H2	15.2	MEDIUM	0.1	G	15.2	0.1

Figure 1 Mapping of load factor mechanism of collapse and overall vulnerability judgement for each compound.

In figure 3 the level of vulnerability both in quantitative and qualitative terms is shown for each building. The vulnerability of the vaulted structures is also assessed for the two main buildings and finally the overall risk judgement is provided. It can be seen that due to the consideration presented above compounded with the extensive damage pattern surveyed on site for Ragip Pasa library, this si rated as being at Very High risk, while Atif Efendi remains at a Medium/High Level.

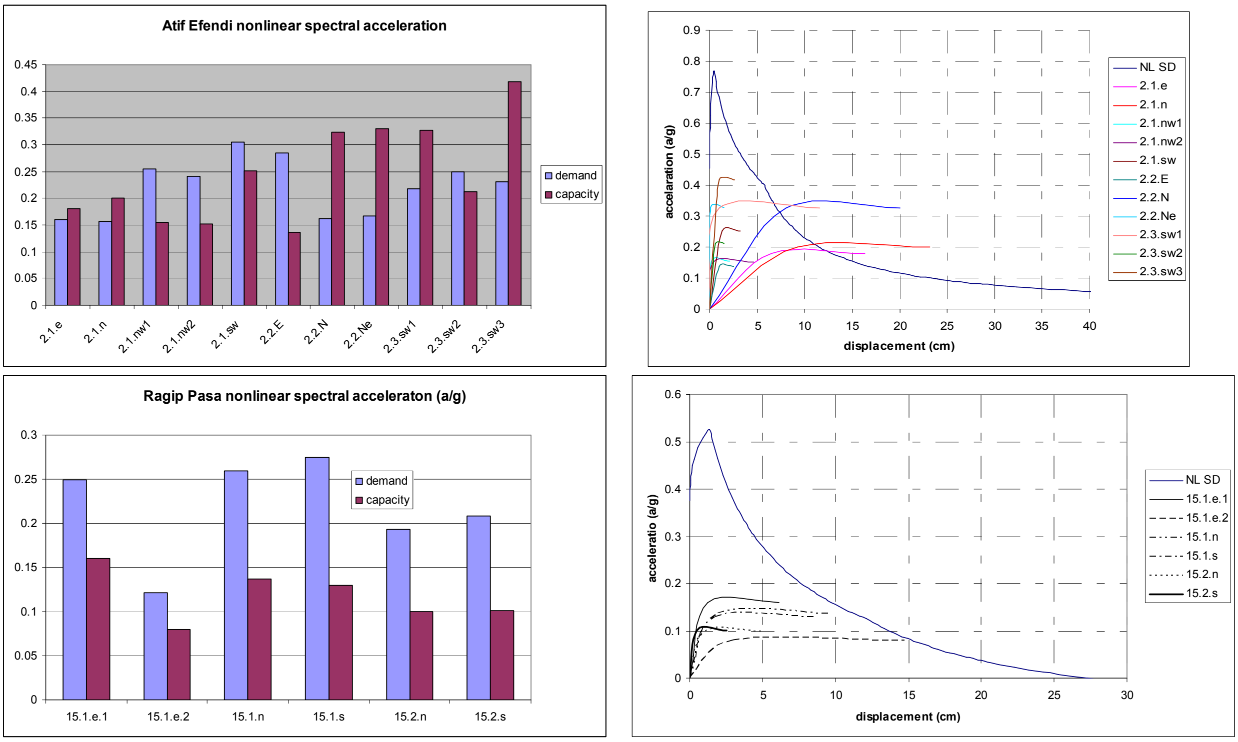


Figure 2 Comparison of capacity and demand for each of the assessed elevations in terms of acceleration and in terms of equivalent push over analysis performance points.

BUILDING INVENTORY				VULNERABILITY ASSESSMENT																								SEISMIC HAZARD			RISK ASSESSMENT			
Architectural complex		Architectural unit		Historical		Qualitative						Quantitative																						
						structure		seismic		seismic		global indicator				FaMIVE					VULVAULT					seismic global								
Id.	Description	Id.	Description	rating	reliability	level	reliability	level	reliability	level	reliability	in plane area ratio	base shear ratio	columns slenderness	wall slenderness	prevalent failure mechanism	prevalent collapse load factor	prevalent vulnerability class	reliability index	global collapse load factor	failure mechanism	collapse load factor	vulnerability class	reliability index	vault safety factor	level	reliability	macroseismic intensity	deterministic PGA	nonlinear spectral acceleration	protection level	safety factor	global risk level	reliability
2.	Atif Efendi Li	2.1.	Library	°	-	M	H	M	L							H2	0.25	M	M	0.19	HNG	0.33	M	M	2.33	H	M	7.50	0.33	0.22	M	0.84	MEDIUM/HIGH	M
		2.2.	Lodgemen	°	-	L	L	M	L							E	0.32	M	M	0.26						M/H	M	7.50	0.33	0.20	M	1.29	MEDIUM/LOW	M
		2.3.	Storage ro	°	-			M	L							B2	0.42	M	M	0.32						M	M	7.50	0.33	0.23	L	1.64	LOW	M
15.	Ragip Paşa (	15.1.	Library	M	L	L	H	M	M	H	M					E	0.14	H	H	0.14	HNG	0.35	M	M	1.90	M/H	H	8.70	0.47	0.32	H	0.35	VERY HIGH	H
		15.2.	Primary Sc	°	-	M	H	H	L							H2	0.10	H	M	0.10						H	M	8.70	0.47	0.30	M	0.33	VERY HIGH	M
		15.3.	Lodgemen	°	-	L	M	L	M			L	Unsafe	No Data	No Data											L	L	8.70	0.47	-	M	-	MEDIUM	L
		15.4.	Annex	°	-	L	M	M	M			L	Unsafe	No Data	No Data											L	L	8.70	0.47	-	L	-	MEDIUM	L

Figure 3 – Comparison among qualitative and quantitative vulnerability judgements and risk class assignment

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