Empirical and Analytical Vulnerability Assessment of the Masonry Building Stock in Antakya (Hatay/ Turkey)

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SUMMARY:
Masonry structures in seismic active regions belong in many cases to the predominant building type with the highest vulnerability. The comparison of recently published fragility curves shows a remarkable variety of the classification criteria and a large scatter of the vulnerability assignments for comparable subclasses. Though the vulnerability affecting parameters are considered, specifics of the masonry building stock might not be covered by a too rigorous simplification. As it will be discussed, no unique typology is available which could be applied to the building stock of a target area (Antakya), directly. Therefore, a multi-level approach is introduced, combining elements and information from empirical, analytical and experience based vulnerability assessment procedures. Instrumental studies are used for the validation and calibration of the analytical models providing the basis for a reliable damage prognosis. Recordings from a building monitoring system applied to a massive stone school building during a magnitude M_L = 4.2 earthquake are presented.

Keywords: Masonry structures; taxonomy; empirical and analytical vulnerability assessment

1. INTRODUCTION

1.1. Motivation and General Problems

The last decade in earthquake engineering research has been dominated by engineered multi-story RC structures because of the occasionally prevalent heavy damages during strong earthquakes and the enormous number of affected people. Damage in masonry structures has escaped focus of interest. Only a few damage reports take note from the surprising situation of nearly undamaged masonry or traditional building types in the vicinity of collapsed RC frame structures (Schwarz *et al.*, 2000). Nevertheless, masonry structures are the dominant building type in many regions until today. Further insight into the vulnerability of masonry structures is of general interest, in particular in low seismicity areas and old city centres.

This is also true for the city of Antakya, founded in 300 BC, which has been an important confluence of states, faiths and peoples from its earliest times. Therefore, various aspects affect the masonry building stock especially in the old part of the city, which leads to the need of new evaluation methods as well as procedures to describe the behaviour under earthquake loads realistically. In the framework of the regional *Seismic Risk Assessment and Mitigation in the Antakya Maras – Region* (SERAMAR) project an empirical and analytical vulnerability assessment of the RC structures has been carried out, in which a building stock survey for the determination of the vulnerability class according to EMS-98 was performed. On the basis of this, a building typology for RC structures has been developed and representative buildings of each type have been investigated experimentally and analytically (Schwarz *et al.* 2009).
Similar investigations have been conducted for masonry buildings by using the available existing local building stock data of the study area from the building stock survey including the previously assigned vulnerability classes according to EMS-98 (Grünthal *et al.*, 1998).

1.2. Methodology

Due to the special character of the city and its building stock as well as all the boundary conditions, current and common evaluation methodologies are not sufficient to describe the vulnerability of the masonry building stock realistically. Therefore, a new procedure is required, combining past experiences, empirical as well as analytical methods together with different experimental testing.

Using a specific scheme of ranking criteria, representative buildings are identified. Depending on the availability of the basic information describing the structural layout, buildings are selected for a multi-tasking in-situ instrumental testing procedure, which in each phase is related to the outcome of parallel analytical investigations by using different analysis methods and programmes. Temporarily installed weak-motion sensitive velocity-seismometers as well as permanent strong-motion building instru-mentations are used to measure the synchronous spatial building reaction at different elevations. On the basis of the instrumental data, the dynamic characteristics are investigated and compared with the numerical results. Instrumental and numerical data are used to calibrate the finite element model.

1.3. Seismicity

The seismicity of the Antakya Maras Region is affected by the South Anatolian Fault and is therefore classified into the highest seismic zone of the current Turkish Seismic Code (TMPS, 1998). Antakya has suffered from many major earthquakes in the past, notably in the years 110, 115, 527/28, 1822 and 1872. The historical earthquakes with epicentres in the close surroundings (approximately 7 km distance) have caused heavy damages corresponding to intensities IX or X (Över *et al.*, 2010).

Judging by historical precedence, major earthquakes on this branch of the Dead Sea-East Anatolian fault system have a real potential of occurrence in the city. The project is concerned with the damage and loss prognosis under earthquake scenarios similar to the size of the historic events. Therefore, comparable events can be taken as deterministic scenarios to quantify the damage potential and to identify the most critical areas and the probable damage extent.

Another problem, which is not discussed in this paper, is the so far unknown and imprecise description of the subsoil conditions. It cannot be excluded that many buildings are constructed on the ruins of previous buildings. The current paper will describe the state of the research and work concerning the project.

2. TAXONOMY

2.1. Building Stock Survey

At the beginning of the SERAMAR project, all project partners agreed and decided to carry out a complete building stock survey despite the fact of the high effort. Buildings of different material types representative for the various times can be found as well as buildings consisting of several materials. Especially in the suburb areas, oftentimes the ground floor is constructed with a different material than the upper floors due to different construction periods. Typically, adjacent buildings are attached to each other because of limited space and without following any rules.

The buildings of the whole building stock were classified on the basis of different parameters relevant to their seismic performance. In addition to the common census of the building types, further criteria are investigated in order to conduct a more detailed vulnerability assessment with regard to the different approaches (see chapter 3.4.). This concerns e.g. criteria of layout irregularity as well as structural peculiarities, which could yield to special damage patterns. Their distribution and locations in the study area are mapped using a GIS-tool together with all elaborated and relevant hazard parameters and risk data layers (i.e. subsoil conditions, topography).

2.3. Building Typology

Due to the inhomogeneous characteristics of masonry structures, the developed building typology for the RC structures (see Schwarz *et al.*, 2009) cannot be directly adopted because of the insufficient consideration of all seismic performance affecting parameters (see chapter 2.1.).

At the current state, a masonry building taxonomy relevant to the variety of structural layouts and vulnerability has to be developed. The distribution and locations of the types in the study area are mapped using a GIS-tool enabling the link with other relevant hazard and risk data layers and socio-economic aspects (see Figure 1). On the basis of the collected data, the predominant building types with respect to their material, use (commercial, private etc.), the number of stories and particular design aspects (soft stories, cantilevering floor slabs, regularity etc.) could be identified. The respective considered story classes are given in brackets below the acronym (see Table 2.1).

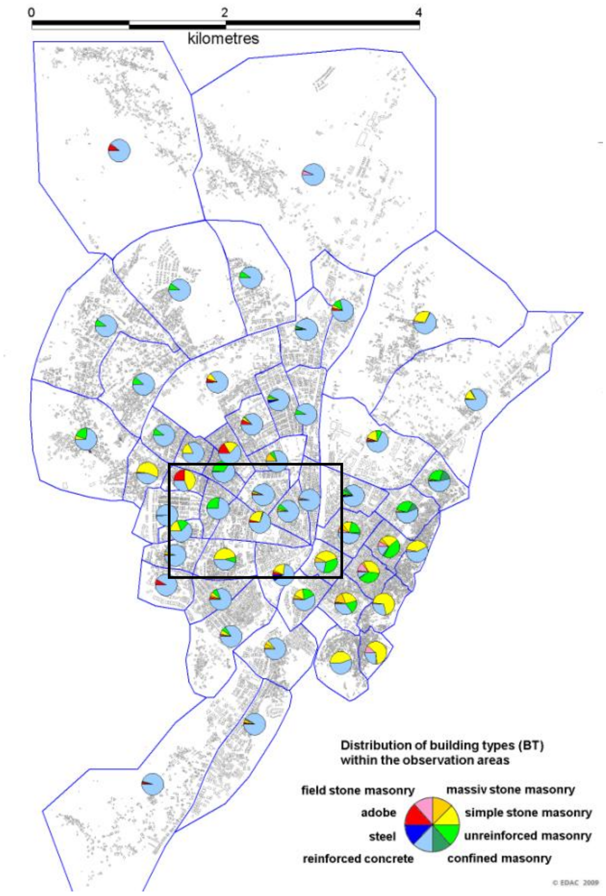
In preparation of the first ground plans for the analytical investigation, a much more refined building typology has to be developed or applied. An attempt has been made to allocate the building types from other studies to the surveyed building stock on the basis of the different assigned materials. Therefore, different typologies from Turkey and Italy were compared with the aim to apply the most suited or to retrieve necessary sub-categories for the extension of the already existing typology from the RC building types (see Table 2.2). There are many classification schemes, which are developed and valid for a broad building stock. However, they do not cover the local building types in Antakya, which were affected by different time periods and cultures, are oftentimes attached to each other and show peculiarities like soft and cantilevering upper stories. In rural areas, no rules can be expected. The comparison of the studies indicates that in each case many different aspects were already considered and investigated. It shows also that the main influencing factor on the entire characteristic of a typology is the local building stock itself and that the existing typologies do not cover all specifics of the masonry building stock. Therefore, it seems to be impossible to directly apply a typology from another area. Only *Lagomarsino et al. (2006)* considered classes of similar building types, but they do not consider the influence of regularity, wall length and opening structures as it was done by *Erberik (2008)*. Thus, it is still necessary to adopt and develop a building typology valid for Antakya and maybe cities with similar historical background in this region on the basis of these two typologies.

Starting with an "external view" of the buildings and their primary structural system, the detailed survey has to deliver more information about the "internal" characteristics to analyze the available ground plan and to consider them in the definition of further sub-classes. The applied typology differentiates into primary (wall materials), secondary (type of slabs, soft story etc.) and tertiary (constructive parameters like wall length and opening structures). Different story classes are not introduced, because of the limited number of stories. Each number of stories defines a separate class. One of the next steps will be the classification of the masonry buildings according to the major structural parameters considering local construction practices. As it can be concluded from Figure 1, masonry type buildings within the old city centre are in general not free-standing. They are closely connected in rows, e.g. stabilizing mutual pounding effects have to be considered as well as other forms of a more-sided interaction due to coupling. Any analytical attempt will fail if this arrangement and the problem of the response are ignored. In the end, the quality in the modeling of the out-off plane failure will become the key criterion for the scenarios.

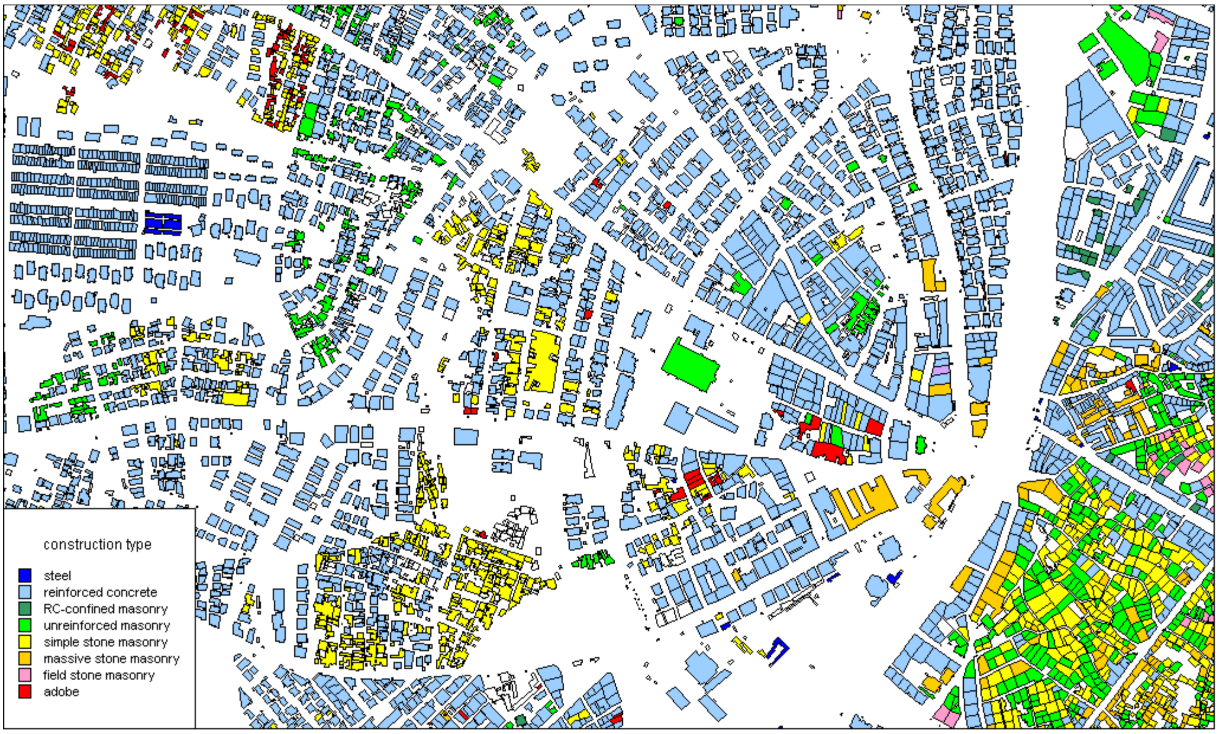
Table 2.1. Distribution of masonry building stock according to material type and number of stories

No. of Stories	Adobe & timber **MR**	Massive stone **MM**	Simple stone **MS**	Unreinforced masonry **MU**	RC-confined masonry **MC**
1	267	162	1952	1242	32
2	86	194	1144	904	109
3	9	30	58	159	61
4	-	2	-	12	16
5	-	-	-	-	2

a) Example buildings



b) Distribution of building types (primary classes)



c) Detailed surveyed construction types of the indicated window in b)

Figure 1. Distribution of the building types in Antakya on the basis of detailed building stock survey

Table 2.2. Comparison of building typologies from Italy, Greece and Turkey applied for risk studies

Reference (study, proposal)	Rubble stone	Massiv stone	Simple stone	URM brick	Confined masonry Brick
HAZUS99	-	-	-	URM (1-2, 3+)	-
Kappos *et al.* (2006)	-	-	Stone (1,2, 1-3)	Brick	-
Lagomarsino *et al.* (2006)	M1 (1-2, 3-5, >6)	M4	M3	M5 & M6	M7
Spence *et al.* (2003)	TURM1	-	-	TURM2 &3 (5.3m)	-
Spence *et al*. (2008)	WM (1-3, 4-7)	-	-	LBM (1-3, 4-7)	SRM
Rota *et al*. (2007)	-	-	-	IMA & RMA (1-2, >3)	-
Erberik (2008)	D3 & D4 (stone) (1, 2, 3, 4, 5)			D1 & D2	-
Borzi *et al.* (2008)	Natural stone (2, 3, 4, 5)			Bricks	-

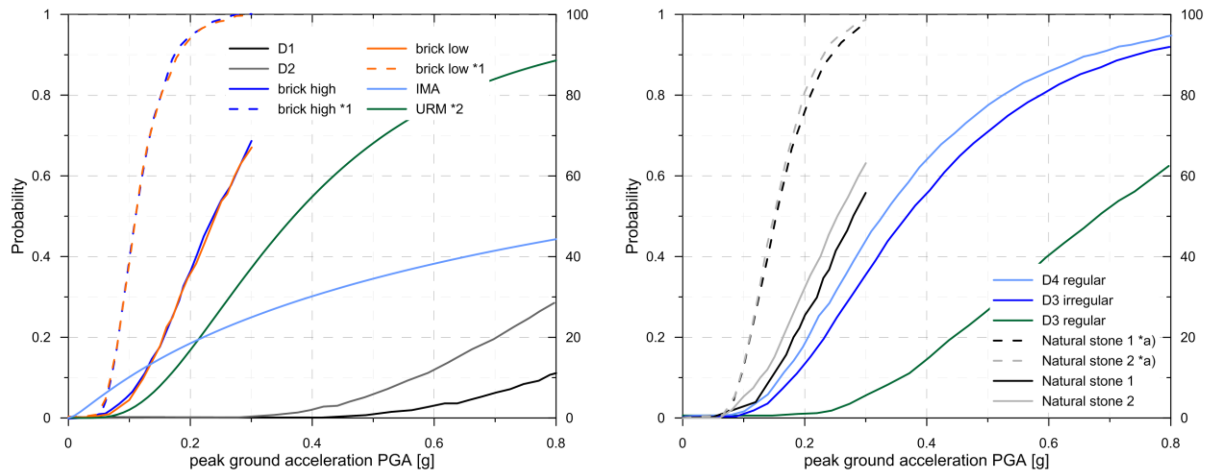
Explanation of the acronyms:

Code		Explanation	Code		Explanation
URM		Unreinforced Masonry Bearing Walls	TURM1		Weak masonry (adobe, rubble masonry)
Stone		Simple stone masonry buildings	TURM2		Brick/block unreinforced masonry with timber floors
Brick		Brick masonry buildings with sufficiently stiff floors to provide diaphragm action	TURM3		Brick/block unreinforced masonry with concrete floors
M1		Rubble stone	WM		Weak masonry (adobe, rubble, irregular stone)
M3		Simple stone	LBM		Brick, concrete block, hewn regular stone, large stone with timber or concrete or metal deck floor diaphragms
M4		Massive stone	SRM		Reinforced brick masonry, confined masonry, dual masonry wall with metal or RC frame system with timber or concrete or metal deck floor diaphragms
M5		Unreinforced masonry (old bricks)	D1	*1	Solid clay brick
M6		Unreinforced masonry – r.c. floors	D2	*1	Hollow clay brick
M7		Reinforced/ confined masonry	D3	*1	Cellular concrete block, stone or adobe (good quality)
Natural stone	1 2	Low-quality Good-quality	D4	*1	Cellular concrete block, stone or adobe (moderate and poor quality)
Bricks	1 2	with a high % of voids with a low % of voids	IMA		Masonry – irregular layout – flexible/ rigid floors – with/ without tie rods or tie beams
			RMA		Masonry –regular layout – flexible/ rigid floors – with/ without tie rods or tie beams

*1 investigate further sub-classes like regularity, code requirements

2.4. Limits of Available Fragility Functions

The comparison of the different available fragility functions for masonry buildings in Italy, Greece and Turkey mainly based on analytical investigation shows a large scatter. Figure 2 illustrates the different fragility curves for 2-story natural stone and brick masonry buildings. The partially contradicting tendencies (optimistic, pessimistic) within the curves support the demand (and inherent project concept) to put the local building stock under a complex evaluation and detailed investigation procedure. Further on and accepting the incompleteness of the comparison, these graphs indicate the advantage of the empirical approach, which finally combines all sources of information within an experience-based vulnerability assessment (see chapter 3.4.). Due to the successful application and reinterpretation of the 1995 Aigio earthquake by *Langhammer et al. 2006*, the effectiveness and robustness of such an approach using vulnerability classes of the EMS-98 could be demonstrated.



*1 – out of plane failure *2 – pre-code

*a – out of plane failure

a) Brick masonry

b) Natural stone masonry

Figure 2. Comparison of fragility functions for 2-story masonry structures (limit state: collapse and out of plane)

3. PROJECT REALIZATION

3.1. Empirical Vulnerability Assessment

On the basis of all surveyed data of the existing building stock, which were edited in several layers of a GIS format, the most likely vulnerability class has been assigned to each building. Further, the collected information allows a refinement of the intensity-based scenarios by:

- Composition of vulnerability classes for each building type, i.e. MM, MS, etc.
- Definition of an average vulnerability class for each building type (as well as optimistic and pessimistic exceptional cases)
- Distinction of building types by consideration of their layout (regularity) as well as structural peculiarities including secondary (floor construction) and tertiary classification criteria.

Simplifications of the intensity-based scenarios are possible if average vulnerability classes are determined for buildings in certain administrative units, districts or raster elements. In each case and as the major outcome of the engineering risk assessment, damage grades must be given for different scenarios. The vulnerability class is a direct indicator for the damage; e.g. higher damage will occur in an area where (averaging the individual contributions) a low level of vulnerability has been identified.
On the basis of the historical earthquake catalogue and the elaborated data layers for the city Antakya, first damage scenarios for intensity VIII, IX and X were carried out and the damage grade distribution and casualty estimations for each Mahalle area were determined. As output of the project phase I, they can be regarded as the reference results enabling a reliability check of analytically based scenarios in project phase II (Abrahamczyk *et al.*, 2012). Figure 3 illustrates, exemplarily, the damage prognosis for an intensity I (EMS) = IX earthquake, with a source under the city center of Antakya.

3.2. Analytical Vulnerability Assessment

In phase II, current methodologies and programs for the assessment of the building response are applied. The capacity curves are calculated by the use of the static nonlinear push over analysis. Representatives of the predominant and categorized building types will be considered in more detail. From local inspections and archive data search, the arrangement of structural walls within the ground plans, the openings, the floor type as well as other vulnerability affecting measures provide the basis for the creation of spatial (3D) models, which will be analyzed by different software tools.

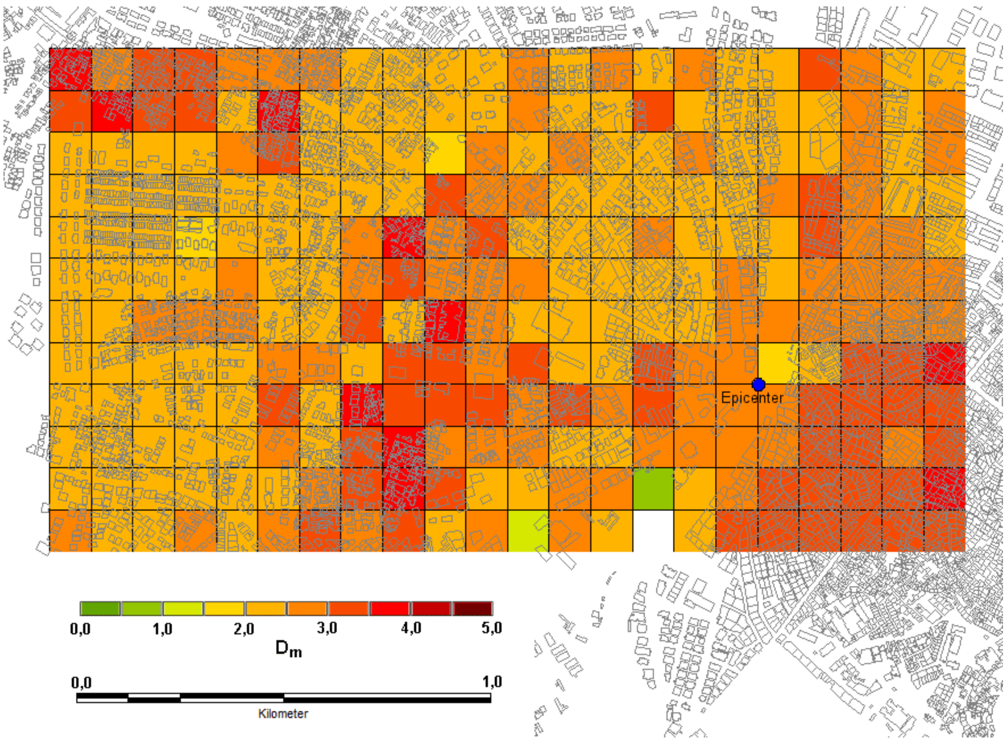


Figure 3. Mean Damage Grades in a 100m x 100m raster for earthquake scenario *I* (EMS) = IX

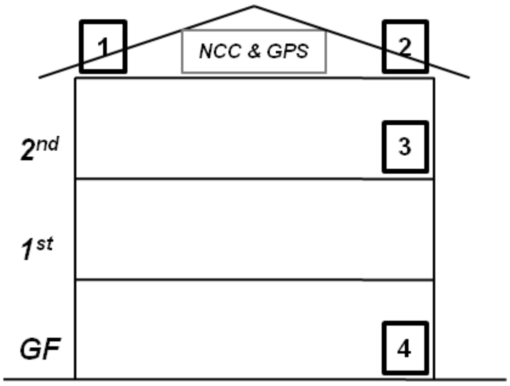
3.3. Experimental Investigation

In the framework of the project, different kinds of tests are foreseen to provide data for the analytical investigation to improve the quality of the structural models as well as the final damage prognosis. At the current state of the project, one masonry building could be already equipped and the instrumentation of another one is in progress. The first masonry building (Figure 4a) could be instrumented by four triaxial strong-motion recorders. Figure 4b indicates the applied instrumentation scheme, which follows the schemes from previous instrumentation of reinforced concrete buildings in Antakya (Abrahamczyk *et al.*, 2008). Due to limited space around the building and the use as a school, no free-field station was installed. Instead of it, one sensor could be installed on the 2nd floor in the same line of the sensor on the ground floor and roof.

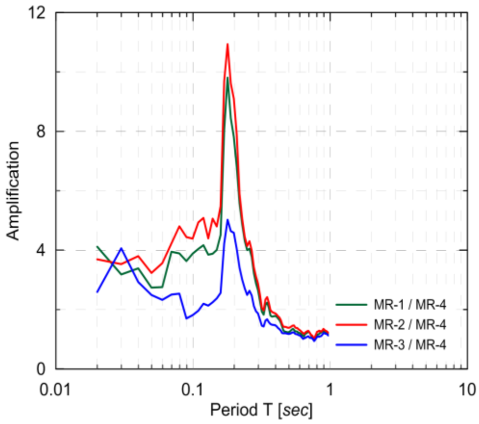
On 4th of April, 2012 a Magnitude M_L = 4.2 earthquake occurred in the vicinity of Antakya and produced amplification at the building, which exceeds the adjusted trigger-levels. It's the first measurement of the response due to an earthquake at that building after its instrumentation in October 2011. However, several other earthquakes occurred within a 200 km radius around Antakya. Most of them couldn't be measured because of the settings of the trigger-level (KOERI, 2012). The recorded ground motion and building response accelerations were analyzed by calculating the response spectra as well as the spectral relations between the top and the basement in each direction separately. Figures 4c) and d) show the spectral relations (amplification) between the two roof sensors to the basement as well as the mid-floor sensor to the basement in the X and Y axes. The distinctive peaks indicate the fundamental periods, *T*, in each direction of the building. By the measurement of further small or larger earthquakes, these first results will be validated.

These instrumental studies are accompanied by laboratory tests using the local construction techniques and materials.

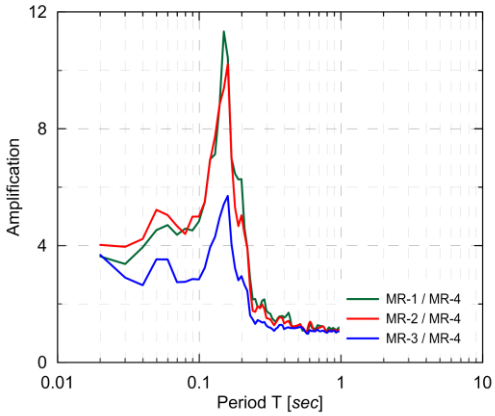
a) View of the instrumented school building



b) Applied instrumentation scheme



c) Analyzed EQ record (amplification) in x- axis



d) Analyzed EQ record (amplification) in y- axis

Figure 4. Applied Building monitoring system and response of the building to first EQ record

3.4. Experience-based Vulnerability Assessment

Next to the number of stories, the seismic behavior of masonry buildings is affected by regularity and symmetry in plan, the load bearing wall material as well as criteria on wall length and openings in walls as it could be indicated in the comparison of the available fragility functions in chapter 2.3. A building rectangular in plan (i.e. shaped like a box) is inherently stronger than a building with wings (i.e. L-shaped or U-shaped). An irregularly shaped building will twist as it shakes, which increases damage. The lateral resistance during earthquakes is provided by the load-bearing walls and is mainly affected by the placement of openings in walls as well as the material itself.
Therefore, different investigation levels will be carried out to evaluate the seismic performance of the representative masonry buildings on the basis of the experiences from past earthquakes (see Figure 5). After gathering the data from the archive of the municipality, a multi level procedure is carried out.

In Level 1, the constructive parameters are investigated on the basis of wall thickness, wall dimensions and opening structures with the purpose to evaluate these parameters and the effects on the seismic performance. Additionally, the wall shear ratio of each building is determined and compared with the requirements according to EC 8. Whereupon it has to be considered that the requirements are only valid for ground accelerations smaller than 0.15g, which is much less than the seismicity in Antakya. According to EC 8, masonry buildings would be not allowed.

Level 2 determine the impact of irregular ground plan, e.g. the increase of the demand in the individual structural walls due to effect of bi-directional eccentricities between mass and stiffness centres as well as the dynamic amplification due the coupling of translational and torsional modes.

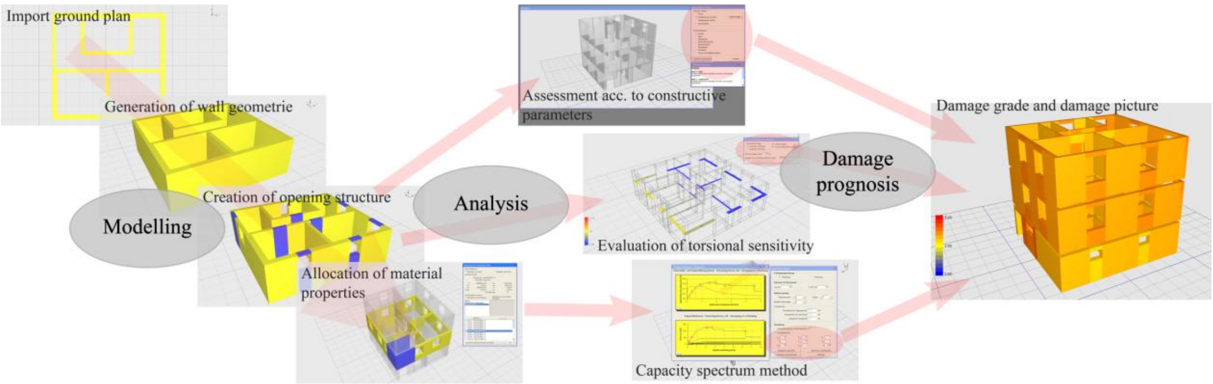
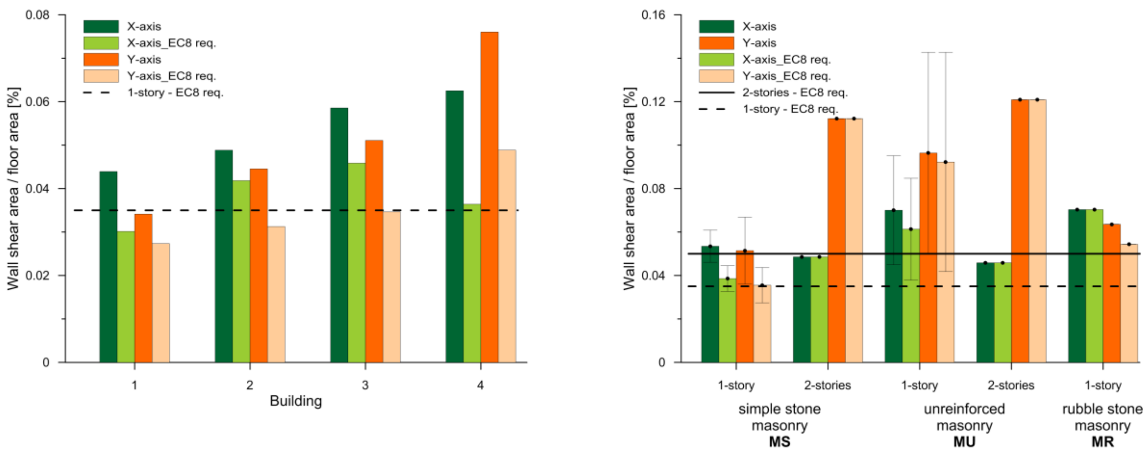


Figure 5. Evaluation and investigation levels for the damage prognosis of masonry buildings

Next to the assessment of the seismic performance; Levels 1 and 2 shall also ensure decision criteria for the transferability of the analytical and experimental investigation on single representative buildings to the whole masonry building types. In Level 3, the capacity curve is calculated by the use of the static nonlinear push over analysis. All the elaborated ground plans will be analyzed by standard software 3Muri as well as BLM software. So far not included in this multi-level approach is the special situation of attached buildings, but it shall be investigated in the next steps.
Additionally and according to the inherent aim to link the empirical and analytical approach, it is indispensable to validate all the results on the experiences after damaging earthquakes. Therefore, it is foreseen to use available damage statistics from Turkey and Germany to provide a data basis for the cross correlation of the applied and developed methods.

5. OUTLOOK

The building stock of the mid-size town Antakya in south Turkey has been elaborated within the SERAMAR project leading also to a first level database for a more refined consideration of the masonry buildings. As it can be concluded from a series of comparative studies, models and vulnerability related functions of similar studies cannot be adopted directly. Because of their high vulnerability and the inherent heterogeneity due to the historical process of modifications and period-depending use of locally available material, it was decided to develop a new building typology, which should be supported by a complex evaluation and detailed investigation procedure.



a) Sample of simple stone masonry (MS) buildings

b) Comparison of Building types

Figure 6. Comparison of shear wall ratio for major building classes with EC8 requirements for <0.15g

In the frame of the project, a masonry school building could be instrumented by a strong-motion building monitoring system and results from the first EQ-record are presented. The main focus of the next step will be to establish a reliable link between the analytical and empirical as well as experienced based approaches. Therefore, further ground plans will be analyzed and calculated with common programs. After the successful installation of the building monitoring systems and the recording of the response during an earthquake, the data will be used to calibrate and validate the analytical models.

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Maps are created with the program Mapinfo© Professional 9.0.

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