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VULNERABILITY ASSESSMENT OF LARGE BUILDING STOCKS – LESSONS FROM THE SERAMAR PROJECT

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Abstract

The description of building vulnerability and resultant derived damage prognoses for different impact levels are the key element for any seismic risk study. In cases where realistic, detailed and reliable risk scenarios should support socioeconomic decisions and mitigation strategies, the entire building stock has to be considered, and a broad database is required to allocate empirical vulnerability and/ or analytical fragility functions for the damage assessment. The engineer-assigned (most probable) vulnerability, performance score or building type specific fragility function have to consider the uncertainty in building response characteristic and the particularities of the local construction practice.

As an outcome of a Turkish-German joint research project on *Seismic Risk Assessment and Mitigation in the Antakya-Maraş-Region (SERAMAR)* different methods and strategies for the vulnerability assessment of a large building stock could be developed, applied and finally compared. Within the SERAMAR project it was decided to carry out a complete building stock survey and a systematic elaboration of a *building typology* including masonry and R.C. type structures. The whole building stock is classified on the basis of parameters relevant to the seismic performance, e.g. criteria of structural layout irregularity as well as structural peculiarities, which could yield to specific damage patterns. The locations of these sub-classes are mapped using a GIS-tool together with the elaborated hazard parameters and risk data layers.

The definition of building types requires the abstraction and reduction of the building characteristics (which is often hidden by the facade) to the basic structural system and the failure and damage-determining criteria under seismic impact. The defined building types and their allocated vulnerability classes have to anticipate comparable damage pattern under comparable shaking intensities.

In this paper the derived building typologies for reinforced concrete structures as well as masonry buildings of the building stock of the study area Antakya will be presented. Similarities and differences of the existing building typologies are discussed. Results of the empirical, analytical and hybrid vulnerability assessment methods will be compared. Not at least, the outcome of instrumental testing and building monitoring is reviewed concerning the refinement and scaling of analytically derived fragility functions.

Keywords: vulnerability assessment, building typologies, taxonomy, building stock survey, building monitoring

1. Introduction

Any reliable seismic risk assessment of large building stocks is in need of a systematic description of building vulnerabilities and resultant derived damage prognoses for different impact levels. Especially for the support of socioeconomic decisions and mitigation strategies, the entire building stock has to be considered. Therefore, a broad database is required to allocate empirical vulnerability and/ or analytical fragility functions for the damage assessment. Not at least, the uncertainty in building response characteristic and the particularities of the local construction practice have to be addressed.

The building stock of the mid-size town Antakya in south Turkey has been elaborated within the research project *Seismic Risk Assessment and Mitigation in the Antakya-Maraş-Region (SERAMAR)* leading also to a high quality database for a more refined consideration of the reinforced concrete (RC) and masonry buildings. The whole building stock was surveyed and classified into a regional building typology.

The paper presents a comprehensive and hybrid approach to determine representative fragility functions for the predominant building types. Representatives of the identified RC and masonry building types were instrumentally investigated to provide input parameter for the calibration and verification of reliable structural models. The analytically derived results allow the comparison with available empirical data (observations) due to the similar description of damage in terms of EMS-98 damage grades.

2. The SERAMAR project

In close collaboration with local partners, Earthquake Damage Analysis Center (EDAC) at Bauhaus-Universität Weimar initiated a Turkish-German joint research project on ***Se**ismic **R**isk **A**ssessment and **M**itigation in the **A**ntakya-Maraş-**R**egion* (***SERAMAR***) [1].

The ancient city of Antakya lies in the southernmost tip of Turkey, and is currently built on an alluvial plain through which the river Asi flows (see Figure 1). The city, founded in 300 BC, has been an important confluence of states, faiths and peoples from its earliest times. As with many other urban settlements in Turkey, Antakya has experienced a rapid expansion during the last several decades, with many vulnerable buildings added to its stock.

The objective of this study is to utilize current tools for earthquake risk mitigation within an environment where research entities from the European Research Area, local universities in Turkey and professional associations as well as local governments are able to establish a unique partnership that would serve as a model for similar future endeavors.

Within the different project phases, the region's specific earthquake hazard, the vulnerability of the city's building stock based on the European Macroseismic Scale EMS-98 [2], and the social vulnerability and resilience to earthquake disasters at different levels of society are identified and elaborated (see also http://seramar.edac.biz).

Fig. 1 – Panorama photo from the building stock in Antakya (indicating the predominance of RC frame type structures in the City area)

3. Building Taxonomy

3.1 Building Stock Survey

Any systematic elaboration of a *building typology for risk assessment* starts and fails with the level and quality of the building survey. In general, statistical data being relevant for an engineering evaluation of the buildings' vulnerability are not available. In some cases, information about the age (construction period), the number of stories or – if the archives offer such documentation – rehabilitation measures can be derived and transformed into GIS-layers (GIS-Graphical Information System).

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

Based on the experience from different risk studies in Central and Southern Europe and from the reinterpretation of recent damaging earthquakes (see [3, 4]) all project partners agreed and decided to carry out a complete building stock survey recognizing the fact an extensive effort would be required at the beginning of the SERAMAR project. The buildings of the whole building stock were classified on the basis of different parameters relevant to their seismic performance within a multi-step procedure.

Step 1: Rapid screening – identification construction types and their structural systems

In preparation for the building stock survey the cadastral map of the target city Antakya was processed. After a first rapid screening of the urban areas and a photo documentation of representative buildings, a preliminary classification of the construction types was assembled. On this basis and according to the European Macroseismic Scale 1998 (EMS-98) [2] data entry forms were prepared for the dominant building types as well as evaluation tools - not at least to recognize design defects and their impact on the appropriate vulnerability class [5] (see 5.1. below for details).

Step 2: Comprehensive survey and assignment of most probable vulnerability classes according to the EMS-98

The buildings were classified on the basis of different parameters related 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. This concerns, for example, criteria of layout irregularity as well as structural peculiarities which could lead to specific (critical) 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). Starting from the historical city center, the entire city with around 22,000 buildings was investigated [6].

Step 3: Evaluation of the structural characteristics and sub-classification of the predominant building types

On the basis of the collected data, the predominant building types with respect to their use (commercial, private etc.), the number of stories and particular design aspects (soft stories, cantilevering floor slabs, etc.) could be identified. As expected, RC buildings are the predominant building type of Antakya with a portion of 67% of the entire building stock (Figure 2a). Due to the high percentage of RC buildings, a more detailed investigation of the RC building stock and its vulnerability was carried. On the basis of a further sub-classification, representatives of each building type are selected for analytical studies of 2D and 3D models [5] (see 3.2 below).

Due to the inhomogeneous characteristics of masonry structures, the developed building typology for the RC structures (see [7]) cannot be directly adopted because of the insufficient consideration of all seismic performance affecting parameters (see 3.3 below).

Step 4: Detailed survey

Among a total of 6,494 masonry buildings, 265 buildings were pre-selected in such a way that this small-sized population represents the general characteristics of the whole inventory.

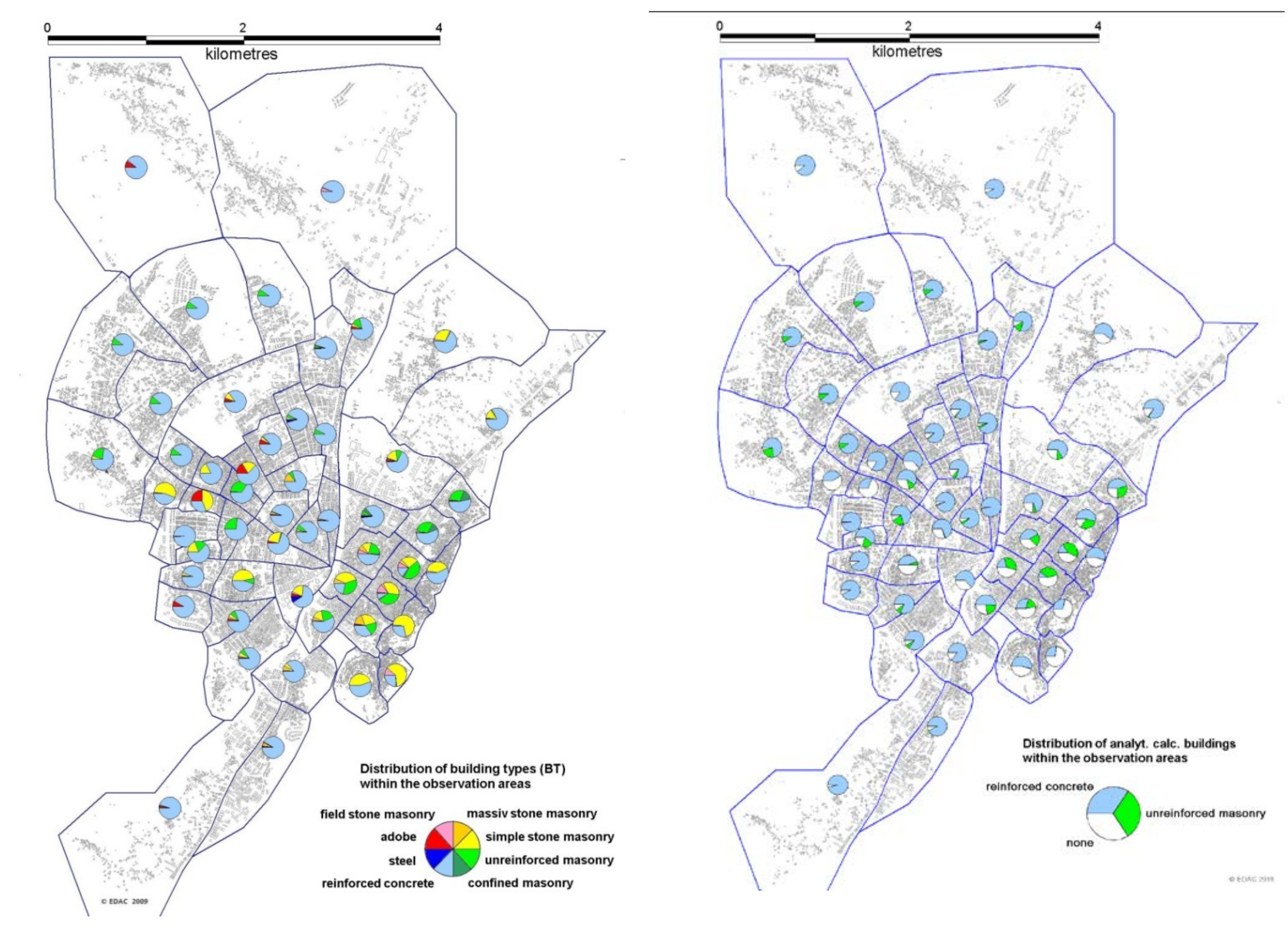
The selected buildings were inspected from the street and the properties of the inspected buildings were docemented in the survey forms. In the second phase of the study, attributes and parameters obtained by the survey were transformed into a database. This statistical information enables the quantification of local characteristics of the unreinforced masonry buildings and their corresponding vulnerabilities (see 3.3 below).

Step 5: Selection of representative buildings for analytical and instrumental investigation

A complete analytical evaluation of a building stock is generally not possible. Therefore, it is necessary to identify structures which are representative for the different assigned building types. On the basis of the derived building taxonomy several representative buildings for the building stock in Antakya could be identified to carry out instrumental and analytical investigation [8] (see 4. below).

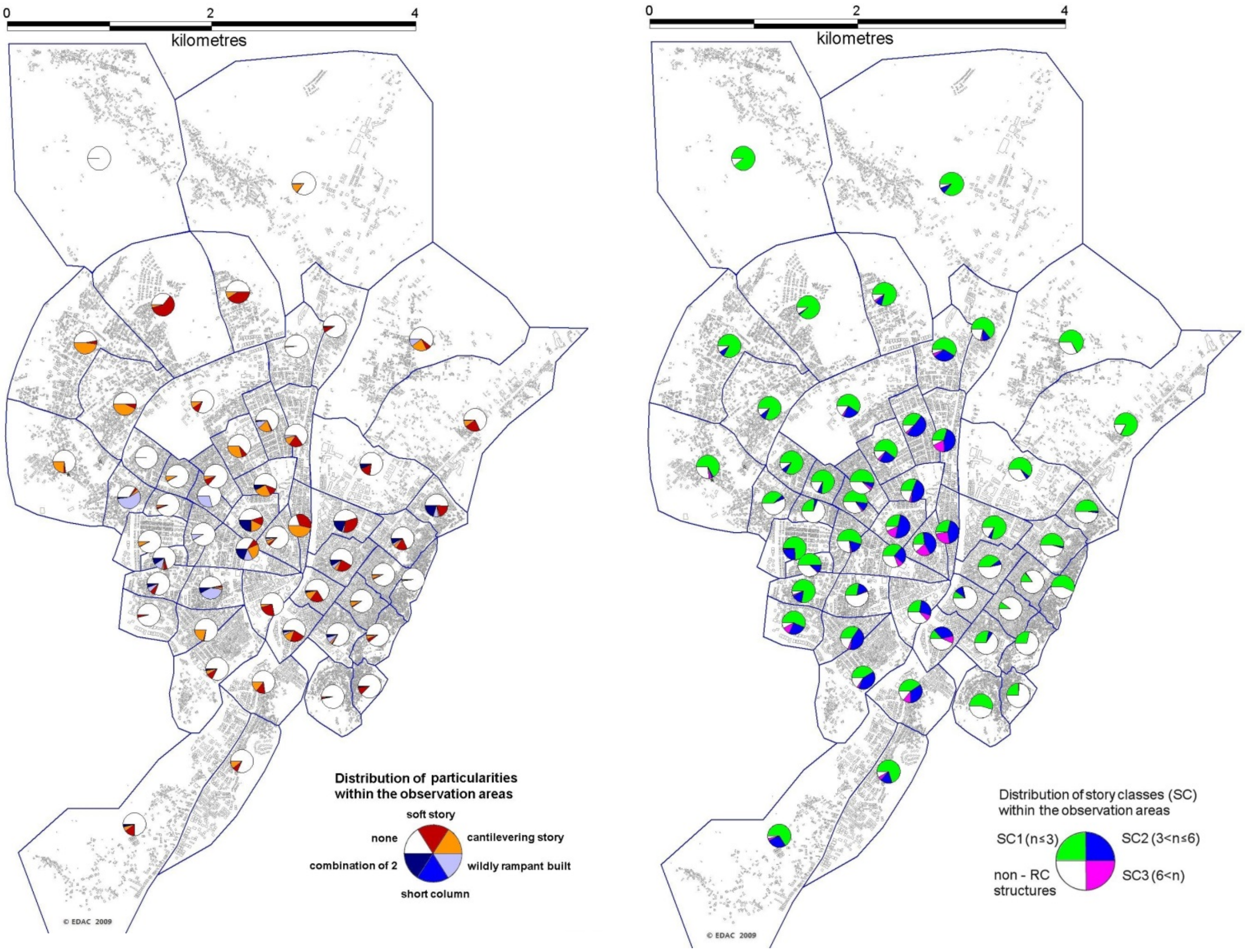
The innovative core of the applied approach is directed to the combination of low budget instrumental testing with analytical studies to carry out reliable and realistic damage prognosis for representative buildings of a specific building stock. Basic elements are the analytical assignment of the different damage grades on the basis of the material stress-strain-relationships and the numerical calibration of the structural models on the basis of the instrumentally gained dynamic response characteristics of the investigated buildings. Finally, fragility functions can be derived using the site-specific ground motion and representative earthquake records [8].

Figure 2b shows the so far covered building stock by the numerical and instrumental studies on representatives from the different building types.



a) Building types b) Building stock covered by representatives

Fig. 2 – Composition and distribution of the building types and the so far covered building stock



a) Vulnerability affecting structural peculiarities b) Story classes (SC) for R.C. buildings

Fig. 3 – Distribution of building types in Antakya

3.2 Reinforced Concrete Structures

While the steps 1 and 2 are related to the empirical, intensity-based approach of seismic risk assessment, any reliable analytical (ground motion based) approach requires a further sub-classification of the predominant building types and the identification of their representatives [7].

The characterization of building types for analytical investigations requires that single objects preferably represent a large number of buildings of the same group/category. The advantage of the investigation area Antakya consists in the fact that a major portion of the building stock are Reinforced Concrete (RC) frame type structures which can be analytically investigated to predict building damage.

The definition of building types requires the abstraction and reduction of the building characteristics (which is often hidden by the external appearance) to the failure and damage-determining criteria of the structural system under seismic impact. This means, the defined building types have to distinguish the most likely or probable vulnerability classes of the existing buildings and to anticipate comparable damage pattern under comparable seismic impact or scenario events.

RC frame structures are further classified according to an encoding-like order: RC-Use-VCP-SCi(n); Use=PB/CB (Private/Commercial Buildings); VCP=vulnerability affecting parameter with: BT=basic type without major damage-enforcing particularities, SS=soft story, CUS=cantilevering beams/floor slabs combined with soft story, and WRB="wildly"(rampantly) built; SCi=story class i (i=1 to 3); n=number of stories. Vulnerability affecting parameters (VCP) are related to design or construction defects (and their combined occurrence). Special attention is given to the "pseudo-regularity" as a synonym for the often from outside not visible, often quite irregular raster and arrangement of (internal) structural elements which could lead to an uncertain transmission and flow of the seismically induced forces.

3.3 Masonry Buildings

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 (Figure 2). 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.

In preparation of the first ground plans for the analytical investigation, a much more refined building typology had to be developed. 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 masonry building types 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 [9, 21].

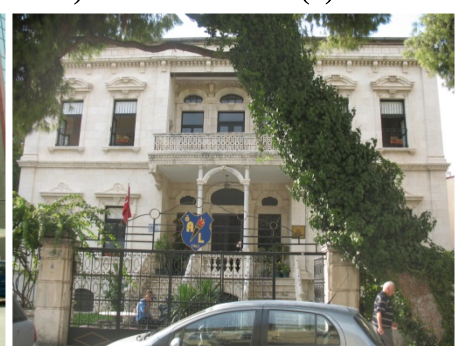
a) RC-PB-BT-SC1(2)

b) RC-PB-BT-SC2(5)

c) RC-PB-BT-SC3(7)

d) MU1RC

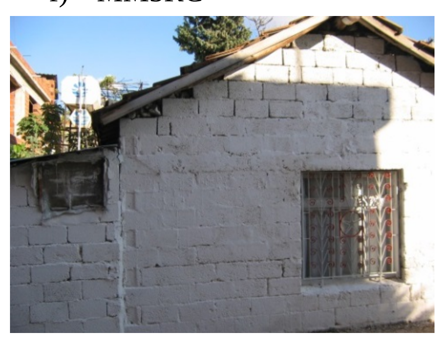
e) MU4RC



f) MM3RC

g) MS2W

h) MR1W

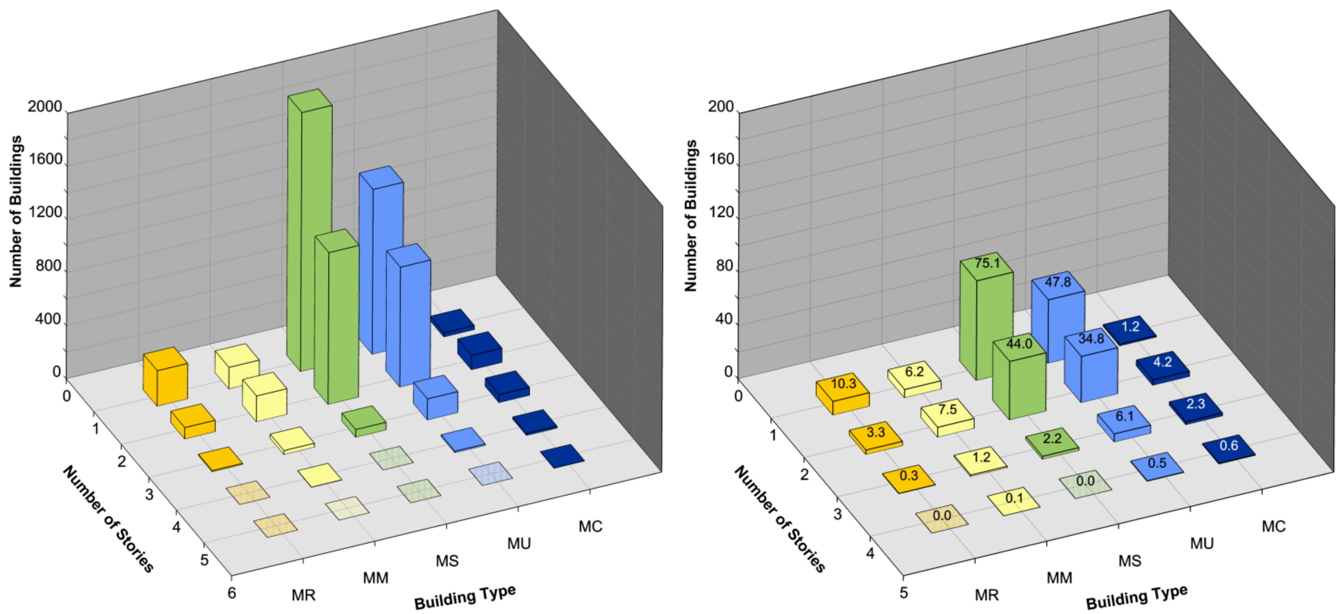


i) MU1W

Fig. 4 – Examples of the masonry and Reinforced Concrete (RC) building types in Antakya

On the basis of the results from the general inspection (Figure 5a) a feasible number of masonry buildings is selected for a second survey to carry out detailed inspection, using the percentage distributions as criteria for the definition of the number of buildings per type (Figure 5b). Starting with an “external view” of the buildings and their primary structural system, the detailed survey (Step 4) 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 between 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.

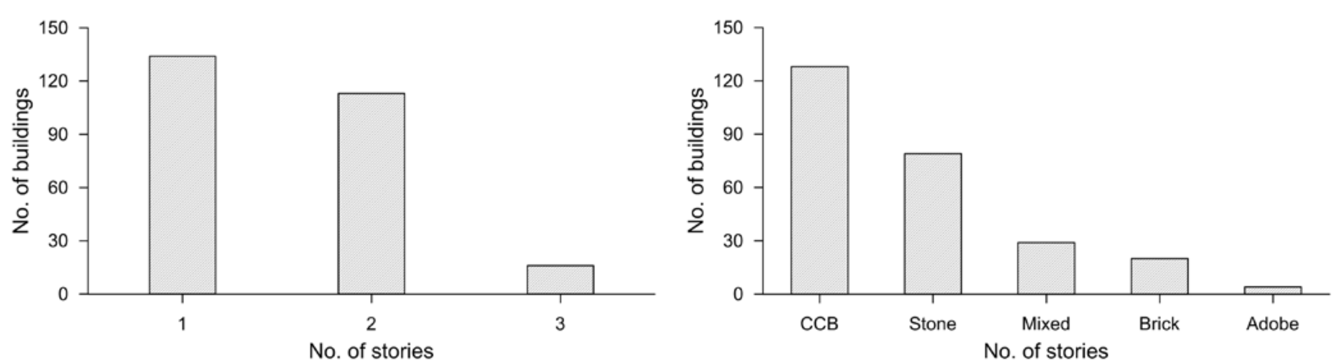
Most of the surveyed masonry buildings are located within the old City. According to the statistical data, majority of the surveyed buildings has either one or two stories (Figure 6a). It is also observed that the most commonly used load-bearing wall elements are cellular concrete block (CCB) and stone (Figure 6b). According to the current Turkish earthquake code (2007), concrete blocks with holes should not be used as load-bearing wall material since they have very low strength. (Unfortunately, this is not the case in practice [10].)



a) Discretization of the masonry buildings b) Number of buildings for detailed inspection

Fig. 5 – Composition of building types in Antakya on the basis of the general inspection

[MR ... adobe & timber MM ... massive stone masonry MS ... simple stone masonry
MU ... unreinforced masonry MC ... RC-confined masonry]



a) Number of stories b) Load-bearing wall type

Fig. 6 – Statistical distribution of post surveyed buildings in Antakya

4. Building monitoring and instrumental testing

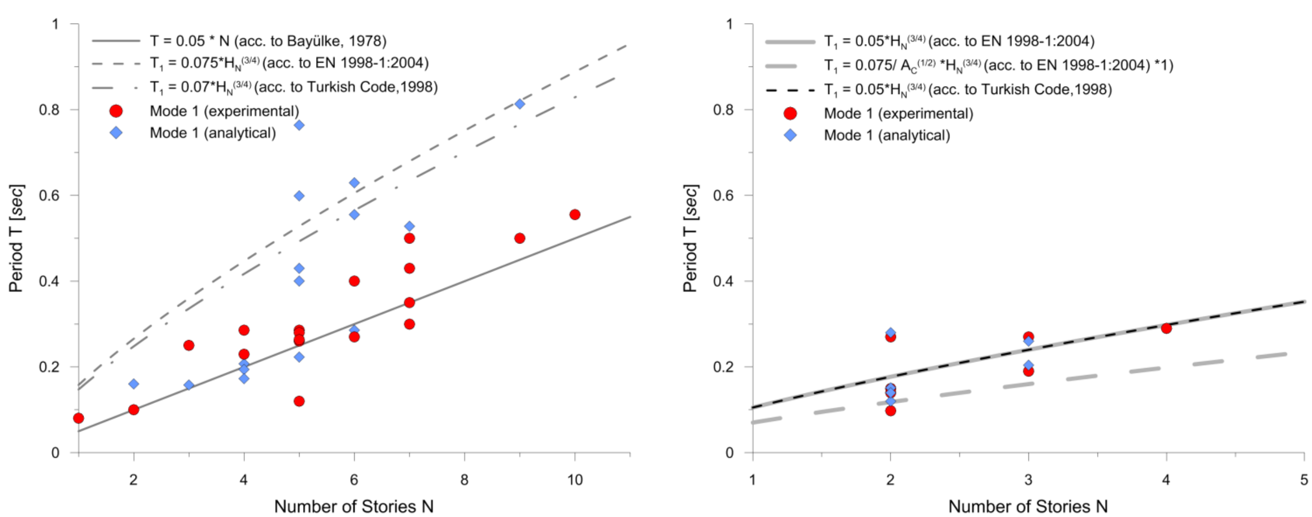
Similar for the masonry and reinforced concrete building types a specific scheme of ranking criteria is used to identify representative buildings. Depending on the availability of the basic information describing the structural layout, buildings are selected for a multi-tasking in-situ instrumental testing 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 instrumentations 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 [5, 8]. Table 1 shows examples of instrumentally investigated buildings for Reinforced Concrete and masonry building types.

Four Reinforced Concrete and two masonry buildings could be permanently instrumented with strong-motion recorders following an efficient instrumentation scheme [5, 11, 12]. Additionally, 25 residential R.C. and 7 masonry buildings with different number of stories could be temporarily tested (see examples in Table 1). Each building was equipped with five or six triaxial velocity sensors Type MS2004+ and the corresponding recorder Type MR2002 (Syscom Inc.).

The sensors were oriented along the main axis of each building. In general, two sensors were installed in two opposite corners on the roof, and two sensors in the same corners on a mid-floor story. The fifth sensor was installed in the middle of the ground floor or basement if available. If six sensors were available, some special aspects could be investigated, e.g. the difference between the response of basement and ground floor when the ground floor is stiffened by staircases or ramps. The elastically building response was determined on the basis of either ambient vibration or forced vibration measurements [5].

Figure 7 shows the fundamental mode periods of instrumentally investigated representative reinforced concrete and masonry buildings in Antakya with respect to the number of stories.

In the frame of the project different kinds of dynamic response data could be gathered depending on the type of instrumental investigation. So far several small earthquakes have been recorded at the permanent instrumented buildings, which happened near Antakya during the last six years. Only non-damaging earthquakes occurred so far; therefore, response measurements for the nonlinear behavior of the structure are still missing.



a) Reinforced Concrete (RC) structures b) Masonry structures [*1) Note: $A_c = 5m^2$]

Fig. 7 – Fundamental mode period of instrumentally investigated representative buildings in Antakya

5. Vulnerability Assessment of Large Building Stocks

5.1 Empirical approach: Vulnerability classes according to EMS-98

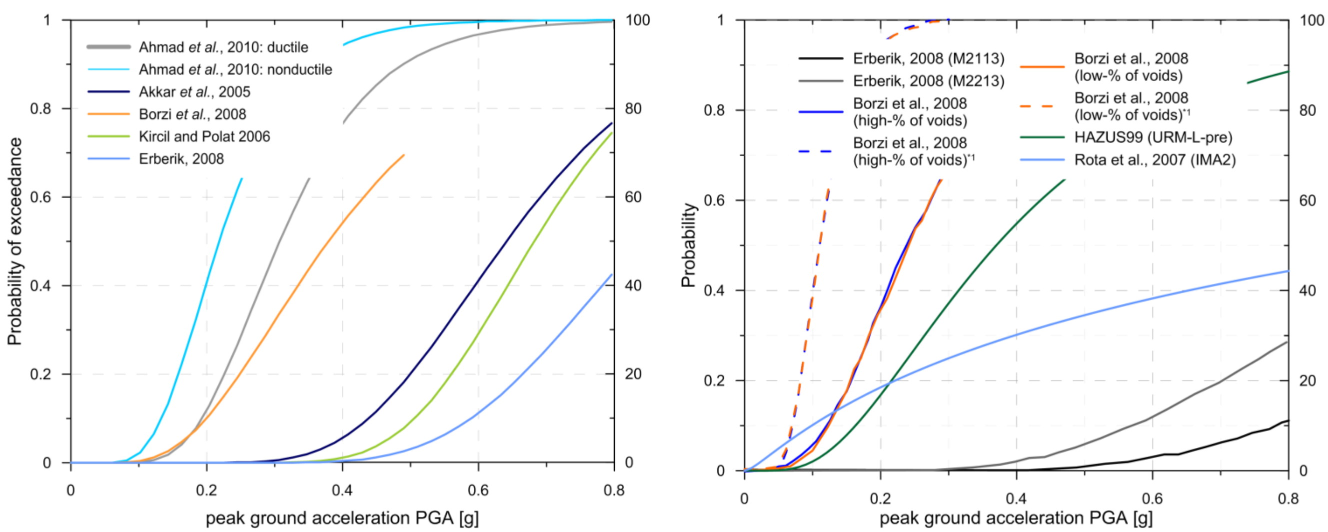
It is one of the inherent advantages of the European Macroseismic Scale 1998 (EMS-98) that for the diversity of building types and structural realizations very stringent rules for their substitution in terms of vulnerability classes are given. The EMS-98 provides a robust and simple method of vulnerability classification, which is directly linked with the damage observations [13, 14]. For each vulnerability class a description of the probable quality (damage grades) and extent (quantity of their occurrence) in dependence on the level of shaking is given.

The elaborated data entry forms distinguish between the main building types and include practical guidance to select the most probable vulnerability class. Collected damage statistics from a number of Task Force (reconnaissance team) missions (field surveys) are used to assign ranges of vulnerability classes. Particular symbols are introduced for the most likely vulnerability classes, the probable range and the range of less probable, exceptional cases. The user decides the appropriate class by considering and evaluating the factors that affect vulnerability (building structure and material, regularity, particular aspects in the ground and elevation plan, quality of workmanship and maintenance) and upon the level of Earthquake Resistant Design (ERD) in the case of engineered structures. Therefore, the building typology for empirical (intensity-based) risk assessment is limited to the assigned Vulnerability Classes (VC), ranging from A to F. Transition classes (e.g. AB, BC etc.) are explicitly allowed [2, 6].

5.2 Analytical approach: Application and development of fragility functions

Scenarios provide the basis for the evaluation of a whole building stock under different seismic action; for this purpose damage grades or loss values of the buildings have to be determined. Commonly these values are assigned on the basis of global building parameters; i.e.fragility functions are requested for the different building types and story classes. Figure 8 shows examples of available fragility functions for (a) five-story (SC 2) Reinforced Concrete (RC) frame structures with masonry infill walls and (b) two-story brick masonry structures.

The comparison of the fragility functions indicates a large scatter for masonry and reinforced concrete 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.



a) Five-story Reinforced Concrete (RC) structures   b) Two-story brick masonry structures

Fig. 8 – Comparison of available fragility functions proposed for RC and masonry building types for the limit state of collapse (including *1out-off-plane failure mechanism)

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 5.1). The effectiveness and robustness of such an approach using vulnerability classes could be demonstrated by the application of the EMS-98 to the 1995 Aigio earthquake, and the successful reinterpretaion of damage distribution [3].

The comparison of the propsed (not allways applicable) fragility functions indicates the need of an adjustment to the existing building stock to come up with reliable damage scenarios. It also shows that the quality of any analytical damage scenario will be mainly influenced by the selection of the fragility functions and adaption of the fragility functions to the local building typology. For the risk assessment of a building stock different aspects are of importance: the validity of the fragility functions; the number of subtypes, and the reduction of the uncertainty of the action/impact influencing parameters (e.g. soil characterisitics, topography).

5.3 Comparative damage scenarios

In different phases of the Turkish–German joint research SERAMAR project, the seismic risk and the vulnerability of the building stock were determined based on the EMS-98 and a building stock survey [Schwarz *et al.*, 2008]. First empirical-based risk studies are presented at the Workshop "Findings of the SERAMAR project" [http://seramar.edac.biz → Workshop 2010] and were published in [6].

The empirical risk studies are compared with different analytical risk scenarios for reinforced concrete buildings on the basis of fragility functions from different authors to check the quality and reliability of the risk scenarios. Different fragility functions are applied to determine the Mean Damage Grade (D_m) of each building type and to compare them with the results of the empirical vulnerability class approach (Figure 9). Whereas the Mean Damage Grade is the sum of the probability of each damage grade multiplied with a damage factor [16]. For each set of fragility functions, the probability of each damage grade could be derived for the different building types (e.g. basis type BT in case of RC structures), for the different story classes and for the year of construction. In Figure 9, the Mean Damage Grades of empirical risk scenarios for Intensity *I* (EMS) = IX and a most likely vulnerability assignment are compared with the results of analytical risk scenarios referring to results for a Peak Ground Accelerations (PGA) of 0.2 g and 0.4 g.

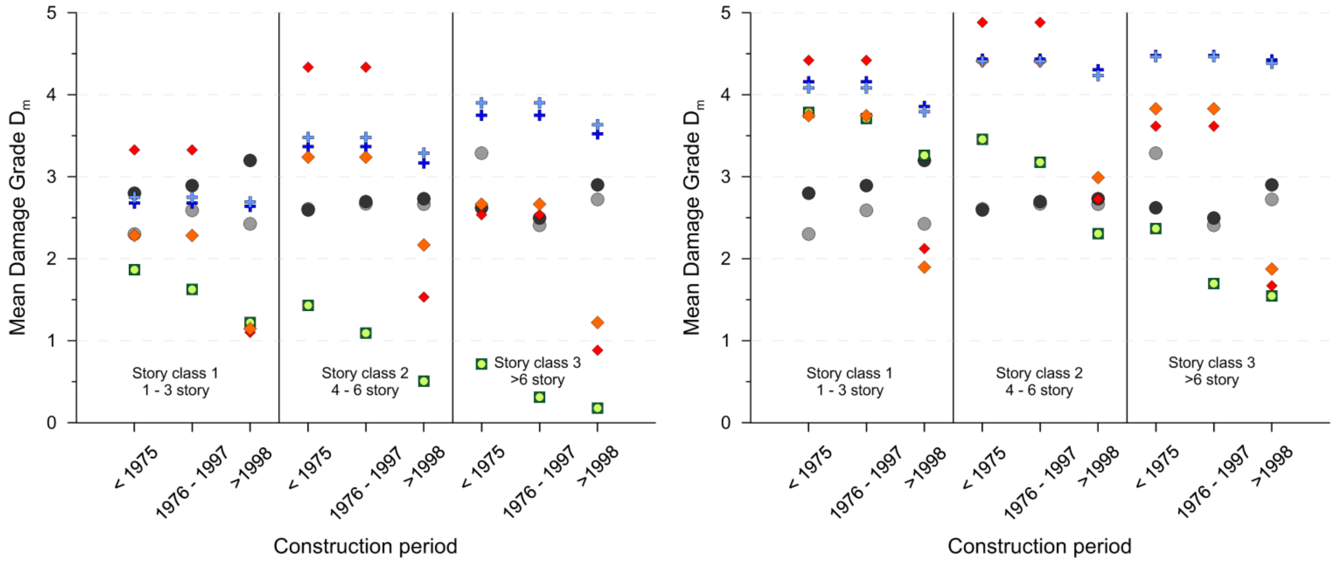
The comparison shows the still missing and plausible consistency between the outcome of the both (empirical and analytical) approaches. Additionally, surprising results can be observed with respect to the story classes and the assumed level of Peak Ground Acceleration. Nearly all of the applied fragility functions lead to a quite pessimistic damage prognosis, which is in contradiction to the protection level of the national seismic building code. Less damage should be especially expected for buildings constructed after 1999.

6. Conclusions

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 reinforced concrete and masonry buildings. As it can be concluded from a series of conducted 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 is supported by a complex evaluation and detailed investigation procedure.

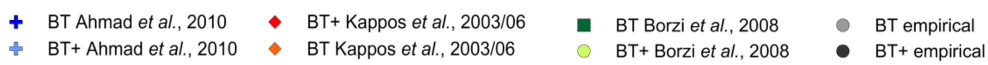
The SERAMAR project highlighted the need of complete building stock survey as the primary basis for reliable risk scenarios. Different parameters have to be surevey for Reinforced Concrete structures and masonry buildings in case of the elaboration of anayltical risk studies and the application of existing fragility functions. The comparision of empirical and analytical approaches for the vulnerability assessment of a large building stock has shown the existing problems and the missing consistency within damage prognosis.

Within ongoing refinement studies, already instrumentally investigated building types will be studied and analyzed to determine a set of fragility functions representative for the study area Antakya and to carry out seismic risk scenarios on the basis of the analytical determined vulnerabilities.



a) *I* (EMS)= IX (*most likely*); PGA = 0.2g b) *I* (EMS) = IX (*most likely*); PGA = 0.4g

Fig. 9 – Comparison of the empirical and analytical Mean Damage Grade for different story classes and construction years for Intensity *I* = IX and two different PGA values (0.2g and 0.4g) [15]



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