Qualification of seismic risk studies on the basis of instrumentally verified vulnerability functions for R.C. Building types

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QUALIFICATION OF SEISMIC RISK STUDIES ON THE BASIS OF INSTRUMENTALLY VERIFIED VULNERABILITY FUNCTIONS FOR R.C. BUILDING TYPES

L. Abrahamczyk[1] , J. Schwarz[2] and M.C. Genes[3]

ABSTRACT

Realistic and reliable risk scenarios for master plan need a broad database to allocate empirical vulnerability and/ or analytical fragility functions for the damage assessment. In any case the engineer-assigned (most probable) vulnerability or building type specific fragility function have to consider the uncertainty in building response characteristic and the particularities of the local construction practice. The comparison of available fragility functions shows the demand on vulnerability (fragility) functions which appropriately represent the behavior of the building types being representative for the target area. The distinction of the building stock into building types is emphasized as an essential step before the suitable fragility function of for the risk study can be selected. In this paper the applied building typology to the building stock of the study area Antakya will be presented. An engineering advanced concept for the determination of realistic fragility function proposed combining instrumental and analytical studied by a hybrid approach. In the focus of the proposed concept is the quantification of the numerical models on the basis of a low budget instrumental investigation as well as the consolidated allocation of damages on the basis of deformation states of the individual elements.

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Realistic and reliable risk scenarios for master plan need a broad database to allocate empirical vulnerability and/ or analytical fragility functions for the damage assessment. In any case the engineer-assigned (most probable) vulnerability or building type specific fragility function have to consider the uncertainty in building response characteristic and the particularities of the local construction practice. The comparison of available fragility functions shows the demand on vulnerability (fragility) functions which appropriately represent the behavior of the building types being representative for the target area. The distinction of the building stock into building types is emphasized as an essential step before the suitable fragility function of for the risk study can be selected. In this paper the applied building typology to the building stock of the study area Antakya will be presented. An engineering advanced concept for the determination of realistic fragility function proposed combining instrumental and analytical studied by a hybrid approach. In the focus of the proposed concept is the quantification of the numerical models on the basis of a low budget instrumental investigation as well as the consolidated allocation of damages on the basis of deformation states of the individual elements.

Introduction

Motivation and General Problems

The description of building vulnerability and resultant derived damage prognoses for different impact levels are the key element for seismic risk studies, especially in the case of the assessment of a whole building stock. Building type specific vulnerability functions are commonly used for the damage assessment under consideration of the different scatters from the impact (action) and building (resistance) sides. Thus, there is a demand on vulnerability (fragility) functions, which appropriately represent the behavior of the relevant building types. The determination of such vulnerability functions can be achieved individually or in combination of empirical, analytical, and/ or instrumental data.

The inherent idea of the proposed analytical concept is the aim to determine damage patterns on the basis of realistic analysis on structural models and to convert them into building type specific vulnerability (fragility) functions. Therefore the method which has to be applied has

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to describe the different deformation states of each element accurate enough at each level of impact. The damage grade can be determined analytically if a realistic correlation between the damage grades and deformation states can be established. Hence the quality of the results depends strongly on the quality of the structural model, the ability of the model to express the real building behavior as well as the reliability of the relationship between deformation and damage. Key elements of the proposed concept are the validation of numerical models on the basis of a (low budget) instrumental investigation and consolidated allocation of global damage grades on the basis of deformation states of the individual structural elements.

In the paper the principle aspects of the concept will be presented and discussed on the example of the building stock of the city Antakya (Turkey) with focus on the reinforced concrete (R.C.) structures. Four R.C. buildings could be permanently equipped with a Building Monitoring System (BMS) using different instrumentation schemes. In addition, temporary measurements were carried out in about 25 multi-story buildings to identify the building response under ambient vibration. These results are taken as input information and scaling parameters to calibrate and validate the numerical models for a more refined non-linear analysis.

Fragility functions are presented for R.C. frame structures distinguishing between three Story Classes (SC) and irregularity indicators. Using the concept of damage grades as introduced in EMS-98 [8], damage causing peak ground accelerations are determined for different seismic action types and ground conditions. The derived fragility functions are compared with functions for R.C. buildings, being currently published.

Risk Project in southern Turkey (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 Seismic Risk Assessment and Mitigation in the Antakya-Maras-Region – SERAMAR (see Fig. 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. 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.

Within the different project phases the region’s specific earthquake hazard, the vulnerability of the city’s building stock based on the EMS-98 principles [8], and the social vulnerability and societal vigorousness to earthquake disasters at different levels of society are identified and elaborated (see also http://seramar.edac.biz).

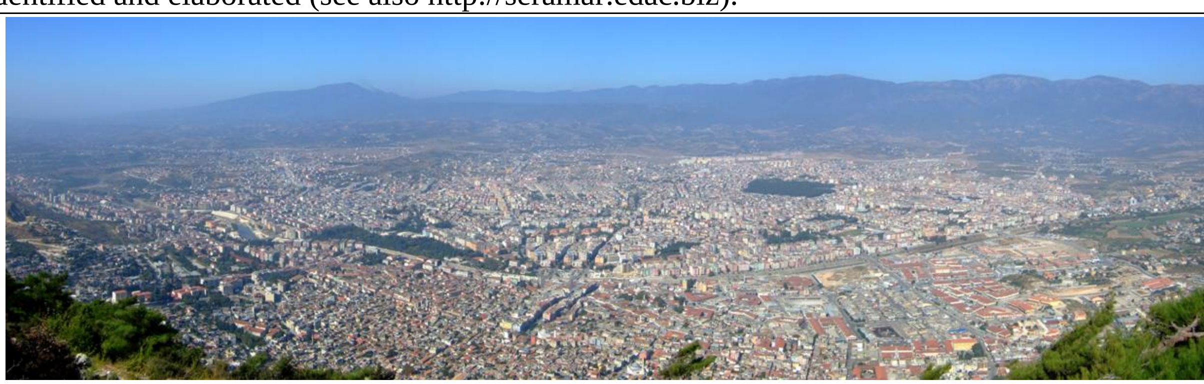


Figure 1. Panoramic view over the study area: Antakya.

Building type classification for seismic instrumentation

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, because 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 – undertaken rehabilitation measures can be derived and transformed into GIS-layers (GIS-Geographical Information System).

The buildings of the whole building stock are 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. This concerns e.g. criteria of layout irregularity as well as structural peculiarities, which could yield to special damage patterns. Their distribution and location in the study area are mapped using a GIS-tool together with the elaborated hazard parameters and risk data layers (i.e. subsoil conditions, topography) [1].

Building Typology

The definition of building types requires the abstraction and reduction of the building characteristics (which is often hidden by the externally appearance) to the basic structural system and the failure and damage-determining criteria under seismic impact. The defined building types have to differentiate the preliminary assigned vulnerability classes of the existing buildings and to anticipate comparable damage pattern under comparable seismic impact.

The characterization for analytical investigations requires that single objects preferably represent a large number of buildings. It is an advantage of the investigation area Antakya that the major part of the building stock can be traced back on R.C. frame type structures which can be analytically investigated to come up with reliable damage prognosis. Around 70 % of Antakya's building stock consists of reinforced concrete structures, leading to the decision to sub-classify these structures into different story classes (SCi). Fig. 2a shows the distribution of story classes for R.C. structures. Three story classes are defined: SC1 ($n \leq 3$), SC2 ($3 < n \leq 6$) and SC3 ($n > 6$); n – number of stories.

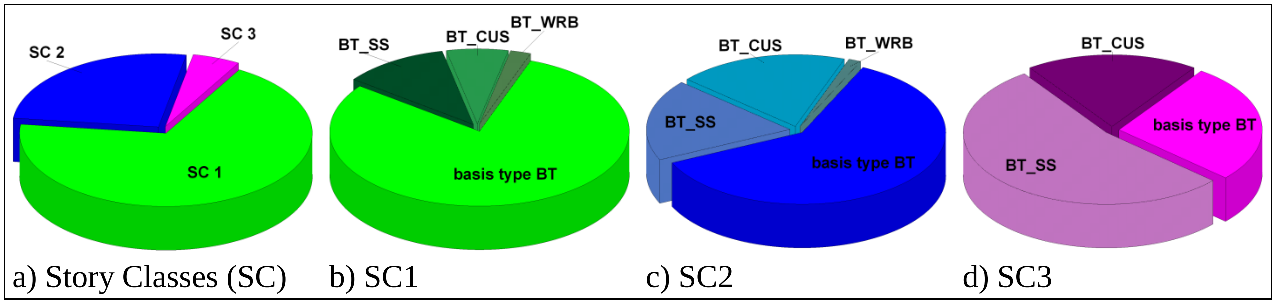


Figure 2. Composition of R.C. building types in Antakya.

In addition to the building type and number of stories, further criteria were investigated in order to derive a more detailed typology as well as vulnerability assessment with regard to the post-processing. For this purpose, criteria of structural irregularity in layout as well as structural peculiarities that could lead to a special damage pattern constituted a focus. Fig. 2b to 2d illustrates the composition of the reinforced concrete building types with respect to the primary and secondary vulnerability-affecting characteristics (VCP, VCS). VCP stands for the ground or basis (primary) type (BT) without major damage-enforcing particularities. Secondary aspects (VCS) are related to design or construction defects (and their combined occurrence) like soft story (ss), cantilevering beams/floor slabs combined with soft story (cus), widely ramped building (wrb) etc. Special attention is given to the 'pseudo-regularity (psr)' as a synonym for the quite irregular arrangement of structural elements leading to relative uncertain transmission and flow of the seismically induced forces. For the predominant types RC-SC2 and RC-SC3 about 2500 and 440 buildings respectively could be documented as an outcome of comprehensive field surveys. Finally about 25 sub-groups are distinguished with more than 50 individual representatives.

In addition to the phenomenological building characteristics, the behavior of structures depends on the seismic design and the assumed code level. Therefore the year of construction as well as the applied code may play an important role for the vulnerability assessment of the structures. In fact this information is quite difficult to determine and remains uncertain.

For the building stock of Antakya the construction year of each building was assigned to the GIS database on the basis of the cadastral data provided by the Municipality of Antakya. Due to incompleteness in the data, the construction year has to be assumed on the basis of the surrounding buildings for these cases. Fig. 3 indicates the distribution of the building stock for the applied building typology and different construction periods. It can be concluded that the majority of buildings was designed using the previous seismic code provisions of 1975 (at least in theory), which were changed after the devastating earthquakes in Turkey starting in 1999.

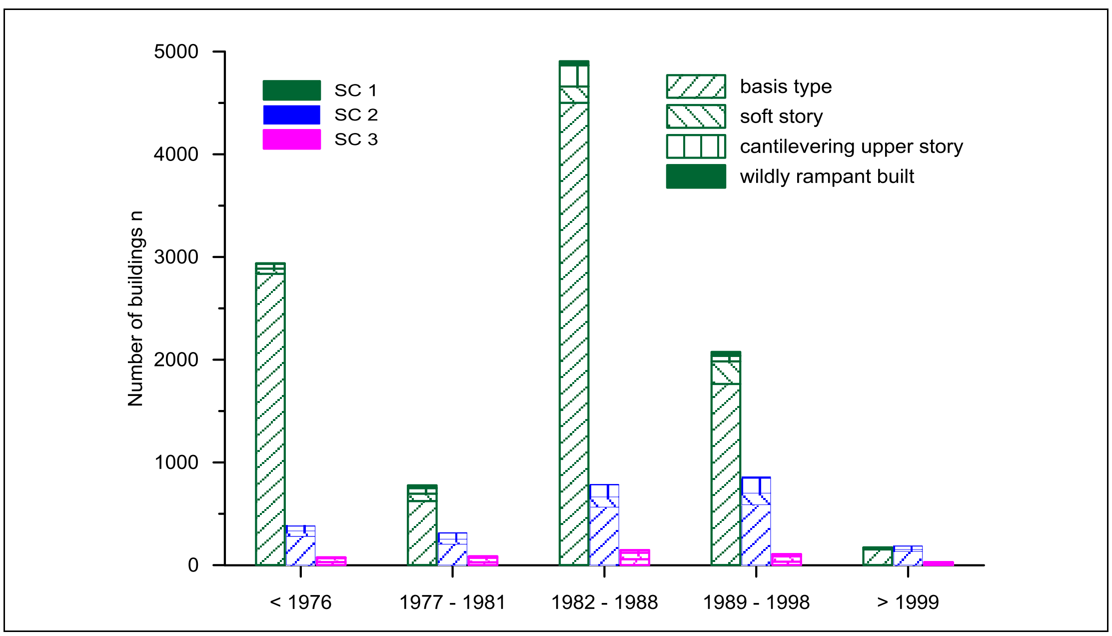


Figure 3. Distribution of the reinforced concrete structures according to the story class, building type and construction period.

Identification of representative buildings for instrumental investigations

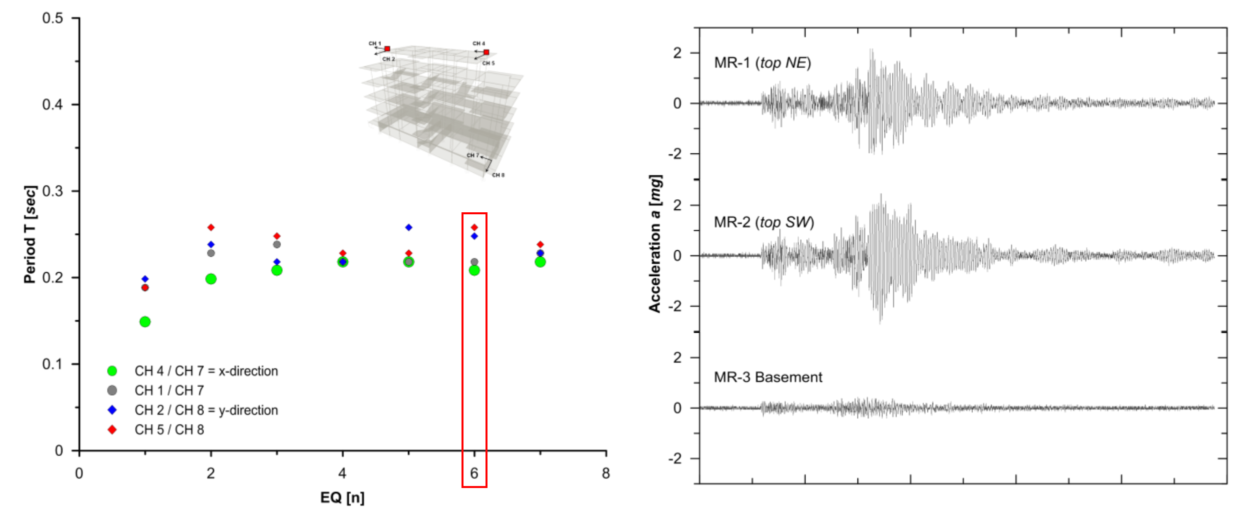
A complete analytical evaluation of a building stock is generally not possible. Therefore it is necessary to identify structures which are representative for the different assigned building types. On the basis of the derived building taxonomy several representative buildings for the building stock in Antakya could be identified to carry out instrumental investigation. Table 1 shows examples of instrumentally investigated buildings for the different R.C. building types.

In the first phase of the project, four reinforced concrete buildings could be permanently instrumented with strong-motion recorders following an efficient instrumentation scheme [2, 10]. Two of them are 5-story residential buildings, belonging to story class SC 2 and are considered to be characteristic for the city center of Antakya (see Table 1 and Fig. 5).

Additionally, 25 residential 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 at 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 [2].

Table 1. Examples of instrumentally investigated buildings of the different story classes (SC); with identification of the building percentage of each building type

SC	%	Example	SC	%	Example
1 (1 – 3 stories) All sub-types	78		2 (4 – 6 stories) Basis type	13	
2 (4 – 6 stories) Soft story, cantilevering upper stories, etc.	6		3 (7+ stories) All sub-types	3	



a) Fundamental periods   b) Example time history of EQ 6

Figure 4. Instrumentally derived fundamental periods of the study building (a) and recorded response caused by one of the strongest earthquake during the operation time (b)

Measurements

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 could be recorded at the permanent instrumented buildings, which happened in the near surrounding of Antakya during the last six years. Unfortunately, only non-damaging earthquakes occurred so far; therefore, response measurements for the nonlinear behavior of the structure are still missing.

Fig. 4a illustrates the main activated fundamental periods of the study building in both horizontal directions (x, y) for the different recordings. The different colored dots represent in each case the period at the main peak of the amplification spectrum. On one hand it indicates the stable dynamic response of the structure but also on the other hand the variation of the period and possible problems for the model calibration. Fig. 4b shows an example recording of a M_L 3.7 earthquake on May 16, 2013 in the near vicinity of Antakya measured at the 5-story reinforced concrete building (see Table 1).

Concept for the analytical vulnerability assessment

Main idea of the proposed concept are 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 building. After the determination of the relevant building response parameters the different damage grades can be allocated on the basis of the deformation states. Finally, fragility functions can be determined using the site-specific ground motion and representative earthquake records.

Main advantages of the concept are:

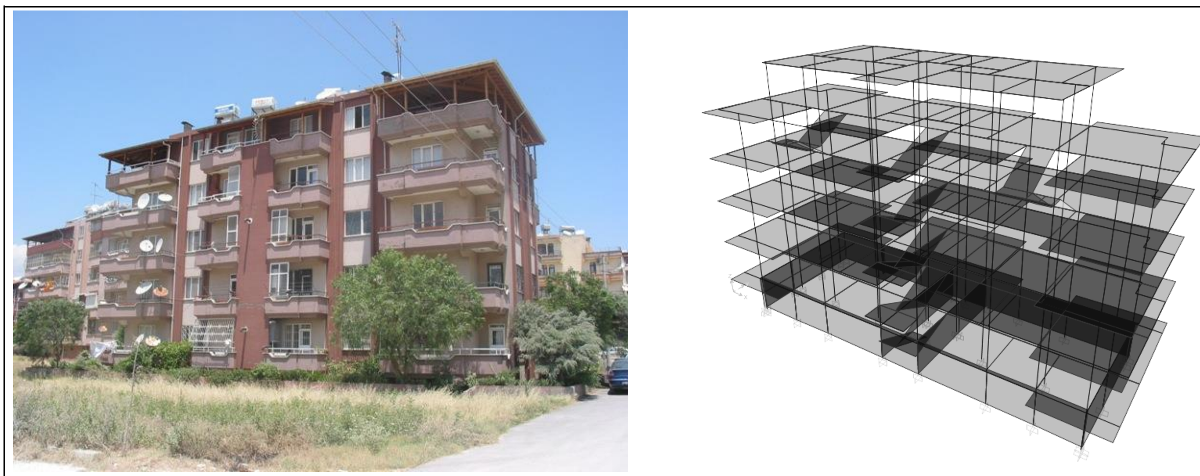
- the consistency of the damage description and allocation;
- the possibility of linking of different evaluation criteria and
- the portability to other building types.

Disadvantages can be the instrumental effort and uncertainties of the applied numerical method, whereas other method e.g. nonlinear time history method could be introduced.

Case study of a 5-story residential R.C. frame building

For the building investigated, three-dimensional model was created using the software tool SAP2000. Construction plans and on-site surveys of the buildings supplied the required geometrical data. Columns were generally assumed as rigidly connected to the underground. Due the fact that the subterranean level is only partially in the ground, the support points of the column were assumed to be at depth of the underground story and the reinforced concrete walls were considered at the model. Floors were modeled as rigid diaphragms; roof constructions were taken into account by planar loads. Diagonal struts were used for modeling the masonry infill walls as described in FEMA 306 [5]. In some cases the stiffness of the walls could be regarded as negligible, and merely their masses are considered. (Note: A detailed description of the building, modeling procedure and subsequent calculations will be provided by a building catalogue [11], which is just under finalization.)

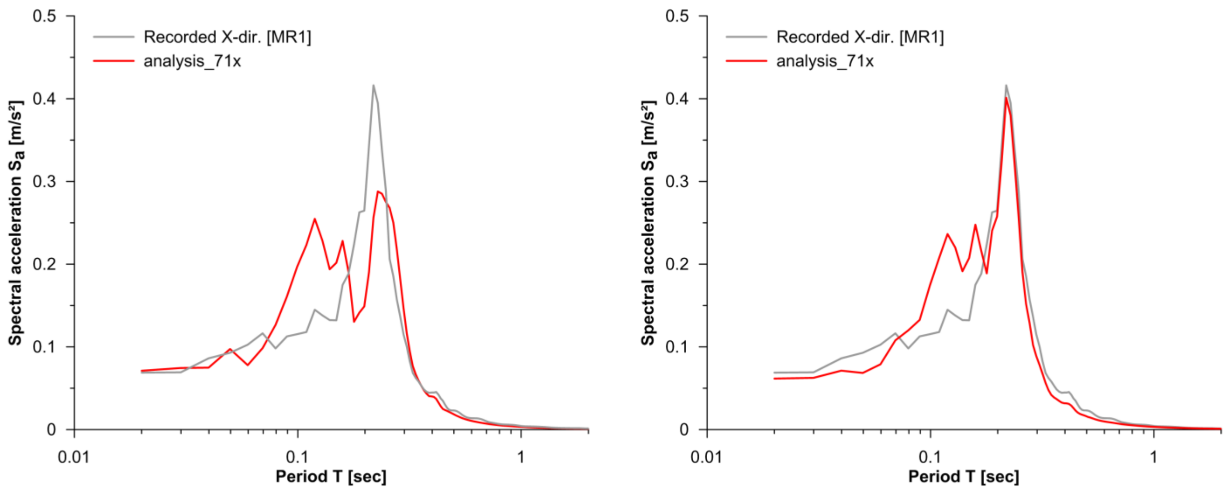
Before starting the calibration of the model the material parameters for concrete were assumed to have a characteristic cubic strength of 16 MPa (as denoted in construction plans). Reinforcement was assumed to be of Turkish steel grade S220a (220 MPa yield strength, 340 MPa ultimate strength and 10 % strain at ultimate strength), also corresponding with specifications in plans. A young modulus of 2.1e+7 kN/m² and characteristic strength of 600 kN/m² are assumed as material parameters for the masonry infill walls. For simplification infill walls are neglected in case of large openings. Nonlinear calculations are based on the tri-linear force-displacement relationship of the masonry infill walls according to Fajfar et al. [4].



a) View of the study object

b) Structural model without infill walls

Figure 5. View and structural model of the example 5-story residential reinforced concrete building.



a) Before calibration   b) After calibration

Figure 6. Comparison of response spectra before (a) and after (b) calibration in x-direction at sensor no. 1 (channel 1)

In case of the presented study object earthquake recordings were used as input and output parameter for the model calibration. Measurements recorded at the foundation of the building were used as input time histories and the response measurements recorded at two opposite positions at the roof used for the comparison of the analytical determined response of the structural model. [The calibration itself was carried out by the use of an optimization algorithm and the open application programming interface of SAP2000 by MATLAB.]

The comparison of the response parameters of the building before and after calibration indicates the need of model validation (see Fig. 6a). It also illustrates the difficulty and complexity of the task. Finally, it has to be decided upon the necessary and still acceptable model accuracy. In case of the here presented building, the first model created on the basis of available ground plans was not satisfactory. A better comparability between the recorded and analytically determined response could be achieved by the modification of the stiffness of structural members (modifying the young's modulus), the distribution of the considered additional masses per story and by the adoption of the damping ratio of the structure (Fig. 6b).

Instrumentally verified vulnerability functions

Limits of available fragility functions

Damage and/or loss scenario are the basis for the evaluation of a whole building stock under different seismic action, but therefore a damage grade or loss value are requested for each building. Commonly these values are assigned on the basis of global building parameters and the application of fragility functions valid for different building types and story classes. Fig. 7 shows examples of available fragility functions for 5-story reinforced concrete frame structures with masonry infill walls, which are compared for two different damage states by the use of the "Fragility Function Manager" [9].

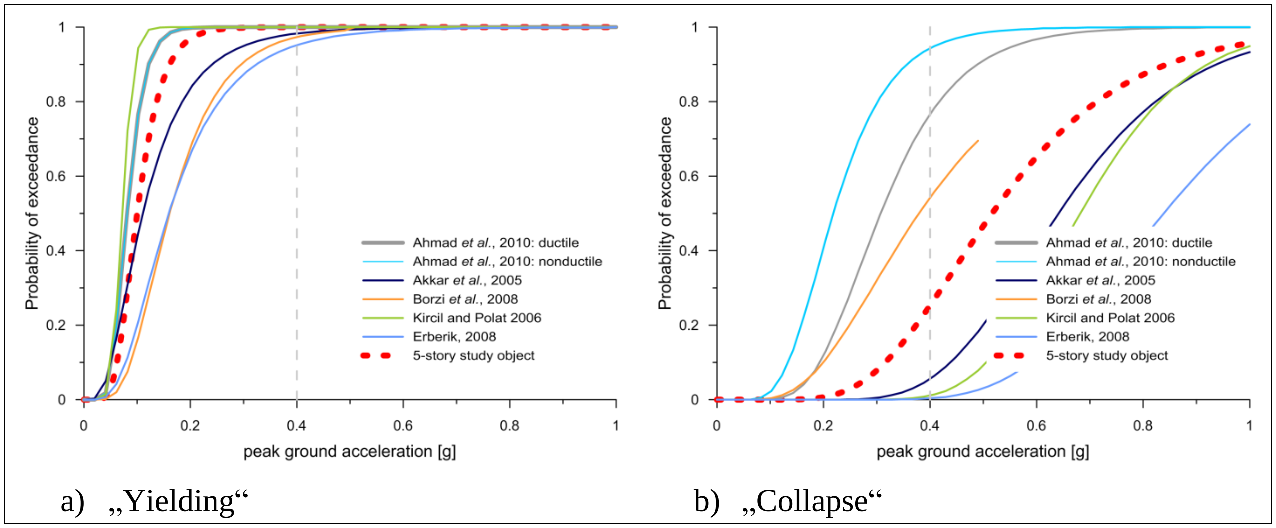


Figure 7. Comparison of fragility functions proposed for 5-story R.C. frame structures with masonry infill walls for different limit (performance) states; definitions acc. to [9].

An example application of these functions to a small-scale area of 100 buildings of the same type and a seismic action of 0.4g illustrated the huge differences. The curves according to [4] lead to 95 light damaged and 5 collapsed buildings; whereas the functions according to [3] predict 55 collapsed buildings. This exemplary comparison indicates the need of adjusting the fragility functions 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 influencing parameters.

Determination of fragility functions for study object

On the basis of the validated structural model the capacity curve and spectrum was determined and the different damage grades assigned according to [10]. In a next step, the capacity spectrum method according to FEMA 440 [7] was applied to analyze the performance points for a set of strong motion records from Californian earthquakes [12]. Finally fragility functions for each damage grade are derived (see Fig. 7).

Conclusions & Outlook

The paper presents a comprehensive and hybrid approach to analytically determine building stock representative fragility functions on the basis of instrumentally verified structural models. It also allows the comparison with available empirical data (observation) due to similar description of damage in terms of EMS-98 damage grades. For the study and target area of Antakya the whole building stock was surveyed and classified into a regional building typology. Representatives of the identified R.C. building types were instrumentally investigated to provide input parameter for the calibration and verification of reliable structural models. The need for it is illustrated for a 5-story reinforced concrete building. On the example of this building a first set of fragility function was determined while indicating the remarkable differences to functions provided by well elaborated databases [9].

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. Further the current applied ground motion data will be replaced by Turkish earthquake records, which are more representative for the study area.

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