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ANALYTICAL ASSESSMENT OF EXISTING MASONRY STRUCTURES UNDER EQ LOADING BY THE USE OF AMBIENT VIBRATION MEASUREMENTS

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

[1] *Earthquake Damage Analysis Center, Bauhaus-Universität Weimar, Germany*
[2] *Engineering Faculty, Civil Eng. Department, Zirve University, Gaziantep, Turkey*
Email: cemal.genes@zirve.edu.tr

ABSTRACT:

The analytical evaluation of masonry structures under earthquake loading comprises several uncertainties and assumptions, which might lead to a misleading interpretation and prognosis of the inherent resistance and overall response. One strategy for the determination of the nonlinear capacity is the transformation of the building into an equivalent frame model and the assignment of non-linear hinges for the (quasi) moment-resistant coupling zones. For the description of the non-linear hinges different models are available, which are mainly derived from experimental data of single walls.
The current study attempts to determine the non-linear capacity of representative masonry buildings being selected to refine and complete the evaluation of the building stock in Antakya within the *Seismic Risk Assessment and Mitigation in the Antakya-Maraş-Region (SERAMAR)* project. For this purpose structural ground plans were collected by archive research. Ambient vibration measurements were conducted to estimate the dynamic characteristics of the building under use. On the basis of the available building information different numerical models are created to adopt the real dynamic response and to discuss the scatter of possible results by the application of different non-linear hinge definitions.

KEYWORDS: masonry structures, equivalent frame model, seismic risk assessment, SERAMAR project

1. INTRODUCTION

1.1. The SERAMAR - Project

In close collaboration with local partners, the Earthquake Damage Analysis Center (EDAC) at the Bauhaus-Universität Weimar initiated a Turkish-German joint research project on *Seismic Risk Assessment and Mitigation in the Antakya-Maras-Region* – SERAMAR. 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 were identified and elaborated following the principles of EMS-98 [*Grünthal et al.*, *1998*] (see also http://seramar.edac.biz). Additionally, the social vulnerability and resilience to earthquake disasters at different levels of society are investigated.

1.2. Equivalent Frame Modeling

A common procedure for the determination of the non-linear capacity of masonry structures is the transformation of the structural system into a so called Equivalent Frame Model (EFM). It allows the conversion of wall-type structure into a frame-like model and the numerical assignment of non-linear hinges.

In the EFM, the structural walls are represented by macro-frame elements composed of piers and spandrels. According to [*Dolce, 1989*], these idealized frames are formed by deformable elements, where the non-linear response should be concentrated, and rigid offsets, representing the zones of the walls which are usually not subjected to damage. By connecting these deformable and rigid elements an ‘Equivalent Frame’ is obtained [Figure 1].

The deformable elements of piers and spandrels are modeled for the elastic–plastic response, and the rigid offsets are modeled as stiff. The perfect coupling effect between the piers and spandrels is formed by the rigid offsets. In order to determine the overall capacity of the wall, the effective height of the pier and the length of the rigid offsets have to be determined.

Depending on the arrangement of openings (regular or irregular), different methods are introduced for assigning the rigid offsets. Different studies [*Demirel, 2010; Kheirollahi, 2013*] indicate that the Equivalent Frame Method following the approach proposed by [*Dolce, 1989*] shows a good agreement with results obtained by finite element calculations. Hence, in part of the project this approach will be considered.

1.3. Definition of Non-linear Hinges

In case of earthquake loadings on unreinforced masonry structure (URM) the damage or failure will usually happen at the pier or spandrel having the lowest strength. The damage mechanisms are either flexure or shear. The flexural failure, such as rocking and toe – crushing are concentrated only at the corners of the piers and spandrels, whereas the shear failure, such as shear sliding and diagonal cracking are concentrated in the mid-section of the piers and spandrels.

Therefore in numerical models, the macro element is divided into three sub-structures [Figure 1]; i.e. the non-linear flexural springs are inserted into the macro element at the extremities of the piers and spandrels. The non-linear shear springs are inserted in the middle section of the piers and spandrels. Regarding the strength criteria for URM piers and spandrels, several nonlinear hinge definitions are available. In general, they are based on the results of experimental investigations [*Pasticier et al., 2008; Bal et al., 2008; Diogo, 2009; Bucchi et al., 2013; Lagomarsino et al., 2013*].

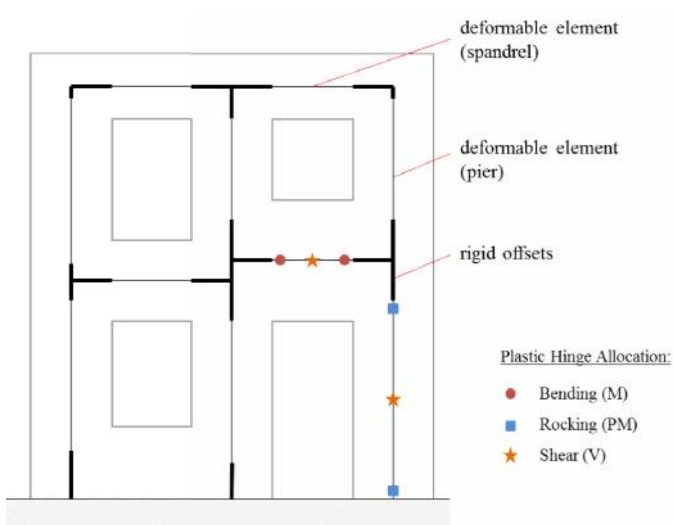


Figure 1. Scheme of the Equivalent Frame Model and the assignment of plastic hinges

2. COMPOSITION OF THE MASONRY BUILDING STOCK

2.1. Building Stock Survey

At the beginning of the SERAMAR project, it was agreed among the contributing partners to carry out a complete building stock survey despite the fact of the high effort. Buildings of different material types being representative for the various construction periods can be found as well as buildings consisting of several materials. Especially in the suburb areas, the ground floor is often constructed with a material otherwise than the upper floors due to the generation-wise (long lasting) construction process. Typically, adjacent buildings are attached to each other because of the 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 as well as to calculate a performance score for each building as basis for a preliminary risk assessment [*Erberik et al., 2013*].

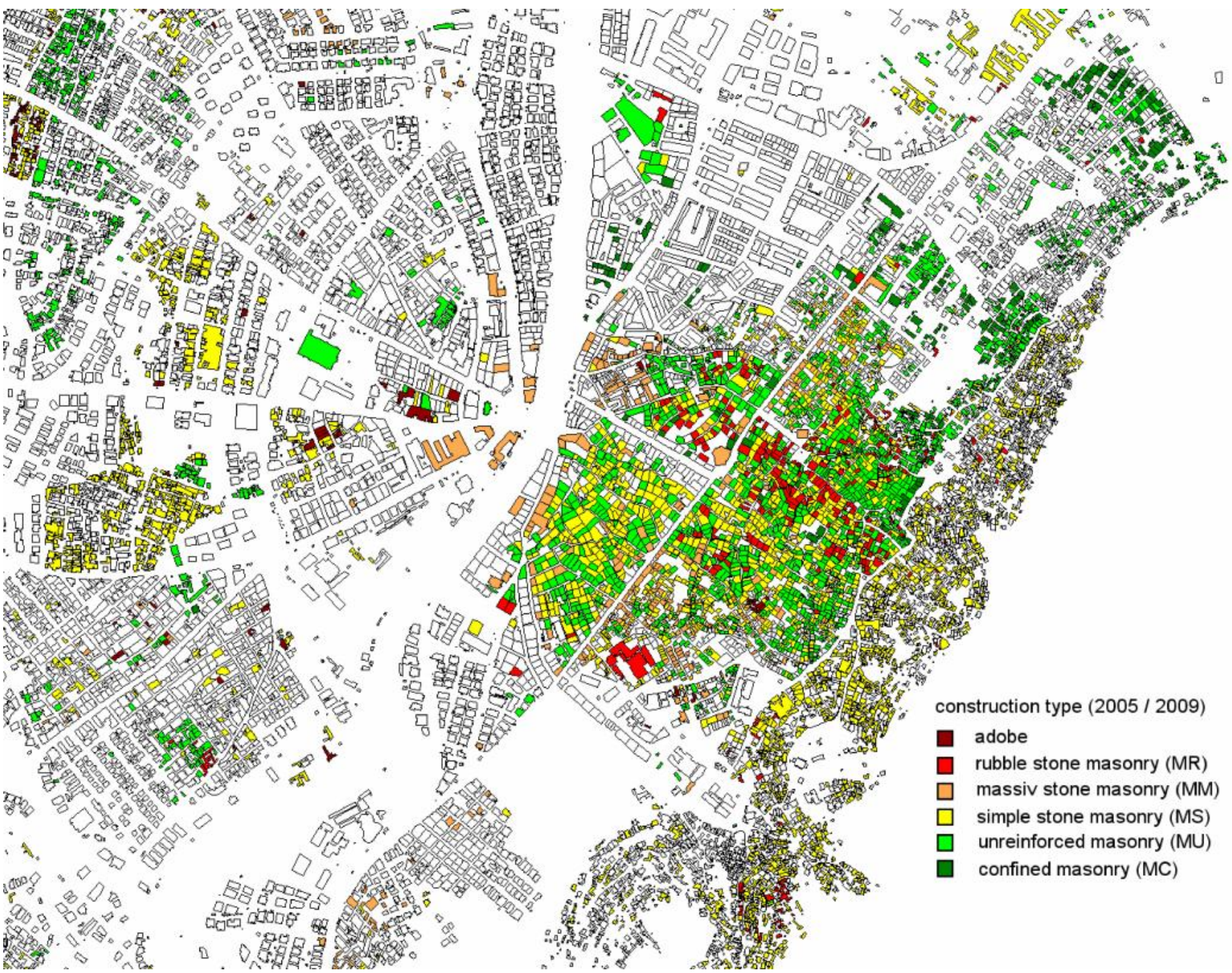


Figure 2. Masonry building types in Antakya (Turkey) based on the building stock surveys in 2005 and 2009

2.2. Building Typology

A first building typology was derived on the basis of data collected during the building stock survey in 2005 and its completion in 2009 [*Abrahamczyk et al., 2013*].

The following parameters were gathered:

- Material of the structural system,
- Number of stories,
- Peculiarities of the structural system (vulnerability affecting solutions like soft story, cantilevering upper story, widely/ rampant built),
- Peculiarities of the location (typographical situation like top of a steep slope),
- Utilization (residential, commercial, etc.).

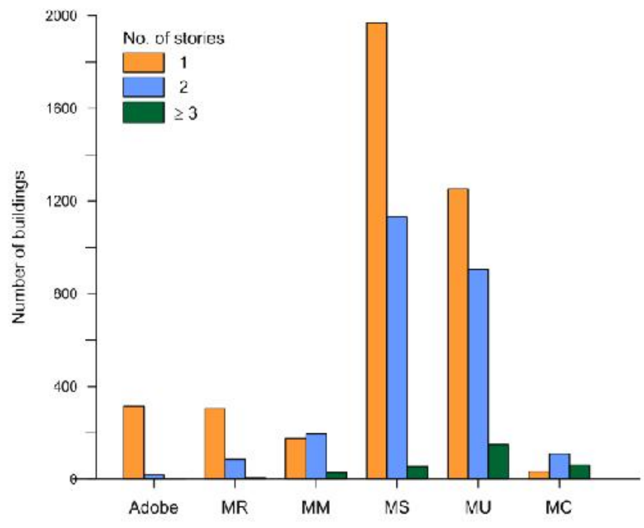
With focus on the residential buildings the following masonry types could be observed and distinguished (Table 1).

Table 1. Masonry building types according to the EMS-98 used for the building stock surveys in 2005 and 2009

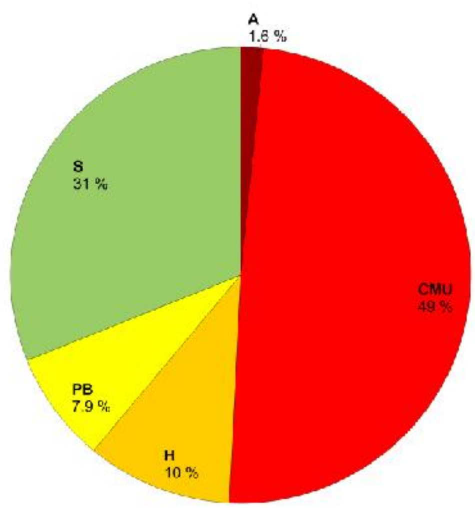
Code	Description
A	adobe
MR	rubble stone
MM	massive stone

Code	Description
MS	simple stone
MU	unreinforced masonry
MC	confined masonry

Figure 3 shows the distribution of the masonry building stock according to the assigned building type and number of stories. It can be clearly seen that the majority of the masonry buildings have 1 or 2 stories and are made off simple stone or unreinforced masonry



a) according to the first draft of building typology and the number of stories



b) according to the refined building typology

Figure 3. Distribution of the masonry building stock

Table 2. Masonry building types according to the EMS-98 and the outcome of different building stock surveys

Parameters	2005 & 2009	2012
Material of the structural system	X	X
Number of stories	X	X
Peculiarities of the structural system	X	X
Peculiarities of location	X	-
Utilization	X	
Geometry	(x)[1]	X
occupancy type, occupancy distribution	-	X
load-bearing wall material (brick type)	-	X
dimension, vertical alignment of openings,	-	X
floor type (W – wooden floor; RC – reinforce concrete)	-	X
adjacency, building height difference in the case of adjacency,	(x)[2]	X
roof geometry and material,	-	X
apparent conditions	(x)[2]	X

Notes:
[1] only in single cases [2] from the cadastral plan

2.3. Refinement of Building Typology

Following the idea of the comparison of the empirical studies according to the EMS-98 and analytical studies based on existing fragility function, a further distinction of the building types was necessary. Therefore, a second building stock survey was carried out in 2012 focusing on the material properties of the used brick types. Additionally all necessary data could be collected to assign a performance score [*Erberik et al., 2013*].

The survey was done exemplarily for 250 buildings. On the basis of the additional data from the 2012 survey, a refined and extended building typology could be derived including the number of stories and floor construction type (see Table 3). From this study, it can be concluded that the majority of the buildings is constructed with RC floors.

Table 3. Masonry building types as result of the field surveys from 2005, 2009 and 2012

2005/09		
Code	No of stories	Description
A	1	Adobe
MR	1, 2, ≤ 3	Rubble stone
MM	1, 2, ≤ 3	Massive stone
MS	1, 2, ≤ 3	Simple stone
MU	1, 2 , ≤ 3	Unreinforced masonry
MC	1, 2, ≤ 3	Confined masonry

2012		
Code	No of stories	Description
A	1	Adobe
S	1, 2, ≤ 3	Stone
CMU	1, 2, ≤ 3	Concrete masonry units
PB	1, 2, ≤ 3	Perforated bricks
H	1, 2 , ≤ 3	Hybrid materials
Floor		
W		Wooden
RC		Reinforced concrete

CMU2RC [No.1] CMU4RC [No.4] CMU2RC [No.7]

Figure 4. Example pictures from the investigated representatives; assignment of building type acc. to Table 3; [No. refer to Table 4]

2.4. Representatives

As an outcome of the ***SERAMAR*** project it was decided to carry out in-situ response measurements within the urban area of Antakya with temporarily *Building Monitoring Systems* provided by SYSCOM Instruments SA. Therefore a variety of eligible buildings had to be pre-selected and checked whether they are suited for the instrumentation or not. On the basis of the conducted surveys and derived building statistics the investigations are concentrated on concrete masonry unit (CMU) building type with at least 2 numbers of stories. Figure 4 shows examples of instrumentally tested masonry structures.

3. AMBIENT VIBRATION MEASUREMENTS

3.1. Experimental Investigation

In part of the project, different kinds of tests are conducted to provide data for the analytical investigation to improve the quality of the structural models as well as the final damage prognosis for a reliable comparison between empirical and analytical studies. Two masonry buildings could be equipped with a long-term Building Monitoring Systems consisting of four tri-axial strong-motion recorders [*Abrahamczyk et al., 2012*].

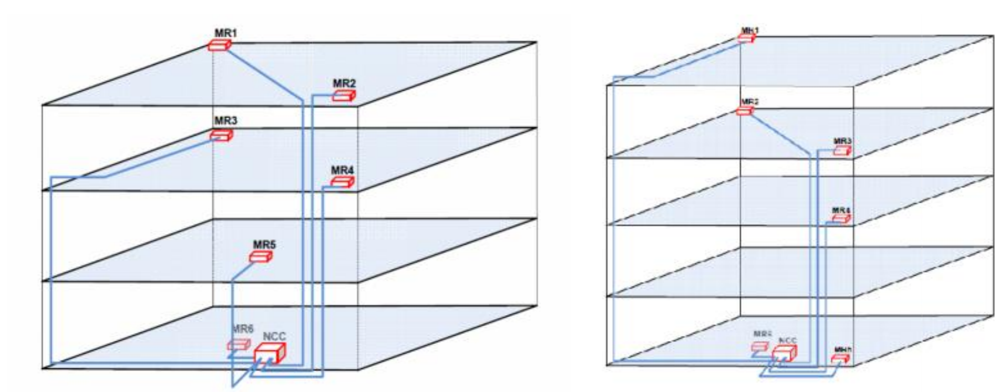


Figure 5. Example schemes of the temporarily ambient vibration measurements; Note: The location of the sensor strongly depends on the accessibility.]

Additionally, seven residential buildings with different number of stories were tested (see examples in Figure 4). Similar to conducted studies on reinforced concrete buildings [*Schwarz et al., 2009*], each building was equipped with five or six tri-axial velocity sensors Type MS2004+ and the corresponding recorder Type MR2002 (Syscom Inc.). All sensors are connected by a Network Controlling Center (NCC), enabling a simultaneous start of the measurements and synchronous data supply from each sensor. The sensors are 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. One sensor was installed in the middle of the ground floor or basement if available (see scheme in Figure 5).

3.2. Identification of the Fundamental Building Frequencies

System identification of the structure subjected to ambient vibration using an output-only identification technique is used for the calibration of the linear elastic numerical model. The modal parameters of the structure consist of natural frequencies, mode shapes and modal damping ratios. A number of mathematical models for output-only identification have been developed and roughly classified by parametric time domain methods and non-parametric frequency domain methods.

In this project the non-parametric frequency domain decomposition (FDD) method has been used to extract the principal modes of the structure from the ambient vibration data. The FDD technique and a manual peak picking algorithm have been implemented into MATLAB to detect the first natural frequency in the longitudinal and transverse direction. Therefore the median-velocity spectra of each sensor were used and for better identification the ratio between the sensors which are located to the top floors and those on the base were calculated.

In general each sensor was active for around 25 minutes and the data was separated into 25 files of 1 minute each. The sampling rate of the sensors was 100 Hz. The divided files were subsequently combined into one master file for each axis and the signal baseline corrected by subtracting the mean value from each measurement. Afterwards the windowing technique was applied to determine the median-velocity spectra out of approximately 30 overlapping segments. Table 4 shows the determined fundamental frequencies of the investigated buildings used for the later model validation.

Table 4. Frequencies of the masonry buildings derived from instrumental investigation

Bldg. No.	No. of Stories	1st Frequency	2nd Frequency
1	2	6.64 Hz	-
2	3	5.26 Hz	6.29 Hz
3	2	3.57 Hz	3.76 Hz
4	4	4.67 Hz	6.15 Hz
5	2	10.15 Hz	-
6	2	6.93 Hz	8.13 Hz
7	3	3.71 Hz	5.18 Hz

4. NUMERICAL STUDIES

According to the provided structural plans, numerical studies were carried out with different software packages. In a first step, 3Muri software tool were applied for the analysis of masonry structures. In addition SAP2000 was used to investigate different hinge properties for the description of the non-linear behaviour. Therefore for each building the equivalent frame was created acc. to [*Dolce, 1989*] similar to the implemented approach in 3Muri software tool. For each frame, in X and Y direction, sections for the piers, spandrels and rigid offsets were assigned in order to obtain the equivalent frame (see 1.2.).

The ambient vibration measurement results (given by Table 4) are used to calibrate and validate the numerical models in order to conduct reliable calculations at least in the linear range.

In a next step, different hinge definitions are applied to investigate the possible scatter of results for the description of the non-linear behaviour, because of the lack of data for the investigated building type as well as used materials in the study area Antakya (see 1.3.). The comparison of the different proposed formulas indicate, that there are substantial differences in the formulas of the strength criteria of nonlinear hinges simulating the behaviour of masonry walls under seismic load.

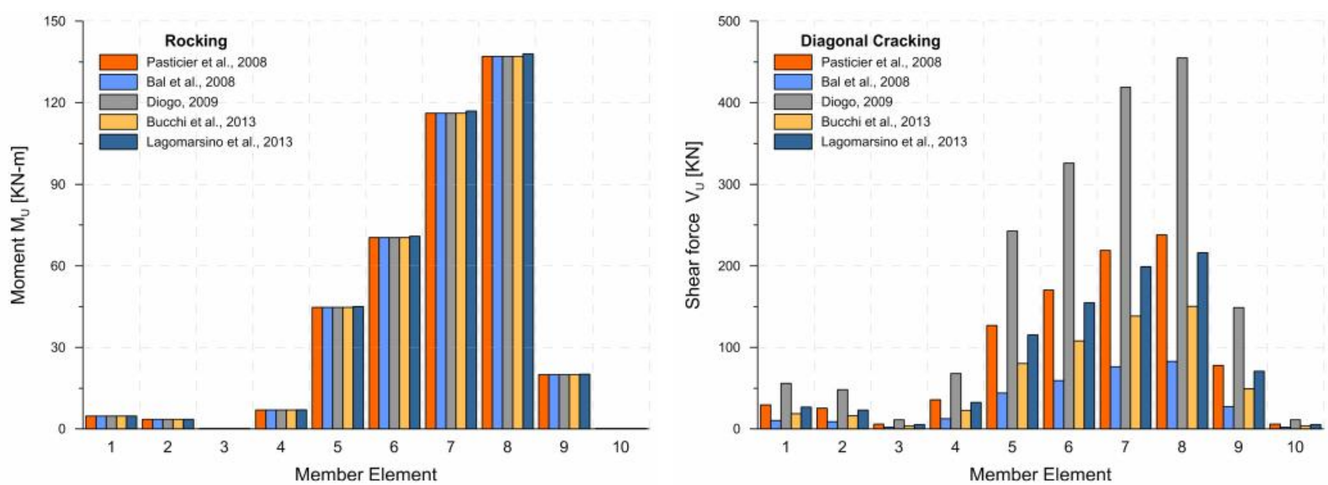


Figure 6. Comparison of non-linear hinge models for masonry piers: failure type rocking and diagonal cracking

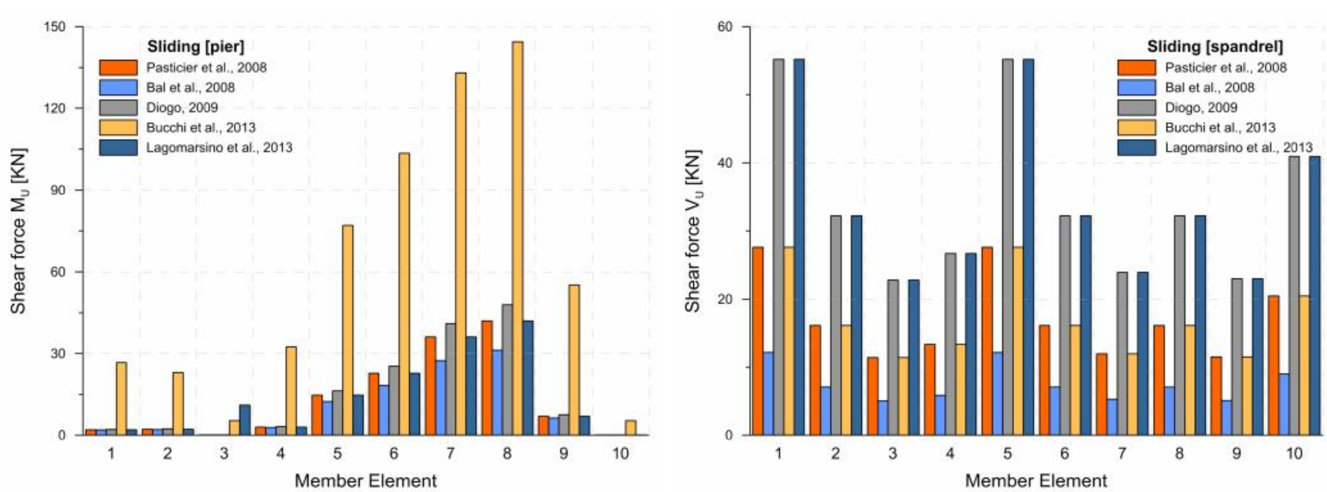


Figure 7. Comparison of non-linear hinge models for the failure type sliding for the masonry piers and spandrels

Figure 6 and 7 show first comparative results from the application of the different hinge properties definitions for a set of example member elements from one of the studied buildings. The example illustrates the common understanding about the failure types “rocking” as well as “sliding” of the piers.

In contrast to that are the results for the failure type “sliding” for the piers and spandrels which shows remarkable differences. Thus material and mechanical parameters involved in hinge definitions leads to under or over prediction of the actual strength of the structure. It is difficult to single out an accurate hinge definition without model validation, due to strong variability in results. Thus further studies and tests are necessary and are just under preparation. Especially the description of the non-linear behaviour of the local material has to be investigated. In part of the project, test’s on brick specimens were already conducted to determine representative material parameters. In one of the next steps, these test results will be used for the refinement of the numerical models.

5. 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 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 [*Abrahamczyk et al., 2012*].

The study presents the step by step procedure to determine the local characteristics of masonry buildings in Antakya based on field survey results. Following the idea of the comparison of the empirical studies according to the EMS-98 and analytical studies several measurements were conducted for the provision of input parameters for the verification of the numerical models.

First comparative studies on available methods applicable to equivalent frame models for the determination of the building capacity under horizontal action showed remarkable differences. Thus further studies and tests are necessary especially to come up with reliable damage prognosis for the locally used material and building types.

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Maps are created with the program Mapinfo© Professional.

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