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SEISMIC VULNERABILTY ASSESSMENT OF ISRAELI HISTORICAL CENTRES

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Abstract. *The configuration of historical centres is often complex and consequence of centuries of modifications. Clustered buildings which compose them are vulnerable, in particular against seismic action. The knowledge of their structural behaviour is fundamental in order to define prevention strategies and to reduce seismic risk. This paper refers to vulnerability assessment of the historical city centres of Safed and Acre, in the North of Israel. The methodology adopted is based on a preliminary knowledge phase. It is focused on the analysis of the seismic activity of the area and its urban and environmental context. Safed stands on a slope with more than ten metres of anthropogenic strata vulnerable to landslides. The town is developed on the contour lines and as a consequence basements and underground vaulted stories are recurring. Vice versa Acre is located on the Mediterranean coast and present continuous stratifications taken place during the centuries as a consequence of historical events. The study is carried out analysing some representative selected blocks. Considering the aim of an urban seismic assessment, specific survey forms are rearranged in order to collect buildings geometrical – typological data and information about vulnerability, exposition and damage. These are statistically analysed and allow to identify recurring typologies. For a global simplified analysis automatic procedures are implemented for each structural unit or group of them, obtaining a linguistic vulnerability assessment and fragility curves. Clustered buildings often do not show a global behaviour while they respond to seismic action as a group of local mechanism of collapse: local out of plane mechanisms are analysed, considering both the survey and the typological data. Comparing all the obtained results, it is possible to appoint a vulnerability assessment and classification. In addition, the aim of this approach is to chart the results to other quarters of the historical centre: using the survey forms it is possible to identify structural units and to assign them the correspondent typologies previously identified and the related vulnerability assessment.*

INTRODUCTION

A key element for the reduction of seismic risk and the development of prevention strategies for existing cultural heritage is the evaluation of the susceptibility to damage of historical buildings against seismic actions.

This paper refers to the vulnerability analyses of the historical city centres of Safed and Acre, in the northern Galilee (Israel).

The Israeli territory is characterized by a significant seismic danger: it extends over multiple tectonic plates whose reciprocal movements can cause recurring earthquakes. Considering these premises, a careful and extensive work of prevention is necessary.

Some aggregate buildings of the two historical centres are analysed. The buildings are located in the Old Jewish quarter of Safed and in the Quarter n.10 of Acre.

The adopted methodology aims to the identification of recurring typologies, the definition of vulnerability assessments and the classification of vulnerability for the analysed buildings.

The final scope is to extend the methodology to other buildings belonging to different quarters of the historical centres where same structural characteristics are traceable and on a territorial scale to other historical centres which are characterised by the same architectural and typological features. This approach refers to an ongoing research and aims to the identification of expeditious vulnerability assessments based on typological identification.

1 IDENTIFICATION OF THE AREA

The approach applied follows the knowledge path defined by the Italian D.P.C.M. 09/02/2011 for evaluation and mitigation of seismic risk to cultural heritage [1]. First of all, a general cognitive analysis is necessary in order to understand features and seismicity of the area.

1.1 Geographical location of Acre and Safed

The Galilee is a mountainous region in the Northern District of Israel and is divided into Upper Galilee in the North, Lower Galilee in the South and Western Galilee.

Safed (Figure 1, 2) is a city located in the Upper Galilee at an elevation of about 900 metres above the sea level. Even if it is located on a mountainous region, it was considered a strategic site because of its height. In fact, on the highest peak of the mountain a fortress was built during the Crusade period and the first settlement was located on the hillside below it. Later buildings developed from the lower margins of the hill up to the central highest area. For many centuries Safed was ruled by Arabs, Turks, Mamluks and Jews leaving historical, religious and architectural heritage [2]. A few meters deep layered anthropogenic material, which is the consequence of more than 2000 years of human habitation, characterized the soil on which the town stands. It is composed by a mechanically weak material that is susceptible to slope failure and to amplification of seismic-shaking. Many buildings in the core of Safed were built no later than the mid-20th century and even before; in many cases they were founded on the anthropogenic talus without any support by the underlying bed rock [3]. The historical centre presents many recurring features (Figure 3) such as passageways, habitable structures, courtyards and often ruins. Internal narrow streets split the historical centre into irregular geometric portions. Steep stairs connect parts of the city in the east west direction and narrow vaulted passages are often located on underground levels.

Figure 1: Identification of the area

Figure 2: The town of Safed Source: Israel Antiquities Authorities

Figure 3: Buildings in Safed historical center

Acre is the second city analysed (Figure 4) and is located in the Western Galilee, at the northern extremity of the Haifa Bay on the Mediterranean Sea. In 2001 UNESCO designated the Old City of Acre (Figure 5) as a World Heritage Site [4]. Acre is characterized by a very complex urban configuration difficult to read because of continuous stratifications taken place over the years: Crusaders, Arabs, Ottomans and the British Empire dominated the area. The old town is bordered by a fortified wall which dates back first to the crusade and then to the ottoman period. The city developed within the fortified wall is very compact, the reduced space led to the creation of narrow streets that linked the neighborhoods. The majority of the city was destroyed or distorted following the Mamluks conquest. The medieval urban structure was divided into well-defined districts. Later it was topped by a structure that partially kept the pre-existing road system; minor routes were privatized and only the major ones were upgraded (Figure 6). The dwelling construction in Acre reflects vernacular architecture and four distinguishing types of buildings can be identified: the courtyard house, the central hall plan house, the captain's house and the apartment house. In addition, the "bridge house" is characterized by rooms that rise above walking tunnels [5].

Figure 4: Identification of the area

Figure 5: The town of Acre Source: Israel Antiquities Authorities

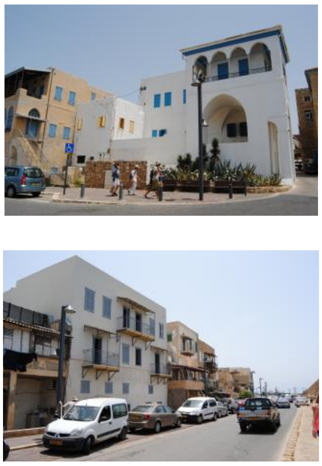

Figure 6: Buildings in Acre historical center

1.2 Seismicity in Israel

Galilee region belongs to the Dead Sea Transform (DST) fault system, also referred to as the Dead Sea Rift (Figure 7). It is composed by series of faults that define the boundary between the African Plate (west Israel) and the Arabian Plate (east Israel). The zone is characterized by left lateral displacement, because of the relative movements of the two plates [6]. Because of this, the Israeli territory is characterized by a significant seismic hazard (Figure 8). It is situated on the Dead Sea fault and suffered earthquakes of different intensities, sometimes characterised by severe damage (Figure 9).

Figure 7: Dead Sea transform fault system
Source: http://www.gii.co.il

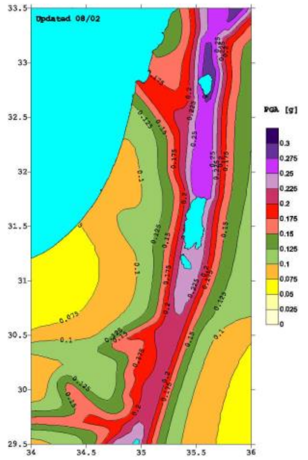

Figure 8: PGA map of the Israeli seismic code SI 413 (1995, 2004 amendment).
Source: http://www.gii.co.il

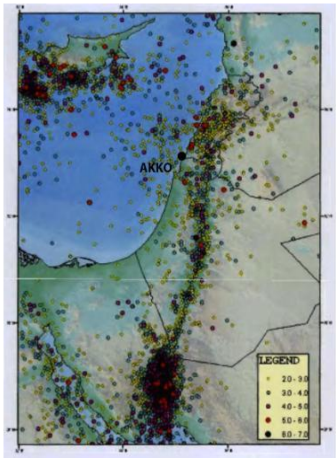

Figure 9: Regional seismicity during 1900-2007
Source: A. Shapira, R. Hofstetter, Geophysical Institute of Israel, Earthquake hazard assessment for building codes. Final report, 2007

The "Safed earthquake", occurred on January 1st 1837, and the earthquake of September 11th 1927 were the most relevant historical earthquakes occurred in northern Israel during the last two centuries. Safed was completely destroyed in the 1837 earthquake because of a slide and Arab villages in the area were severely damaged. The earthquake had an estimate magnitude (Ms) > 7. The 1927 earthquake was less pronounced in Galilee but caused heavy damage in Nablus [7].

Two earthquakes struck the northern part of Israel in October and November 1759. The first one had a magnitude (Ms) of approximately 6.6 (estimated epicentre on the Jordan fault, north of the Sea of Galilee). The second one had a magnitude (Ms) of 7.4 (estimated epicentre further north). Fifty kilometres south-west of Safed another earthquake occurred on August 1984. In Safed it was characterized by an intensity of V, according to MSK scale, with no reported induced landslides. The fault is not in the immediate vicinity of Acre and the town has not yet undergone major earthquakes but it can be assumed that is close enough to have suffered, at least partially and with no historical evidences, the effects of the strongest earthquakes.

2 METHODOLOGY

The seismic vulnerability analysis of historical buildings at a territorial level is based on simplified methodologies and models, that are reliable, based on empiric parameters. The carried out analysis is characterized by an expeditious survey on typological base in which information about building structures, vulnerability and exposition to damage are collected.

The analysed aggregate buildings are consequence of different architectural sequences, use of materials and customers intervention occurred during centuries of unplanned transformations. As a consequence their structure does not allow studying them as simple buildings [8]. The study is focused on the analysis of clustered buildings whose architectonical, structural and typological features are representative of the historic urban fabric. For the town of Acre (Figure 10) they are located in Quarter n.10; for the town of Safed (Figure 11) in the Safaradim quarter.

Figure 10: Localization of the buildings in Old Acre

Figure 11: Localization of the buildings in Safed

The main steps of the applied methodology are:

1. collection of information related to historical evolution, previous interventions, damage mechanisms of the analyzed buildings and identification of vulnerability elements;
2. compilation of in situ forms;
3. for some buildings, complete identification and characterization of walls types, masonry elements and horizontal diaphragms;
4. statistical analyses of data collected through the use of specific forms, with the aim of studying the main features of the historical centres and identifying recurring typologies;
5. assignment of seismic vulnerability assessment about building systems, considering each structural unit or group of them;
6. macroelements analysis;
7. assignment of vulnerability assessment and classification on typological base.

The methodology for seismic vulnerability assessment is carried out considering both the existing aggregate buildings and the identified typologies to which they belong. The buildings present state is used in order to calibrate and validate typological results.

3 PRELIMINARY PHASE

The adopted methodology is based on a preliminary knowledge phase [1, 9, 10]. The first step of the study aims at collecting any information about cities and quarters.

City master plans or general cartography, orthophotos, historic plans and photos are the required preparatory material. Information about typological, architectural and urban characteristics of the cities, morphology and historical evolution of the analysed quarters cannot be disregarded. Moreover, for some buildings, complete identification, recognition and characterization of typology and components are essential.

3.1 On-site activity

The on-site activity starts with a general reconnaissance of the blocks with the aim of subdividing the aggregate buildings into structural units. A visual survey is carried out in order to collect information about buildings structural behaviour. The assistance of expert Israeli technicians is fundamental in order to identify typologies, constructive techniques and used materials. A form compilation for masonry and concrete buildings is filled, collecting:

- geometrical, typological, vulnerability information about each structural unit (i.e. horizontal and vertical structures, number of stories, age of construction, interventions undergone, reinforcing elements present state, in plan and in elevation irregularities);
- information about exposure and damage (level and extension of damage for structural and non-structural elements).

The survey forms are specifically organized in order to be adapted to Israeli historical buildings.

During the on-site activity, a photographic survey is done. Photos are taken inside and outside structural units (including roofs), with a particular attention to damages or alterations (such as the presence of cracks or materials deterioration),architectural features, interactions due to aggregation, courtyards and contrast elements between buildings.

3.2 Statistical and typological analysis

Data collected during on-site activities are essential in order to understand clustered buildings behaviour. They are statistically analysed in order to identify the most recurrent buildings features and typologies. The towns are characterised by many features in common. Their dwelling clustered buildings were usually built before the XX century and nowadays they appear reshaped as a result of numerous interventions occurred during the years. Their main vertical structures are ascribable to two leaves walls with inner core and one leaf walls, mostly made of sandstone (in Acre) whereas of limestone (in Safed). Vaults systems often characterise groundfloors and underground levels, moreover in Acre wide discharge arches stiffen wall structure. Nevertheless more recent horizontal diaphragms are made of concrete and metal beams. Roofs are usually flat and the prevalent typology of Acre is characterized by wooden structures, and sometimes concrete slab. Also in Safed roofs are flat and walkable too; they are usually covered with a mix of mortar and small stones then beaten with a wooden hammer [11]. In the evaluation of recurring elements, it is important to identify the elements which can reduce the vulnerability of buildings also toward seismic actions. In Acre reinforced elements such as contrast arches (also built contrast arches, i.e. bridge houses) and tie rods are frequent, external stairs can often be considered as contrast elements (for walls subjected to out-of-plane mechanisms). Vice versa these elements are not recurring in Safed. For both the towns misaligned openings, heavy roofs, overhanging, towering or standing out elements are quite frequent vulnerable parts; they must be evaluated in order to understand buildings structural behaviours. In particular in Acre there is often an increase of upper floors area (overhanging elements regularize storey geometry). Another important consideration is related to buildings present state, indeed over the years they have sometimes undergone a slow process of decay. As a consequence bad conditions or medium damage are mostly due to abandon or neglect.

The information are collected with the aim of carrying out a statistical and typological analysis in order to identify recurring typologies, giving a vulnerability assessment concerning structural units and blocks as a whole.

In Figure 12 is reported an example of the statistical analysis performed, in which connection between horizontal and vertical diaphragms are evaluated. The evaluation of buildings seismic vulnerability through the use of expeditious methods disregards the complete structural survey of each building since it is not coherent with the proposed approach. In this term statistical results allow to complete and integrate lack of information.

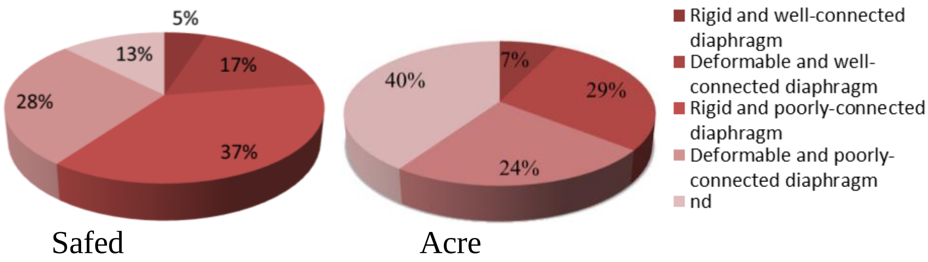

Figure 12: Horizontal structures connections

The previous analysis are fundamental in order to identify recurring typologies and main buildings features, allowing a classification which tackles the variation of different parameters such as number of underground floors, structural typology, horizontal and vertical structures, rigid or deformable horizontal structures including roofs and joints connections.

Buildings are grouped considering the same recurrent characteristics and statistical results provides to fill missing data about each individual structure. The identification of typologies is not immediate. Initially the 40 structural units of Safed are linked to 17 typologies, although 18 S.U. up to the 42 belong to 2 typologies. On the other hand in Acre the 42 surveyed structural unites are attributed to 9 representative structural typologies. It must be underlined that the analysed towns are characterized by some recurring typologies which are not attributable to the defined classification because of noticeable differences. They represent “exceptions” compared to the defined typologies. “The bridge house”, “the captain house” and the “Lebanon palace” are considered as “exceptions” related to the analysed blocks, even if they are recurring inside the quarters of the historical centre.

A standard volumetric module defined as consequence of geometrical data is the basis for each typological model. In the next phases, seismic analysis are also performed on it and then compared to buildings actual configuration. In fact the careful study of buildings plans allows finding measures traceable in almost all structures. A fixed interstory height is considered for all modules, defined by the average interstory height of all the buildings; same considerations are related to openings.

4 SEISMIC VULNERABILITY ANALYSIS

The next step is the seismic vulnerability analysis, which is carried out through the use of the Vulnus methodology [12].

The software provides the values of the average critical horizontal acceleration level which corresponds to the activation of in plane (I1 index) and out of plane (I2 index) mechanisms. I1 and I2 indexes provide a preliminary assessment of vulnerability: when I1 is greater than I2, the greater vulnerability is related to out of plane mechanisms, otherwise to in plane ones. Vulnus also provides a linguistic vulnerability assessment for the whole aggregate and for each structural unit which composed it. Assessments are obtained combining I1 and I2 with I3 index. I3 index evaluates some additional factors resulted from the second level GNDT form, assessing the structural deficiencies of each building. Vulnerability can also be identified using fragility curves which relate the expected values of severe damage E[Vg] in function of different values of PGA/g ratio (PGA: peak ground acceleration; g: acceleration of gravity). Fragility curves define lower, central and upper limits: the range of the most probable values of expected severe damage is enclosed between upper and lower curves.

The following analyses consider critical acceleration levels (PGA/g) referring to Israeli Code values (PGA/g=0,17 for Acre, PGA/g=0,23 for Safed) [13] and to lower values (PGA /g=0,05, PGA /g=0,06, PGA /g=0,07) possibly ascribable to historical earthquakes.

For the aggregate buildings of Safed thirty-eight structural units are analyzed. Considering I1 and I2, one index doesn't exceed the other and their distribution is diversified. A vulnerability assessment for each structural unit and for the totality of them is evaluated considering different values of PGA/g and the obtained linguistic vulnerability assessments are graphically represented in Figure 13 and Figure 14. Considering the group, it is "medium" for PGA/g=0,23, while for the other critical acceleration levels it is "very small". These assessments are confirmed by the results obtained through fragility curves. Indeed the E[Vg] values show that for PGA/g between PGA/g=0,07 and PGA/g=0,05 there is a low expectation of severe damage equal to 1,6% with the range of expectation variability between 0% and 5%. For values of PGA/g higher than PGA/g=0,23 the expectation of severe damage increases to 40% with the range between 15,5% and 58,2%.

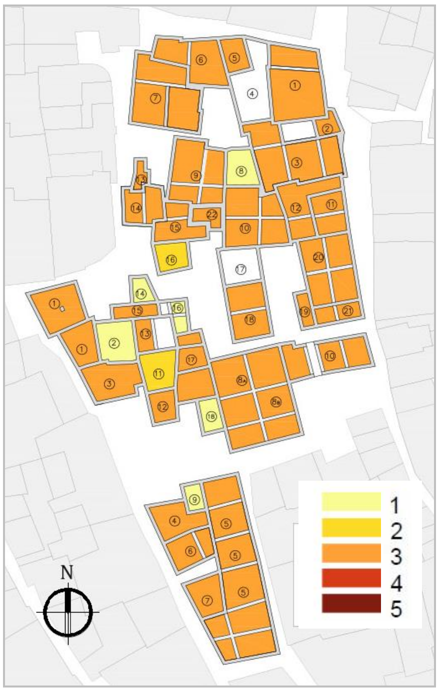

Figure 13: Graphic representation of the linguistic vulnerability assessment provided by Vulnus for PGA/g = 0.23 (1: very small; 2: small; 3: medium; 4: severe; 5: very severe)

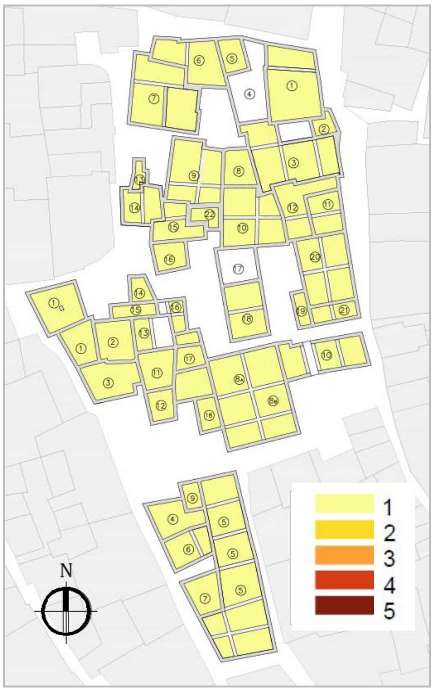

Figure 14: Graphic representation of the linguistic vulnerability assessment provided by Vulnus for PGA/g = 0.07, PGA/g = 0.06 and PGA/g = 0.05 (1: very small; 2: small; 3: medium; 4: severe; 5: very severe)

The analyses are carried out considering both real structures and standard modules representative of the existing structural and architectonical organization of the analyzed buildings. Materials, structural loads and aggregation modes are maintained. For a preliminary analysis, the buildings defined as "exceptions" for Acre are evaluated using modules in order to assess if results deviate from real structures ones and how relevant this variation is.

Concerning Safed, the comparison between I1 and I2 indexes doesn't show a clear predominance of an index compared to the other and their distribution is diversified. Comparing indexes of real structures and of modular ones, the highest index is the same for both cases in almost all models, showing a correspondence in vulnerability assessment (in plane or out of plane). Despite some differences in vulnerability assessment for some buildings, group vulnerability is kept unchanged: “medium” for PGA/g=0,17 and “very small” for lower PGA/g values.

Relevant differences between modular and realistic structures occur for those buildings defined as “exceptions” since modules regularize and simplify structures, changing dimensional parameters often significantly. The most significant variations are related to changes in story height, regularization of in plan and in elevation configuration, modification of buildings openings percentage and dimensions, regularization of their position on facades and change of conventional resistance. For instance, the “Lebanon palace” is characterized by the I1 index greater than the I2 index both in realistic and modular representation, so the vulnerability assessment (greater vulnerability for out of plane mechanisms) is still the same. Both indexes are higher in modular representation, showing an increase of in plane and out of plane building resistance which is due to halving of building interstory height, reduction of plan area and openings percentage/dimensions, and absence of internal walls. The building linguistic assessment changes and becomes definitely less severe for modular representation. The improvement is also linked to differences between I3 indexes. The main variations (for the analyzed case and for many other buildings) are noticed for in plan and in elevation configurations and for conventional resistance (the parameter provides an estimate of masonry building resistance toward horizontal actions using a simplified method which relates the building to a shear wall). Moreover the existence of double height arcade, cannot be represented using modular schematization. Furthermore the assessment given for conventional resistance is improved for modular schematization. It is therefore suitable to consider these buildings as separate typologies characterized by their own dimensional parameters.

Considering expected values of severe damage, the obtained fragility curves are compared (Figure 15 and Figure 16). They show the same trend even if E(Vg) Low is lower for modular structures: the range of most probable values of severe damage expected frequency is grown, showing lower expected values of severe damage for the level of acceleration stated by the Israeli code. Therefore, considering the curves trend, existing buildings are represented quite realistically by the module schematization.

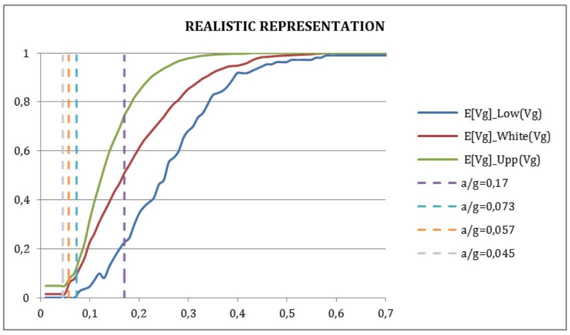

Figure 15: Fragility curves - realistic representation

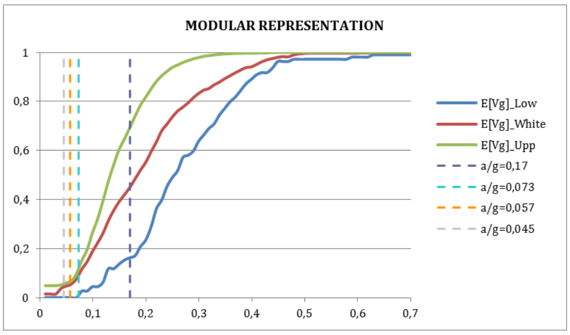

Figure 16: Fragility curves - modular representation.

In order to carry out the seismic vulnerability analysis of masonry aggregate buildings, the analysis of local mechanisms of collapse cannot be disregarded: “[…] when the building does not show a easily recognizable global behavior but responds to the earthquake as a set of subsystems (local mechanisms) […], the global analysis can be performed considering an exhaustive set of local analyses” [8].

For the towns of Acre and Safed the analyses of most probable out of plane mechanisms of collapse are performed, related to out of plane overturning and vertical bending of outer walls. In particular they are the consequence of technicians expert assessment defined during surveys and elaboration data phases.

In order to carry out the equilibrium limit approach (kinematic analyses) it is essential to identify conditions that could cause the activation of local mechanisms of damage and collapse and to evaluate the best representative configuration. These information are acquired by means of the statistical and typological analyses: walls and horizontal diaphragms materials, interactions with other elements of adjacent buildings and presence or absence of tie rods. The analyses evaluate each wall feature (one leaf wall or two leaves walls with an inner core of limited thickness) and the quality of vertical and horizontal connections is considered in terms of friction forces.

A linear kinematic analysis is performed for each local mechanism of collapse. If the analysis is not verified, a nonlinear kinematic analysis is carried out.

For all the buildings, the analyses consider the most significant out of plane mechanisms of the perimeter walls, identified through their geometrical and structural configuration and by the presence of contrasting elements.

For the town of Safed the simple overturning of essentially resting on the ground walls is performed. 52 mechanisms are evaluated and only the 11% of the performed linear kinematic analyses are verified. Nonlinear kinematic analyses are carried out and increase to the 17%. However some simplifications are necessary. For example the lack of information about vaults structure is quite significant for the results. Changing only geometrical parameters, related to the uncertainty about the real configuration (but approximately similar to it), different results are determined: a reduction of the 40% of horizontal and vertical components of vaults thrusts does not entail a significant difference in term of satisfaction of the analyses (from 11% to 14%). Otherwise it is associated to a considerable increase of the linear safety coefficient, determined by the ratio between spectral acceleration and required one. These evaluations are carried out considering the application of the vault horizontal thrust with an arm equal to the interstory high. Vice versa reducing it, there is an increase of the satisfied verification up to the 15% in the linear kinematic analyses and a resulting enhance of the safety coefficients. In safety condition and for rapid evaluation, therefore the worst geometrical configuration is considered. Nevertheless results must be examined and suitable changes could be required.

For the town of Acre simple overturning of walls essentially resting on the ground and of the upper part of them are performed. Considering the first condition, 36 mechanisms are performed and the 44% of them are satisfied in linear analysis, the 52% in non-linear one. Modifications of vaults geometry with a reduction of the 40% of their components lead to an increase up to the 55% of the linear analysis. For the overturning mechanism related to the upper part of the wall, only the 20% of the 48 walls are satisfied in non-linear analysis. Vertical bending analyses are performed considering one story. 39 walls are analyzed and the 53% are verified in nonlinear analysis.

Results of each local mechanism of collapse are represented through safety coefficients for each building. They are arranged by means of a qualitative color scale in order to highlight most vulnerable walls. In Figure 17 and Figure 18, safety coefficients of walls overturning essentially resting on the ground (worst configuration) are reported both for linear and nonlinear kinematic analyses. Nonlinear safety coefficient, determined by the ratio between ultimate displacement capacity and required displacement, is generally higher than linear one.

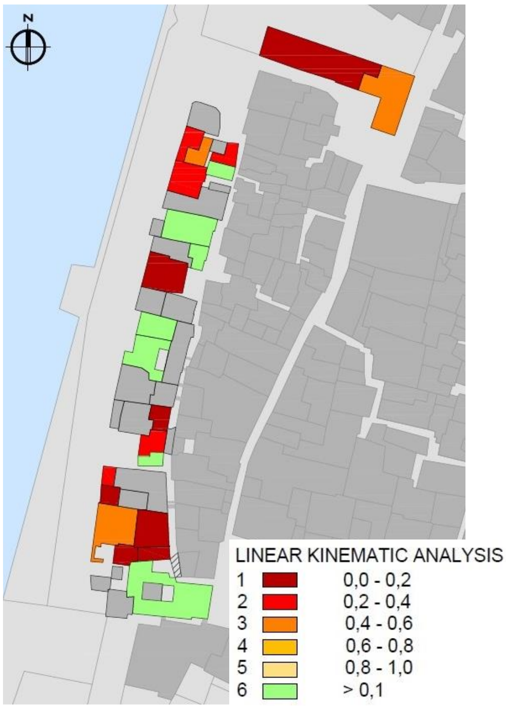

Figure 17: Representation of linear analysis results through the safety coefficient

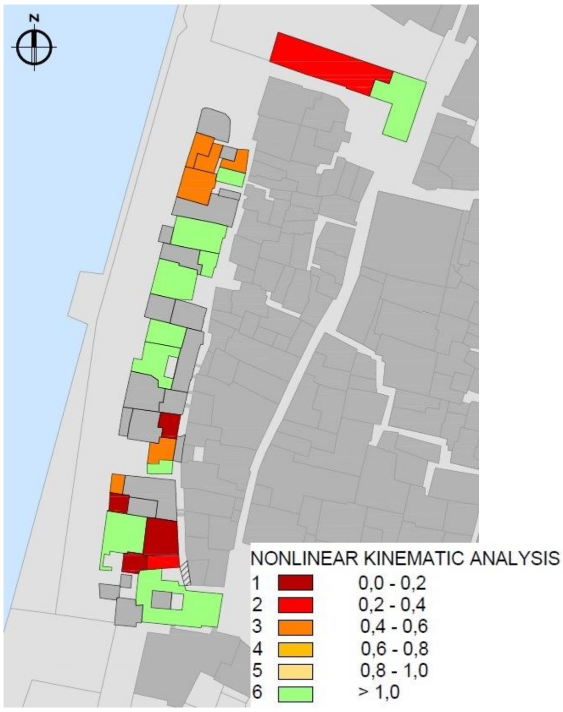

Figure 18: Representation of nonlinear analysis results through the safety coefficient

CONCLUSIONS

The development of prevention strategies cannot disregard the evaluation of the susceptibility to damage of historical buildings. In this context, a vulnerability analysis is therefore fundamental to reduce the seismic risk of existing cultural heritage.

The aim of this paper is to define a methodology for the seismic vulnerability analysis of clustered buildings in Acre and Safed. The purpose is to extend the adopted approach to other quarters of the historical centres which are characterised by same architectural and typological features. As a consequence, calibrated rapid forms to be filled on site will be drawn up in order to recognize the previously identified typologies, associating to them the seismic vulnerability assessment. Concerning a larger scale, it will be implemented to other Israeli cities. It is an ongoing study, nevertheless the substantial correspondence between the vulnerability assessment for the real case and the schematic representations through standard modules validates its applicability. Buildings defined as "exceptions", which represent particular typologies, must be separately evaluated considering specific and appropriate simplifications.

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