Structural Vulnerability Assessment under Natural Hazards: A review

D. Vamvatsikos
Department of Civil and Environmental Engineering, University of Cyprus, Cyprus

L.A. Kouris, G. Panagopoulos & A.J. Kappos
Department of Civil Engineering, Aristotle University of Thessaloniki, Greece

E. Nigro
D.I.ST., Department of Structural Engineering , University of Naples Federico II, Italy

T. Rossetto & T.O. Lloyd
Department of Civil, Environmental and Geomatic Engineering, University College London, UK

T. Stathopoulos
Department of Building, Civil and Environmental Engineering, Concordia University, Canada

ABSTRACT: The state of the art is presented in the field of structural vulnerability assessment under earthquake, landslide, tsunami and wind hazards. We seek common avenues of research and points of contact among the existing philosophies used in these four different fields in the context of multi-hazard assessment frameworks. In essence, this is a step towards the identification of a common underlying structure between different fields that will allow the future unification of vulnerability methodologies under a single framework.

1 INTRODUCTION

Structural vulnerability and associated methodologies for its assessment have been identified as a key research field in structural engineering. Vulnerability itself can be defined in multiple ways and it can be evaluated using widely different formats that are typically inconsistent with each other, especially when considering different hazards. For example, it can be defined either deterministically or probabilistically, it can be based on the concept of one or more limit-states or performance levels and it can be evaluated using static or dynamic methods including or ignoring aleatory randomness and epistemic uncertainty.

Thus, at least for frequent actions from well understood hazards such as wind, fire or snow, there are several methods to estimate it, some complex and other simplified, some of which are deeply entrenched in the professional practice, forming a cornerstone of past, current and forthcoming design codes and guidelines. On the other hand, infrequent actions from extreme natural hazards, such as floods, hurricanes, volcanoes, avalanches, tsunamis and earthquakes are often less well understood and researching methodologies for their assessment is an ongoing project. With the emergence of multi-hazard assessment concepts, it is now important to collectively discuss such methods, understand their merits and attempt to cast them in a format that is suitable for integration within a single practical assessment framework. Therefore, in the sections to follow we will present a review of existing methodologies for structural vulnerability assessment under earthquake, tsunami and wind actions.

2 SEISMIC VULNERABILITY

2.1 *General*

Seismic vulnerability can be defined as the degree of loss to a given element at risk (e.g. buildings) resulting from the occurrence of an earthquake event (Coburn & Spence, 2002). The reliable estimation of the economic, as well as human, losses incurred by an earthquake is a necessity for the development of seismic risk scenarios which are now widely accepted as an essential tool for seismic risk management and for prioritizing the pre-earthquake strengthening of the built environment (e.g. Bal et al. 2008; Kappos et al. 2008; Lang & Bachmann 2004; Strasser et al. 2008).

2.2 *Classification of the building stock*

With regard to the scope of a vulnerability study, an approach using detailed assessment of individual buildings or a coarser one utilizing appropriate classification of building populations may be adopted. The first one is usually tailored to buildings of great significance, such as monumental or important (e.g. hospitals) public buildings, while the latter is more suitable for risk scenarios in a greater urban area.

The vulnerability of monumental masonry buildings with unique historical value and a very limited population in every urban area is commonly estimated for every single monumental structure since there are some difficulties beyond the usual ones such as long history (which involves multiple phases of construction, repairs, alterations etc.), degradation of the materials, strong limitations in the experimental investigation of the strength of the materials etc.

Methods involving statistical data with structural damage from past earthquakes are insufficient in this case. Thus, the vulnerability is individually estimated using detailed (Rota et al. 2005) or more simplified (Augusti et al. 2001; Lagomarsino 2006; Lagomarsino & Podestà 2004a,b; Valluzzi 2007) models.

For the vulnerability assessment of ordinary building populations several classification methods have been proposed, taking into account characteristics that affect their seismic performance, such as the construction material (i.e. concrete, steel, brick or stone masonry, etc.), the level of seismic design and detailing, the building height, the configuration of infill panels etc. Various sets of building classifications have been proposed in the literature, as a result of the different construction practices applied in each country. An effort to introduce a classification scheme that establishes a common basis for vulnerability studies in Europe has been made within the framework of the project Risk-UE (Kappos et al. 2006, 2008, Lagomarsino & Giovinazzi 2006), in a similar fashion that HAZUS (FEMA-NIBS 2003) classification is currently considered as a reference for North America.

2.3 *Damage definition*

The choice of a damage scale for the assessment of buildings is fundamental to the definition of vulnerability functions. From the simple Green-Yellow-Red characterization to more refined damage state definitions, a wide variety of damage state sets has been proposed in order to describe damage levels from negligible damage up to collapse of the structure (ATC-13; FEMA-NIBS 2003; FEMA 273/356; SEAOC 1995; EMS-98, etc.). Comparisons between several approaches have been presented by Hill & Rossetto (2008), along with the proposal of a homogenized scale for R/C buildings (Rossetto & Elnashai 2003).

Each damage state can be defined in terms of structural and non-structural damage, as well as in economic or loss terms such as the ratio of repair cost to replacement cost (Kappos et al. 2006). Damage state descriptions can be different for various building classes since damage evolves at varying rates in structures with different characteristics (i.e. R/C and masonry buildings). Furthermore, economic approaches introduce a time and location dependency that can limit the scale application and lead to erroneous physical damage predictions (Miyakoshi et al. 1997), especially if used in absolute, instead of normalised terms.

2.4 *Ground motion characterisation*

The choice of a ground motion parameter that represents the seismic demand is crucial for the vulnerability assessment of buildings. Mercalli-type intensity based approaches (e.g. ATC-13) can be misleading since it is a rather subjective quantity, associated with a great amount of uncertainties, that is also dependant on the performance of the building stock. Nevertheless, the fact that the limited available damage data (see next section) is usually associated with intensity levels leads to the need of incorporating them into many vulnerability assessment procedures.

Direct ground motion quantities such as PGA or PGV can be utilized (Kappos et al. 2006, 2010; Boatwright et al. 2001) or even spectral quantities like S_d (HAZUS) or S_a (Singhal & Kiremidjian, 1996) to account for the frequency content of seismic motion. An extensive investigation on the correlation of building performance with recorded ground motion and the subsequent development of empirical motion-damage relationships in the form of log-normal fragility curves has been carried out by King et al. (2005).

2.5 *Vulnerability functions*

While for individual buildings the capacity curves (derived from inelastic pushover analyses) seem to be convenient for the description of their seismic performance, for populations of buildings a probabilistic approach is usually adopted. The building stock of an urban area is classified in a limited number of categories (classes) with, approximately, equal vulnerability (see section 2.2). Each class is related to a cluster of vulnerability (fragility) curves, or equivalently to a damage probability matrix (DPM). Vulnerability curves relate, for a predefined damage degree, the severity of the seismic motion with the probability that the damage suffered by the structure will exceed this specific damage degree. Similarly, each term of a DPM represents the probability that a building class suffers a certain degree of damage (e.g. light, moderate, severe, collapse), when struck by an earthquake of a predefined severity level (the macroseismic intensity is usually utilized herein).

Existing vulnerability curves can be classified into the four generic groups of empirical, judgmental, analytical, and hybrid, according to whether the damage data used in their generation stems mainly from observed post-earthquake surveys, expert opinion, analytical simulations, or combinations of these (Rossetto & Elnashai 2003).

2.5.1 *Empirical approach*

The construction of empirical vulnerability curves (or the corresponding DPM's) requires available statistical damage data reported in post-earthquake surveys from previous seismic events (Rota et al. 2008; Spence et al. 2008). The observational source, when available, is the most realistic as all practical details of the exposed stock are taken into consideration alongside soil–structure interaction effects, topography, site, path and source characteristics (Rossetto & Elnashai 2003).

The most common problem when applying a purely empirical approach is the unavailability of (sufficient and reliable) statistical data for several intensities. By definition, Modified Mercalli Intensities up to five lead to negligible damage, particularly cost-wise, therefore gathering of damage data is not feasible, while, on the other hand, events with intensities greater than nine are rare, especially in Europe, so there are not enough data available. This unavailability leads to a relative abundance of statistical data in the intensity range from 6 to 8 and a lack of data for the other intensities, making difficult the selection of an appropriate cumulative distribution, since the curve fit error is significant and the curve shape not as expected. The absence of available data necessitates recourse to other procedures such as expert judgement (Fäh et al. 2001; Oliveira 2008). A convenient but sometimes misleading approach of adopting data from different regions with similar construction practices should be treated with caution. A good example of the problems involved in adopting models from another country is outlined in the paper by Barbat et al. (1996) who had to adapt the vulnerability models developed for Italian masonry buildings to study the ones in Barcelona

2.5.2 *Judgement-based and rating methods*

The concept of judgement-based methods involves use of the opinions of expert panels of engineers with experience in earthquake engineering who are asked to make estimates of the likely damage distribution within building populations when subjected to earthquakes of different intensities. Although the reliability of such methods can be questionable due to the subjectivity of each expert engineer, these methods were used as the predominant source in the United States for the generation of damage probability matrices and vulnerability curves (ATC-13).

Rating methods adopt the idea that experienced engineers fill in special questionnaires, which include structural characteristics of the buildings that affect their seismic vulnerability. The final outcome of these methods is typically a vulnerability index. The magnitude of this index represents the building capacity against earthquake. Sometimes, for the derivation of the rating, analytical procedures are also needed, hence the entire procedure can be classified as hybrid.

A very detailed method for masonry buildings was developed by the GNDT (1989) (see also Benedetti et al. 1988; Casciati et al. 1994). The GNDT method includes the filling of two forms: at level 1 collection, building by building, of some informative elements; at level 2 qualitative and quantitative aspects referring to the configuration, foundation type, material quality etc. are scored (in four classes) and lead to the vulnerability index. Modification of this methodology has been developed for the application in other types of masonry buildings (Gent Franch et al. 2008). These methodologies have been applied for the estimation of the expected building damage for a deterministic hazard in several urban centres (Cole, Xu, & Burton 2008; Grant et al. 2007; Faccioli et al. 1999).

2.5.3 *Analytical approach*

Analytical vulnerability curves adopt damage distributions simulated from the analyses of structural models under increasing earthquake loads. The analytical procedure followed ranges in complexity from the elastic analysis of equivalent single-degree-of-freedom systems (Mosalam et al. 1997) to inelastic pushover analysis (HAZUS), or non-linear time history analyses, of realistic models of reinforced concrete (R/C) structures, mostly in 2D (Singhal & Kiremidjian 1997, Masi 1998, 2006), to reduce the cost of analysis. Several analysis-based curves have also been proposed for the vulnerability assessment of masonry buildings (Barbat et al. 2008; Borzi et al. 2008; Erberik 2008a,b; Lang 2002; Lang & Bachmann 2003; Park et al. 2009).

Significant work has recently appeared in codified documents on the analytical estimation of vulnerability or fragility of buildings and bridges, based on nonlinear analysis methods. For example, ASCE/SEI 41 (2007) and Eurocode 8 (2004) offer a comprehensive methodology based on the static pushover method. On the other hand, the SAC/FEMA-350 (2000) guidelines propose the use of nonlinear timehistory analyses, encompassing the use of incremental dynamic analysis (IDA, Vamvatsikos & Cornell 2002) for the assessment of seismic demand and capacity.

Purely analytical approaches should, in principle, be avoided, since they might seriously diverge from reality, typically (but not consistently) overestimating the cost of damage (Kappos 2001). Analytical methods should be supported by experimental results in order to increase their reliability (Ruiz-García & Negrete 2009).

2.5.4 *Hybrid approach*

Hybrid vulnerability curves attempt to compensate for the scarcity of observational data, subjectivity of judgemental data and modelling deficiencies of analytical procedures, by combining data from different sources.

Kappos and his co-workers have developed over the previous years a hybrid methodology that combines statistical data with appropriately processed results (utilising repair-cost models) from nonlinear dynamic or static analyses, which permit interpolation and (under certain conditions) extrapolation of statistical data to PGAs and/or spectral displacements for which no data is available (Kappos et al. 1998, 2006, 2010). An extensive set of 54 building classes for R/C and 4 unreinforced masonry (URM) building classes has been analysed, representing most of the common typologies in S. Europe.

All statistical data are from earthquakes that struck Greece in the past few decades. The analytical part of the procedure differs with regard to the structural material, since for URM buildings only pushover analyses have been utilized, while for R/C buildings both incremental inelastic dynamic (for 16 dully selected accelerograms) and static analyses have been tackled. Vulnerability curves are derived in terms of peak ground acceleration or spectral displacement. A lognormal distribution was assumed for constructing fragility curves for each class (common assumption in seismic fragility studies). Median values for each damage state in the R/C fragility curves were estimated based on the plot of the damage index (defined as the ratio of repair cost to replacement cost) against a function of the earthquake intensity (PGA) through incremental dynamic analysis, until collapse. These plots are then corrected using the corresponding available statistical data and appropriate empirical weighting factors based on the reliability of the statistical data (Kappos & Panagopoulos 2010). Fig. 1 shows a complete set of fragility curves (for 5 damage states) for old, medium-rise, R/C buildings with dual (wall+frame) system, without significant discontinuities in the arrangement of masonry infills.

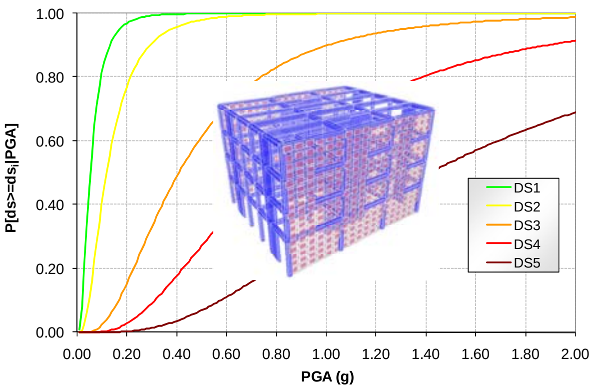


Figure 1. Fragility curves in terms of PGA for low code, medium rise, regularly infilled R/C buildings with dual system

The hybrid approach for vulnerability assessment of masonry buildings combines statistical data with appropriately processed results from nonlinear static analyses. The statistical data used for masonry buildings were from Greek earthquakes, i.e. the Thessaloniki 1978 and the Aegion 1995 events, with some additional data from the Pyrgos 1993 earthquake used for comparison (Penelis, Kappos & Stylianidis 2003). Non-linear analysis of masonry buildings is generally more cumbersome than that of R/C ones. A simplified equivalent frame model with concentrated non-linearity at the ends of the structural elements can be used for the non-linear static analysis of masonry buildings (Penelis 2006; Borzi, Crowley, & Pinho 2008). The damage (limit) states can be defined according to a drift-based damage index (Calvi 1999). An alternative definition, more suitable when pushover curves have been derived for the building classes studied, is to express the damage states as a function of the yield and the ultimate displacement of each building (Penelis et al. 2003). However, statistical data are not available in such terms; as said previously, in Greece statistics were available in terms of the economic damage index (ratio of repair to replacement cost). Hence, a correlation between the two sets of definitions is necessary for applying the hybrid approach, as proposed in Penelis et al. (2003) and Kappos (2007).

Fragility curves for URM buildings can be derived either in terms of PGA (as in Fig. 2) or of S_d; in the hybrid procedure these values are inevitably based on the spectra of the specific ground motions recorded in the (broader) areas wherein damage statistics are available. It is noted that the S_d-based procedure is more sensitive to the type of 'representative' spectra selected for each earthquake intensity.

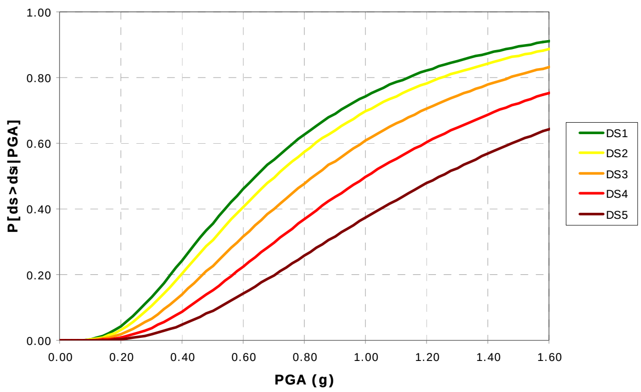


Figure 2. Fragility curves for single-storey stone-masonry buildings.

An earthquake loss scenario for contemporary and historical buildings in Thessaloniki has been developed by the AUTh group (Kappos et al. 2007; Kappos, Panagopoulos & Penelis 2008) using the aforementioned methodology.

2.6 *Epistemic uncertainty*

Epistemic uncertainties stem from the incomplete knowledge of the actual problem and its parameters, or simply from the, often unavoidable, modelling and methodology errors. The estimation of the seismic vulnerability under the influence of such uncertainties has been recognized as an important constituent of the structural design and analysis process, as exemplified, at least qualitatively, by the SAC/ FEMA-350 guidelines (FEMA, 2000). Nevertheless, only recently have we seen actual attempts to quantify this effect for realistic structural models in a way that is consistent with current performance-based earthquake engineering frameworks.

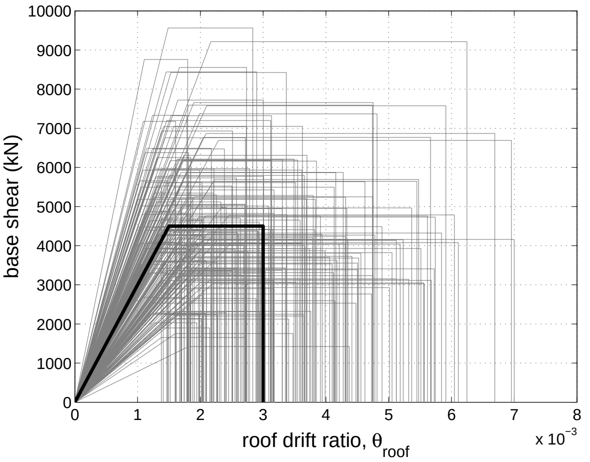


Figure 3. 200 realizations of static pushover capacity curves for a two story masonry building, caused by epistemic uncertainty (Vamvatsikos & Pantazopoulou 2010).

Such studies include mainly the work of Dolsek (2008), Liel et al (2009) and Vamvatsikos & Fragiadakis (2010) who propose methods to account for the uncertainty in modelling parameters and its effect on the estimated structural fragility using Monte Carlo techniques on incremental dynamic analysis. However, such methodologies remain computationally intensive and often difficult to apply for practical purposes. As a partial remedy, Fragiadakis & Vamvatsikos (2010) have offered a simplified process based on the static pushover and the SPO2IDA tool (Vamvatsikos & Cornell 2005) that manages at least two orders of magnitude reduction in the processing load at an insignificant loss of accuracy for first-mode dominated buildings. Finally, on the same track, Vamvatsikos & Pantazopoulou (2010) have recently applied such efficient techniques for the simplified evaluation of the seismic vulnerability of groups of masonry structures, typical of historical city cores. Nevertheless, there is still considerable room for refinement in this area, and future developments will play a major role in the new generation of seismic guidelines.

3 VULNERABILITY TO LANDSLIDES AND FLOWSLIDES

Flowslides and debris flows can be considered as one of the most dangerous slope movements for their capability to produce casualties and remarkable economic damage. Such phenomena are widespread in many countries and involve different kind of soils, generally in a loose state, which in the post failure stage collapse and rapidly reach the toe of the slope; the initial mobilised mass often increases during its path downslope either by inducing additional slope failure and/or by eroding the stable in place soils (Cascini *et al.*, 2003).

Significant examples of this type of slope movements have occurred in several areas of the world. For example, those periodically occurring in the Campania Region (South Italy) triggered by critical rainfall events. They involve unsaturated pyroclastic soils – originated by the explosive phases of the Somma-Vesuvius volcano – which mantle the limestone and tuffaceous slopes over an area of about 3000 km^2 .

In this area, there are more than 200 towns that frequently suffer from flowslides, as pointed out by historical data acquired over a period from the 16^{th} century up to the present (Cascini & Ferlisi, 2003). One of the worst events occurred on May 5-6, 1998, when 159 casualties and serious damages were recorded in four towns (Bracigliano, Quindici, Sarno and Siano) located at the toe of the Pizzo d’Alvano relief. During the quoted hydrogeological disaster of 1998 in the Campania Region, numerous flowslides due to the detachment of the pyroclastic deposits from the calcareous massif of “Pizzo d'Alvano” impacted the structures which were located near incisions and valleys, determining wide-spread damage.

The following paragraphs contain the description and the assessment models concerning the effects of the dynamic impact of the flowslide on structures, generally buildings, with special care taken of structural resistance and/or vulnerability.

3.1 *Damage and collapse mechanisms*

The surveys and the analysis of building damage during the quoted hydrogeological disaster of 1998 in the Campania Region, realised immediately after the event, allow us to better understand the impact of debris flows on structures and their collapse mechanisms and allow an evaluation of the impact velocity of the flows on the structures (Faella & Nigro, 2003a,b).

The effects of the debris flow impact are significantly different depending on the following parameters:

– position of the structure with reference to the impact direction (Figure 4);
– level of kinetic energy of the debris flow, related to its velocity;
– structural typology (reinforced-concrete or masonry buildings, structural or non-structural members).

On the basis of the analysis of the structural and non-structural damages in the buildings impacted by the debris flows, it is possible to derive the following synthesis (see Faella & Nigro, 2003a), referring to the main collapse mechanisms (Figures 5–6):

– *Reinforced concrete framed buildings:*
  A) Collapse of the ground floor external walls, directly impacted by the flows, without significant damage to the structural parts (columns and beams);
  B) Serious damage or collapse of single structural elements, generally columns, without collapse of the whole structure, but with formation of

plastic hinges at the ends and/or in the midspan of the columns;

C) Serious damage and/or collapse of the structure, with formation of floor mechanism (plastic hinges at the top and bottom of the column);

D) Translation of part of the building as a consequence of the collapse of the ground floor bearing structures.

– *Masonry buildings:*

E) Serious damage and/or collapse of bearings walls at ground floor, directly impacted by flows, without collapse of the overall building;

F) Serious damage and/or collapse of the overall building.

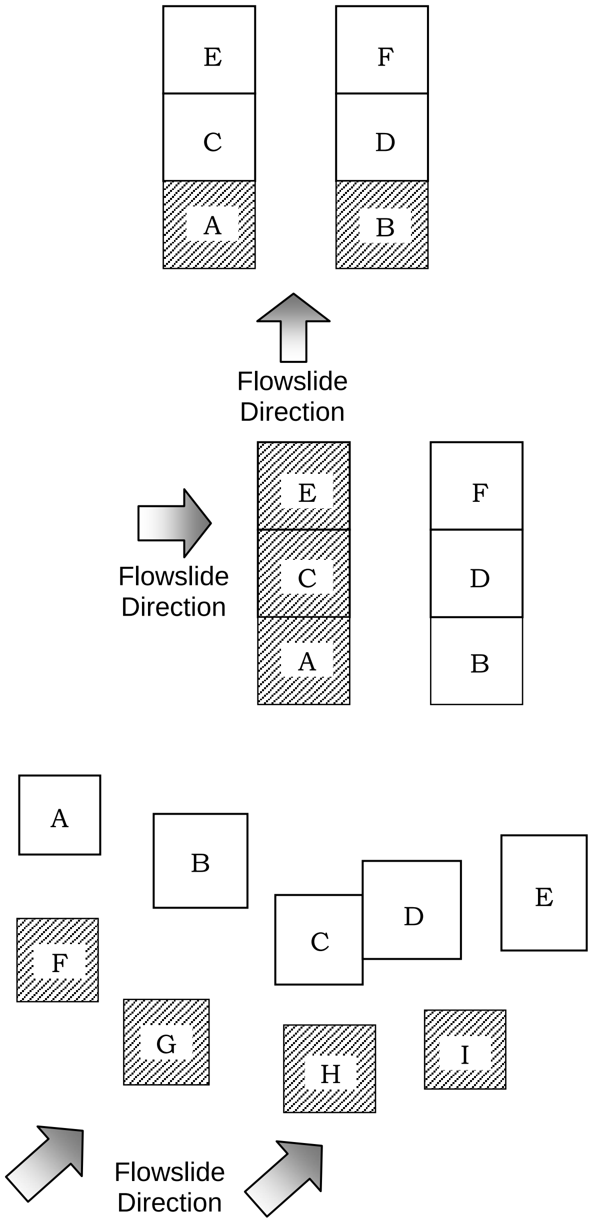


Figure 4: Position of the structure with reference to the impact direction of the flowslide.

The described types of damages may be interpreted by means of appropriate collapse mechanisms in order to assess the bearing capacity at the ultimate limit state of elements or of the overall structure and, with furthermore considerations of hydrostatic and hydrodynamic, also an approximate evaluation of the impact velocity of the debris flows.

Figure 5a,b: R.C. structures: (a) Plastic collapse mechanism of columns; (b) Failure of corner column.

Figure 6a,b: (a) Masonry building impacted by debris flows; (b) Residual parts of masonry buildings

3.2 *Vulnerability assessment of structures subjected to flowslides*

The analysis and the interpretation of the structural and non-structural damages in the buildings impacted by the debris flows point out some types of collapse mechanisms for reinforced concrete and masonry buildings, described in the previous paragraphs.

The described damage types can be interpreted by means of appropriate collapse mechanisms, which allow us to assess the ultimate bearing capacity of members or of the overall structure. The comparison between the ultimate bearing capacity and hydrostatic and hydrodynamic thrusts due to the flow impact on the structures allows assessment of the impact velocity which determines the collapse of the member or the structure. In the hydrodynamic models the hypothesis of a fluid stream of constant density is assumed, neglecting the possible presence of mass concentration (for instance trees, rocks and other transported material).

In Table 1 and Table 2 the mechanical models related to the main collapse mechanisms and the analytical formulations to evaluate the corresponding impact velocities are summarised with reference to reinforced concrete and masonry structures, respectively. More details can be found in Faella & Nigro (2003b).

Table 1. Collapse resistant models for assessment of reinforced concrete buildings

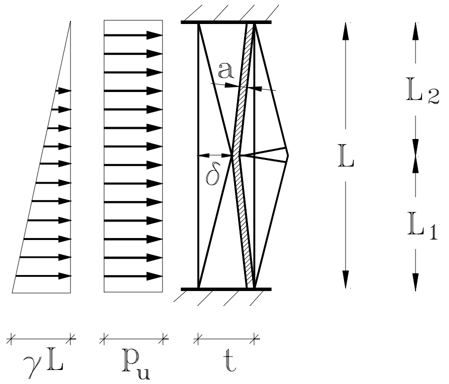
Type-A Mechanism

Collapse of the tuff or brick external walls

$$p_u = \frac{P_u \cdot 2}{L} - \frac{1}{2} \cdot \gamma \cdot L$$

$$p = C_f \cdot \rho \cdot V^2 \cdot \cos^2 \alpha = \frac{\gamma}{g} \cdot V^2 \cdot \cos^2 \alpha$$

$$V = \sqrt{\frac{g}{\gamma} \cdot \frac{p_u}{\cos^2 \alpha}} = \frac{1}{\cos \alpha} \sqrt{\frac{g}{\gamma} \cdot \left(\frac{P_u \cdot 2}{L} - \frac{1}{2} \cdot \gamma \cdot L \right)}$$



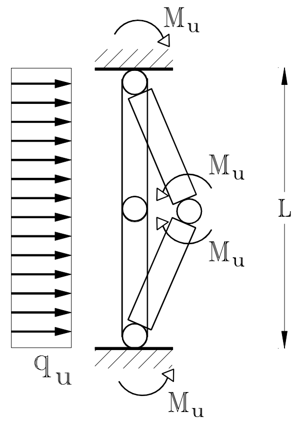
Type-B Mechanism

Three-plastic-hinges collapse mechanism in reinforced concrete columns

$$q_u = \frac{16 \cdot M_u}{L^2}$$

$$q = C_f \cdot \rho \cdot D \cdot V^2 = \frac{\gamma}{g} \cdot D \cdot V^2$$

$$V = \sqrt{\frac{g}{\gamma} \cdot \frac{q_u}{D}} = \sqrt{\frac{g}{\gamma} \cdot \frac{16 \cdot M_u}{L^2 \cdot D}}$$



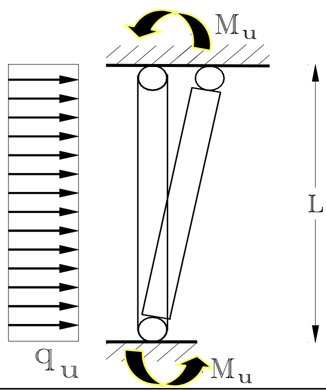
Type-C Mechanism

Two-plastic-hinges collapse mechanism in reinforced concrete columns

$$q_u = \frac{4 \cdot M_u}{L^2}$$

$$V = \sqrt{\frac{g}{\gamma} \cdot \frac{q_u}{D}} = \sqrt{\frac{g}{\gamma} \cdot \frac{4 \cdot M_u}{L^2 \cdot D}}$$

$$V = \sqrt{\frac{g}{\gamma} \cdot \frac{4 \cdot \sum_i M_{u,i}}{L^2 \cdot \sum_i D_i}}$$



Type-D Mechanism

Shear collapse mechanism in reinforced concrete columns

$$q_u = \frac{2 \cdot T_u}{L}$$

$$q_u = \frac{2 \cdot T_u}{L} \cdot \frac{1}{L_1 / L \cdot (2 - L_1 / L)}$$

$$V = \sqrt{\frac{g}{\gamma} \cdot \frac{q_u}{D}}$$

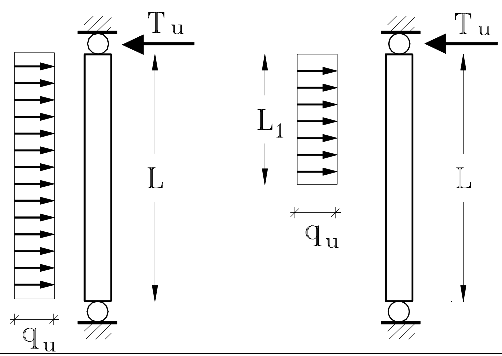


Table 2. Collapse resistant model for assessment of masonry buildings

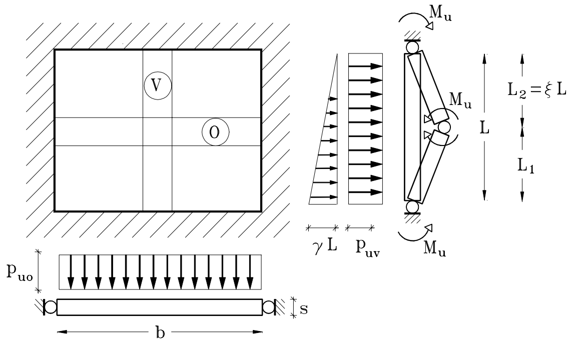
Type-E Mechanism

Debris flow impact against the ground floor walls of masonry buildings

$$p_{uv} = \frac{4 \cdot M_u}{L^2 \cdot \xi \cdot (1-\xi)} - \frac{\gamma \cdot L}{3} \cdot (1+\xi)$$

$$p_{uo} = 2 \cdot \tau_k \cdot \frac{s}{b}$$

$$V = \sqrt{\frac{g}{\gamma} \cdot \frac{p_u}{\cos^2 \alpha}} = \frac{1}{\cos \alpha} \sqrt{\frac{g}{\gamma} \cdot (p_{uv} + p_{uo})}$$



It is important, to point out the uncertainties in both of the hydrodynamic and structural models. In the hydrodynamic models, the direction of the debris flow has to be assumed on the basis of the position of the structure, considering with approximate formulations the influence of the impacted member shape; moreover, the height of the debris flows is generally assumed equal to the first floor height on the basis of the surveys of the real cases. In the structural models, the approximations refer to the material strength and the evaluation of the internal forces due to vertical loads. Nevertheless, the whole approximations do not invalidate the results of the assessing models, due to the moderate influence of the different parameters of uncertainty.

3.3 *Application of the models for vulnerability of structures subjected to flowslides*

The models described in the previous paragraph are now applied to some significant buildings, selected between those surveyed in the post-event of the quoted hydrogeological disaster of 1998 in the Campania Region, with the purpose to assess the debris flow impact velocity on the basis of the surveyed damages.

In some cases it is possible only to deduce a lower bound of the velocity, as for instance in the case of masonry walls destroyed by the debris flow and in the case of global collapse of the building. In other cases, instead, the range which contains the probable impact velocity can be evaluated: this is possible, for instance, when the debris flow has destroyed the external walls of a reinforced concrete building without the failure of the ground-floor columns, or when some impacted columns have collapsed and others have withstood the impact due to their greater bearing capacity. (the last one is the case of Figure 5).

In the application of the interpretative models described in the previous paragraph it is assumed that the specific weight of the fluid is equal to $\gamma = 14.00$ kN/m^3 (density $\rho = 1427.1$ kg/m^3). The complete results in terms of debris flow impact velocity are reported in Faella & Nigro (2003b). The analysis of the results allows some interesting remarks:

- The collapse of masonry buildings impacted by debris flows occurs in the presence of relatively low velocities (approximately lower than 5÷6 m/s); in some cases, moreover, only hydrostatic thrust is enough to determine the collapse.
- The collapse of external walls in reinforced concrete buildings occur for very low velocities (about 3 m/s).
- Reinforced concrete buildings completely impacted by debris flows exhibit intermediate values of collapse velocity (about 10 m/s); in this case the collapse model is interpreted by the two-plastic-hinges mechanism (see type-C mechanism in Table 1), related to the formation of storey-failure-mechanism at the ground floor.
- In the case of reinforced concrete buildings only partially impacted by debris flow, instead, the failure of single columns may occur; the corresponding velocities are greater than the previous cases (within the range 15÷20 m/s), due to the most favourable three-plastic-hinges failure mechanism (see type-B mechanism – Table 1).
- Obviously, the obtained results are related to the examined building types, characterised by two or three-floors buildings; if the number of floors increases, the collapse velocity also increases both for masonry and reinforced concrete buildings: in the first case, the resistance capacity of the ground-floor walls increases thanks to the increments of the acting vertical load and the wall thickness; in the second case, the geometric dimensions of the ground floor columns and the corresponding axial forces increase, determining the increment of the ultimate bending moments.

Finally, the main topic of this subsection is to investigate the possible effects of flowslides on the urban areas exposed to such risks, e.g., the urban areas around the Vesuvius. With this aim, mechanical models deduced utilizing also hydrodynamic concepts are introduced; the models are capable of interpreting the effects of the landslide impact on structures and the collapse mechanisms of various types of structures. The application of these models to building types representative of the urban areas around the Vesuvius allow us to estimate their vulnerability against the expected landslide events, providing some useful information concerning the risk mitigation.

4 TSUNAMI VULNERABILITY

Vulnerability analysis is a concept still in it's infancy for tsunami hazard assessment. It is fraught with issues due to scarcity of events, which result in lack of knowledge on their behaviour in the near and onshore regions. Due to their rarity, observational damage data required for the generation of vulnerability curves is insufficient. Nevertheless, the potential value of such vulnerability curves has meant several researchers have tried to derive vulnerability functions based on particular events using data from damage surveys (e.g. Peiris 2006, Ruangrassamee et al. 2006 and Reese et al. 2007). These empirical vulnerability functions are based on few data points and due to the nature of recent tsunami events encompass only certain types of non-engineered buildings (generally low-rise masonry). Koshimura et al. (2009) have attempted to improve their sample of damage data through the interpretation of building damage from pre- and post- tsunami satellite imagery. Although this does produce a larger sample size, only the damage state of collapse can really be identified from the satellite imagery. Also, structure type cannot be discerned from the roof type and hence all buildings are considered together.

Assets that play a key role in the response to disaster like tsunami are often elements of the transport infrastructure. A functional road network is essential for rapid evacuation, the deployment of medical supplies and movement of injured persons. Serviceable routes for transportation continue to be vital during the recovery stage for the management of reconstruction. However, though there are limited studies regarding vulnerability of structures, even fewer exists for the assessment of the often critical bridges in transport infrastructure. Shoji & Moriyama (2007) examined the vulnerability of bridge structures in Indonesia and Sri Lanka following the Boxing Day 2004 Indian Ocean tsunami. 60 data from Sri Lanka and 27 from Indonesia (collected by the JSCE) were used to derive vulnerability curves using inundation height only as the severity parameter. Differences in vulnerability were found between the two locations and also between bridge construction types, though the data was limited in quantity. Similar studies and damage data collection for future events would be advantageous to this type of work.

All existing empirical vulnerability functions for tsunami adopt inundation depth as the parameter describing tsunami flow intensity, as this is one of the only measurable parameters of tsunami onshore flow that can be obtained in the field following an event (e.g. through observation of water level marks on the sides of buildings). Most tsunami design codes, where they exist (FEMA 2008, Okada *et al* 2005), predominantly use inundation heights to derive maximum forces for design, so this is a reasonable parameter to link to vulnerability. However, it should be noted that design formulae for pressures and forces are also dependant on velocity, so height of water alone may not be the sole parameter that should be considered. Unfortunately readings of tsunami velocities are almost always not available. Discrepancies in the determination of these forces also exist between various design guides from around the world. Koshimura *et al.* (2009) adopt a numerical model to simulate the onshore flow of the Indian Ocean Tsunami in Banda Aceh. The numerical model is based on non-linear shallow water wave equations and the presence of structures is accounted for as an additional roughness term. This numerical model is shown to provide reasonable inundation depths but unrealistic flow velocities. This observation is common to most commercial numerical models for onshore flow estimation, with none being able to account for the complex interaction between the water, buildings, sediments etc. Hence, the derivation of vulnerability functions is hindered significantly by a lack of appropriate numerical models, and the development of the latter is hampered by the scarcity of field data for their calibration and validation. This also causes a significant problem for the development of methods for the assessment of individual structures for tsunami actions.

Codes and guidance is an ongoing area of research. Where they exist, the prescriptive steps to assessing a structure in terms of its tsunami vulnerability is not usually dealt with, rather pointers as to what analysis is needed are given. Some codes give example calculations for certain types of force (FEMA 2005), but significant engineering judgment is required for all such designs. An issue with the force calculations present in codes is the data they are based upon. Actual measurements from tsunami in the ocean have been limited to tide gauge data (elevations) which often get drowned out and are subject alteration of the wave due to interactions with the continental shelf. Tsunami buoys and bottom pressure sensors have been deployed in an attempt to acquire readings in this area for the validation of numerical models. This data while extremely useful for offshore modeling bears very little correlation with what actually happens in the near shore region, and inundation zone. Unfortunately there is no such data recording forces on structures and what information is available is due to physical scale models. Wave modeling until recently has been entirely conducted using piston-type wave generators which have limited stroke length, so the wave length of the generated wave is a limiting factor to the generation of realistic tsunami waves. To address this problem a novel pneumatic system of wave generation has been developed (Lloyd *et al*, 2009, Rossetto *et al.* 2010). In 2008-9 large-scale tests were carried out in a flume in HR Wallingford in the UK specifically to look at near shore and onshore processes. In these experiments, velocity, pressure and force measurements of waves on model building structures have been determined and a better understanding of tsunami forces will be gained enabling better vulnerability analysis in the future. Physical modeling undoubtedly still has a large role in better understanding tsunami and developing better design codes to deal with them.

5 VULNERABILITY TO STRONG WIND EVENTS — HURRICANES

Existing studies on the vulnerability of structures to extreme wind events are generally classified as dealing with (a) damage assessment, (b) field examinations of wind-structure interaction and (c) hurricane risk assessment from the insurance perspective. We will discuss each of these categories in the pages to follow.

5.1 *Damage assessment*

Research in this area mostly deals with observed damage from extreme wind events. The main objectives are to correlate building damage intensity to measured wind speeds and to examine building performance for those cases where wind speeds were close to building code values. A good example is the work of Mehta et al (1983). Therein, buildings were grouped in various categories:

- Fully engineered buildings, which performed well, even for wind speeds above the code-specified values. Limited damage was observed on roofing material and façade.
- Pre-engineered buildings suffered from structural framing damage for wind speeds close to, or over, the code-suggested values. Weak links (e.g. overhead door) were identified in such structures and held responsible for progressive damage.
- Marginally engineered buildings, which were affected significantly at all wind speed regimes.
- Non-engineered buildings, which were severely damaged when wind speed reached the code-specified values.

Furthermore, wind-induced damage can be classified to structural (lack of uplift load path, roof sheathing loss at corners and gable end wall loss) and non-structural (loss of roof shingles and vinyl siding, vulnerability of soffits, breach through attic vents and better performance of hip roofs over gable roofs) – see Van de Lindt et al (2007). The concept of wind load path has been also used and discussed by Stathopoulos et al (2008).

5.2 *Field studies of wind-structure interaction*

This category deals with the effect of wind-structure interaction, which can be very important for groups of buildings, where the wind force acting on each building is heavily influenced by the nearby structures that may be shielding it or channeling the wind. Typical studies of this type include the following:

- National Bureau of Standards (Marshall 1975)
- Aylesbury Experiment (Eaton & Mayne 1975)
- Texas Tech University Project - WERFL (Levitan et al. 1990)
- Silsoe Structure – BRE (Robertson & Glass, 1988)
- Southern Shores Project (Caracoglia & Jones 2004)
- Florida Coastal Monitoring Project – FCMP (Datin et al., 2006)
- Load Paths on Wood Buildings and Engineering Design of Low-Rise Wood Buildings Projects (Doudak 2005 and Zisis 2007)
- International Hurricane Research Center and Florida International University (Leatherman et al. 2007)
- Insurance Research Lab for Better Housing (Bartlett et al. 2007).

5.3 *Hurricane risk assessment*

Within the context of insurance and risk modeling, it has become important to estimate the risk faced by structures, especially in the catastrophic event of a hurricane. Friedman (1984) has discussed the Risk related information related to hurricane events in the context of defining risk assessment models to be used for insurance purposes. Furthermore, he has dealt with the loss-producing potential of a structure influenced by various factors, among which is vulnerability, and also with wind speed-damage models used by insurance companies

Berz & Smolka (1988) attempted to carry out risk assessment and rating, which involve not only detailed weather data but information regarding local design and construction practices. Khanduri & Morrow (2002) discussed vulnerability assessment of buildings to strong wind events. Their effort was mainly focused on refining the “general” vulnerability models by specific and detailed models related to factors such as different building types, occupancy, construction material, height etc. Finally, Stewart (2003) offers a discussion about building vulnerability models for hurricane/cyclone events, especially on the effect of vulnerability variations (e.g. retrofitting, enhancement of building standards etc) on existing models.

6 CONCLUSIONS

Although we have only briefly touched upon a number of difficult problems, it appears that there is a common structure underlying the estimation of seismic, landslide, tsunami and wind vulnerability of structures. There is a significant focus on the use of empirical data from historical events while there are many efforts underway to provide powerful analytical tools to assess vulnerability at various scales, ranging from a single building up to an entire city. This is especially true for the more mature fields of seismic and wind research were abundant data and methodologies are available. On the other hand, comparative research efforts in landslide and tsunami modeling are still under way but on the right path to catch up eventually. In summary, it seems that the proper groundwork already exists for preparing a common framework for vulnerability assessment in all four areas, and it is expected that future research will lead towards this promising direction.

7 REFERENCES

Ambraseys, NN. 1962. Data for the investigation of the seismic sea-waves in the eastern Mediterranean. Bull. Seismol. Soc. Am. 52, 895-913

ASCE/SEI 41, 2007. ASCE Standard ASCE/SEI 41-06, *Seismic Rehabilitation of Existing Buildings*, ASCE, Reston, VA.

ATC. 1985. *Earthquake damage evaluation data for California*. Applied Technology Council Report ATC-13, Redwood City, California, USA

ATC. 1996 *ATC-40: Seismic evaluation and retrofit of concrete buildings*, Rep. SSC 96-01, CSSC-ATC, Redwood City, California, USA

Augusti, G., M. Ciampoli & P. Giovenale. 2001. Seismic vulnerability of monumental buildings. *Structural Safety* 23, (3): 253-74.

Bal, I. E., H. Crowley & R. Pinho. 2008. Displacement-based earthquake loss assessment for an earthquake scenario in istanbul. *J.Earthqu.Eng.* 12, (SUPPL. 2): 12-22.

Barbat, A.H., Moya, F.Y., Canas, J.A., et al. 1996. Damage Scenarios Simulation for Seismic Risk Assessment in Urban Zones. *Earthquake Spectra* 12(3): 371-394.

Barbat, A. H., L. G. Pujades & N. Lantada. 2008. Seismic damage evaluation in urban areas using the capacity spectrum method: Application to barcelona. *Soil Dynamics and Earthquake Engineering* 28, (10-11): 851-65.

Bartlett, F. M., Galsworthy, J. K., Henderson, D., Hong, H. P., Iizumi, E., Inculet, D. R., et al., 2007. The three little pigs project: A new test facility for full-scale small buildings. 12th International Conference on Wind Engineering, Cairns, Australia. 1623-1630.

Berz, G. & Smolka, A., 1988. Windstorm hazard and insurance. Journal of Wind Engineering and Industrial Aerodynamics, 30, 191-204.

Benedetti, D., G. Benzoni & M. Parisi. 1988. Seismic vulnerability and risk evaluation for old urban nuclei. *Earthquake Engineering & Structural Dynamics* 16 (2): 183-201.

Boatwright, J., Thywissen, K. & Seekins, L.C. 2001. Correlation of Ground Motion and Intensity for the 17 January 1994 Northridge, California, Earthquake. *Bulletin of the Seismological Society of America,* 91(4): 739-752.

Borzi, B., H. Crowley & R. Pinho. 2008. Simplified pushover-based earthquake loss assessment (sp-bela) method for masonry buildings. *International Journal of Architectural Heritage* 2, (4): 353-76.

Calvi, G. M. 1999. A displacement-based approach for vulnerability evaluation of classes of buildings. *J.Earthqu.Eng.* 3, (3): 411-38.

Caracoglia, L., & Jones, N., 2004. Full-scale pressure measurement during hurricanes. Proceedings of 5th Intern. Colloquium on Bluff Body Aerodynamics & Applications, Ottawa, ON, Canada, 485-488.

Casciati, F., L. Faravelli & X. D. Liu. 1994. Lessons of rehabilitation design learned from statistical analyses of masonry seismic-vulnerability data. *Structural Safety,* 16, (1-2) (10): 73-89.

Cascini L., Ferlisi S., 2003. Occurrence and Consequences of Flowslides: a Case Study, in L. Picarelli (Ed.), Proceedings of Int. Conf. on Fast Slope Movements-Prediction and Prevention for Risk Mitigation (FSM2003), Napoli (Italy), 11-13 May 2003. Patron Ed.: Bologna.

Cascini L., Sorbino G., Cuomo S., 2003. Modelling of flowslides triggering in pyroclastic solis, in L. Picarelli (Ed.), Proceedings of Int. Conf. on Fast Slope Movements-Prediction and Prevention for Risk Mitigation (FSM2003), Napoli (Italy), 11-13 May 2003. Patron Ed.: Bologna.

CEN 2004, Design of Structures for Earthquake Resistance, Part 3, Assessment and Retrofitting of Buildings, EN 1998–3, Brussels.

Coburn, A. & Spence R. 2002. *Earthquake Protection*, Second Edition, John Wiley & Sons, Ltd.

Cole, S. W., Y. Xu & P. W. Burton. 2008. Seismic hazard and risk in Shanghai and estimation of expected building damage. *Soil Dynamics and Earthquake Engineering* 28, (10-11): 778-94.

Datin, P. L., Liu, Z., Prevatt, D. O., Masters, F. J., Gurley, K., & Reinhold, T. A., 2006. Wind loads on single-family dwellings in suburban terrain: Comparing field data and wind tunnel simulation. Structures Congress 2006, St. Lois, Missouri, USA. , 201(40889) 13.

Dolce, M., A. Kappos, A. Masi, Gr. Penelis & M. Vona. 2006. Vulnerability assessment and earthquake damage scenarios of the building stock of potenza (southern italy) using italian and greek methodologies. *Engineering Structures,* 28, (3) (2): 357-71.

Dolsek M., 2008. Incremental dynamic analysis with consideration of modeling uncertainties. *Earthquake Engineering and Structural Dynamics*, 38: 805–825.

Doudak, G., 2005. Field determination and modeling of load paths in wood light-frame structures. PhD Thesis, McGill University, Montreal, QC, Canada.

Eaton, K. J., & Mayne, J. R., 1975. The measurement of wind pressures on two-storey houses at Aylesbury. Journal of Wind Engineering and Industrial Aerodynamics, 1, 67-109.

Erberik, M. A. 2008a. Fragility-based assessment of typical mid-rise and low-rise RC buildings in turkey. *Engineering Structures* 30, (5): 1360-74.

Erberik, M. A. 2008b. Generation of fragility curves for turkish masonry buildings considering in-plane failure modes. *Earthquake Engineering & Structural Dynamics* 37, (3): 387-405.

Faccioli, E., V. Pessina, G. M. Calvi & B. Borzi. 1999. A study on damage scenarios for residential buildings in catania city. *Journal of Seismology* 3, (3): 327-43.

Faella C., Nigro E., 2003a. Dynamic Impact of the Debris Flows on the Constructions during the Hydrogeological Disaster in Campania-1998: Description and Analysis of the Damages, in L. Picarelli (Ed.), Proceedings of Int. Conf. on Fast Slope Movements-Prediction and Prevention for Risk Mitigation (FSM2003), Napoli (Italy), 11-13 May 2003. Patron Ed.: Bologna.

Faella C., Nigro E., 2003b. Dynamic Impact of the Debris Flows on the Constructions during the Hydrogeological Disaster in Campania-1998: Failure Mechanical Models and Evaluation of the Impact Velocity, in L. Picarelli (Ed.), Proceedings of Int. Conf. on Fast Slope Movements-Prediction and Prevention for Risk Mitigation (FSM2003), Napoli (Italy), 11-13 May 2003. Patron Ed.: Bologna.

Faella C., Nigro E., 2003c. A Hypothesis of Technical Code on the Structural Design and Repairing in Urban Areas with High Debris Flow Risk, in L. Picarelli (Ed.), Proceedings of Int. Conf. on Fast Slope Movements-Prediction and Prevention for Risk Mitigation (FSM2003), Napoli (Italy), 11-13 May 2003. Patron Ed.: Bologna.

Fäh, D., F. Kind, K. Lang & D. Giardini. 2001. Earthquake scenarios for the city of Basel. *Soil Dynamics and Earthquake Engineering* 21, (5) (7): 405-13.

FEMA 1997. NEHRP *Guidelines for the Seismic Rehabilitation of Buildings, FEMA-273*, Federal Emergency Management Agency,Washington D.C.

FEMA 2000. Prestandard and commentary for the seismic rehabilitation of buildings, FEMA-356, Federal Emergency Management Agency, Washington D.C.

FEMA 2000. Recommended seismic design criteria for new steel moment-frame buildings. *Report No. FEMA-350*, SAC Joint Venture, Federal Emergency Management Agency, Washington DC.

FEMA & NIBS. 2003. *Multi-hazard loss estimation methodology - earthquake model: HAZUS® MH technical manual*, Federal Emergency Management Agency, Washington D.C.

FEMA. 2005. Coastal Construction Manual (3 vols.). 3rd ed. (FEMA 55). Federal Emergency Management Agency, Washington DC.

FEMA. 2008. Guidelines for design of structures for vertical evacuation from tsunami (FEMA P646). Federal Emergency Management Agency, Washington DC.

Fragiadakis M. & Vamvatsikos D. 2010. Fast performance uncertainty estimation via pushover and approximate IDA. Earthquake Engineering and Structural Dynamics, 39(6): 683–703.

Friedman, D.G., 1984. Natural hazard risk assessment for an insurance program. The Geneva Papers on Risk and Insurance, 9, No. 30, 57-128.

Gent Franch, K. A., G. M. Giuliano Morbelli, M. A. Astroza Inostroza & R. E. Gori. 2008. A seismic vulnerability index for confined masonry shear wall buildings and a relationship with the damage. *Engineering Structures* 30, (10): 2605-12.

Grant, D. N., J.J. Bommer, R. Pinho, G. M. Calvi, A. Goretti & F. Meroni. 2007. A prioritization scheme for seismic intervention in school buildings in italy. *Earthquake Spectra* 23, (2) (May 2007): 291-314.

Grünthal G. ed. European macroseismic scale 1998 (EMS-98). Cahier du Centre Européen de Géodynamique et de Séismologie, Conseil de L'Europe, Luxemburg, Vol.15.

Hill, M., Rossetto, R. 2008. Comparison of building damage scales and damage descriptions for use in earthquake loss modelling in Europe, *Bull. Earthq. Eng*., 6(2): 335-365

Imamura, A. 1942. History of Japanese tsunamis. Kayo-No-Kagaku (Oceanography), 2, 74-80 (in Japanese)

Kappos, A.J. 2007. Seismic vulnerability and risk assessment of urban habitat in Southern European cities. Keynote lecture, *Urban Habitat Constructions under Catastrophic Events Workshop* (COST C26), Prague, Mar., 115-129.

Kappos, A.J., Panagopoulos, G., Panagiotopoulos, C. & Penelis, Gr. 2006. A hybrid method for the vulnerability assessment of R/C and URM buildings. *Bull. Earthq. Eng*., 4(4): 391-413.

Kappos, A. J., V. Lekidis, G. Panagopoulos, I. Sous, N. Theodulidis, Ch Karakostas, T. Anastasiadis, T. Salonikios & B. Margaris. 2007. Analytical estimation of economic loss for buildings in the area struck by the 1999 athens earthquake and comparison with statistical repair costs. *Earthquake Spectra* 23, (2): 333-55.

Kappos, A. J., K. C. Stylianidis & K. Pitilakis. 1998. Development of seismic risk scenarios based on a hybrid method of vulnerability assessment. *Natural Hazards* 17, (2): 177-92.

Kappos, A. J., G. Panagopoulos & Gr. G. Penelis. 2008. Development of a seismic damage and loss scenario for contemporary and historical buildings in thessaloniki, greece. *Soil Dynamics and Earthquake Engineering* 28, (10-11) (0): 836-50.

Kappos A.J. & Panagopoulos G. 2010. Fragility curves for reinforced concrete buildings in Greece. *Structure and Infrastructure Engineering.* 6(1-2): 39-53.

Khanduri, A.C. & Morrow, G.C., 2003. Vulnerability of buildings to windstorms and insurance loss estimation. Journal of Wind Engineering and Industrial Aerodynamics, 91, 455-467.

King, S.A.,. Kiremidjian, A.S, Sarabandi, P. & Pachakis, D. 2005. *Correlation of Observed Building Performance with Measured Ground Motion. Report TR148*. The John A. Blume Earthquake Engineering Center. Department of Civil and Environmental Engineering Stanford University

Koshimura, S., Oie, T., Yanagisawa, H., Imamura, F. 2009. Developing Fragility Functions For Tsunami Damage Estimation Using Numerical Model and Post-Tsunami Data From Banda Aceh, Indonesia. *Coastal Engineering Journal*, Vol. 51, No. 3 (2009) 243–273.

Lagomarsino, S. & S. Podestà. 2004a. Seismic vulnerability of ancient churches: I. damage assessment and emergency planning. *Earthquake Spectra* 20(2): 377-394.

Lagomarsino, S. & S. Podestà. 2004b. Seismic vulnerability of ancient churches: II. statistical analysis of surveyed data and methods for risk analysis. *Earthquake Spectra* 20(2): 395-412.

Lagomarsino, S. 2006. On the vulnerability assessment of monumental buildings. *Bulletin of Earthquake Engineering* 4, (4): 445-63.

Lagomarsino, S. & Giovinazzi, S. 2006. Macroseismic and mechanical models for the vulnerability and damage assessment of current buildings. *Bull. Earthq. Eng.* 4(4): 415-443.

Lang, K. 2002. *Seismic vulnerability of existing buildings.* PhD thesis, ETH, Zurich, Hochschulverlag AG.

Lang, K. & H. Bachmann. 2004. On the seismic vulnerability of existing buildings: A case study of the city of Basel. *Earthquake Spectra* 20 (1): 43-66.

Lang, K. 2003. On the seismic vulnerability of existing unreinforced masonry buildings. *Journal of Earthquake Engineering* 7 (3): 407.

Lantada, N., L. G. Pujades & A. H. Barbat. 2008. Vulnerability index and capacity spectrum based methods for urban seismic risk evaluation. A comparison. *Natural Hazards*: 1-24.

Leatherman, S. P., Gan Chowdhury, A., & Robertson, C. J., 2007. Wall of wind full-scale destructive testing of coastal houses and hurricane damage mitigation. Journal of Coastal Research, 23(5), 1211-1217.

Levitan, M. L., Mehta, K. C., Chok, C. V., & Millsaps, D. L., 1990. An overview of Texas Tech's wind engineering field research laboratory. Journal of Wind Engineering and Industrial Aerodynamics, 36(Part 2), 1037-1046.

Liel A., Haselton C., Deierlein G. & Baker J. 2009. Incorporating modeling uncertainties in the assessment of seismic collapse risk of buildings. *Structural Safety* 31(2):197–211.

Lloyd TO, Allsop, W, Charvet I, Robinson D, Robinson T, Rossetto T. Physical modelling of violent flows and their impact using a new tsunami generator. 9th ICE Coasts, Marine Structures and Breakwaters Conference 2009.

Marshall, R. D., 1975. A study of wind pressures on a single-family dwelling in model and full scale. Journal of Wind Engineering and Industrial Aerodynamics, 1, 177-199.

Masi, A. 2003. Seismic Vulnerability Assessment of Gravity Load Designed R/C Frames. *Bulletin of Earthquake Engineering* 1(2): 371-395.

Mehta, K.C., Minor J.E. & Reinhold T.A.,1983. Speed-damage correlation in Hurricane Frederic. Journal of the Structural Division Vol. 109, ASCE, No. 1 .

Miyakoshi J., Hayashi Y., Tamura K. & Fukuwa N. 1997. Damage ratio functions of buildings using damage data of the 1995 Hyogoken-Nanbu Earthquake. ICOSSAR 1997. pp. A.19-A.24

Mosalam K.M., Ayala G., White R.N. & Roth C. 1997. Seismic fragility of LRC frames with and without masonry infill walls. *Journal of Earthquake Engineering* 1(4): 693-719.

Oliveira, C. S. 2008. Lisbon earthquake scenarios: A review on uncertainties, from earthquake source to vulnerability modelling. *Soil Dynamics and Earthquake Engineering* 28, (10-11): 890-913.

Okada, T., Sugano, T., Ishikawa, T., Ohgi, T., Takai, S. & Hamabe,C. 2005. Structural design methods of buildings for tsunami resistance (SMBTR). The Building Center of Japan, Japan.

Papadopoulos, GA., Imamura, F. 2001. A proposal for a new tsunami intensity scale. ITS Proceedings, 569

Park, J., P. Towashiraporn, J. I. Craig & B. J. Goodno. 2009. Seismic fragility analysis of low-rise unreinforced masonry structures. *Eng.Struct.* 31, (1): 125-37.

Peiris, N. 2006. Vulnerability functions for tsunami loss estimation. First European Conference on Earthquake Engineering and Seismology.

Penelis, Gr G., A. J. Kappos & K. C. Stylianidis. 2003. Assessment of the seismic vulnerability of unreinforced masonry buildings. Paper presented at 8th International Conference on Structural Studies, Repairs and Maintenance of Heritage Architecture, Chalkidiki, Greece, WIT Press, Southampton, UK, .

Penelis, Gr G. 2006. An efficient approach for pushover analysis of unreinforced masonry (URM) structures. *Journal of Earthquake Engineering* 10, (3): 359-79.

Reese, S., Cousins, WJ., Powers, WL., Palmer, NG., Tejakusuma, IG. and Nugrahadi, S. 2007. Tsunami vulnerability of buildings and people in South Java – field observations after the July 2006 Java tsunami. Nat. Hazards Earth Syst. Sci., 7, 573–589.

Robertson, A. P., & Glass, A. G., 1988. The Silsoe structures building - its design, instrumentation and research facilities. AFRC Inst. Engng. Res., Silsoe, Div. Note DN 1482.

Rossetto, T. Allsop, W., Charvet, I. & Robinson, D. (2010). The Generation of Realistic Tsunami using a New Wave Generator. *Coastal Engineering*. Submitted.

Rossetto, T., Elnashai, A. 2003. Derivation of vulnerability functions for European-type RC structures based on observational data. *Engineering Structures* 25, 1241–1263

Rota, M., A. Pecker, D. Bolognini & R. Pinho. 2005. A methodology for seismic vulnerability of masonry arch bridge walls. *Journal of Earthquake Engineering* 9, (SPEC. ISS. 2): 331-53.

Rota, M., A. Penna & C. L. Strobbia. 2008. Processing italian damage data to derive typological fragility curves. *Soil Dynamics and Earthquake Engineering* 28, (10-11) (0): 933-47.

Ruangrassamee, A., Yanagisawa, H., Foytong, P., Lukkunaprasit, P., Koshimura, S. & Imamura, F. 2006. Investigation of tsunami-induced damage and fragility of buildings in Thaliand after the December 2004 Indian Ocean Tsunami. *Earthquake Spectra, 22*, S377.

Ruiz-García, J. & M. Negrete. 2009. Drift-based fragility assessment of confined masonry walls in seismic zones. *Eng.Struct.* 31, (1): 170-81.

SEOAC. 1995. *Performance based seismic engineering of buildings*. Vision 2000 Committee, Structural Engineers Association of California, Sacramento, California, USA.

Shoji, G. Moriyama, T. 2007. Evaluation of the Structural Fragility of a Bridge Structure Subjected to a Tsunami Wave Load. Journal of Natural Disaster Science, 29, 2, 73-81.

Singhal, A. & Kiremidjian, A.S. 1996. A method for probabilistic evaluation of seismic structural damage. *Journal of Structural Engineering*, ASCE, 122 (12), 1459-1467

Spence, R., E. So, S. Jenny, H. Castella, M. Ewald & E. Booth. 2008. The global earthquake vulnerability estimation system (GEVES): An approach for earthquake risk assessment for insurance applications. *Bulletin of Earthquake Engineering* 6, (3): 463-83.

Stathopoulos, T., Baniotopoulos, C.C. & Zisis, I., 2008. Structural Failure and prevention during catastrophic wind events. Proceedings of Urban Habitat Constructions under Catastrophic Events, COST Action C26, Malta.

Strasser, F. O., J. J. Bommer, K. Şeşetyan, M. Erdik, Z. Çagnan, J. Irizarry, X. Goula, et al. 2008. A comparative study of european earthquake loss estimation tools for a scenario in Istanbul. *J.Earthqu.Eng.* 12, (SUPPL. 2): 246-56.

Valluzzi, M. R. 2007. On the vulnerability of historical masonry structures: Analysis and mitigation. *Materials and Structures* 40, (7): 723-43.

Vamvatsikos D. & Cornell C.A. 2002. Incremental Dynamic Analysis. *Earthquake Engineering and Structural Dynamics,* 31(3): 491–514.

Vamvatsikos D. & Cornell C.A. 2005. Direct estimation of the seismic demand and capacity of MDOF systems through Incremental Dynamic Analysis of an SDOF Approximation. *ASCE Journal of Structural Engineering,* 131(4): 589–599.

Vamvatsikos D. & Fragiadakis M., 2010. Incremental Dynamic Analysis for seismic performance uncertainty estimation. *Earthquake Engineering and Structural Dynamics,* 39(2): 141–163.

Vamvatsikos D. & Pantazopoulou S.J., 2010, "Simplified vulnerability assessment of historical city cores — the example of the city of Xanthi", *Proceedings of the 9th US National Conference on Earthquake Engineering,* Toronto, Canada.

Van de Lindt, J.W., Graettinger, A., Gupta, R., Skaggs, T., Pryor, S. & Fridley, K.J. 2007. Performance of wood-frama structures during Hurricane Katrina. Journal of Performance of Constructed Facilities, Vol. 21, No. 2, 108-116.

Zisis, I. 2007. Structural monitoring and wind tunnel studies of a low wooden building. MASc Thesis, Concordia University, Montreal, QC, Canada.