Improving Seismic Risk Assessment for the Insurance industry by using 3-D Finite Element Modelling

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ABSTRACT

Assessment of damage losses due to an earthquake is an important issue for the insurance and reinsurance industry, since it currently lacks the level of detail that is required for realistic pricing of individual risks. Sophisticated numerical tools, which are widely used to assess structural behaviour in great detail (like FEM), have evolved to a level where they may be used with confidence in seismic risk assessment and, as such, enable the insurance industry to perform more realistic assessments.

This paper presents a preliminary proposal of how to integrate sophisticated 3D-FE modelling in insurance risk assessment. To exemplify the procedure, the risk of masonry structures is assessed under the L'Aquila earthquake of April 6, 2006, Italy (IUSS Press 2009) and compared to available economic loss data.

1 INTRODUCTION

The insurance and reinsurance market offer an important solution for the society to promptly recover after natural catastrophies. The earthquakes that in the last two years stroke Chile (Maule, Mw 8.8, February 6, 2010), New Zealand (Darfield, Mw 7.0, September 3, 2010 and Lyttelton, Mw 6.1, February 21, 2011) and Japan (Honshu, Mw 9.0, March 11, 2011) proved, once more, the strategic importance of this kind of industry and renewed the crucial question of how to develop a resiliant concept for society. The reader may find more detailed information concerning these earthquakes on the web page of the U.S. Geological Survey (USGS).

Any further advancement in that respect is strictly related to our capabilities to reliably model the involved natural risk. This process implies a better understanding of the hazard, of the vulnerability and of the exposure that are dealt with.

Even if important on-going projects, like The Global Earthquake Model (GEM), will likely succeed in improving our knowledge in the future, often the "state-of-the-art" of the empirical data-set regarding earthquake economic losses available is quite poor: they cover randomly the whole world, both from a quality and geographic perspective.

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Since earthquakes are rare events, the situation will not likely change in the foreseeable future, therefore it is necessary to further investigate the development of innovative concepts.

A good overview of the development of seismic vulnerability assessment methodologies over the past 30 years is given in (Calvi 2006). On one hand, there are the empirical methods, like *Damage Probability Matrices (DPMs)* (Whitman 1973), the *Vulnerability Index Method* (Benedetti 1984), the *Continuous Vulnerability Curves* (Spence 1992) and the *screening Methods* (JBDPA 1990). On the other hand, Calvi describes also six different analytical methods, like the *Analytically-Derived Vulnerability Curves and DPMs* (Singhal 1996), *Hybrid Methods* (Kappos 1995), *Collapse Mechanism-Based Methods* (Bernardini 1990) to cite some of them.

In the analytical fragility assessment of Park (Park 2008), a two-storey unreinforced masonry (URM) building is created to represent a typical essential facility, i.e. a firehouse, in the central and southern US region. In the interest of achieving a simpler model for dynamic analysis, Park reduced the complex 3D model into several models that are based only on a two dimensional behaviour. It is also assumed that the earthquake excitation is parallel to a wall. For the modeling of "*In-Plane Walls*" Park utilizes a very simple composite nonlinear spring model, while for "*Out-of-Plane Walls*" a single nonlinear spring with bi-linear hysteresis behaviour is used.

Park's study works with the idea to simplify a 3D model into a 2D spring model and, therefore, that this approach is not useful for estimating realistically the damage area of a structure.

Nowadays it is possible to take advantage of numerical simulations of buildings subjected to earthquake load, using the classical finite element method, which has evolved rapidly in the last few decades (Zienkiewicz 1967).

The present work provides a preliminary contribution in this direction. The aim of this work is to develop a concept study for the insurance and reinsurance industry for a more realistic assessment of regional earthquake damage to masonry buildings on the basis of numerical simulation of structures.

The core of this approach is to create detailed 3D Finite Element models for a large number of realistic masonry buildings. Subjected to earthquake loading, the damage is assessed for each building creating a virtual damage database similar to the "Düzce database" (Suzuoglu 2007), which uses real damage data for reinforced concrete buildings. Estimation of the damage area for each building model allows determining its repair costs, and this latter can be related to the insurance rate for a particular class of buildings. A fast process can be required to estimate the insurance rate of a particular building on site, and this should be based on features, which are visually assessable on a building. Furthermore, a specific tool is developed to implement this approach in an automatic way.

2 THE NEW APPROACH FOR THE ASSESSMENT OF EARTHQUAKE DAMAGE

2. 1 Basic Procedure

The concept presented here (Mühlhausen 2010) uses a similar approach as the one that has been developed for rapid seismic assessment of reinforced concrete buildings in Turkey (Suzuoglu 2007), in which the potential damage of a building due to the action of an earthquake is determined using a classification of visually assessable building features, such as the number of floors or the presence of a soft storey.

Such a concept has to satisfy the following criteria:

- The concept must be easy to understand,
- The concept must be reliable,
- The concept must be cheap,
- The concept must be flexible to accommodate new building types,
- The concept must be applicable after a short introduction to the operator.

While the Turkish rapid assessment method is based on real seismic damage (Düzce database), the damage experienced by masonry buildings is simulated using structural FE software (in this case SAP2000 software) since observed damage data are missing. Analysing a large number of realistic FE models, a virtual damage database is created, which allows the computation of the insurance rate for a particular building class. Each class is described using several vulnerability parameters, which are similar to the one used in the Turkish seismic assessment method, mentioned above (Suzuoglu, 2007).

The task of the observer is to visit the building and identify its class by analysing its vulnerability parameters using the following seven simple questions:

– How many storeys does the building have?	1 to 6
– How is the visual condition of the building?	Good, moderate, bad
– Does the building have a symmetrical ground plan?	Yes/no
– Does the building have a square plan?	Yes/no
– Does the building have a soft storey?	Yes/no
– Does the building have an offset in the wall?	Yes/no

The possible answers allow distinguishing 576 building classes for masonry structures. A large number of variants exist within each class, with different overall dimensions, locations of windows and doors, thickness of walls etc. (Fig. 1). For each variant, a 3D FE model must be created and its performance assessed for different earthquake hazard levels. Thus, thousands of these models are needed to create the virtual database.

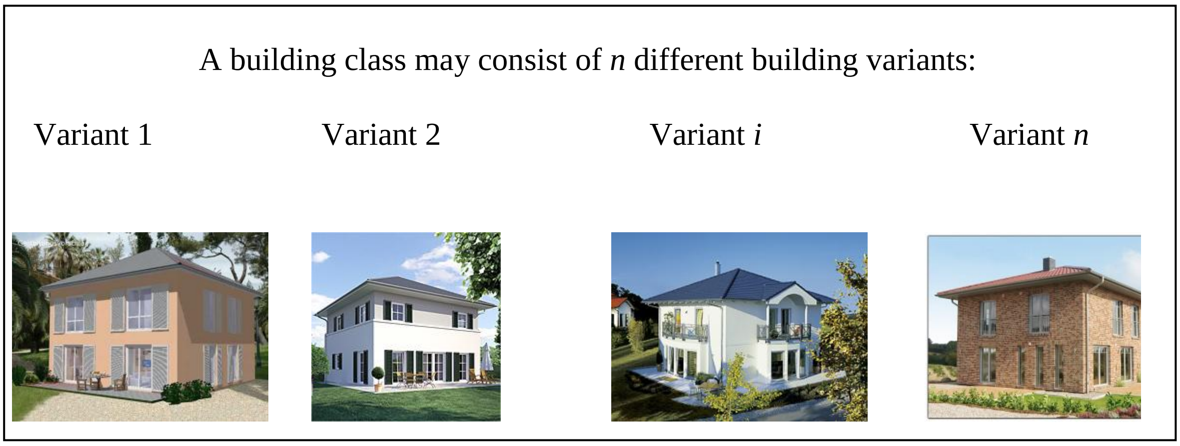


Fig. 1. Variants within a building class,
(Fertighaus & Massivhaus 2011), (Online-Magazin für Häuser, Bauen, Garten und Lifestyle 2011),
(Das eigene Haus 2011)

In order to reduce the assessment duration, the observer must be trained in the concept process. Fig. 2 shows how the assessment is performed in three steps: the first step is to input the data, the second step is the computing process and the third step is the output. This latter is the insurance rate per year and building.

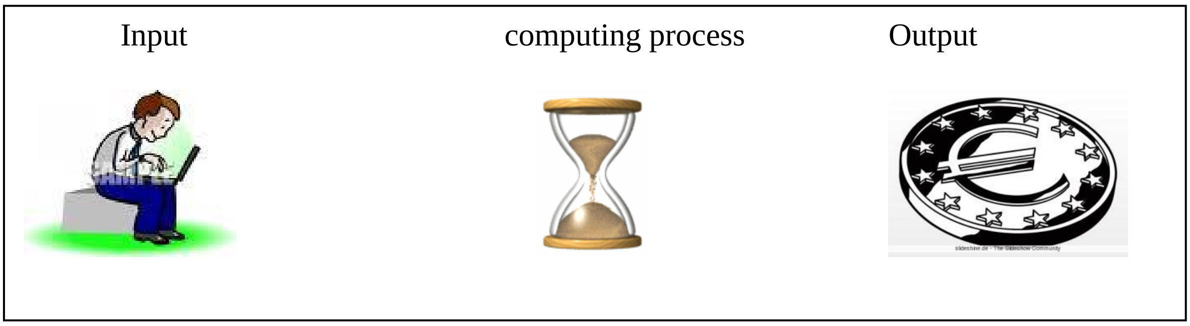
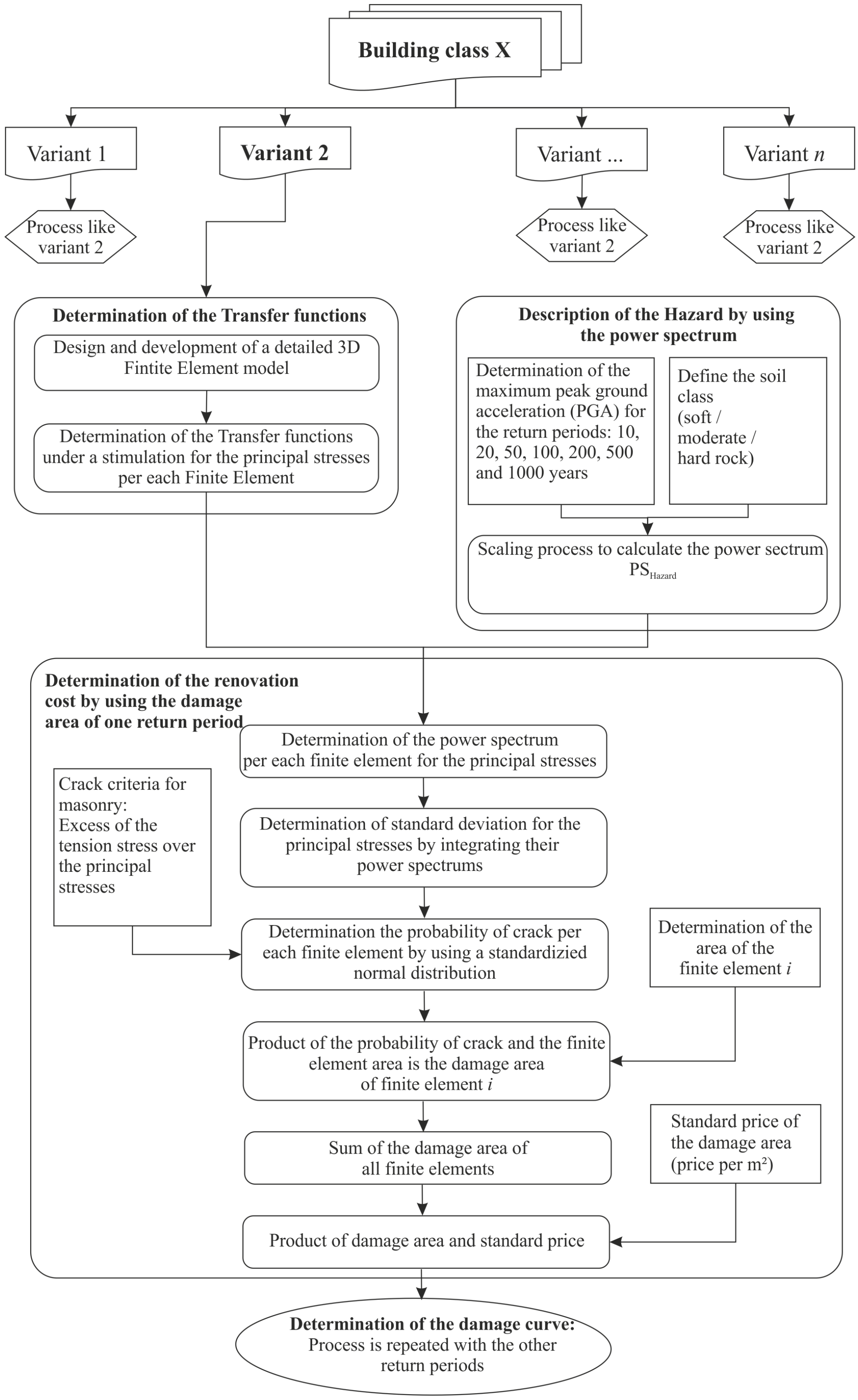


Fig. 2. Rapid process to assess the insurance rate of a particular building on site

Figure 3 shows the flow chart of the computing process, which is the core of this concept. It is broken down into six steps.



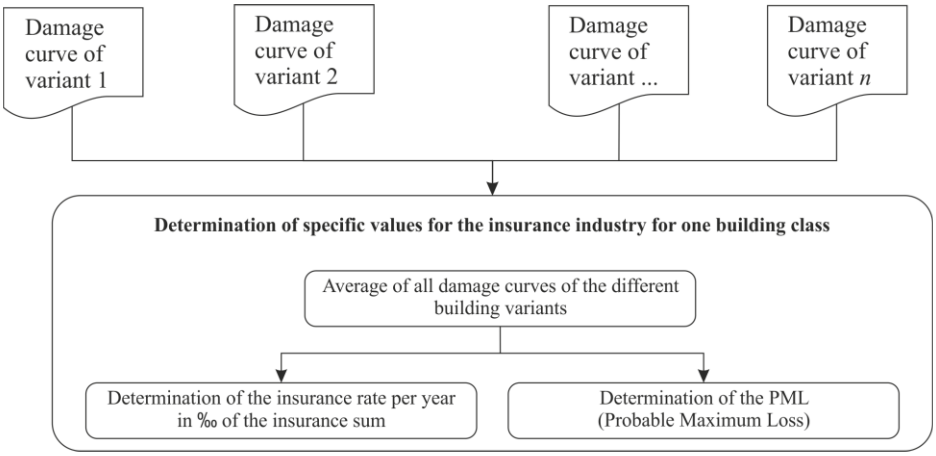


Fig. 3. Working process of the insurance concept to calculate the insurance rate by an example of a masonry building

2. 2 Determination of the standard deviation of local stresses using a power spectrum

If the power spectrum of a local stress is known, the standard deviation (STD) can be determined by integrating it. This is an important statistical value to estimate the local damage risk. The power spectrum can be determined using transfer functions in the case of linear structures.

Transfer functions represent the relationship between a local mechanical parameter (e.g. stresses) and loading (e.g. loads at the foundation – earthquakes). They are a property of an individual structure, and they can be determined without the knowledge of the loading event. Only the location where the load is applied must be known. Tranfer functions describe the relationship between the local output and the normalized input in the frequency domain. For linear structures, these functions are constant over time and therefore, they only have to be computed once. To obtain the power spectrum of a local stress, the transfer functions are multiplied with the power spectrum of the load (PS_{Hazard}). Subsequently, the standard deviation of the local stress can be determined as described above.

2. 3 Determination of the power spectrum of the earthquake process

The local soil and the peak ground acceleration (PGA) are two hazard parameters that have a major influence on seismic damage. The first is responsible for concentrating the seismic energy in certain frequency ranges, while the PGA is responsible for the expected intensity and depends on the return period of the earthquake (Wakabayashi 1986). Accordingly, these two parameters (soil type and the maximum expected PGA) characterize the power spectrum (PS_{Hazard}) of the earthquake loading.

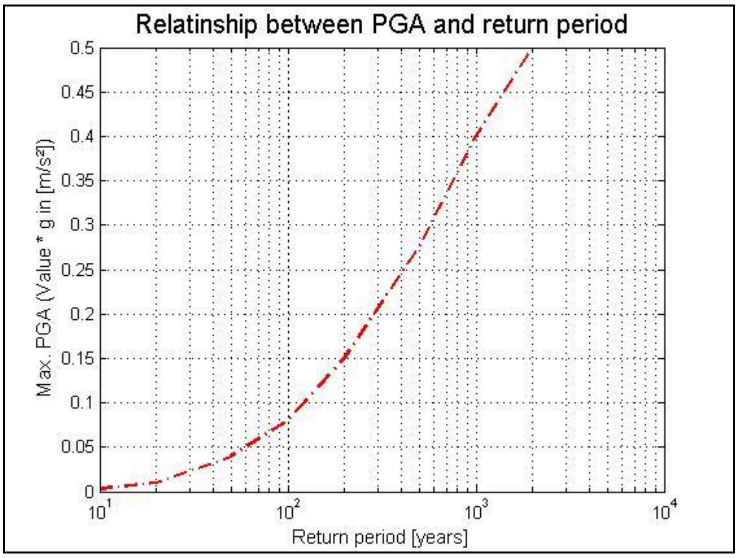


Fig. 4. Relationship between PGA and return period for the region L'Aquila

Power spectra are created by the Fourier transform of the autocorrelation function of a time series (Schlittgen 2001). The recorded acceleration of the earthquake in L'Aquila (Station AQG - Aterno-Colle Grilli, date: April 6, 2006) is used here for illustrative purposes and can be found in (Itaca 2010). The recorded acceleration along three components (NS, EW, UD) was used to determine the autocorrelation function.

To demonstrate the capability of the concept, only one soil class with wave velocities 360 to 800 m/s (DIN 1053-1 2006) is chosen. For the region of L'Aquila, the reference PGA has a value of 0.275 g for a return period of 475 years. Fig. 4Figure 4 shows the other PGAs for return periods of 10, 20, 50, 100, 200, 1000 and 2000 years. With these inputs, the PS_{Hazard} is found for each return period and soil class.

2. 4 Determination of the expected damage area for a building variant.

Assuming linear elastic behavior, the average of a local value (here principal stress) is zero, because the average of the ground acceleration is zero. Assuming a normal distribution for the principal stress as a first approximation, its probability of exceeding a predefined threshold can be calculated using its standard deviation (STD).

As a first approximation for a crack criterion for masonry, a threshold for the principal tension stress can be chosen. This enables an estimation of the development of cracks in term of probability for each point of the strucutre and this latter is translated in the expected damage area of the wall.

The tension threshold for cracking of masonry can be determined throught the strength of its bricks and mortar. The scatter of these values is neglected and the mean value is adopted. An average brick class 12 and mortar class III (Schneider 2010) is chosen in this study. Without the partial safety factor, the average rupture stress is 0,2 N/mm² for this kind of masonry. Using the tables of the standard normal distribution (Papula 2008) allows for the calculation of the probability of development of cracks of each point in the structure.

For a single finite element (Fig. 5), the expected crack probability is taken as the average of the crack probabilities in its four integration points.

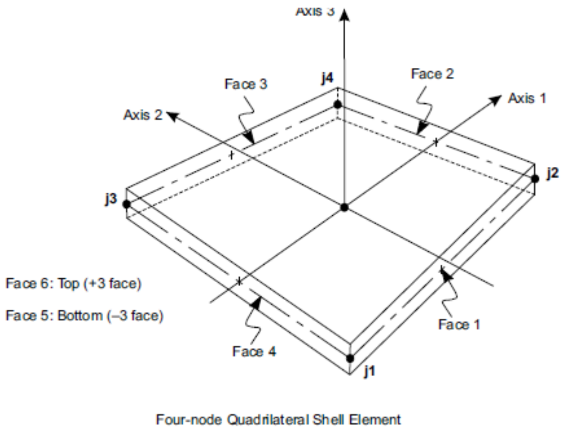


Fig. 5. 3D linear Shell Element (SAP 2000 2008b) used to model the masonry structures in this study

This is multiplied with the area of the element to obtain the expected damage area of the element. This process has to be repeated for all elements of the structure. The sum of these damage areas is the expected damage area for one particular building variant.

2. 5 Determination of repair cost

As a first approximation, a linear relationship between costs and damage area is assumed. The repair costs are set to 265 € / m² (Mühlhausen 2010) but it should be mentioned that there are very large regional variations due to human resources and material costs. It is advantageous to express these costs as a percentage of the insured value. This translates into 0.1% of the total insured sum per square meter.

2. 6 Determination of damage curve and insurance rate

Damage curves (Fig. 6) are an important tool for the insurance industry to estimate the potential risk and damage to a building and they are used to compute the insurance rate for a building.

The damage curve describes the relationship between repair costs and return period. To determine the insurance rate per year for a building variant, a simplified formula is used:

$$X_{\text{variant 2}} = \sum \frac{\text{renovation cost}}{\text{returnperiod}} \qquad (1)$$

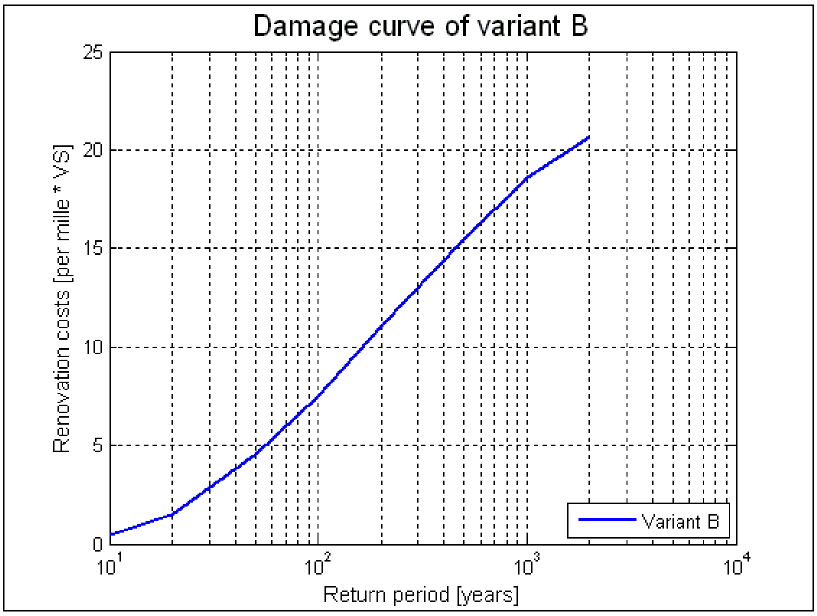


Fig. 6. Damage curve of building variant 2

To determine the insurance rate for a building class that consists on *n*-building variants, the average of the insurance rate for each building variant will be calculated as

$$X_{\text{Building class}} = \frac{1}{n} \sum X_{\text{variant 1}} + \ldots + X_{\text{variant n}} \tag{2}$$

3 RESULTS

In (Mülhausen 2010) four variants (representing different distributions of wall openings, ground plan size, etc.) of a building class were modelled in SAP 2000 with linear Shell Elements (Fig. 7).

The capability of SAP 2000 to produce graphical output allowed the comparison of the results for the four variants. As expected all building variants show peak principal stress in the corners of doors and windows. This can be seen in Fig. 10 where a snapshot is given for the structures under maximum displacement during a time history simulation.

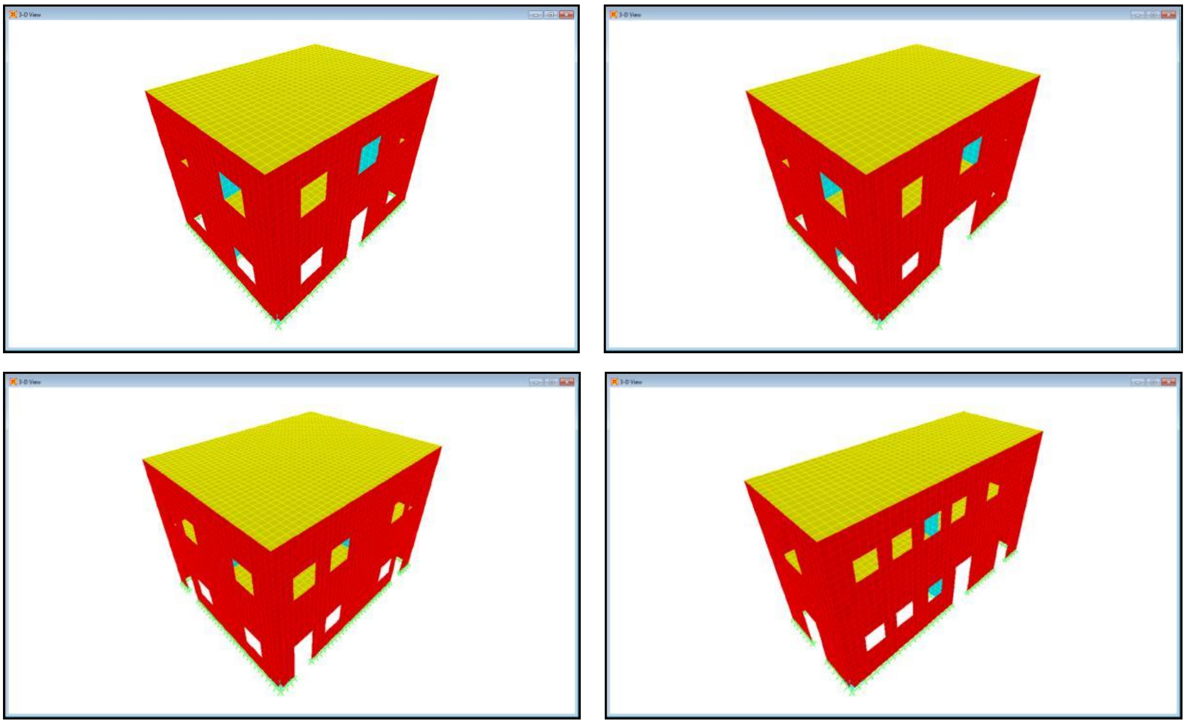


Fig. 7. The four building variants
Top left: Model A
Top right: Model B
Bottom left: Model C
Bottom right: Model D, (SAP 2000 2008a)

Models A and B (Fig. 7) are only slightly different (only the locations of openings vary) and therefore their damage curves are similar (Fig 9). On the other hand, models C and D have more openings and their damage is higher. This could lead to a more realistic pricing by introducing an additional easily observable criterion, such as the ratio of openings to wall area. This demonstrates one of the advantages of this new concept.

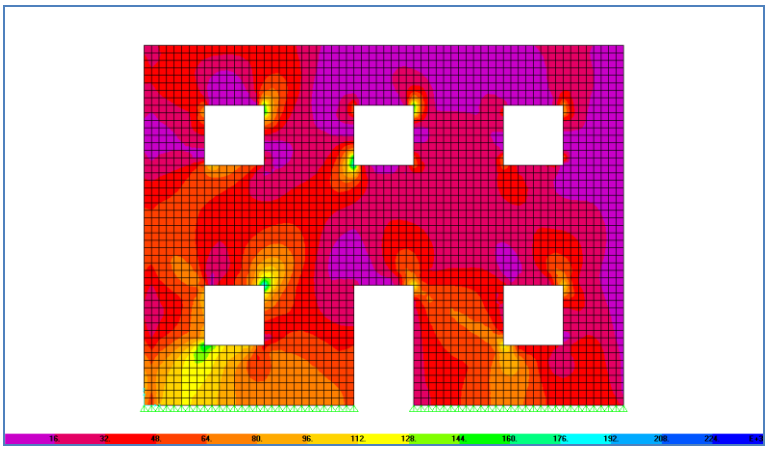


Fig. 8. Example for the principle stresses in a masonry building variant as a result of an earthquake.

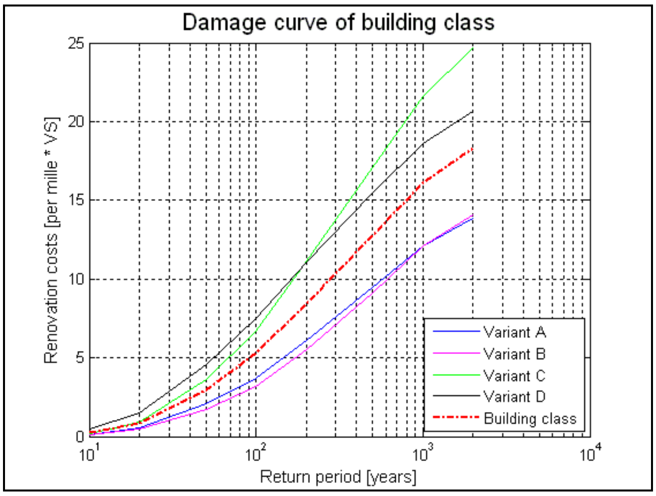


Fig. 9. Damage curves of four building variants for the region of L'Aquila, Italy

The calculated insurance rate for this building class resulted in 0,275 ‰ of the insured sum. Supposing for example that the insurance sum of a building is 300.000 €, the insurance rate would be 81,15 €, which may be regarded, for a first result, as a realistic and plausible technical value. It should be mentioned that only the most important return periods, the ones with most influence on the insurance rate (75% of weight), have been considered, namely: 20, 50, 100 and 200 years. Also the Probable Maximum Loss (PML) of 17 ‰ defined for a return period of 1000 years, can be classified as realistic.

$$X_{\text{Building class}} = Sum \cdot \sum \frac{0{,}002}{10} + \frac{0{,}009}{20}\frac{0{,}03}{50} + \frac{0{,}053}{100} + \frac{0{,}085}{200} + \frac{0{,}128}{500} + \frac{0{,}161}{1000} + \frac{0{,}183}{2000} \qquad (3)$$

$$X_{\text{Building class}} = Sum \cdot 0{,}2705‰ \qquad (4)$$

4 CONCLUSIONS AND OUTLOOK

The cooperation between the University of Kassel and the Munich Re has resulted in the development of a first proposal of how to integrate sophisticated 3D-FE modelling in insurance risk assessment and the results have proven to be realistic.

The computed results of this concept are evaluated stochastically, which is the base to determine the insurance rate and the PML (probable maximum loss) for buildings. The largest contribution to the insurance rate arises from hazard levels 20, 50, 100 and 200 years. It is not expected that significant overall nonlinear behaviour occurs in masonry building for these hazard levels. It is therefore sufficient to work with linear FE models.

In linear structures, the use of power spectra provide an efficient way to calculate the required statistical values of local variables (principal stresses), which can be obtained by multiplying the transfer function of the local principal stress with the power spectrum of the ground motion. A crack criterion, defined by a limit on the principal tensile stress, provides an estimation for the damaged wall areas and thus the expected repair costs for a particular hazard level.

Even if the analyses here presented are preliminary and refer to a specific class of masonry buildings located in the region of L'Aquila, the insurance rate and PML, calculated with the previously described approach, seem to be reliable and offer a good basis for further development.

This proves that detailed three-dimensional finite element models are suitable to realistically estimate building damages and they could offer a concrete chance to compensate the lack of empirical damage data for earthquakes with synthetic one. The approach presented can significantly improve the calculation of premiums and PMLs, and will allow for a better differentiation between types of buildings.

The presented concept can be fully automated. Currently a tool is under development for this purpose at the University of Kassel in cooperation with Munich Re. This software may be also used with other kind of type of structure (e.g. reinforced concrete) as soon as suitable 3D FE models are available.

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