A technical overview on vulnerability assessment for cultural heritage assets threatened by natural hazards

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The writing below deals with vulnerability derivations in a quantitative framework. Such derivations are very useful for quantitative risk assessment and disaster risk management in general. First, a brief paragraph details the definition and differences between the concepts of vulnerability and fragility; then, the levels of physical fragility are described; then, the vulnerability quantification is highlighted; finally, an overview of derivation methods is proposed.

Definition and differences between vulnerability and fragility

In the community of natural hazard risk engineering, fragility is usually defined as the distribution of physical damage, function of the value of the intensity measure of the studied natural hazard (e.g., pressure for snow avalanche, peak ground acceleration for earthquake). Vulnerability is defined as the distribution of losses, which is expressed as a function of the value of the intensity measure of the studied natural hazard. Fragility is expressed as the percentage of damage or the probability of being in a damage states whereas vulnerability is expressed as the percentage of loss or the probability of loss exceedance. Loss is commonly estimated via the quantification of deaths, dollars or downtimes. For cultural heritage assets, the estimation of loss is based on a much wider range of criteria/values (cf. WP1).

Levels of physical fragility study

When dealing with physical fragility of a building, several levels of study can be defined: structural, non-structural and content-oriented. Structural components ensure stability of the building towards gravity load, horizontal loads (e.g., earthquake, wind) and other loads. Non-structural components do not fulfill a load-bearing role but are part of the structure; they are composed of architectural, mechanical, electrical and plumbing components such as partition walls, doors, glazing, pumps, chillers and piping. Contents include all the furniture, fixtures and equipment in the building (e.g., storage racks, computers, museum artifacts). The structural fragility analysis of an element consists in identifying the load-bearing capacity failure of the element after being stroked by a natural hazard characterized by a given intensity measure. The non-structural and content fragility analysis consists in identifying the failures of non-structural elements and the content in the building.

As an illustrative case, let us take the example of the Sanctuary of Gallivaggio damages after the landslide on May 29th, 2018. Figure 1 shows pictures taken after the landslide event, where rocks hit the main structure, came through the walls and roof, and induced damages inside the sanctuary. Structural, non-structural and content damages were observed. As a structural damage, a big hole in (what is assumed to be) a load-bearing wall of the structure is observed (Figure 1a). As a non-structural damage, one part of the coating of the wall, which consists in a 17th century painting, has been partially damaged by a rock mass. Finally, as content damage, Figure 1b shows partially damaged benches of the nave.

Fragility is expressed either as the probability of being in a given damage state, either as a damage index. Both are function of the intensity measures of the given natural hazards. Two illustrative examples are displayed in Figure 2 for the rockfall hazard type and their derivation is detailed below.

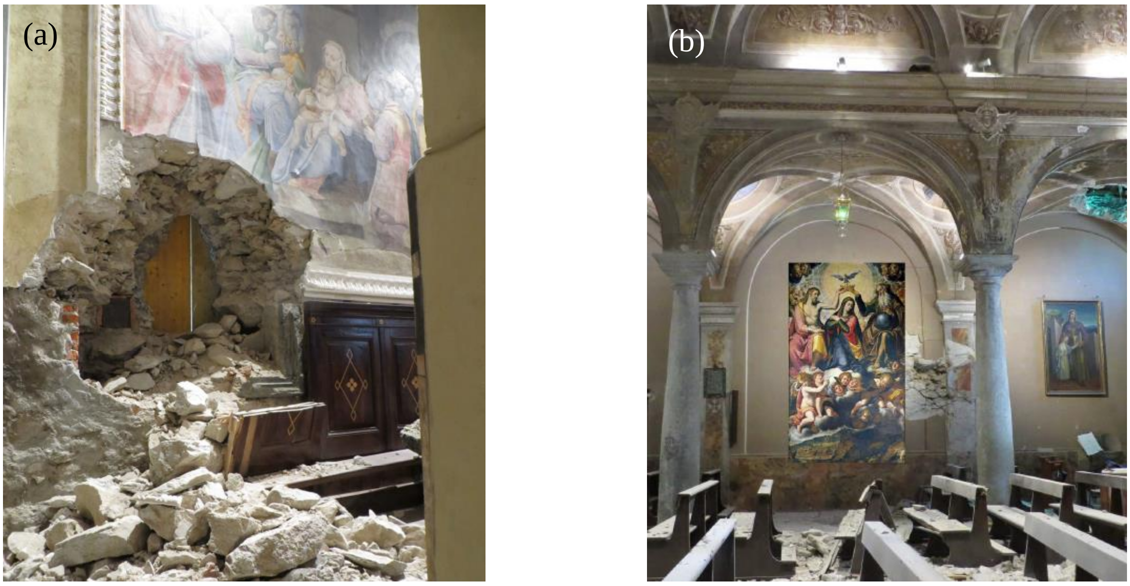

Figure 1: Damages in the Gallivaggio Sanctuary after the May 29th, 2018 landslide on: (a) a lateral wall and to the frescos by Domenico Caresana (1605-1606); and (b) the benches of the nave (Photo credits: Daniela Lattanzi).

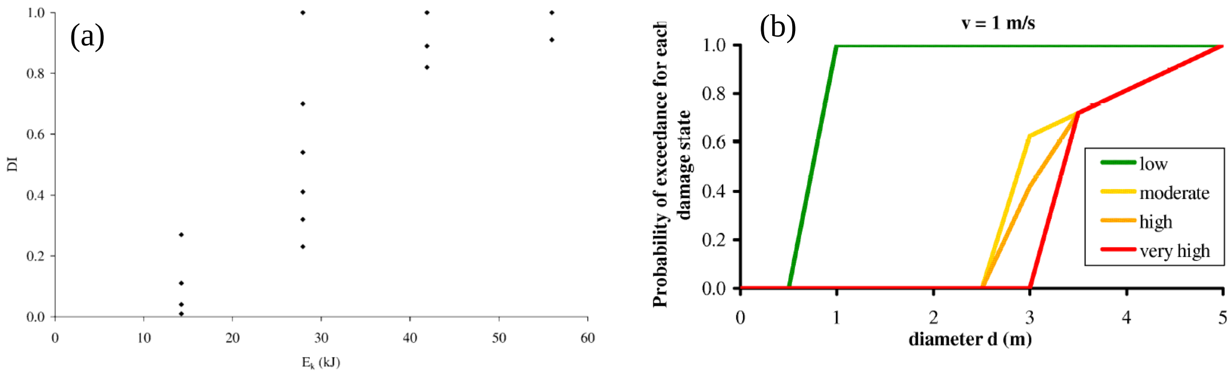

Figure 2: Rockfall fragility curves expressing (a) damage index as a function of kinetic energy of the rock [1]; (b) probability of exceeding a damage state function of the velocity and diameter of the rock [2].

Vulnerability quantification

In the context of quantitative risk assessment for natural hazards purposes, vulnerability is defined as the distribution of losses (e.g. economic loss, human loss) conditioned by the intensity measure of the natural hazard (e.g. impact pressure for snow avalanche hazard, kinetic energy for rockfall hazard). Vulnerability is expressed either as the probability of being or exceeding a given amount of loss, or as a deterministic loss index. The most common units of interest are dollars, deaths or downtime.

Vulnerability curves (Figure 3b) can be derived from fragility curves (Figure 3a), which is expressing the conditioned damage state distribution. For instance, a percentage of losses ($l_i =$

{12.5%, 50%, 87.5%, 100%}, $i = \{1, 2, 3, 4\}$, n = 4) is associated to each of the four damage states (ds_i, $i = \{1, 2, 3, 4\}$, n = 4). The probability of being in a given damaged state conditioned to an intensity measure (i.e., $p(ds_i|IM)$) is delimitated by each of the three curves as illustrated in Figure 3a. Then, it is possible to calculate the conditioned expected loss: $E[L|IM] = \sum_{i=1}^{n} l_i \, p(ds_i|IM)$, as illustrated in Figure 3b.

The same levels distinction as the ones previously described for fragility can be used herein for vulnerability, i.e. structural, non-structural and contents. Indeed, the losses corresponding to each of those categories are very different. A study from the United States Federal Emergency Management Agency (FEMA) reported the distribution of the relative costs in between those categories in various buildings types (i.e., office, hotel and hospital; Figure 4). Even if previous illustration does not count with cultural heritage type buildings, there is every reason to believe that the distribution would be similar, with even higher costs for content items in the case of a museum.
It would be appropriate, in case of cultural heritage, to assess similar curves also for other sort of values, the most tangible among the ones considered in the valuation methodology suggested by CHEERS A.T. 1.2

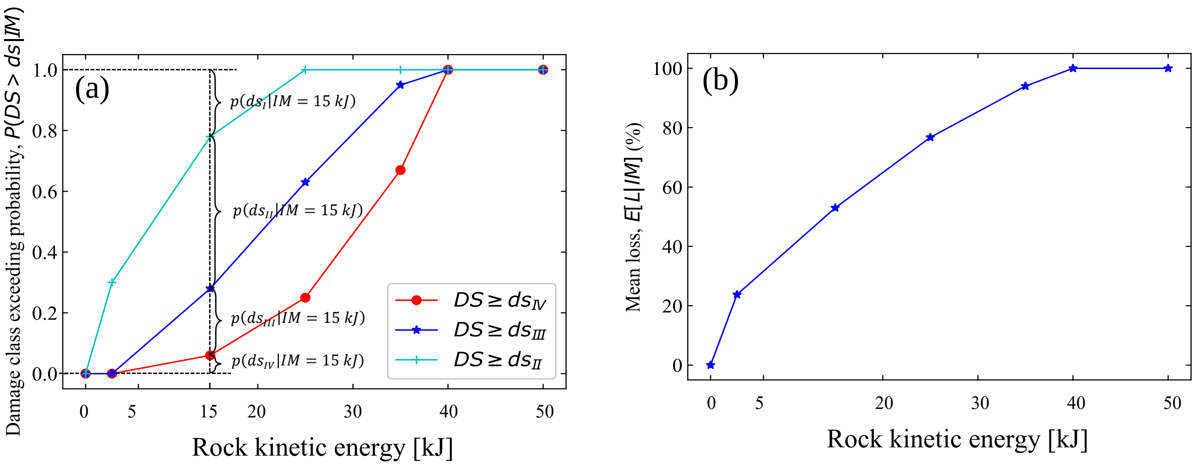

Figure 3: Fictitious example to pass from (a) three fragility curves delimitating four damage states to (b) a vulnerability curve.

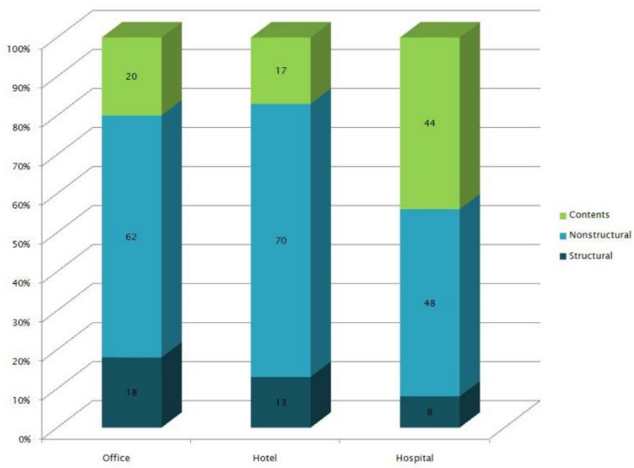

Figure 4: Typical investments in building construction [3].

Fragility/Vulnerability derivation methodologies

Empirical, numerical, expert judgment-based or hybrid methods are the four main categories of methodologies that are usually used to derive fragility and/or vulnerability relations.

Empirical approaches (e.g., for seismic natural hazard [4]) consist in using database, which are collected in the aftermath of a natural disaster event. To build fragility, or vulnerability, relations, collection database has to count with damage states, or losses respectively, and intensity measures of the given studied hazard. Disasters data collection and feedbacks are essential for widening the knowledge of the effect of natural hazards on the built cultural heritage environment. Feedback information comes from various sources (e.g., municipalities, technical services, insurance). However, it often suffers incompleteness and is usually not publically accessible.

Numerical approaches (e.g., for snow avalanche natural hazard [5]) consist in using numerical models, which are capable of predicting the structural/physical damages or losses of an element function of the intensity measures of the hazard of interest.

Expert judgment-based approaches (e.g., for snow avalanche natural hazard [6]) consist in using the knowledge of experts to build fragility or vulnerability relations.

Hybrid methods are methods that gather at least two of the three methods previously described (e.g., via Bayesian approaches).

References

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