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Vulnerability assessment of different types of building structures to debris flow events

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Debris flow events are responsible for a fair amount of disasters worldwide that have caused a great deal of damages in the built environment. All the same, this phenomenon has caused many casualties. It is therefore, amongst the most dangerous natural hazards due to the elevated impact pressures it can reach.

Debris flow destructive character is the main reason for the abundant research done regarding the processes of debris flow itself as well as the interaction between the latter and the built environment. Nevertheless, there is still no general approach available for quantification of the physical vulnerability of the built environment to debris flow events.

The present paper aims towards attaining a universal method for quantification of the vulnerability appertaining to the built environment, taking into consideration the buildings features that contribute to their vulnerability. To this end, in this work, will be presented and evaluated the existing methodologies for the vulnerability assessment of different types of buildings to debris flow and then, will be presented our own suggestion.

The final aim of this paper is the construction of vulnerability curves based on the resistance of a given building typology and therefore its vulnerability to debris flow and debris flow intensity.

Keywords: Debris flow; Building vulnerability; Vulnerability curves.

1. Introduction

With the climate change and the intensification of land use, not suited to natural hazards, the risks associated with these hazards are only becoming more pronounced. Consequently, the frequency and intensity of natural disasters are likely to intensify in the years to come.

In Switzerland, natural hazards have caused a material damage of around 305 million francs per year in the period between 1972 and 2018, according to the Federal Office for the Environment (FOEN). Nighty percent of the material damage was caused by floods and debris flow events.

Debris flow is considered as one of the most dangerous natural hazards. powerful and destructive, with the ability to move large volumes of debris and destroy infrastructure. They have caused a lot of damage to the built environment throughout the years and represent a great risk to the human life.

Depending on their composition, debris flow can be classified into two categories; muddy debris flow which contains a large fraction of fine particles and granular debris flow which contains a high concentration of large particles, with a low fraction of fine ones. Granular debris flows are more dangerous than muddy debris flows because their fronts contain large boulders and rocks, resulting in higher velocities and greater destructive force. For this reason, this study will be concentrated on granular debris flow and the vulnerability that the build environment shows to it.

The loss of human life and property during debris flow events is associated with the damage to buildings, which depends on their vulnerability to debris flow. However, the vulnerability of infrastructure to debris flow is still not well understood. Meanwhile, the study of the interaction between the built environment and debris flow phenomena is now more important than ever for all the reasons mentioned above.

There exist several studies that deal with the subject of the vulnerability of buildings to debris flow events (Fuchs *et al*., 2007; Akbar *et al*., 2009; Quan Luna *et al*., 2011; Jakob *et al*., 2011; Hu *et al*., 2012; Totsching and Fuchs., 2012; Papathoma-Köhle *et al*., 2012, 2016; Kang *et al*., 2016; Cuirean *et al*., 2016).

Nevertheless, there is still no general understanding of the different damage that buildings can suffer during a debris flow event depending on the characteristics of the buildings that contribute to their vulnerability.

This work aims toward developing a general approach for quantitative assessment of physical building vulnerability depending on the debris flow intensity and the resistance of buildings. To this end, there will be considered methodologies and results from other studies that analyze the interaction between the built environment and the debris flow events as well as the data collected from the brief historical survey made in the present work.

2. Vulnerability assessment

From a natural science and engineering perspective, vulnerability is defined as the degree of loss, in terms of percentages of structural damage, to a given feature or set of features within the affected area. Vulnerability is very often expressed on a scale of 0 (no damage) to 1 (total damage).

According to Jakob *et al*. (2011), vulnerability is the most difficult parameter to estimate with complete certainty. First because casualties caused by debris flows are linked to the collapse of buildings and are therefore an incidental consequence. Second, the type and level of damage to buildings is very difficult to assess.

The three most common methods used to assess physical vulnerability are described in Table 14. These approaches are based on general assumptions and each of them has certain advantages and shortcomings.

2.1. Methodology

In order to assess the vulnerability of the buildings to debris flow in this study, a combination of the following two methods will be used: vulnerability indicators and vulnerability curves.

The vulnerability assessment of buildings will be carried out through two essential parameters:
1. The intensity of the debris flow;
2. The structural strength of the element at risk.

Regarding the intensity of debris flow this study will consider the different categories suggested by Miteva and Prina Howald (Table).

The structural strength of the element at risk influences its vulnerability to debris flow events. There are many factors that contribute to the vulnerability of buildings and should be considered in its assessment.

2.2. Quantification of intensity

The intensity of the debris flow will be calculated with an adapted form of Li *et al*. (2010), with the pressure expressed in [kN/m^2]:

$$I = 0.005\, q_a \qquad (1)$$

with I: debris flow intensity
q_a: static impact pressure

2.3. Quantification of elements structural strength

The resistance of each type of building will be calculated in this study, using the equation proposed by Li *et al*. (2010):

$$R = \left(\prod_{i=1}^{n_s} \xi_i \right)^{\frac{1}{n_s}} \qquad (2)$$

with R: structural strength of element at risk
ξ_i: resistance factor
n_s: total number of indicators where $n_s \geq 1$

In order to determine the resistance of each building, a score must be attributed to each resistance factor. In this study, scores will be assigned based on existing studies (Li *et al*., 2010; Ciurean *et al*., 2016) and personal reflections.

2.3.1. Building materials

As we have already seen in the various studies cited in this work, reinforced concrete buildings have a particularly high resistance compared to other construction materials. For this reason, the score determined in the study by Li *et al*. (2010) seems to be

Tab. I – Vulnerability assessment methods.

N°	Method	Description	Applied by
I.	Vulnerability curves	Vulnerability curves are generally specific to each building. They have a direct correlation to the intensity of the risk, providing quantitative results (Papathoma-Köhle 2016). The disadvantage of this method is that it neglects the characteristics of buildings that contribute to their vulnerability	Fuchs *et al*. (2007); Akbas *et al*. (2009); Quan Luna *et al*. (2011); Totschnig *et al*. (2011);
II.	Vulnerability matrices	Vulnerability matrices are qualitative methods, the construction of matrices often depends on expert judgment or empirical data (Papathoma-Köhle *et al*. (2017)). According to Menoni (2006), vulnerability matrices are composed of intensities and ranked damage levels. The disadvantage of this method is that it neglects the characteristics of buildings that contribute to their vulnerability.	Zanchetta *et al*. (2004); Sterlacchini *et al*.(2007);
III.	Vulnerability Indicators	The «vulnerability indicator» method is still in the development phase. Since there are many uncertainties associated with using an indicator-based approach, some studies use them in combination with a well-established approach, such as vulnerability curves.	Li *et al*. (2010); Rheinberger *et al*. (2013); Du *et al*. (2014); Godfrey *et al*. (2015); Ciurean *et al*. (2016);

Tab. 2 – Evaluation of debris flow intensity used in this study.

Intensity		Debris flow height h_f [m]		Debris flow velocity v_f [m/s]	Impact pressure q_f [kPa]
1	Low	< 1	Or	< 1	< 22
2	Medium	$1 \leq h_f \leq 2.5$	Or	$1 \leq v_f \leq 2.5$	22-55
3	High	$2.5 < h_f \leq 5$	Or	$2.5 < v_f \leq 3.5$	56-110
4	Extreme	> 5	Or	> 3.5	> 110

underestimated. Accordingly, in this study, the score of reinforced concrete buildings defined by the study by Ciurean *et al*. (2016) will be used.

In the studies made by Li *et al*. (2010) and Ciurean *et al*. (2016), no scores are distributed for cases where the construction materials are steel and reinforced concrete mixed with wood (ground floor in reinforced concrete, upper floors in wood). This is because the results in these two studies are obtained empirically and no buildings constructed with these materials were present in both studies.

Regarding the mixed constructions (ground floor in reinforced concrete, upper floors in wood) it is important to take into consideration that buildings with this type of construction are often placed on a slope, thereby making it easier for the debris flow to reach the upper floors in wood, in this case the score distributed to this type of construction is more likely to be similar to that used for wooden constructions than the one used for reinforced concrete constructions. However, in the case where a building is not placed on a slope and depending on the height of the debris flow, the strength of reinforced concrete, which is much higher than that of wood, can strongly influence the degree of damage. Thus, in this study, the score we will consider for buildings with this type of construction is 0.6.

As for the score assigned for steel constructions, it is well known that steel is a very ductile material; this characteristic increases its strength compared to masonry and wood. However, in the case of industrial halls, the supporting structure is made of steel, while the facades are generally made of other materials (for example sandwich panels) that are much less resistant than steel. The score of 1.0 will therefore be assigned in this study.

2.3.2. Number of floors / height

Regarding the "number of stories / height" indicator, the scores that this study is going to use are a combination of those defined by Li *et al*. (2010) and Ciurean *et al*. (2016). For one- to two-story buildings, the scores from the first survey are preferable; as the second survey's scores appear overstated. For the other two categories (three or more stories), the scores defined by Ciurean el al. (2016) were preferred. The reason being that in the study by Li *et al*. (2010), the authors regroup buildings of three to five floors into one category, while in the study by Ciurean *et al*. (2016), a differentiation has been established.

However, the score of 0.1 given in the case of a single floor seems quite low. In this study, we will replace the latter with a score of 0.2.

Finally, the indicators will be weighted according to their influence on the building's resistance capacity.

The construction material of the building (ξ_{mat}) has a greater influence on the vulnerability of the building to debris flow than the number of floors / height of the building.

Thus, the weighting coefficients assigned to these two indicators are: 2.0 for the building material and 1.0 for the number of floors/ building height.

Hence, equation (2) used for the calculation of the resistance of buildings, proposed by Li *et al*. (2010) will take the following form:

$$R = (2\xi_{mat}\xi_{floor})^{\frac{1}{2}} \quad (3)$$

Tab. 3 – Scores used in existent studies for the indicator "construction materials".

Material	Score – Li *et al.* (2010)	Score – Ciurean *et al.* (2016)
Wood	0.2	0.25
Reinforced concrete and wood	-	-
Masonry	0.8	0.9
Steel	-	-
Reinforced concrete	1.3	1.95

Tab. 4 – Scores used in this study for the indicator construction materials.

	Construction materials				
	Wood	Reinforced concrete and wood	Masonry	Steel	Reinforced concrete
Score	0.2	0.6	0.8	1.0	1.95

2.4. Vulnerability function

The vulnerability (V), will be calculated according to the intensity of the hazard (I) and the resistance of the frame (R) through the function proposed by Li *et al.* (2010):

$$V = \begin{cases} 2\frac{I^2}{R^2} & \frac{I}{R} \leq 0.5 \\ 1 - \frac{2(R-I)^2}{R^2} & 0.5 < \frac{I}{R} \leq 1.0 \\ 1 & \frac{I}{R} > 1.0 \end{cases} \quad (4)$$

2.5. Vulnerability curves

Vulnerability curves were developed for each typology of vulnerable structure defined in the study by Miteva et Prina Howald represented on Table X, based on the two indicators selected (construction materials and number of floors/height).

3. Results

The vulnerability curves obtained for each type of structure are illustrated in Figure 1.

According to the results obtained in this study, the most vulnerable structures are those built entirely of wood. On the other hand, the least vulnerable buildings are those constructed of reinforced concrete. It should be noted, however, that according to the results obtained in this study, a three-story chalet with the ground floor constructed of reinforced concrete and the two upper floors of wood, has a lower vulnerability than a two-story masonry building. This can be explained by the fact that reinforced concrete has much higher structural strength than masonry.

Thus, for a debris flow of medium intensity (according to the

Tab. 5 – Scores used for the number of floors.

Number of stories	Score – Li *et al.* (2010)	Score – Ciurean *et al.* (2016)	Score – Present study
1	0.1	0.4	0.2
2	0.4	0.85	0.4
3	0.9	1.0	1.0
> 3	0.9	1.2	1.2

Tab. 6 – Brochure of the different types of vulnerable structures defined by Miteva et Howald Prina.

N°	Construction type	N°	Construction material(s)	Number of stories
1	Chalet	1.1	Wood	1
		1.2	First floor in concrete, upper floors in timber	2-3
2	Individual villa	2.1	Masonry	2-3
		2.2	Reinforced concrete	2-3
3	Industrial building	3.1	Steel	3
		3.2	Wood	3
4	Residential building	4.1	Masonry	≥ 3
		4.2	Wood	≥ 3
		4.3	Reinforced concrete	≥ 3

The function used for the construction of the various curves is V = f (I, R), (4) with the intensity of the hazard calculated according to equation (1) and the resistance of the buildings determined by means of equation (3).

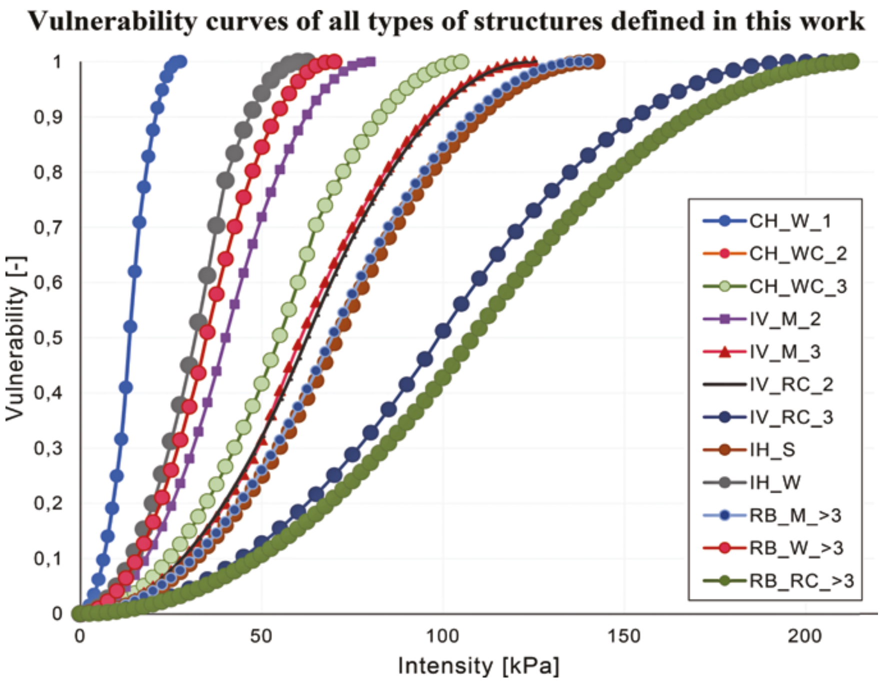

Fig. 1 – Vulnerability curves for all the types of vulnerable structured defined previously in this study.
Explanation of the legend: the first two letters indicate the type of structure (CH = Chalet; IV = Individual villa; IH = Industrial hall; RB = Residential building), the next letter/two letters indicate the building material (W = Wood; WC = Reinforced concrete and wood; M = Masonry; RC = Reinforced concrete; S = Steel) and the number at the end indicates the number of floors of the building.

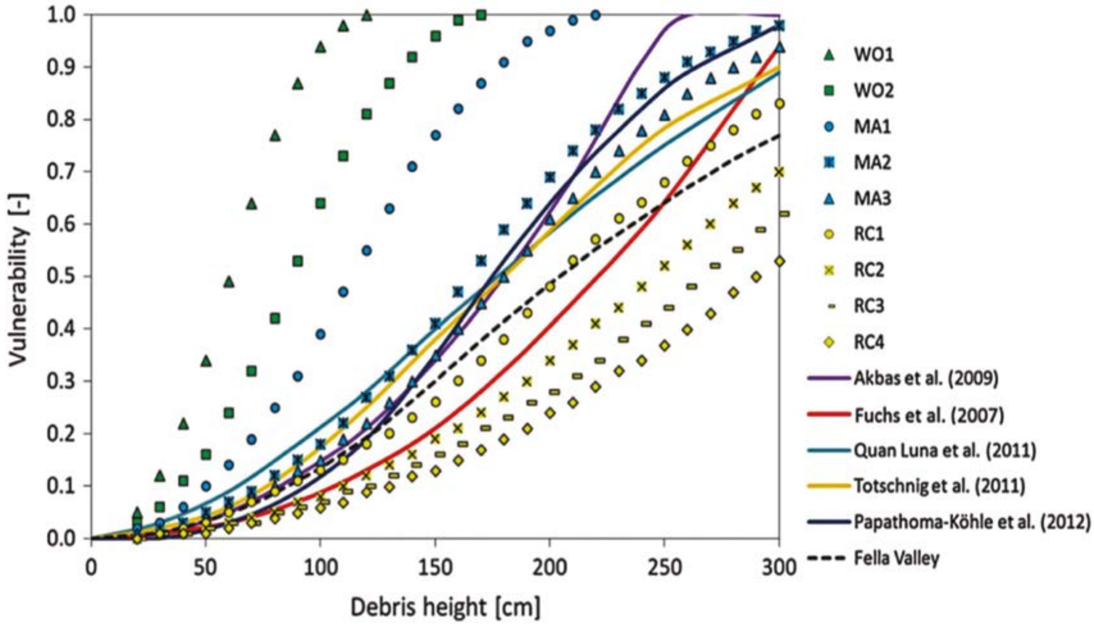

Fig. 2 – Vulnerability curves established by Ciurean *et al.* (2016).

intensities defined in this work (Table 13), maximum height of the debris flow: 2.5 [m]), a masonry building will suffer major structural damage or will be completely destroyed, while a building with a reinforced concrete ground floor will suffer only minor structural damages (because the debris flow won't reach the wooden floors).

Furthermore, we can notice that a three-story individual villa made of masonry has almost the same vulnerability to the hazard as a two-story individual villa made of reinforced concrete. One initial explanation is the fact that the vulnerability of one-story building increases as soon as the debris flow reaches 2 [m] in height. However, an overestimation of the strength can might have been made due to the indicator "number of floors / height" and the scores assigned to it. This can also be noticed in the case of the steel industrial hall and the masonry residential building with more than three floors. According to the results of the present study, these two distinct typologies of building present almost identical vulnerability curves. Thus, we can conclude that the indicator "number of floors / height" and the corresponding scores must be further examined.

Finally, this work shows that the typology of structures most vulnerable to debris flows is the one-story chalet. On the contrary, the one that presents a minimal vulnerability is the reinforced concrete residential building of over three floors.

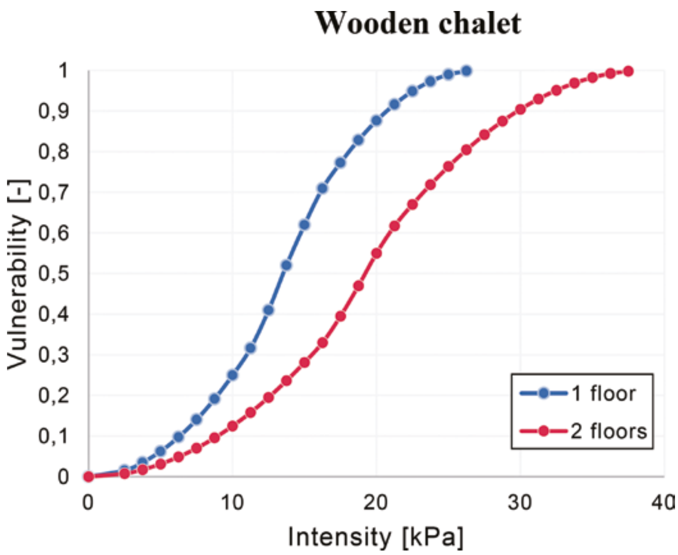

Fig. 3 – Vulnerability curves established by the present study – Wooden chalet.

3.1. Comparison with other studies

First comparison of this study's results can be made with the results derived in the study by Ciurean *et al.* (2016). However, it is important to mention that the vulnerability in the latest is assessed based on the cost of damage caused to the built environment and not the structural strength of the latter as established in this work.

Based on the study by Cuirean *et al.* (2016), for one-story wood buildings and two-story wood buildings to achieve a vulnerability of 1.0, a pressure of about 26 [kPa] (debris flow height of about 1.2 [m]) and respectively 37 [kPa] is required. This is in concordance with the results of the present stu-

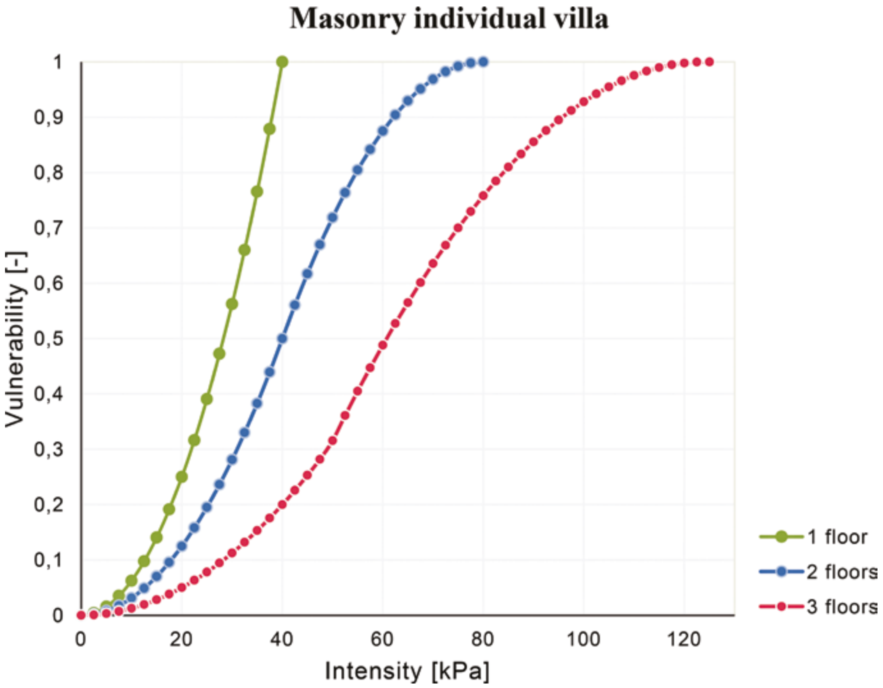

Fig. 4 – Vulnerability curves established by the present study – Masonry individual villa.

dy, according to which a one-story wooden chalet achieves a vulnerability of 1.0 for a pressure of 27.5 [kPa] and a two-story wooden chalet achieves it at an impact pressure equaling 37.5 [kPa].

Also, when comparing the curves for masonry buildings established in the Cuirean *et al.* (2016) study and the present one the findings are rather close. For a one-story masonry building with a vulnerability of 1.0, an impact pressure of 45 [kPa] is required according to the research of Cuirean *et al.* (2016), from the results of this study, the impact pressure under such conditions is 40 [kPa]. Then, for two-story masonry buildings to attain a vulnerability of approximately 0.97, an impact pressure of about 68 [kPa] and 70 [kPa] is needed according to Cuirean *et al.* (2016) and this study, respectively.

Another study's results that will be compared with this works results are those obtained by Kang *et al.* (2016).

In the study by Kang *et al.* (2016), the structures were classified into two main groups: buildings constructed with a material other than reinforced concrete (non-concrete frame) and reinforced-concrete frame buildings. In the group of buildings made of a material other than reinforced concrete, they have considered wood and masonry buildings. It should be noted that in the study by Kang *et al.* (2016), the building material, is the only indicator considered.

According to the graph shown in Figure 5, from the study by Kang *et al.* (2016), for "non-concrete frame" buildings the vulnerability reaches 1.0 as the impact pressure approaches 50 kPa. This is consistent with the results obtained in this study for one-story wood and masonry buildings.

Then, for reinforced concrete buildings, the impact pressure required in order to obtain a vulnerability equal to 1.0, according to Kang *et al.* (2016) is of about 225 [kPa]. The pressure obtained in the present work is about 215 [kPa].

To conclude, the results established in the present work remain close to those established in previous studies.

4. Discussion

This paper suggests a combined method in the quest of vulnerability assessment of buildings to debris flow. The proposal of which as well as the function for vulnerability determination have emerged from thoughtful study.

Regarding the vulnerability of buildings, it would be interesting to do a more in-depth study that would take into consideration several indicators and then finally, to analyze the vulnerability of buildings according to several combinations of indicators in order to be able to assess their influence on the resistance of the building in a more precise way.

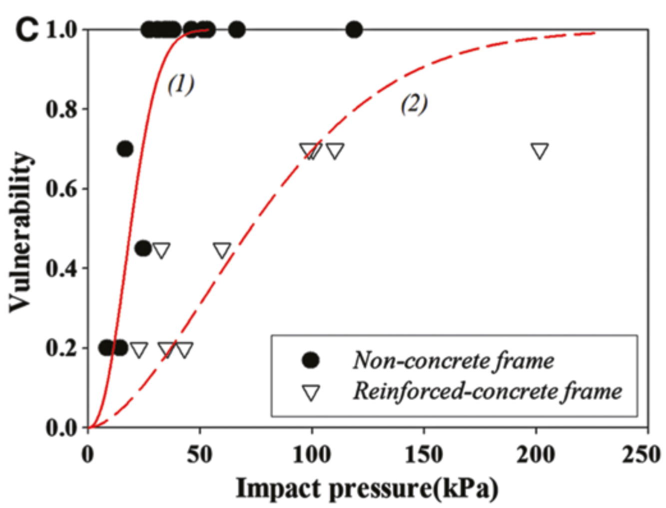

Fig. 5 – Vulnerability curves obtained by Kang *et al.* (2016).

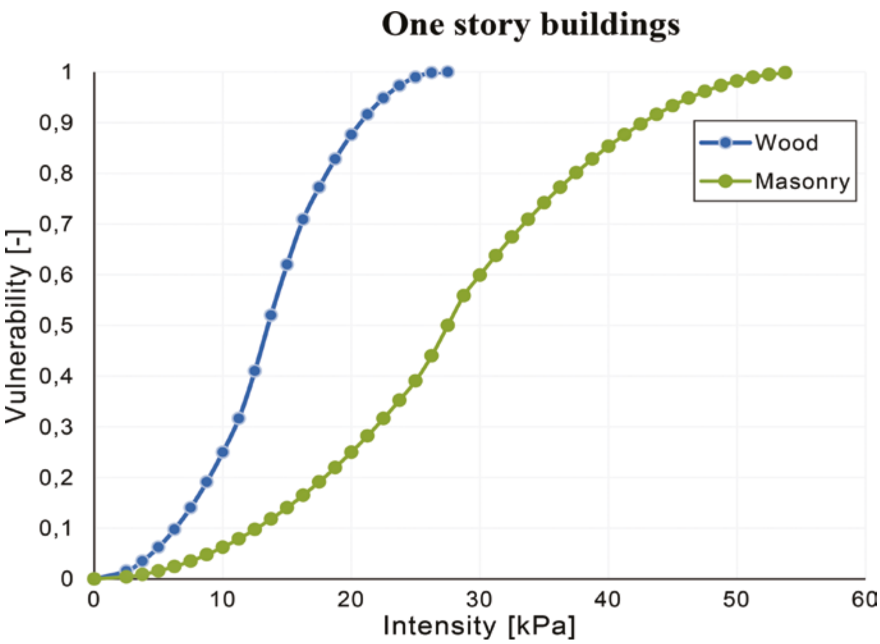

Fig. 6 – Vulnerability curves established by the present study – One story wood and masonry buildings.

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