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Analytical structural vulnerability and classification of Italian residential building stock to tsunami hazard

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ABSTRACT The increasing exposure of Mediterranean coastal regions to tsunami risk, also due to climate changes, leads to the need of tools to support disaster risk management and loss assessment. This study presents a tsunami structural vulnerability model for Italian residential buildings based on numerical analysis and Monte Carlo simulation. Starting from national building census repositories, typical building typological classes and main attributes are defined. Monte Carlo simulation is performed to simulate building stocks statistically representative of existing Italian residential buildings, and analytical models are adopted for the structural damage assessment of such buildings under tsunami inundation. The structural damage is classified according to a unified damage scale adapted for different structural typologies, and a damage index is computed to describe the structural vulnerability to tsunami hazard. Based on the analytical vulnerability curves, tsunami vulnerability classes for Italian residential buildings are finally proposed to be used for an informed definition and prioritisation of risk mitigation strategies. Results from this study can be also applicable to other Mediterranean regions with a similar construction practice.

Key words: tsunami vulnerability class, tsunami risk, tsunami loss assessment, tsunami fragility, Variable Depth Pushover.

1. Introduction

The structural vulnerability to tsunami hazard represents the susceptibility of buildings to structural damage during an inundation of a given intensity. In the context of risk analysis and loss assessment at regional scale, vulnerability classes are usually defined to easily identify the performance of buildings against natural hazards for an effective disaster management. Indeed, vulnerability classes categorise buildings based on their response to a generic hazard, irrespective of their structural typologies. In the field of seismic risk assessment, several methods have been developed over years to assess the seismic vulnerability of existing assets (Calvi *et al.*, 2006), and well-assessed seismic vulnerability classes are incorporated in risk analysis at regional scale (Grünthal, 1998, among others).

In the field of tsunami risk analysis, limited empirical data are available to define tsunami vulnerability classes of buildings. Post-tsunami survey reports allow to identify the main damage mechanisms for buildings depending on the construction material (EERI, 2011; Suppasri *et al.*, 2012). These data have been used to derive empirical fragility curves for the damaged building typologies, useful for a local loss assessment (Koshimura *et al.*, 2009; Reese *et al.*, 2011; Suppasri *et al.*, 2013). Structural vulnerability of buildings to tsunami hazard can be influenced by the number of storeys. Indeed, past post-tsunami surveys revealed that mid- and high-rise structures (i.e. 3 or more storeys) exhibit a better structural behaviour under tsunami inundation than low-rise buildings with 1 or 2 storeys (Suppasri *et al.*, 2013). Dias and Edirisooriya (2019) derived the relative vulnerability of single-storey timber, masonry and concrete buildings, starting from empirical fragility curves. A thorough review of current gaps in physical vulnerability assessment of assets to tsunami hazard is reported in Behrens *et al*. (2021).

Italian coastal communities are exposed to tsunami hazard (Antoncecchi *et al.*, 2020), but studies about the vulnerability of Italian building typologies for an informed disaster planning are currently lacking. In the framework of the European Scenarios for tsunami Hazard-induced Emergencies Management (SCHEMA) project (Tinti *et al.*, 2011), five structural vulnerability classes for building typologies typical of European coastal regions are identified based on structural material, number of storey and occupancy (i.e. residential or other use). This classification was built analysing the empirical damage to constructions observed in Banda Aceh after the Indian Ocean tsunami (2004), and then adapted to European buildings (Valencia *et al.*, 2011). However, empirical data are strongly influenced by the location and by the costal morphology, the construction material properties and the local construction techniques.

The main aim of this paper is to assess and classify the vulnerability of Italian residential buildings to tsunami hazard to perform risk analysis at regional scale. To this scope, an extensive probabilistic simulation is performed to assess the damage caused by tsunami loading on different Italian building typologies [i.e. masonry and reinforced concrete (RC) frame buildings]. Typical building types are identified from a detailed analysis of available building census data, and main attributes for the classification of vulnerability are considered. A damage scale is also proposed for a consistent structural damage assessment of different structural typologies; other types of damage are not considered (i.e. water entrance). Finally, analytical vulnerability curves are derived and vulnerability classes for Italian residential buildings are proposed based on data from numerical modelling and probabilistic simulation. The definition of such vulnerability model can be also helpful to define and prioritise risk mitigation strategies in Italian coastal areas exposed to tsunami hazard (Belliazzi *et al.*, 2021b; Fabbrocino *et al.*, 2021). It is important to note that the vulnerability curves proposed are related only to structural damage while damage to other building components (e.g. doors, windows, furniture, etc.) are not considered in this study.

2. Methodology

This study investigates the vulnerability of Italian residential building stock to tsunami hazard with focus on structural damage through mechanical models and Monte Carlo simulation. Indeed, limited information is currently available about attributes that affect the definition of vulnerability classes for Italian residential buildings to perform tsunami loss assessment and risk analysis at regional scale, and empirical data from past events are lacking.

Analytical vulnerability curves are herein derived for the most diffused Italian typological classes of residential buildings. Attributes for the definition of typological classes are preliminary selected based on the GED4ALL (Silva *et al.*, 2018) building taxonomy for multiple natural hazards (e.g. earthquakes, floods, volcanoes, strong winds, tsunamis, and drought). In detail, according to the simplified multi-hazard GED4ALL taxonomy, the minimum attributes needed to characterise the vulnerability of a building stock are: material of lateral-load resisting system, lateral-load resisting system, height, date of construction, occupancy, ground floor hydrodynamics, and roof shape. The latter is not significant for tsunami inundation and is herein neglected. A detailed description of the building attributes considered in this work is reported in Fig. 1.

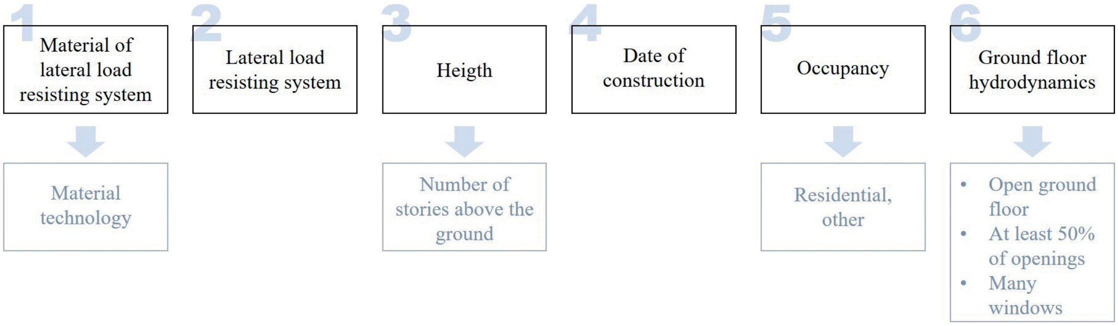


Fig. 1 - Building attributes for the vulnerability assessment (GED4ALL).

Data for the definition of Italian residential building typological classes are herein taken from opensource national building census repositories (i.e. ISTAT database), which collect all the residential building attributes before mentioned, except for the ground floor hydrodynamics. Given the lack of data, assumptions are made for the ground floor hydrodynamics (e.g. opening ratio) of residential buildings in coastal areas using the Monte Carlo simulation.

After the definition of typological classes, a simulated residential building stock is generated for each typological class through Monte Carlo simulation, explicitly accounting for the design code in force at the time of construction, the uncertainties related to geometrical and mechanical properties and the building-to-building variability. The damage assessment under tsunami inundation is performed for each building realisation in the simulated building stock through global or local structural analysis (Belliazzi *et al.*, 2020; Del Zoppo *et al.*, 2022), and accounting for uncertainties related to tsunami loading. For the damage assessment, a unified damage scale is proposed to classify the structural damage for different structural typologies in a consistent approach. Finally, to derive tsunami vulnerability curves, a Damage Index (*DI*) is introduced to correlate the tsunami inundation depth (H_w) [selected as intensity measure (Park *et al.*, 2017)] with the damage level experienced by residential buildings. Based on vulnerability curves obtained for different typological classes, homogeneous vulnerability classes are proposed for the Italian residential building stock to be used in tsunami loss assessment and risk analysis at regional scale.

2.1. Definition of typological classes

Typological classes are defined for the Italian residential building stock from available national building census data (ISTAT, 2001, 2011), which provide information about structural system material (i.e. masonry, RC, steel, etc.), age of construction and number of storeys, among others.

According to the most recent available ISTAT (2011) data, the total number of Italian residential buildings is 12,187,698, 57% of which corresponds to masonry buildings, 29% are RC buildings, and the remaining 14% refers to other structural materials. Based on ISTAT data and on the traditional Italian construction practice, the tsunami vulnerability analysis, herein developed, focuses on unreinforced masonry buildings and RC frames with unreinforced masonry infill walls, which represent the most diffused Italian structural typologies for residential buildings.

Statistics about the distribution of number of storeys and age of construction are derived from ISTAT (2001) data and reported in Figs. 2a and 2b for masonry and RC buildings, respectively. The data about the number of storey distributions show that about 79% of the existing masonry building stock is characterised by 1 or 2 storeys (Fig. 1a), whereas about 66% of the existing RC building stock has 1 or 2 storeys (Fig. 2b). Buildings with more than 5 storeys are less than 0.6% and 4% for masonry and RC constructions, respectively.

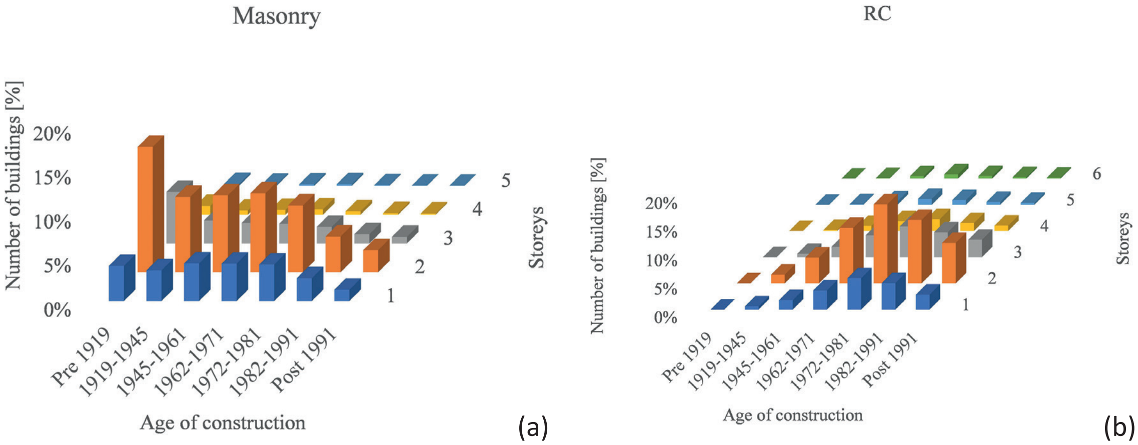
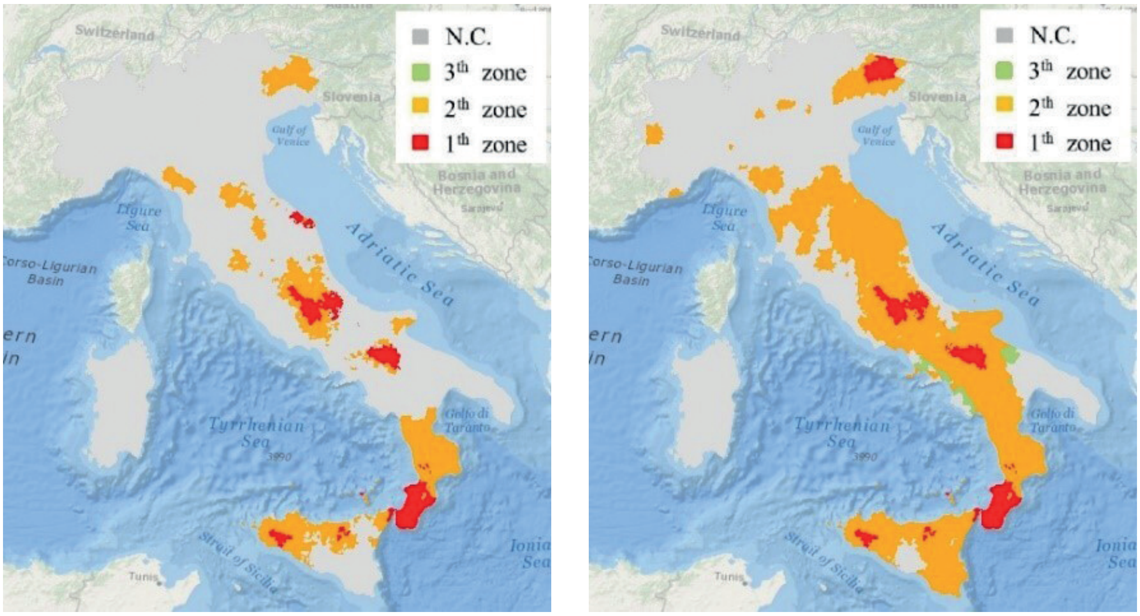


Fig. 2. - Building distribution depending on number of storeys and age of construction: a) masonry and b) RC buildings (ISTAT, 2001).

Data related to the age of construction distribution show that masonry buildings built before 1919 constitute 29% of the masonry existing building stock, whereas modern masonry constructions (construction age > 1991) represent 3% of the stock (Fig. 1a). Conversely, less than 3% of RC buildings dates back prior to 1945, whereas 60% was constructed between 1946 and 1981 and 37% thereafter (Fig. 1b).

It is worth noting that the historical evolution of Italian design codes plays an important role in the classification of the lateral-loads resisting system. Indeed, after the Irpinia earthquake of 1981 most of Italian regions have been classified as seismic zone (see Fig. 3), and buildings built after the 1980s are mostly designed following seismic design criteria (D.M., 1975). Conversely, before that date, only a few areas were classified as seismic, and buildings were designed either for gravity or seismic actions, as shown in Fig. 3.

Typological classes for Italian residential buildings are preliminary defined assuming a constant number of storeys for each class. In details, building typological classes characterised by 1 to 5 or 6 storeys are considered to assess the effect of the building's height on the structural vulnerability during a tsunami inundation. Buildings with a higher number of storeys are neglected since they represent a negligible portion of the existing Italian residential building stock. Based on the statistics derived from census data and on the historical evolution of Italian design codes, three different ages of construction are considered to further define the typological classes, as reported in Table 1. In detail, the AGE0 is defined only for masonry buildings built before 1919 and designed for gravity loads (i.e. AGE0_Gravity). Conversely, AGE1 includes both masonry



(a) (b)

Fig. 3 - Italian seismic zone classification in 1976 (a) and 1984 (b).

and RC buildings built between 1920 and 1980 and designed for either gravity loads or seismic actions (i.e. AGE1_Gravity and AGE1_Seismic). Finally, AGE2 is defined for both masonry and RC buildings built after the 1980s and designed for gravity or seismic action (i.e. AGE2_Gravity and AGE2_Seismic). The class AGE2_Gravity is considered only for masonry buildings, since a negligible difference in design criteria and material properties for RC structures is observed between AGE1_Gravity and AGE2_Gravity; by contrast for masonry buildings, the design criteria affect the geometrical characteristics of the masonry walls in terms of maximum wall length or wall thickness (mainly gravity or seismic building classes), while the age of construction has a significant influence on the masonry mechanical properties. Table 1 also reports the number of storeys considered for each typological class.

2.2. Mechanical models for structural damage assessment

The analytical structural damage assessment is herein performed by means of simple mechanics-based models developed by the authors for masonry (Belliazzi *et al*., 2020) and RC buildings (Del Zoppo *et al*., 2022) subject to tsunami loading. Both procedures implement the nonlinear static analysis called Variable Depth Pushover for Breakaway Infilled Frames (VDPO-BI) (Del Zoppo *et al*., 2021a, 2021c), which consists in assessing the performance of buildings for increasing tsunami H_w, accounting for the damage to both structural and non-structural components. It is noted that in the case of masonry buildings, all exterior walls are structural components; non-structural components (i.e. interior walls) are neglected in the analysis for both masonry and RC buildings. The procedure is implemented in Matlab code for both masonry and RC buildings.

In the VDPO-BI analysis the tsunami-induced hydrostatic (q_s) and hydrodynamic (q_d) loads are applied to the structure in their actual distributions, and are progressively increased up to

Table 1 - Definition of Italian residential building typological classes based on age of construction and number of storeys (M = masonry, RC = reinforced concrete).

Age of construction	Period of construction	Description of design criteria	Design criteria	Structural material	No. of storeys
AGE0	≤ 1919	This typological class includes residential buildings built before 1919. The 1919 is the oldest reference year according to the ISTAT census data. In 1919 only a restricted part of Calabria region and some Sicilian cities were classified as seismic areas after the Reggio Calabria earthquake (1908); therefore, it is assumed that the buildings built before 1919 were designed only for gravity loads. It should be noted that this building class refers exclusively to masonry buildings, given the limited percentage of RC buildings built prior 1945	Gravity	M	1, 2, 3, 4, 5
AGE1	1920-1981	This typological class includes residential buildings built between 1920 and 1980. Buildings built in such period can either be designed for gravity loads or seismic actions according to RD 1937 and RD 1939	Gravity, Seismic	M	1, 2, 3, 4, 5
				RC	1, 2, 3, 4, 5, 6
AGE2	> 1981	This typological class considers residential buildings built after 1980s. In this construction period, buildings are designed for seismic actions based on the DM 1975	Gravity, Seismic	M	1, 2, 3, 4, 5
			Seismic	RC	1, 2, 3, 4, 5, 6

the structural collapse. The hydrostatic load is modelled as a triangular pressure distribution (Petrone *et al.*, 2017), while a uniform pressure distribution is adopted for hydrodynamic loads as prescribed by the American code for the design of tsunami evacuation buildings ASCE 7-16 (ASCE, 2017), see Fig. 4. Tsunami-induced hydrodynamic loads are herein computed following the empirically-validated model proposed by Foster *et al*. (2017) for steady flows. The effect of tsunami-induced uplift loads on interior slabs is neglected in the analysis since it provides relevant structural damage (i.e. blow-out slabs) only for mid to high-rise buildings with 6 or more storeys (Del Zoppo *et al*., 2021b). However, such buildings are not typical for existing Italian assets and are not included in the typological classes investigated herein, as reported in Table 1. Other effects induced by tsunamis on structures, such as debris impact, are not considered in this study given the high uncertainties in floating debris generation and propagation inland. However, it is recognised that fragility and vulnerability curves that ignore debris impact loads are unbiased for residential areas due to the relevant shielding provided by surrounding buildings (Reese *et al*., 2011).

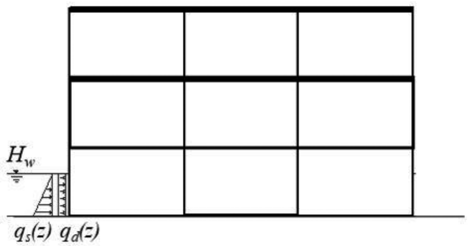


Fig. 4 - Tsunami-induced loads on structures for the structural analysis.

2.2.1. Masonry buildings

For existing masonry structures, the analysis of global collapse mechanisms is not straightforward due to the premature activation of local failure mechanisms. Hence, the damage assessment for masonry buildings is performed focussing on the development of local mechanisms on exterior walls through simple mechanics-based models. Both in-plane (IP) or out-of-plane (OOP) damage mechanisms are considered for masonry walls.

The IP shear capacity of masonry walls at ultimate limit states is based on Mohr-Coulomb (Labuz and Zang, 2012) and Turnšek-Cačovic (Turnšek and Cačovic, 1971) capacity criteria, respectively for sliding and diagonal shear failures (Augenti and Parisi, 2019), according to Eurocode 6 (CEN, 2005a) and Italian building code (NTC, 2018). Conversely, shear force thresholds at cracking are conventionally defined as one half of the ultimate capacity, as shown in diagonal compression experimental tests results available in literature (Prota *et al*., 2006). The bending moment capacity of masonry walls at cracking is evaluated in the elastic field, whereas ultimate bending moment equations are taken from Lignola *et al*. (2008).

Horizontal and vertical flexural failures are considered as main OOP damage mechanisms of masonry walls; conversely, flexural failure, sliding shear failure, and diagonal shear failure are identified as main IP damage mechanisms.

For the OOP damage assessment of exterior masonry walls, the generic wall is modelled as a simply supported beam, as a safety criterion (Belliazzi *et al*., 2018).

IP damage mechanisms are analysed by means of a macro-elements modelling (Augenti and Parisi, 2019) assuming three different types of structural modelling of the walls depending on the level of connection between consecutive piers (Fig. 5). In detail, in Wall Model I, the masonry walls are modelled as isolated cantilevers (Fig. 5b); in Wall Model II, masonry walls are modelled as cantilevers connected by trusses (Fig. 5c), while in Wall Model III, the entire structure is modelled as shear-type frame (i.e. indefinitely rigid beams) (Fig. 5d).

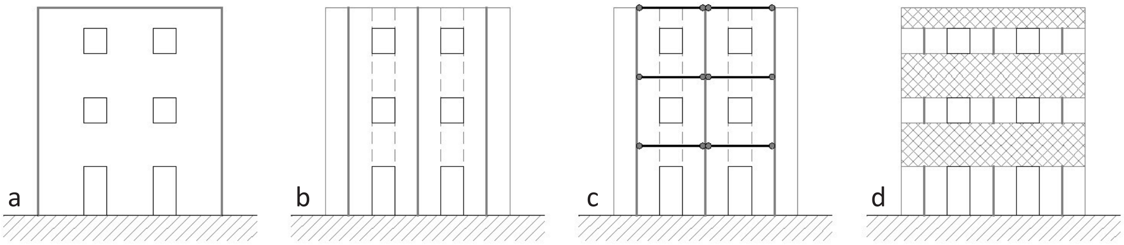


Fig. 5. - Physical model (a), Wall Model I (b), Wall Model II (c), and Wall Model III (d).

2.2.2. RC buildings

In the case of RC frame buildings with unreinforced masonry infill walls (i.e. breakaway walls), the structural performance of the frame under tsunami loads is assessed via simplified structural analysis suitable for large-scale applications (Del Zoppo *et al*., 2022). The VDPO-BI analysis is performed on 2D central frames of residential RC buildings under the assumption of shear-type frames. In detail, the structural performance of a 2D frame under tsunami lateral loads is computed by adopting the Stiffness Method, whilst the ultimate capacity is evaluated from the energy approach by means of the Virtual Work Principle (Fig. 6). The activation of the first shear failure in columns is assessed comparing the tsunami demand with the shear capacity of structural components, computed according to the Eurocode 8-3 (CEN, 2005b). A detailed description of the structural modelling can be found in Del Zoppo *et al*. (2022) and it is not reported herein for the sake of brevity.

The OOP performance of masonry infill walls at each storey is explicitly modelled within the VDPO-BI analysis, since it affects the tsunami-induced loads magnitude and distribution on structural components. In detail, the activation of the double-arch failure mechanism is assessed analytically for infill walls in RC frames subject to tsunami inundation (Del Zoppo *et al*., 2021a). Openings in infill walls are modelled as a reduction of OOP capacity in the masonry panel according to the empirical model proposed by Liberatore *et al*. (2020).

This simplified structural analysis procedure has been validated against refined analysis performed in OpenSees, showing an accuracy greater than 95% in predicting the performance of RC frames subject to tsunami lateral loads (Del Zoppo *et al*., 2022).

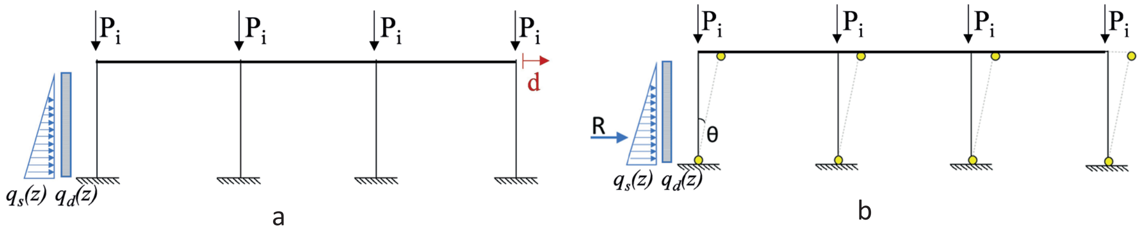


Fig. 6 - Mechanics-based VDPO-BI: Lateral Stiffness Method (a) and Virtual Work Principle (b).

2.3. Structural damage levels classification

Empirical damage caused by tsunami inundation is commonly classified following the Ministry of Land, Infrastructure and Transportation of Japan (MLIT) guidelines. According to MLIT, six damage levels are identified ranging from minor damage to washed away. Even though the qualitative nature of this classification, it is helpful to understand the progression of damage. Damage states DS1-3 (i.e. minor to major) are mainly related to non-structural components. Conversely, only damage states DS4-5 (i.e. complete and collapsed) focus on structural damage. Damage state DS6 (i.e. washed away) refers to the observed complete destruction of a building.

The structural damage level classification herein adopted has been proposed by Del Zoppo *et al*. (2021b) based on the HAZUS Tsunami Model Technical Guidance (FEMA, 2017), that provides a quantitative estimation of damage levels for risk and loss assessment purpose. This classification originally proposed for RC frames is herein extended to unreinforced masonry buildings as reported in Table 2.

In detail, four structural damage levels are considered herein, from slight to complete (FEMA, 2017). Following the HAZUS approach, structural damage associated with a global ductile failure mechanism is considered for RC buildings. Indeed, the HAZUS classification neglects the occurrence of local failure mechanism of structural components and, hence, does not provide any information on how this kind of damage mechanism should be classified for a vulnerability analysis. However, previous numerical studies have found that the brittle failure of RC columns due to shear can be a damage mechanism for such structures (Alam *et al*., 2017; Petrone *et al*., 2017). It is also noted that several uncertainties arise with the shear failure prediction for RC structural components, and no data or models are currently available for the case of RC members subjected to tsunami loading. Hence, the vulnerability of RC members to local brittle mechanisms (i.e. shear failure of one vertical member) is herein investigated independently.

Conversely, for masonry buildings only local damage mechanisms at vertical-member level are considered, as previously discussed in Section 2.2. For such buildings, damage mechanisms are defined as summarised in Table 2, and only moderate to complete damage levels are identified. Indeed, the slight damage is hard to be defined for masonry walls subjected to tsunami inundation. In detail, a moderate damage is associated with the achievement of the first cracking in exterior masonry walls either due to IP or OOP loads. Extensive damage is defined as the failure of any non-load-bearing wall (i.e. walls not carrying gravity loads) due to IP or OOP mechanisms. Conversely, the failure of a load-bearing wall is considered as a complete damage for the buildings, compromising the stability of the entire structure.

With respect to the qualitative damage scale provided by the MLIT, the proposed damage classification considers a more detailed quantification of the structural damage, introducing slight and moderate damage levels. The definition of extensive and complete damage levels is in agreement with the qualitative definition of DS4-5 of the MLIT. Damage to non-structural components is not included in the proposed damage classification as the present vulnerability assessment refers to structural damage only.

Table 2 - Structural damage levels classification for RC and masonry buildings.

	SLIGHT	**MODERATE**	**EXTENSIVE**	**COMPLETE**
REINFORCED CONCRETE	First achievement in any vertical member of concrete cracking	First achievement in any vertical member of ½ steel yield strain in the longitudinal steel	First achievement in any vertical member of steel yield strain in the longitudinal steel	Maximum base shear capacity
MASONRY	N.A.	First achievement of masonry cracking in any exterior wall for IP or OOP mechanisms	First achievement in any non-load-bearing structural wall of IP or OOP failure	First achievement in any load-bearing structural wall of IP or OOP failure

3. Vulnerability assessment of Italian residential building stock

To assess the structural vulnerability of the previously defined Italian typological classes of buildings to tsunami loads, simulated residential building stock is generated through Monte Carlo simulation for each typological class. The structural performance of masonry and RC buildings is, then, assessed as discussed in the previous Section 2.2., and H_w, corresponding to the achievement of selected mechanical damage mechanisms, is computed for each building in the simulated stock.

In line with previous vulnerability studies performed for seismic hazard at regional scale (Rosti *et al.*, 2020), the tsunami damage is expressed in terms of mean *DI*, representing the normalised mean damage grade of the damage distribution given the intensity measure (i.e. tsunami H_w), as reported in Eq. 1:

$$DI = \frac{\sum f_i}{n} \tag{1}$$

where f_i is the frequency of occurrence of a given damage level (i = 1-4 for ductile mechanisms in RC buildings and i = 1 for the local brittle mechanism; i = 1-3 for masonry buildings) and n is the total number of damage levels considered for masonry and RC buildings, respectively. The *DI* ranges between 0 and 1, where 0 indicates the absence of damage and 1 corresponds to a complete damage.

The distribution of *DI* derived for each typological class is fitted by a lognormal function to provide a continuous description of *DI* as a function of the tsunami H_w, which represents the vulnerability curve for a typological class.

3.1. Residential building stock definition

For each typological class identified in Section 2.1. (i.e. homogeneous number of storeys, age of construction, and design criteria), a simulated building stock is generated to derive analytical vulnerability curves. Geometric and mechanical properties are treated as random variables for the generation of the stock, as reported in Tables 3 and 4 for RC frames and masonry buildings, respectively. In detail, 10^4 building realisations are generated for each typological class for both masonry and RC buildings, and a Monte Carlo simulation with a Latin Hypercube sampling is performed to derive a vector of random variables that characterise each building realisation in the stock.

Buildings are assumed to be regular in both plan and elevation. Statistics for random variables are taken from the National Group for the Defence against Earthquakes (GNDT) database, which provides data in terms of storey gravity loads, interstorey height, and mechanical properties of materials. Bay lengths in RC structures are limited to the range of 4.0-6.0 m (Borzi *et al.*, 2020), whereas the minimum and maximum bay lengths for masonry buildings are fixed depending on design criteria and existing building codes. Different mechanical properties of construction materials are considered before and after the 1980s, due to the improvement in the quality control of materials over time. To assess the influence of material mechanical properties in typical Italian masonry buildings, five masonry types are considered: poor stone, tuff stone, hollow clay brick, clay brick, and full clay brick. The compressive and shear strength are derived from available building code limits for each of the coded masonry types (CIBC, 1981, 2009, 2019). For RC buildings, five classes of concrete characterised by a poor to good quality are considered and randomly selected. Similarly, for the reinforcing steel four mean values typically found in Italian existing buildings are considered, as reported in Table 3.

Assumptions are made about the opening ratio at ground storey level, which affects the ground floor hydrodynamics (Fig. 1). Since the vulnerability assessment focuses on typical residential buildings in coastal areas, it is reasonable assuming that several windows are present in the *façade*. Hence, an opening ratio randomly ranging between 8% and 30% is adopted to consider the reduced capacity of exterior walls caused by the openings.

Geometrical dimensions of structural components (i.e. masonry walls thickness, RC column cross-sections, and reinforcement details) are, then, computed for each building realisation through a simulated design procedure according to the Italian code in force at the considered construction period.

It is worth underlining that masonry buildings built before the 1920s are not designed according to a proper simulated design procedure. Indeed, empirical equations retrieved from historical literature (Augenti and Parisi, 2019) are adopted to define the wall thickness depending on structural geometric characteristics such as number of storeys, length, or height of building.

Uncertainties in tsunami loads are also considered when deriving analytical vulnerability

Table 3 - Variables for the RC building stock generation.

			Before 1981	After 1981
	Parameter	**Distribution**	**Mean (CoV)/Range**	**Mean (CoV)/Range**
GEOMETRY	Number of bays	uniform	2 - 7	
	Bays length	uniform	4 - 6 m	
	Interstorey height	constant	3 m	
	Infill walls thickness	uniform	0.12 – 0.35 m	0.24 – 0.35 m
MATERIALS	Steel yielding strength	normal	315 – 375 – 430 MPa	375 – 430 – 500 MPa
	Concrete compressive strength	normal	15 – 20 – 25 MPa (10%)	25 – 30 – 35 MPa (10%)
	Masonry compressive strength (infill walls)	normal	1.5 MPa (14%)	
LOADS	Dead load – intermediate floor	normal	3.0 (0.5) kN/m^2	
	Dead load – roof	normal	2.5 (0.5) kN/m^2	

Table 4 - Variables for the masonry building stock generation (Belliazzi *et al.,* 2021b).

					Before 1981	After 1981
	Parameter	**Masonry substrates**		**Distribution**	**Mean (St.Dev)/range**	**Mean (St.Dev)/range**
GEOMETRY	Interstorey height	Poor stone		normal	3.5 m (1.13)	
		Tuff stone		normal	3.5 m (1.1)	
		Hollow clay brick		normal	3.1 m (0.9)	
		Clay brick		normal	3.4 m (1.1)	
		Full clay brick		normal	3.22 m (1.1)	
MATERIALS	Compressive strength	Poor stone		uniform	1.0-3.0 MPa	2.5-3.0 MPa
		Tuff stone		uniform	6.0-8.0 MPa	6.0-10.0 MPa
		Hollow clay brick		uniform	1.5-2.0 MPa	3.0-8.0 MPa
		Clay brick		uniform	3.0-8.0 MPa	4.0-10.0 MPa
		Full clay brick		uniform	3.0-4.4 MPa	5.0-10.0 MPa
LOADS	Dead loads	Flat roof	Poor stone	normal	2.64 kN/m^2 (1.4)	
			Tuff stone	normal	2.92 kN/m^2 (1.3)	
			Hollow clay brick	normal	3.02 kN/m^2 (3.4)	
			Clay brick	normal	2.82 kN/m^2 (1.1)	
			Full clay brick	normal	2.48 kN/m^2 (0.7)	
		Generic floor	Poor stone	normal	4.7 kN/m^2 (3.6)	
			Tuff stone	normal	4.5 kN/m^2 (2.2)	
			Hollow clay brick	normal	4.16 kN/m^2 (3.2)	
			Clay brick	normal	4.07 kN/m^2 (2.2)	
			Full clay brick	normal	3.75 kN/m^2 (1.3)	

curves. In detail, a Froude number ranging between 0.7 and 2 is considered, and both conditions of dense and sparse urban environment are randomly adopted to compute tsunami loading according to Foster *et al*. (2017).

3.2. Typological vulnerability curves for masonry buildings

Vulnerability curves derived for each building stock representative of the Italian masonry building typological classes are plotted in Figs. 7 and 8 as a function of *DI* and H_w. In detail, Fig. 7 shows the *DI* curves grouped by age of construction and design criteria; conversely, Fig. 8 shows the *DI* curves grouped by number of storeys.

The plots attest that the number of storeys significantly affects the tsunami vulnerability curves of masonry buildings. This is reasonable since structures with a high number of storeys are characterised by larger cross-section of structural elements at the ground storey level that is mainly responsible of the entire behaviour of a structure.

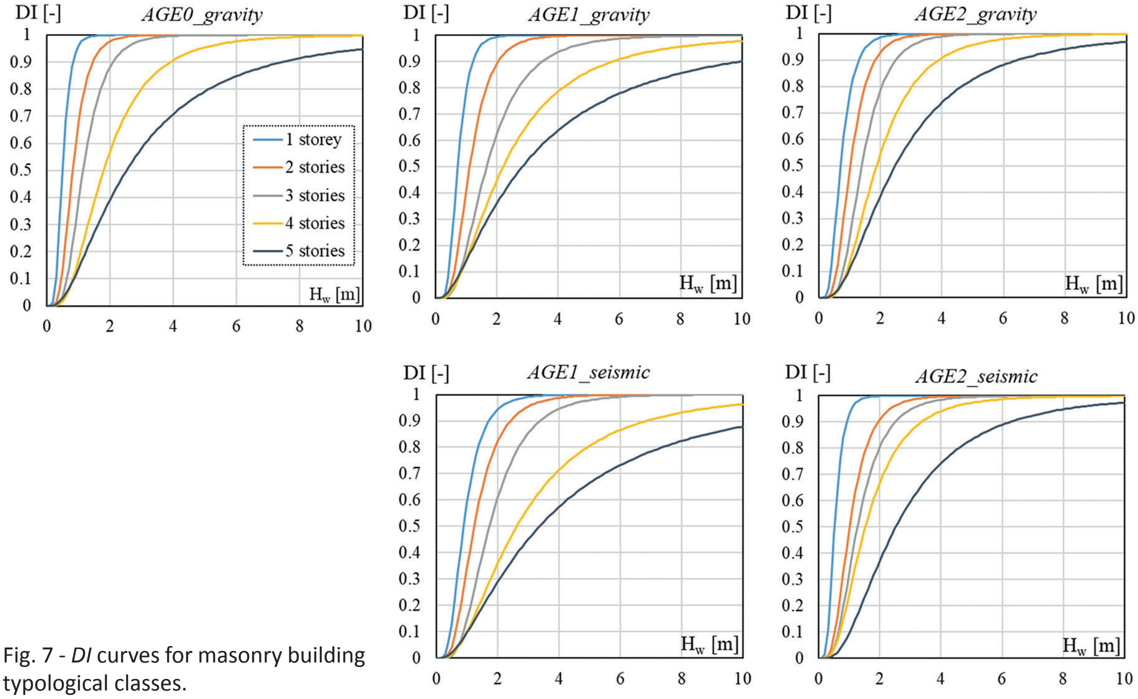


Fig. 7 - *DI* curves for masonry building typological classes.

Age of construction and design criteria slightly affects the vulnerability of masonry buildings with less than three storeys (Fig. 8). Conversely, the effect of such attributes is more evident for buildings with a higher number of storeys. Indeed, Fig. 8 shows that masonry building classes AGE1_Gravity and AGE1_Seismic have a quite similar vulnerability to tsunami independently from the number of storeys. Similarly, little difference is visible in *DI* curves for building classes AGE0_Gravity, AGE2_Gravity, and AGE2_Seismic. This leads to the possible conclusion that the seismic design criteria do not play a significant role in tsunami vulnerability of masonry buildings, and the age of construction can be considered as the most significant attribute for such buildings. It is also noted that buildings built in AGE0 and AGE2 exhibit a similar vulnerability under tsunami loading. This result may appear unrealistic; however, the improvement in construction materials quality and design equations adopted in AGE2 lead to masonry buildings with lower exterior walls thickness with respect to AGE1 buildings. Thus, such light buildings are more vulnerable to tsunami damage with respect to buildings with thicker walls.

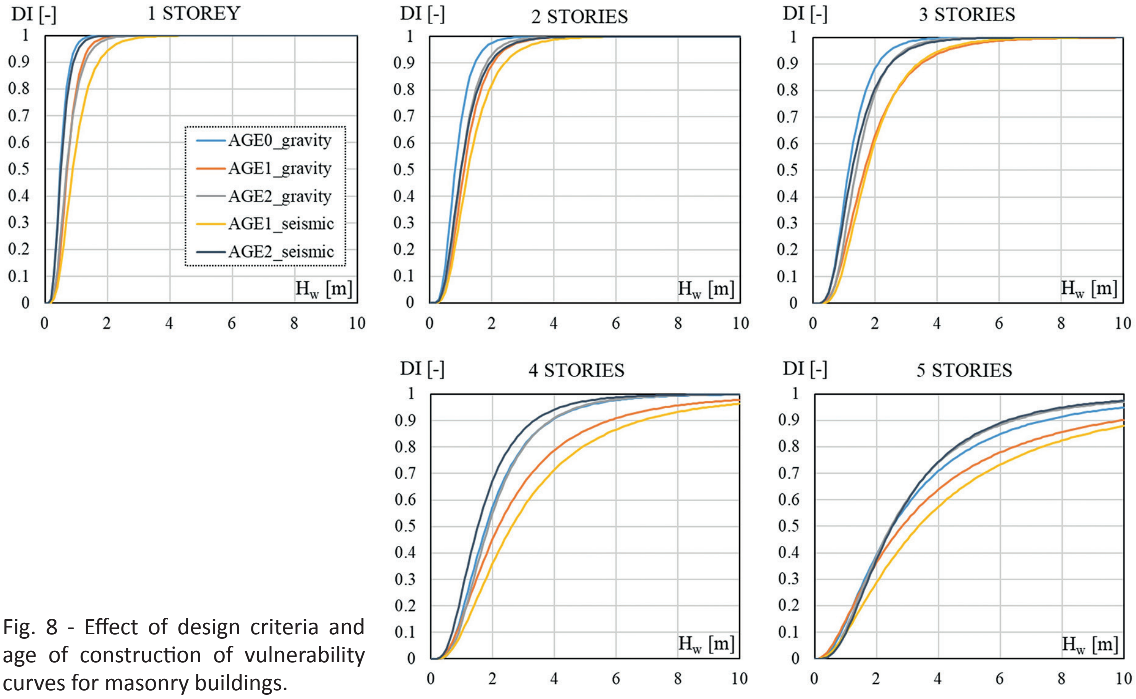


Fig. 8 - Effect of design criteria and age of construction of vulnerability curves for masonry buildings.

3.3. Typological vulnerability curves for RC buildings

DI curves as a function of the H_w are depicted in Fig. 9 for RC residential building typological classes. In details, Fig. 9 shows the variation of *DI* as a function of the number of storeys for a fixed age of construction and design criteria (i.e. AGE1_Gravity, AGE1_Seismic, AGE2_Seismic). The

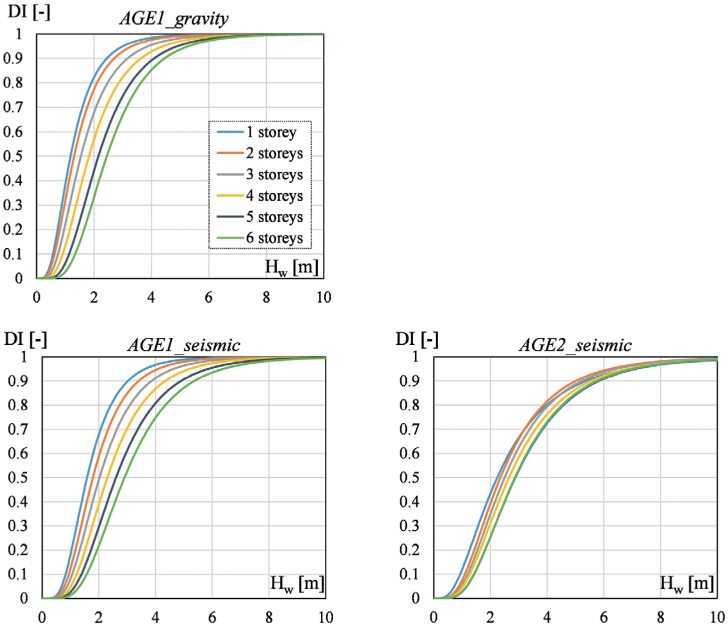


Fig. 9 - *DI* curves for RC building typological classes (ductile mechanisms).

comparison shows that the number of storeys affects the structural vulnerability of RC buildings designed for AGE1_Gravity and AGE1_Seismic. Conversely, vulnerability curves are only slightly affected by the number of storeys for buildings designed after the 1980s according to modern seismic standards (AGE2_Seismic). This can be related to the seismic detailing requirements in ground storey columns that only slightly differs for low-rise and mid-rise frames.

Focusing on the effect of the age of construction and design criteria on tsunami vulnerability curves for ductile mechanisms, *DI* curves are grouped in Fig. 10 for different number of storeys. The comparison shows that both age of construction and design criteria significantly affect the structural vulnerability for RC buildings with less than 5 storeys. For 6 storeys, the different performance of buildings designed for gravity and seismic loading is still significant, whereas the *DI* curves are quite similar for AGE1_Seismic and AGE2_Seismic.

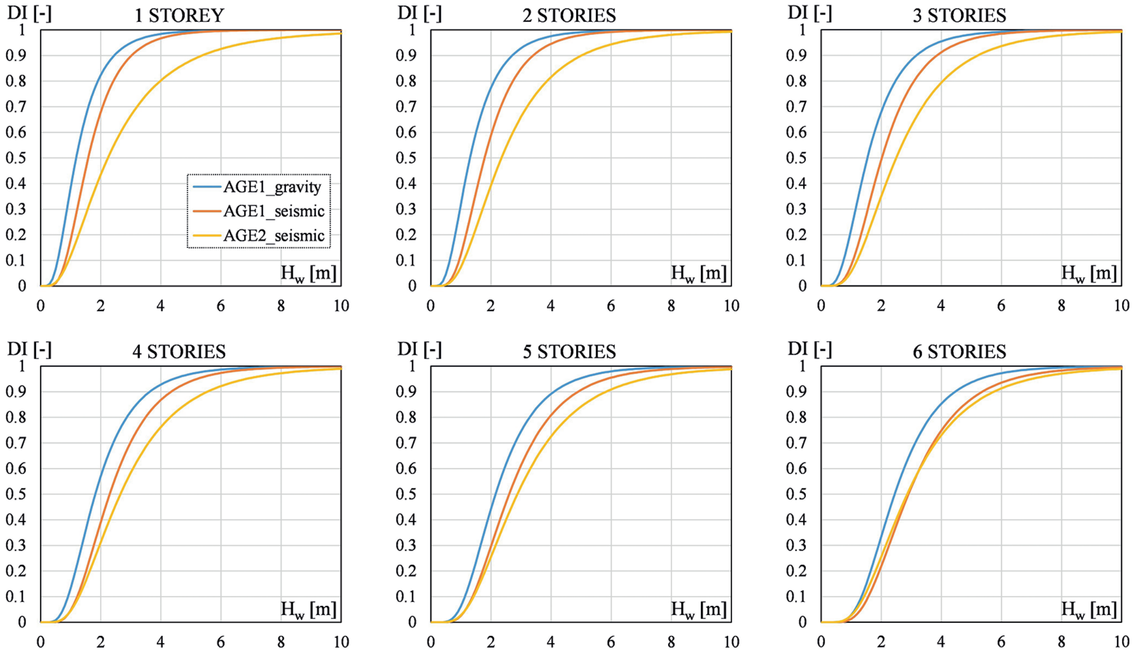


Fig. 10 - Effect of design criteria and age of construction of vulnerability curves for RC buildings.

DI curves are also derived for the local brittle mechanism to assess the vulnerability of single structural components. Curves are reported in Fig. 11 for the 2-storey and 6-storey building stock for each age of construction to show the influence of number of storeys and design criteria on the vulnerability to such failure mechanism. The figure clearly shows that both parameters significantly affect the *DI* curves related to brittle mechanism. It is observed that the *DI* values related to such local mechanism are higher than ductile ones for the same H_w in AGE1, confirming that analytical models identify the shear failure of RC columns as a possible local damage mechanism under tsunami loading for such building typologies. Conversely, in AGE2 buildings the shear failure can be prevented due to the modern seismic detailing adopted for columns.

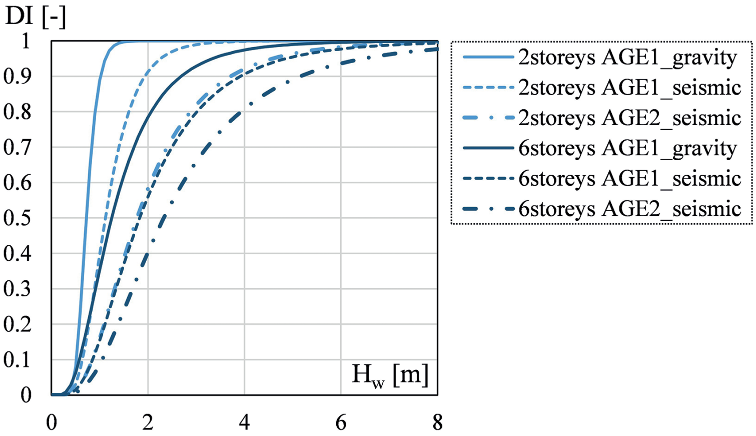


Fig. 11 - *DI* curves for local brittle mechanisms of single RC columns (2 and 6 storeys).

4. Analytical tsunami vulnerability classes

In previous sections, tsunami vulnerability curves have been derived for each identified typological class of residential masonry and RC building stock. However, the association of building typologies to tsunami vulnerability classes is not straightforward. Conventional approaches for risk assessment at regional scale define vulnerability classes with decreasing vulnerability and identify typical attributes of buildings to easily allow the classification without performing specific analysis. In the context of seismic risk assessment, the European Microseismic Scale EMS98 (Grünthal, 1998) identifies six vulnerability classes for masonry, RC, steel, and timber constructions. In the Italian framework, Borzi *et al*. (2018) defines five seismic vulnerability classes for Italian residential buildings. Based on empirical data from the 2009 L'Aquila earthquake, Rosti *et al*. (2020) observed that the lowest three vulnerability classes refer to masonry buildings and the other two to RC buildings.

To provide a similar vulnerability classification for Italian residential buildings subject to tsunami loading, a cluster analysis is first performed to obtain only two vulnerability sub-classes for each age of construction by grouping the buildings by number of storeys (i.e. low-rise and mid-rise). The clustering procedure assesses the similarity between *DI* curves and iteratively merges typological classes with the shortest inter-distance in a single macro-class. The outcomes of the cluster analysis for masonry buildings result in two sub-classes with similar vulnerability consisting of low-rise buildings with 1-2 storeys and mid-rise buildings with 3-5 storeys. Conversely, for RC buildings, the low-rise sub-class refers to 1-3 storey frames whilst the mid-rise sub-class refers to 4-6-storey buildings. This classification is consistent with the building classes provided by the HAZUS Tsunami Model (FEMA, 2017), that identifies low-rise (1-2 storeys) and mid-rise (+3 storeys) unreinforced masonry bearing walls, respectively named URML and URMM, and low-rise (1-3 storeys) and mid-rise (4-7 storeys) concrete frames with unreinforced masonry infill walls, called C3L and C3M, respectively.

The merged vulnerability curves are plotted in Fig. 12 for both masonry and RC buildings, for the latter considering only the global damage mechanisms reported in Table 2. As aforementioned, local failure mechanisms of single structural components are not herein included for the definition of global damage states for the vulnerability classification of buildings, following the HAZUS approach. More investigation should be performed to include local failure mechanisms into a global damage classification similar to that proposed by the HAZUS Tsunami Model. To derive the merged vulnerability curves for low-rise and mid-rise buildings, the real proportion of Italian residential buildings by number of storeys for each age of construction is taken from ISTAT data (Fig. 1). For instance, the vulnerability curve for low-rise RC buildings in AGE1 comprises 21% 1-storey, 57% 2-storeys and 22% 3-storey buildings.

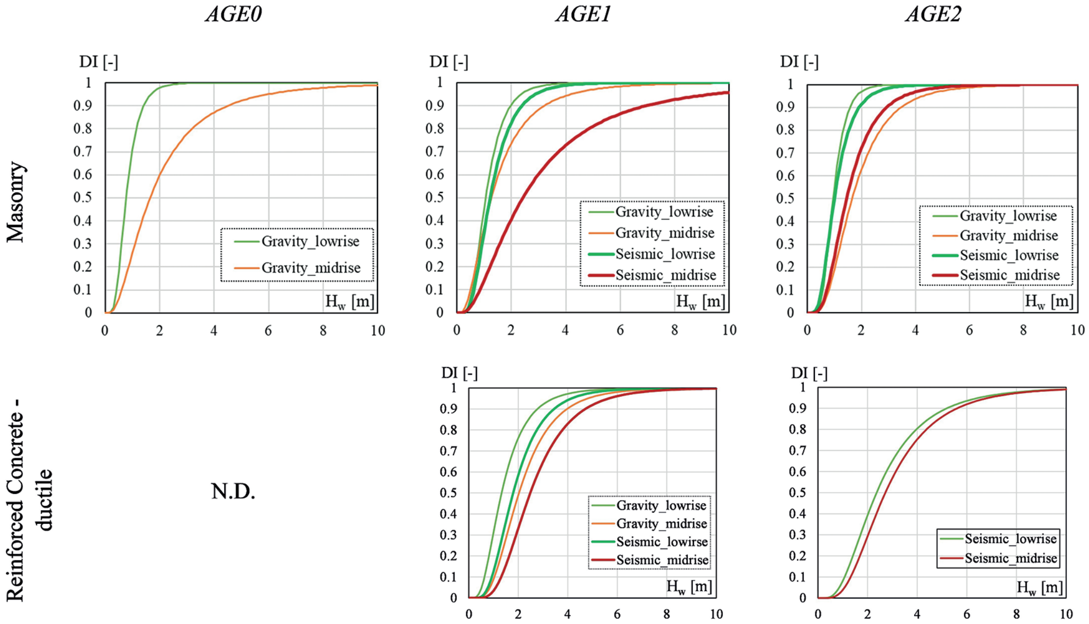


Fig. 12 - Vulnerability curves for low-rise and mid-rise residential buildings with different age of construction and design criteria.

To further classify the vulnerability of residential buildings, *DI* curves for the merged sub-classes are compared to define a list of classes with decreasing vulnerability for tsunami hazard. Results are summarised in Table 5 for both masonry and RC buildings and 5 vulnerability classes

Table 5 - Proposed tsunami vulnerability classes.

VULNERABILITY CLASS	MASONRY	RC
A	AGE0_gravity_lowrise AGE2_gravity_lowrise	
B	AGE1_gravity_lowrise AGE2_seismic_lowrise AGE1_seismic_lowrise	
C1	AGE1_gravity_midrise AGE2_seismic_midrise	AGE1_gravity_lowrise
C2	AGE2_gravity_ midrise AGE0_gravity_midrise	AGE1_seismic_lowrise AGE1_gravity_midrise
D	AGE1_seismic_midrise	AGE1_seismic_midrise AGE2_seismic_lowrise AGE2_seismic_midrise

are proposed for tsunami hazard, following the approach already adopted for seismic risk (Borzi *et al.*, 2018). Vulnerability classes A and B refer to low-rise masonry buildings, while classes C1, C2, and D comprise mid-rise masonry buildings. Mid-rise masonry buildings designed with seismic criteria resulted the less vulnerable to tsunami loading among the masonry typological classes investigated.

RC buildings are classified in vulnerability classes C1 to D, where the latter class refers to RC buildings designed with modern seismic criteria (AGE2) and mid-rise buildings designed with obsolete seismic criteria (AGE1). Mean and lognormal standard deviation of the analytical *DI* curves are finally reported in Table 6.

Table 6 - Mean and lognormal standard deviation (μ [m] and β) of *DI* curves.

	MASONRY		**RC**	
	μ	β	μ	β
AGE0_gravity_low-rise	0.8	0.47	-	-
AGE0_gravity_mid-rise	1.7	0.78	-	-
AGE1_gravity_low-rise	1.1	0.49	1.3	0.58
AGE1_gravity_mid-rise	1.3	1.0	2.0	0.52
AGE1_seismic_low-rise	1.2	0.52	1.8	0.51
AGE1_seismic_mid-rise	2.4	0.82	2.5	0.50
AGE2_gravity_low-rise	1.0	0.39	-	-
AGE2_gravity_mid-rise	1.7	0.58	-	-
AGE2_seismic_low-rise	1.0	0.51	2.4	0.61
AGE2_seismic_mid-rise	1.5	0.55	2.7	0.57

5. Conclusions

This paper assesses the structural vulnerability of Italian typical residential buildings to tsunami hazard through numerical analysis and Monte Carlo simulation. To perform the structural vulnerability analysis, a deep investigation of typical Italian residential building typologies and their attributes is performed, based on data from opensource national building census repositories. Structural material, number of storeys and age of construction/design criteria are selected as main attributes for the preliminary definition of building typologies according to cited repositories. Structural models able to assess structural damage under tsunami loading are presented for different building typologies (i.e. unreinforced masonry buildings, RC frame buildings with unreinforced masonry infill walls), and a homogeneous damage scale is adopted to classify global structural damage in a consistent approach. Monte Carlo simulation is performed to simulate building stocks, statistically representative of Italian existing residential buildings, and analytical vulnerability curves are derived for each typological building stock. A *DI* has been selected as indicator of the global damage level of buildings to derive structural vulnerability curves, and the tsunami H_w has been selected as intensity measure.

The outcomes of the analysis attested that both number of storeys and age of construction/design criteria can significantly affect the structural vulnerability of buildings to tsunami loading. This is more evident for RC building built before the 1980s. For masonry buildings, the design criteria affect the geometrical characteristics of the masonry walls in terms of maximum wall length or wall thickness, while the age of construction has a significant influence on the mechanical properties of masonry.

Masonry buildings are generally more vulnerable to tsunami loading with respect to RC buildings in terms of structural damage.

The analysis of structural vulnerability curves for each residential building typology allowed to define sub-classes and relevant vulnerability curves by grouping the buildings as function of number of storeys (for different age of construction): low-rise buildings with 1-2 storeys or 1-3 storeys for masonry or RC buildings, respectively; and mid-rise buildings with 3-5 storeys and to 4-6 storey buildings for masonry or RC ones. Finally, vulnerability classes for tsunami hazard, from A to D, have been proposed for the specific sub classes.

The local vulnerability of single structural components to brittle failure mechanisms has also been analysed in RC buildings. The results allowed to assess for which classes of buildings such kind of local damage mechanism can be achieved. However, more research is needed for the inclusion of local brittle failure mechanisms in a global damage classification that follows the HAZUS Tsunami Model approach for the vulnerability assessment of existing assets. Future studies will also look at the inclusion of non-structural components in the vulnerability classification of buildings.

The presented tsunami vulnerability curves can be adopted for simulating tsunami structural damage at regional scale and for supporting informed disaster risk management planning within a more comprehensive disaster risk reduction approach. The definition of such vulnerability models can be also helpful to define and prioritise risk mitigation strategies in Italian coastal areas exposed to tsunami hazard; however, due to the general lack of empirical vulnerability functions in the literature for tsunami hazard, further data are necessary for the validation of the proposed ones.

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