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A faced hazard-oriented taxonomy of envelope technical elements for vulnerability analysis

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ABSTRACT

Understanding how well the building envelope technical elements can withstand natural hazards is of interest for many purposes, such as adapting to a changing climate, or reducing safety issues and economic losses associated with damaged technical elements. On this matter, the present work proposes a novel flexible hazard-oriented taxonomy for technical elements of building envelope to characterize the envelope's vulnerability to a given hazard. The taxonomy was built by identifying technical elements' vulnerability factors considering a set of hazards of interest. It was then tested on a case study area located in Naples (Italy) to classify two technical elements, namely, roof cornice and household drain system, and to assess their vulnerability against earthquakes and heavy rainfall events. The application proved to support the vulnerability investigation of technical elements which is, in turn, useful in identifying areas of potential concern and intervention. The results contribute to expanding the already available taxonomies (e.g., GED4ALL) and to more comprehensive building vulnerability assessments using a structured and flexible hazard-oriented approach.

1. Introduction

In a rapidly changing climate, meteorological hazards are expected to occur even more frequently, and although the number of deaths will likely decrease, the number of economic losses will likely rise [1]. In this context, the interest in the vulnerability of building envelope technical elements arises from the recognition that they are vulnerable assets able to jeopardize the functionality of entire buildings, and they can pose urban settlements at risk leading to economic losses and safety issues. Indeed, architectural and plant systems are particularly vulnerable to natural hazards (e.g. earthquakes, wind, heavy rainfall events etc.). Their failure has significant consequences in terms of safety, property, and functional losses [2,3], as well as entailing severe effects on entire communities [4].

It has also been observed that these elements are vulnerable to either high and low-intensity hazards, as well as to sudden and slow-onset events [5,6]. Following the terminology given by UNDRR [7], depending on the severity and frequency of the hazard, the risk at the urban scale relies on the correlation of exposure and vulnerability. Namely, the intensive disaster risk infers high-severity and mid/low-frequency hazards, acting on a global or regional large scale (e.g. tsunamis, volcanic eruptions, earthquakes and flooding in large basins). Intensive risks are thus strictly related to significant trends of mortality and losses, given the confluence of vulnerable

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people, economic activities and assets. Conversely, extensive risk implies low severity of high-frequency occurrences, usually provoked by localized hazards (e.g. flash floods, fires, storms, and bradyseisms).

When dealing with more than one hazard at a time, the terms multi-hazard and compound hazard are usually applied [8]. Urban settlements are particularly prone to risks, due to the relevant interconnected parts which can trigger cascading events. In this regard, an extended partnership, named "multi-risk science for resilient communities under a changing climate - Return", has been founded in Italy with the goal of strengthening the governance in risk management at a national level. The authors are contributing to that by addressing the risks to urban systems deriving from the vulnerability of building envelopes against natural hazards. Vulnerability is here referred to as the physical property which increases the susceptibility of the envelope to be impacted by hazards [9]. The vulnerability at the building scale is strictly related to the composing technical elements.

The assessment of the building's vulnerability to different hazards is complex due to the variety of configurations, compositions and practices [10] and it relies on the integration of census data, expert judgment and field data collection [11]. On this matter, aiming to assess buildings, the implementation of hazard-oriented taxonomies is widely regarded as a suitable approach to encode building typologies [12]. Taxonomies dealing with the vulnerability of urban environments (e.g. GED4ALL taxonomy) exist, as detailed in Section 2. Nevertheless, a specific assessment of the technical elements at the building scale is still lacking.

In this context, this work aims to structure a proper taxonomy for building envelope technical elements based on the detailed assessment of constructive features and properties influencing their vulnerability under various forces. The proposed taxonomy, by integrating the structure of existing ones, should be intended as a tool to assist in the definition of a vulnerability scoring system for each technical element of a building when varying the hazard occurrence. The proposed taxonomy can be thus considered as tailored, notably "faced", since its complexity can be reduced according to the hazard and the data availability.

2. Materials and methods

The research started from the analysis of the vulnerability factors of envelope technical elements and from the study of existing taxonomies, such as ATC-13, EMS-98, HAZUS, PAGER-STR, Syner-G, GEM, GED4ALL. A new taxonomy for envelope technical elements – arranged according to vulnerability factors – is thus proposed starting from the structure of GED4ALL, resulting the latter more in line with the objectives of the proposed research.

2.1. The vulnerability factors guiding the taxonomy definition

The building envelope has several vulnerable technical elements such as wall finishes (plaster, clinker, panels), roof elements (tiles, sheaths, chimneys), cornices, balconies, the household drain system, windows, etc. Depending on their technological features and state of conservation, these elements may undergo a severe progression of their condition, which significantly affects their service life [13–17]. In this sense, identifying the performance of technical elements under changing external conditions can help define the most suitable and durable solutions, following the logic that less vulnerable elements will suffer less damage. Reports and technical guides on the vulnerability of building elements against earthquakes were used to retrieve potential vulnerability factors, such as those published by the Civil Protection Department in Italy [18], by the Pacific Earthquake Engineering Research Center [19] and by the Federal Emergency Management Agency [2]. The main reasons for an element to fail in case of an earthquake are related to its fragility, mass, and deformability. For example, the vulnerability analysis of cornices against earthquakes includes the cornice construction technique and the shape factor. The cornice construction technique is strictly linked to the fragility and mass of the cornice, whereas the shape factor affects the deformability of the cornice itself. A more detailed analysis can include the finishings of the intrados, face, and extrados, accounting for their fragility and fixing solutions. Indeed, an elastic and monolithic finishing, such as a waterproof membrane, is less vulnerable to earthquakes than a fragile and composite finishing, such as clay tiles. As regards the elements of the household drain system, the reference literature suggests that reducing the distance between the support systems close to direction changes may help reduce the probability of pipe failure [20,21]. In addition, the higher the ratio between the pipe thickness s and the internal diameter Di - and the corresponding increase of the moment of inertia - the lower the vulnerability [22]. Thus, it is worth relevant the type of material for the assessment of the vulnerability of the household drain system against earthquakes, aiming to investigate the elements' rigid, fragile or deformable mechanical behaviour [23].

Regarding rainfalls, the authors referred to studies on the vulnerability of building elements to meteorological hazards [24], the analysis of how salts migrate and deteriorate stones [25], and the damages induced by wind-driven rain on building envelopes [26]. Architectural elements report damages, such as mould, cracks, or detachment of portions, because of water infiltration and water vapour penetration. Thus, the absence of a waterproof membrane and the high-water permeability of technical elements and materials represent specific vulnerable factors against heavy rainfall events. Also, the extrados inclination, for example of cornices and balconies, plays an important role in terms of protection against water stagnation. About the household drain system, the main relevant attributes are the shape factor and the junction. Notably, the most significant feature is the former, given the higher hydraulic capacity of the system when increasing the diameter of the pipe. Indeed, the greater the shape factor, the lower the vulnerability. The junction, given the different response of the system when increasing the fatigue provoked by intense rainfall events, plays a fundamental role in the determination of the vulnerability. As easily identifiable, the greater the anchoring solidity, the lower the vulnerability.

Concerning wind, it can cause damage to non-structural elements due to high-pressure forces that affect joints and fragile components [27]. Factors incrementing the vulnerability of the envelope technical elements to wind hazard include low suction resistance, due to large and exposed surfaces, light weight and poorly designed connections. For instance, the shape factor of the parapet above the cornice and its continuity should be properly account for assessing the vulnerability to wind, as slender and continuous parapets tend to report more damage than stocky and discontinuous parapets.

Several studies addressed the thermal performance of envelope technical elements and their impacts on energy consumption and indoor comfort [28,29], while other research focused on the deterioration caused by high temperature [30]. Metal and plastic elements can undergo deformation and expansion due to high temperature [31] leading to distortion, cracks, or splits in the joints. The main factors that increase vulnerability to these elements are the coefficient of thermal expansion and the coefficient of thermal conductivity.

Such a preliminary review of the scientific literature highlights that multiple technical elements of the building envelope are susceptible to the impacts of external hazards, with the risk of threatening both the functionality of the building and the related urban system. Notably, elements such as cornices and household drain systems arise as highly critical, as their failure during hazardous events, like earthquakes and heavy rainfalls, can result in severe falling hazards and cascading effects, underscoring their role as key points of vulnerability within the built environment.

The Table below (Table 1) summarises the identified vulnerability factors, which are used to define the taxonomy presented in Section 2.3 and to guide the vulnerability assessment of Section 2.4.

2.2. The state of the art of existing building taxonomies

To support vulnerability evaluations, reasonable classifications of the objects under study are needed. In this way, taxonomies rely on the organization of entities into groups or types, often in a hierarchical manner, to structure possible vulnerability assessments. Taxonomies can be considered as systematic classifications or categorizations of entities facilitating various applications such as organizing knowledge into libraries or databases.

Numerous taxonomies raised from the late 1980s onwards for the analysis and evaluation of the building sector. The first taxonomies appeared poorly generic and strongly related to specific geographic contexts. While ATC-13 [32] focused solely on Californian constructions and HAZUS generally only on US constructions [33], EMS-98 [34] addressed only a few European construction types. These taxonomies exhibited limited adaptability and flexibility across different locations. GEM V2.0 tried to overcome these constraints [35], instead.

Initially, structural aspects were the only attributes considered in defining taxonomies aimed at vulnerability functions for seismic hazards exclusively. Notable examples include ACT-13 [32], FEMA 154 [36], and HAZUS [33] in the US, and EMS-98 [34] and RISK-EU [37] in Europe. Syner-G [38] introduced a more adaptable approach. In any case, location limitations persisted across all taxonomies. At a global level, the World Housing Encyclopedia serves as a suitable tool for seismic evaluation [39].

PAGER-STR [40] stands out as the most comprehensive global building taxonomy developed before 2010, although it disregards vernacular architectures. GEM V2.0 was specifically developed for seismic risk assessment, employing a faced multi-level methodology. Each attribute can be described with up to three levels of detail, depending on the available information and desired level of detail and accommodating various materials and technologies at the global scale.

GEM V2.0 attributes relate to the expected vulnerability of assets to specific natural hazards: materials and lateral load-resisting systems primarily address seismic hazards; roof type and materials consider cyclones and storms; basement height relates to floods. However, multi-hazard considerations are inadequately addressed. Flood modelling, for instance, poses challenges due to its intricate nature at various stages of the process and poor information provided seems insufficient. Furthermore, the taxonomy proposed by GEM V2.0 seems not to be related to vulnerability models based on the intensity of the considered hazards.

Finally, the progress of the GEM V2.0 seems, however, inadequate for multi-hazard evaluations since the whole proposed classification system is poorly detailed and attributes are not relevant to other hazards besides earthquakes, limiting its applicability. Exposure modelling for multi-hazard purposes is hindered by the taxonomy's lack of attributes or options for other perils.

An expanded version of the GEM V2.0, called GED4ALL [41], was then proposed to rectify these shortcomings. Significant enhancements are referred to seismic evaluations and to the addition of new attributes (14 in total) pertinent to structural response of buildings under multi-hazard actions, such as ground floor hydrodynamics for floods, fire protection for fire, and window resilience for wind events. GED4ALL is considered a comprehensive, modular, flexible classification system to characterize buildings. It seems a consistent step forward to multi-hazard risk assessment. In any case, several hazards remain unaddressed, and the limited number of attributes may constrain some evaluations for specific elements of the building.

With specific reference to household drain systems, few works were devoted to classifying and assessing the vulnerability of the system and of its elements against hydrometeorological hazards. Although several authors listed sets of performance indicators and generated vulnerability maps of households against such hazards and, specifically, against flood events [42–45], very few attention was paid to implement structured taxonomies and frameworks for the characterization of the household system vulnerability. Among

Table 1
– Summary of the identified vulnerability factors of building envelope technical elements against the investigated natural hazards.

Hazards	Vulnerability factors
Earthquake	Fragility; mass; deformability; moment of inertia.
Heavy rainfall	Water permeability; water stagnation; hydraulic capacity.
Wind	Fragility; area; mass.
High temperature	Thermal expansion; coefficient of thermal conductivity

them, Sorensen & Mobini [46] investigated the effects of intense rainfall events and resulting flood occurrences on both the internal household drain system and the sewer system of Malmo municipality (Sweden), showing the strict correlation between the spatial distribution of the hydrometeorological event with the damaging outcomes of the hydraulic infrastructures.

A comparison of the analysed taxonomies is provided in Table 2. The analysis of existing protocols shows that the elements of the envelope are not well investigated even if often particularly fragile and therefore vulnerable (Section 1). Existing taxonomies may prioritize broad classifications over detailed analysis, assuming a level of homogeneity that overlooks the diverse array of factors influencing envelope performance. Consequently, essential considerations such as material properties and assembly techniques may be marginalized or omitted. For these reasons, the proposed research targets a gap to define a taxonomy that is suitable to describe the technical elements and support further analysis, such as vulnerability assessment.

2.3. *The general structure of the new taxonomy attributes*

As abovementioned, the existing taxonomies most successfully used (ATC-13, EMS-98, HAZUS, PAGER-STR, Syner-G, GEM, GED4ALL, to name a few) are aimed at categorizing almost exclusively structural aspects (geometric shape in plan and elevation, structural typology, structural materials, year of construction, types of foundations, floors, roofs, …) depending on multi-hazard risk, which is again mostly focused on earthquakes and to a lesser extent on heavy rains, floods, volcanoes, winds, tsunamis, and droughts.

For these reasons, the existing and most well-tested taxonomies should be properly integrated by referring to those building exterior technical elements that are most sensitive to geophysical, hydrological, meteorological, biological, and energy hazards.

In this regard, the research aims to integrate the structure of the GED4ALL Building Taxonomy with a series of envelope technical elements that, similarly to the structural elements (or even more), are vulnerable to the hazards of the external world, producing great risks for the safety of people and properties.

The herein proposed taxonomy relies on the following technical elements of the building envelope, as an integrating umbrella of the other attributes of the GED4ALL: cornice; balcony; string course; decoration; exterior wall; parapet; chimney; household drain system; roof covering; window (Fig. 1).

These elements were identified by comparing the databases of the Italian fire safety and rescue service, with reference to the first intervention following construction failures, with direct observation and experience in the field. Also, the reports produced by Italian Department of Civil Protection in the aftermath of earthquakes which occurred in recent years [18]. Italy has been chosen as a proper case study on this theme for the widespread mid- and high-intensity events suffered, as well as for the general obsolescence of building stock.

The abovementioned envelope technical elements have been structured in a hierarchical taxonomic framework. The goal is to provide the dissemination of detailed building information to be eventually added to existing taxonomies for multi-hazard vulnerability assessments of urban environments.

The envelope technical elements introduced in Fig. 1 have been collected in a total of six attributes: Roof shape, Exterior walls, Openings/Windows, Cornice construction technique, Balcony construction technique, Household drain system material. Each attribute has been structured in several sub-attributes providing further details. Therefore, where logical and constructive relationships can be established between envelope technical elements, they can be collected into the same attribute.

The investigation around the building envelope technical elements' attributes is described by up to three levels of detail. Based on the accessible data, the required granularity, and the increasing depth of examination, each attribute can be articulated through a maximum of three hierarchical levels of detail.

The base level of detail is referred generically to the attribute level itself and provides information on the global features of the analysed envelope technical elements (e.g. the cornice construction technique or the material of the household drain system). The first level of detail is based on several sub-levels and provides information and details that help assess further features influencing vulnerability. The second level of detail is often referred to specific characteristics and needs a certain level of knowledge of the elements considered (e.g. the finishings).

For the sake of an exemplified application, only the attributes related to Cornice construction technique and the Household drain systems material are herein presented, as detailed in Sub-Sections 2.3.1 and 2.3.2, respectively. These two attributes have been identified as the most suitable for the application of the proposed methodology, owing both to their constructive relevance and to their

Table 2
– Comparing various building taxonomies according to the territorial validity, hazard considered, and information provided.

Taxonomy	Territory validity	Hazard considered	Information
ATC-13	California (U.S.A.)	Seismic	Structural
HAZUS	U.S.A.	Seismic	Structural
EMS-98	Europe (few countries)	Seismic	Structural
Risk-EU	Europe	Seismic	Structural
FEMA154	U.S.A.	Seismic	Structural
SYNER-G	Global	Seismic	Structural
WORLD HOUSING ENCYCLOPEDIA	Global	Seismic	Structural, Architectural
PAGER-STR	Global	Seismic	Structural
GEM V2.0	Global	Seismic, Cyclones, Floods	Structural, Roof, Exterior walls, Basement
GED4ALL	Global	Seismic, Floods, Fire, Wind	Structural, Roof, Exterior Walls, Ground floor, Basement

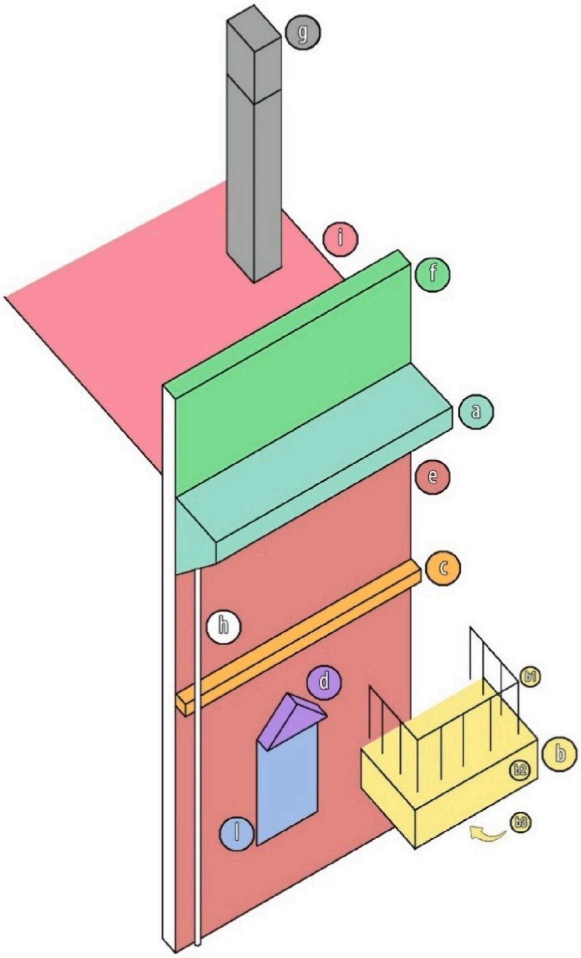

Fig. 1. – The technical elements of the building envelope (a: cornice; b. balcony; c. string course; d. decoration; e. exterior wall; f. parapet; g. chimney; h. household drain system; i. roof covering; l. window).

inherent susceptibility to damage when subjected to external forcing events. Their selection is further justified by the critical role they play in the overall vulnerability of the system under hazardous conditions [47].

Generally, the overall framework of the proposed taxonomy is given in Table 3. Considering the relationships between technical elements: within the attribute "Roof shape", information about the chimney ("Standing-out elements") is provided; within the attribute "Exterior walls", information about string courses and decorations ("Decorations and mouldings") is given; and within the attributes "Cornice construction technique" and "Balcony construction technique", information about parapets ("Parapet shape" and "Parapet material") is provided, respectively.

2.3.1. The cornice attribute

A cornice can be defined as a horizontal moulding projecting outward at the top edge of a building's facade serving both aesthetic and functional purposes, proving a visual crown to the building while directing rainwater away from external walls. It enhances the facade's appearance and support functions like roof drainage. Historically made of stone, wood, or plaster, modern cornices can also be realized in reinforced concrete or metal.

Within the general framework herein proposed, the main materials of the cornice and the specific construction technique have been introduced in the "Cornice construction technique" attribute. To reach a comprehensive framework able to describe main existing construction techniques, an extensive literature review was performed, based on the collection of didactic books [48–56], historical and design manuals [57–61], field analyses and photographic retrieval. The Italian building scenario has been considered as the main starting point. As the other attributes herein presented, the cornice is structured into three levels of detail: attribute level regarding the general information related to the cornice construction technique; level 1 related to geometrical and technological features of various sub-components (intrados, extrados, face, and parapet) and the general shape factor of the cornice; level 2 providing information on the finishings and the shape factor of the parapet. In Fig. 2, the various sub-categories composing the level 1 are detailed.

The detailed framework of the attribute "Cornice construction techniques" is reported in Table 4. Masonry cornices (CM) are

Table 3
– Attributes and sub-attributes.

Attribute	Sub-attribute – level 1	Sub-attribute – level 2
A. Cornice construction technique	Intrados shape	Finishing
	Extrados shape	Finishing
	Face height	Finishing
	Parapet shape	Parapet material
	Shape factor	
B. Balcony construction technique	Intrados shape	Finishing
	Extrados shape	Finishing
	Face height	Finishing
	Parapet shape	Parapet material
	Shape factor	
E. Exterior walls	Thermal/Acoustic insulation and position	
	Decoration and mouldings	
	Finishings	
H. Household drain system material	Anchoring	Material
	Junction	Material
	Position	
	Shape factor	
I. Roof shape	Roof covering material	
	Roof system material	
	Roof connections	
	Thermal/Acoustic insulation, water protection, covering position	
	Standing-out elements	Slenderness, size, and material
L. Openings/Windows	Windows protection	
	Frame	
	Panel	Area

articulated into only two categories. The CM1 describes all the general cornice construction techniques based on the use of cantilever bricks or stones, stone shelf slabs and hollow clay bricks, or brick and mortar components. In the CM2 category all the cornice construction techniques based on the use of cantilever metal elements are collected. The CM2 category gathers cornices realized with metal cantilever shelves and hollow clay blocks or clay vaults, and metal shelves and hollow clay blocks. Examples of cornices are shown in Fig. 3. Concrete cornices (CC) are articulated into two categories. The CC1 category refers to a cornice based on a cast-in-place concrete slab projecting outward from the external wall. The CC2 category refers to precast reinforced concrete cornice. The other cornice construction techniques are introduced: CS for steel; CP for polystyrene/FRP/polyurethane; CW for wood; CC for composite or other.

In Table 5, the intrados shape (level 1) and the related finishings (level 2) are listed. The intrados is divided into two categories: shaped (CIS) or flat (CIF). Concerning the finishings, plaster finishings (CIP), brut (CIB), decorated (CID), and render mash finishings (CIRM) are considered.

The second feature of level 1 entails the extrados inclination: 0 for flat extrados; 5 with a slight inclination up to 5°; 15 up to 15°; 16 with an inclination higher than 16°. The various finishings of the extrados can be retrieved in the right columns of Table 6.

The face height (Table 7) describes the vertical dimension of the face of the cornice: 0 in case the face is absent; 10 for a height up to 10 cm; 30 up to 30 cm; 31 for a dimension higher than 31 cm. The finishings are the same of the "Intrados shape" level 1 features.

Another item of level 1 concerns the parapet shape, which describes both the element's continuity and geometry. The linked level 2 is the "Parapet material". Both levels are shown in Table 8.

The last item of level 1 is the general shape factor of the cornice (Table 9). It is the only item of level 1 that is not connected to a detailed level 2.

The attributes presented above allows describing the main characteristics of the cornice and serve as a classification system. The

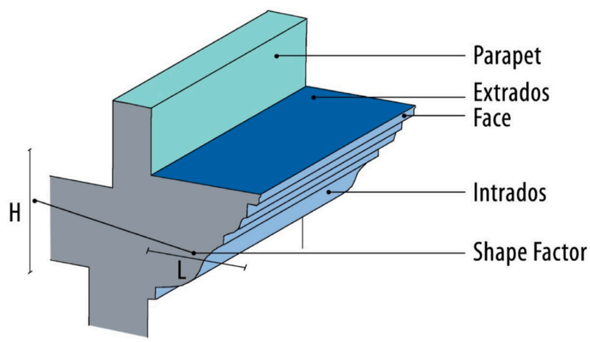

Fig. 2. – Sub-attributes of level 1 for the "Cornice construction technique".

Table 4
– Attribute "Cornice construction technique".

Code	Attribute "Cornice construction technique" - A
–	Unknown cornice construction technique
CM1	Masonry general
CM2	With metal cantilever
CC1	Cast-in-place reinforced concrete
CC2	Precast reinforced concrete
CS	Steel
CP	Polystyrene/FRP/Polyurethane
CW	Wood
CC	Composite/other

Fig. 3. – Examples of a masonry roof cornice (Fig. 3a, left) and a reinforced concrete roof cornice (Fig. 3b, right).

Table 5
– "Intrados shape" (level 1) and the linked "Finishing" sub-attribute (level 2).

Code	Intrados shape – level 1 – A.1	Code	Finishing – level 2 – A.1.1
–	Unknown intrados shape	–	Unknown intrados finishing
CIS	Shaped intrados	CIP	Plaster finishing
CIF	Flat intrados	CIB	Brut
		CID	Decorated
		CIRM	Render mash finishing

Table 6
– "Extrados shape" (level 1) and the linked "Finishing" sub-attribute (level 2).

Code	Extrados inclination –level 1 – A.2	Code	Finishing – level 2 – A.2.1
–	Unknown extrados inclination	–	Unknown extrados finishing
0	Flat extrados	CENP	Extrados without protection
5	Up to 5°	CEW	Extrados with waterproof membrane only
15	Up to 15°	CEWT	Extrados with waterproof membrane and clay tiles or stone slabs
16	More than 15°	CEWM	Extrados with waterproof membrane and metal sheet
		CET	Extrados with clay tiles or stone slabs only
		CEM	Extrados with metal sheet only

attributes can be resumed by a taxonomy string that briefly describes, by a combination of codes, the cornice's characteristics. For example, a stocky (CSF2) masonry roof cornice (CM1), with a flat plastered intrados (CIF,CIP) and a plastered face height of more than 31 cm (31,CFP), clay tiles on an inclined extrados (15/CET), and a continuous and stocky masonry parapet (CPCS/CPMA) is classified by the following code: CM1/CIF,CIP/15,CET/31,CFP/CPCS,CPMA/CSF2 (Fig. 3a, left side). A very slender (CSF4) reinforced concrete roof cornice (CC1), with a plastered flat intrados (CIF,CIP) and a plastered small face (10,CFP), waterproofing membrane at the slightly sloped extrados (5,CEW), and a slender metal parapet (CPCL, CPST) is classified as follows: CC1/CF,CIP/5,CEW/10,CFP/CPCL,CPST/

Table 7
– “Face Height” (level 1) and the linked “Finishing” sub-attribute (level 2).

Code	Face height – level 1 – A.3	Code	Finishing – level 2 – A.3.1
–	Unknown face height	–	Unknown face finishing
0	No face	CFP	Plaster finishing
10	Up to 10 cm	CFB	Brut
30	Up to 30 cm	CFD	Decorated
31	More than 30 cm	CFRM	Render mash finishing

Table 8
– “Parapet shape” (level 1) and the linked “Parapet material” sub-attribute (level 2).

Code	Parapet shape – level 1 – A.4	Code	Parapet material – level 2 – A.4.1
–	Unknown shape	–	Unknown material
CPCS	Continuous and stocky	CPMA	Masonry
CPCL	Continuous and slender	CPCO	Concrete/Reinforced concrete
CPDS	Discontinuous and stocky	CPST	Steel
CPDL	Discontinuous and slender	CPWO	Wood
		CPCOM	Composite/Combined

Table 9
– “Shape factor” (level 1).

Code	Shape factor – level 1 – A.5
–	Unknown Shape factor
CSF1	H > L
CSF2	H = L
CSF3	H < L
CSF4	H < < L

CSF4 (Fig. 3b, right side).

By combining the various items introduced in Tables 4–9, structuring the taxonomy of the cornice, the total number of possible combinations reaches more than 1,400,000. Only by a building-by-building on-site survey campaign using, for example, Unmanned Aerial Vehicle (UAV) system [62], the proper taxonomy strings referred to the considered buildings can be thus deduced.

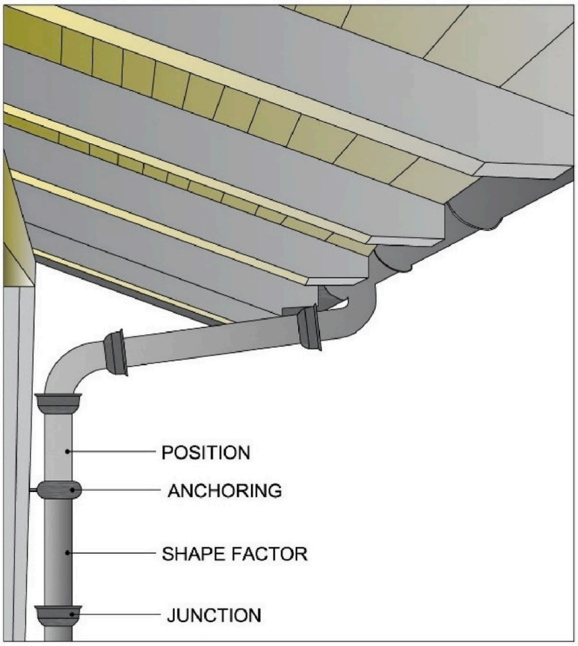

Fig. 4. – Sub-attributes of level 2 for the “Household drain system”.

2.3.2. The household drain system attribute

Consistently with the cornice attribute, for the household drain system a structured classification is given, based on both literature investigation [63–65] and authors' knowledge, to investigate the main features to account for. Notably, the composing material, the anchoring and junction types, the location on the envelope, and the shape factor are selected as the main parameters for this assessment (Fig. 4).

Specifically, at the attribute level, the material of the drain system is specified as per the following Table 10.

The criteria to follow for the selection of the system material basically depend on the constructive features of the building and, specifically, on the construction style and on the drain system location [63]. As an example, historical buildings usually own earthenware (DE) and copper or brass pipes (DCB) deployed in exposed position on the envelope. Conversely, plastic material (DP) is usually installed for contemporary buildings according to a built-in configuration. Metal types, such as cast iron (DI), galvanized steel (DS) or foil (DF), can be found in both historical and contemporary buildings, depending on the external forcing acting on the envelope [66].

The level 1 attribute relies on the identification of the anchoring, junction, and position items. Notably, the anchoring (DA) is a relevant standpoint for the assessment of the household drain system against hazards such as earthquakes and wind, given its role to strength the structural resistance of the system. Wider type of anchoring is the exposed muff one, as listed in Table 11 (left).

The second feature of level 1 entails the type of pipe junction (DJ), depending on the pipe material. For galvanized steel and foil, the welded junction (DJW) is widely applied, whereas cast iron, plastic, copper, brass, and earthenware pipes usually exhibit socket type (DJS). Muff coupling junction (DJM) can be used for HDPE material, instead (Table 12).

The position (DP) of household drain system relies on its location on the envelope, allowing for detecting exposed (DPE) and built-in (DPB) configurations. It specifically depends on the constructive features of the building, the construction style and age and the main characteristics of the envelope (Table 13).

The last item of level 1 concerns the shape factor (DSF), namely the conveyance capacity of the household drain system, representing its main feature against some hydrometeorological hazards, such as heavy rainfall events. Namely, it is estimated as the pipe internal diameter for circular pipe, while being the equivalent diameter for different geometries. Notably, known the transversal area of the pipe, it is equal to the diameter of the circular pipe having the same area. Depending on the conveyance capacity of the system, three SF classes are accounted for: DSF60 for equivalent diameter not higher than 60 mm, DSF100 for equivalent diameter from 51 mm to 100 mm and DSF 101 for values greater than 100 mm (Table 14).

Level 2 of the household drain system characterizes and specifies the anchoring and junction material, depending on both the pipe material and the constructive features of the building. The items of level 2 are shown in the right side of Tables 10 and 11. For both attributes of level 1, galvanized steel (DAMS and DJMS), copper or brass (DAMCB and DJMCB), plastic (DAMP and DJMP) and earthenware (DAME and DJME) are included.

As for the cornice, the items composing the household drain system attribute, and the related levels and sub-levels, are resumed in a taxonomy string. For example, a plastic element (DP), with exposed galvanized steel anchoring (DAE, DAMS), socket junctions (DJS), exposed (DPE) and of diameter of 100 mm (DSF100) is detected by the following string: DP/DAE,DAMS/DJS,DJMP/DPE/DSF100 (Fig. 5a, left side). A cast iron element (DI) with exposed anchoring (DAE) and muff coupling junction (DJMS) of unknown material (–), exposed (DPE) and with diameter of more than 100 mm (DSF101) is described by the following string: DI/DAE,–/DJM/DPE/DSF101 (Fig. 5b, right side).

By combining the various items introduced in Tables 10–14 structuring the taxonomy of the household drain system, the total number of possible combinations reaches around 3500.

2.4. Hazard-oriented taxonomy adaptation: the case of earthquakes and heavy rainfall events

The large number of possible combinations the taxonomy may assume can be reduced to a more feasible number through a hazard-oriented analysis. Depending on the hazard considered, not all sub-attributes structuring the taxonomy are equally involved. Some, not directly exposed, are explicitly excluded from the classification of the analysed envelope's technical element. In this way, an exposure matrix has been defined, pinpointing the sub-attributes that are either directly involved or excluded when a specific hazard is considered in building evaluations.

In Figs. 6 and 7, the exposure matrices for the "Cornice construction technique" and "Household drain system" attributes and the related sub-attributes are given. The attribute and sub-attribute information, directly exposed to each hazard, are highlighted in dark grey (attribute and sub-attributes level 1) and light grey (sub-attributes level 2). As an example, for seismic hazard, not all the sub-attributes of the cornice are directly exposed: in detail, only the "Cornice construction technique" (A), the "Parapet shape" (A.4),

Table 10
– "Household drain system material" attribute.

Code	Household drain system material - H
–	Unknown material
DI	Cast iron
DS	Galvanized steel
DF	Galvanized foil
DCB	Copper or Brass
DP	Plastic (PV, HDPE, PP)
DE	Earthenware

Table 11
– “Anchoring” (level 1) and the linked “Material” sub-attribute (level 2).

Code	Anchoring – level 1 – H.1	Code	Material – level 2 – H.1.1
–	Unknown anchoring	–	Unknown material
DAE	Exposed muff anchoring	DAMS	Galvanized steel
DA0	No anchoring	DAMCB	Copper or Brass
		DAMP	Plastic (PVC, HDPE, PP)
		DAME	Earthenware

Table 12
– “Junction” (level 1) and the linked “material” sub-attribute (level 2).

Code	Junction – level 1 – H.2	Code	Material – level 2 – H.2.1
–	Unknown junction	–	Unknown material
DJW	Welded junction	DJMS	Galvanized steel
DJS	Socket junction	DJMCB	Copper or Brass
DJM	Muff coupling junction	DJMP	Plastic (PVC, HDPE, PP)
		DJME	Earthenware

Table 13
– “Position” (level 1).

Code	Position – level 1 – H.3
–	Unknown
DPE	Exposed
DPB	Built-in

Table 14
– “Shape factor” (level 1).

Code	Shape Factor (SF) - H.4
–	Unknown SF
DSF60	SF $\leq$ 60 mm
DSF100	60 mm $<$ SF $\leq$ 100 mm
DSF101	SF $>$ 100 mm

Fig. 5. – Examples of a plastic (Fig. 5a, left) and cast-iron household drainage system element (Fig. 5b, right).

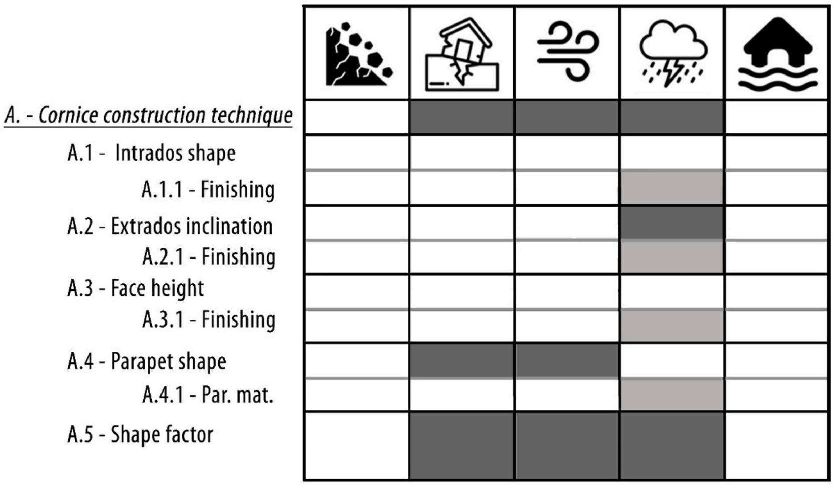

Fig. 6. – Exposure matrix of the "Cornice construction technique" attribute.

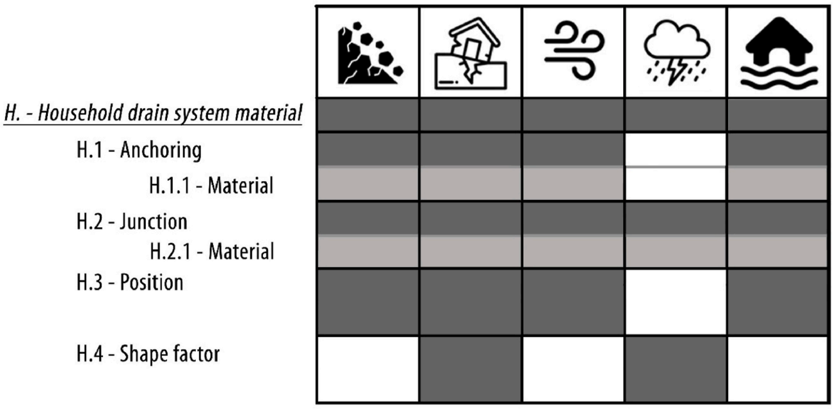

Fig. 7. – Exposure matrix of the "Household drain system material" attribute.

and the "Shape factor" (A.5) are involved. This simplification, when the seismic hazard is considered, reduces the number of possible combinations the taxonomy string may assume for cornices from near 1,400,000 (the total number of combinations if all the attributes and sub-attributes are considered) to "only" 128. Thus, a meticulous survey allows for the identification of the relevant taxonomy string without requiring an evaluation of 1.4M potential possibilities since not all attributes and sub-attributes are concur to the vulnerability analysis to a specific hazard. In this way the number of applicable combinations is significantly reduced based on the specific hazard considered.

In the frame of the current work, earthquake and heavy rainfall hazards were investigated, given their relevance in affecting the building envelope components when varying the seismic- and the flood-prone areas [67,68]. Notably, the higher the proneness of the investigated area to the specific hazard, the greater the vulnerability affecting the components, thus, strictly linking the compelling awareness of the composition of the building envelope with the significance of the class group.

As an example, when heavy rains are considered, the "Intrados shape" (A.1), the "Face height" (A.3), and the "Parapet shape" (A.4) should be excluded since not concurring with the damage the cornice can report due to that hazard. In this way, the total number of combinations within the taxonomy may be reduced from around 1,400,000 to around only 60,000.

For the assessment of household drain systems against seismic hazard, the taxonomy cannot undergo a simplification since all the attributes and sub-levels are equally exposed while, against heavy rains, the number of combinations lowers from near 3500 to only 218 since the "Anchoring" (H.1) and the related "Material" (H.1.1) and the "Position" (H.3) are not relevant for the assessment.

This simplification is useful to limit the computational time of vulnerability analysis, even more aggregate buildings at a large scale are investigated.

As an example, the taxonomy strings "CM1/CIF,CIP/15,CET/31,CFP/CPCS,CPMA/CSF2" and "CC1/CF,CIP/5,CEW/10,CFP/CPCL,CPST/CSF4", describing the cornices shown in Fig. 3a and 3b respectively, can be simplified to "CM1/CPCS/CSF2" and "CC1/CPCL/CSF4" when seismic hazard is considered, and to "CM1/CIP/15,CET/CFP/CPMA/CSF2" and "CC1/CIP/5,CEW/CFP/CPST/CSF4" in the case of heavy rains, thus defining more manageable string length. The same applies to the strings related to household drain systems shown in Fig. 4a and 4b, “DP/DAE,DAMS/DJS,DJMP/DPE/DSF100” and “DI/DAE,–/DJM,–/DPE/DSF101” respectively. For seismic hazard, the taxonomy string cannot be simplified and remains unchanged, whereas for heavy rains, a simplification occurs, resulting in the reduced strings “DP/DJS,DJMP/DSF100” and “DI/DJM,–/DSF101”.

2.5. Example of a taxonomy application using vulnerability assessments

In this section, an example of a possible application of the proposed taxonomy is presented. The structure of the taxonomy is herein applied to propose qualitative vulnerability assessments, aimed to investigate the envelope technical elements in multi-hazard scenarios.

The proneness of the envelope elements to report damage in case of hazardous events depends on two main factors: the technological features and the physical condition of those elements, i.e., their degradation level. It is worth assuming that elements with the same characteristics are more prone to collapse if they are in poor physical conditions (i.e., there are signs of mechanical deterioration, such as cracks and deformations) rather than if they are in good physical conditions. Degradation functions are an amplifying factor applied to the technological vulnerability value. For example, two balconies of distinct construction technologies, masonry and reinforced concrete, may exhibit different baseline vulnerabilities to seismic loads even when equally preserved, with the masonry element being inherently more vulnerable [69]. Nevertheless, when degradation progresses unevenly, the resulting overall vulnerabilities can diverge markedly.

Given the scope of this paper, which is to develop and test a novel taxonomy for building envelope elements, this work does not address the burden of the level of degradation on the level of vulnerability. Nevertheless, this section shows preliminary results on the use of the proposed taxonomy to assess the envelope’s vulnerability to specific hazards, considering technological characteristics only. Vulnerability assessments regarding envelope elements remain in the qualitative domain and are made based on the vulnerability factors listed in Table 1.

Risk, and by analogy, vulnerability assessment can be carried out using several approaches, namely quantitative, semi-quantitative and qualitative [70,71]. More specifically, qualitative approaches rely on experts’ opinions or systematic literature reviews and lead to the development of matrices, checklists, and comparative tools which provide a good preliminary overview of a system vulnerability without excessive time investment. Conversely, quantitative estimations need a large amount of data to validate the employed models. Given the limited number of quantitative studies addressing building envelope vulnerability, the authors adopted a qualitative approach to perform the analysis.

Based on the identified vulnerability factors (Section 2.1), the authors have graded the technical solutions described by the taxonomy in terms of proneness to suffer damage when subject to a specific hazard. For example, knowing that the greater the element’s fragility, the higher its vulnerability to earthquakes, masonry cornices are assumed to have a higher vulnerability to earthquakes compared to steel cornices (assuming identical shape features).

It is herein presented an application of the taxonomy to assess the vulnerability of cornices and household drain systems against earthquakes and heavy rainfall events. For the sake of brevity, the vulnerability grades are reported for two attributes only (A and H) for seismic and heavy rains. These two hazards have been selected as the primary focus due to their pronounced impact on envelope-related technical elements, specifically cornices and household drain systems.

In this sense, the vulnerability assessment is performed in a qualitative manner by comparing how different technological solutions can increase the vulnerability of an element when an earthquake or rainfall occurs.

In Table 15 the vulnerability judgments for the general “Cornice construction technique” attribute are shown, whereas the vulnerability judgments for the general “Household drain system material” attribute are given in Table 16. The various items have been classified into five qualitative classes: very high, high, moderate, low, and very low, in accordance with similar studies on building envelope component vulnerabilities [72].

3. Case study and results

The developed taxonomy was applied to a sample of buildings located in the Campi Flegrei area, at the western side of the city of Naples (Italy). This area (Fig. 8), located in the surrounding of the Engineering Departments of the University of Naples Federico II affiliated with the authors, was selected for its ease of inspection and the accessibility of building data. Indeed, as well known, the

Table 15
– Vulnerability class of “Cornice construction technique” against earthquake and heavy rains.

Code	Cornice construction technique – A	Vulnerability class against earthquakes	Vulnerability class against heavy rains
–	Unknown cornice construction technique	VERY HIGH	VERY HIGH
CM1	Masonry general	VERY HIGH	VERY HIGH
CM2	With metal cantilever	HIGH	HIGH
CC1	Cast-in-place reinforced concrete	HIGH	MODERATE
CC2	Precast reinforced concrete	MODERATE	MODERATE
CS	Steel	VERY LOW	VERY LOW
CP	Polystyrene/FRP/Polyurethane	VERY LOW	MODERATE
CW	Wood	LOW	VERY HIGH
CC	Composite/other	LOW	MODERATE

Table 16
– Vulnerability class of "Household drain system material" against earthquake and heavy rains.

Code	Household drain system material - H	Vulnerability class against earthquakes	Vulnerability class against heavy rains
–	Unknown material	VERY HIGH	VERY HIGH
DI	Cast iron	VERY LOW	VERY LOW
DS	Galvanized steel	VERY LOW	VERY LOW
DF	Galvanized foil	VERY LOW	VERY LOW
DCB	Copper or Brass	VERY LOW	VERY LOW
DP	Plastic (PVC, HDPE, PP)	MODERATE	MODERATE
DE	Earthenware	VERY HIGH	VERY HIGH

Campi Flegrei area experiences high-frequency but low-intensity earthquakes under the umbrella of bradyseism activity [73,74]. Notably, only between August 2023 and December 2024, more than 30 events with duration magnitude larger than 2.4 were observed in this area [75] and they are occurring so far. It gives rise to a frequent earthquake swarm that both alerted the population and the civil authorities and significantly stressed the buildings, as well as their envelope components, resulting in a high vulnerability of collapse risk even under low-intensity external forces [76].

Additionally, the Campi Flegrei area and, namely the Fuorigrotta district where the investigated buildings are located, is widely affected by flood events, given its undersized urban drainage system [77] and the rainfall events occurring especially in the last years, as a consequence of the climate change [78,79]. These features make the need to properly focus the attention on the building elements susceptible to earthquake and heavy rainfall hazard even more relevant.

Within the study area, the buildings' roof cornices and household drain systems were classified, and a taxonomy string for each of them was defined. The case study area shows a variety of materials and construction techniques, allowing testing the validity and the efficiency of the proposed method. Indeed, in the study area, both masonry and concrete cornices can be found. Conversely, a lesser variety of household drain systems is observable.

In total, thirteen buildings - being part of six aggregates - were inspected, also with the use of drones [80]. They comprise two main cornice types: masonry with metal cantilever (CM2) (five out of thirteen) and cast-in-place reinforced concrete (CC1) (eight out of thirteen), while one cornice is made of tuff blocks (CM1). Most cornices have plastered intrados (CIP) (twelve out of thirteen) and water-proof membranes as a covering of the extrados (CEW) (eleven out of thirteen). Masonry cornices are coupled with masonry parapets (CPMA), concrete cornices are coupled with concrete parapets (CPCO). Finally, most cornices (eleven out of thirteen) have a span length bigger than the height length (CSF3 and CSF4).

Regarding household drain systems, it must be said that data collection was possible in nine cases out of thirteen, where the elements were exposed or visible from the street. In most of the cases (eight out of nine) the drain system material is plastic (DP), with exposed (DAE) galvanized steel anchoring (DAMS). The socket junction (DJS) with galvanized steel (DJMS) is the most common type of junction (eight out of nine), while the diameter is equal to 80 mm (DSF100) (five out of nine) or more (DSF101) (four out of nine). In Tables 17 and 18 list the classification of the analysed buildings related to the cornices and the household drain systems, along with the relative taxonomy strings, respectively.

Given the collected data, an illustrative application was also developed to show how the taxonomy can assist in the vulnerability analysis. Cornices and drain systems' vulnerability to earthquakes and rainfall events were assessed for three buildings (Fig. 9).

Based on the two considered hazards, for the cornices of the three considered buildings, a significant reduction in the taxonomy string can be retrieved, as shown in Table 19.

Tables 20 and 21 report the vulnerability grades assigned to the cornices and the household drain system, respectively, consistent with the exposure matrices and qualitative vulnerability grades discussed in Section 2.4 and Section 2.5. Only for the sake of application, qualitatively vulnerability judgments are expressed even for sub-levels not covered by Section 2.5. The way each attribute contributes to the element's vulnerability varies with the specific hazard of interest.

The formulation of how different characteristics are combined is not covered by this paper. However, the first potential solution is not to combine them at all, and to act with a conservative approach, where only the worst grade is used to assess the overall element vulnerability against a specific hazard.

4. Discussion

From the results presented above, it is worth remarking that the proposed taxonomy allows a detailed description of the technical elements, resulting in a suitable approach to compare their vulnerability.

Regarding cornices' vulnerability (Table 20), the judgments around the vulnerability for three specific buildings (5.1, 6.1, and 3.1), have been directly compared. Buildings 5.1 and 6.1 have a metal cantilevered masonry cornice (CM2) and are considered to have a high propensity to damage in case of earthquakes while building 3.1 has a tuff stone cornice (CM1) and is considered to have a very high propensity to damage in case of earthquakes (i.e., very high vulnerability). However, they have different shape factors, as the long-span cornice of building 5.1 (CSF4) can increase the propensity to be damaged compared to building 6.1 (CSF3). Regarding building 3.1, a conservative approach can be assumed and the cornice vulnerability to earthquakes can be considered very high, based on the evaluation of the cornice construction technique, however neglecting the potential balancing impact of a short-span shape factor (CSF3).

Similarly, the three cornices have a different proneness to damage when a heavy rain event occurs. Indeed, the lack of a water-proof

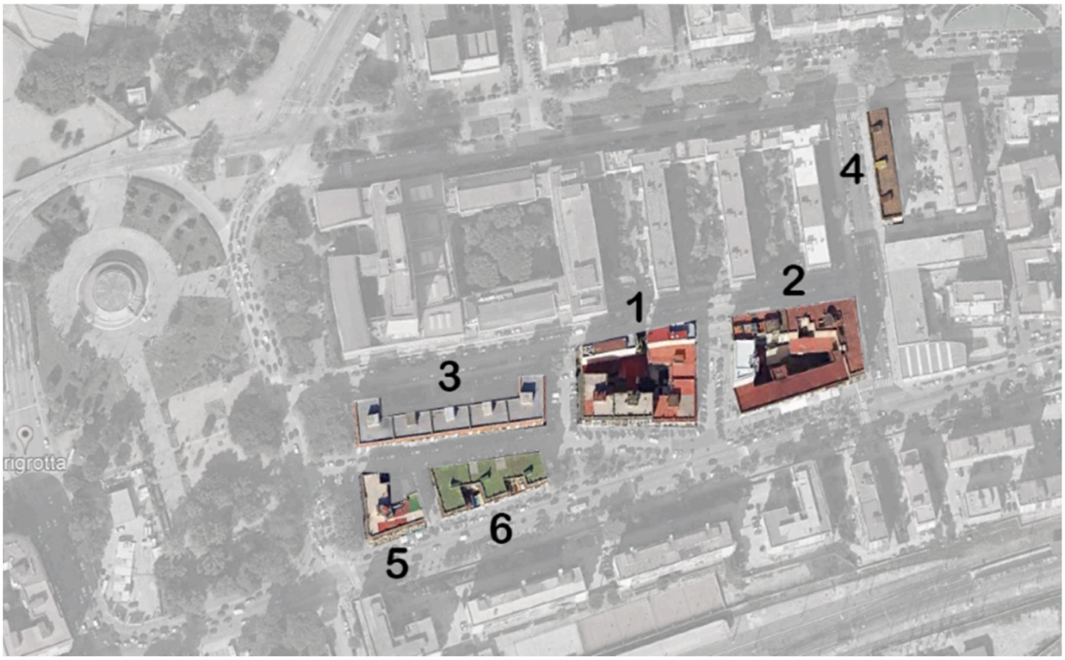

Fig. 8. – Selected case study area with the analysed buildings.

Table 17
– Cornice characteristics defined by the taxonomy strings.

Site	Building	Cornice taxonomy string
5	5.1	CM2/CIF,CIP/5,CEW/30,CFP/CPCS,CPMA/CSF4
6	6.1	CM2/CIF,CID/5,CEW/30,CFP/CPCS,CPMA/CSF3
3	3.1	CM1/CIF,CIP/5,CET/10,CFP/CPCS,CPMA/CSF3
1	1.1	CC1/CIF,CIP/5,CEW/30,CFP/CPCS,CPCO/CSF3
	1.2	CM2/CIF,CIP/5,CEW/10,CFP/CPCS,CPMA/CSF4
	1.3	CC1/CIF,CIP/5,CEW/10,CFP/CPCL,CPMA/CSF3
	1.4	CC1/CIF,CIP/5,CEW/30,CFP/CPCS,CPCO/CSF2
	1.5	CC1/CIF,CIP/5,CEW/10,CFP/CPCS,CPCO/CSF3
2	2.1	CM2/CIF,CIP/5,CEW/10,CFP/CPCL,CPMA/CSF4
	2.2	CC1/CIF,CIP/5,CEW/10,CFP/CPCL,CPCO/CSF4
	2.3	CC1/CIF,CIP/5,CEW/10,CFP/CPCL,CPCO/CSF3
	2.4	CC1/CIF,CIP/5,CEWM/10,CFP/CPCS,CPCO/CSF2
4	4.1	CC1/CIF,CIP/5,CEW/10,CFP/CPCS,CPCO/CSF3

Table 18
– Household drain system characteristics defined by the taxonomy strings.

Site	Building	Household drain system taxonomy string
5	5.1	DP/DAE,DAMS/DJS,DJMP/DPE/DSF101
6	6.1	DP/DAE,DAMS/DJS,DJMP/DPE/DSF101
3	3.1	DP/DAE,DAMS/DJS,DJMP/DPE/DSF101
1	1.1	DP/DAE,DAMS/DJS,DJMP/DPE/DSF100
	1.2	DP/DAE,DAMS/DJS,DJMP/DPE/DSF100
	1.3	DP/-,-/DJS,DJMP/DPB/DSF101
	1.4	DP/-,-/DJS,DJMP/DPB/DSF100
	1.5	DI/DAE,DAMS/DJS,DJMS/DPE/DSF100
2	2.1	DP/DAE,DAMS/DJM,DJMS/DPE/DSF100

membrane at the extrados of building 3.1 cornice (CET) can lead to water infiltration and eventually to the collapse of the element.

With reference to the household drain system, a substantial uniformity of vulnerability grades against both earthquake and heavy rainfall events was observed. Indeed, all buildings show plastic pipes, corresponding to medium vulnerability grade to both hazards. They all show exposed muff anchoring, thus reaching the lowest vulnerability grade (very low). Concerning the junction sub-attribute,

Fig. 9. – Photos of buildings 5.1 (left), 6.1 (middle), and 3.1 (right).

Table 19
– The reduction of the taxonomy strings for buildings 5.1, 6.1, and 3.1 based on the considered hazards.

	Building 5.1	Building 6.1	Building 3.1
Complete taxonomy string	CM2/CIF,CIP/5,CEW/30,CFP/CPCS, CPMA/CSF4	CM2/CIF,CID/5,CEW/30,CFP/CPCS, CPMA/CSF3	CM1/CIF,CIP/5,CET/10,CFP/CPCS, CPMA/CSF3
Taxonomy string against earthquake	CM2/CPCS/CSF4	CM2/CPCS/CSF3	CM1/CPCS/CSF3
Taxonomy string against heavy rains	CM2/CIP/5,CEW/CFP/CPMA/CSF4	CM2/CID/5,CEW/CFP/CPMA/CSF3	CM1/CIP/5,CET/CFP/CPMA/CSF3

Table 20
– Cornice characteristics and vulnerability values. The color-based scale refers to the vulnerability grades presented in Section 2.5 (red = very high vulnerability, orange = high vulnerability, yellow = moderate vulnerability, yellow-green = low vulnerability, green = very low vulnerability). The attributes are the following: A = Cornice construction technique; A.1 = Intrados shape; A.1.1 = Intrados finishing; A.2 = Extrados inclination; A.2.1 = Extrados finishing; A.3.1 = Face finishing; A.4 = Parapet shape; A.4.1 = Parapet material; A.5 = Shape factor.

	Vulnerability to earthquake			**Vulnerability to heavy rainfall events**						
Building	**A**	**A.4**	**A.5**	**A**	**A.1.1**	**A.2**	**A.2.1**	**A.3.1**	**A.4.1**	**A.5**
5.1	orange	green	red	red	yellow	orange	yellow-green	yellow	red	red
6.1	orange	green	orange	red	yellow	orange	yellow-green	yellow	red	orange
3.1	red	green	yellow-green	red	yellow	orange	orange	yellow	red	yellow-green

the three systems exhibit socket configurations, thus having moderate vulnerability. In terms of shape factor sub-attribute, this owns the worst vulnerability grade (very high) to earthquakes but very low to rainfall events.

Tables 20 and 21 show the differences between the technical elements in detail. This detailed representation of the results allows a clear identification of the factors which can potentially increase the vulnerability of the analysed envelope technical elements, and which serve as a first step towards planning interventions to reduce the vulnerability and prevent risks associated with damaged technical elements.

This paper proves that the proposed taxonomy is a ready-to-use tool, and its implementation is doable, as per results exposed in Section 3. The results show a twofold value.

- At the building and element scale, they allow the identification of the vulnerability-increasing items, clearly detecting the weak spots of a building envelope where intervening to reduce arising risks for people and urban contexts.
- At the urban scale, they allow comparing several buildings to understand the most vulnerable areas which might need interventions,

The implementation of the proposed taxonomy helps classify and assess the central role of the envelope technical elements. The envelope, as the first portion of the building to be hit by external stressors, frequently sustains severe damage when hazardous events occur, leading to significant consequences that justify such kind of investigations. Furthermore, few studies have focused on this

Table 21
– Household drainage system characteristics and vulnerability grades. The color-based scale refers to the vulnerability grades presented in Section 2.5 (red = very high vulnerability, orange = high vulnerability, yellow = moderate vulnerability, yellow-green = low vulnerability, green = very low vulnerability). The attributes are the following: H = Household drain system; H.1 = Anchoring; H.1.1 = Anchoring material; H.2 = Junction; H.2.1 = Junction material; H.3 = Position; H.4 = Shape factor.

	Vulnerability to earthquake							Vulnerability to heavy rainfall events			
Building	**H**	**H.1**	**H.1.1**	**H.2**	**H.2.1**	**H.3**	**H.4**	**H**	**H.2**	**H.2.1**	**H.4**
5.1											
6.1											
3.1											

subject except for energy and thermal performances in the case of high temperature stresses, which are commonly addressed topics of concern.

5. Conclusions

In recent years, the vulnerability of building envelopes to various natural hazards has become an increasingly critical concern, especially in the context of a changing climate that heightens the frequency and intensity of these events. Some of the most frequent effects caused, for example, by heavy rainfall are damages to roofs, cornices, household drain systems, and exterior walls.

A hazard-oriented and user-friendly taxonomy for envelope technical elements can bring significant benefits to the quantification of the vulnerability and to plan repair works and preventing actions.

Traditional taxonomies, such as GED4ALL, have primarily focused on structural elements and their response to major hazards like earthquakes, often neglecting the more frequent and less intense impacts on architectural and plant system technical elements. This paper addresses this gap by introducing a novel taxonomy specifically designed to assess the vulnerability of building envelope technical elements — such as cornices, balconies, and household drain systems — against a range of hazards, including hydro-meteorological events.

The primary contribution of this paper is the development of a detailed and flexible classification system that goes beyond existing frameworks. Unlike previous taxonomies, the proposed system accounts for the technological characteristics of building envelope elements, providing a more nuanced approach to vulnerability assessment.

The proposed taxonomy should be intended as a tailorable, oriented instrument, useful to address the assessment of building envelope vulnerabilities, offering a new tool for researchers and practitioners. However, the taxonomy's effectiveness is contingent upon the availability and quality of relevant data, and it currently does not account for degradation state, which is a relevant task for future exploration. In this way, interesting theoretical improvements of the research may rely on the consideration of degradation in the formulation of vulnerability assessment, as well as of quantitative metrics for defining vulnerability judgments. Including potential outcomes from stress tests on technical elements or the same degradation indices can further enhance the robustness of the investigation.

The reliability of the taxonomy was tested on a case study in the Campi Flegrei area (IT), showing its effectiveness for the preliminary vulnerability assessment of the elements of a building envelope against earthquake and heavy rainfall hazards. The selected area represents a suitable benchmark for the investigation, because affected by recurring high-frequency, low-intensity bradyseismic phenomena, as well as frequent flood and rainfall events. From its application several shortcomings raised, as well. Among them, the initial stage of data collection showed to be a challenging step, given the hurdle to gather homogeneous database to extract the specific required information and the huge time-demanding to perform survey and categorization activities. The type of available data is also strictly related to the investigated context. Thus, the next steps of the research will entail the improvement and testing of the provided taxonomy to case studies located in different geographical areas, where various building configurations and hazards are detected. The application of the method to different seismic and flood-prone regions would enable the validation of the proposed methodology. Finally, the ex-post application of the method in areas experiencing significant damages from one or more hazards considered can further strengthen and improve the effectiveness of the developed investigation.

CRediT authorship contribution statement

Lorenzo Diana: Writing – review & editing, Writing – original draft, Methodology, Investigation, Conceptualization. **Francesco Pugliese:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Conceptualization. **Rossella Marmo:** Writing – review & editing, Writing – original draft, Methodology, Investigation. **Saverio D'Auria:** Writing – review & editing, Writing

– original draft, Investigation. **Roberto Castelluccio:** Writing – review & editing, Methodology, Funding acquisition, Conceptualization.

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Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Roberto Castelluccio reports financial support was provided by European Union. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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