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Damage to Technical Elements of the Building Envelope in the Typical Multi-Risk Scenario of the Campi Flegrei Area

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Abstract. Damage to technical elements of the building envelope can have unacceptable consequences for the functionality and safety of a building. Recent interest in such damage is mostly linked to intensive events, neglecting the study of extensive events. Despite the known connection between technical envelope vulnerability and building functionality and safety, systematic vulnerability studies are missing. This study proposes investigation sheets for damaged technical elements as preliminary tools for assessing envelope vulnerability and hazardous events, related to this vulnerability, in urban areas. The study focuses on frequent but non-catastrophic hazards, typical of the Campi Flegrei area, where recent bradyseismic activity has renewed national interest and necessitated risk prevention measures. The research methodology involves three phases: identification of the most vulnerable technical elements, comparison with bibliographic data, and direct application in a multi-risk scenario, specifically bradyseismic activity combined with different environmental exposures. Analysis reveals balconies and cornices as the most frequently damaged elements, particularly vulnerable to bradyseismic activity and environmental exposure. Associations between observed damage and hazard characteristics will support the identification of the degradation pattern of technical elements which is needed to analyse their vulnerability and to assess the risk onto the urban system associate with it.

Keywords: Building Risk · Building Envelope · Bradyseism · Multi-risk · Damage

1 Introduction

1.1 Damage to Technical Elements of the Building Envelope and the Associated Hazards

Damage to the technical elements of the envelope can have consequences on the functionality and safety of a building organism, which are deemed unacceptable for the usability of buildings, even when the load-bearing characteristics remain uncompromised.

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Interest in this type of damage is relatively recent and is mainly related to the occurrence of intensive events, characterised by high intensity and low frequency, neglecting the study of the effects of extensive events, characterised by low intensity and high frequency [1]. In this regard, Italian guidelines, as provided by the Italian Civil Protection Department [2], and US guidelines, as provided by the National Institute of Standards and Technology [3] and the Federal Emergency Management Agency [4] emphasise how damage to so-called "non-structural" elements can entail at least three types of consequences: economic losses; disruptions to services; and threats to people's safety.

Economic losses are directly tied to the costs of repairing the damaged elements and indirectly connected to disruptions. The entity of these losses is high since architectural elements are more frequently damaged than structural elements (the former being vulnerable even to low-intensity events) and, along with plant elements, they represent at the same time most of the total construction cost of a building, ranging between 60% and 90% [5].

People's safety is directly affected by falling elements from façades and indirectly influenced by the obstruction of escape routes, such as streets and open spaces. Assessing the risk of people being injured due to falling bodies from façades is an issue not yet thoroughly explored, even though it represents the primary concern for Public Administration in ensuring public and private safety [6]. Two studies in this regard propose a risk index evaluation [7] and the calculation of the probability of detachment [8], both starting from the analysis of a façade's degradation conditions.

The studies offer interesting methodological insights, although the results are limited to homogeneous construction techniques and do not account for different factors of environmental exposure. The issue of escape route obstruction following the collapse of technical elements of the building envelope has been exclusively analysed for seismic events, where the vulnerability of a building to an earthquake of a certain intensity is associated with the volume of debris generated during the event and the subsequent obstruction of escape routes [9–11].

In parallel to concerns explicitly related to the safety of urban environments, there is a growing research interest focused on describing the impact of climate change on the performance of the building envelope. Extreme weather events reduce the service life of the technical elements of the envelope and cause performance loss, requiring a revision of maintenance policies and design guidelines [12].

From the above, it is evident that while the connection between the vulnerability of the technical elements of the envelope and the functionality and safety of buildings, as well as the urban system they are part of, is well known, the subject is currently confined exclusively to characterisation studies of the vulnerability of structural elements or within the context of maintenance management. The authors have emphasised the necessity to systematise vulnerability studies of the technical elements of the envelope, to be included in the "Building Risk" [1] assessment, not only to analyse the effects of hazardous events on the building but also to consider the hazardous events that the building itself may pose to the surrounding context.

The current article aligns with this line of research and proposes the elaboration of investigation sheets for damaged technical elements, which serve as preparatory tools for measuring the vulnerability of the building envelope and the consequent measuring of hazardous events that may impact the surrounding urban areas.

The issue is particularly relevant in contexts exposed to frequent but non-catastrophic hazardous events, which result in damage to building envelope elements without, however, affecting structural elements. A typical example of such a scenario is the Phlegrean context in the province of Naples. The centre of Pozzuoli, along with the entire Phlaegrean Fields area, has recently returned to the centre of national interest due to the intensification of bradyseismic activity, which has necessitated the issuance of an ad hoc decree, Decreto Legge 140 of 12/10/2023 [13], addressing the mapping and prevention of seismic risk associated with it.

1.2 Critical Analysis of Damage Inspection Sheets

Based on the above considerations, the significance of analysing the technical elements of the envelope in terms of performance, functionality, and safety of the building systems emerges. Additionally, there is the need for adequate surveying tools for their characterisation and knowledge of the state of preservation associated with multi-risk exposure.

In the context of the prompt analysis of the consistency and damage of building systems, various types of indirect survey sheets are currently employed in Italy. In this section, a critical analysis of the most frequently used ones is proposed: the sheets by the Gruppo Nazionale Per La Difesa dai Terremoti (G.N.D.T.), the AeDES and the CARTIS sheets [14–18]. All the sheets are structured in sections, each associated with distinct types of information, and classified according to the level of detail and the purpose of data collection. The initial sections have an introductory character, focusing on identifying, locating, and describing general characteristics (i.e., metric data, use, age) and typology; this information pertains to either the homogenous category of buildings or the individual building under consideration [14, 19, 20]. Conversely, the subsequent sections are differentiated according to the specific objectives set by each sheet, orienting the systematisation and type of data required for compilation accordingly [19, 20].

In specific terms, the G.N.D.T. sheets are aimed at surveying masonry or concrete buildings, either across entire urban areas (1st level sheet) or for a limited number of homogeneous buildings (2nd level sheet). They present a dedicated section for analysing the degree of damage, expressed in terms of both the extent and severity of the damage observed [14, 15]. The collected information, when combined with vulnerability factors associated with the building type's characteristics, serves earthquake exposure and vulnerability assessments. Concerning the technical elements of the envelope, the sheet focuses solely on plasters, enclosures, and external fixtures, encompassed within a marginal section dedicated to the "State of Finishes and Installations". This section limits the evaluation of the state of consistency to residual efficiency. This highlights a disparity, in terms of importance, between elements of the technological unit class "Load-bearing structure" and those belonging to the classes of "Enclosure" and "External partitions" [1, 14, 15, 21].

The AeDES (Agibilità e Danno nell'Emergenza Sismica) sheet is a more recent form designed for the expeditious survey of typological characteristics and damage suffered by buildings in the aftermath of an earthquake. Its primary focus is on evaluating the usability of ordinary buildings during the post-earthquake emergency phases and determining appropriate emergency response measures [16, 20, 22, 23]. In this case, there is a dedicated section for assessing the damage suffered by "non-structural" elements, which includes a higher number of technical elements of the envelope such as plaster, cladding, roof tiles, chimneys, cornices, and parapets, among others [16, 20, 22]. However, the collected data is limited to noting the presence or absence of damage, proving insufficient for an effective assessment of the state of damage and the potential risk associated with it. Although it may be assumed that the fall of a cornice or the detachment of plaster from the wall support may not necessarily compromise the practicability of the building, the damage to such elements represents an equally significant hazard in post-emergency phases, for both public and private safety and in terms of obstruction of escape routes.

The CARTIS and CARTIS EDIFICIO sheets represent an updated version of the AeDES sheet, albeit with overall different contents and purposes [17, 18, 24]. The former is designed for the survey of ordinary building types present within plots, characterised by typological-structural homogeneity of the building fabric, while the latter is configured as a second-level sheet and is dedicated to the survey of individual ordinary buildings [17, 18, 20]. Both are structured to collect information required for a typological-structural characterisation of the built environment as close as possible to reality, being functional for different areas and purposes of application. Despite the broad perspective underlying the data collection approach, they still prioritise the assessment of seismic vulnerability as primary objective. With regard to the technical elements of the envelope, an autonomous section dedicated to "vulnerable non-structural elements" is proposed. This section gathers information on the presence of particularly vulnerable elements and the percentage extent of those addressed in "poor condition". The classification proposed here, albeit superficially, provides valuable insights for the assessment of their conservation status and introduces the concept of vulnerability associated with these elements. Although there have been efforts so far to assess the vulnerability of technical elements of the envelope, the scarcity of information collected by the sheets and the specificity of the hazard considered require further studies. These studies should aim at characterising these elements and assessing their vulnerability to a different set of hazards, including multi-hazard scenarios. The methodology promotes the development of proactive and preventive measures aimed at preventing and mitigating risks faced by buildings and urban systems. Such an approach is particularly relevant for strategic, monumental, or cultural heritage buildings [25–28].

In light of the above considerations, we propose a methodology for investigating damaged technical elements. The goal is to identify parameters useful to describe their state of preservation and to provide information about their vulnerability to multi-hazard conditions.

2 Methodology

The research methodology elaborated to determine the impact of a multi-risk scenario on the technical elements of the envelope, was developed in three main phases: a reconnaissance of the technical elements with greater susceptibility to damage, carried out through an experiential and indirect analysis of the most recurrent damage reports in national newspapers (§2.1); a comparison of the data obtained in the first phase with bibliographical data, by analysing a database of reports collected in a similar study conducted previously (§2.2); a direct application on an urban context characterised by a specific multi-risk scenario—namely, Phlaegrean Bradyseism—combined with two distinct environmental exposure conditions.

This phase involved a field survey conducted to assess the state of preservation of technical elements of the building envelope for several building sections. The collected data were uniformly catalogued in inspection sheets dedicated to damaged technical elements. The comparative and critical analysis of the sheets allowed the correlation between the parameters describing the susceptibility to damage of the technical elements of the building envelope and the parameters describing the hazards to which they are exposed in the specific multi-hazard scenarios investigated (§2.3).

2.1 Most Frequent Types of Damage to Technical Elements of the Building Envelope

The technical elements analysed in this research, included in the "building envelope" category, refer to all the components belonging to the Classes of Technological Units, as defined by the UNI 8290 Standard [29], which directly interface the urban environment posing, in the event of detachments and collapses onto roads and people, a hazard to public and private safety. Therefore, the technical elements of façades belonging to the Classes of Technological Units of "Enclosure" and "External Partitions" are taken into consideration.

Collapses of cornices, plasters, gables, and parts of projecting elements onto more or less crowded places are recorded with very high frequency in the interventions that the Firefighters carry out daily on urban systems. To identify which technical elements of the building envelope show a higher susceptibility to being damaged due to external forces and their state of maintenance, an initial survey was conducted by reviewing recurrent reports in national newspapers, accessible through common search engines. The collected reports were catalogued, indicating, when present, the type of damage produced and the possible causes (Table 1).

The causes of the observed damages, when reported, are mainly related to weather phenomena associated with climate change (strong wind gusts, heavy rainfall, and strong thunderstorms) or to the state of preservation of the building envelopes (age of the building). Issues of a static nature are only rarely identified as contributing causes, confirming the greater vulnerability of "non-structural" technical elements due to the interface with the external environment compared to the mechanical behaviour of the load-bearing structure alone. As a result of this expeditious investigation, although there is no correlation with the specific risk scenarios in which the damages were reported, it emerges that the technical elements of the envelope are most vulnerable to the action of external forces and the natural ageing of building materials, are façade elements: walls plasters, claddings, balconies, and cornices.

To focus the study on the hazard induced on urban systems by the vulnerability of the technical elements of the building envelopes, understood as the Building Risk rate [1], the investigation excluded all reports of damage to other elements of urban furniture

Table 1. Summary of reports of damage to technical elements of the envelope

Year	Newspaper	Report	Cause of damage
2023	Il Giorno	detachment of part of the façade	/
2023	La Voce	falling bricks and rubble	age of the building and heavy rainfall
2023	Ansa	detachment of part of the façade and bells	age of the church and heavy rainfall
2022	La Nazione	detachment of part of the façade	/
2023	Il Giorno	detachment of marble slab	/
2022	la Repubblica	church façade collapse	/
2023	Torino Today	falling bricks	/
2023	il Risveglio	detachment of an entire façade	water seepage
2023	Umbria On	detachment of a large portion of the façade	/
2021	Il Messaggero	church façade collapse	/
2023	Salerno Notizie	partial collapse of the façade	strong wind gusts
2023	Corriere del Mezzogiorno	cornice collapse (historic building)	heavy rainfall
2020	Il Mattino	cornice collapse	strong thunderstorm
2023	La Stampa	collapse of cornice and railing	/
2023	Pisa Today	cornice collapse	static disruption
2023	Corriere del Mezzogiorno	cornice stone collapse	old age and deteriorated safety net
2023	Rai News	cornice collapse	/
2022	Il Giorno	cornice collapse	/
2023	Livorno Today	cornice collapse	/
2023	Lecco Today	cornice collapse	/
2023	La Nazione	cornice collapse	/
2023	Chiaro Quotidiano	inner cornice collapse (church)	water seepage
2022	Palermo Today	cornice collapse	age of the building

(*continued*)

Table 1. (*continued*)

Year	Newspaper	Report	Cause of damage
2022	Torino Today	collapse of a long cornice	/
2020	Il Post	cornice collapse	structural failure
2023	Il Giorno	partial collapse of the cornice	/
2023	la Repubblica	unreinforced balcony slab failure	age of the building
2023	Il Gazzettino	collapse of stone patio	/
2023	Notizie Virgilio	failure of marble balcony	/
2021	Il Mattino	marble balcony failure	age of the building
2023	Il Giorno	balcony marble slab collapse	structural failure
2021	Napoli Today	entire balcony collapse	severe weather
2023	Corriere di Saluzzo	a portion of the balcony collapse	/
2023	Lecce Prima	portions of balustrade collapse	/
2023	Roma Today	balcony collapse	/
2022	Palermo Today	breaking of stone balcony shelves	heavy rainfall
2023	La Gazzetta del Mezzogiorno	entire balcony collapse	/
2013	Today Cronaca	entire balcony collapse	/
2009	Il Giornale	collapse of 4 balconies	/
2022	Bari Today	balcony and roof collapse	/
2023	Today Città	collapse of parapet	/
2014	Ansa	entire balcony collapse	lack of maintenance

Source Google, survey December 2023

(trees, lampposts, illuminated signs, and planters) and provisional works (scaffolding), that represent additional hazards if not subject to periodic monitoring and maintenance.

2.2 Comparison of the Analysis Results with Previous Studies

The reports in Table 1 align with the results presented in a study concerning the collapse of technical elements of the façade that occurred in the city of Naples between 2011 and 2020 [7]. The referenced study describes forty-two events, specifying the elements that collapsed, the heights from which they detached, and the resulting damage. The analysis deduced that half of the collapses involved portions of cornices (47%), finishes, and decorative elements of vertical enclosures (31%), specifically the backplane (10%), the stringcourse (8%), corner cornices (8%), and stuccoes and decorations (5%), and portions of plaster on the intrados of balconies (12%), and other elements (e.g., shutters and signs).

One in three collapses resulted in damage to property and/or persons. Four events led to damage to cars and motorbikes, while eight events caused injuries to individuals, primarily to the head (lacerated and contused wounds/head injuries). The two fatalities recorded always involved blows to the head. Concerning fall heights, it is noteworthy that no incidents were reported for the lower part of the buildings—within the first 4 m—and no serious injuries were documented within the initial 10 m. This information is particularly relevant for evaluating the potential hazard posed by façade elements and assessing the associated risk of causing damage and harm to property and individuals.

2.3 The Field Survey

The field survey was conducted by analysing the state of conservation of the building fronts of certain buildings in the Phlegrean area, specifically those directly overlooking the escape routes, as identified in the Civil Protection Plan of the Municipality of Pozzuoli. To compare various multi-risk scenarios, buildings within two different perimeter sub-compartments were considered, based on the "Studio degli scenario di Rischio", conducted in 2017 by the research group of the Department of Civil, Building and Environmental Engineering (DICEA) of the University of Naples Federico II [30] and the subsequent in-depth research carried out in 2022 with the "Gruppo di Lavoro Pozzuoli", in collaboration with the Department of Civil Protection, the Regione Campania, the Municipality of Pozzuoli, the Interdepartmental Study Centre PLINIVS, the National Institute of Geophysics and Volcanology (INGV-OV), the Institute for Electromagnetic Sensing of the Environment (CNR-IREA), the Consortium of the Network of University Laboratories for Seismic and Structural Engineering (RELUIS) and the DICEA of the Federico II [31]. Within the sub-compartments, identified as areas characterised by coeval and similar building types, the building fronts that most closely overhang public roads, and therefore directly impact safety and for which it is considered a priority to initiate punctual survey campaigns, have been identified. The two urban areas analysed are included in Compartment C02—Lungomare and Compartment C05—Solfatara (Fig. 1).

The first urban area analysed, located within Compartment C02—Lungomare, extends over an area between the sea and the upper city which is enclosed, to the west, by Rione Terra and, to the east, by the boundary with the Municipality of Naples. The sub-compartment under study, C02.1, overlooks the portion of Via Napoli occupied by the seafront promenade. Consequently, the area experiences significant vehicular traffic, pedestrian crowds, and various business activities, mainly for catering purposes, with the occupation of public soil contributing to a higher level of exposure to the hazards of falling portions of technical elements from the building front along the street. The urban area is predominantly characterised by a dense agglomerate with 3 $\div$ 4 storeys above ground level for residential use, except for the ground floor which is used for businesses; a mixed construction system, with vertical load-bearing structure in masonry blocks of Neapolitan yellow tuff, and horizontal elements and overhangs mostly constructed in

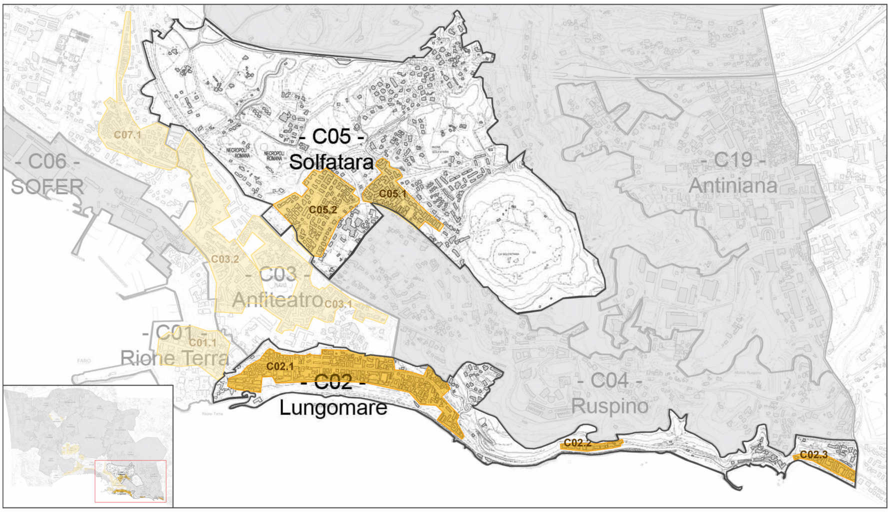

Fig. 1. (down) Boundary of Compartment C02—Lungomare and sub-compartment C02.1; (up) Boundary of Compartment C05—Solfatara and sub-compartments C05.1 and C05.2—© 2022, R. Castelluccio

reinforced concrete with lightening elements; aligned and regular openings; flat roofs (Fig. 1). The "Building Age Map" indicates that the construction of the buildings under analysis dates back to a period before 1964, while the "Building Vulnerability Map" identifies a moderate level of vulnerability for the same sub-compartments [30].

The second urban area under analysis is situated within Compartment C05—Solfatara. The sub-compartments under study, C05.1 and C05.2, overlook the Solfatara area to the east and the archaeological site of interest of the Flavian Amphitheatre to the south, respectively. Due to the area's tourist significance, the presence of key connections and escape routes, the passage of the Cumana railway line, and the high population density, this area is also particularly exposed to Building Risk [1]. The buildings in this urban area mainly consist of $4 \div 5$ storeys above ground level for residential use; reinforced concrete frame construction system; aligned and regular openings; flat roofs (Fig. 2). According to the "Building Age Map" the construction of the buildings along Via Solfatara and the railway axis predominantly dates back to a period before 1964, with some lots dating between 1964 and 1980, while the "Building Vulnerability Map" identifies a high level of vulnerability for both sub-compartments [30]. Both compartments are exposed to the impacts of the Phlaegrean Bradyseism risk scenario, which manifests itself with stresses on the built-up area caused both by soil deformation phenomena, which produce the cyclic uplift and subsidence of foundation soils, and by low-intensity and high-frequency seismic activities, which particularly affect the vulnerability of the technical elements of the envelope.

Sub-compartment C02.1, directly facing the coastal shoreline, is also subject to environmental exposure characterised by chloride attack and wind action. These salts, conveyed by the marine aerosol, are absorbed through capillarity action by the surface layers of the façade construction materials, and crystallise leading to an increase in volume and the formation of efflorescence phenomena, with the subsequent activation of internal tensions in the microcrystalline porous structures, eventually resulting in pulverisation and detachment from the wall supports [32–36].

Sub-compartments C05.1 and C05.2, situated in the proximity of the Solfatara, are subject to environmental exposure characterised by sulphate attack. These salts, transported by water vapour, are absorbed through capillary action by the surface layers of the façade construction materials and deposited in the sub-surface Layers of the finishing components. Similar to the previous scenario, the crystallisation of salts and the chemical-physical interaction with the building materials result in phenomena such as pulverisation, stratified flaking, and detachment from the wall support [32–36]. In addition to these risk scenarios, there is the action of meteorological agents, intensified by climate change.

The field survey phase employed indirect survey techniques, including detailed photographic documentation of the building fronts under investigation (Fig. 2a) and the examination of images from Google Maps (Fig. 2b and c). The second approach allowed for investigation at a closer distance, albeit with a lower degree of definition, the state of conservation of the technical elements of the envelope situated at a higher elevation than the road level, to bypass the interference of trees and elements of street furniture while facilitating a correlation with images from the historical archive to assess the evolution over time of the state of conservation and the highlighted damages.

Fig. 2. **a** and **b** State of preservation of some technical elements in detail, building in sub-compartment C02.1—© 2024, Chierchia C. **c** State of preservation of a building from sub-compartment C02.1—© 2023, Google Maps. **d** State of preservation of a building from sub-compartment C02.1—© 2008, Google Maps

The data collected in the field was implemented with information commonly required for damage investigation sheets compilation (CARTIS and AEDES), leading to the elaboration of an investigation sheet detailing the damaged technical elements, as further described in the Results section (§3).

The field survey covered a total of 65 buildings, each corresponding to a unique sheet drawn up for documentation.

As a result of this survey phase, recurring construction types of the technical elements of the envelope considered most vulnerable were identified; these elements, therefore, contribute with higher relevance in determining the hazard rate for urban systems within the Building Risk assessment [1]: stone balconies with iron struts; laterocemento balconies; balconies with steel girders, hollow core slabs, and reinforced slab on the intrados; stone cornices with plaster cladding; reinforced concrete cornices. For each type, the corresponding construction detail was elaborated, identifying the constituent components, and establishing measurable physical parameters capable of expressing the effects induced by the aggressive actions typical of the context considered.

As an illustrative example, the analytical sheet prepared for concrete balconies with hollow core brick lightweight elements is provided. This construction type has been broken down into the following components: pavement, plastered front edge, concrete cover, hollow core brick, reinforcing bars and balustrade. Table 2 shows the correlation between the components of the technical element and the effects induced by the deformation action and vibrations associated with the Phlegraean Bradyseism phenomena (Table 2).

Table 2. Correlation between the components of the technical element and the effects induced by Phlegraean Bradyseism—© 2023, Cantisani D.

Risk scenario	Phlegraean Bradyseism	
Component	Effect on the element	Parameter describing the effect
PAVEMENT	Cracking and possible detachment	Crack and gap width
PLASTERED FRONT EDGE	Lesions and possible detachments	Lesion and gap width
CONCRETE COVER	Carbonation; cracking and possible detachments	Matrix PH; crack and gap width
HOLLOW CORE BRICK	Spalling of the intrados	Percentage of extension
REINFORCING BARS	Oxidation	Reduction of the resistant section
BALAUSTRADE	Weakening of the support around the anchorage; punching of the uprights in relation to the top transoms	Relative displacements of the strut in relation to the support e of the upright in relation to the transom

In Table 3, the effects on the same components induced by the risk scenarios involving exposure to marine chlorides and sulphates are reported. In this case, the information has been consolidated, considering that, despite the differing aggressiveness of the two salts, the parameters describing their effects remain the same (Table 3).

Under the influence of the Phlegraean Bradyseism, the pavement may exhibit cracking, while the plastered facade could detach. The incidence of such effects can be assessed by measuring the extent of cracks and lesions.

In the case of chloride and/or sulphate attack, both components may manifest the formation of surface and sub-surface efflorescence. The incidence of such effects can be assessed by measuring the extent of the degradation phenomenon and, for the plastered façade, further investigation using non-invasive thermographic diagnostic tools can be employed to determine detaching portions by measuring changes in surface temperatures. Regarding the concrete cover, the most concerning degradation effect in the

Table 3. Correlation between the components of the technical element and the effects induced by Phlegraean Bradyseism—© 2023, Cantisani D

Risk scenario	Exposure to marine chlorides and sulphates	
Component	Effect on the element	Parameter describing the effect
PAVEMENT	Chromatic alteration and/or superficial and sub-superficial efflorescence	Percentage of extension
PLASTERED FRONT EDGE	Superficial and sub-superficial efflorescence	Surface temperature variation
CONCRETE COVER	Carbonation	Variation in the pH of the cement matrix
HOLLOW CORE BRICK	Spalling of the intrados	Percentage of extension
REINFORCING BARS	Oxidation	Reduction of the resistant section
BALAUSTRADE	Oxidation	Reduction of the resistant section

analysed risk scenarios is the manifestation of carbonation phenomena, leading to cracking of the cementitious matrix, loss of adhesion with reinforcing bars, and oxidation of the bars themselves. The incidence of these effects can be assessed by evaluating the carbonated portions, utilising the phenolphthalein colourimetric test and, for reinforcing bars, by measuring the reduction of the resistant sections.

Within the considered risk scenarios, the hollow core brick may undergo breakthrough phenomena caused by both the vibrations induced by the Bradyseism and by the loss of adhesion with the cementitious matrices due to the formation of efflorescence and saline sub-florescence. Additionally, for the iron balustrade, weakening phenomena may become evident in the connection between the uprights and the cantilever, or between the stringers and the wall support. The subsultory component of these stresses, moreover, may lead to the puncturing of the upright with respect to the transom, resulting in a weakening of the bond. Exposure to chlorides and/or sulphates leads to oxidation phenomena of the balustrade, leading to a loss of resistant section. Therefore, the incidence of these effects can be assessed by measuring the extent of degradation phenomena and, where present, the reduction of metal sections.

3 Results

The data collected during the surveys were organised into an investigation sheet for damaged technical elements (Fig. 3). The sheet is configured as a 2nd level one (§1.2), focusing on surveying individual buildings rather than homogeneous complexes. It is structured in a digital format for interactive completion. The form is divided into four sections, and the contents of each section are described below. In Fig. 3, to facilitate the understanding of the specific compilation process for Sect. 3, an example is provided, hypothetically referring to the technical element “balcony” with reinforced concrete construction type and hollow core bricks as lightning elements.

Section 1, “Building system identification” aims to identify the building by information regarding the Province, Municipality, and the Sub-compartment to which it belongs. It also provides details on its location, graphically displayed with satellite coordinates using the interactive features of the sheet.

Section 2, “Building system description” gathers data useful for characterising the building, including the “Number of storeys” (above ground and underground floor); values of “Average storey height” and “Average ground floor height” presented in bands; the “Construction type” related to the Class of technological units “Load-bearing structure” [31]; and the “Intended use”. The section is complemented by an initial image of the surveyed building, providing an overview.

Section 3, “Damage to the technical elements of the building envelope”, is intended to collect all the necessary information for assessing the damage to the technical elements of the envelope and the hazard scenarios in which it is embedded. The required data refer to “apparent” damage, i.e., damage identified through an expeditious survey carried out by direct observation at the time of the inspection.

The first part focuses on including detailed images of the technical elements surveyed along with their anomalies. Building upon the information gathered in the first phase of the methodology (*§*2.1), the technical elements of the envelope considered in this section are the clad or plastered external partitions, balconies, and cornices.

The second part features a drop-down menu, allowing the sequential selection of individual elements surveyed and, for each of them, the option to associate the collected data with one or more of its components is provided. In the example case, the menu enables the selection of the components into which the balcony under consideration can be decomposed, by choosing from: pavement, front edge, concrete cover, hollow core brick, reinforcing bars and balustrade (*§*2.3).

Subsequently, data are given regarding the identified type of damage, with a specific characterisation of their addressed “level”, indicated with a numerical index from 1 to 5 depending on severity, and extent, understood as the percentage of damaged surface compared to intact surface. The example illustrates the most recurrent types of damage observed during the field survey described in phase *§*2.3 of the methodology. A section dedicated to “notes” is also proposed, allowing the description of degradation conditions or particular risk factors observed; the inability to detect some elements or parts thereof; and the presence of any provisional works (such as green safety nets).

The last section of the sheet, “State of conservation over time”, provides images of the building referring to previous years, obtained using online mapping and navigation services (e.g., Google Street View) or by consulting other types of available historical photo archives. The purpose of this section is to assess the evolution over time of the state of conservation of the technical elements surveyed and, consequently, of the related facades.

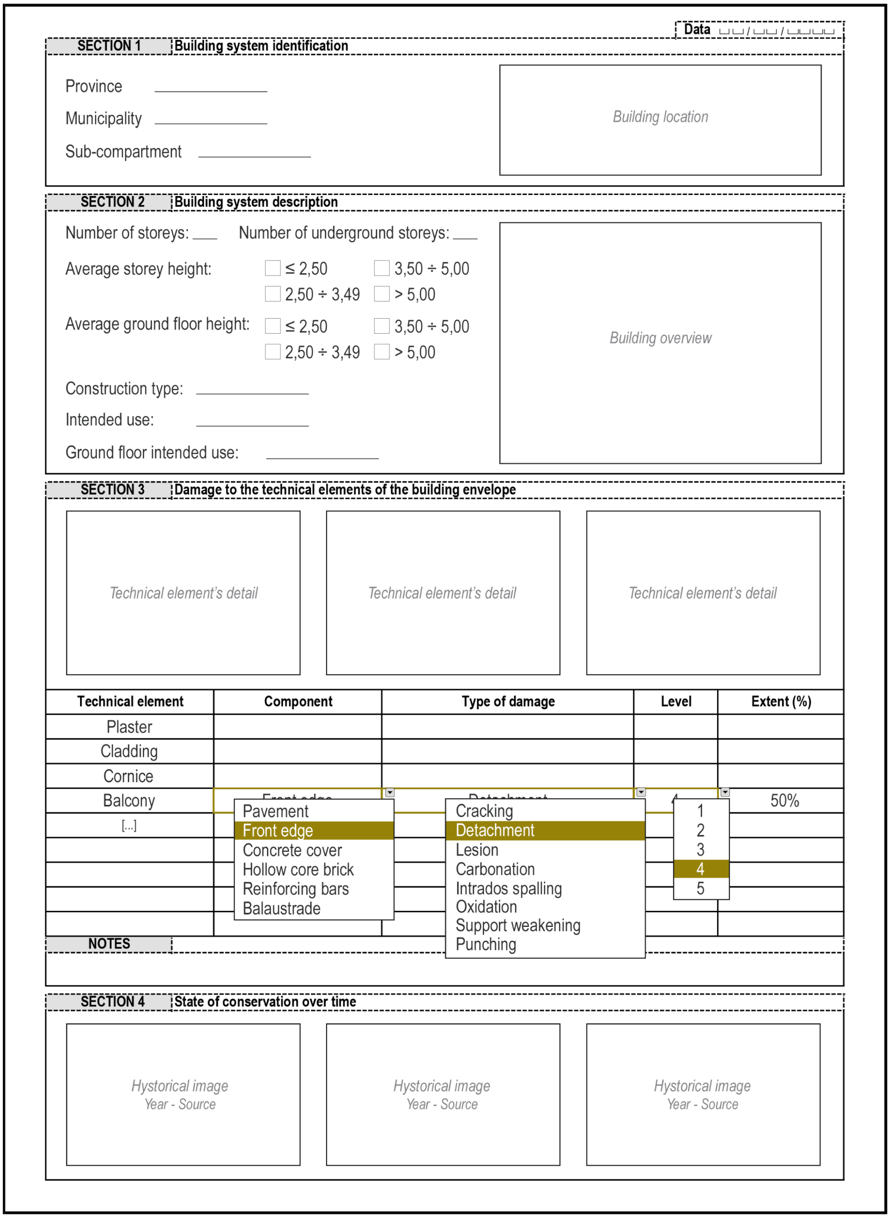

Fig. 3. Damage investigation sheets for the technical elements of the building envelope. Section 3 presents an illustrative example of a possible compilation for the technical element "balcony", with reinforced concrete construction type and brick lightening elements—© 2024, Authors

3.1 Discussion

A comparison of the field survey results of the damage in the two sub-compartments reveals a higher incidence of certain hazards compared to others. Notably, in both sub-compartments, the projecting elements (balconies and cornices) are the most damaged technical elements of the envelope. These elements suffer from the subsurface stress due to Bradyseism, showing almost similar intensity in both contexts. Common occurrences include frequent detachments of plaster and concrete cover at the intrados and front edge of balconies, as well as at the intrados of cornices, leading to the consequent exposure of reinforcing bars.

On the contrary, the aggressive impact of environmental exposure is more pronounced in the marine context compared to the Solfatara area. In the "Lungomare" sub-compartment, there is a more widespread occurrence of plaster degradation phenomena, including detachment from the wall supports, compared to what emerges from the analysis of buildings in the "Solfatara" sub-compartment.

The integration of the information gathered in the damage inspection sheet, along with the detailed analysis of cause-and-effect relationships processed using the queries described in Tables 2 and 3, provides a simplified method for quantifying the extent and severity of the observed degradation phenomena. This information serves as the basis for evaluating the consistency of the façade, the vulnerability of technical elements to a defined system of hazards, and the rate of danger they pose to the relevant urban environment.

4 Conclusions and Future Developments

The paper proposes an inspection sheet for damaged technical elements as a preliminary step in assessing the vulnerability of the technical elements of the envelope in a given multi-risk scenario. The information collected expeditiously can serve as guidance for subsequent in-depth surveys and diagnoses aimed at elaborating maps of building consistency, vulnerability, and hazards for the relevant urban system.

The applicability of the sheet has been tested on real case studies. Surveys conducted in the Phlegrean area (§2.3), regarding the "Lungomare" and "Solfatara" sub-compartments revealed the most frequently damaged elements, such as: cornices, balconies, finishing elements, and infill claddings.

The sheets are structured to find a balance between the level of detail needed for analysis and the time required for completion. Additional information on the characteristics and location of individual elements would enhance the assessment of the risk associated with the façade, but these details are not currently considered to expedite the investigation.

Future research developments aim to expand data collection and correlate knowledge of the state of damage to the vulnerability of the elements of the envelope. In this perspective, the survey of degradation becomes instrumental in assessing the likelihood that an element may collapse and detach from the façade following the occurrence of an exogenous event. Information related to the heights of the elements will contribute to the assessment of damage associated with severe falling from the façade, while information concerning uses will help understand the exposure of people to this hazard. Through the integration of hazards, vulnerability, and exposure parameters, the determination of the rate of Building Risk to which urban systems are exposed will be derived.

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