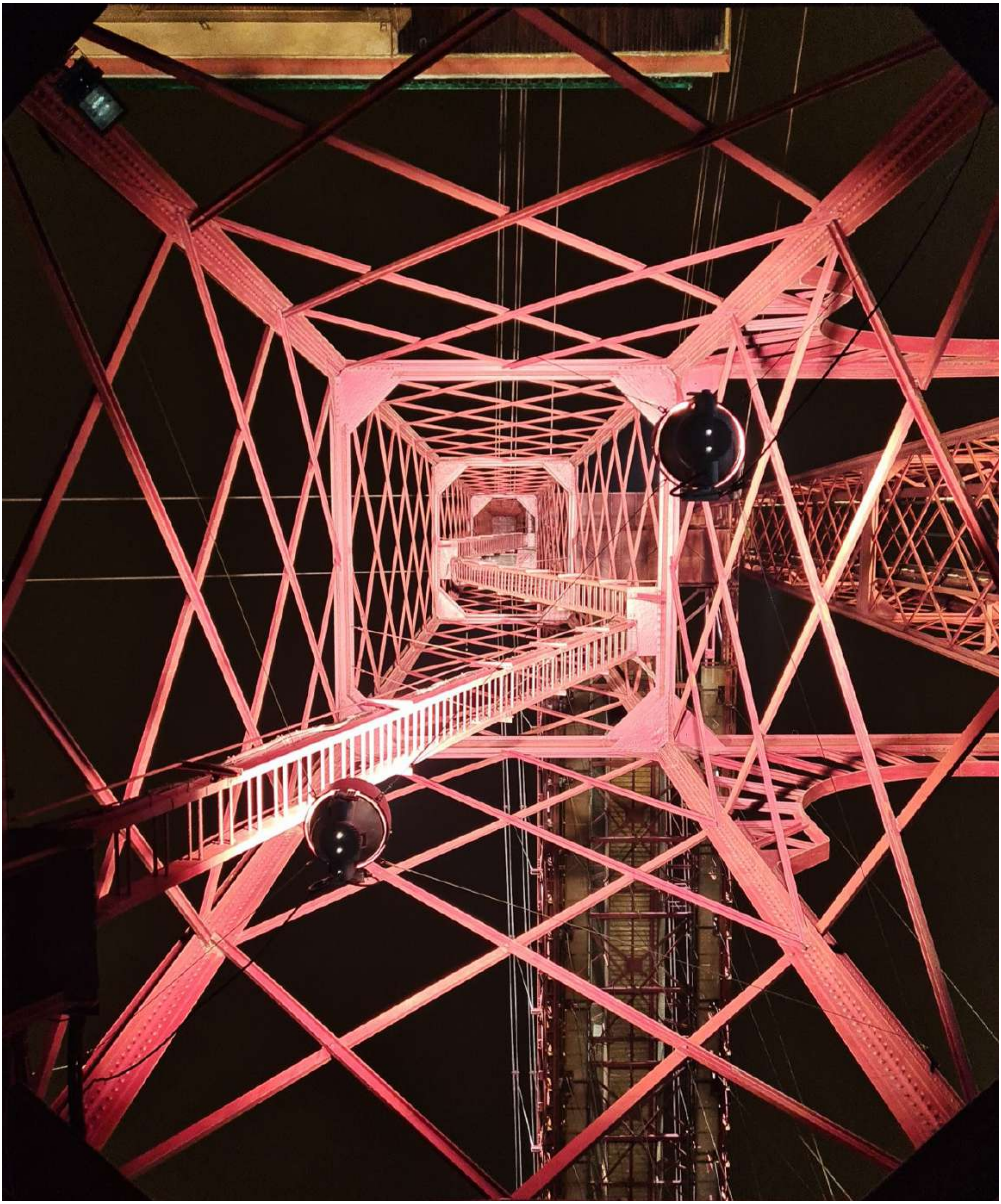

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EDITORIAL

RESEARCH PERSPECTIVES IN THE DOMAIN OF THE BUILT ENVIRONMENT

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This Issue presents research contributions from seven Italian university groups: Ancona, Bari, Bologna, Catania, Messina, Sapienza Rome, and Salerno. Two primary criteria marked the selection process. The first one concerns adherence to the themes represented by the three main sections of the Journal: 1) Construction history and preservation; 2) Construction and building performance; 3) Building and design technologies. The second one regards the scientific approach adopted by the researchers based on a two-way relationship between theory and practice. This correspondence concerns both methods and tools, ranging from historical and process issues to experimental testing.

The first cluster can be identified for papers presented by the researchers of the University of Bari (De Fino M., Fatiguso F., *Brick masonry staircases of the early 20th century: historical research, condition assessment and diagnostic investigation of a "transition" construction type*), the Sapienza University of Rome (Ferrero M., Arena G., Ciardiello A., Rosso F., *The marble envelope of the* Casa delle Armi *by Luigi Moretti: documentary and experimental knowledge finalized to digital modeling*), and the University of Messina (Lione R., Fiandaca O., Minutoli F., Cernaro A., Palmero L.M., *The disused precious stone elements are not CDWaste. A digital management chain to save them*). These three papers follow the same way to combine historical investigation with diagnostic and process analysis finalized to safeguard the studied artifact. In the first case, the object of interest is represented by the masonry staircases from the early 20th century in central-southern Italy, while the other two contributions focus on stone cladding from the 1920s-1930s Italian architecture. The leading feature of these three works is the importance credited to the knowledge of the object, that is the prerequisite for deriving the methods and aims of the investigation: instrumental, in the case of the Bari research group; procedural and related to the use of digital Historical Building Information Modeling (HBIM), in the other two cases.

The second type of study is oriented to investigate the redevelopment and enhancement of existing heritage, from the urban to the building scale. The works presented by the researchers of the University of Salerno (D'Andria E., Fiore P., Sicignano E., *Proposal for a new housing model for the inland areas regeneration. The BioVillage 4.0*) and the University of Bologna (Dragonetti L., Prati D., Ferrante A., *Impact of modelling on the assessment of energy performance in existing buildings: the case of Concordia Sagittaria*) belong to this domain. For the Salerno research group, the focus is the preservation of the historic village's identity and possible strategies for their re-functionalization; in the case of Bologna, the aim is the expeditious analysis methods for energy savings of the residential building stock. In both cases, the inquiry includes the topic of the active participation of inhabitants in defining design choices.

Finally, the four contributions presented by the University of Catania (Vitale M., Cascone S.M., *Orange peels as a potential ecological thermal insulation material for building application*; Tardo C., Margani G., *Technological analysis of a prefabricated timber-based system for the integrated renovation of RC framed buildings*; Monteleone A., Rodonò G., Gagliano A., Sapienza V., *SLICE - Solar Lightweight Intelligent Component for Envelopes: application for the ICARO pavilion*) and the University of Ancona (Marchione F., Agliata R., Munafò

P., *Application of adhesive technology to a new type of glazed panel for curtain walls with an integrated frame*) deal with the experimentation of innovative building systems and components in terms of theoretical investigation and experimental testing. The *trait d'union* of these research works can be identified in environmental impacts and structural safety, from the scale of buildings to that of materials. Indeed, this scaling dimension, framed within the broad domain of the built environment, constitutes the focus of the TEMA Journal, as a bridge between the two worlds of Construction Engineering and Architecture. This vision embraces the complex and multi-sectoral dimension of knowledge, from objects to processes, including digital ones.

PROPOSAL FOR A NEW HOUSING MODEL FOR THE INLAND AREAS REGENERATION. THE BIOVILLAGE 4.0

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Abstract

In addition to cities and metropolises, the European territory is made up of many small settlements, custodians of a vast material and immaterial heritage, very often of great historical, cultural and environmental value. In recent decades, these realities have undergone a significant demographic decline induced by the new requirements of contemporary life: the lack of job opportunities, inadequate infrastructure, and poor essential services have encouraged the population to move to the cities, starting a process of social, cultural and economic marginalisation of rural areas. However, the current environmental crisis and the problems of urban densification are encouraging the birth of a "new perspective" that considers the enhancement of inland areas and small towns as a possible driver for the sustainable development of territories and the definition of a new city-countryside relationship. Therefore, recovering inland areas is becoming an increasingly important necessity, which is leading to the drafting of many plans and interventions aimed at reversing the demographic decline trend. Among the most representative projects, two European strategies are based on the Ecovillage and Smart Villages models. Both models emphasise the role of local communities in deciding what action should be carried out to valorise small towns. However, the modalities and nature of the interventions and their methodological approach are substantially different.
In view of the above, and starting from the analysis of some emblematic case studies, the paper investigates the peculiarities of the Ecovillage and Smart Villages models, with the aim of highlighting their main criticalities and potentials. From the comparison between the two strategies, a new model for the recovery and valorisation of small towns is proposed, which is called BioVillage 4.0.

Keywords

Inner areas, Small towns, Smart Villages, Ecovillages, New regeneration model.

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1. INTRODUCTION

In recent decades, the changing housing and economic needs have favoured the demographic decline in small centres of inland areas which, from being key elements in the territorial organisation, have become "marginal" places. The main causes are the lack of job opportunities, the absence of adequate infrastructure and services, and the distance from urban centres, which have led to the rapid degradation of the local tangible and intangible heritage. Today, the environmental crisis and the current health emergency have encouraged a reconsideration of the role of inland areas, the enhancement of which can promote the sustainable development of territories, rebuilding the lost balance between man and nature and the reciprocal relationship between town and countryside. It is now a consolidated idea that small towns can represent valid alternatives to the models of living in cities and metropolises because they are characterised by healthier rhythms and lifestyles and offer a more organic distribution of anthropic activities throughout the territory. Moreover, these small realities host a vast cultural heritage, a palimpsest of collective identities and memories, which needs to be preserved as a still tangible testimony of the different Countries' history. In order to achieve this, it is essential to set up intervention models that assess issues linked not only to the new possibilities offered by digital technology but also to local traditions, territories' productive vocations, environmental protection, job opportunities for young people, services supply, etc. [1].

Based on these considerations, the paper deals with the issue of small towns regeneration, proposing the characterisation of a new housing model in the light of two strategies adopted in Europe. The contribution is structured in four sections: 1) a general overview of the actions implemented in Europe, with particular attention to the Ecovillage and Smart Villages models; 2) a comparison between the two models previously analysed, highlighting their criticalities and potentials; 3) proposal of an innovative valorisation model, resulting from the critical analysis of the strengths and weaknesses of both Ecovillage and Smart Villages; 4) conclusions that summarise what has been presented, outlining research developments.

2. STRATEGIES FOR THE VALORISATION OF RURAL VILLAGES

In recent years, Europe has been considering the role and potential of inland areas and small towns, proposing several models for their regeneration. Among these, there are: the Bioenergy Villages project, developed in Germany and based on the use of renewable sources for energy independence; the *Albergo Diffuso* (Widespread hotel), born in Italy in 2004 with the aim of reconverting villages into innovative accommodation structures, extended to the entire historic centre; the *Borgo dell'accoglienza* (Welcoming village) designed to host and integrate immigrants from different countries; etc. [2]. What is striking about some of these initiatives is the thematic specificity of the interventions. In fact, each project focuses on a single field of action, with aims that involve distinctly individual issues: social, cultural or environmental. Moreover, in most cases, these strategies are "imposed" from the top, without a proper "recognition" phase of the places and their vocations. The result is often not as successful as expected: funds are spent without looking at the real problems of the territories, leading to dissatisfaction with what has been achieved, especially by local communities.

2.1. THE ECOVILLAGE MODEL: PRINCIPLES AND BEST PRACTICES

Among the strategies for enhancing and recovering small towns, the Ecovillage model is particularly significant. It stems from the studies [3–7] on the utopian city developed from the 16th century onwards, which saw collective wellbeing and cooperation between the inhabitants as the key elements for the development of a balanced and happy reality [8]. In parallel with these theories, considerations on the urban layout of the ideal city also emerged, which, in its formal evolution, acquired increasingly geometric and regular features [9].

This long process of theoretical, experimental and empirical studies is linked to the Ecovillage model, which adopts the paradigms of the utopian city, reworking them in a contemporary way with the influence of other theories and cultural movements, mostly oriental. In fact, even before the definition of a univocal and shared terminology of "Ecovillage" [10], the concept of "eco-sustainable community" was already hinged on the studies of the Indian philosopher Sri Aurobindo and the Frenchwoman Mirra Alfassa. The latter, in particular, in 1968, founded the "experimental city" of Auroville, India, with the aim of setting up a "universal city" based on hospitality and inclusion [11].

A significant turning point came in 1991, with the founding of the Global Ecovillage Network (GEN): an international network of ecovillages aimed at supporting and encouraging the evolution of sustainable settlements around the world through cooperation and sharing of experiences. The GEN states that the Ecovillage model is characterised by three main elements: intentionality (i.e., the conscious choice made by each inhabitant when choosing to live in a community with shared ideals), eco-sustainability (i.e., the adoption of low environmental impact lifestyles) and sharing (i.e., the communion of many services and earnings). Furthermore, the different realities can actively engage in agriculture, sustainable resource management and green building [12]. With regard to this last point, the Ecovillage model has developed, over time, two different intervention approaches. The first concerns the construction of new buildings; the second relates to the ecological recovery and reuse of the existing building stock. In this last case, a significant example is that of Torri Superiore, an Italian village recovered in 1983 by two private owners. The aim was to revitalise the old settlement and establish a new community based on the values of eco-sustainability, mutual respect and harmony [13]. To date, about 90% of the buildings in Torri Superiore have been recovered. Thus, dwellings and cultural, production and catering centres were created. All the interventions carried out – in many cases by the inhabitants themselves – have been particularly careful with the existing buildings, respecting the formal structure of the built heritage as well as the typological-constructive characteristics. The materials and technological solutions used are in line with the principles of eco-sustainability, exploiting local resources and renewable energy sources [14].

A different experience is that of the sustainable village of Agios, on the Greek island of Evia, where the Telaithrion project was launched in 2010 to establish a self-managed community that shares the ideals of solidarity, ecology and essentiality. Compared to what was done in Torri Superiori, in this small settlement, the houses were built from the beginning according to the local building tradition, which sees the *yurt* as a distinctive element, characterised by a circular plan and a removable and mobile structure. In fact, the *yurt*'s "foundation" usually consists of a wooden platform, on which a floor made of wooden boards is placed. The load-bearing structure is made up of wooden pillars, while the perimeter closures have different layers, characterised by a rhomboid wooden mesh, on which a cotton cloth, an insulating felt and a waterproof film are overlaid. Permaculture techniques – i.e., ecological methods applied to agricultural production systems aimed at preserving natural ecosystems – are used to manage all agricultural production, and there are courses in land rehabilitation and houses self-building.

The topic of "self-building" is a key element of the Ecovillage model. It concerns not only European examples (such as those already described), but also South American ecological villages. One example is the Argentinian village of Gaia, located near the city of Navarro. Set up by the Gaia Association in 1996, the village covers about 20 hectares of land, most of which is dedicated to permaculture activities while the other part is used for the houses, some of which are newly built, others recovered. The building technique used is that of the traditional *adobe*, i.e. bricks made from a mixture of sand, clay and dried straw, which is highly ecological and has a low environmental and landscape impact. The load-bearing structure is made of wood, while the curtain walls are made of *adobe* bricks, finished on the outside with a layer of slaked lime mixed with clay. As regards the principles of community life, they are perfectly in line with those already present in the villages of Agios and Torri Superiore, i.e. sharing, self-sufficiency and ecology [15].

2.2. EUROPEAN SMART VILLAGES

Another model, particularly prevalent in Europe, is that of "Smart Villages". Although the origin of the Smart Village concept dates back to 2014, when a few initiatives were implemented in Africa and Asia, in Europe, it emerged in 2016, when a number of stakeholders from rural contexts met in Cork to draw up the main development guidelines for inland areas and small towns [16]. In the light of the considerations raised during this event, in 2017, the European Commission presented the document *EU Action for Smart Villages*, in which it provided the first definition of "Smart Villages". This definition describes Smart Villages as «rural areas and communities which build on their existing strengths and assets as well as on developing new opportunities. In Smart Villages, traditional and new networks and services are enhanced by means of digital, telecommunication technologies, innovations and the better use of knowledge for the benefit of inhabitants and businesses […]. The concept of Smart Villages does not propose a one-size-fits-all solution. It is territorially sensitive, based on the needs and potentials of the respective territory and strategy-led, supported by new or existing territorial strategies» [17, p. 3]. The EU Action aims to improve the quality of life in rural areas in order to tackle their increasing depopulation by coordinating a series of actions related to different EU policies, such as rural and regional development, mobility, renewable energy and ICT. In this regard, the document includes the Pilot Project Smart eco-social villages (later shortened to "Smart Villages") among the concrete actions for promoting and supporting the establishment of "smart" communities and small towns. Within this project, in 2018, two online consultations, accompanied by expert workshops, took place, which led to the modification of the previous definition of "Smart Villages" into «communities in rural areas that use innovative solutions to improve their resilience building on local strengths and opportunities. They rely on a participatory approach to develop and implement their strategy to improve their economic, social and/or environmental conditions, in particular by mobilising solutions offered by digital technologies. Smart Villages benefit from cooperation and alliances with other communities and actors in rural and urban areas» [18, p. 60].

In this framework, a key role is played by the European *Network for Rural Development* (ENRD) which, in 2018, established a working group on the topic of smart municipalities (the Thematic Group on Smart Villages). In addition, ENRD included the pilot project, called Smart Village, in the European programme Smart and Competitive Rural Areas. The idea is that of developing proposals and disseminating good practices by creating an open-access platform [19].

To date, there are many examples of "smart" projects that have been implemented, and, for this reason, the ENRD Thematic Group has divided the different initiatives into seven macro areas: Multiservices Hubs; Digital and ICT; Energy and Environment; Mobility; Health and Social care; Education; Culture and Tourism [20]. In each sector, targeted interventions are reported, including the Finnish project "Village Shop: A Meeting Point Of Private And Public Services", which, as part of the "Multiservice Hubs" macro area, involved 12 villages with the aim of innovating the traditional "village shop" by including multiple functions and services, both for residents and tourists.

For the Digital and ICT sector, an interesting example is the Incubating Technological Innovations in Dieuze, which is inserted in the French regional strategy Saulnois Innovation. The project aims to implement social and digital innovation to promote local entrepreneurship and employment. Currently, three lines of action are being developed: *Digital services*, which includes initiatives such as the Smart City Rural and the Lorraine Fab Living Lab; *Renewable energy* with the BioMethane action SAS Seille Environment; *Agro-industrial production*, in which the University of Lorraine drew up projects that are being carried out.

Germany is also developing innovative actions closely linked to the use of digital technology. This is the case of the Smart Countryside Lippe/Höxter initiative aimed at implementing basic services in 16 villages and promoting digital education in a further 26 municipalities. All interventions are decided by/with residents, favouring bottom-up participatory processes. The results saw the creation of a number of digital products: the Digital Village Platform, on which it is possible to order local food and other products, to access news or announcements about events; the "Caring Village", a service dedicated to volunteering; the "Faith Platform", intended for the organisation of religious life; the "Living Platform", for the "smart house"; and the "Digital Education", specifically for training, conferences and cultural activities [21].

3. THE TWO MODELS IN COMPARISON: STRENGTHS AND WEAKNESSES

From the experiences summarised in the previous paragraphs, it is possible to outline both analysed models' main strengths and weaknesses.

With regard to the Ecovillage, the first and crucial strength is the sense of community and sharing of the initiatives promoted by the model. This prerogative, if effectively managed, is a winning element in the enhancement of small towns, as the sense of belonging, closely related to the presence of common values and ideals, induces and motivates the preservation of local identities, producing development.

Another key factor is the "self-building practice", which is implemented not only for the reuse of existing architectural artefacts but also for the construction of new buildings. In both cases, this practice uses environmentally friendly materials and easily removable construction/recovery solutions. In particular, the reuse of the built heritage testifies the model's attention to the reduction of land consumption and the preservation of local morphological and typological-constructive characteristics. All this is supported by the respect for nature, tangible in the ways of cultivating the land, based mainly on the practices of permaculture, co-farming and self-sufficiency. In addition, there is the adoption of clean and renewable energy sources, which, combined with common service areas, guarantee significant economic savings. Also interesting is the joint education of the youngest and the shared care of the elderly. However, it has to be said that, in some cases, the application of the model has led to "closed" realities, with self-referred communities that are not inclined to accept new residents. In addition, the principles of sharing, proximity, self-sufficiency and self-management often give rise to decision-making differences as well as uncomfortable and tiring lifestyles. This is compounded by the lack of use of innovative technologies, which would improve the quality of life, involving both social issues, such as upgrading services, and economic ones, such as developing production activities.

As in the Ecovillage, the analysis of the Smart Villages model highlighted the decisive role of the population in the choice of the valorisation actions that need to be undertaken. Although in both models, the conception, definition and implementation of any intervention are established with local communities, the nature of this participation is different. A first gap can be seen in the fact that, in the Ecovillage, the inhabitants consciously choose to move to a specific place, creating a new reality. In the Smart Village, it is the resident population that takes action to create a "smart" change. This triggers an initial awareness among residents, which, however, results in mostly "narrow" solutions related to one single issue or field of action. Very often, in fact, the outcome of the collected ideas takes the form of mobile phone applications to menage services, the installation of digital connections for first aid, and the technological-digital upgrading of education and mobility. One of the strengths of Smart Villages is the use of innovative technologies to improve the quality of life and the attractiveness and knowledge of territories. It has to be said that this advantage, while on the one hand providing the opportunity to accelerate any development choice, on the other hand, requires the population to be continuously updated on the latest IT/technological possibilities. Also important is the opportunity to establish reciprocal and cooperative relationships between several public authorities or between public and private entities in order to optimise both the allocation of funding and the management of services and infrastructure. Nevertheless, it often happens that in the concrete implementation of such collaborations, conflicts arise between the different administrations or stakeholders involved. In addition to this, the costs of the interventions to be carried out (e.g., large-scale upgrading of digital connections and home automation) are usually higher than those realised in an Ecovillage, where most of the actions are self-made and therefore financially sustainable.

In the light of these considerations, Table 1 summarises the main potentials and criticalities of both models.

	ECOVILLAGE	*SMART VILLAGE*
Strengths	Strong sense of belonging and community	Bottom-up participatory processes
	Recovery of the existing built heritage	Awareness of the community about the potentials and criticalities of its territory – "Places awareness"
	Use of materials, technologies and design solutions compatible with existing architecture and environment	Active communities aimed at spontaneously identifying local needs, rather than simply chasing available funding
	Use of eco-friendly materials	Use of digital technologies
	Bioclimatic and self-built architecture	Use of energy from renewable sources
	Recovery of traditional activities	Development of local enterprises
	Self-management	Public-private partnerships
	Use of energy from renewable sources	Inter-municipal management of basic services
	Energy saving	Recovery of the existing built heritage
	Consortia for the management and coordination of common services	Accelerating development choices
	Contact with nature	
	Adoption of permaculture practices	
	Adherence to common values and ideals	
	Priority of community interests over those of the individual	
Weaknesses	Tendency to ghettoisation	Mostly "sectoral" interventions
	Difficulties in integrating into the community	Constant updating of the population on new development possibilities and new technologies
	Internal conflicts in community life	Risk of knowledge loss of the most appropriate enhancement goals for the local resources
	Difficulties arising from practising agriculture in a mostly archaic way	Conflicts between the different administrations or stakeholders
	Discomfort due to the lifestyle	Higher implementation/adaptation costs
	Lack of use of innovative technologies	

Tab. 1. *Strengths and weaknesses of the Ecovillage and Smart Villages models.*

4. AN INNOVATIVE REGENERATION MODEL: THE BIOVILLAGE 4.0

In view of the above, it is clear that both of the analysed models, although widely used, are characterised by a number of critical points: on the one hand, the difficulty of finding a broad consensus within the communities involved in the definition of the actions to be implemented; on the other hand, the need to adopt organic strategies that contemplate systematic interventions in several areas (social, economic, environmental, cultural). It is often the case that, in order to respond to a problem that emerges most strongly, other needs are neglected, which, over time, may acquire greater importance and become real barriers to the development of places. Therefore, it seems useful to structure a model which, based on a careful analysis of the experiences already carried out, highlights their strengths, critically reviewing the actions and detecting the achieved targets. In this sense, it is essential to preserve the community policy of the Ecovillage, together with the co-design process typical of Smart Villages. The population's active participation, well-informed and ready for change, is the starting point for offering real growth prospects. From this awareness, the BioVillage 4.0 model takes form, which, referring to the Ecovillage and Smart Villages models, is characterised by the union of their strengths, thus capturing their potentials and neglecting their disadvantages, as summarised in the following graph (Fig. 1).

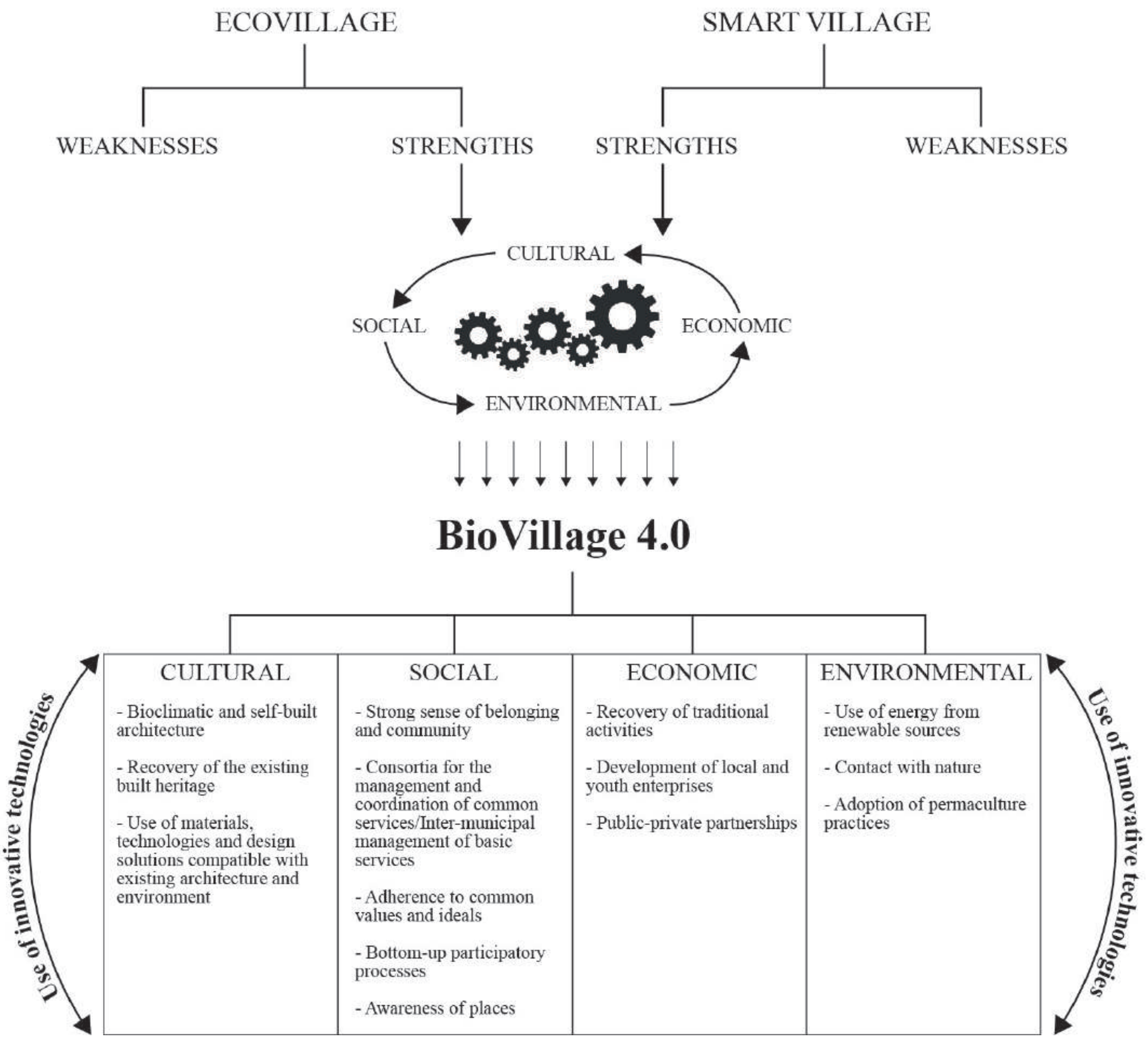

Fig. 1. *Characterisation of the BioVillage 4.0 model.*

The community value, rooted in the link with places, is an essential element of the model to be considered a priority because it is a key component in rebuilding local identities and a sense of belonging. Thus, BioVillage 4.0 starts with a "shared approach", whereby residents work together to achieve common goals. Furthermore, in considering the cornerstones of sustainable development, it seems significant to refer also to the ideals of ecology and low environmental impact typical of the Ecovillage. In this respect, this model includes the use of renewable energy and the reuse of existing buildings to ensure less land consumption. Hence the concept of self-building is valid for both architectural recovery and new constructions. With regard to the first action, special attention is given to the reversibility of the interventions, i.e. the possibility of restoring the original state of the building at any time. The materials used for recovery must be local, highly ecological and recyclable. The respect and preservation of the typological-constructive and formal characteristics of the architectural artefact are essential prerogatives for any type of operation. Even in the case of new constructions, the BioVillage 4.0 model includes buildings made with local materials and construction techniques. In addition, the model is based on the willingness to build new development scenarios starting from young people, directing funding towards the creation of new enterprises and start-ups aimed at testing the combination of traditional practices and digital systems. In particular, the latter can be an integral part of any activity involving the service sector (health, education, mobility) and the production one (agriculture, crafts, etc.), inspired by the Industry 4.0 principles. Innovative technologies can also be used in the residential field, providing home automation and "smart house" solutions. At the same time, it is essential to invest in the generation of renewable energy, both for productive and domestic use.

All the prerogatives described so far outline the layout of the new valorisation model, based on the most relevant elements of the two examined strategies, structured and organised according to the principles of sustainable development. The methodological approach of the BioVillage 4.0 starts by considering the state of places, collecting, both through archival sources and with the help of specific living labs with stakeholders, all the data necessary to build the profile of opportunities and needs to be assessed. Therefore, the model's methodological process can be outlined in 5 steps:

- data collection (direct and indirect sources, living labs, listening and participation workshops, etc.);
- re-elaboration of the collected information, useful for framing problems, needs, potentials, shared imaginaries, collective development trends;
- definition of intervention fields and related funding;
- choice of organic actions working in the selected fields;
- implementation of the identified projects in some pilot areas, with the support and collaboration of local enterprises and cooperatives.

5. CONCLUSIONS

For many centuries, small towns in Europe's inland areas played a crucial role in the organisation of territories, representing the main defensive bastions and strategic nodes of economic exchange. With the industrialisation processes of the 19th and 20th centuries, the *exodus* from the countryside to the cities became significant, intensifying especially in recent decades, with the manifestation of a considerable demographic decline in inland areas, induced by the new demands of contemporary living. However, more recently, the problems linked to climate change and the increased awareness of health and hygiene issues (see Covid-19 pandemic) have led to a rethinking of man's position on the territory in view of new settlement balances. In this context, small towns in wider areas play a key role, as they are extremely livable, located in places with large green spaces and high environmental quality. Therefore, there is no doubt about the importance of protecting and safeguarding these realities, which are crucial for rebuilding balanced and fair territorial scenarios. For this reason, the European Union and part of the scientific world and institutions are implementing actions and plans aimed at enhancing the inland areas, with a view to protecting resources and promoting the territories' development. A variety of strategies have been adopted, but what emerges is the widespread difficulty in undertaking organic and structured intervention approaches [22]. The need arises to "rethink" places through the ideas of those who live there, equipping them to achieve what they really envisage. This is the premise behind the BioVillage 4.0 model, which establishes resident listening as the starting point for an effective growth strategy. This concept, taken in part from the Smart Villages approach, is integrated here since it is related to the Ecovillage concept of "community making". In fact, the copresence of the listening and community-generating needs leads the inhabitants to "recognise the places" and rebuild their local identities to provide solutions that fully meet their aspirations while overcoming divergent opinions and internal conflicts. Furthermore, there is the need expressed by the model to investigate the reasons behind the depopulation of each specific case, starting from the idea that in order to plan well for the rebirth, it is necessary to understand the decline. In this scenario, the role of new technologies is crucial because, if intelligently addressed, they can be the bridge between the past material and immaterial heritage and the modernity requirements.

In the light of these considerations, the work analysed two emblematic models for the valorisation of small towns, highlighting their potential in order to use them in the characterisation of a new approach: the BioVillage 4.0. This latter, building on the strengths of Smart Villages and Ecovillage and taking into account the sustainability principles, considers the co-design processes and the building of resilient and equitable communities as key elements. Research developments, which are currently being defined, will concern the improvement of the model and its application to case studies.

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BRICK MASONRY STAIRCASES OF THE EARLY 20TH CENTURY: HISTORICAL RESEARCH, CONDITION ASSESSMENT AND DIAGNOSTIC INVESTIGATION OF A "TRANSITION" CONSTRUCTION TYPE

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Abstract

Staircases play a key role in the rehabilitation and retrofitting of historic public buildings in terms of respecting building regulations for fire protection, accessibility and seismic resistance. Assessing their construction materials and techniques, as well as their current condition and residual performances, are paramount in order to employ effective, compatible and low-intrusive conservation measures. In particular, staircases dating back to the early 20th century call for a comprehensive understanding of technical and technological solutions. This is because they were conceived in a "transition" phase from traditional masonry structures to modern systems based on the employment of metal elements. Thus, they show a variety of hybrid solutions, often depending on the local practice and the specific application. Consequently, historical research from technical handbooks of the time should help define the purposes and boundaries of the diagnostic investigation of characteristics and pathologies. Additionally, both documentary records and on-site/laboratory tests should support the identification of potential local failures, which are generally omitted in global analytic simulations. In the light of the above-mentioned issues, the paper provides an overview of the historical evolution of masonry staircases of the early 20th century, with a specific focus on brick structures in central-southern Italy. Based on the most documented systems and the most recurring pathologies, this research outlines a methodological framework for on-site and laboratory diagnostic investigation, aimed at the identification of construction materials and techniques, detection of decay patterns and characterisation of mechanical performance. The proposed framework is applied to a case study, the monumental staircase of a school building, and some insights into the operational procedures are also addressed.

Keywords

Historical handbooks, Masonry staircases, Mixed structures, Building pathology, On-site diagnostics.

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1. INTRODUCTION

Staircases play a key role in the rehabilitation and retrofitting of historic public buildings in terms of respecting building regulations on fire protection, accessibility and seismic resistance. To this end, the well-established pipeline of anamnesis, diagnosis, therapy and controls should move from the correlation of direct observation to historical research, structural analysis, experiments and tests [1] so that the accurate assessment of construction materials and techniques, as well as of current conditions and residual performance, might address effective, compatible and low-intrusive conservation measures.

The review of the state-of-the-art points out that most studies on masonry staircases, mainly located in the Mediterranean area and based on the Roman building tradition, are focused on the evaluation of their structural stability and earthquake response [2–5]. However, the analytical models are necessarily based on simplified typological schemes. Thus, although essential for understanding the overall behaviour of a system, they should be integrated with detailed qualification of technical-technological characteristics and state of conservation in order to identify local vulnerabilities and failures that are generally omitted in global system simulations. Consequently, documentation as a holistic approach to the collection and interpretation of data related to history, geometry, construction, pathology and performance is usually the most fundamental and crucial process that can affect and facilitate any required procedures to preserve and safely operate heritage buildings [6].

The above-mentioned issues are particularly relevant whenever the technical solutions belong to a relatively short period and/or to the local construction practice because they might be less documented in terms of scientific research and practical case studies. In this sense, brick staircases dating back to the early 20th century are representative. In fact, they were conceived across a "transition" phase from traditional masonry structures to modern systems with metal elements, which were initially employed as local reinforcement and afterwards as structural members completed with non-structural brick blocks. Thus, they show a variety of hybrid systems, often depending on the specific site and requiring comprehensive technical and technological understanding, based on the above-mentioned integration of documentary records, direct surveys and experimental measurements toward phenomenological and analytical modelling.

According to the recalled research lines, the paper provides a description of the historical evolution of brick masonry staircases between the 19th and 20th centuries in central-southern Italy, based on technical handbooks and inventories on the most common construction techniques. Thus, a methodological framework is proposed for on-site and laboratory diagnostic investigation, aimed at the identification of construction materials and techniques as well as detection of decay patterns and characterisation of mechanical performance. The framework is discussed and validated in a case study, the monumental staircase of a school building, where some insights into operational procedures are also addressed.

2. RESEARCH BACKGROUND

2.1. HISTORIC OUTLINE

The employment of bricks between the 19th and 20th centuries for building masonry staircases is widely documented in several geographical areas, in general in Europe [7, 8] and in particular in central-southern Italy [9–12], where the Roman founded construction practice inspired the building tradition until pre-modern times and then radically evolved as a result of the nascent and revolutionary technology of reinforced concrete. According to a well-established classification, the staircases in historic buildings might belong to two main types: the former has a central structure, either linear (walls) or punctual (pillars, columns) with elements that «cooperate with the perimeter walls as further creating a second support for the steps or for the elements on which they rest»; the latter is supported only by the border cage, and it is preferred in order «to take advantage of the lighting from above» and «give the staircase a light, pleasant appearance» [13]. With a specific focus on central-southern Italy, the second type was mainly used with the development of a peculiar sub-type, known as the "Roman" staircase. In general, these are stairs with landings on barrel or cross vaults and flights on a barrel, lame barrel, low barrel or cross vault, cantilevered on the longitudinal walls with mutual contrast of the flights. The intermediate landings are typically built as half-pavilion intersections of the inclined vaults of the flights. Alternatively, the flights might be supported by rampant vaults whose generator line is perpendicular to the slope. In this case, their intersection with the landing is more complex, from both the geometrical and constructional point of view, due to the relevant thrusts of the rampant, which often require the construction of transverse connecting arches. Finally, further variants concern «systems of rampant vaults that have the lower shutter on the side of the previous rampant vault and the upper shutter on the opposite wall and so on» or stairs «with self-supporting steps so that it is not necessary to prepare an underlying structure to lay on» [13].

The construction materials used mainly depended, in central-southern Italy as elsewhere, on the geographical area with prevailing solutions in both natural [11, 12] and artificial [9, 10] stone. In the case of brickwork, the blocks are generally arranged in two or three courses with stretchers along the longitudinal section of the flights. The steps are typically made of marble or travertine and rest on a filling of mortar and stone aggregates. Furthermore, as regards the planimetric layout, in most cases, there are two parallel flights or, alternatively, three flights, two on the long side and one on the short side opposite the floor landing. However, there is no lack of more complex solutions, such as polygonal, oval, curved or, in the case of monumental stairs, pincer flights, to amplify the perspective effect [14]. The above-mentioned general features were predominant until the end of the 19th century, whereas from the beginning of the 20th century, similar construction solutions began to be integrated with metal elements. At an early stage, the metal elements were used as a support/reinforcement of the primary masonry structure, and they were often hidden in order to «show convenient decoration [...] in harmony with the other parts where the stairs are located» [15]. These are generally U or double T-shaped metal profiles, arranged longitudinally on the free side of the flight, connected to the surrounding walls by transverse iron tie rods and to the landings by transverse iron beams (Fig. 1). Latterly, in analogy with the evolution of slabs and balconies, the metal elements were used as bearing joists [14, 16], either parallel or perpendicular to the flight slope, and completed by light hollow brick tiles, both flat and curved (Fig. 2). In this case, if the iron joists are parallel to the flight slope, they are placed on both sides of the flight, at the interface with the perimeter wall and the stairwell to withstand the thrust of the brick

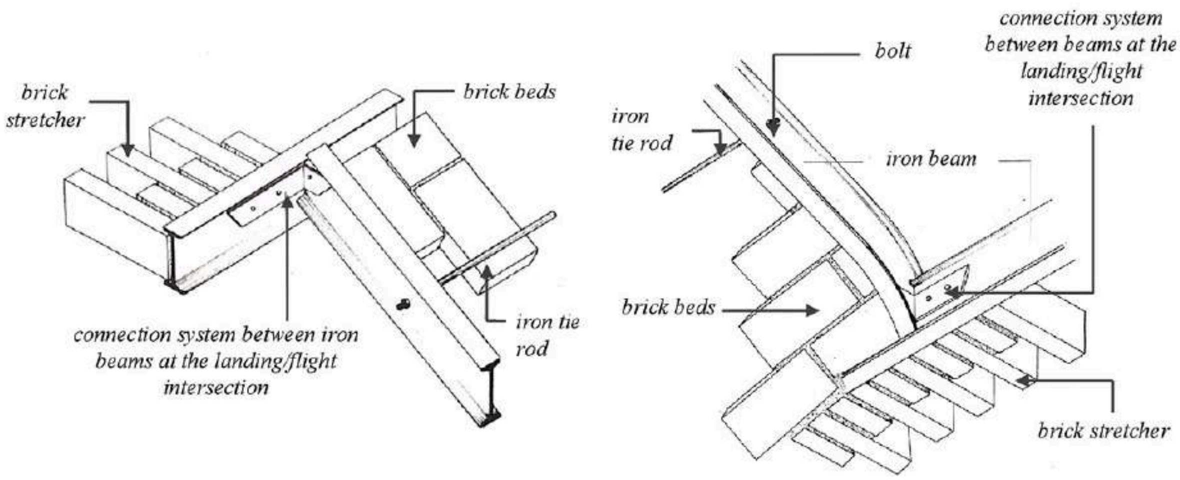

Fig. 1. *Details of brick masonry staircases with support/reinforcement metallic elements [9].*

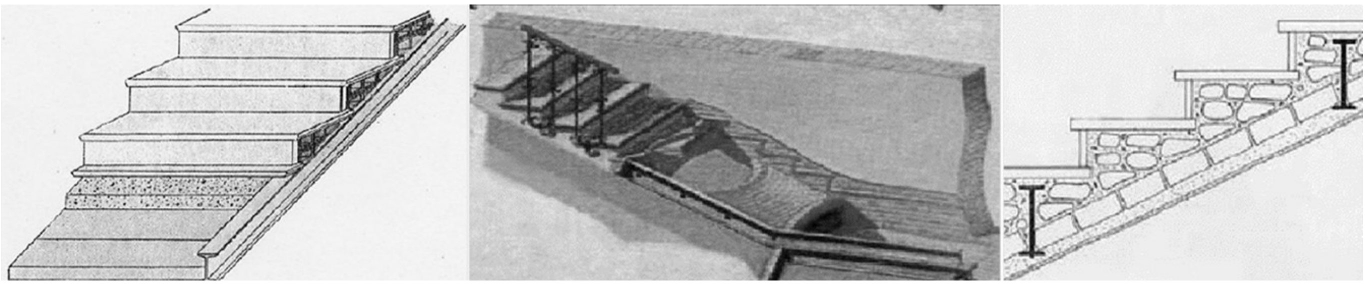

Fig. 2. *Examples of mixed brick/iron staircases: from the left, iron beams parallel to the flight and flat brick blocks [16]; iron beams parallel to the flight and vaulted brick blocks [16]; iron beams perpendicular to the flight [14].*

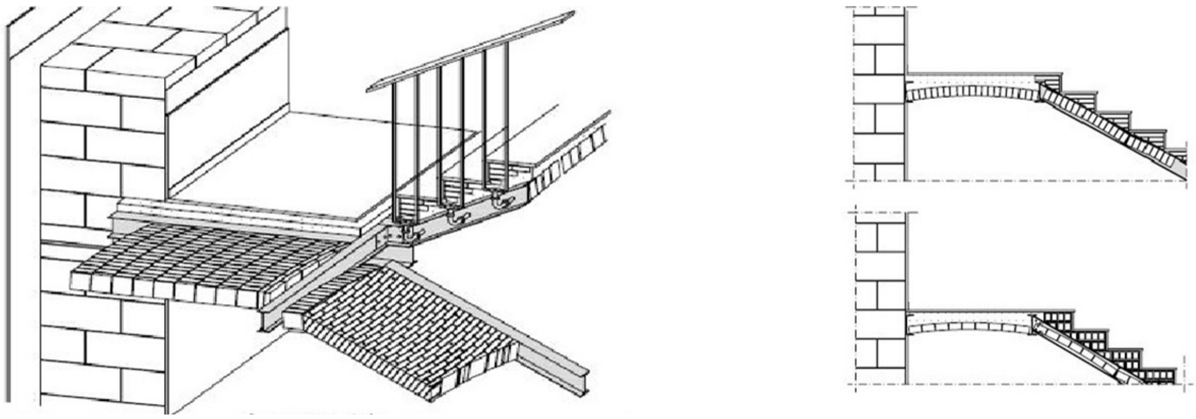

Fig. 3. *Axonometric schemes of mixed-structure stairs: from the left, profiles parallel to the flight and vaulted brick blocks; profiles perpendicular to the ramp and vaulted brick blocks set on headers (top) and stretchers (bottom). (Drawing by the Authors).*

curved tiles and/or accommodate the flat brick tiles at the endings of the slab span (Fig. 3). However, suppose the iron joists are perpendicular to the flight slope. In that case, they are cantilevered from the perimeter wall, spaced about one meter apart and connected to each other and to the edge beams of the landings by means of round iron ties [17].

The technical construction solutions may, in some cases, appear similar in the two phases, especially in the presence of wall structures with lowered vaults and large spans. However, the load transfer from the flights to the landings, from the flights to the walls and from the landings to the underlying structures are substantially different and thus require a critical understanding of the technical choices. Moreover, the structures that can be found in such a transition period might be affected by the specific local practices and contingent needs, in particular, «in Rome and in central and southern Italy» where «special vaulted structures are frequent in terms of shape and orientation of the materials» [14].

2.2. PATHOLOGY AND DECAY PATTERNS

Brick masonry staircases primarily show decay and pathologies of the brick itself, which might be considered a porous stone, with alteration mechanisms caused by the hydrophobic behaviour of the blocks [13]. Thus, for taxonomic classification, references should be made to well-established codes, such as the Italian standard UNI 11182 *Cultural heritage. Natural and artificial stone. Description of the alteration - Terminology and definition*, as well as to international guidelines *ICOMOS-ISCS. Illustrated glossary on stone deterioration patterns*. Aside from manufacturing defects, the most recurrent phenomena may concern erosion and disintegration due to the crystallisation of salts, especially at the interface with the mortar, as well as freezing, biological colonisation and efflorescence; the latter is less frequent for indoor components unless exposed to aggressive atmospheric agents due to disuse and abandonment. The aforementioned signs of deterioration also extend to the joints and coatings, with possible pulverisation of the mortar and deformation/detachment of the plaster (Fig. 4 left).

Furthermore, specific problems can be found due to the employment of iron beams, tie rods and bolting in early 20th century constructions. In such cases, problems might occur related both to the deterioration of the metal elements and to the physical-mechanical incompatibility between iron and brick. For instance, oxidation phenomena caused by the absence of protection and/or unfavourable conditions of temperature and relative humidity are recurrent (Fig. 4 middle), with the consequent danger of corrosion and reduction of resistant sections. Moreover, the aforementioned oxidation phenomena are generally associated with the swelling and/or cracking of the layer of plaster at the interface between profiles/bars and bricks (Fig. 4 right) due to the increase in volume and the onset of tensions from the corroded metal products on bricks and mortar. Interface cracks can also be caused by the physical-mechanical incompatibility of the different contiguous materials due to their different thermal, hygrometric and deformation behaviour.

Fig. 4. *Examples of decay patterns and pathologies.*

3. METHODS AND TOOLS

It is widely known that the diagnostic investigation of historical buildings should rely on the preliminary qualification of the specific case study, through bibliographic-archivist research on the original configuration and following modifications and a direct survey of characteristics and decay patterns. Such a qualification is paramount to guiding the choice of the most suitable on-site and laboratory techniques based on the investigation objectives and the surrounding conditions [18–22]. Nevertheless, in the light of the historical framework outlined in section 2 and on the basis of the experience developed by the authors through academic research and technology transfer [23–26], a general framework (Fig. 5) was outlined that relates several well-established diagnostic tests with the technical and conservative peculiarities of brick masonry staircases of the early 20th century.

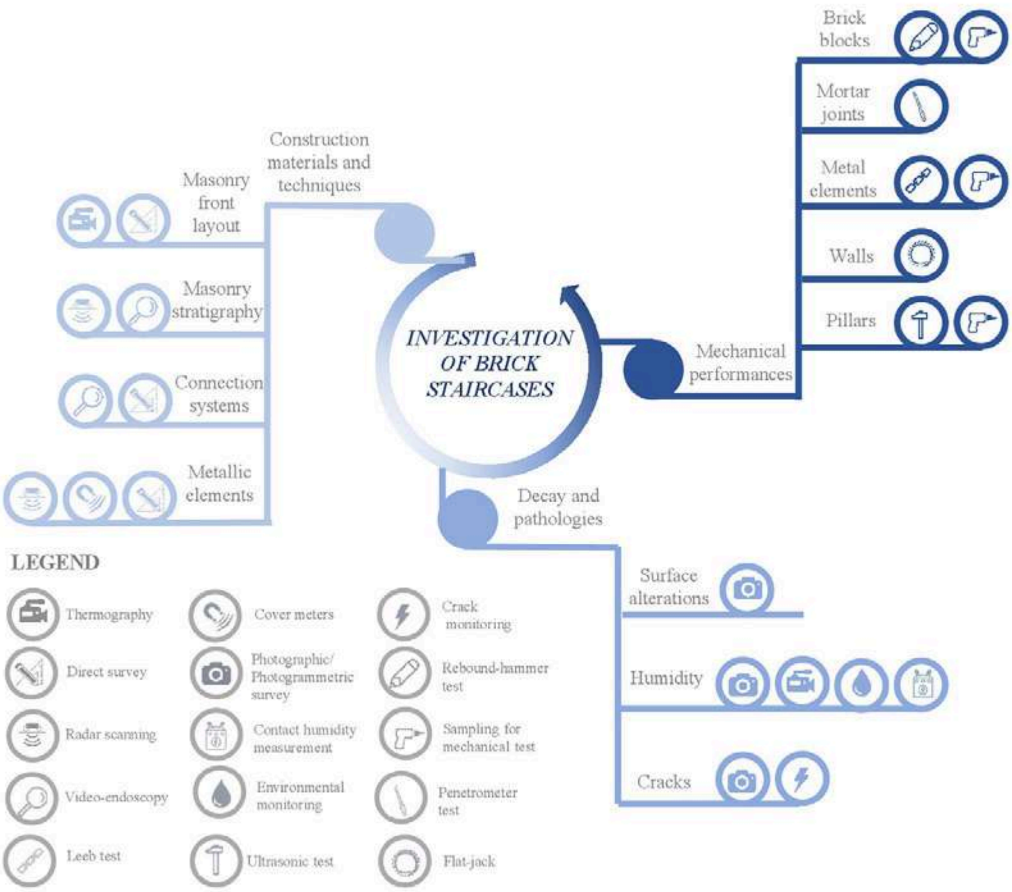

Fig. 5. *General diagnostic framework.*

In detail, three main investigation areas are highlighted:

- identification of construction materials and techniques, as related to flights, landings and perimeter walls, in order to classify the masonry front layout and stratigraphy, connection systems between contiguous flights and between flights and landings, as well as possible metal elements;
- detection of anomalies, as related to decay and pathologies, in order to map cracks, humidity patterns and surface alterations, also in terms of their evolution over time;
- characterisation of mechanical performances, as related to materials and components, with the double purpose of addressing reliable analytical modelling and identifying local vulnerabilities/inconsistencies.

A number of non-destructive (NDTs) and destructive (DTs) techniques are proposed below for each investigation area, and relative targets, based on the principle that NDTs should enable the preliminary, extensive and qualitative assessment and, thus, support the selection of representative elements whereas DTs can provide local and quantitative measurements as validation.

Concerning the identification of construction materials and techniques:

- the front layout of the masonry might be conveniently surveyed using thermography when it is covered by a finishing layer since the underlying support should show a different response in the infrared spectrum from the brick blocks and mortar joints. However, it is not unlikely that the surface thermal distribution could be fairly homogenous if the indoor temperature is stable and the thermal exchanges between contiguous materials as well as between the materials and the environment are low. In this case, active thermography could be useful. In any case, the thermographic acquisition should be subsequently supported by a direct survey to observe representative areas and local anomalies after the removal of the finishing layer;
- the masonry stratigraphy is generally successfully assessed by radar scanning, which detects inner material discontinuities based on the transmission of electromagnetic waves that are scattered back at the interface between media with different dielectric properties. To this end, some operational recommendations might be useful. Both longitudinal and transversal profiles should be acquired on the extrados for the flights that are under investigation. For the longitudinal profiles, the installation of temporary inclined supports (e.g., rigid plastic or wooden boards) should facilitate the antenna sliding. Moreover, for the transversal profiles, whenever surrounding metallic elements are close to the antenna (e.g., stairwell railings), they should be protected by insulating solutions in order to prevent any interference in the signal reflection. The direct validation of the radar scanning results is subsequently achievable with video-endoscopy inspection through significant cross-sections;
- the connection systems between contiguous flights and between flights and landings are difficult to qualify through indirect non-destructive tests due to their limited extent and morphological complexity. Consequently, they might greatly benefit from direct micro-drilling, video-endoscopy inspection and visual survey after the removal of the finishing layer;
- the metal elements, eventually installed within the flights and the landings, could be investigated by radar scanning, given the different behaviour of masonry and steel in the propagation/reflection of the electromagnetic waves. The above-mentioned operational recommendations also apply to the flights. Alternatively, a preliminary cover meter test could localise any metal element within 8-10 cm of the surface using much lighter portable equipment. However, the subsequent direct examination should be considered after the removal of covering layers in order to survey the typology and size of the elements.

Concerning the detection of decay and pathologies:

- the systematic photographic acquisition should be used to map and analyse cracks, humidity patterns and surface alterations. In particular, beyond conventional photography, 360° panoramic spherical images can support the overall documentation and decay annotation using photo-editing tools. Moreover, when the surfaces are not covered by a finishing layer, photogrammetric processing tools can be used to reconstruct a 3D model and extract 2D othoplanes by taking high resolution close range pictures with suitable overlapping percentages;
- humidity patterns can be further investigated by thermography, following the potentialities and limitations previously discussed for the identification of the masonry front layouts. However, in this case, the possible presence of active imbibition should be detectable due to the moisture evaporation that lowers the local temperature. For direct confirmation, measurements of the moisture content of the materials should be taken by the weight method, as well as a campaign of local environmental monitoring;
- cracks can be further investigated in terms of their progression over time using manual, mechanical or electronic devices. The monitoring activity, which includes the compensation for seasonal oscillations by temperature measurements, should be extended to a period of at least 12 months.

Concerning the characterisation of mechanical performances:

- the compressive strength of brick blocks can be preliminarily assessed for an extensive number of points by the rebound-hammer test, which measures the surface hardness opposed by the material to the impact of a spring-loaded mass. Therefore, at a limited number of points, borehole samples can be extracted to carry out laboratory compression testing;
- by means of the penetrometer test can be used on-site to measure the compressive strength of the mortar joints, based on the measurement of the penetration depth of a steel needle inserted into the joint by means of a striking mass. This measurement, although indirect, is effective and feasible, whereas the extraction of samples might result in specimens of inadequate size to carry out laboratory compression testing;
- the tensile strength of metallic bars and beams can be measured in analogy to the method referred to for brick blocks through preliminary extended qualification on a significant number of elements by the Leeb test for measuring the surface hardness and subsequent extraction of samples to carry out the tensile test;
- the characteristics of resistance and deformability of the masonry walls and pillars supporting the flights and the landings can be measured by several methods, including flat jacks, borehole sampling and sonic/ultrasonic tests. However, it should be noted that these aspects are beyond the specific construction type under investigation and fall within the broader case of the characterisation of the masonry structures.

4. CASE STUDY

In order to validate the general framework, as presented in §3, the main experimental results achieved on the monumental staircase of the school building "G. Carducci" in Cerignola (FG), South Italy, are discussed below. The design and construction of the staircase, as of the entire building dating back to the early 20th century, are not documented by specific archivist and bibliographic records. For this reason, the diagnostic investigation plan required for the fire safety assessment of the building system was mainly based on the preliminary direct survey.

4.1. DIRECT SURVEY

The monumental staircase under study (Fig. 6) develops on two floor levels. It is arranged according to a "pincer" scheme: for each floor, from the central starting flight (span 2.1 m), free on both sides, one arrives at the first intermediate landing, from which two transversal symmetrical flights (span 1.6 m) develop, each one connected,

Fig. 6. *Equirectangular 360° panoramas of the ground floor starting flight (left) and second floor landings (right).*

through a further landing, to a flight (span 2.1 m) parallel to and opposite the starting one. The landings are built on a system of three rib vaults set on corner pillars on the first floor and on a recently built reinforced concrete slab on the second floor.

From a typological point of view (Fig. 7), the flights are "gooseneck" rampant vaults, the curved intrados line of which continues seamlessly onto the next intermediate landing. The intrados also has a vault profile which is greatly lowered in the transversal direction. The construction technique is based on the use of brick blocks, somewhat visible due to the presence of a thin lime plaster. They show heterogeneous colours, from yellow ochre to light red, and are arranged with the header or the stretcher along with the line of the flight in two or three rows (average thickness of 12 cm). In some cases, the blocks have been replaced with more recent analogues. The material and construction of the structure are char-

Fig. 7. *Construction details: transversal flight from the ground to the first floor (top left); flights ending on the second floor (top right); flights showing metal edge beams (bottom left) and connecting tie rods (bottom right).*

acterised by the presence of some visible metal elements, including a longitudinal edge beam on the free ending of one of the two flights leading to the first floor, as well as two beams on both free endings of the central flight starting from the first-floor landing. Moreover, the latter two beams are connected by transverse tie rods, visible on the intrados. The state of conservation was found to be generally good, except for the detachment and deterioration of the thin coating plaster and some infiltration humidity stains on the second floor, which probably developed before the original roof was repaired by a metal one.

4.2. ON-SITE AND LABORATORY INVESTIGATION

The investigation campaign on the monumental staircase was planned and applied, starting from the general diagnostic framework presented in Figure 5, then adapted to both the specific targets and conditions. In detail, it mainly focused on the identification of construction materials and techniques. In fact, the key goal was to understand whether the staircase was originally conceived as a mixed iron-brick structure with beams and tie rods systematically used as main resistant elements and possibly hidden, or whether, on the other hand, it was a load-bearing masonry structure with local metal reinforcements. Nonetheless, the diagnostic investigation took into account the temporal and economic resources that could be allocated in order to plan further tests for the detection of decay and pathologies as well as the characterisation of the mechanical performances. Thus, focusing here on the flights and landings for the sake of brevity, the on-site and laboratory activities involved several diagnostic techniques, as described below.

Concerning the identification of construction materials and techniques, radar scanning and direct survey techniques were employed. Radar scanning was used for both the assessment of the masonry stratigraphy and the detection of metallic elements. The equipment consisted of a 16-bit single-channel IDS DAD FastWave system and IDS TRHF 2000 MHz antenna. For the flights, two longitudinal profiles, at a distance of about 30 cm from the endings, were acquired by means of wooden boards to allow the continuous and easy sliding of the probe. Moreover, a series of transversal profiles, spaced about 90 cm apart, were acquired directly on the step treads. For the landings, grids of longitudinal and transverse profiles spaced 50 cm apart were recorded using transparent plastic sheets on which a metric reference had previously been drawn as a guide. Furthermore, the presence of metal elements and the configuration of the connection systems were checked when NDTs indicated representative areas by a direct survey after the removal of external brick elements and/or by micro-perforations into the elements.

Decay and pathologies were detected using a virtual tour of 360° panoramic spherical images developed from the acquisition of equirectangular pictures (Fig. 6) with a Samsung Gear 360 camera, which uses two fisheye lenses with 15-megapixel sensors on both sides of the device to simultaneously capture two 180° views which are then recomposed into a 360° image. Thus, all the panoramic photos, previously edited with Adobe Photoshop® for mapping the decay textures, were later integrated into the virtual tour using Easypano Tourweaver® software and enriched by conventional navigation switches. Moreover, a FLIR T430sc thermocamera was used for thermography to assess the potential presence of active humidity phenomena, eventually related to the detachment or deterioration of the thin coating plaster and the infiltration humidity stains at the roof level.

Concerning the mechanical characterisation of materials and components, the diagnostic campaign involved: sampling brick blocks by performing axial compression laboratory tests on three representative specimens of different colours; penetrometer tests using RSM - DRC equipment on mortar joints from eight different construction components to estimate the on-site compressive strength; and, Leeb tests with a DMQ - QH2 steel microdurometer, run on eight representative points from each of the main metal elements to estimate the on-site tensile strength.

4.3. DISCUSSION OF RESULTS

The identification of construction materials was carried out using techniques such as radar scanning for the assessment of the masonry stratigraphy, and the detection of metal elements of the flights enabled the identification of the inner configuration through the cross-section. Specifically, two continuous reflection planes were generally visible, one at the interface between the steps and underlying filling materials and the other at the interface between the filling materials and underlying masonry support. In no case were there any echo signals due to the presence of metal elements, except in situations already visible from a direct survey. On the other hand, in some cases, areas of high reflection could be found due to possible repairs/replacements of elements carried out after the original construction. In contrast, radar scanning of the landings (Fig. 8 left) revealed the presence of several metallic elements. In fact, as expected, in the recently built slab on the second floor, small and regularly spaced reflection hyperbolas were detected that are typical of the metal bars in reinforced concrete structures and are arranged in both directions of the component. Moreover, similar echoes were identified on the extrados of the vaults that support the first-floor landing. However, in this second case, the distance between the hyperbolas (about 50 cm) and the wider amplitude of the reflected signals led to the hypothesis that the inclusions were due to metal beams running in the longitudinal direction of the landing.

Temporary scaffolding was then erected to reach the investigation areas in order to validate all the above-mentioned results by direct observations and inspections. In particular, when radar scanning ruled out the presence of metal elements, the removal of some outer brick blocks and micro-perforation through the cross-section confirmed the preliminary assumptions. Similarly, when the radar detected relevant signal reflections, samples revealed iron bars and beams in geometrical and construction surveys. For instance, in the case of the connection between the first-floor landing and the arriving flight, the beam visible on the flight edge (Fig. 7 bottom left) was qualified as “INP” type (height equal to 14.5 cm), with transversal stiffening by metal rods (approximately 2 cm in diameter). Said beam is supported on the lower flange of another perpendicular “INP” beam (height equal to 22 cm) that is at the landing edge and corresponds to the first hyperbola of the transversal radar profiles of the

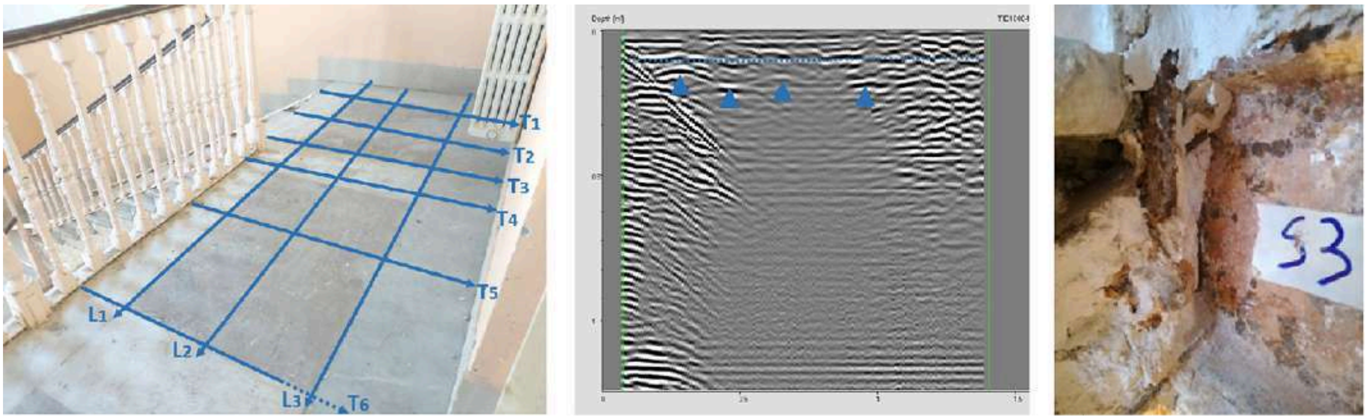

Fig. 8. *From the left: radar scanning grid of the first-floor landing; transversal profile T6 showing reflection hyperbola due to iron beams in the longitudinal direction; direct survey showing the connection between two iron beams at the flight/landing interface.*

landing (Fig. 8 middle). The outcome of the diagnostic investigation for the identification of construction materials and techniques, integrating the above-mentioned radar scanning tests and direct essays, resulted in thematic 2D and 3D drawings, documenting the layout of each flight and landing (Fig. 9).

Furthermore, concerning the detection of decay and pathologies, the virtual tour (Fig. 10) displaying the decay textures enabled rapid and comprehensive documentation of current conditions, remote inspection and analysis of the visible surface alterations and localisation of the areas investigated by diagnostic tests through

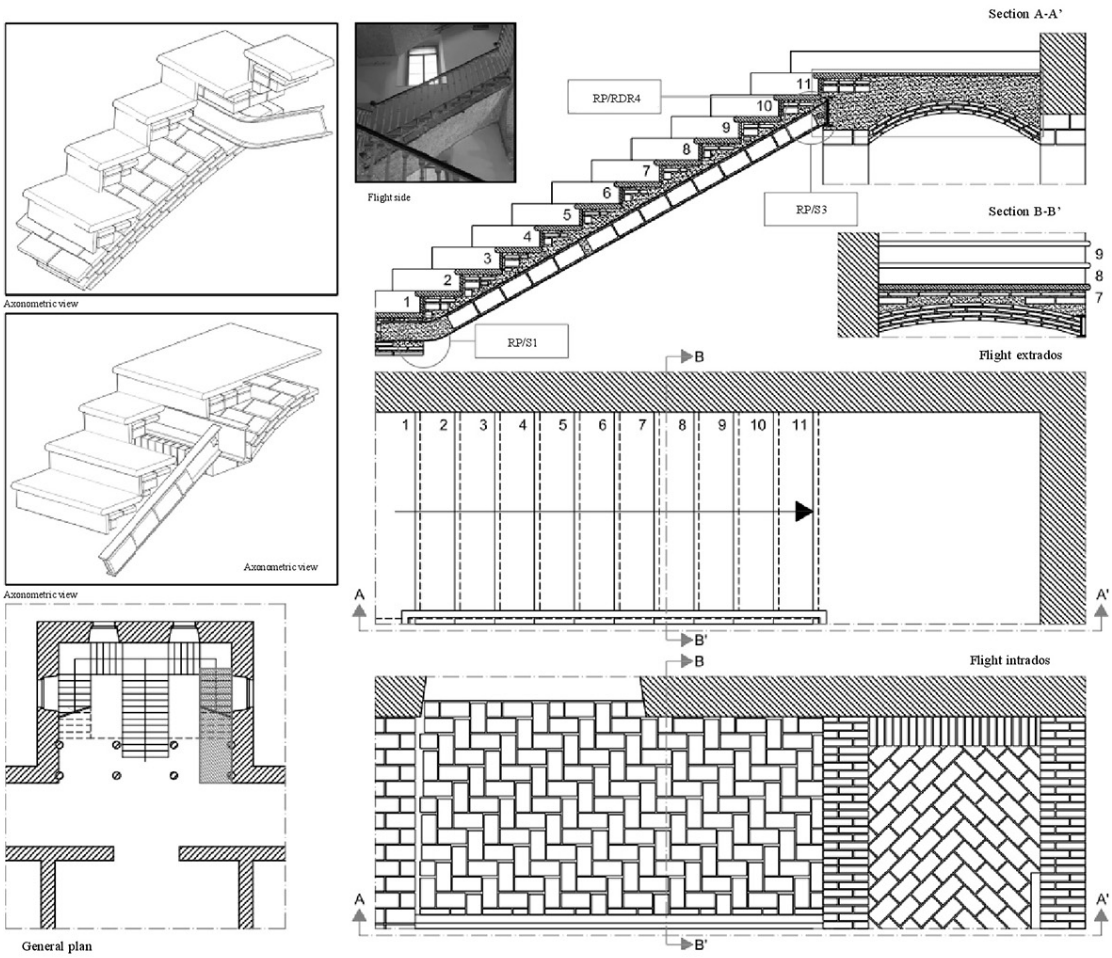

Fig. 9. *Example of datasheet with morpho-typological and material-constructional identification of a flight.*

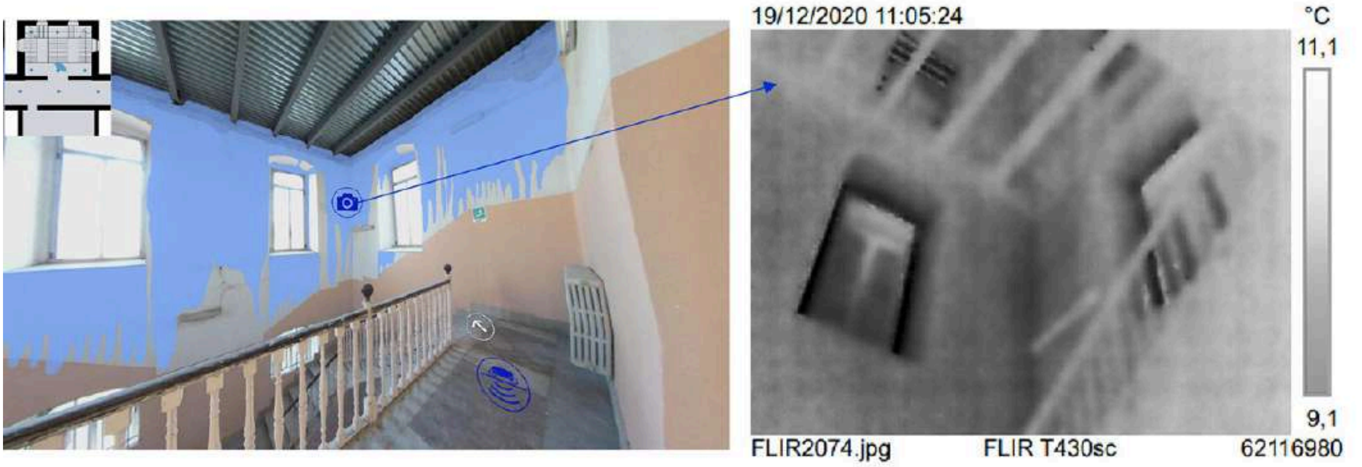

Fig. 10. *From the left: virtual tour displaying the decay maps and localising the diagnostic report; thermographic survey showing no active infiltration phenomena.*

hotspots to external links. The thermographic survey of the surfaces showing infiltration humidity stains on the second floor ruled out the occurrence of active phenomena since only localised variations in temperature due to constructional thermal bridges were found.

Finally, the results of the mechanical characterisation of materials might be summarised as follows. The axial compression tests on brick blocks (IIa2) showed fairly consistent values for different types/colours (C1 = 17.79MPa; C2 = 19.55MPa; C3 = 23.79MPa) that perform in a very comparable way. Similarly, the Leeb tests estimated quite regular tensile strengths for different elements and points under investigation, with average values of approximately 400MPa, proving that the elements are likely to belong to the same construction phase. On the contrary, the penetrometer tests on the mortar joints provided very heterogeneous results (PM1 = 1.3MPa; PM2 = 1.9MPa; PM3 ≤ 0.4MPa; PM4 = 1.15MPa; PM5 = 2.5MPa; PM6 = 1.5MPa; PM7 = 1.5MPa; PM8 = 2.4MPa), proving that possible replacements have taken place over time.

The overall assessment of the achieved results support the identification of some critical issues affecting the monumental staircase under investigation, both at the local and global levels. Firstly, from the direct geometry survey, it can be seen that the flights are generally quite slender, considering their thickness/length ratio. Moreover, they show non-homogenous stiffness, taking into account that they host a limited number of metal elements – only the visible ones, considering that no hidden beams, bars or ties were detected as internal inclusions by radar scanning. Thus, it is likely that the monumental staircase was originally conceived as a masonry brick structure and only reinforced after its construction with some sub-systems.

The variable material-constructional configuration is proved by further aspects. The construction survey found that the blocks had been replaced with more recent analogues in some areas. The radar scanning detected the presence of areas of high reflection due to possible repairs/replacements of elements carried out after the original construction, as well as the presence of metal beams as a reinforcement system at the extrados of the first-floor vaults. The penetrometer tests on the mortar joints provided quite heterogeneous results in terms of estimated resistance and thus proof of possible replacement interventions that have taken place over time. Finally, the recently built reinforced concrete slab on the second floor features another local anomaly: the radar scanning ruled out the presence of metal elements, such as edge beams and tie rods running along with the adjacent flights. Thus, the connection between flights and landings and the relative load transfer is left constructively unsolved.

All the above-mentioned issues should be carefully considered in the restoration measures involving local interventions, beyond the overall strengthening strategy, as addressed by analytical simulations.

5. CONCLUSIONS

The development of a diagnostic campaign for brick masonry staircases of the early 20th century should rely on a well-established methodological framework, based on historical technical handbooks, in order to target NDTs and DTs in the general investigation purposes and conditions toward reliable identification of construction materials and techniques, detection of decay and pathologies, and characterisation of mechanical performances. Nevertheless, the above-mentioned framework should be applied to a specific case study by operational procedures and practices that are strictly related to the outcome of archive/bibliographic research and direct survey on the one hand and on the available time and resources on the other.

Consequently, the diagnostic results can provide effective and comprehensive information supporting the retrofitting/maintenance activities, as well as contribute the knowledge of the characteristics of a certain construction type, albeit locally from contingent practices and needs. Finally, for technical applications in which a variety of solutions are linked to the historical transition from a traditional to a "modern" construction phase, the experimental measures make it possible to assess the current behaviour, state of conservation and residual performances, as well as increasing the available database on representative case studies, in terms of construction details, technical solutions, decay patterns and mechanical parameters of materials and components.

Authors contribution

Conceptualization of the research, F.F.; conceptualization of the paper, M.D.; methodology, F.F., M.D.; historical research, F.F., M.D.; experiments, M.D.; validation, F.F., M.D.; writing, M.D.; supervision, F.F.

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TECHNOLOGICAL ANALYSIS OF A PREFABRICATED TIMBER-BASED SYSTEM FOR THE INTEGRATED RENOVATION OF RC FRAMED BUILDINGS

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Abstract

Most of the building stock in European seismic countries is highly energy-intensive and earthquake-prone since it was built before the enforcement of effective energy and seismic codes. Renovation actions that synergically integrate both energy-efficient and anti-seismic interventions are strongly needed in these countries. However, the implementation of such interventions is currently limited by barriers that are mostly related to the high cost and invasiveness of traditional seismic retrofit techniques.

A new holistic design approach to the building renovation is required to overcome these barriers. This should result in innovative and integrated retrofit interventions able to specifically meet the needs of cost-effectiveness, quick installation, reduced users' disruption, and low environmental impact.

In this framework, the use of cross-laminated timber (CLT) has been recently investigated for retrofit purposes in light of its good mechanical and physical performance.

In this research context, this paper illustrates a novel timber-based retrofit technology for RC framed buildings developed within the e-SAFE H2020 project. This technology consists of cladding the external building envelope with a new prefabricated timber-based shell that acts as seismic-resistant and energy-efficient skin, also contributing to renovating the architectural image of the building. The new skin combines structural CLT-based panels – equipped with novel devices for seismic energy dissipation – with non-structural wooden-framed panels.

Specifically, this paper presents a construction analysis of the proposed retrofit technology, investigating its technical feasibility, versatility, and potentialities, as well as possible application limits.

Keywords

Timber-based panels, Cross-laminated timber, Prefabrication, Seismic and energy renovation, Friction damper.

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1. INTRODUCTION

In European seismic countries, a recent issue in the building renovation sector is the need to combine the energy-efficient measures promoted by the current environmental and energy policies with anti-seismic interventions. Indeed, the building stock designed without energy-efficient and anti-seismic criteria is extremely wide in these countries, mainly including masonry or reinforced concrete (RC) framed buildings [1].

At present, roughly 75% of the EU building stock is energy inefficient [2], thus contributing to the increase in greenhouse gas emissions and, consequently, climate change and related natural hazards. At the same time, the strong earthquakes that occurred in Europe in the past decades demonstrated the high level of seismic vulnerability of the building stock and the catastrophic consequences that the damage or collapse of buildings can entail. For instance, in the last 50 years in Italy alone, earthquakes caused around 5000 deaths and over €180 billion in monetary losses, destroying a considerable portion of the affected building stock [3]. Furthermore, the recent earthquakes that occurred in Italy (i.e., L'Aquila 2009, Emilia 2012, Amatrice-Norcia-Visso 2016), have seriously damaged several buildings previously subjected to only energy efficiency interventions, frustrating these interventions and the related economic investment. The environmental impact in terms of the carbon footprint associated with buildings repair or reconstruction after a seismic event is also relevant. In particular, the expected annual embodied equivalent CO_2 associated with seismic risk has been estimated equal to 87% of the annual operational CO_2 after only energy retrofitting interventions [4]. The framework depicted above evidences that in earthquake-prone countries, energy-efficient and anti-seismic renovation interventions must be synergically combined in order to: 1) prevent human and economic losses caused by seismic events; 2) reduce buildings damage in case of earthquakes and avoid the environmental impact associated to their repair or reconstruction; 3) avoid doubling several costs in case of implementation of the two retrofit interventions in distinct periods (e.g., for building-site setup, demolition works, scaffolding, renders and finishings, etc.) [5, 6]; 4) increase the living comfort and safety of the occupants; 5) enhance the building value; 6) extend the building lifetime.

However, several barriers currently hinder the combination of seismic and energy renovation actions. On the one hand, there is a lack of attractive, cost-effective, and low-disruptive technical solutions. Indeed, the most common seismic upgrading techniques are very expensive and highly invasive, requiring a long time for implementation, the interruption of the building operativity, and the occupants' relocation during the works, often for several months [7]. On the other hand, the building renovation is also hindered by social and cultural barriers, mainly due to the insufficient spread of seismic risk culture and environmental protection culture. In particular, the poor or partial knowledge of the seismic risk often leads to the low propensity of building owners to prioritise the adoption of anti-seismic interventions.

New holistic approaches to building renovation have been recently investigated to overcome the main technical and economic barriers. In particular, some studies have examined evaluation methodologies for combining current structural and energy retrofit techniques [8, 9]. Other studies have been focused on the development of novel integrated retrofit solutions that can be able to meet the current needs of cost-effectiveness, quick installation, and reduced disruption for users [10–13].

In this framework, wood has shown great potential as a sustainable and renewable retrofitting material to upgrade the seismic and thermal performance of buildings, thanks to the recent advancement of engineered timber products, such as cross-laminated timber (CLT), as well as wood-based insulating materials.

In this regard, this paper firstly presents a state-of-the-art review of the topic of CLT-based retrofit technologies for RC framed buildings. Then, the paper describes a novel integrated retrofit solution that has been recently proposed by Margani et al. [14], and is still under development within the Horizon 2020 innovation project called e-SAFE (Energy and Seismic AFfordable rEnovation solutions). This solution consists of cladding the external envelope of the building with structural and insulating prefabricated timber-based panels. Specifically, this work presents a construction analysis of this retrofit solution to investigate its technical feasibility, versatility, and main technical requirements. The potentialities and limits of the application of the proposed technology are also examined to evaluate its replicability.

2. STATE-OF-THE-ART REVIEW OF CLT-BASED RETROFIT TECHNOLOGIES FOR RC FRAMED BUILDINGS

CLT is a plate-like engineered timber product consisting of an uneven number of timber board layers (usually ranging from three to five, but even more), which are arranged crosswise to each other at an angle of 90° and are connected by adhesive bonding. The result is a rigid composite element having high mechanical performance. In fact, the crosswise build-up provides the CLT panel high capacity of bearing loads both in-plane and out-of-plane, allowing its application as a full-size wall and floor element. The engineered CLT configuration also minimises swelling and shrinkage rate, providing the panel with high dimensional stability in-plane [15]. Furthermore, CLT is a bad heat conductor thanks to its low thermal conductivity (0.10 ÷ 0.13 W m^{-2} K^{-1}), with good thermal insulation and thermal inertia properties. The high mechanical and physical performance, the good environmental properties as well as the high level of prefabrication of the CLT have promoted its rising spread, as attested by the growing number of residential and office buildings worldwide, with a growth of the production capacity rate of 15÷20% per year [16].

In recent years, the increasing attention to environmental sustainability has led the research community to investigate the building renovation sector as a further application field for CLT. Specifically, recent studies investigated the use of CLT walls as strengthening elements to increase the seismic performance of the existing buildings, with potential results in terms of improvement of the strength and stiffness capacity under seismic loads. The advantages of such potential use are the low increase of the building mass compared to other seismic upgrading techniques, thanks to the low density of CLT, and the benefits of dry installation, such as quick and easy implementation and materials recyclability. The insulating properties of CLT, in combination with additional insulation layers, can also improve the thermal performance of the building in view of an integrated and sustainable approach to the building renovation. The high level of prefabrication of CLT also makes it much more attractive for retrofitting uses, making the industrialisation of the building renovation sector one of the main future challenges.

Different applications of CLT walls to the existing RC framed building have been investigated for retrofit purposes.

First works on this topic have been carried out by Sustersic and Dujic [17], who proposed a low invasive retrofit solution consisting in applying a new outer CLT-shell to the external envelope of the building by realising the connection between the panels and the RC structure through special steel brackets provided of ductility and energy dissipation capacity. The external application of CLT panels has also been investigated within the AdESA project [18], resulting in a real application in a case study. The Adhesa system uses dissipative connections with out-of-plane bending capacity and provides for cladding the CLT panels on-site with insulation and finishing materials. Conversely, a totally prefabricated CLT shell has been proposed by the Italian company Wood Beton S.p.A., which has recently introduced the “Rhinoceros-wood” system in the building market [19]. However, its application is currently limited to buildings up to a maximum of three storeys that require a low stiffness increase since the improvement of the building seismic performance is provided only by the strengthening actions of the CLT panels.

One more CLT application includes the use of CLT panels as infill shear walls [20, 21]. Specifically, Stazi et al. [20] analysed the elastic and post-elastic in-plane shear behaviour of CLT specimens, while Haba et al. [21] investigated shear walls composed of narrow CLT elements bonded to each other and onto the RC frame with epoxy resin, achieving possible results in terms of improvement of stiffness, strength and ductility capacity of the structure. Different arrangements of CLT panels, both to the outside of the building or in replacement of the external masonry wythe, have also been proposed by Smiroldo et al. [22]. Then, a low-damage and low-invasiveness retrofit alternative has been recently investigated by Sandoli et al. [23], who proposed using post-tensioned, re-centring, and dissipative rocking CLT walls in the external perimeter of the buildings.

The recent and rich literature on the topic of buildings retrofitting through strengthening CLT walls shows that these solutions are of great interest and highly topical, even if they are still at a preliminary stage. In particular, the use of dissipative devices as connection systems between the CLT panels and the building envelope has a high potential to increase the effectiveness of this solution thanks to the dissipation of a part of the seismic energy, thus reducing the displacement demand of the building structure. Overall, the dampers investigated so far have been mainly conceived to allow seismic energy dissipation by exploiting their ductility capacity. This dissipation mode is less effective in terms of technological and operational efficiency since it requires replacing the dampers and removing the CLT panels after the seismic event.

Based on the above, further investigations on the versatility and practical replicability of CLT-based retrofit technologies, as well as more effective dissipative connections between the CLT panels and the existing building envelope, are required.

3. THE RETROFIT TECHNOLOGY

3.1. MATERIALS AND COMPONENTS

The proposed retrofit technology consists of cladding the external envelope of RC framed buildings with a new prefabricated timber-based shell that acts as seismic-resistant and energy-efficient skin, also contributing to renovating the architectural image of the building. The new skin combines structural CLT-based panels (called e-CLT) fixed to the existing RC frame through novel devices for seismic energy dissipation, with non-structural wooden-framed panels (called e-PANEL), which integrate high-performing windows that replace the existing ones (Fig. 1).

In terms of seismic performance, the e-CLT aims to increase the seismic and dissipative capacity of the existing structure by exploiting the high mechanical properties of CLT and the additional energy dissipation source, respectively. The effect of these multiple features is the reduction of the story drifts caused by the seismic excitation, i.e. the improvement of the seismic resilience of the building.

In terms of energy performance, e-CLTs and e-PANELs integrate insulating materials to increase the thermal resistance of the existing walls, thus reducing the energy demand of the building for space heating and cooling.

Both panels are conceived to be prefabricated off-site and installed from the outside of the building through mobile lifting equipment. The use of prefabricated components and the external dry installation avoid demolition interventions and the occupants' relocation during works, thus significantly reducing implementation costs and time and minimising waste production.

A detailed description of the e-CLT and e-PANEL is reported in the following sub-sections.

3.1.1. THE E-CLT COMPONENT

The e-CLT panel (Fig. 2) is the structural component and has the primary role of reducing the seismic vulnerability of the building. It consists of a prefabricated CLT-based panel and is applied to the outer blind walls of the building. Each e-CLT is equipped with energy dissipation devices that connect it to the beams of the existing RC framed structure. The non-linear behaviour of this seismic

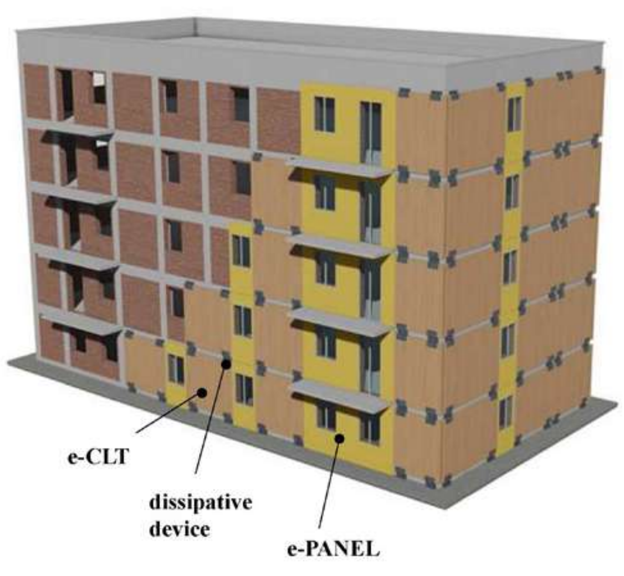


Fig. 1. *Concept of the proposed retrofitting technology.*

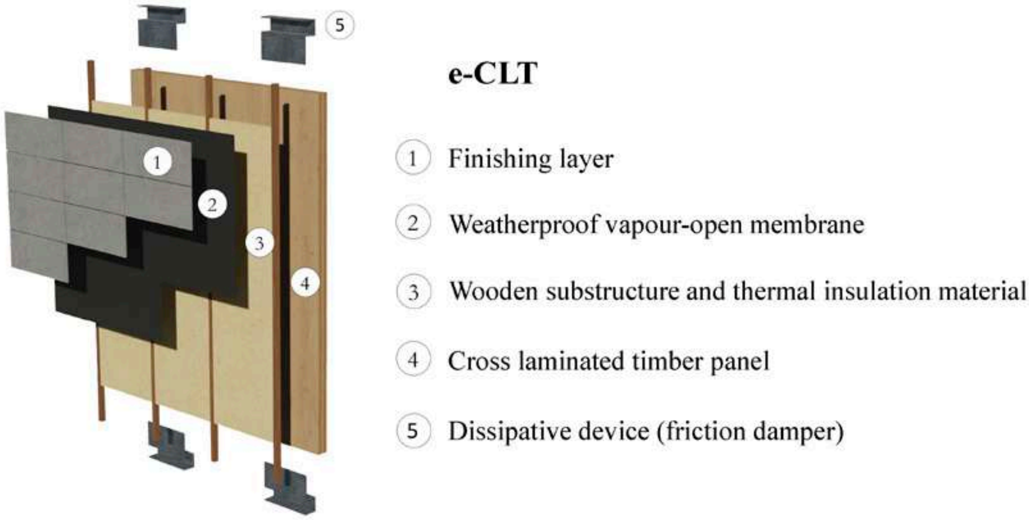


Fig. 2. *e-CLT component.*

upgrading technology is concentrated on the connection devices to protect the CLT panels from damage. In fact, in case of moderate ground motions, the CLT panels increase the seismic capacity of the structure, while in case of stronger ground motions, the friction dampers dissipate part of the input seismic energy, thus reducing the seismic demand of the structure. This further resource of the system reduces the damage to structural components and the possibility of collapse. The size and number of the e-CLTs are defined in accordance with the seismic deficiency of the building and the assumed target performance.

Each e-CLT integrates: 1) a layer of thermal-acoustic insulation material; 2) a weatherproof vapour-open membrane and Ethylene-Propylene Diene Monomer (EPDM) soft bands to prevent rainwater leakage and condensation problems; 3) a finishing layer.

The seismic dissipation device has been conceived to dissipate seismic energy by friction to meet the need for structural efficiency even after seismic events. Indeed, friction dampers overall have one of the most efficient and damage-free energy dissipation mechanisms, without degradation of their resistance and energy dissipation capacity over time.

Figure 3 shows two configurations of the friction damper, which are currently under development [24, 25].

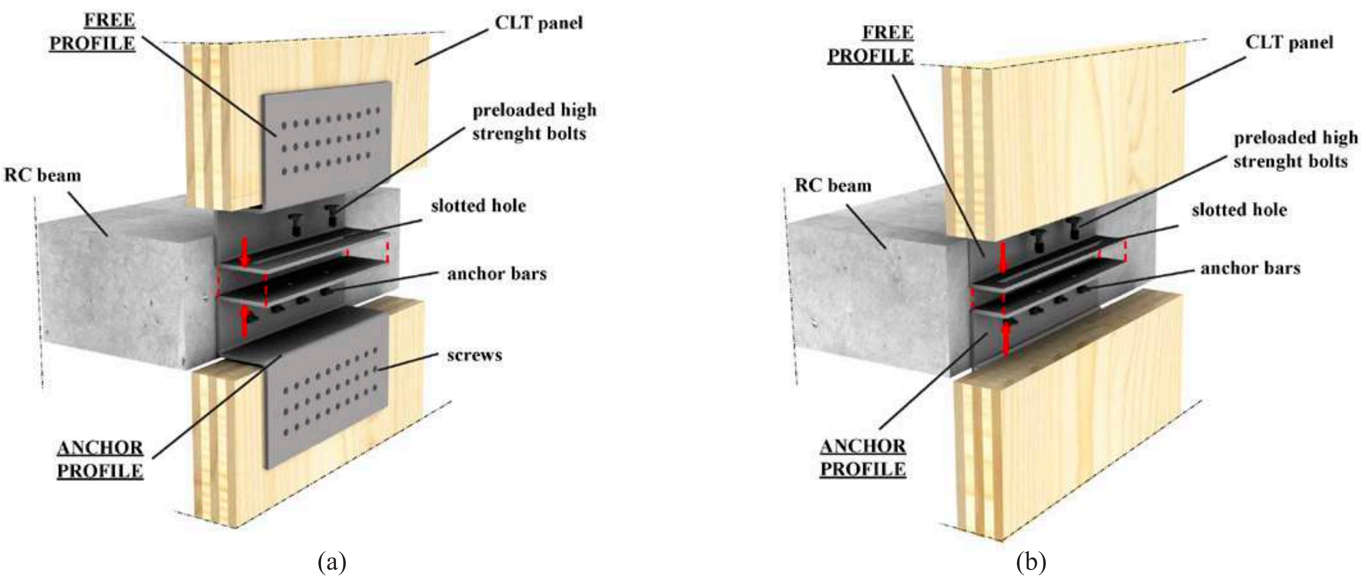


Fig. 3. *Friction damper configurations: (a) multiple-bended configuration with CLT-steel connection on the external side of CLT; (b) single-bended configuration with CLT-steel connection on the internal side of CLT.*

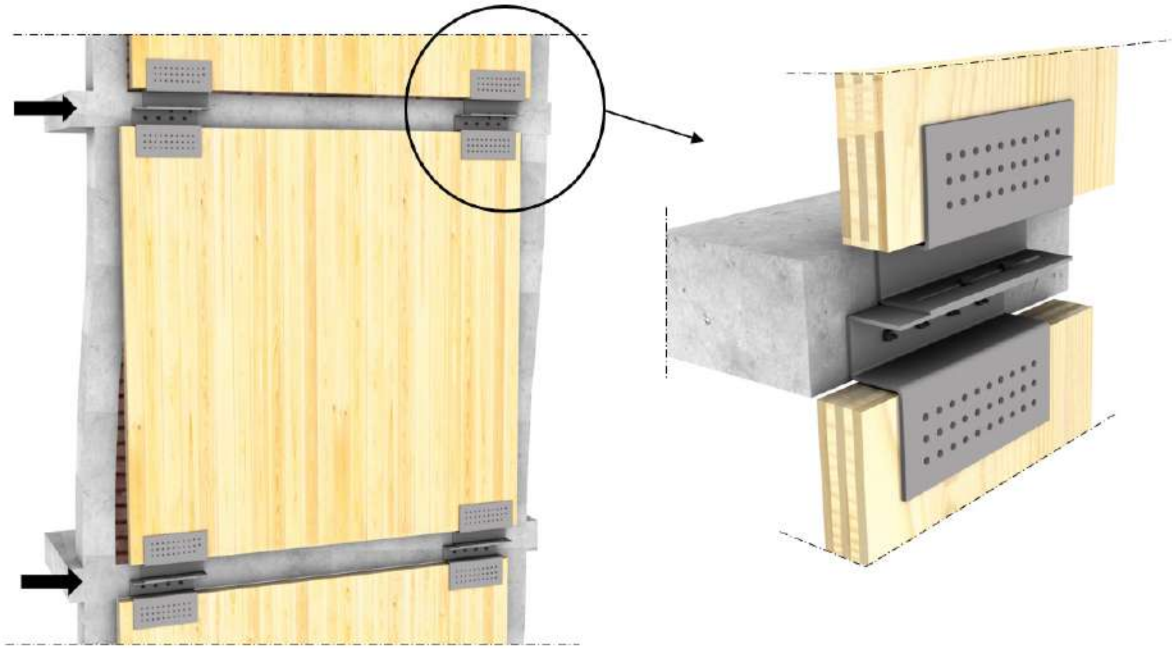


Fig. 4. *The behaviour of e-CLT in the event of dampers activation.*

In both configurations, the damper consists of two press-bended steel profiles that connect the CLT panels of two consecutive storeys. One profile, called "anchor profile", is connected to the RC beam by anchors for concrete. The other profile, called "free profile", is provided with a slotted hole and is connected to the "anchor profile" by preloaded high strength bolts. Standard timber screws connect the two steel profiles to the CLT panels. The difference between the two configurations of the damper concerns their geometry. In particular, one configuration (Fig. 3a) is multiple-bended and provides the connection to the CLT on its external side. On the other hand, the other geometry (Fig. 3b) is single-bended and provides the connection to the CLT on its internal side. Overall, the shear force is transmitted between the two profiles by means of the friction exerted on the contact surfaces. During an earthquake, when the force transmitted by the damper attains the value of the friction force, the "free profile" of the damper slides on the "anchor" one thanks to the slotted hole, thus dissipating seismic energy (Fig. 4).

The two dampers have been investigated to evaluate their behaviour under cyclic load. More details on the numerical and experimental investigations regarding these damper configurations can be found in [25]. Further experimental studies are ongoing to optimise the damper geometry.

Overall, the activation of the damper by a predefined force allows controlling the internal forces on both the damper components and the CLT panels, which are dimensioned to limit or avoid their damage and consequent replacement after a seismic event. The length of the slotted hole should also be designed in accordance with the maximum allowable lateral drift of the building to avoid the shear failure of the preloaded bolts before the RC structure could exploit its maximum drift capacity. Furthermore, on an industrial scale, the proposed geometries of the damper facilitate their manufacturing process since the profiles are produced by cutting, drilling, and press bending of steel sheets. These are common processes in metal parts factories, thus increasing the potential commercial success of the damper.

3.1.2. THE E-PANEL COMPONENT

The e-PANEL (Fig. 5) is combined with the e-CLT to complete the new prefabricated envelope by retaining an aesthetic uniformity. It is applied to the outer windowed walls of the building and integrates new high performing windows (multiple glazing with inert-gas filling, thermal-break frames or wooden frames, low-emission coatings, etc.), which replace the existing ones. The new windows can be equipped with external sun shading sys-

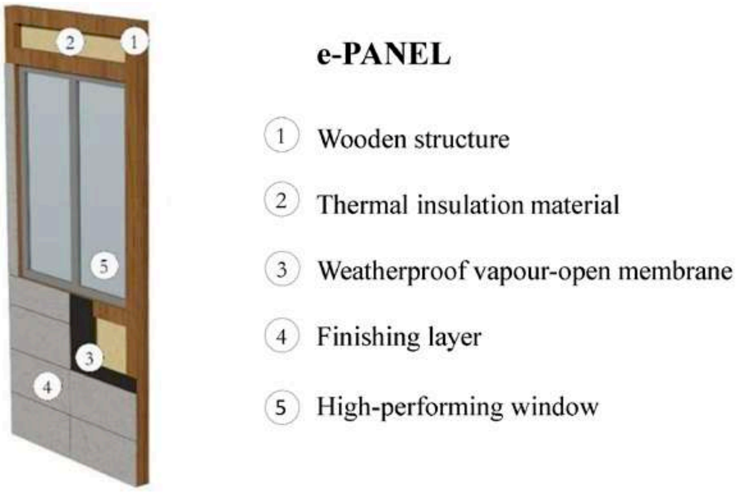


Fig. 5. *e-PANEL component.*

tems (e.g., Venetian blinds, roller shutters etc.) to reduce indoor overheating in summer.

Since the e-PANEL has no structural role, it is made of a lightweight wooden frame to ensure easier manufacture, low environmental impact, and cost savings.

The e-PANEL integrates an insulation layer, a weatherproof vapour-open membrane, and a finishing coating, as much as the e-CLT. A non-ventilated air cavity between the insulation and the cladding layers can be required to match the overall thickness of the e-CLT.

3.2. CONSTRUCTION ANALYSIS

The proposed retrofit technology is characterised by a high level of prefabrication, which makes its implementation fast and easy. Indeed, the panels are entirely prefabricated and are installed through mobile lifting equipment (cranes, lifting platforms, etc.), which avoid the disruption of traditional scaffoldings (Fig. 6).

The installation of the panels takes place from the ground storey of the building to the top one, and from the right corner to the left (or vice versa). Specifically, the e-CLTs are connected to the RC beams through the "anchor profiles" of the friction dampers. These profiles are pre-assembled on the top side of each e-CLT. An additional steel plate between the beam and the profile is provided to ensure the vertical alignment of the e-CLTs and also cover the gap resulting from the removal of the finishing layer of the beam for a higher profiles grip.

Once the e-CLTs of two consecutive storeys are installed, each "anchor profile" is connected to the corresponding "free profile". Based on the damper configuration, the "free profiles" can be installed on-site (Fig. 6a) or can be pre-assembled on the bottom side of each e-CLT (Fig. 6b). The first option allows to properly align and connect the friction surfaces of the two steel profiles, but it requires more time to tighten screws on-site. Conversely, the second option makes the installation process faster, but more prone to errors since the alignment of the friction surfaces cannot be guaranteed on-site. In this regard, additional alignment components are under investigation to avoid installation errors.

Unlike the e-CLTs, the e-PANELs are not equipped with friction dampers since they do not have a structural role, but they are connected to the building structure through steel connectors with seismic resistance properties (Fig. 6). Specifically, the e-PANELs are fixed at the top through commercial angle steel brackets, while specific sliding connectors are provided at the bottom. In this way, they undergo the same sliding movement as the e-CLTs in case of damper activation, while their out-of-plane rotation is avoided.

The e-CLT and e-PANEL are not connected to each other to avoid the transmission of forces from the structural panel to the non-structural one, which could damage the latter.

After the e-CLTs and e-PANELs installation, cladding solutions to cover the dampers are required. These solutions must be easy to install and remove for damper

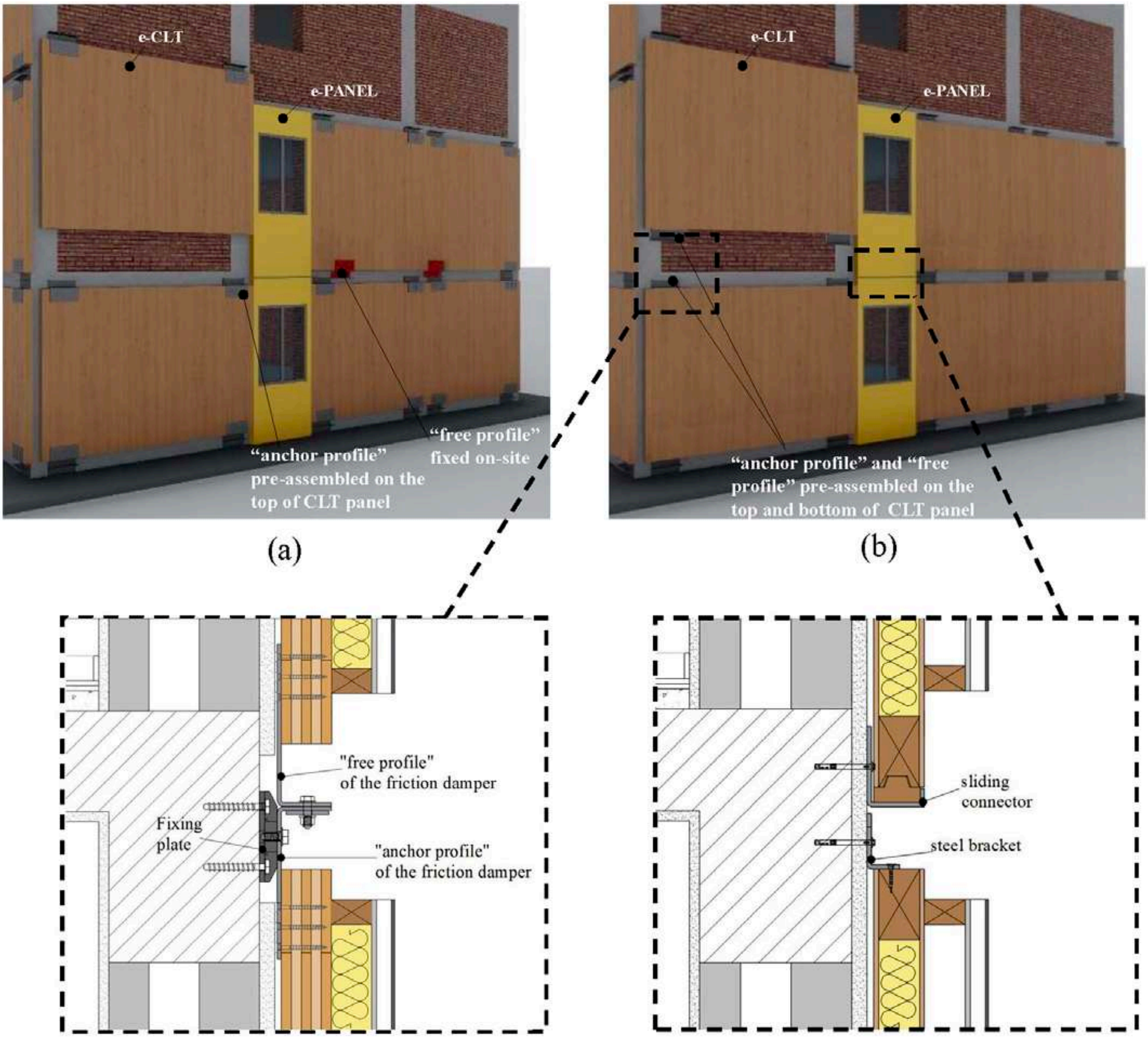


Fig. 6. *Scheme of installation of the proposed retrofit technology in case of damper connection (a) on the front side and (b) on the back side of the CLT panel.*

inspection and maintenance (e.g., preload friction bolts that may have loosened after a seismic event). They also need to reduce the thermal bridges at the beams level.

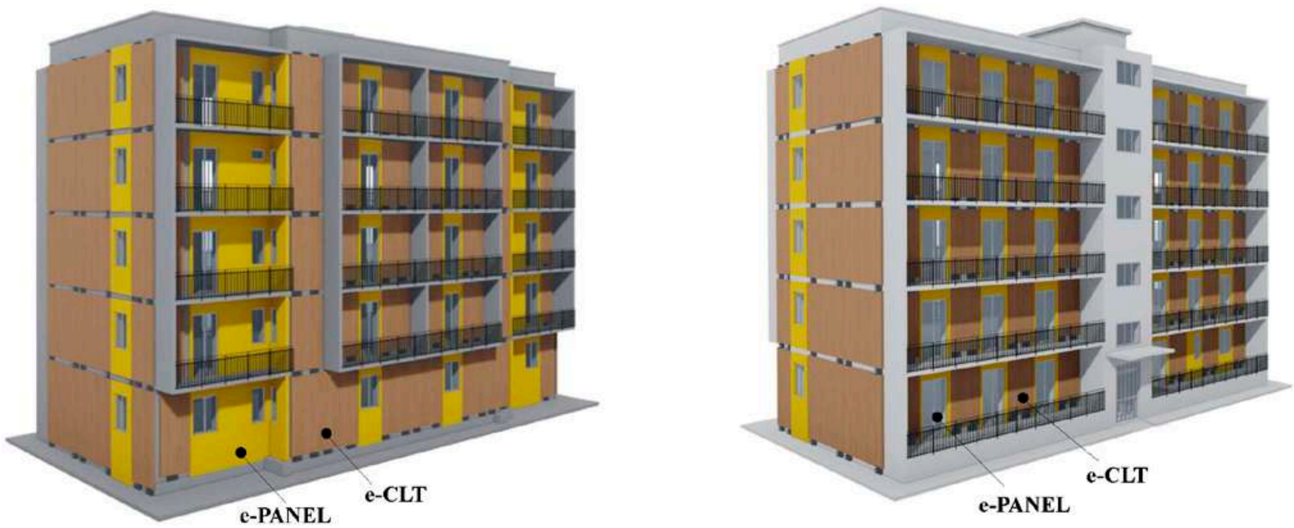
Based on the above construction analysis, potential application solutions of the proposed retrofit technology are illustrated in Section 4 to investigate its technical feasibility and versatility.

4. APPLICATION SOLUTIONS

Figure 7 schematically shows an example of the application of the proposed technology to a case study.

The case study is an RC framed apartment block (Fig. 7a) built in 1964 and located in the city of Catania (Sicily, Southern Italy). It belongs to a public housing compound and is representative of the buildings erected in Southern Italy before the issue of the most recent and restrictive national regulations on seismic resistance and energy efficiency in buildings. Indeed, the RC framed structure is mainly arranged along the longitudinal direction, while the external infill walls are made of two leaves of hollow concrete light blocks (8-cm thick internal leaf and 12-cm thick external one), with an intermediate non-ventilated, non-insulated air cavity (9-cm thick).

(a)



(b)

Fig. 7. *Pilot building in its current state (a); application of e-PANELs and e-CLTs to the pilot building (b).*

In the post-renovation state, the structural e-CLT panels are applied to the outer blind walls of the building by assuming their uniform arrangement on the opposite building fronts, according to the concept of the retrofit technology (Fig. 7b). Conversely, the e-PANELs are applied to all the windowed walls.

Potential application solutions of the proposed technology are here illustrated, with a focus on the main technological issues discussed in Section 3.2. These solutions are aimed at: 1) ensuring the correct operation of the technology in case of dampers' activation; 2) ensuring the high durability and the quality performance of the system; 3) providing a proper architectural integration of each component.

Figure 8 shows an example of stratification for the e-CLT and e-PANEL. The e-CLT is assumed to be made of a 10-cm thick CLT panel coupled with a 6-cm thick wood fibre insulation layer, while the e-PANEL integrates an 8-cm thick wood fibre insulation layer. These stratifications allow reducing the U-value of the existing wall by complying with the limits set by the current regulations for the climate zone B (Catania). Cement-based boards are inserted into both the panels to ensure adequate fire performance, preventing the wood-based insulating material from contributing to the spread of a fire. Moreover, a weatherproof vapour-open membrane protects the main layers of each panel (i.e., insulation materials, CLT panel,

1. CLT panel, 10 cm
2. Wood fibre thermal insulation, 6 cm
3. Cement-based board, 1.25 cm (e-CLT)/ 1-1.25 cm (e-PANEL)
4. Weatherproof vapour-open membrane
5. Ventilated air cavity, 3 cm
6. WPC slats
7. EPDM softband
8. OSB board, 1 cm
9. Wood fibre thermal insulation, 8 cm
10. Non-ventilated air cavity, 6 cm

Fig. 8. *Horizontal section of e-CLT and e-PANEL.*

etc.). A 3-cm thick air cavity is also provided between the insulation and the cladding layers to reduce building thermal loads in summer while also drying rainwater infiltration or winter moisture. Then, a cladding layer made of wood-plastic composite (WPC) slats is assumed for both kinds of panels. According to the above stratifications, the total panel thickness is 24 cm.

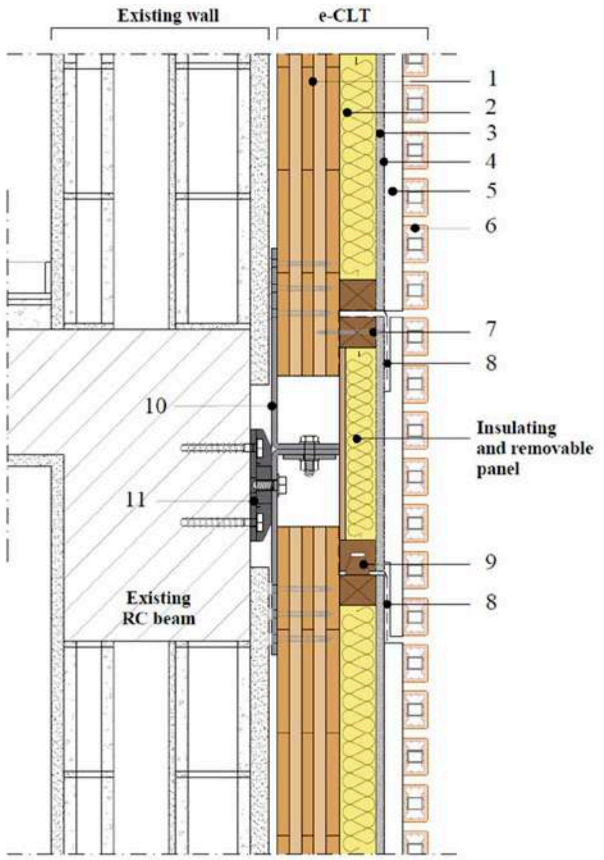
The e-CLT and e-PANEL are not connected to each other, as reported in Section 3.2. Instead, they are separated by a 2.5-cm wide joint that is protected from rainwater infiltration through an UltraViolet (UV)-resistant EPDM softband.

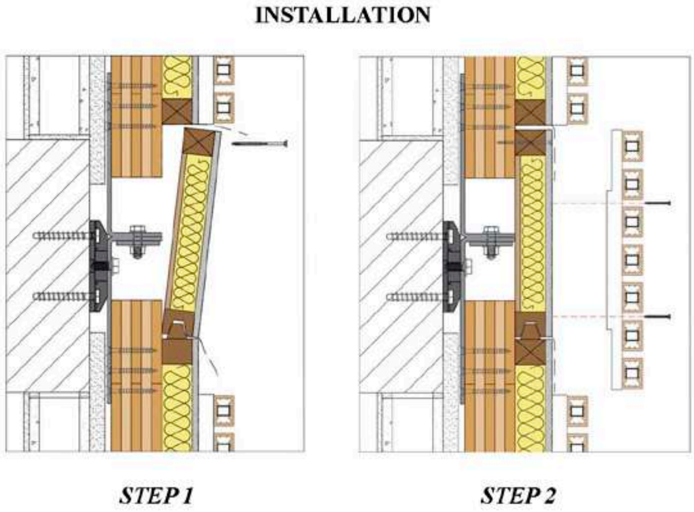
Figure 9 reports potential components to cover the dampers after e-CLT and e-PANEL installation. These components are prefabricated panels that must be removable for dampers inspection and maintenance. They have a wooden frame structure and integrate insulation material. On one side, each panel is fixed to the e-CLT of the upper storey through standard screws, while it is put on the e-CLT of the bottom storey by means of a tongue and groove joint; in this way, it can follow the sliding of the upper e-CLT in case of dampers activation without suffering damage.

The solution in Figure 9a provides for the installation of the cover panel in multiple steps, which include: 1) installing the cover panel and overlapping its weatherproof membrane to one of the upper and bottom e-CLTs to protect the joints from water infiltration; 2) fixing the cladding substructure (e.g., aluminium or wooden studs) and then the cladding layer. This solution is suitable for various cladding materials. For instance, porcelain stoneware tiles can be fixed and removed through standard clip systems, while pre-plastered cement boards or wooden staves through pre-painted screws.

On the other hand, the solution in Figure 9b provides for the total prefabrication of the panel, which also integrates the cladding layer off-site. In this case, the panel is screwed to the upper e-CLT using an aluminium plate that is pre-fixed to it. Aluminium flashings are also provided on its upper and lower side to avoid water infiltration since the overlapping of the weatherproof membranes cannot be achieved in this case.

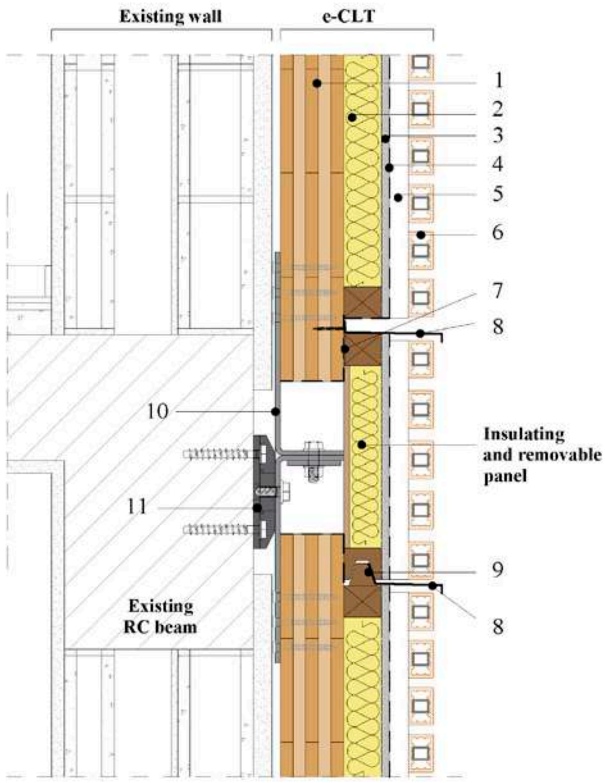
The above-described insulating and removable cover panel is also used to connect two consecutive e-PANELs, thus ensuring an architectural uniformity of the entire façade.





1. CLT panel, 10 cm
2. Wood fiber thermal insulation, 6 cm
3. Cement-based board, 1,25 cm
4. Weatherproof vapour-open membrane
5. Ventilated air cavity, 3 cm
6. WPC slats
7. Screw connection to the e-CLT of the upper storey
8. Overlapping of the weatherproof membranes
9. Tongue and groove joint
10. Friction damper
11. Fixing plate

(a)



1. CLT panel, 10 cm
2. Wood fiber thermal insulation, 6 cm
3. Cement-based board, 1,25 cm
4. Weatherproof vapour-open membrane
5. Ventilated air cavity, 3 cm
6. WPC slats
7. Aluminium plate pre-fixed to the panel and to be fixed to the e-CLT of the upper storey
8. Aluminium flashing
9. Tongue and groove joint
10. Friction damper
11. Fixing plate

(b)

Fig. 9. *Cladding solutions to cover the dampers after the e-CLTs installation: (a) partially prefabricated cover and (b) totally prefabricated cover.*

5. POTENTIALITIES AND APPLICATION LIMITS OF THE PROPOSED RETROFIT TECHNOLOGY

The main target of the proposed retrofit technology is multistorey residential RC framed buildings built between the 1950s and the 1990s. These buildings usually have regular openings on façades, which allows for uniformly applying the structural e-CLT panels to each building storey. Specifically, the system can be effectively used in buildings provided with outer blind walls where an adequate number of structural panels should be applied to ensure the expected level of seismic upgrading.

Detached buildings are better suitable for this technology since the e-CLTs can be added to each front of the building. Otherwise, the internal application of the e-CLTs to the walls between two buildings might be required.

If there are colonnades at the ground story of the building, the e-CLT panels will need to be applied to them. This will be possible if the CLT application does not affect the use of these areas.

Many garages or commercial premises with many large shop windows may also preclude the e-CLTs application, unless the surface of the windows is reduced during the renovation works. Even an extensive use of bow-windows limits the application of the structural panels, which cannot be connected directly to the beams of the RC structure, thus considerably reducing the effectiveness of this solution.

Figure 10 shows some examples of buildings suitable to be renovated with the proposed retrofit technology.

The above analysis of the main target buildings is at a preliminary stage. More investigations are required based on the developments of the technology.

6. CONCLUSIONS

This paper describes and analyses the technical feasibility and versatility of a novel technology for the integrated seismic and energy renovation of RC framed buildings. The proposed technology consists of applying prefabricated, insulating timber-based panels to the existing outer walls of the building by combining structural CLT-based panels equipped with innovative friction dampers with non-structural wooden-framed panels hosting high-performing windows. The result is a new prefabricated shell that acts as seismic-resistant and energy-efficient skin, also contributing to renovating the architectural image of the building.

Specifically, this work analyses the main technological issues of the proposed intervention and investigates technical solutions to ensure a correct operation during seismic events, a high durability and quality performance of the main components, as well as a proper architectural integration. The investigated solutions, applied to a case study located in Southern Italy, show the effective applicability of this retrofit technology to the main target buildings (multistorey residential RC framed buildings built between the 1950s and the 1990s) and ensure a high level of prefabrication, thus significantly reduce implementation costs and time and occupants' disruption. Moreover, the proposed intervention turns out to be highly versatile since it does not require too much space

Fig. 10. *Examples of target buildings located in Catania (Southern Italy, high seismic zone).*

around the building, thanks to the limited thickness of the panels.

Further technical investigations will be conducted according to the results of the ongoing multidisciplinary research that is involved in developing the proposed retrofit technology.

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Authors contribution

Conceptualization, G.M. and C.T.; writing – original draft, C.T.; writing – review and editing, G.M. and C.T.

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THE MARBLE ENVELOPE OF THE *CASA DELLE ARMI* BY LUIGI MORETTI: DOCUMENTARY AND EXPERIMENTAL KNOWLEDGE FINALIZED TO DIGITAL MODELING

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Abstract

The application of digital modeling for safeguarding the built heritage is a consolidated research field and carries substantial operational interest. The methodological aspects of this application are theoretically outlined but far from being commonly applied. In the perspective of delineating a more straightforward method for implementing these practices among the built heritage, modern Italian architectural production constitutes an ideal field of investigation, both for the significance of the built heritage and for the construction problems that characterize them. Indeed, in the case of stone cladding – which is typical of the Fascist period – the decay conditions and the peculiarity of the material make the investigation specific and paradigmatic of the implementation of the above-mentioned digital methodologies. The *Casa delle Armi* built heritage by Luigi Moretti in Rome, which has been the research subject of the Authors for years, features a marbled envelope detailed by the designer in every aspect, not only during the design phase but also during construction. This uniqueness makes the recovery of the envelope extremely challenging, as it should not alter its extremely complex nature, while today, the marble envelope is profoundly degraded by natural and anthropogenic factors. Digital modeling appears to be an optimal operational solution for guiding the recovery, but it presents many issues illustrated in this article and to which we have begun to give answers in this contribution. In particular, we delineate the knowledge of the case mentioned above study-built heritage, pursued through documentary analysis integrated by direct and instrumental observation on site.

Keywords

HBIM, Marble envelope, Luigi Moretti, Digital model.

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1. INTRODUCTION

Digital technologies present important development possibilities for the management of the built heritage. In particular, Building Information Modeling (BIM), conceived for the informed digitalization of the building process in the case of new constructions, is applied to the built heritage under the Heritage BIM (HBIM) definition, for which there are still open questions and challenges.

This contribution addresses these issues with respect to a key work of the Italian twentieth-century architecture: the *Casa delle Armi* by Luigi Moretti, built in the *Foro Mussolini* (now *Foro Italico*) located in Rome in the years 1933-1937. The marble cladding of this building is the first modern stone envelope built in the city and presents a peculiar technical solution – thin stone slabs anchored with mortar and metal clamps to the wall- which was still experimental and highly innovative at the time and destined to be a reference for many works of that historical period. The early deterioration of the cladding is a consequence of the experimental nature of this technical solution and is common to similar applications characterizing modern architecture.

The recovery actions, aimed at conservation, maintenance, and improvement, can be supported by the digital methods, which are investigated together with their limits, in this contribution, with the aim of delineating a framework.

The framework is articulated into three main aspects:

- the application issue for the HBIM;
- the significance of the considered case study;
- the research method that is here applied and its results.

While HBIM was investigated in previous works [1], the research currently addresses the problem of survey data restitution on the BIM platform (*ScanToBIM*). On this aspect, there are significant results, as highlighted in [2], but the debate is open on the definition of "Level Of Knowledge" (LOK) [3], HBIM and database [4], and the semantics of modeling [5, 6]. Equally important for their potential development are also the tools related to virtual and augmented reality [7].

The stone facade of the *Casa delle Armi* by Moretti was examined. The realization of such a facade is paradigmatic of the definition phase of the modern architectural lexicon, deriving from the synthesis between stylistic innovation and technical experimentation. The desire to propose a solid reference for classicism in defining the language of the new Italian architecture, not extraneous to the ideological thrusts of the Regime that sought its cultural legitimacy in this reference, leads to having to solve utterly new construction problems to reconcile the needs of marble, fragile and heavy, with the lightness required by the structural cage, moreover elastic [8–11]. Inexperience and lack of knowledge of the properties of the materials were the conditions for such a quick deterioration experienced, as in other buildings, a few decades after its construction. Even the restoration interventions, which have occurred over time, have been conducted without the necessary skills. From a certain point on, they have also been vitiated by political prejudices that have drastically reduced attention to the specificities of the work, creating further and often irreversible damage [12].

This research represents the first phase of a broader program undertaken by the authors. The program aims to develop a protocol for modeling the modern architectural heritage in the context of sustainable informed management. The theoretical approach to the understanding of the heritage, which is the first preliminary phase of the modeling process, is here integrated with the geometric survey of the heritage and with the documentary research on the project and its construction features [13] through on-site observation through instrumental analysis and technical construction evaluation. However, the central problem is the definition of the criteria for digitizing the observations, as already stated previously, with respect to the construction of the HBIM model. The description and discussion of what has been done constitute the subject of this contribution, as detailed in the following paragraphs.

2. METHOD

2.1. IDENTIFICATION OF THE CASE STUDY

As already mentioned, the *Casa delle Armi* by Moretti is a significant case in the architecture of the Fascist period for many reasons. With respect to this specific research, the presence of one of the first thin stone claddings in marble – an architectural element destined to characterize the very image of the Regime, due to the references to Italic history and ancient Rome – is particularly relevant. The cladding is applied with a construction technique derived from that of traditional stone walls, but with a fundamental difference: indeed, the thickness of the marble slabs is reduced to a very few centimeters (3, in some cases even 2), thus entrusting the task of supporting the slabs to a layer of mortar integrated with metal anchors.

The limits and problems presented by this choice were the basis of the so-called "issue of marbles", which kept technicians and architects busy for a couple of decades [9, 13].

Due to this initial flaw and incorrect or badly executed interventions over time, the building is now severely degraded. The recovery appears very complex due to strong formal geometric constraints that do not allow any tolerance, considerably limiting the construction techniques applicable for consolidation. In addition, Moretti had designed every detail of the cladding, personally chosen each slab, and applied pictorial retouching on the texture of the marble veins, which makes the hypothesis of any replacement of the deteriorated slabs extremely critical.

In fact, the Architect conceived the cladding as a continuous envelope, a kind of unitary sculpture that encloses the building like an immutable skin. As a methodological premise, it should be specified that this very conception allows – specifically in this case – to analyze the problem of recovering this envelope, freeing it from considerations relating to the building as a whole. In other words, there are no alternatives to the stone envelope restoration, along with everything this entails in terms of the technical difficulty of the intervention.

If, on the one hand, the reduced thickness of the slabs leaves no room for rehabilitation of the material, on the other hand, the petrographic peculiarities of the marble make replacement difficult; moreover, every solution has to deal with the same causes of deterioration that degraded the current one in order not to incur in a repetition of the same problems. In this context, the digital approach appears to be the most suitable for formulating intervention scenarios that meet the many conflicting conditions and are also compatible with the economic resources available for recovery.

2.2. KNOWLEDGE AND DOCUMENTARY PHASE

Like all stone construction elements, the stone cladding requires a preliminary and detailed design of each construction element, specifically made in the factory. Not even Moretti, who was in the habit of making many changes during construction, could not escape this need. Indeed, by attributing importance to the stone envelope in the architectural definition of the building, he designed every single element in a well-known document, an accurate file concerning the entire supply of marble [14, 15].

By starting from this "abacus", the research examines the subsequent phases of the construction history: from the verification of the envelope's actual weaving to consolidation interventions and replacement of slabs, up to the survey of the current situation.

Another important aspect is the type of marble. There is no agreement on this and other information between the scientific literature and the documentary sources relating to the executive phase of the building construction. An in-depth doctoral research work, conducted by Vannucchi [16], has clarified many questions relating to the cladding, including the type of marble used (a veined *statuario* marble) and even the quarry of origin, without this being able to solve the problem of finding suitable material for possible replacements, as the current conditions of the basin are very different from those of the time.

The work is currently owned by CONI and is managed by Sport e Salute SpA, whose Office for Historical and Cultural Documentaries is part of the research group. The historical archives of the institution constitute a relevant documentary basis, integrated with the Ph.D. research mentioned earlier, conducted not only in the central and private archives but also in the field with interviews with the heirs of the Architect and of the Operators of the time.

Documentary knowledge, however, is not sufficient for the technical understanding, which is integrated with direct observations on the cladding and instrumental analyses. Those latter, still under development, provide additional information with non-destructive methods. In particular, the thermographic analysis promptly reveals the surface temperature differences of the stone slabs. These differences are an indication, on the one hand of the different reflections of the thermal radiation connected to the nature of the material and of the mineral intrusions that determine its veins; on the other hand, they indicate the degradation state of the surface and even the presence of the metallic supports, both the original anchors and the passing fixings inserted during the consolidation phase. Due to the different thermal properties, the thermography clearly shows the slabs replaced with others of different marble.

Finally, thermal fluxes crossing the envelope have been measured in order to verify the thermal transmittance property of the façade. Measurements have been performed employing thermal flux meters, during suitable monitoring days, according to UNI EN ISO 6946:2008 regulation. The measurements were conducted during February for fifteen days. The investigated façade is the west one due to the possibility of applying the instrument on both the inner and outer face of the envelope and its peculiar architectural significance due to marble cladding.

2.3. DIGITAL STRUCTURING OF THE KNOWLEDGE

The digital organization of knowledge is the following phase, which preludes to the actual digitization by realizing the informed model. The modeling process must include the building's geometric shape, the construction techniques used, and the characteristics of the materials as a prerequisite for the definition of the intervention, the performance improvement, and the building management over time. For this purpose, the multidimensional structure typical of BIM (and HBIM) is used, which integrates the three geometric dimensions (3D) with aspects related to development over time (4D), costs (5D), management of the work in its life cycle (6D), up to the so-called facility management which defines the social, economic, and environmental sustainability of the building (7D). Despite the apparent descriptive breadth, the available practices do not match the actual modeling needs.

The major problem is represented by the limited possibilities of taking into account subsequent interventions over time, with differentiated and not predetermined phases, contrary to new buildings. In fact, consolidation and alteration interventions do not follow one another in a predictable way as in construction site operations; in addition, the model must allow for the integration of information with knowledge acquired in subsequent times. The problem was dealt with by Cernaro [17], who, in her doctoral research, developed the problem for a contemporary construction in Messina [18].

There are, however, other aspects that the digital model fails to take into account.

The facade of the *Casa delle Armi* is the result of a meticulous dimensional study, which Moretti made on the basis of the classical proportions and the Golden Section. The restitution of these relationships, implicit in the project drawings, fails in the reconstruction of the finished work and is further compromised in the current state. Obviously, the recovery intervention cannot ignore the compliance to these relations, but the digital model is not able to make them available for automatic processing aimed at supporting the decision-making process.

3. RESULTS AND DISCUSSION

3.1. THE DOCUMENTARY KNOWLEDGE OF THE BUILDING

Casa delle Armi is considered a masterpiece of the architect Luigi Walter Moretti. Also known as the *Accademia di Scherma* and in its first name as the *Casa Sperimentale Balilla*, it is located inside the sports complex of the *Foro Italico* in Rome, at the top of the southern section. Born as an advanced typological experiment, *Casa delle Armi* is considered the most modern of the buildings of the *Opera Nazionale Balilla*. Moretti creates a kind of architecture with a clear image and considerable functional complexity. At the end of Viale Angelico, its strategic location with connections to the historic city and San Pietro has allowed a representative designation.

As is well known, almost all the documents of the Moretti Archive have been lost.

The lack of textual materials in the archives obliges the research to reconstruct the design phases through a "circumstantial" process. This process has been followed by deepening the techniques used by the Architect according to the existing technologies during the construction period. The project started with an in-depth study by Moretti for the construction of a gym with a swimming pool; straddling the volume was a collector of curvilinear trends buried at 19 meters; in the second volume, which arose almost simultaneously, it was planned to include offices.

The two volumes appear independent and without connections from the archival findings. The connections appeared only in the second phase with pencil traces in the form of notes and only regarding the basement level. Subsequently, to these notes are added others where the two buildings appear connected with horizontal paths at two levels, and the building assumes the "L" arrangement, divided internally by different elevations joined by a third volume in the shape of an ellipse, that distributes and welcomes the two wings. The construction process is testified by the executive drawings, representing only the initial phase: many decisions were taken during the works, and only some were codified in notes or sketches. The dates of the documentation are various. In the archives are kept three photos, dated April 4, 1934, of the building being completed and two photos by Alinari, dated 1935, which, as an archival location, are inserted in the photo pool of 1937. Although among the first official shots, an event appears – the first official, the *Exhibition of Sport* set up in the body of the Library and the *Exhibition of the Houses of Balilla* set up in the body of the weapons room – the first official date is linked to a visit by Benito Mussolini on October 28, 1936.

In 1937, the building appeared to be divided architecturally into two parallelepiped volumes, namely the Library (and its ancillary spaces for meetings and room for the Museum) and the *Sala della Scherma* (and its ancillary spaces, such as the services). Before this final functional subdivision, the building was first intended as *Casa Sperimentale* ("experimental house"), then as a gym, then as the swimming pool, and all of these functional variations are testified by only one drawing. According to the saying of the time, the combination of the Library and the *Sala della Scherma* is seen by some historians as a recall of the "book and musket". In the spring of 1937, when the Balilla Statue by Bellini was placed, the project of the *Casa delle Armi* was considered concluded. During the same year, in August, the famous article by Plinio Marconi was published in the magazine *Architettura* [19], which described the geometry, functions, and characteristics of the *Casa delle Armi*. Therefore, in the document on the marble envelope of the building, the 1937 date will be used as a reference for the conclusion of the construction.

The area of the *Foro Italico*, with the construction of the Morettian building, takes on a new trend compared to the rest of the existing buildings; its tendency is almost abstract and metaphysical because it is characterized by the rigorous use of white tones woven between classicism and baroque. The *Casa delle Armi*, "dressed in white", also imposed its image on the *Foresterie Sud* by Enrico Del Debbio, who had to modify his work painted in red – called Pompeian – both in volume, raising a floor the artifact, and in style and functionality, covering the building with white marble. The white imposed by Moretti was not to be absolute. However, several whites with similar facets were sought and created by the Architect with detail, craftsmanship, and careful technique, as well as with a great work of research of the material and its relative technique aimed to propose the architectural language of the *Foro Italico* as "modern".

For the *Casa delle Armi*, Moretti opted, differently from what he did for previous works for example in the Monoliths of the Piazzale dell'Impero, for marble with fewer veins as possible. Although the documents found as evidence are not many, the choice of the cladding material of the architecture is clear, a Moretti choose slightly veined white and bright Carrara marble, called *lunense*. In the archival documents, there are a series of executive drawings relating to the marble cladding blocks: a sequence signed by Moretti and qualified as "architectural orders". The same care taken in the paper restitution of the slabs characterizing the facades was carried out in the immediate outdoor space of the building, both for the outdoor paving and for the decorative pool.

Moretti's approach is a methodological and design approach that connects the "rediscovery" of the rules of antiquity with the projection forward allowed by scientific-technological innovation, of which the cladding is one of the most striking examples. In the marble cladding, the Architect interprets, reworks, and implements the teaching of the past. At the same time, he developed an almost scientific methodology, using his mathematical skills and new theories and technological practices, making the *Casa delle Armi* a work aimed at seeking a new classicism. The external cladding in Carrara veined statuary marble has a design of the slabs developed very carefully by Moretti, who wanted to give the impression that the building was made from a single block of marble, almost a sculpture. The slabs, with thickness from 2 to 5 centimeters, in the linear parts of the elevations, have a variable height starting from 48 cm at the base of the building and then gradually decreasing upwards with bands of 47 and 46 cm. The curvilinear slabs placed in the joints have considerable architectural and technological value. The *Casa delle Armi* fits perfectly into the personal research of Moretti aimed at identifying a modern

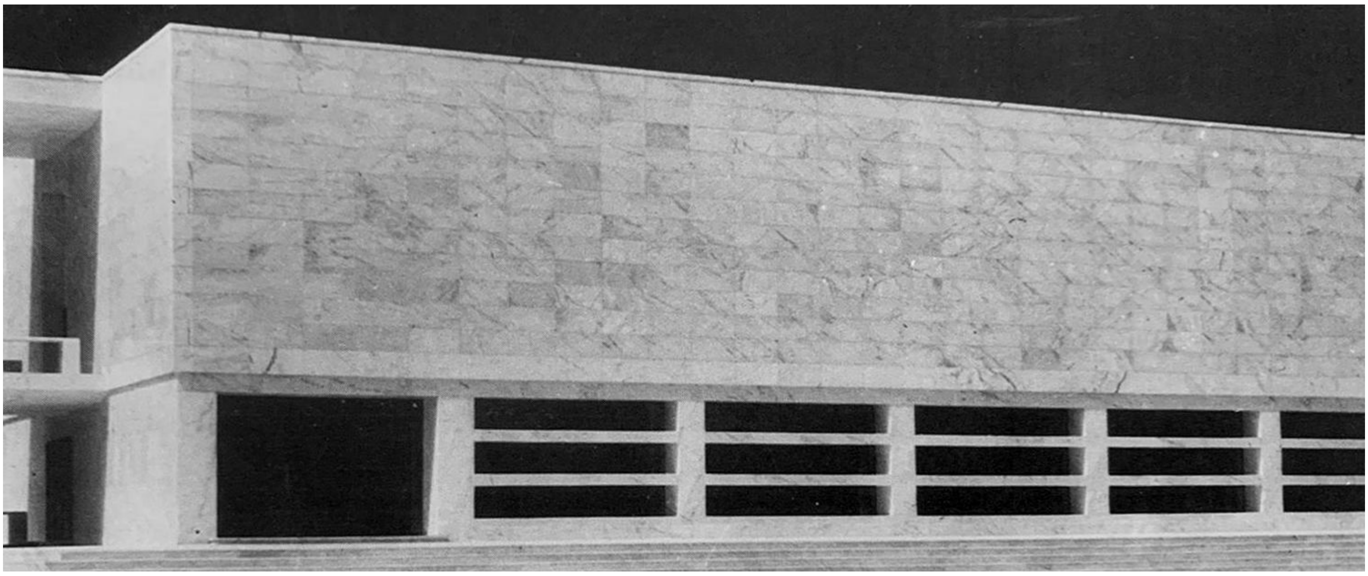

Fig. 1. *Casa delle Armi, Rome, 1935. (Photo © Sport e Salute Spa, Direzione Infrastrutture Sistemi e Ingegneria Dello Sport - Archivio storico CONI).*

architecture capable of alluding to classicism without repeating the forms. Plinio Marconi underlined this aspect in the article mentioned above published in *Architettura* in August 1937: «On the outside, the *Casa delle Armi* is completely covered with Carrara veined marble slabs, which vary in height from cm 48 at the base of the building, to 47 and then 46 at the top. The squares, the tub, and the external floor guides are in common Carrara marble».

3.2. THE FACADE CLADDING AND THE MORETTI ABACUS

In the archival documentation, there are tables of the orders of the marble slabs that surround, like a marble skin, the *Casa delle Armi* and that – in a systemic, mathematical, and technological way – generate a maieutic and prodromic study on the technology of stone material in modern times. These slabs, signed by the Architect on March 10, 1935, were represented in a special abacus, complete and complex, and sent directly to the quarry Simonelli Marina di Carrara.

The choice of the cladding of the artifact is the result of Moretti's studies on baroque and classicism combined with his mathematical-operational research and revision of past architecture, identifying those fundamental and symbolic aspects that, when transferred to contemporary architecture, give it new strength. The intent is to extract from the works of antiquity those geometric, functional, and spatial rules that govern the architecture and its space. Moretti's relationship with the constructions of the past clearly emerges from the cognitive investigation of the rules of the artifact, highlighted by the generative geometric matrices that characterize the design of the elevations and the base of the abacus of the stone blocks. Moretti declares and pays particular attention to the need to act in the design process of his prospects with an approach that finds its starting point in the mathematical formulation. In the design approach to the representation of the exterior marble cladding, the Architect reveals with immediacy the mathematical rule that highlights the univocal link between external and internal with balances of forces represented in the thickness and connections of the slabs that concretize the Vitruvian triad: *venustas-utilitas-firmitas*.

These concepts can be deduced and found in the external cladding abacus tables, divided into lot A and lot B, respectively, for the Hall of weapons and the Library volume. Each slab follows the geometric characteristics in function of the vertical and horizontal placement and the activities housed in the interior of the volume. The different thicknesses of the slabs are identified, from the photographic survey, in correspondence with the internal hosted functions so that the observer can read the architecture from the outside to the inside without revealing the structure covered and protected by the stone material. The slabs, divided in alphabetical order, from A to Z, have specific characteristics: they are wider near the elevation angle and higher, vertically, while going up. The thickness varies from 2 to 3 cm in the linear parts, reaching a thickness of 10 cm for the special elements placed at the corners. The latter, like the curvilinear strokes, have been obtained from unique marble blocks following the technique of "cutting to the reverse", so each type of slab is considered as a single piece whose calculations and drawings are specified in the tables, slab after slab, without neglecting any geometric details. The best-known facade in the historical photographs has been examined in detail to better understand the compositional criteria of the stone cladding. The facade is that of the gym, photographed by Alinari and Vasari between 1935 and 1936, then promoted in the magazine *Architettura* of 1937 and, since then, always identified with the exterior of the *Casa delle Armi*, as reported in documents: *Casa Sperimentale al Foro Mussolini* – Lot A (gym), Order I (facade towards the *Foresteria*). In the orders of this facade appear 1052 ordered slabs for a total area of approximately 500 square meters.

In the table, there are special pieces such as the S-shaped slabs and the 55 cm x 10 cm linear one, with 1 cm x 1 cm x 2 cm indentation, placed as a finishing layer on the facade cladding with the indentation as a drip edge. Among the corner slabs of particular interest is the T of only two pieces, size 104 cm x 104 cm x 55 cm, with a recess in the corner part, which, drawn in dashed line, acts as a 2 cm deep drip edge. The other corner slabs of the above-cited table are the U and V. The first one has 26 pieces of orders, while the second one has only 2 of them, like the T. The V has relatively small dimensions, 30 cm x 30 cm with a thickness of 5 cm, while the U has wings of different sizes, that is 58 cm x 38 cm with a thickness of 10 cm. Both slabs have a rounded inner corner. The curved solid blocks, specially designed for all atypical concave and convex places in order to make a softer transition between one surface and the other, are particular and of great interest, because they give the building the image of a classic and abstract monolith, made of matter ideally compact and free of connections. The slab that covers most of the surface on the façade is the A, 48 cm x 100 cm for a total of 420 pieces, occupying the central part of the facade. In order to deepen the study of the stone slabs of the facade and understand their characteristics, and also better define the technique used by Moretti, the weight of slab A was calculated considering it as a sample: given slab A of the aforementioned facade, with dimensions 48 cm x 100 cm and thickness 2 cm, and the specific weight of the statuary veined marble of Carrara, 2702 kg/mc, gives the total weight of the slab equal to 25.94 kg. From the calculation, the slab is light and delicate as to defend well the body of the wall, concealing, in particular, the internal structure, with a reference even to Borromini's technique, revisited in a modern key.

The technique of positioning thin slabs is typical of the 30s in Europe. The cut of the material, of mechanical type, allowed to obtain, from a block of marble more slabs of 2–4 cm thick. The laying work provided that the elements had to be fixed to the structure and the infill wall by previously mounted metal anchors. For this reason, the cut took place along the veins, contrary to what happened in previous eras, as it was no longer the compressive resistance to matter but the one to the impact and bending. After the cut, the slabs were expected to be polished off by rubbing, using mechanical ground tools and lead filings, after moistening the slab's surface with potassium alum water. Special holes were provided for fixing the slabs to the structure and infill wall on metal anchors previously mounted. The technique was different from the one used, for example, in the same period in America. In that case, it was used to mount a thicker cladding, between 12 and 20 cm, in which the stone blocks supported each other like an independent wall, which was built together with the structure. The stabilization of the cladding was necessary, above all, for tall buildings – e.g., for the first skyscrapers – through metallic elements that tied the slabs between them and to the structure.

The marble slabs of the *Casa delle Armi* are attached to the wall by a layer of mortar and fixed reinforcing anchors in the wall itself. The fact that it was a usual technique is confirmed by the fact that its description is little present in the archival documents, just sketched in the margin of some tables. The resulting structural problems can be deduced from photographic surveys, where it is seen that the surface below the slab appears perfectly smooth; this is due to the different thermal expansion between marble and mortar. This phenomenon is particularly evident in the elevations facing south because they are more exposed to the sun. In correspondence with the fixings, the metal anchors are present only in some cases. It should be noted that the cladding technique described above was not applied to architraves and ceilings for aesthetic and functional reasons. Orders for the slabs were signed by Moretti in March 1935 and requested by Marina di Carrara in Rome by the end of the month indicated in the orders. Along with the specifications on the drawings, there are precise indications to follow in the preparation and shipping phase of the stone slabs, manually written by Moretti. He had recommended that «all the slab elements […] had to have a surface perfectly

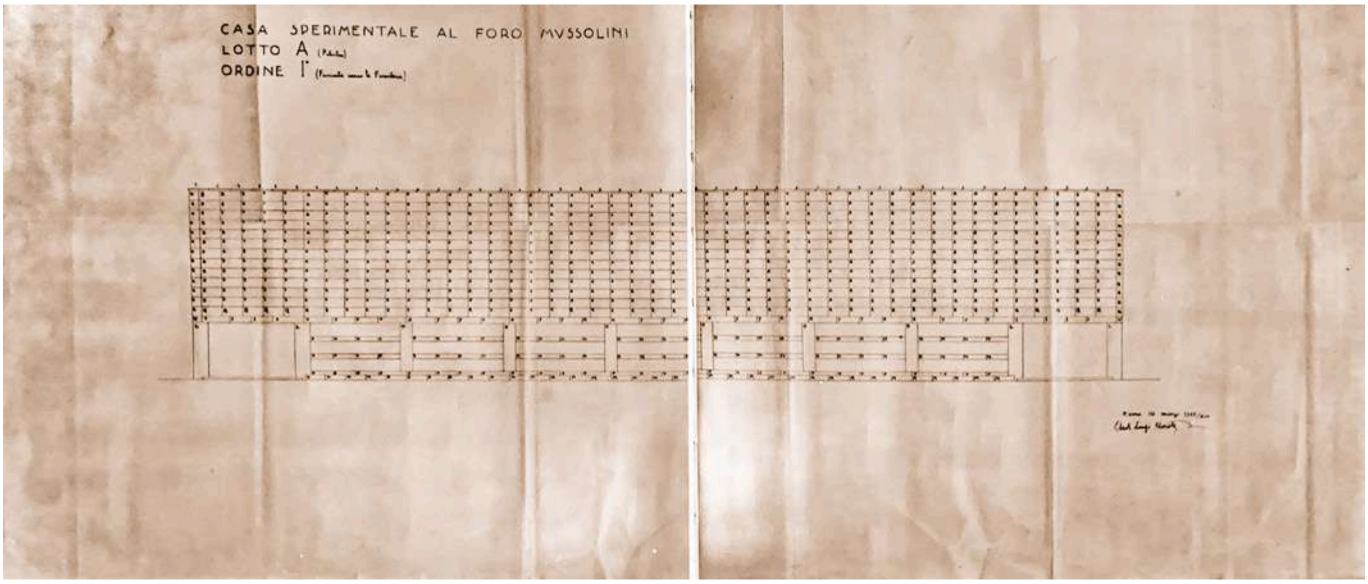

Fig. 2. *Moretti Abacus for one of the facades.*

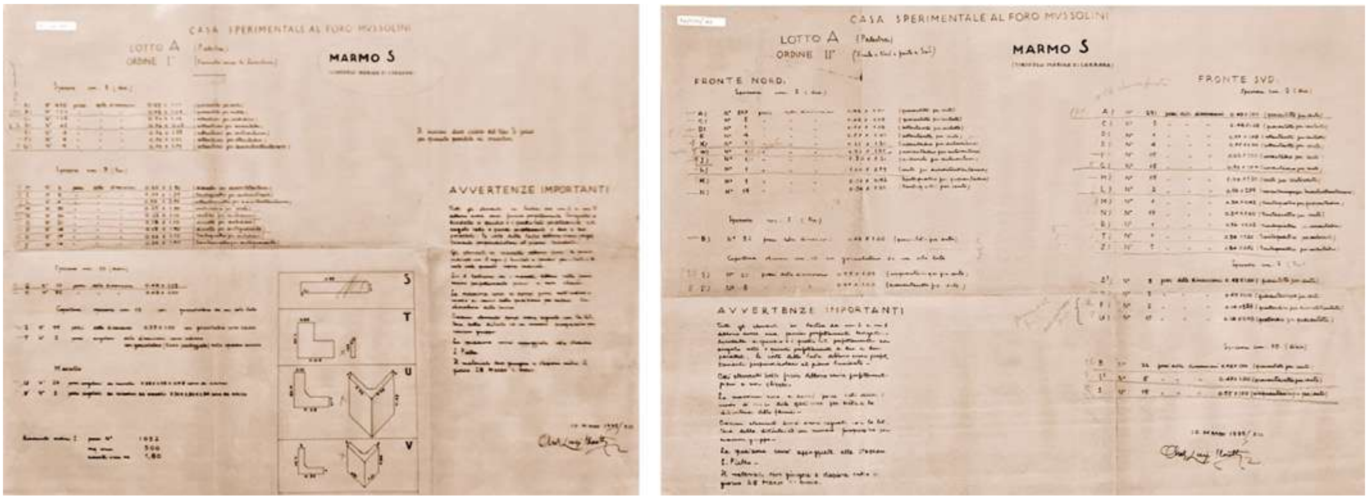

Fig. 3. *Drawings of the commercial orders for the marble slabs.*

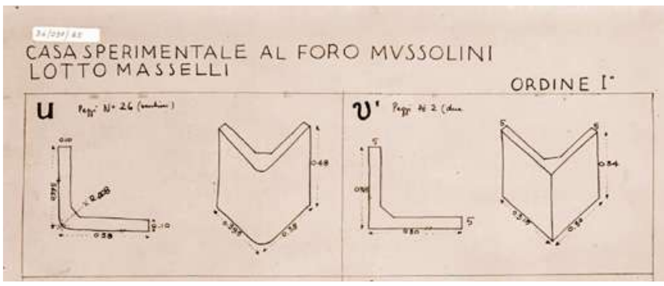

Fig. 4. *Moretti Abacus: detail of the corner slabs U and V.*

polished to mirror and the four sides […] perfectly parallel with each opposite side; the edges of the slabs must be perfectly perpendicular to the polished surface. […] Both the slab and the solid must come perfectly flat in the faces. The utmost care must be taken when loading the shipment to avoid the bending of the faces. Each element must be marked with the letter of the bill and a progressive number for each group».

3.3. COMPARISON BETWEEN THE ABACUS, THE BUILDING IN 1937, AND THE CURRENT STATE

Once chosen the facade to be studied, a macroscopic analysis has been carried out by comparing Moretti's abacus of the selected facade and the photos from 1937 (the year of the inauguration of the building) and those from January 2021. The choice of these three images is because they represent significant moments of the building's history: the design project, the inauguration, and the current state. These phases will be considered in the digitalization of the building, creating a model that can represent and describe its different phases to share knowledge on the building's history and plan maintenance activities.

After straightening and scaling the photos, the images are placed side by side and compared. This study aims to understand if there have been any changes during the construction phase compared to the original project and also to identify any interventions or replacements on the original marble slabs carried out to date, given the scarce presence of archival information on the restoration activities on the stone envelope of the *Casa delle Armi*. Therefore, this macroscopic analysis is preliminary for further, more in-depth investigations that will be able to verify the hypotheses made by the photographic comparison.

Thanks to the comparison of the archival documents and the photographs of today with Moretti's abacus, it can be deduced that the building construction precisely followed the design project, at least as regards the arrangement of the marble slabs. Furthermore, the slabs visible today appear to be the same as those in the inauguration photo – except for the second slab in the seventh row: the darker slabs and the more pronounced veins are clearly visible in both photographs.

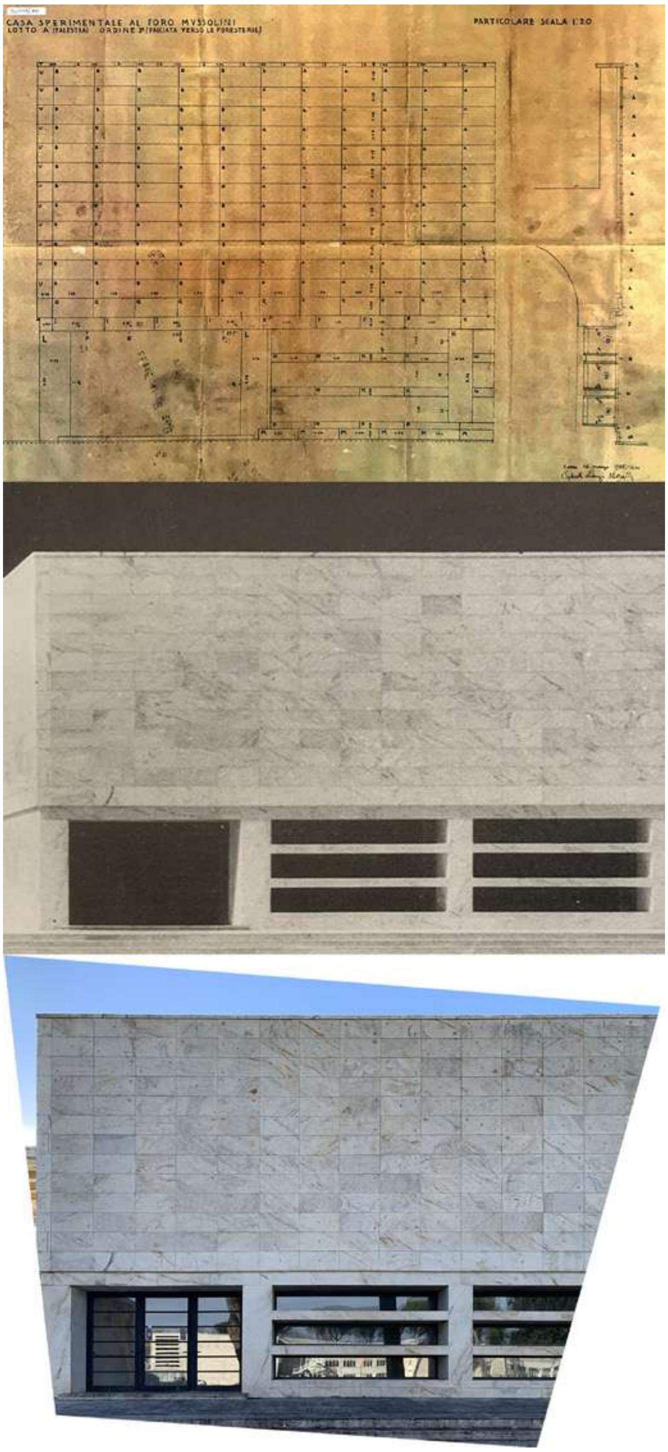

Fig. 5. *Photographic comparison between the abacus, the façade in 1937 and nowadays.*

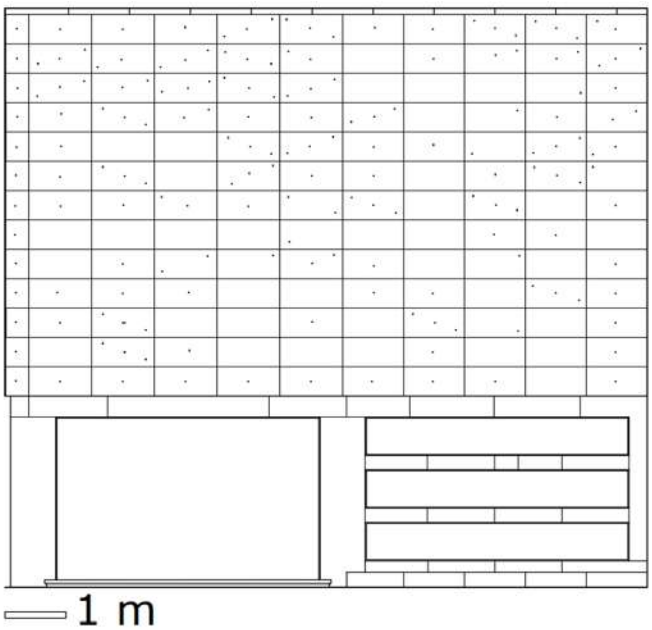

Fig. 6. *Part of the considered facade on which the metallic elements are highlighted.*

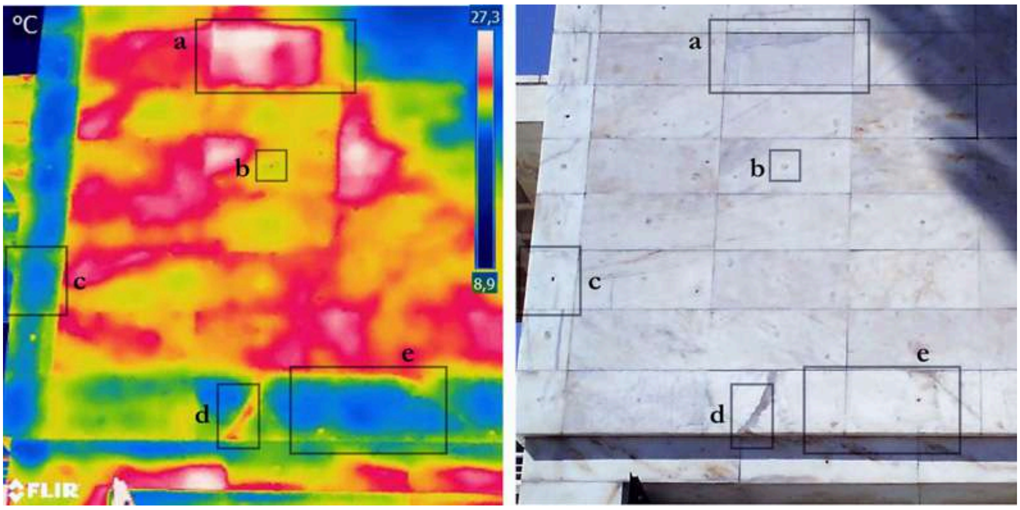

Fig. 7. *Thermographic analysis on a portion of the considered façade.*

The photographic comparison shows some additional metal elements put on the envelope irregularly, intending to further hold the thin slabs. These elements can be visible, from 1 to 3, in most of the slabs but not on all of them.

Another analysis is conducted employing a thermographic camera. This tool allows for non-destructive testing that can give important information on the construction techniques or the material and its level of decay. Figure 7 compares the thermographic image (on the left) and the photograph (on the right) of the same part of the considered façade. Through this comparison, some information can be found (Fig. 7):

- different thermal behavior of a replaced slab (a);
- the presence of metal elements (b);
- the presence of some thicker marble slabs on the corners and the lower row (c);
- the different thermal behavior of the veins that can bring to a faster decay because of the different thermal expansions (d) (e).

Finally, further non-destructive testing has been performed on a portion of the façade to measure the thermal flux crossing the envelope and assess the thermal transmittance. Results (Fig. 5) show that indoor temperature, as expected, is much more stable due to the thermal inertia of the wall than the outdoor temperature. Indoor temperature varies from 16 to 20°C, while outdoor temperature ranges from 2 to 21°C. The thermal transmittance is equal to 0.53 W/m^{2}K.

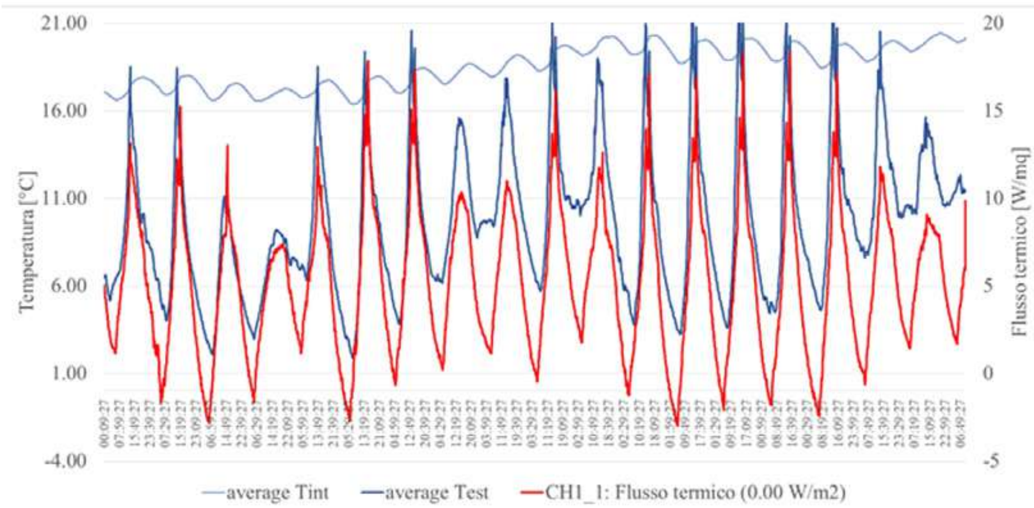

Fig. 8. *Results of thermal flux measurements.*

4. CONCLUSIONS

The results described in the previous paragraph are only an exemplary part of the information available on the *Casa delle Armi*. Currently, the documentary research phase can be considered concluded. The information already available in the scientific literature and the consulted archives have been integrated by the research in the marble mine mentioned above and by further data emerging from the research work carried out by the aforementioned Vannucchi [16].

The geometric survey of the facades has already been done but can be integrated by applying digital techniques not available in the previous phase, such as the laser scanner and the aerial survey drone. The point clouds, in this case, lead to errors due to the possible interference of the marble veins, which the recognition algorithm tends to confuse with the metal elements on the slabs and the joints between the slabs themselves.

Thermography, as mentioned, also integrates the geometric survey in identifying discontinuities that are not visible externally, which are highlighted by the variation in heat capacity that leads to a difference in temperature as a result of daily thermal excursions. Even the combined effects of sun exposure and pollution can be highlighted with this system.

The reconstruction of the maintenance interventions is expected to be more demanding because many of those activities are not testified by documents, but they are clearly evident, as this work has shown, in the effects of deterioration that they have caused.

The digitization phase will need to organize the whole knowledge of the building in a compatible way with the dimensions of a building information model. This phase, which has already begun and tested on individual slabs, will be the subject of specific study as part of the national research program mentioned in the introduction of the paper.

At the end of this discussion, the profound difference between the knowledge of the building and the historical, geometric, in-field monitoring and construction analysis described so far should be emphasized. Indeed, the actual knowledge involves understanding and reconstructing – the so-called “decoding” – the genetic and creating criteria of the work – the marble envelope. For Moretti, these criteria correspond to real “classic” harmonic rules and require a specific design approach to be correctly understood and interpreted. In this sense, the main difficulty of the digitization process lies in modeling it according to this approach, when only numerical values can be used for the model creation. On the other hand, only from this understanding the restoration project will be able to start, aiming to reconstruct not the simple geometry but the actual shape of the studied architecture.

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THE DISUSED PRECIOUS STONE ELEMENTS ARE NOT CDWASTE. A DIGITAL MANAGEMENT CHAIN TO SAVE THEM

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Abstract

One of the most significant contributions to the circular economy that has emerged at the EU level (EU Protocol 2016) is the optimized management of the entire construction and demolition waste (CDWaste) chain: from selective dismantling to reuse in the building process as materials/products/components. The aim of this study has been to contribute to this systematization process of the currently not converging but stimulating initiatives by proposing an investigation for the Valuable Stone Elements Waste (VSEWaste) chain, removed in the process of replacement operations. In particular, we note that they have a sort of added value that demolition does not cancel, both for the nobility of the raw material and the processing they received, which is not always replicable nowadays. So they deserve separate treatment in the broader field of advanced circular building design, capable of harnessing the full potential that this type of waste can still express.

On the basis of an analysis of the best practices pioneered in several EU pilot projects, the digitalization of all the management phases of this CDWaste class has been undertaken: specifying the most suitable production chain; implementing analog cataloging based on shared but specific criteria; drawing up, using BIM tools, an inventory of waste, to be assessed on a representative sample; identifying marketing systems for dismantled stone elements relevant to a given geographical area.

Keywords

Valuable Stone Elements (VSE) Waste, Marketplace, BIM (Building Information Model/Modelling/Management), GIS (Geographic Information System), Central and Maritime Station of Messina.

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1. THE DESTINY IN THE EUROPEAN COMMUNITY OF THE VALUABLE STONE ELEMENTS (VSE) WASTE FROM SELECTIVE DEMOLITION

In the cultural framework laid down by the European Union for the management of construction and demolition waste (CDWaste), it appears that the emphasis is directed mainly towards their recycling, as an activity that implies paths to turn them into resources through an end-of-waste process, and their feeding back into industrial production cycles [1–3].

For this study, attention was paid to a specific category of CDWaste, i.e., the valuable building elements that result from selective demolition; these do not necessarily have to undergo a recycling, energy recovery, or dumping process; instead, they can be reused through minor adjustments. So, the focus was on fragments of stone artifacts, more or less remarkable, resulting from decommissioning, removal, and demolition in the context of interventions on the built environment that have appeared to be quite unrelated to safeguarding and protecting instances. There seems to be no urge to document these operations, let alone preserve for future generations the marks that natural aging and cultural history have left on these elements, imprinting unreproducible traces of our past that make them a precious resource.

For this reason, an early reflection addressed the concept of value, filtered not so much and not only through the quality of the stone material that characterizes these wastes but also through the rarity of the lithotype used, the craftsman's expertise (i.e., adherence to the best practice), the state of conservation, the dimensional parameters, and other factors that should be incorporated into the assessment of each fragment foreseeable fate.

It should be emphasized that construction and demolition waste introduced in the EWC code 17 class of the European Waste Catalogue (Decision 2000/532/EC) does not explicitly include stone materials, not to mention valuable ones. It is hence essential to highlight the peculiarities and importance of this category, which cannot be overlooked, let alone directed towards the most widespread recycling process, namely the production of aggregates. This vision would implicate only their crushing and use in embankments and backfills or, more rarely, as a prised aggregate in the formulation of mixtures for artificial stone (Stonethica and Catalyst from marble milling waste).

An overview carried out on some maintenance operations has pointed out two opposing tendencies: strict conservation of each stone element through removal, restoration, and reassembly, even if relocated; replacement after removal, with imitations (*simulacra*) being put in place, and indifference to what has been removed, considered as waste to be disposed of in landfills.

The first case, for which there is no question of the fate of the parts concerned, has been found in the context of historical architecture, whenever the concept of memory has prevailed over the pragmatism of the choices: relics are dismantled, collated and when not stored in a museum, put back in situ, or elsewhere, to reassert their historical-architectural value associated with the formal composition and/or the quality of the material (capitals, friezes, architraves, columns, etc.) [4]. In the second case, which has been proposed in many rehabilitation projects of 20th Century Architecture, disposal in landfills of the items removed has been – except in rare cases – the norm, as if artificial stone elements, thin slab claddings, litho-ceramic finishes, could not achieve a sufficient degree of interest for conservation or, at least, reuse in other contexts [5, 6].

Regarding the latter case, it could question the criteria employed for (Fig. 1):

- the maintenance throughout the years of the veined Carrara marble cladding of the Casa delle Armi at the Foro Italico [7] in Rome (Luigi Moretti, 1933-1937), where the detachment of slabs, set in *a sorella* pattern, without offset between joints as if they were a malleable plaster, has been partially braced with improper fixings made with nails or threaded pins;
- the complete replacement of the peperino slabs on the main façade of the Central Station [8] of Reggio Calabria (Angiolo Mazzoni 1936-1938), which were all discarded and disposed of in landfills;
- the successive substitutions of the Alcamo pinkish travertine slabs in the Central and Maritime Station [9] of Messina (Angiolo Mazzoni, 1934-1940) with different lithotypes and the waste storage occasionally used as a quarry for minor repairs;
- other instances where «in the last decades, these precious and vulnerable claddings have been subjected to various interventions that clearly show the widespread tendency to rebuild, restore and correct, rather than to find specific solutions to preserve material authenticity» [5].

The decision to return to a meaning congruent with the conservative instances, the one that should guide the restoring procedures for the operations of replacement of valuable stone elements, which belong to this praxis, has prompted a second reflection: how the relics removed from the buildings could be returned to a global construction market, where they would cease to be waste and take on the role of a resource that could be used elsewhere, valuable precisely because of the added value layered on the material over time.

A futuristic topic entailing the digitized circular management of CDWaste has been explored here and

Rome. Academy of Fencing at the Mussolini Forum, Luigi Moretti 1933-1937. On the right, a detail of the stone cladding of the south façade in which numerous replacement slabs, misaligned or out of plane slabs and traces of mechanical fixings added over the years are evident. (Photos by M. Ferrero).

Reggio Calabria. Central Station, Angiolo Mazzoni 1936-1938. On the right, the rehabilitation worksite of the main façade carried out in 2018 and the façade with the new slabs in place. The original marble cladding has been "pulled down, demolished and thrown away" (left and right down photos by R. Castiglia, right up [8]).

Messina. Central and Maritime Station, Angiolo Mazzoni 1934-1940. On the right, a detail of the original Alcamo travertine slab cladding compared with others replaced during the maintenance work carried out (1960-2000 span). (Photos by A. Cernaro).

Fig. 1. *Maintenance interventions of 20th Century Architectures examined, which have produced slabs of valuable stone material disposed to landfills.*

specifically applied to a highly representative pilot study: the dismantling over time, due to inconsistent maintenance, of the stone cladding of Messina's Central and Maritime Station. The designer, Angiolo Mazzoni, purposely determined the railway complex identity through the choice of material, dimensions, arrangement, and texture of the slabs, as well as through their laying procedure.

None of these factors guided the ensuing works on the stone cladding, except for the rehabilitation after World War II, the only one in which an attempt was made to preserve the specific nature of the railway complex. The maintenance of the 1980s and the restoration of the 2000s disregarded any demand to preserve the original cladding. In fact, slabs of Tivoli travertine were used, or, in any case, travertine of a different color and texture, laid with vertical veining, often thinner than the original ones, with the reduced depth being compensated for by significant layers of mortar as an infill. In addition, there are hints of gaps or misalignments due to negligent workmanship, and, above all, there is an evident lack of concern for the fate of the replaced slabs, some of which are carelessly stacked nearby.

It is precisely to safeguard conservative instances that this contingency has been adopted as a paradigm for the circular management of valuable stone waste (in the specific case, the travertine slabs that will be disposed of), by envisioning a digital chain investigated from the selective demolition to the reintroduction of these waste building elements into a unique and innovative production cycle.

2. A VIRTUOUS DIGITAL CHAIN FOR CIRCULAR VSEW MANAGEMENT

Even if, in the past, people "built by destroying", at the same time, they "destroyed by building", meaning that whatever was demolished, pulled down, dilapidated, or deleted had seldom merely been wasted. Using *spolia* has been a constant feature in historical buildings that show cultural stratifications in which demolition appears as a productive stage in relation to the pursued transformation objectives [4].

A lost awareness, this one, which only the last century is attempting to revive by including it in the current concepts of sustainability – conservation of material and energy resources, reduction of emissions and waste – and of the circular economy that redefines the lifecycle of materials from "cradle to cradle". It is thus necessary not to set construction against demolition but to set it against deconstruction, an inverse and specular procedure that can lead, as far as possible, to a selective repurposing of the constituent parts, to be directed to different uses compatible with the inherent value of each of them.

In this sense, these valuable building components, when, for some reason, not restored and kept *in situ*, should be selectively removed and managed through a hierarchical digital chain, envisioned as consisting of four steps in a previous study carried out by authors based on state of the art [10, 11].

The Registry of dismantled stone waste is the first stage in prefiguring its reuse. The analog approach to classification criteria cannot ignore the value identifiers that each piece carries with it: rock type (waste code), quarry depletion, size and type of surface finish, state of conservation, and other peculiar data.

Digital conversion is a second complementary level that should assume reasonable scenarios related to each specific worksite. The aim is to keep in archive valuable stone building elements dismantled from their original site to protect them despite their decontextualization, sometimes questionable. The cataloging activity includes, as a priority, BIM modeling of the item to be decommissioned, with emphasis on the identification of the composing parts, points, or lines of reciprocal joining obtained from survey operations or the design documentation. Supplementary tools to parametric methodology will then allow each conceivable scenario to be virtualized through an easy implementation of abacuses to assess quality and amount and/or end-of-life assumptions to ensure effectiveness and viability.

At this point, the construction of a virtuous digital supply chain must reach the third stage by introducing each BIM-based inventory into a digital platform for commercialization where all the operators involved in the supply-demand pair could meet. Marketplaces, and

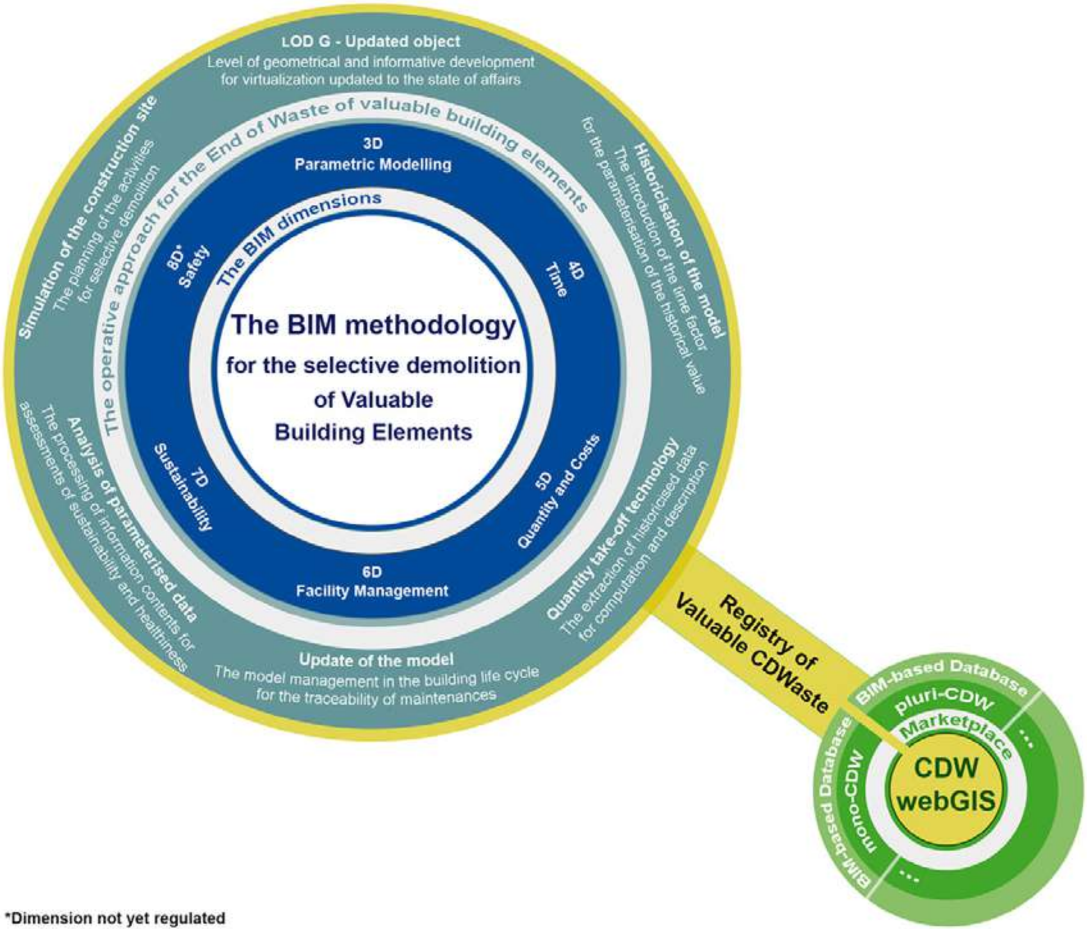


Fig. 2. *A first hypothesis of the supply chain for CDWaste digital management. (Drawing by the Authors [11]).*

those comprising construction and demolition waste, were thoroughly investigated to verify their functional structure, their correlations with structuring databases, the potential they hold, and the still unresolved loopholes to outline a hypothetical platform for VSEWaste.

Finally, but still in progress, the fourth tier of the hierarchy was addressed. It consists of a GIS (to be implemented as a WEBGIS) to determine its role and place in the digital supply chain, whether it should concern an inherent access part to the conceived marketplace or should be a container in which all the implemented and implementable datasets will be organized, through georeferencing (Fig. 2).

3. SUPPLY CHAIN STAGES FOR VSEWASTE DIGITAL MANAGEMENT

The phases, already developed as crucial moments of the investigation aimed at building the digital supply chain of valuable stone waste, are outlined below; for each of them, the results achieved and the effects on the case study of the methodology will be analyzed as follows:

- cataloging criteria for valuable stone elements;
- BIM-based Digital Registry of Valuable Stone Elements Waste (VSEWaste);
- marketing platforms modeled on marketplaces.

3.1. CATALOGING CRITERIA FOR VALUABLE STONE ELEMENTS

Recent developments such as teleworking, broadband, 5G, BIM and GIS software, and e-commerce are all equally emerging and competing premises in the development of the idea, which is presented here, to deploy the latest technologies to establish an open, continuously implementable and global market for some "scrap/

8. Recommended template for inventory of building element

BUILDING:								
Level:								
Other relevant information:								
Construction unit:								
Element	Units	Location	Reusable	Possible markets	Quantity	Materials identification and Waste codes	Precautions to take during the deconstruction phase	Pictures and notes

Materials present in the different elements should be detailed using the templates provided in section 8.

9. Recommended template for waste management recommendations

BUILDING:							
Level:							
Other relevant information:							
Construction unit							
Type of material	Waste code (EWC and EURAL)	Location	Possible outlets[1]	Recommended outlet[2]	Precautions to take during the deconstruction phase[3]	Handling precautions	Legal storage /transport/ treatment conditions

[1] Reuse; recycle; backfill; energy recovery; elimination
[2] The recommended outlet must be identified taking into account the hierarchy of waste treatment and the potential possibilities in the proximity of the jobsite
[3] Ex: do not leave the frame on the plasterboards; be careful to remove the power plugs, etc.

Fig. 3. *EC cataloging tools for CDWaste management.*

waste" (authors' note: between quotation marks because these are not materials that can be classified in this way, but genuine resources, sometimes precious) of stone elements, which do not come directly from quarries or processing centers, but mainly from sites of work on existing buildings.

State of the art holds up promising trends aimed mainly at the entire lifecycle of buildings, for which a cultural revolution is called for right from the early design stages. In that sense, several projects and academic studies have developed the concept of the Material Passport [12], devised for a circular economy of the construction sector that does not disperse or discard waste. It recommends a relatively complete classification of the construction materials of each project, specifying their physical, chemical, and biological properties, without overlooking the ecological quality aspects linked to their entire lifecycle, up to outlining the framework of a document certifying their identity, healthiness, and potential end-of-life scenarios.

With a focus on the demolition and renovation stages of the existing building stock, the European Union has suggested templates for the inventory of building elements and component materials (Fig. 3) for a preliminary assessment of the waste generated. The rating criteria are geared towards a marketing policy that relies on summary descriptions of quantity, geographical area, EWC code, target, and potential markets [1–3]. At the national level, in Italy, only the Abruzzo Region, in 2010, for obvious reasons related to the earthquake that hit this territory, issued directives to reduce the production of construction and demolition waste by increasing its reuse and recycling (in compliance with LR 45/2007 *Norme per la gestione integrata dei rifiuti e s.m.i.*), entrusting the municipalities with the task of recording the waste produced within each intervention [13].

Not one of the criteria considered addresses the cultural value, which by going beyond the contribution of waste reduction to a global sustainability problem,

Minimum Documentation Fiche	Full documentation Fiche
1. Identity of building/group of buildings/urban scheme/landscape/garden	
1.1 Current name of building	1.1 Data for identification [current name; former/original/variant name; number(s) and name(s) of street(s); town; province/state; post code; block; lot; country; national topographical grid reference; current typology; former/original/variant typology; comments on typology]
1.2 Variant or former name	
1.3 Number & name of street	
1.4 Town	
1.5 Province/state	
1.6 Zip code	
1.7 Country	
1.8 National grid reference	
1.9 Classification/typology	
1.10 Protection status & date	1.2 Status of protection
---	1.3 Visually or functionally related building(s)/site(s)
2. History of building	
2.1 Original brief/purpose	*See 2.2 Summary of development*
2.2 Dates: commission/completion	2.1 Chronology
See 2.1 Original brief/purpose	2.2 Summary of development
2.3 Architectural and other designers	2.3 Relevant persons/organizations
2.4 Others associated with building	2.4 Other persons/events associated with building(s)/site
2.5 Significant alterations with dates	2.5 Summary of important changes after completion
2.6 Current use	*See 3.2 Current use*
2.7 Current condition	*See 3.3 Present (physical) condition*
3. Description	
3.1 General description	3.1 Site/building character
3.2 Construction	
See 2.6 Current use	3.2 Current use
See 2.6 Current condition	3.3 Present (physical) condition
3.3 Context	3.4 Note(s) on context, potential developments
4. Evaluation	
4.1 Technical	4.1 Technical
4.2 Social	4.2 Social
4.3 Cultural & aesthetic	4.3 Cultural and aesthetic
---	4.4 Canonical status (local, national, international)
4.4 Historical	4.5 Historic and reference values
4.5 General assessment	---
5. Documentation	
5.1 Principal references	5.1 Archives/written records/ correspondence
	5.2 Principal publications (in chronological order)
5.2 Visual material attached	5.3 Visual material (state location/ address)
---	5.4 List documents included in supplementary dossier

Fig. 4. *Comparison between the contents of the two forms introduced by the international cultural association DOCOMOMO to describe the heritage of the 20th century: the Minimum Documentation Fiche and the Full one.*

targets those identitarian principles inherent in certain essential traits of one culture or another, which must therefore be preserved. In this regard, it could refer to the activity carried out by DOCOMOMO (DOcumentation and COnservation of buildings, sites, and neighborhoods of the MOdern MOvement) for the conservation of 20th Century Architecture, which in two forms, one general and the other synthetic, has attempted to introduce the historical, architectural, and technical data through which the intangible cultural heritage would be described. These, too, have been considered in our pursuit of classification criteria for valuable stone waste (Fig. 4) [14].

In light of the overwhelming prevalence of the old over the new and the consequent exponential growth in maintenance work, which is by all accounts expensive, even too much so when compared to the current funds available for the construction sector, the approach of reclaiming and marketing all decommissioned or deconstructed stone materials appears to be a must.

This approach requires a methodological effort to identify classification criteria and suitable search keys to set up a kind of online market for stone fragments that can meet the needs of the building sector, avoiding wastage and the *ex novo* creation of pieces which, if new, would not blend easily with existing works.

In the proposed solution, a naturally homogeneous time frame has been singled out, that of the Modern experienced and manifested in the 20th Century Architecture, which in this first work hypothesis plays the role of a case model to test the effectiveness of the devised tool, which if "successful" could then be extended to other time spans.

Subdividing the filing of valuable stone waste by epochs allows them to be recorded according to a first homogeneity criterion, that of the techniques and tools with which these stones were crafted. This breakdown constitutes a critical factor for their reuse, capable of ensuring that the material is preserved in its broader meaning of material culture, which must also consider the modification received in a given period and in a given technical and technological context. The chronological perspective appears, in this respect, more relevant and of more significance than the geographical one.

In order to calibrate the digital management chain under consideration here, it was considered correct to ask ourselves what specific goals the chain should pursue in addition to the general one of reducing/recovering/reusing waste. Furthermore, the question was to what categories of users it should be destined to, but also what existing digital tools could or should be referred to and, consequently, what characteristics/properties of materials were to be considered.

The answers, apparently self-evident, are far from obvious and prompted many afterthoughts and refinements as the details came into focus. Actually, the choice of methodological approaches, such as BIM and GIS, was fairly predictable, and yet not without consequences and rather constraining; the possibility of envisioning a multifunctional system capable of equally satisfying the needs of a variety of users has been recognized primarily in researchers, designers/buyers, demolition specialists, not excluding other operators in the supply chain with tasks of storage, repair, restoration, etc., has proved more challenging.

These prerequisites have informed the definition of the classificatory categories of the stone elements to be filed, mainly as two-dimensional but also as three-dimensional form, pinpointing the key aspects to be incorporated to enable a digital management that, as desired, could be open, flexible, and plural:

- based upon the intrinsic characteristics: mineralogical identity, provenance, dating;
- based upon the previous locations: building element type and position;
- based upon the characteristics of the single piece: geometric configuration and processing techniques.

Without overlooking the fact that a true "virtual shop" is to be implemented, a sort of identification with the needs of the assumed user figures was deemed necessary, which led to considering: some historical-critical specifications to suit the scholars identified with the category of researchers (e.g., some data on the originating building); or some specific details that may be relevant for designers/buyers (such as those related to the specifics of the single pieces or the previous destination, but also the available quantities); or again, indications for the category of demolition specialists or other companies implementing other supply chain activities (e.g., the EWC code, although this is currently too general, and risk factors). A further consideration concerns the players involved in the dismantling sector because it is believed they can draw ideas both from knowledge and inclusion in a digital management chain of this waste if not real programmatic and pragmatic indications to better set up the deconstruction plan.

This consideration determined the information structure of the "operational tool" designed for this study (Tab. 1).

Each data necessary to implement an objective and effective database to return the extreme variability of valuable stone waste must respond to specific information characteristics which, in compliance with protocols or standards, make the content objective and repeatable.

In the absence of a currently shared international perspective on the problem, operational tools have been deduced from other sectors that propose solutions to the identified gap, albeit in a transitory form (Cf. Note to Tab. 1).

Parameter	Description
BASED UPON THE INTRINSIC CHARACTERISTICS	
Material type	Natural/Artificial
Stone class	If available, petrographic and mineralogical aspects
Colour	Identifiable shade or dominant tonalities
Quarry	Locality, Denomination, GIS Coordinates, Active/Closed
Quarrying date	Exact date, if available, or estimated dating
BASED UPON THE PREVIOUS LOCATIONS	
	Function and position with respect to the building
Interior/Exterior	Interior, exterior (exposure NSEW), both
Supporting structure	Wall/Arches/Vaults/Columns/Piers/…
Cladding	Floors/ Wall facing/…
Decorative element	Bases/Pilasters/Capitals/Friezes/Cornices/Corbels/Furniture/…
Previous re-use	For an element with a possible previous use
	Information about the building of VSEWaste origin
Name of building	Actual denomination
Variant or former name	Original or different denomination
Original use	Original intended use
Current use	Actual intended use
Address	Name of street, Postcode, Town, Province, State
Geolocation	Latitude, Longitude
Original Customer	Appellative of the original building owner
Actual Customer	Appellative of the current building owner
Designer/s	Name, Surname, Qualification
Company/ies	Denomination
Dates of commission and completion	Exact date, if available, or estimated dating
Stylistic features	Architectural current
History of building	Brief Construction History
Significant alteration	Intervention type (Ordinary or extraordinary maintenance works/ Volumetry variation/…), exact date, if available, or estimated dating
Current condition	Excellent/Good/Fair/Mediocre/Bad/Vary bad
Principal references	Main archival, bibliographic, photographic sources
BASED UPON THE CHARACTERISTICS OF THE SINGLE PIECE	
	Geometrical features
Type	Ashlars for Supporting Structures Ashlars, Slabs, Tiles for Claddings Mouldings for Decorative elements
Dimensions	Greater side, Smaller side, Thickness, Radius, … Other parameters related to the specific geometry of the element
Volume	To count the total volume of pieces with similar features
Shape	Regular/Irregular
	Production features
Primary processing	Related to extraction from the quarry
Secondary processing	Related to obtaining the element from the quarry block
Surface finish	Smoothing/Polishing/Bush hammering/…
	Historical phases
Phase "Created"	Moment of laying
Phase "Maintened"	Moment of maintenance
Phase "Demolished"	Moment of removal
	Conservation
Conservation state	Excellent/Good/Fair/Mediocre/Bad/Vary bad
Photographic records	To document the state of conservation
	Riskiness
CER CODE	CER 1709 "Other construction and demolition waste" is currently applicable, although generic
Other factors	Other aspects related to the riskiness
	Technical features
Measured parameter (1)	Result of the test carried out
Measured parameter (2)	result of the test carried out
…	…
Attachments	Documents of the test carried out

Notes The textual content requires no further specification. Concerning the iconographic apparatus that must reproduce the quality of the decommissioned stone resource in terms of chromatic, textures peculiarities, as well as the state of preservation in terms of the presence of anomalies, patina, degradation, reference should be made to international conventions or, in its absence, to specially designed guidelines.
For digital photographs, the 2016 F_version 4.0 form of the MIBACT_ICCD was considered a valid reference by appropriately declining the required guidelines: 1) file compression/extension format: .png for web-based viewing; raw for post-production; .tiff for professional viewing; 2) visualization, storage and processing program: Adobe Photoshop type or similar; 3) color depth: RGB or CMYK; 4) resolution 72 dpi for web and 300 dpi for quality faithful reproductions; 5) technical specifications: orthogonal shot of which to provide distance and color control device (ColorChecker) to carry out any post production operations [15].
The coding should be alphanumeric including place-type element-number shot-chronology.
For graphic conventions with which to describe degradation, if the photographic repertoire was not sufficient, the national and international normative panorama consulted was not considered effective and a specifically designed information convention was used.

Tab. 1. *The criteria adopted for the cataloging of valuable stone elements.*

3.2. BIM-BASED DIGITAL REGISTRY OF VALUABLE STONE ELEMENTS WASTE (VSEWASTE)

In order to optimize resources and results, the digitalization of the construction sector is leading to the reconfiguration of the entire supply chain processes in search of innovative approaches with a forecasting function to evaluate the envisioned solutions before their actual implementation. The CDWaste sector is no exception [10, 16–18]. The informative vocation of the BIM methodology, stemming from the possibility of associating data to the geometric-threedimensional virtualization of a building element, is driving the conception of the Material Passport [12, 19], the cataloging tool, which is conceptually close to the proposal here presented to encourage the reuse of valuable stone elements. However, this identification tool, since it does not include historical and cultural data, which instead for the particular category under consideration should be assessed in the same way as purely technical indicators, cannot provide solutions for its parametrization.

This led to a specific nature of this research, aimed at attaining the BIM-based Digital Registry of Valuable Stone Elements Waste, both tailored to the multidisciplinary parameters selected to provide a detailed description that would meet the needs of the various kinds of users and targeted towards being used by marketing platforms.

The hypothesis of a restoration work envisaging the selective demolition of the envelope cladding slabs of Messina Central and Maritime Station allowed the outlining of a methodological path that can be applied to similar cases and, with the appropriate generalizations, to other classes of CDWaste to be preserved.

The Autodesk Revit 2022® software has been selected for the pilot study, as it is the most widely used parametric IT tool at the international level for research purposes. Depending on the content and operational requirements outlined, a procedure consisting of the following phases has been laid out:

1. an in-depth documentary and diagnostic investigation to acquire the information for a multidisciplinary characterization of a building's valuable stone elements (Fig. 5);
2. the parametric modeling of the actual state of each element by conceiving a specific BIM object which represents the geometric configuration and whose informative content reflects the established classification criteria, including those aimed at its inherent historical and cultural heritage value (Fig. 6);
3. the implementation of a preliminary "Registry of valuable stone elements" of a building, that is to say, in the BIM perspective, an abacus that gathers the cataloging of all the edifice's stone pieces and that serves as a support based on the systematized knowledge, to plan the maintenance and/or start pre-demolition audits (Fig. 7);

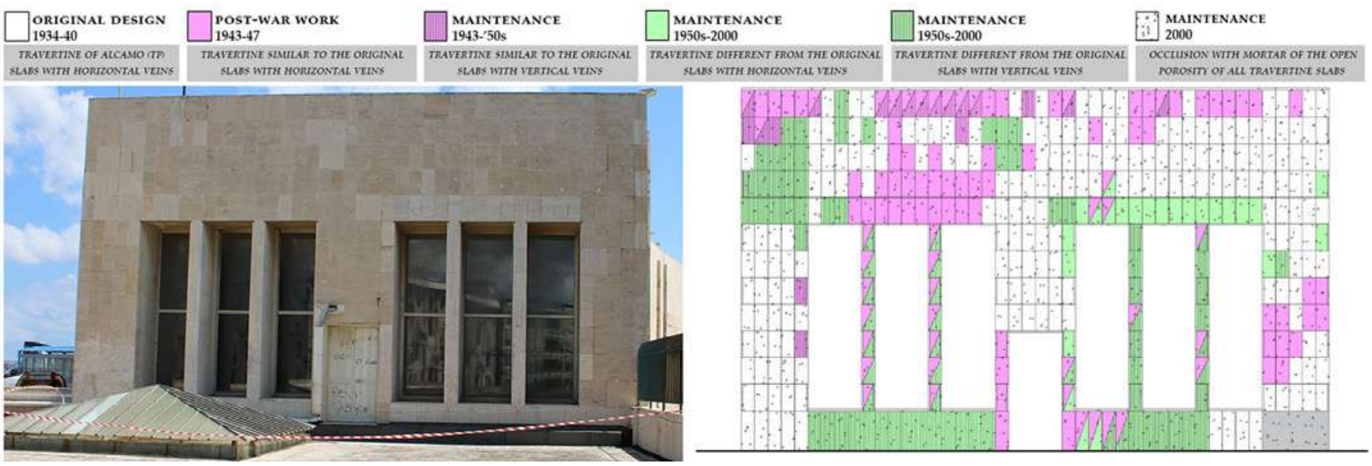
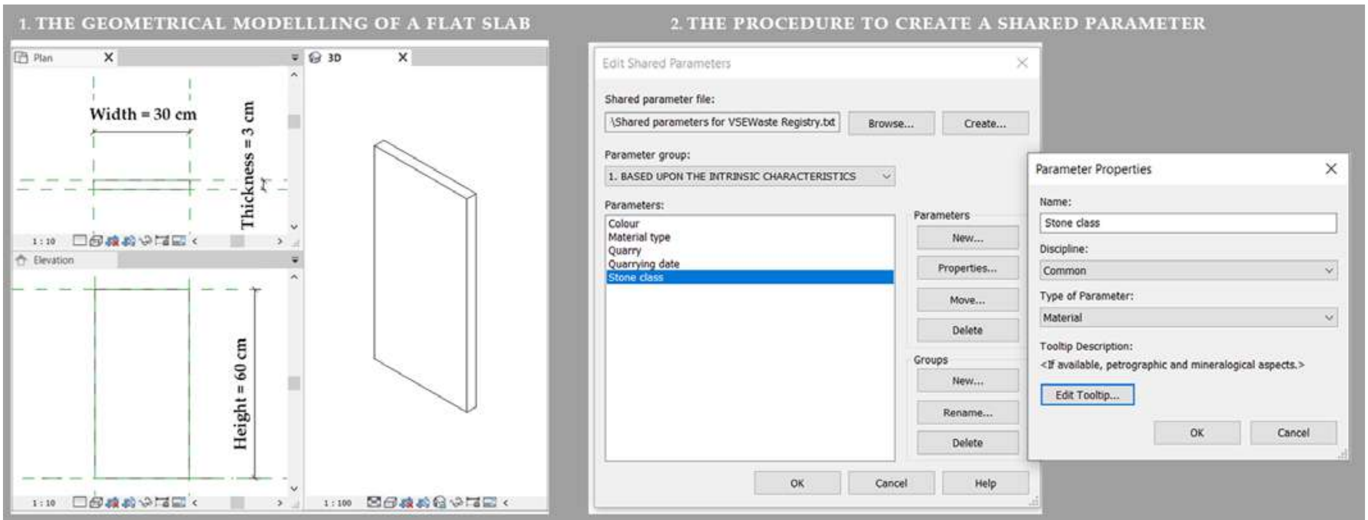


Fig. 5. *An emblematic elevation of the Messina Maritime Station: the mapping of replacement and maintenance work on the slabs as it results from the documentary and diagnostic survey.*



3. HOW TO TRANSLATE INTO BIM ALL THE "ANALOGUE" CRITERIA FOR THE CLASSIFICATION OF THE VALUABLE STONE ELEMENTS

Name of parameter	Type of parameter
BASED UPON THE INTRINSIC CHARACTERISTICS	
Material type	Text
Stone class	Material
Colour	Text
Quarry	Text
Quarrying date	Text
BASED UPON THE PREVIOUS LOCATIONS	
Function and position with respect to the building	
Interior/Exterior	Text
Supporting structure	Text
Cladding	Text
Decorative element	Text
Previous re-use	Text
Information about the building of VSM origin	
Name of building	Text
Variant or former name	Text
Original use	Text
Current use	Text
Address	Text

Name of parameter	Type of parameter
...continues from the previous column	
Geolocation	Text
Original Customer	Text
Actual Customer	Text
Designer/s	Text
Company/ies	Text
Dates of commission and completion	Multiline text
Stylistic features	Multiline text
History of building	Multiline text
Significant alteration	Multiline text
Current condition	Text
Principal references	Multiline text
BASED UPON THE CHARACTERISTICS OF THE SINGLE PIECES	
Geometrical features	
Type	Text
Dimensions	Lenght
Volume	Volume
Shape	Text
...continues in the next column	

Name of parameter	Type of parameter
...continues from the previous column	
Production features	
Primary processing	Text
Secondary processing	Text
Surface finish	Text
Historical phases	
Phase "Created"	Text
Phase "Maintened"	Text
Phase "Demolished"	Text
Conservation	
Conservation state	Text
Photographic records	URL
Riskiness	
CER CODE	Text
Other factors	Text
Technical features	
Measured parameter (1)	
Measured parameter (2)	
...	
Attachments	URL

Fig. 6. *The BIM object of the travertine slab at the scale of the LOD G: the geometric modeling of the stone element in its actual state and the informative modeling through the definition of multidisciplinary parameters, including the historical-cultural data.*

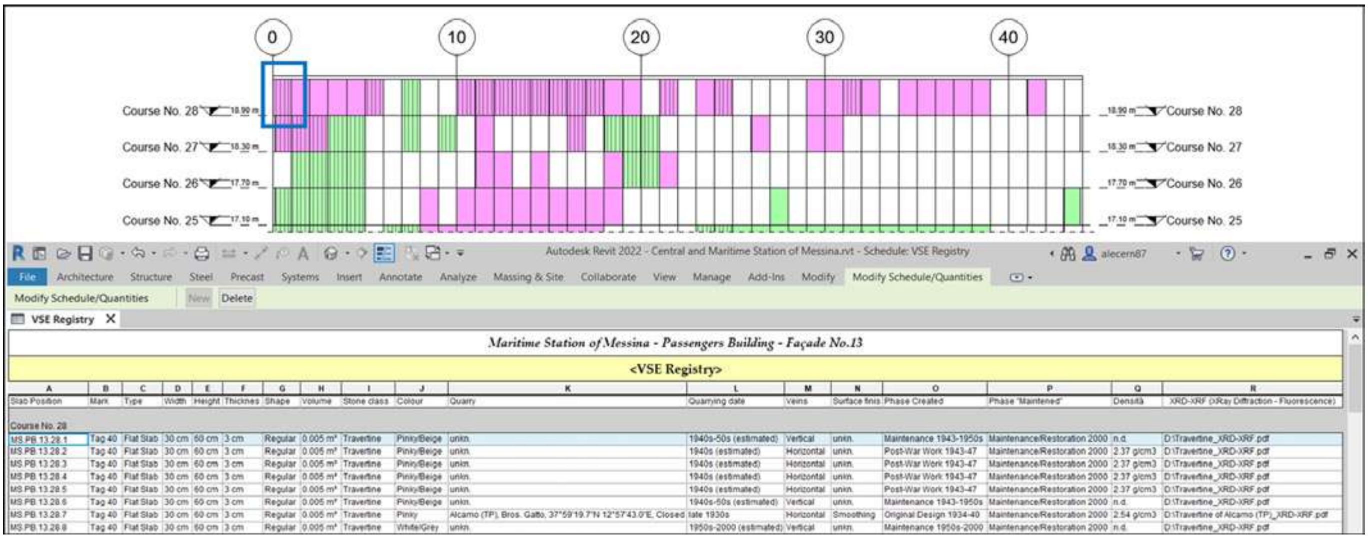


Fig. 7. *The Registry of the valuable stone elements of the Messina Station envelope cladding: the systematization of the documentary findings and diagnostic surveys aimed at supporting management plans and/or pre-demolition audits.*

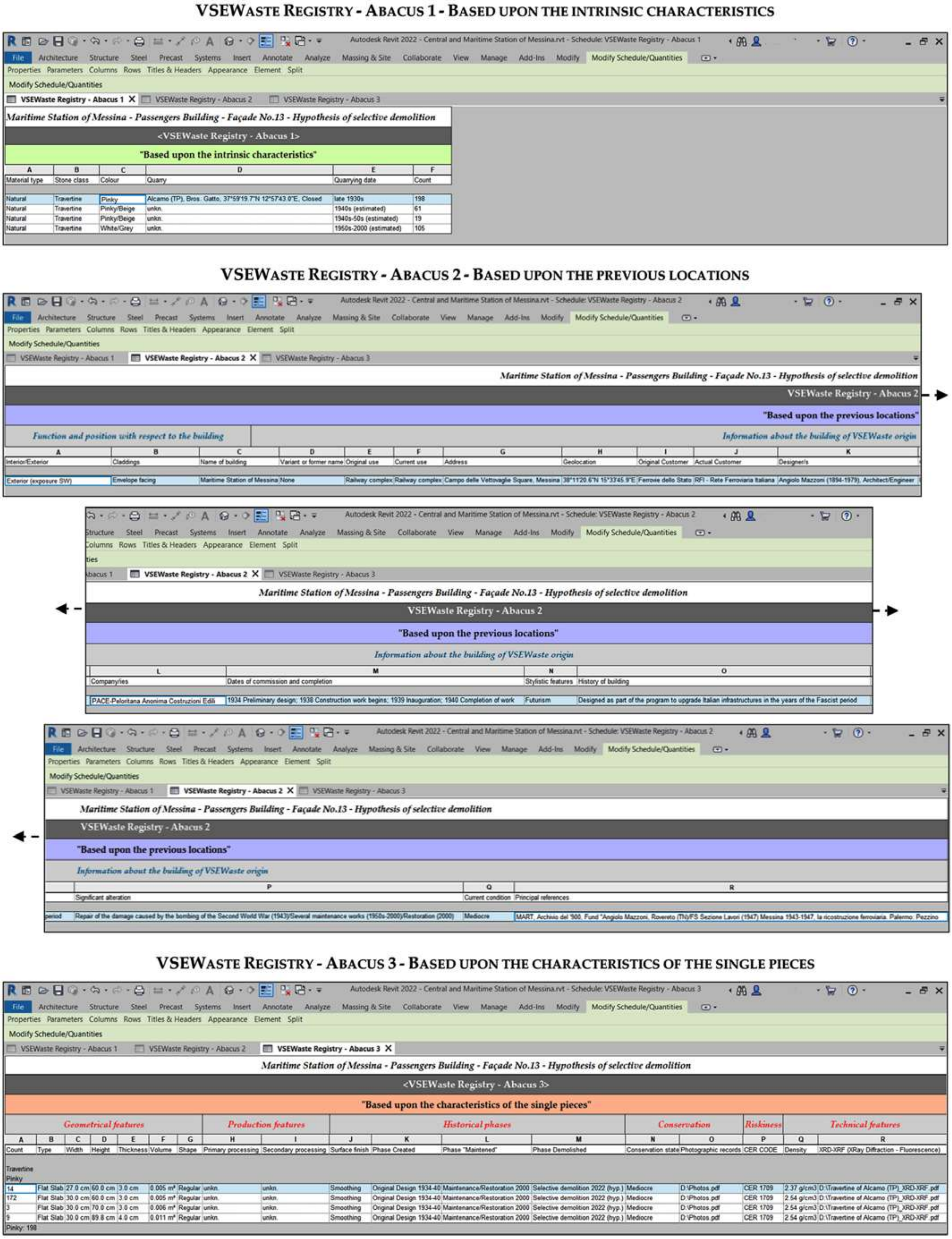


Fig. 8. *The Registry of Valuable Stone Wastes: the thematic abacuses, sorted according to the three cataloging criteria, can be retrieved in the databases of the marketing platforms.*

4. the extraction of the “Registry of valuable stone waste” from the previous and general inventory tool in order to gather the data of the pieces affected by the selective demolition intervention in thematic abacuses that can meet the query needs of the various kinds of users through commercialization platforms of which, in the later part of this paper, the simulation of an application will be illustrated (Figs. 8, 11 and 12).

3.3. MARKETING PLATFORMS MODELED ON MARKETPLACES

In the process of the digitization of CDWaste management [20–22], it is essential to thoroughly investigate the topic of sharing platforms; to verify their current development, the hypothesized structures, their limits, and their potential. The upcycling that, in this field, can be triggered by marketplaces is now indisputable, yet their presence in the construction waste sector is still somewhat limited and does not take off.

The literature of the last decade (2010-2021), published in Scopus, Web of Science, and ProQuest databases, has been systematically analyzed, along with the classification and ordering of marketplaces dealing with the construction sector, in order to get an overview of the trends in scientific production and to analyze those factors that are crucial for a sector-based and IT-based conduction of construction and demolition waste/resources [23].

In the last two years, scientific production has increased by more than 30% over the previous years concerning the general topic of CDWaste reuse; 33 articles were selected for the specific considerations of this study, which numerically highlight the emerging nature of this field of investigation. These papers deal specifically with materials such as concrete (n = 13), bricks (n = 7), steel (n = 5), wood (n = 4), plastics (n = 3), glass (n = 1), for which, according to the authors, an easier path to reintroduction into the waste-resource chain exists. They can be divided into four research branches: 1) management methods, 2) benefits of using e-commerce, 3) models for an online marketplace linking sellers and buyers, and 4) constraints and potentials of a CDWaste marketplace.

Similar results emerged from the web survey of marketplaces, which highlighted many differently originated experiences that had been developed for:

- facilitating the recycling/reuse of a specific type of waste, the so-called “vertical waste”;
- classifying, storing, and reselling materials or elements from rehabilitation interventions;
- offering exchange platforms and expert services referred to as “horizontal waste”;
- linking scrap/waste producers with recyclers, retailers, and users.

The trend, as evidenced by the analysis of the scientific literature, describes a market aimed at concrete, brick, steel, and plastic components, for which there is the greatest demand for a second-use life, mainly resulting from recycling actions. Stone materials are equated to rocks or aggregates.

The specific features of the twenty-four marketplaces active on the international scene were analyzed, and three core categories were identified:

1. platforms for the dissemination of circular economy principles that act as interfaces between supply and demand by working on projects, assessing/selecting requests of the best offer on the market, and looking for the most suitable market for a given offer (Business to Business – B2B);
2. platforms where alongside an e-commerce catalog, there is a customer facilities section (Business to Consumer – B2C or Consumer to Business – C2B);
3. consumer-to-consumer platforms, such as eBay, where photo ads are posted to meet supply with demand (Consumer to Consumer – C2C).

To understand which kind of structure should be given to the VSEWaste e-commerce platform, it is therefore essential to determine the specific properties of this


SALVOWEB, B2C started in the UK since the 1995
CYRKL, B2B d start-up in the Repubblica Ceca since the 2015

Fig. 9. *Retrieving rare stone elements from active marketplaces.*

particular section of CDWaste (classification criteria); the nature of the production basin (generation, storage, transformation places); the benefits and advantages associated with this organization mode through e-commerce (BIM-based Registry); the end users' profile. Only after these assessments have been performed can the best management mode be determined and the specific marketing platform structured.

An initial search for sections related to valuable stone elements within these instruments revealed a minimal presence, a territoriality of exchange confined by transportation reasons, a lack of data beyond quantities, and only sometimes of the exceptionality of waste.

The few examples found are illustrated here above (Fig. 9).

Concerning valuable stone waste, affected by the depletion of raw materials, obsolete and uneconomical work methods, and the lack of availability as a result of the policy of replacing rather than restoring, most notably in the field of 20th Century Architecture, it appears appropriate to imagine a platform conceived for reuse paths and, only if not achievable, recycling, in order to turn them into a resource again.

Designing an e-commerce tool dedicated to this class means choosing the most suitable structure which, as illustrated, follows four management methods: B2B (business to business) marketplaces between companies; B2C (business to consumer) between companies and consumers; C2B (consumer to business) between consumers and companies; C2C (consumer to consumer) between consumers.

In the CDWaste field, the surveyed platforms for mono-materials fall into the B2C category, i.e., waste collection consortia that interact with end-users. Those related to urban regeneration are of the C2C or C2B type; this means that large amounts of waste are offered by those who generate them as part of the selective demolition of large housing estates (not always digitized) to those who will then reuse them. The last category is predominantly B2B that are exchange platforms, from producers/collectors to storage and/or repair operators and then from these to consumers; they include complementary expertise services for companies willing to introduce circular economy principles in their waste sector.

The organizational model of a marketplace for VSE-Waste could be a combination of the four types (C2C; C2B; B2B; B2C). By having a waste producer as the origin and being directly addressed to other end users or to companies that take care of some repair/restoration interventions (resinating and plastering of slabs; cutting them into pieces of different sizes; addressing some forms of degradation, etc.) before returning them to the consumer's market. However, in this study, it was considered essential to add a supplementary category

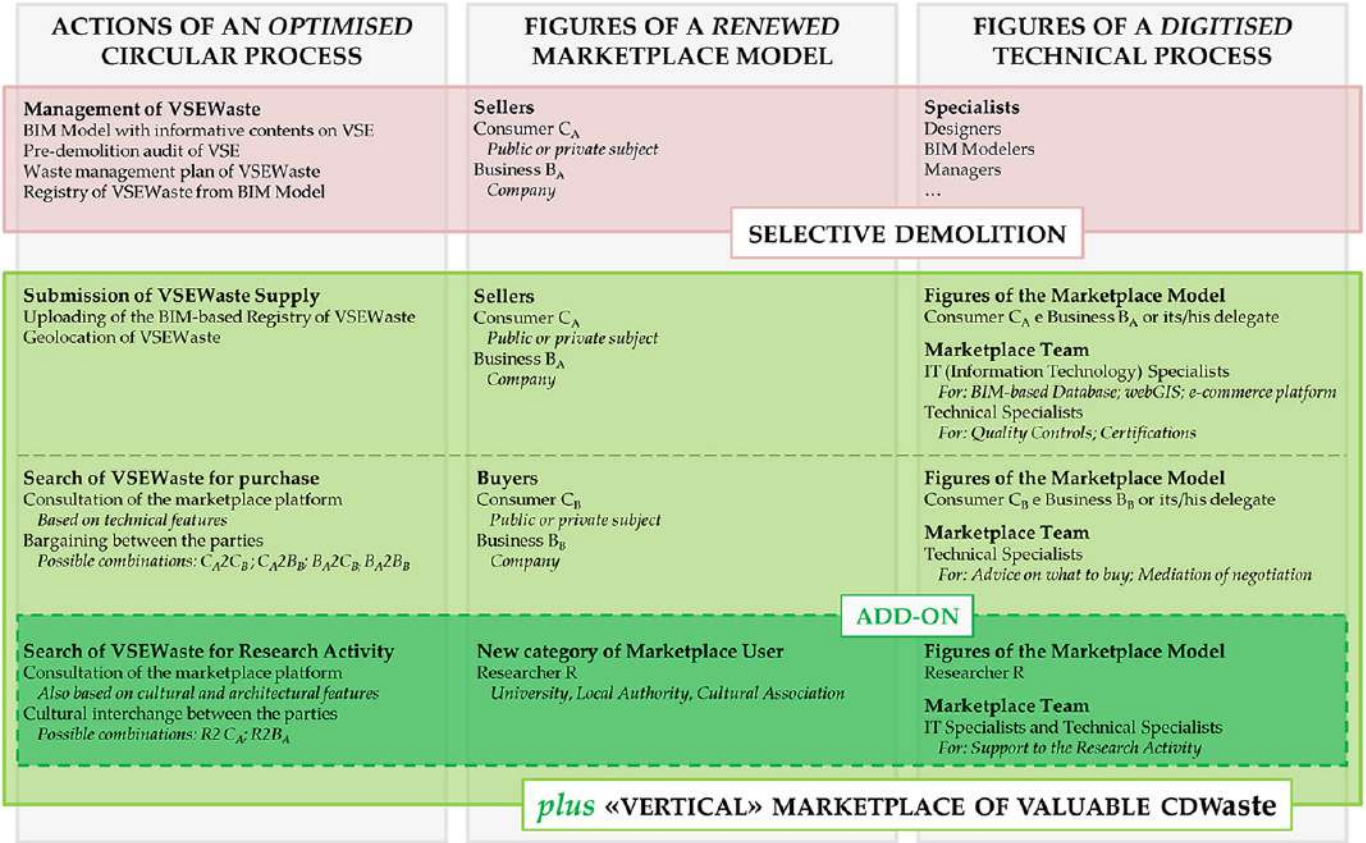


Fig. 10. *VSEWaste trading platform.*

of users, that being researchers (universities, local authorities, cultural associations) who, by exploring and understanding the subject, could lead and promote the spread of a culture of conservation and reuse of these "*spolia* materials".

Moreover, as already noted above, by reviewing the current virtual showcases of reusable CDWaste, an almost absolute lack of information emerges for an in-depth functional evaluation prior to their purchase, which cannot be missing in the case of valuable stone elements derived from selective demolition. For this motif, an interface tool was conceived that provides a reasoned inventory of VSEWaste generated through BIM methodology.

The general structure conceptualized for the platform is above (Fig. 10).

A simulation complements the proposed conceptual revision of the marketplace structure to provide an example of what the operational implementation might look.

The marketplace featured differs from the solutions found on the web in its target audience and in its strict dependence on the data associated with the BIM model of the building from which the valuable waste originates. Moreover, it also builds on the future CDWaste WebGIS platform. From the envisioned homepage, three paths should be possible, structured according to the objectives of the end user and based on progressive steps: "Let's sell", "Let's buy", and "Let's study" (Fig. 11).

The add-on path for Researchers, "Let's study", is displayed below: it has been introduced for the very first time in the course of this study for the Researcher R category (university, local authorities, cultural association), a new figure in the marketplace context; this category will be able to use a direct monitoring tool on the marketing of valuable CDWaste for research purposes or for orienting circular recovery/reuse policies, with the opportunity to refine the search by keywords (designer, style, timeframe, site, intended use) and then

Fig. 11. *The simulation of the marketplace "Valuable CDWaste". From its homepage, the three paths: "Let's Sell!" for Consumer CA e-Business BA; "Let's Buy!" for Consumer CB e-Business BB; "Let's Study!" for Researcher R.*

further deepen it by downloading the BIM abacuses entered by the CA/BA user. So, the platform's usage has been simulated through a scenario of selective demolition of a façade of the Maritime Station of Messina cladding slabs, for which the VSEWaste BIM-based Registry is provided (Figs. 5–8). It was supposed that the Archaeology, Fine Arts, and Landscape Superintendence for the provinces of Siena, Grosseto, and Arezzo, has to provide guidelines for a (hypothetical) restoration of the pinkish Villanova (SI) travertine cladding of the Siena Station. The cladding was designed by the same Angiolo Mazzoni, for which it could consult the marketplace to check the scope of slab supply from a building with comparable historical-architectural peculiarities (Fig. 12).

4. BARRIERS TO THE CIRCULAR MANAGEMENT OF THE IMPLEMENTED TOOL AND HYPOTHESIS OF OVERCOMING

The dealing of CDWaste, from their generation to integration as a resource, in essence, presents the critical issues attributable to:

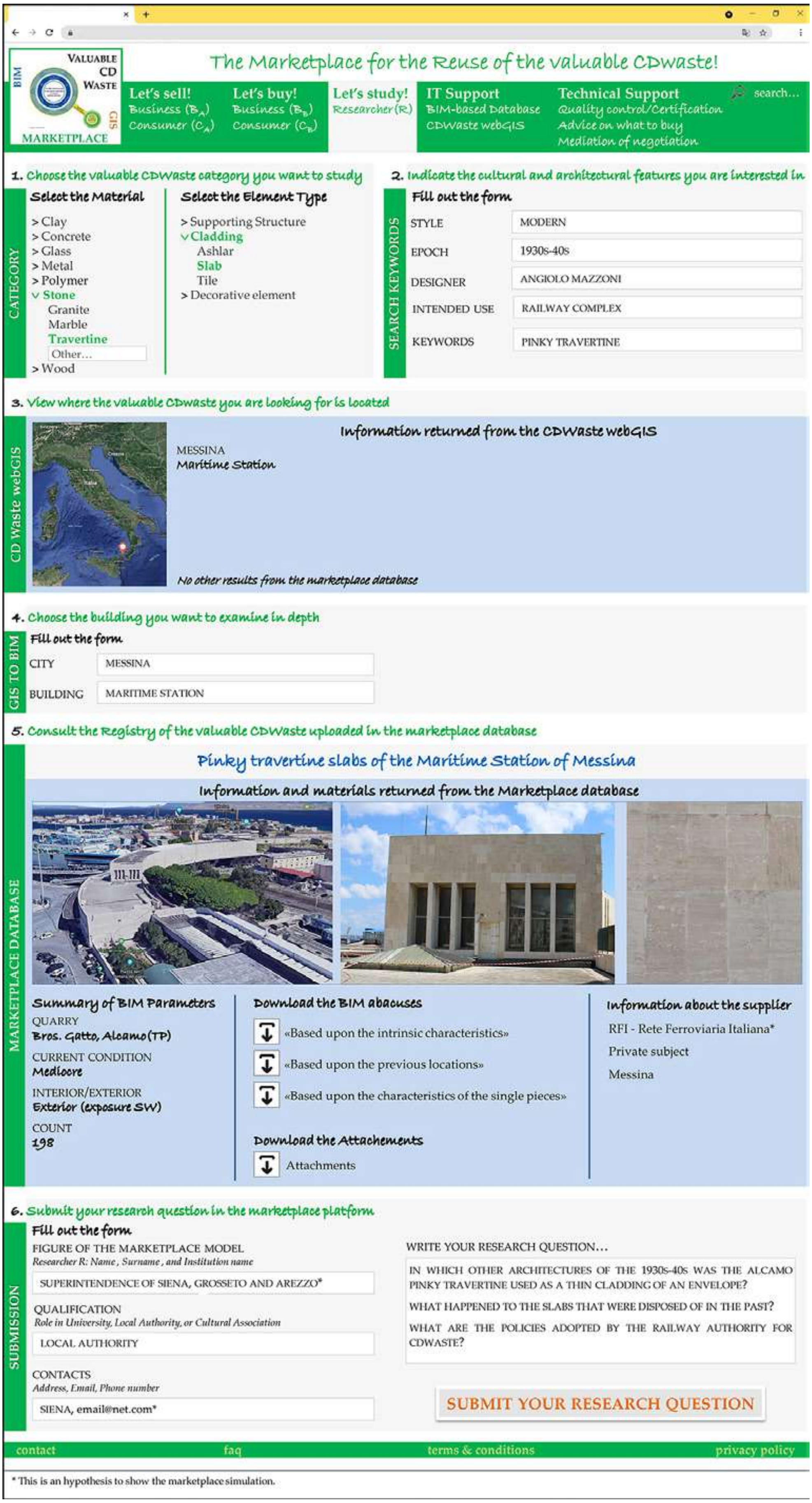


Fig. 12. *The simulation of the marketplace: the path "Let's study!".*

- cultural barriers, a lack of awareness/discomfort with the waste problem;
- institutional barriers, absence/lack of oriented policies and regulations;
- operational barriers, disorganization/fragmentation of supply/processing/ marketing chains;
- digital barriers, inadequacy/ deficiency of BIM digitization of the historic-architectural heritage;
- commercial barriers, and lack/neglect of an effective market for matching supply and demand.

The digitalization of an infrastructure, such as the one elaborate, which starts from the places where CDWaste is produced, in this case, VSEWaste, and goes all the way to the conception of a georeferencing system of the operators involved in the processes of selective dismantling, recycling/reuse, and marketing, is definitely a fundamental part of the environmental issue with the introduction of circular economy criteria aimed at addressing the entire lifecycle.

However, the effectiveness of the proposal presented lies not only in the inclusion of a single conceptual framework of the entire chain, including all the operational and commercial figures concerned but also in having to encompass the cultural grounds by providing accessibility to researchers. Their action of exploring and deepening the process may include, besides the potential of digital management of VSEWaste, also the limits that can be identified in the following issues:

- the dissemination of a new cultural and strategic approach triggered by the synergy between ecological transition and digitization of processes;
- the management of this digital application, carried out by an entity, whether institutional or corporate, but uniquely in charge of the implementation and protection (control, supervision) actions from a legislative, procedural, operational, perspective, etc;
- the funding of the entire sector, including its digital transition (BIM, Marketplace, GIS), with incentives to make the adoption of a different cultural model "attractive";
- the preparation of information models of historical heritage buildings, in addition to serving for maintenance actions, could be optimized to facilitate obtaining the Registry of Valuable Stone Waste if conducted with a view to the Material Passport.

Surveying the marketplaces operating in the field of waste has highlighted some significant factors: a structured running by Local Authorities that see in this marketing tool the possibility to implement ZeroWaste strategies; a geographical perimeter that paradoxically reflects national and not global boundaries; the total absence of shared parameters for an informed choice.

Accordingly, one of the main important points has been the consideration that the envisioned instrument had to open to the intellectual panorama in a bid to entrust to cultural management, even before that regulatory or political, specific intangible assessments concerning ecological benefits, digital advantages, safeguarding requirements, etc.

A further observation concerned geographical boundaries: it is desirable to have a window on the world, but the mobilization of VSEW needs to define its radius of influence, both reasonable and commensurate with logistics and transport rates. The perimeter, even for government conduction, should be, as in the US case, georeferenced, highlighting, on variable kilometric ranges, all the operators that enable the implementation of an organized process: from the construction sites to the places of conservation/storage and rehabilitation (repair, restoration).

Last, yet that structured the tool in its earliest formulation, is the consideration of the informative apparatus, which is currently very reductive in these systems of running waste. Although digital methodologies have been available for quite some time now, applications have not yet been conceived that can support different scenarios and variable management plans in relation to criteria determined on a case-by-case basis. This has led to the adoption of a BIM-based VSEWaste Registry, which down-stream of a demolition worksite modeling, which may soon become State Law, can automatically provide the Passport Material, adopted as early as the design stage of the building, to keep track of the stock of resources available throughout the whole lifecycle of buildings. Its transposition to existing buildings is what has been attempted in this study to assess its effectiveness with reference to a theme – the decommissioning and restoration of modern architecture – and then to a specific case: the reuse of stone slabs decommissioned during maintenance work on representative architectures.

In the short term, it is difficult to imagine the implementation of a new technological-productive chain for these specific resources due to the absence of appropriate investments; policies promoting selective dismantling; involvement of the territory and the businesses in the development of a circular economy; deterrent taxes on landfill; an institutional culture; technological and information cooperation between start-ups and companies able to foster new future business models; a government policy able to regulate this fledgling market, through regulatory acts and economic-commercial criteria [24].

However, it is possible to benefit from an operative transfer from related fields. The digital platform Tech-Marketplace, which has been active since 2015 in the energy/sustainability/smart building fields, works in this direction by showcasing innovative start-ups and SMEs to establish effective partnerships; providing support for "anticipating change" by describing emerging technologies and industry trends (updated to 2019).

The CDWaste sector would require an incubator capable of systematizing the best practices in the institutional, cultural, operational, and commercial domains to structure an effective management system.

5. A SHORT-TERM OPERATIONAL PROGRAM

Implementing the proposed approach to manage the fate of decommissioned valuable stone elements, and in general for CDWaste to be preserved, requires procedural changes that must be operationally concerted in short-, medium- and long-term programs. Downstream of all that has been experimented with, the methodology articulated in the four phases illustrated should be considered a correct practice to achieve when fully operational due to a normative, cultural, and professional coordination leading to the layering of progressive digital information, functional to knowledge, preservation, and enhancement of the architectural heritage, in the case under consideration the Modern one.

An immediate development for the protection of decommissioned valuable stone elements, imagining their reinsertion in a commercial circuit as spoliation material, may involve the preparation of a digital register, starting from the analog catalog, in view of a complete Materials Passport derived from H-BIM/GIS oriented reproductions of each architectural asset. This first product, with scientifically prepared textual and iconographic specifications, in place already drafted for the pink Alcamo travertine cladding of the Messina Maritime Station, could be included in a dedicated marketplace with commercial but also cultural values. This implementation could allow the public (MIBACT, UNESCO, etc.) or private (DO.CO.MO.MO, GBC Italia, etc.) management protection that follows the cultural heritage of our architectural heritage for the entire life cycle, from cradle to cradle.

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ORANGE PEELS AS A POTENTIAL ECOLOGICAL THERMAL INSULATION MATERIAL FOR BUILDING APPLICATION

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Abstract

Most of the national orange production, estimated at 900,000 tons per year, is processed in several cities in the south area of Italy. Half part of this amount corresponds to the peels, which are separated in the orange selection and processing plants. In this work, the possibility of using orange peels as raw material for the manufacture of building materials for the civil construction industry is studied. Recently, some attempts to reuse by-products derived from citrus waste have been proposed. For example, it was used as a source of nutrients in food, pharmaceutical, and cosmetic industries and as a source for energy production. There are precedents in the use of biomass residues in different building blocks, mainly with the aim of generating insulating materials. With this objective, insulating materials were obtained from agriculture by-products also manufactured without a binder. After a drying process, orange peels were characterized with electronic scanning analysis and thermal analysis in order to analyze the application in the building sector. The same by-products for the production of samples in the form of panels were used. In order to establish the best panel composition, physical and thermal properties, as well as mechanical and durability performances of the samples, were characterized.

Keywords

Agro-waste, Citrus fruit, Thermal insulator, Circular economy, Environmental impact.

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1. INTRODUCTION

In Italy, citrus agricultural surfaces are 143.540 ha. Most of the citrus crops are in Sicily, which represents 52% of national citrus production, with 80.478 ha cultivated [1]. From the citrus industrialization, different by-products are generated, which are separated in the selection and processing plants. Half part of the citrus weight is a by-product, mainly composed of peel, seeds, and residue of pulp. Incineration or use as animal food is the usual disposal method of orange peels. Other reuse methods applied to recover orange by-products are based on compost production, organic fertilization, biogas or pectin, bioactive and essential oils extraction [2, 3]. The huge quantity of this waste can be an environmental problem for the land. When the peels are burned in the open air, significant impacts are caused. On the one hand, large amounts of CO_2 and microparticles in suspension are produced, on the other hand, the soil is rendered unusable, and the degradation of the burning area is caused. A circular approach could help the building sector to reduce the environmental impact and rising costs [4]. There are precedents in the use of this type of residue of biomass to create construction panels or bricks. Agricultural residues from rice [5], sugar [6], corn cob [7], or pineapple [8] are used to make thermal insulation material. Other sources are represented by industrial by-products from the agricultural transformation of peanut [9], coffee [10], coconut [11], sunflower [12], or walnut [13]. Novel and green approaches to directly using the extract of citrus fruit's peel as a print transfer medium, solvent for recycling polystyrene waste, and natural polymers were also developed [14]. Shan et al. studied a new type of plastic made from citrus peel whose properties are similar to those of polystyrene [15]. Orange peel ash was analyzed in addition to cement, mixing orange peel ash with cement in different percentages between 2.5 and 10% [16]. In Sicily, orange peel is an abundant by-product with a low market value but with potential use as building materials. In this work, the possibility of using oranges by-products as raw material for the manufacture of bio-insulation for the civil construction industry is studied. So, in order to obtain a new ecological material, a microscopical analysis was conducted on orange peel. After the characterization of the grains, the creation of particleboards with a pressing and drying process was investigated. Three different types of panels have been made in order to obtain the best thermal and mechanical performances. After thermal characterization, each panel was divided in two pieces and mechanical performances were compared before and after a test in a climatic chamber.

2. MATERIAL AND METHOD

2.1. CHARACTERIZATION OF ORANGE PEEL

The citrus peels used for this research were obtained from the production waste of the orange juice machines. This type of machine is widespread in coffee shops and supermarkets, which produce a large quantity of waste every day. The citrus by-product obtained is composed of 60-65% of the weight of peels, 30-35% of pulp, and the residue part of the seed, in variable percentage as a function of the orange type used [17]. The peel is composed of two different parts; the flavedo (exterior yellow peel) and the albedo (interior white spongy peel). Albedo is about 17% of the citrus weight and is rich in pectin. [18] The chemical composition of the orange peel is mainly influenced by the external climatic condition, the cultivation method, and the type and maturation of the fruit. It is mainly composed of cellulose, pectin, sugar, acids, lipids, mineral elements, essential oil, and vitamins. Table 1 presents the chemical characterization of wet citrus waste. Furthermore, citrus peels are characterized by a high acidity with a pH from 3.5 to 5.8. Bulk density, which depends on the possible storage techniques, varies approximately from 900 kg/m^3 for the wet peel to 200-300 kg/m^3 for dried biomass. The large density variation between wet and dry depends on the large water content of orange citrus fruit. Water content varies from 90% for wet material to 8-10% for dried biomass.

Parameter	**Wet citrus waste** [% dry matter]
Water content	72.50 – 87.00
Volatile solids	93.80 – 96.70
Protein	6.53 – 8.30
Fat	0.90 – 3.30
Fiber	10.60 – 42.10
Starch	1.00 – 2.90
Sugar	15.00 – 46.60

Tab. 1. *Range of physical-chemical composition of CPW.*

2.2. MICROSCOPICAL OBSERVATION

A scanning electron microscopy of the materials was made in order to evaluate the microstructure and the elementary chemical composition of orange peel and panels. This experimental work has been performed at the Microscopy Laboratory of the Universidad Complutense de Madrid. The dry orange peel without compaction process and the orange peel panels obtained from the pressing phase were analyzed. In order to increase the conductivity, samples were coated with a gold film. An analysis of the microstructure of the samples was obtained using a scanning electron microscope (SEM) model JEOL JSM 6400, with an acceleration voltage of 20kv.

2.3. MANUFACTURING OF SAMPLES

In order to prepare the material to be used in the tests, shredding and drying activities were carried out, obtaining wet and dry products. The wet product is only derived by shredding the by-product by a manual mill, while the dry product has undergone a drying process and subsequent shredding with a manual mill. A ventilated oven with a temperature of 50ºC was used for the drying of the material carried out for 48h. A weight variation of less than 1% on three consecutive measurements has been defined as the end of the drying process. After drying, the peels were shredded with a manual mill and sieved, obtaining the grain sizes as shown in Table 2. Diameters smaller than 0.65 mm and larger than 6 mm have been discarded. Three types of samples were obtained from granules: G1, with 0.65 < d < 1.25 mm, G2, with 1.25 < d < 4 mm and G3, with 4 mm < d < 6 mm. For the tests, a 250 x 250 mm mold with a thickness of 30 mm was used, and the granules without compaction were placed inside.

Samples	N. Samples	Particle size
G1	3	0.65 < d < 1.25 mm
G2	3	1.25 < d < 4.00 mm
G3	3	4.00 mm < d < 6.00 mm

Tab. 2. *Granulometries of dried and sieved orange peels.*

For the realization of specimens in the form of panels, a pressing process and subsequent drying in a ventilated oven were carried out. A wooden mold 250 mm x 250 mm x 30 mm was used, and a pressure of 0.02 MPa, equivalent to a weight of 126 kg, was impressed on all the specimens. According to the scheme shown in figure 1, the load from two marble slabs of 9 kg and cylindrical concrete blocks of 12 kg each was obtained. Each sample was kept under pressure for 15h at the ambient temperature of 21 ± 1°C and 50 ± 10% of relative humidity.

Different types of samples can be distinguished depending on the starting material used. As shown in Table 3, three specimens from the compaction and pressing of the material of the wet product were obtained (W100), and three from the mixing of wet product and dried product in granules with a diameter of 1.25 mm> g> 0.65 mm were derived (CW75_G2) and others three from the mixing of wet product and dried product in granules with a diameter of 4 mm> g> 1.25 mm (CW70_G1). After pressing, the specimens were unmolded and dried at 50°C for 48 hours in a ventilated dryer.

Samples				Weight of specimen parts	
Name	N. of samples	% wet	% dry	Wet [g]	Dry [g]
CW100	3	100	0	500	0
CW75_G2	3	75	25	500	180
CW70S_G1	3	70	30	500	250

Tab. 3. *Samples from cold pressing and subsequent drying.*

2.4. THERMAL PROPERTIES

A guarded hot plate apparatus, model HFM 436 Lambda from Neszcht was used for the thermal characterization. The test was carried out according to the European Standard EN ISO 13787 and consisted of the placement of the samples between two heated plates at different temperatures. The temperature of the plates and the average temperature of the sample were defined by the user. The heat flux q through the sample by a calibrated heat flux transducer was measured. Once the thermal equilibrium had been reached, the measurements were performed.

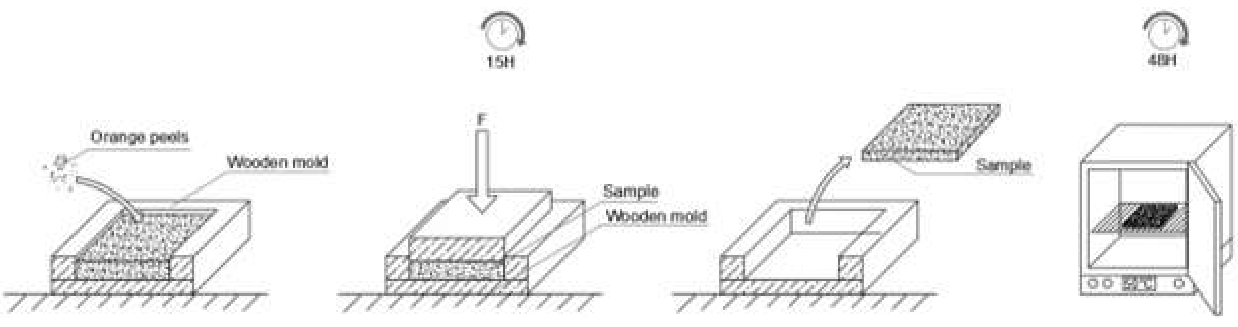


Fig. 1. *Cold press scheme.*

Plate temperatures were controlled by two-way heating/ cooling systems integrated into a forced-air heat exchanger that generates a closed-loop flow.

According to the standardized test technique, samples measuring 250 x 250 mm with an average thickness of 30 mm were tested. Both granular samples (G1, G2, and G3) and samples in panel form were measured (CW100, CW75_G2, and CW70S_G1). For the granular samples, a containment mold was used. The samples were measured at 10°C, 20°C, and 30°C with a temperature gradient of 20°C.

2.5. MECHANICAL PROPERTIES

Mechanical characterization was performed using a three-point bending strength test. A Universal Test Machine was used, which provided values describing the force-displacement curve. The load cell was 10kN with a displacement rate of 10 mm/min and a span of 100 mm. The maximum displacement value that could be registered was limited to 14.6 mm. According to the European Standard EN [17], Values for Modulus of Rupture (MOR) by flexural stress were determined using the following Eq.:

$$\sigma\,[N\,mm^{-2}] = \frac{3\,F_m L}{2\,b\,d^2}$$

Where F_m is the force applied (N), L is the distance between the supports (mm), b is the width of the sample (mm), and d is the thickness of the sample (mm). Due to the capacity of deformation of the samples, RILEM TFR1 [18] was used as a reference for the acquisition of load. According to this, the maximum load was considered when the displacement value was 10% of span support. Results were considered as the average of four measurements on specimen size of 250 mm x 125 mm x 30 mm.

In addition, the module of elasticity (MOE) at flexural strength was also calculated with the following Eq.:

$$MOE\,[N\,mm^{-2}] = \frac{F\,L^3}{y\,48\,I}$$

Where F is the force applied (N), L is the distance between the supports (mm), y is the strain of the sample (mm), I is the moment of inertia (mm^4). Samples in the form of panels were measured (CW100, CW75_G2, and CW70S_G1) before and after the durability test.

2.6. DURABILITY TEST

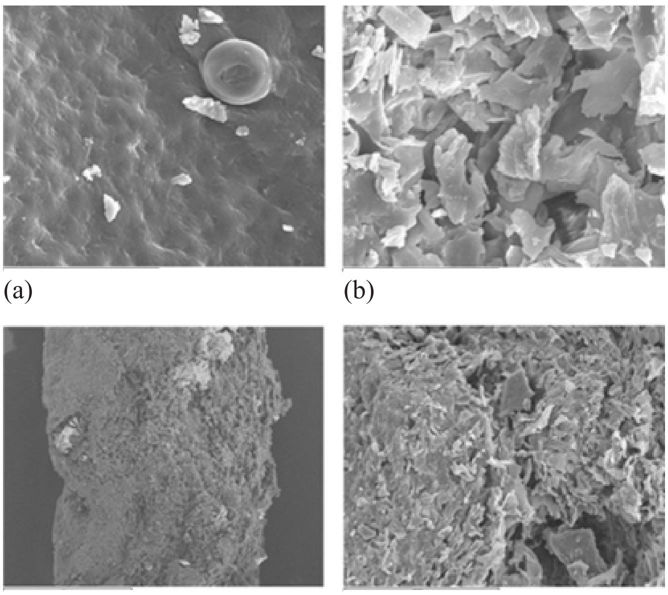
Durability tests were carried out in order to evaluate the mechanical properties of the samples after hot-rain cycles. According to EN12467, the test consists of the execution of 50 dry-wet cycles in a climatic chamber. Each dry-wet cycle consists of drying for 3h at 60°C and 20% of relative humidity, followed by 3h at 25°C and 90% of relative humidity. Before and after the test, the weight and the dimensions of each sample were measured. Before performing the test, each sample type 250 mm x 250 mm x 30 mm was divided into two equal parts. One part for each type was placed in the climatic chamber to perform the test; the other part was taken as a reference without the climatic chamber. After 50 cycles, a three-point bending test on both samples was conducted in order to compare their mechanical performance.

Fig. 2. *Climatic chamber used for durability test.*

3. RESULTS

3.1. MICROSCOPICAL OBSERVATION

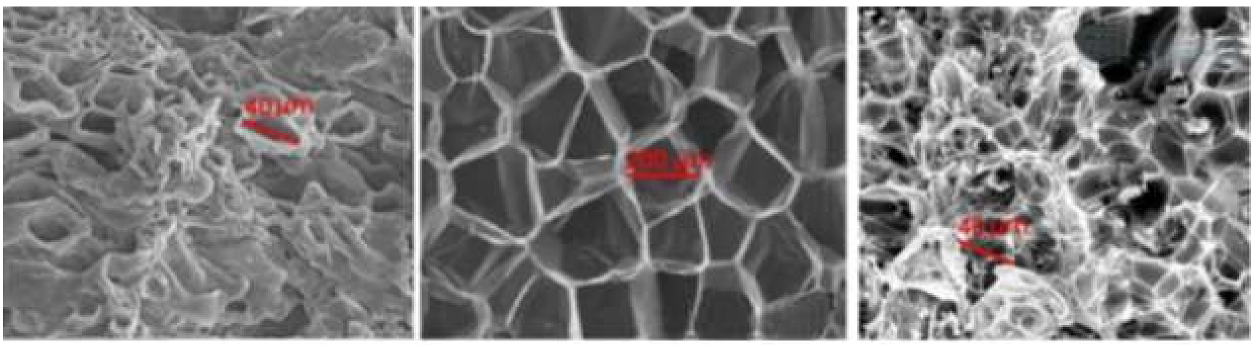
The microscopical observation of the dried orange peel shows two different layers. The external part (Fig. 3a) is characterized by a compact structure and small hole; this part corresponds to the exterior orange part, called flavedo. The interior part (Fig. 3b) is much porous and corresponds to the inner white part of the orange peel, called albedo. This part is composed of a small sac or cavity, which gives the material the thermal insulation proprieties. Fig. 3c and 3d show the joint between the two parts and show that the peel is half composed of the external part and half of the inner part. The microstructure of the peel, although heterogeneous, can be therefore divided into two main parts, a rigid external that performs the "structural" function and a spongy internal that performs the function of thermal insulation.



(a) (b) (c) (d)

Fig. 3. *Scanning electron microscopy images of dried orange peel.*

The internal structure (Fig. 4a) can be compared to commercial products such as extruded polystyrene (XPS) (Fig. 4b) or expanded perlite (Fig. 4c). By comparing the three materials, they all have a closed-type cellular structure, and microstructure similarities can be found. As expected, with respect to the cell structure of the orange peel, a much more regular and uniform shape characterizes the XPS. Polystyrene has sacs with a diameter of about 200 μm; the perlite has holes of about 40 μm. In terms of microstructure, expanded perlite is similar to dried orange granules. Other differences in density and thermal conductivity can be found. The XPS has a density of 35 Kg/m^3 and a conductivity of 0.035 W/mk, values significantly lower than the citrus granules. Expanded perlite, with a density of 100 Kg/m^3 and a conductivity of 0.045 W/mk, has similar properties to orange granules but differs in the microstructure. A homogeneous structure characterizes the expanded perlite, while a heterogeneous structure characterizes the orange peels, composed of an inner spongy layer and an outer rigid layer. The comparison of microstructures was made using only the inner part of the orange granules as a reference. This part provides samples with good insulating properties, but represents only 60% of the base material. The remaining 40% of the base material, consisting of the outer part of the peel and the seeds, contributes to the improvement of the mechanical performance of the samples.



100 μm (a) 500 μm (b) 100 μm (c)

Fig. 4. *Images from SEM: microstructure orange peel (a); XPS microstructure (b); expanded perlite microstructure (c).*

3.2. DENSITY

Bulk density was determined as the relationship between the mass and the volume of the boards according to European Standard 1602 [35]. Testing was carried out on dry samples under laboratory conditions (21 ± 1°C and 50 ± 10% relative humidity). An electronic balance with a precision of 0.001 g and a digital caliber VOGEL model 202112 with a resolution of 0.01 mm were used. Table 4 shows that, for the granular samples, the density increases as the diameter of the granules decreases. A mean density of 500 kg/m^3 was measured in granular samples without compaction.

Samples	Density [kg/m^3]
G1	509.52
G2	497.37
G3	492.71
CW100	507.32
CW75_G2	503.00
CW70S_G1	520.74

Tab. 4. *Density of dried orange peel granules.*

An average density of 510 kg/m^3 of the samples in the form of panels is obtained. Compared to traditional building panels (Tab. 5), the samples are medium-high density panels. Other panels from agricultural by-products have similar densities as those derived from Sunflower (500.00 Kg/m^3) [19], Corncob (413.00 Kg/m^3) [20], and Durian (442.00 Kg/m^3) [21]. Other panels derived from agricultural by-products have higher densities, such as panels from walnut (599.10 Kg/m^3) [22] and Sugar cane (686.00 Kg/m^3) [6], or lower densities, such as panels from Coconut (338.00 Kg/m^3) [21] and pineapple (210.00 Kg/m^3) [23].

3.3. THERMAL PROPERTIES

Thermal conductivity is calculated at 10ºC, 20ºC, and 30°C on dry specimens. Table 5 shows the conductivity of the grains, which is directly related to the density of the specimens. Thermal conductivity increases as the diameter of the grains decreases. The higher percentage of voids reduces density and ensures better thermal insulation. Therefore, the smaller diameter of the granules conducts more heat than the larger ones. By comparing the results obtained, a higher conductivity is reached by the granules with respect to others from agricultural by-products such as rice husk (0.050 W/mk), sugar cane fiber (0.048 W/mk), coconut fiber (0.053 W/mk), and a comparable conductivity, although higher, than the granules from the cladodes of Opuntia ficus-indica (0.057 W/mk) is obtained. Samples from citrus with higher grains have a lower conductivity than some commercial products such as expanded clay (0.090 W/mk), pumice (0.100 W/mk), expanded vermiculite (0.080 W/mk), and cellulose granules (0.069 W/mk).

Orange by-products	Density	Thermal conductivity		
		10°C	*20°C*	*30°C*
	[kg/m^3]	*[W/mK]*	*[W/mK]*	*[W/mK]*
G1	509.52	0.068	0.072	0.078
G2	497.37	0.066	0.071	0.075
G3	492.71	0.066	0.070	0.073
CW100	507.32	0.067	0.069	0.073
CW75_G2	503.00	0.079	0.082	0.088
CW70S_G1	520.74	0.081	0.085	0.090

Tab. 5. *Density of building panels from agricultural waste.*

An average conductivity of 0.075 W/mk, in a range between 0.067 W/mk and 0.081 W/mk, is obtained from the samples in the form of panels. The minimum conductivity of 0.067 W/mk is from samples CW100 and shows this formulation's interesting property.

Equal or superior properties are shown by this sample in comparison with others of similar density. The sample CW75_G2 has the lowest density with thermal conductivity of 0,079 W/mk. The CW100 thermal conductivity is 0.067 W/mk and increases by 1.2 times to reach 0.081 W/mk in W70S_G1. As shown from microscopic analyses, these properties can be justified by the type of microstructure obtained from the use of the composition of a wet and dry part. The wet material, in fact, generates closed air pores with a higher thermal resistance than the open ones in the case of the addition of dry matter. During drying, the replacement of the water contained in the citrus with air becomes greater in samples with a higher percentage of wet matter (CW100).

Some differences between the results at 10ºC, which is the reference temperature for construction materials, and those at 20ºC, need to be highlighted. The increase in test temperature corresponds to an increase in thermal conductivity in a range from 4% to 12%. The hygroscopic characteristics of this material affect the thermal properties of the samples. Compared to literature, orange peel samples showed higher thermal conductivity than other non-natural commercial insulators such as mineral wool or polystyrene. However, the conductivity values obtained from orange peel panels are in line with the conductivity of other insulating materials from agricultural by-products such as durian [21]. In addition, the conductivity is lower than the panelboard made from sunflower [19] and walnut shells [13] and higher than the panelboard made from coconut shells [21], pineapple leaves [23], and sugar cane [6].

3.4. MECHANICAL PROPERTIES

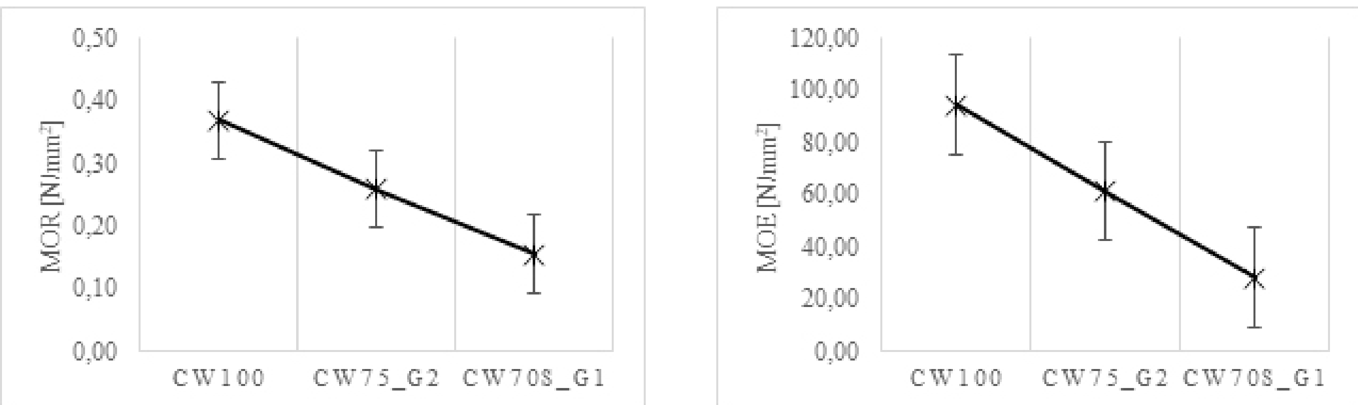
The mechanical properties of the samples in the form of panels are shown in Figure 5. The addition of dried peels provoked a reduction of flexural strength. CW100 samples have a flexural strength of 0.36 MPa, which fell down to 0.15 MPa in CW70_G1. This can be explained by the homogeneity of the microstructure of CW100 panels compared to the mixtures of the other samples. The addition of dried granules in the samples CW75_G2 and CW70S_G1 generated a discontinuity in the microstructure, resulting in a loss of particle bond and mechanical strength. Other research has shown that the addition of aggregates reduces the mechanical properties of mixtures, such as cement with the addition of perlite [24] or plastic grains [25].

Compared to the literature, strength is lower than other agro-wastes boards with corncob [7], coconut coir [21], and sunflower [26], although similar to the bagasse ones [27]. However, the differences can be explained by the different manufacturing process or the presence of an external binder. The use of a higher compression pressure would increase the material's mechanical strength and density, resulting in an increase in thermal conductivity. Moreover, the addition of external binder would improve the bonds between the particles, resulting in a non-biodegradable panel.

Modulus of elasticity (MOE) followed the same pattern as the MOR (Fig. 5b), and the stiffness is higher in the sample without dried peels. Indeed, CW100 samples show a modulus of elasticity higher than the other two. This performance can be explained due to the formation of closed porous and homogeneity in the mixture compared to the others.

3.5. DURABILITY TEST

Samples after 50 cycles in the climatic chamber have a weight reduction directly proportional to the increase in the percentage of dried particles. The weight difference before the cycles, calculated as the average between 3 samples, is -3,62% in the samples made with the only wet part. As shown in table 6, a larger decrease has characterized CW75_G2 and CW70S_G1 samples.



(a) (b)

Fig. 5. *Flexural (a) strength and modulus of elasticity (b) of the samples.*

The higher weight decrease indicates a better ability of the material during the hot cycle to release the water absorbed during the wet cycle. A greater weight reduction in the samples with a greater quantity of pre-dried grains is measured. So, the panels' ability to absorb and release environmental humidity is related to the dry grains' quantity. In particular, the addition of the dry part results in a better hygrometric behavior of the panels. This improvement can be explained by the heterogeneity of the panel and by the presence of more empty parts inside the material.

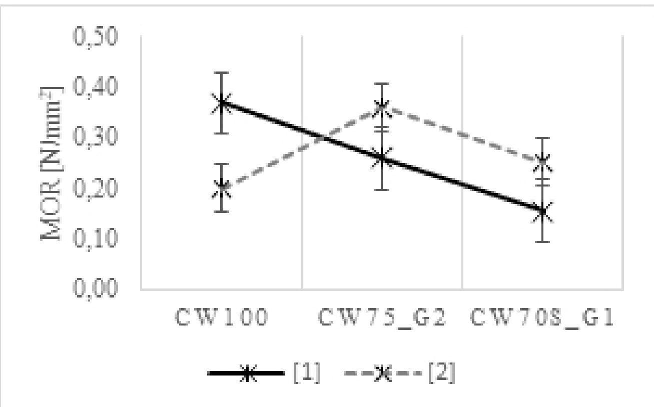
Sample	Weight before cycles [g]	Weight after cycles [g]	Weight difference [%]
CW100	96.64	93.14	-3.62
CW75_G2	154.68	148.60	-3.93
CW70S_G1	177.36	169.51	-4.44

Tab. 6. *Weight before and after climatic chamber.*

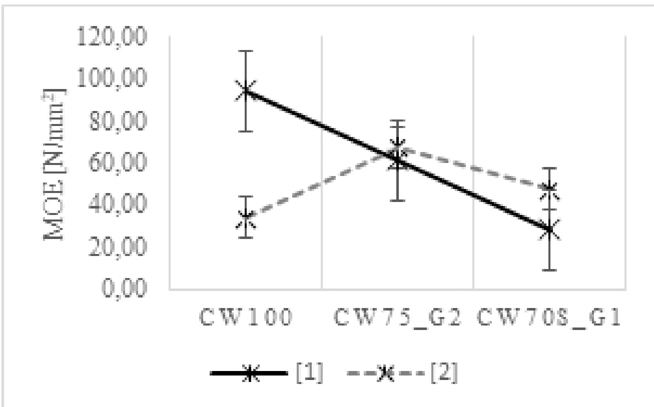
As a consequence of the weight reduction of the samples after the durability test, figure 6 shows an increase in the modulus of rupture. In particular, flexural stress increases in the CW75_G2 and CW75_G2 samples while decreases in the CW100 samples. Results of the mechanical tests on samples after 50 dry-wet cycles show an increase in mechanical performance on materials with low water content. As for thermal tests, this is demonstrated by the microscopic structure of the panels and the increased presence of voids in the samples with dry grains. Despite the more porous structure, the tests show that the bonds between the citrus granule particles are retained in the mixture with dry grains, and that is improved with lower water content.

4. CONCLUSION

In this work, the possibility to use orange by-products as based material for building insulation is shown. Some similarities form microscopical observations are founded in microstructure between orange peels and commercial thermal insulators. Comparing the density of citrus peels with other building insulation materials from agriculture by-products, it appears that the results are similar. Panels by a cold-pressing process without the use of binders can be produced using citrus by-products and without sophisticated machines. A pressing and subsequent drying process creates a rigid panel with a density of 507 kg/m^3. The conductivity of 0.066 W/mk classifies the panel as a thermal insulator. The climatic chamber test shows that mixing wet and dry parts of citrus granules improves the material's ability to absorb environmental moisture and release it. After 50 cycles in the climatic chamber, mechanical properties have seen samples with dry parts and an improvement in the rupture modulus. Panels with higher water absorption showed worse thermal and mechanical properties. Moreover, the presence of water could also create an environment conducive to biological attacks. However, the ability of the panel to absorb and release moisture could be a good way to maintain constant thermo-hygrometric conditions in an indoor environment.



(a)



(b)

Fig. 6. *Flexural (a) strength and modulus of elasticity (b) of the samples before [1] and after [2] durability test.*

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IMPACT OF MODELLING ON THE ASSESSMENT OF ENERGY PERFORMANCE IN EXISTING BUILDINGS: THE CASE OF CONCORDIA SAGITTARIA

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Abstract

Energy efficiency in existing building stock is a priority for achieving the decarbonization objectives imposed by the European Union. Several European projects have addressed the issue and suggested strategies. In particular, the TripleA-reno project has among its objectives the development of a web tool for the energy assessment of buildings so that users can simulate the economic and energy benefits of the renovation process.
The paper aims to assess the impact of simplification in geometric, energetic and modelling input on the calculation of the energy performance of buildings. The study was conducted on a case study of the TripleA-reno project, located in Concordia Sagittaria (Venice).
The architectural configuration, the structural typology and the stratigraphies of the building and the interventions foreseen by the redevelopment project are described.
After defining the energy modelling software intended to be used, a detailed energy assessment was carried out, which was subsequently approximated by maintaining unchanged only the gross heated volume and the characteristics of the opaque and transparent elements. The different energy assessments were then analyzed to compare and evaluate the parameters most influenced by the simplification introduced and the variation of the S/V ratio.
Finally, the TripleA-reno platform was used to compare the results with both the detailed and the simplified model.

Keywords

Sustainability, Energy efficiency, Energy modelling, Deep Renovation.

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1. INTRODUCTION

TripleA-reno [1] is a European project funded by the Horizon 2020 programme whose aim is to increase the awareness of users and experts of energy renovation by providing tools to simplify and accelerate this process.

During the initial phase of the project, several case studies were analyzed in different European countries. Thanks to the results of these analyses, the processes of energy renovation and their activation were investigated. The project then focused on the actors involved in this process, the end-users and the professionals [2]. In-the-field ethnographic analyses have been carried out to illustrate how the context defines and influences the renovation process [3], highlighting its complexity and variability [4, 5]. In order to achieve the objectives set, the TripleA-reno project exploits the dynamics and mechanisms of gamification through various tools and a gamified platform where users can simulate and understand the process of renovation by using easy-to-use tools.

To carry out these simulations, it is also necessary to quickly and easily estimate the energy consumption of the buildings in pre and post renovation scenarios. However, before using these results, it is necessary to validate the process of energy modelling simplification through the phases described in this article, particularly in one of the case studies of the project.

The case study analyzed in this article concerns a multi-apartment building located in the province of Venice and managed by ATER Venezia. A renovation project has been approved for this property that includes interventions to improve the facade insulation, internal comfort, and static safety. After a general description of the building, in terms of geometry, materials used, and stratigraphies, the plant systems will also be described in the current state and the renovation project state.

Once the modelling software to be used was defined, a detailed assessment of the energy performance was carried out and then went on through several simplifications to understand if the margin of error due to the simplification could be considered acceptable. The study was conducted both for the current state and the project state in two different configurations; the first provides only the envelope improvement while the second also adds the replacement of the heating system.

Finally, energy performances have been compared to assess which parameters are most affected by the simplification introduced [6].

2. THE TRIPLEA-RENO GAMIFIED PLATFORM

One of the objectives of the TripleA-reno project is to provide the main actors of the renovation process with an easy-to-use tool conceived as a platform based on the principles of gamification [7], which can:

- connect directly with end-users, investors, manufacturers and professionals;
- give investors a tool from which to access the information entered by end-users, expanding the database of buildings that can be candidates for deep Renovation projects;
- provide professionals with a tool to make them enter the deep renovation process as mediators between end-users and investors.

One of the results of TripleA-reno is the creation of an open user-oriented platform based on solutions, experiences and methodologies applied in these recent projects. This tool will allow end-users to simulate the redevelopment of their homes, making guided choices on the various technological solutions available. It will also be possible to share experiences, solutions, and performances with a community of users of this tool to create a network that can further help users in their decisions through different means.

In particular, the Design Wizard Pro allows the user to evaluate different energy renovation actions using the measures stored in the TripleA-reno archive through a cost-benefit analysis.

To achieve this, the following steps are needed:

- input some data about the building; the needed data are simple, building dimensions and typology, through which the wizard will calculate the most likely thermophysical data;
- create a geometric model of the building; to simplify the input of data by the user, a module called Sketcher has been developed that allows the user to enter the geometric data of the building using a simplified CAD;
- input the thermophysical data of the building in the current state;
- choose the most suitable strategy for the renovation among the one proposed (maintenance, ecology, economical, lifespan, low energy, comfort);
- choose the measures that are proposed, ordered by performance according to the selected strategy;
- check the results, as improved energy class and CO_2 savings and investment payback time.

The Tabula approach has been followed for the insertion of thermophysical data (IEE Project Tabula 2009-2012 Typology approach for building stock energy assessment-funded by The Intelligent Energy Europe Program of the European Union, IEE/08/495 - IEEE Project Episcope 2013-2016, Energy Performance Indicator Tracking Schemes for the Continuous Optimization of Refurbishment Process in European Housing Stocks, co-founded by The Intelligent Energy Europe Program of the European Union, IEE/12/695/SI2.644739 - EPISCOPE). Based on a few input data (such as the country, the year of construction and the type of building), the data necessary to perform the energy calculation are extracted from the Tabula database to suggest the end-user plausible values for the energy assessment. A professional can adjust these values that, otherwise, would remain based on the end-user's skills.

3. THE CASE STUDY

The case study is located in Concordia Sagittaria (Venezia), owned by the social housing company ATER Venezia. It is a residential building with 21 apartments with tenants; the owner, ATER, is therefore responsible for the maintenance and conservation of the building. ATER has planned a restructuring to meet tenants' requests and access regional and national funding to reduce the investment cost.

3.1. ARCHITECTURAL DESCRIPTION

The building has a rectangular shape (80 m long and 12 m wide) along the east-west axis, with the most windowed facades to the north and south. It is divided into two blocks and comprises 21 apartments on four floors.

The ground floor is divided longitudinally into a garage area on the same side of the access from the road and a rear porch slightly raised connected to the park. The east block rises to four floors above ground and consists of semi-duplex specular apartments. Instead, the west block rises to three floors above ground and consists of one-storey flats on the first floor, while the upper floors consist of semi-triplex type apartments.

The flat roof is not accessible and is scattered longitudinally by half a floor. On the street side, the building has a height of 12.00 m above the ground, while on the park side, the west block has a height of 10.20 m and the east block of 13.50 m (Fig. 2).

Three staircases conceived as independent structures from the main blocks guarantee access to each dwelling. The main stairwell is located in the middle of the two blocks, while the other two staircases are situated in the eastern and western extremities of each block. The stairs lead directly to the external balconies, which extend the entire length of each main block. The east block has two balconies at two different heights, while the west block needs only a balcony to allow access to all apartments. Therefore, the architectural concept is based on similar or mirror-like apartments, arranged one above the other, and repeated several times along the central longitudinal axis. This arrangement favours a prefabrication logic, even if the construction is made of traditional reinforced concrete and prefabricated solutions are minimal.

3.2. STRUCTURAL DESCRIPTION

The supporting structures of the building consist of pillars and lowered reinforced concrete beams, weakly reinforced concrete partitions and slabs in prefabricated reinforced concrete panels with 20 cm high slabs. The structural typology of the flat roof is similar to that of the intermediate floors.

Fig. 1. *On the left, the north facade towards the road. On the right, the south facade overlooks the public park adjacent to the archaeological park side. (Photo © 2021, D. Prati).*

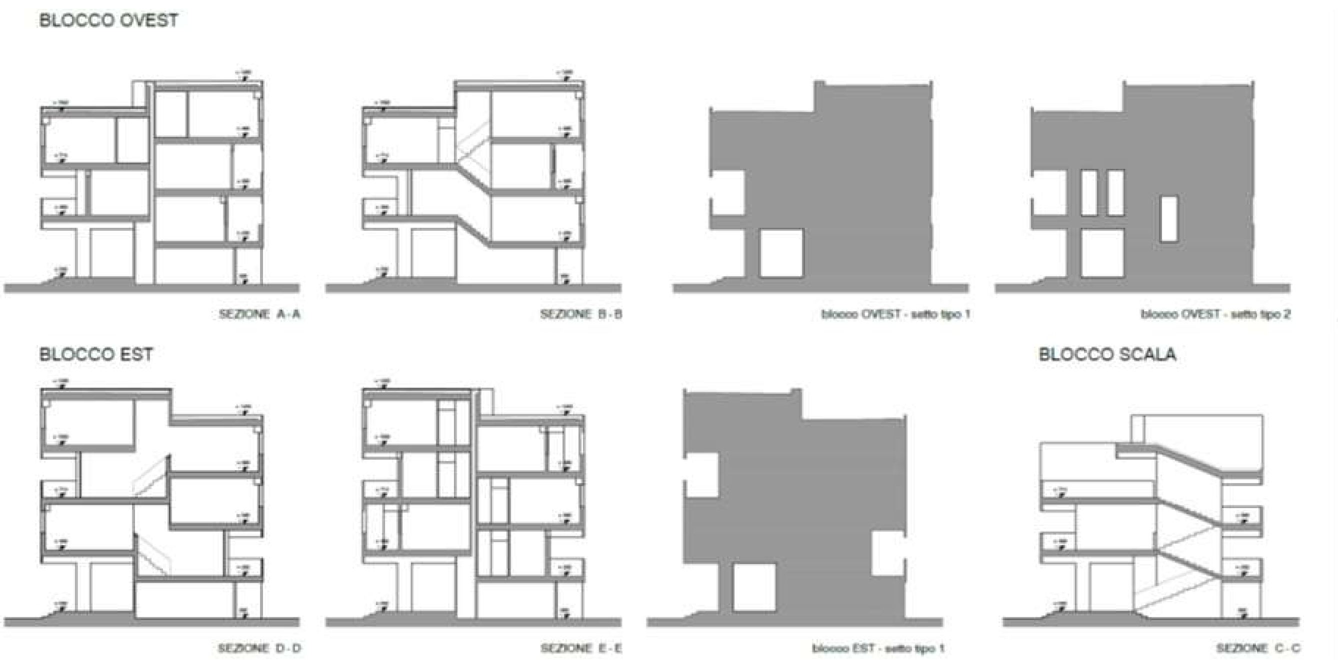

Fig. 2. *Structural design of the building. Identification of floor slabs, internal and external stairs. Schematic representation of the different transverse partitions of the east and west blocks. (Picture © 2021, D. Prati).*

Both the east and west blocks are marked longitudinally by seven 18 cm thick reinforced concrete walls with two outer layers of Heraclit (mineralized wood wool panels) 2.5 cm thick on each side. These walls give a peculiar characterization to the architectural organization and structure of the building. The concrete partition walls divide the dwellings into repetitive patterns, which are replicated, as in a mirror, and become the primary vertical supporting structure. They support the main beams and all internal stairs.

The internal structure of these partitions is not homogeneous: they are generally weakly reinforced, but on the inside, more reinforced vertical and horizontal parts are visible. These parts allow identifying an internal warp of beams and pillars. Given the horizontal offset of the floors of a half-plane, the internal structure of the partitions is particularly dense. Each septum contains four posts and beams of different thicknesses at the junction of the floor and above each gallery overhang. The foundations consist of reinforced concrete beams placed on underground poles (Fig. 3).

The main stairwells are not connected to the main structure and were built later: each stairwell has a reinforced concrete wall in the centre of the ramps, and all the loads of the landings are supported by a knee-high protrusion coming out of the slabs of the blocks. The foundations of the stairs (except for the central one) are not connected to those of the building but have their own reinforced concrete beams; as a result, the differential settling of the ground caused the sagging of the side stairs, causing vertical subsidence of 2-3 cm with respect to the building. The building has no seismic or expansion joints despite its considerable longitudinal length.

The walls along the north and south sides of the building have the following stratigraphy from the outside to the inside: 1 cm of plaster, 12 cm of brick, 2 cm of rock wool, 8 cm of perforated bricks, 1 cm of plaster, for a total thickness of 24 cm.

The windows are placed only on the long facades (the short sides are entirely blind), and the windows are still the original ones, made of single glass steel and without thermal break. Some tenants have installed double aluminium frames outside. There were also private balconies for each house on these elevations, which in many cases were closed with double aluminium windows. Additional aluminium windows were also installed on the end parts of the common balconies to limit the entrance of rainwater.

The heating system and domestic hot water production are centralized on the ground floor, where there is a boiler room with a diesel generator. Many residential units have individually installed an air conditioning system for summer cooling. Only one apartment in the west block was weakly insulated with a 4 cm thick outer coat.

3.3. THE RENOVATION PROJECT

The building is in a poor state of preservation due to the original construction imperfections and the lack of maintenance over time. Some residents who attended the construction site said that the project of the building was not well defined and that its construction was poorly managed and controlled. The building has certainly been designed in a short-sighted way, without considering the ageing of generations, the elderly and the disabled, and future changes in lifestyles. Beyond the possible reasons for the current situation, the fact is that the occupants face these problems in their daily lives.

At first sight and even more after inspection, several technical deficiencies in the building can be reported. In addition to insufficient, or better none, insulation, the low drainage capacity of the roof and the formation of moisture patches in the most exposed walls have often been highlighted. The flat roof, protected only by a thin bituminous coating, has a compluvium that leads from the facades to the centre of the building and drains water into the internal open vertical shaft from the roof down to the ground. As a result, the apartments have considerable problems with rainwater infiltration on the upper floors: stains in the ceiling, blooming in the plaster or moisture penetration.

Another typical problem, due to the specific internal arrangement of dwellings on different floors, is related to cooling and heating. The interior stairwells act as air convectors and make it difficult to maintain an optimal temperature both in winter and summer. Other general complaints concern the positioning of the glazed front to the north, which is often hit by heavy rains in cold seasons, causing water infiltration. Conversely, the southern front is unlivable in the summer due to a considerable heat accumulation caused by the lack of shielding elements. In addition, due to the foundation displacements, the original steel frames of the windows manifested significant air seepage over time. All this, together with the poor stratigraphy of the walls and the entrance doors made of honeycomb sandwich wood, lead to a level of insulation of the apartments that is not adequate to current standards [8] (Fig. 4).

The maintenance status of the facades is not particularly good, with damage and detachments of plaster. In particular, the detachment of portions of plaster on the northern façade, more exposed to the weather, the detachment of the concrete cover in the walls of the stairwells and the lower outer corners of the longitudinal beams. Evident cracks are visible in the connection where the external infill walls rest on the concrete beams. Where steel armour emerges to the eye, it causes the inhabitants a particular concern which, although excessive, is not entirely unfounded in non-expert people. No elevator system is available in the building, and people with disabilities also have to deal with a few stairs inside the apartments (Fig. 4).

For the reasons explained, ATER has planned for this building a retrofitting project promoted in collaboration with the Veneto Region, aimed at improving its energy performance, which consists of several interventions aimed at reducing or removing the main energy criticalities:

- thermal insulation (12 cm fibreglass panels) of the entire external envelope of the building, including the roofing and the lower surface of the garages and porch;
- replacement of window frames and glazing and renovation of the heat generation system by integrating energy from renewable sources.

At the same time, during the thermal retrofitting intervention, some actions will be taken to improve the seismic performance of the building:

- in the outermost parts of the two blocks, the thermal insulation will be stiffened by the construction of a 15 cm thick reinforced concrete wall filled inside the insulation, which will be divided into two layers of 8 cm (externally) and 4 cm (internally);
- installation of an eccentric bracing system along the longitudinal axis of the building to support the seismic mantle and transfer the horizontal actions to the ground;
- realization of a series of reinforced concrete diaphragms at the north facade, built between the foundations and the first floor so as not to block the entrance of the garages but able to act as an effective structural reinforcement.

4. SIMPLIFIED ENERGY MODELLING

Implementing the TripleA-reno platform has necessitated a simplified architectural and energy modelling of buildings, both for data management by the algorithm and to simplify user input. This study aims to verify that simplification does not lead to a significant error and reduces the reliability of the results.

The building has been studied in three conditions: current state, envelope-only project (scenario of intervention on the only envelope), envelope-and-plants project (scenario of intervention with replacement of the heat generator and installation of photovoltaic panels). These three conditions were then analyzed through a detailed energy model and a simplified one, having the same heated volume but regular geometric shape. The simplified model was then used for analysis through the TripleA-reno platform.

4.1. THE CHOICE OF THE SOFTWARE

For the first analysis, it was decided to use Logical Soft's Termolog software for the calculation of energy performance. The software in the Epix 10 version is updated with the dynamic hourly assessment in accordance with the Italian legislation, the UNI EN ISO 52016, and the new UNI TS 11300-2:2019 [9].

On Termolog, the user can create the BEM (Building Energy Model) energy model of the building from scratch, using the integrated modeller, or import an existing BIM model from files in the IFC standard format. The program has broad flexibility for modelling; it recognizes, in fact, .dwg/.dwf file, .pdf and gives the opportunity of tabular data entry, thus allowing the geometry of the envelope to be mirrored by automatically obtaining orientation and shading from the outline of the building. Termolog quickly models the various types of plants and implements any energy efficiency measures. The software has a database containing all the materials required by the technical standards and the stratigraphies pre-calculated provided by the UNI TR 1152 standard. Still, it also provides the opportunity for manual input by the user. It also allows for the automatic creation of windows through a wizard.

4.2. THE DETAILED MODEL

The detailed model fully reflects the case study building in its volume, which was created by importing in Termolog the plans of the various floors. Since these are at scattered heights, 8 levels have been modeled based on the dispersion characteristics, and 21 thermal zones corresponding to the apartments have been identified and created. No unnecessary elements for energy modelling

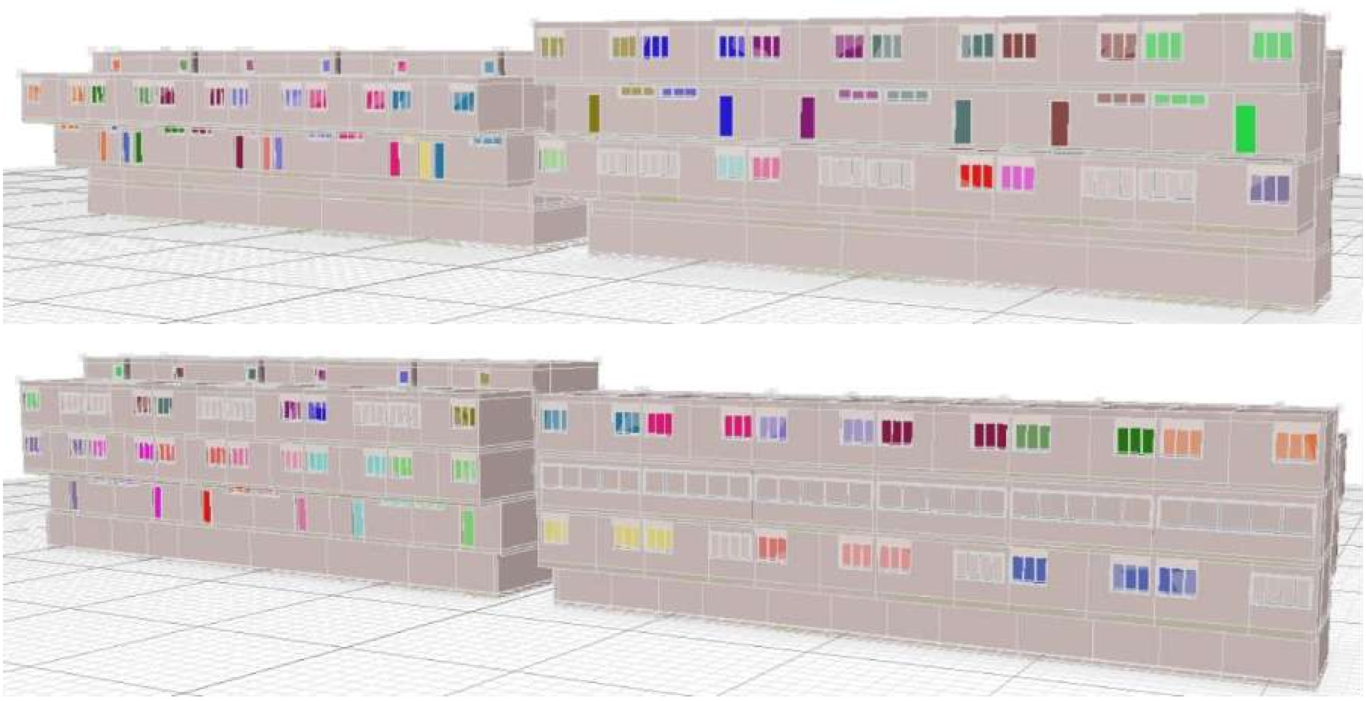

Fig. 3. *3D views of the detailed energy model. Above, South-East view. Below, North-West view. (Picture © 2021, D. Prati).*

have been added, such as the internal stairs of the flats, the pillars in the portico and the balcony parapets.

4.3. THE SIMPLIFIED MODEL

The simplified model was created from the heated gross volume resulting from the detailed model, dividing the building into east and west blocks. The value was then divided by the actual length and height, obtaining in this way the width of each block. This procedure led to a model that respected the distribution of the heated volumes. The building is, in both blocks, divided longitudinally with the volumes scattered half a floor from the opposite side.

With the method used for simplification, given the differences in the heated gross volumes, the two blocks now result in two different floor heights and floor numbers. In particular, the east block was modelled with three floors (from 6 scattered half-floors), lowering the half-planes of the south side to the height of those of the north side. In the simplified model, the west block is transformed from 5 scattered half-floors to 2.5 floors. On the ground floor, the garage boxes on the north side and the porch on the south side were preserved in the model to keep the same dispersant surface as much as possible. However, the dispersant surface is smaller in the simplified model because the balconies have been eliminated by incorporating those volumes in the main building body.

The volumetric simplification is evident looking at how the east and west elevations change; the scattered trend is no longer visible and is replaced by a regular shape. No internal partitions have been added to the simplified model. In contrast, the original design has not been heavily modified as far as windows and doors are concerned. Only the doors to access the terraces have been eliminated, while in correspondence with the windows of the terraces, a "double window" has been created, replacing the two single glass windows present on the line of the external wall and the inside wall of the terrace. At the plant systems level, however, trying to make the energy estimations as close as possible, the same number of terminals was inserted in the detailed model, even if the two blocks were not divided into thermal zones.

4.4. THE MODEL FOR THE TRIPLEA-RENO PLATFORM

The TripleA-reno platform is designed to allow end-users to simulate how a renovation process can improve their building. Because of that, the input needed is more straightforward than the one required by energy simulation software.

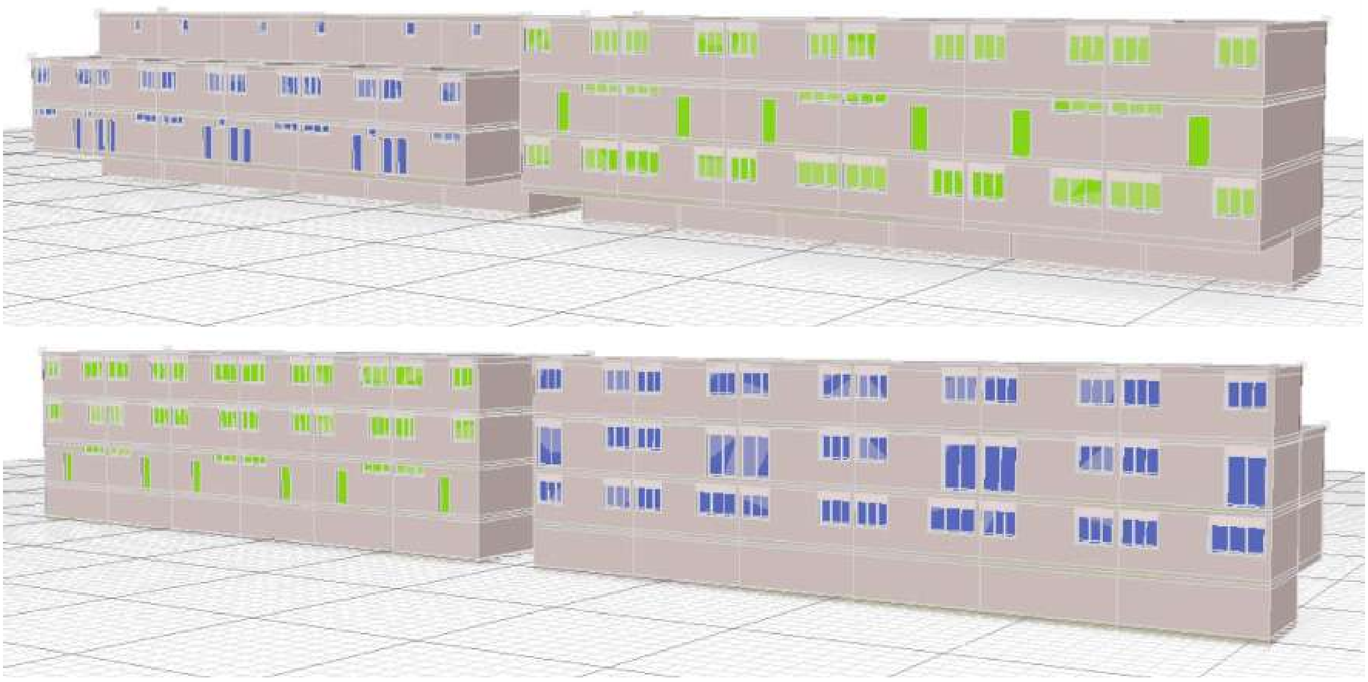

Fig. 4. *Three-dimensional views of the simplified energy model. Above, South-East view. Below, North-West view. (Picture © 2021, D. Prati).*

The calculation is then performed through the UNI/TS 11300 standard based on the parameters entered by the user, which are mainly geographical and typological. Based on these types of input, the main thermal and performance parameters of the structures are deduced according to the approach developed in the Tabula project mentioned in par. 2.

As for geometric input, the user can choose whether to enter it in a tabular way or via CAD (Sketcher). In the latter case, the detail is not as precise as the one of a traditional CAD because the average user needs to simplify the building. For example, the balconies and garages were not modelled in the present case study.

5. RESULTS

There are no shape variations between the current state and the post-renovation scenario while the heated gross volume slightly increases. The modelling process of the simplified model has been described in the previous paragraphs, and from the results, it is evident that it has not led to significant errors; in fact, the two models are very similar, and the most important difference is in the total dispersant surface that is slightly underestimated with 3917.51 m^2 for the detailed model and 3749.88 m^2 for the simplified one.

When the post-renovation scenario is concerned, which involves changes in the stratigraphy of the outer walls, there are changes in the dispersant surfaces and the heated gross volumes. However, the simplification process entails a difference that is constantly below 1% compared to the detailed model. In both cases passing from the current state to the post-renovation state produces a variation of about 10% of the heated volume, as seen in Table 1.

The energy analyses of the six scenarios were carried out using Termolog® software in a semi-dynamic monthly regime. The overall performance index is underestimated in the simplified model for the current state, while it is overestimated in the renovation scenario with the plant systems replacement. The energy requirement for heating in the current state scenario is remarkably accurate in the simplified model; in fact, the needs are respectively 511917 kWh for the detailed model and 505885,9 kWh for the simplified one. While for the renovation scenario, the detailed and simplified models present much more different values, as shown in Table 2.

The current state and post-renovation scenarios energy assessments were also carried out using the TripleA-reno platform. The first one differs from the detailed model by about 16%, while in the post-renovation scenario, the difference is more significant and is about 31%. The simplified model is accurate for the current state (around 1% difference), while the post-renovation differs by 55%, as seen from the following table.

	Detailed model		Simplified model	
	Current State	Renovation (envelope+system)	Current State	Renovation (envelope+system)
Net heated Area	2135.57	2135.57	2266.53	2266.53
Gross Heated Volume	7961.28	8751.79	7995.8	8803.82
Dispersant Surface	3917.51	4280.97	3749.88	3989.16

Tab. 1. *Geometrical data of the models.*

	Detailed model		Simplified model		TripleA-reno model	
Primary energy demand for heating (kWh)	Current State	Renovation (envelope+system)	Current State	Renovation (envelope+system)	Current State	Renovation (envelope+system)
Primary energy heating non-renewable	511643.10	145388.30	505615.20	224647.90	431899.80	190152.60
Primary energy heating renewable	273.90	0.00	270.70	0.00	44.50	280.50
Primary energy total	511917.00	145388.30	505885.90	224647.90	431944.30	190433.10

Tab. 2. *Primary energy demand for heating.*

	Difference Simplified Model - Detailed Model		Difference TAR Model - Detailed Model	
	Current State	Renovation (envelope+system)	Current State	Renovation (envelope+system)
Primary energy heating non-renewable	-1%	55%	-16%	31%
Primary energy heating renewable	-1%	N/A	-84%	N/A
Primary energy total	-1%	55%	-16%	31%

Tab. 3. *Primary energy comparison between models.*

6. CONCLUSION

From the analysis of the results, it is possible to make some considerations about the use of simplified models for the energy assessment of buildings. First, the procedure chosen to simplify the building model correctly maintains the geometric conditions, with almost unchanged values of heated gross surface area, dispersant surface and heated gross volume.

It is necessary to distinguish discrepancies according to the scenarios concerning energy results. There are inconsistent trends between the various scenarios when comparing the results obtained for winter heating. The simplified model results, related to primary energy demand for heating, differ from the detailed model by a maximum underestimation of -1% and a maximum overestimation of +55%, and from the TAR model from -16% to +31%, the first values for the current state and the second for the renovation (envelope+system).

The second scenario, which involves the replacement of the generator of the heating system, presents a converse behaviour. In this case, not only are the results overestimated, but the differences with the previous scenario are not consistent with those obtained in the detailed model. The simplification of the plants is a critical point, as well as the modelling of particular areas such as lodges or greenhouses, and must be improved.

In the TripleA-reno platform, the energy demand of the current state was 15% underestimated, while the one of the post-renovation state was overestimated by 30%. This variability could mean that the simulation with the TripleA-reno platform could make renovation action less convenient than it actually is, but also ensures that the user "acts in safety" and continuing with more in-depth estimations, the scenario will only improve, and this will not discourage end-users from undertaking a real redevelopment.

Therefore, it turns out to be fundamental to analyze further case studies to refine the method. On the one hand, the case study of Concordia Sagittaria was hard to model in detail since it consisted of a multiapartment building with scattered floor dwellings. This complexity resulted in difficult management of the thermal zones within the software. On the other hand, a higher number of case studies will minimize the differences between the detailed model and the simplified one, giving a better simulation for the user. As already said, the case under consideration is a rather complex building, which has been reduced to a sum of simple shapes and spaces during the modelling process. As a consequence, it creates a scattering of the error. Therefore, it is suggested to choose geometrically simpler cases to refine the method with simple shapes.

Furthermore, it is utterly necessary to test the platform with several case studies, to understand better the threshold values for which the geometric, energetic and input simplification can work and how to refine the simulations to have results that deviate less from detailed energy simulations while making the use of the tool accessible to non-expert users.

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SLICE - SOLAR LIGHTWEIGHT INTELLIGENT COMPONENT FOR ENVELOPES: APPLICATION FOR THE ICARO PAVILION

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Abstract

In the ongoing race to reduce polluting emissions, a significant contribution is made by the introduction of intelligent building management systems. The European directive 2002/91 on energy performance in buildings already invited us to look at a new generation of almost zero energy buildings. Research in the field of multifunctional facades offers the opportunity to provide an immediate response to improving air quality and, at the same time, optimizing the use of resources. In fact, adaptive facades can be traced to one of the most effective strategies to efficiently manage the interactions between external and internal environments to maximize winter heating, summer shading and natural ventilation, sound insulation, daylight transfer, glare-free, and interior comfort for the occupants. Nowadays, adaptive enclosures are not only able to interact with the environment and the user but allow the energy needs of buildings to be reduced by integrating technologies to produce energy from renewable sources.
The contribution will present the latest developments of an innovative kinetic device for architecture, developed by the University of Catania; it is the result of a multidisciplinary research project involving important local industrial companies. The component consists of a composite material substrate with integrated high-efficiency photovoltaic technology. The results shown below made it possible to evaluate the use of the designed component in light and stand-alone architectures, representing a valid solution to reduce the impact on the territory even in fragile contexts.

Keywords

Adaptive architecture, Innovative envelope, Photovoltaic, Composite material, Lightweight architecture.

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1. INTRODUCTION

In recent years, scientific research and the production market focused their attention on adaptive, highly flexible and lightweight architecture components. This phenomenon becomes more important if these experimentations concern materials that improve the sustainability of architectural works both in the production phase of the components and during their use. The purpose of this line of research is to reduce energy costs by reducing the weight of the elements used and by simplifying the mechanical components.

Kinematics and adaptability are characteristic properties in the definition of intelligent envelope systems. As kinetic architecture, we define «buildings or building components with variable mobility, localization and/or geometry» [1]. The use of smart materials can be a simplification in the adaptive components but limits the possibility of controlling the movement if you consider that they are calibrated on specific thermophysical environment conditions. This is the case of the Shape Memory Polymers, which change their shape only under certain temperature variations [2]. On the other hand, the movement must be managed through an actuator; it presupposes the use of energy deriving from the network or produced onsite. This last case guarantees the potential self-sufficiency of the system if the integration of the adaptive component with energy production systems is reached.

The most promising field of application seems to be that concerning small residential modules (the so-called "tiny houses"), exhibition pavilions and, in general, light flexible multipurpose architectures.

With the introduction in the 1990s of amorphous flexible silicon cells, experiments aimed at offering new solutions for the integration of solar technology in building components began. The first photovoltaic textile structure called "Under the sun" dates to 1998 (Fig. 1a). It was built in the Cooper-Hewitt National Design Museum in New York and consists of a 9.7 m high enclosure equipped with amorphous silicon solar cells of 120 µm thickness, encapsulated and laminated on shaped fabric panels [3].

Ackermann & Partner Architects in 2011 designed the roof for the AWM Carport waste disposal warehouse, providing 220 three-layer ETFE cushions to cover a total surface area of 9600 square meters (Fig. 1b). The project includes thin-film photovoltaic modules inserted in the central layer with mechanical fastening devices in order to maintain certain flexibility and reduce the risk of deformation, that is due to the bending or stretching of the cushion. The outer membrane of the cushion protects the modules and allows the correct solar radiation with its high transparency. It can be opened to facilitate the maintenance and replacement of defective cells [3].

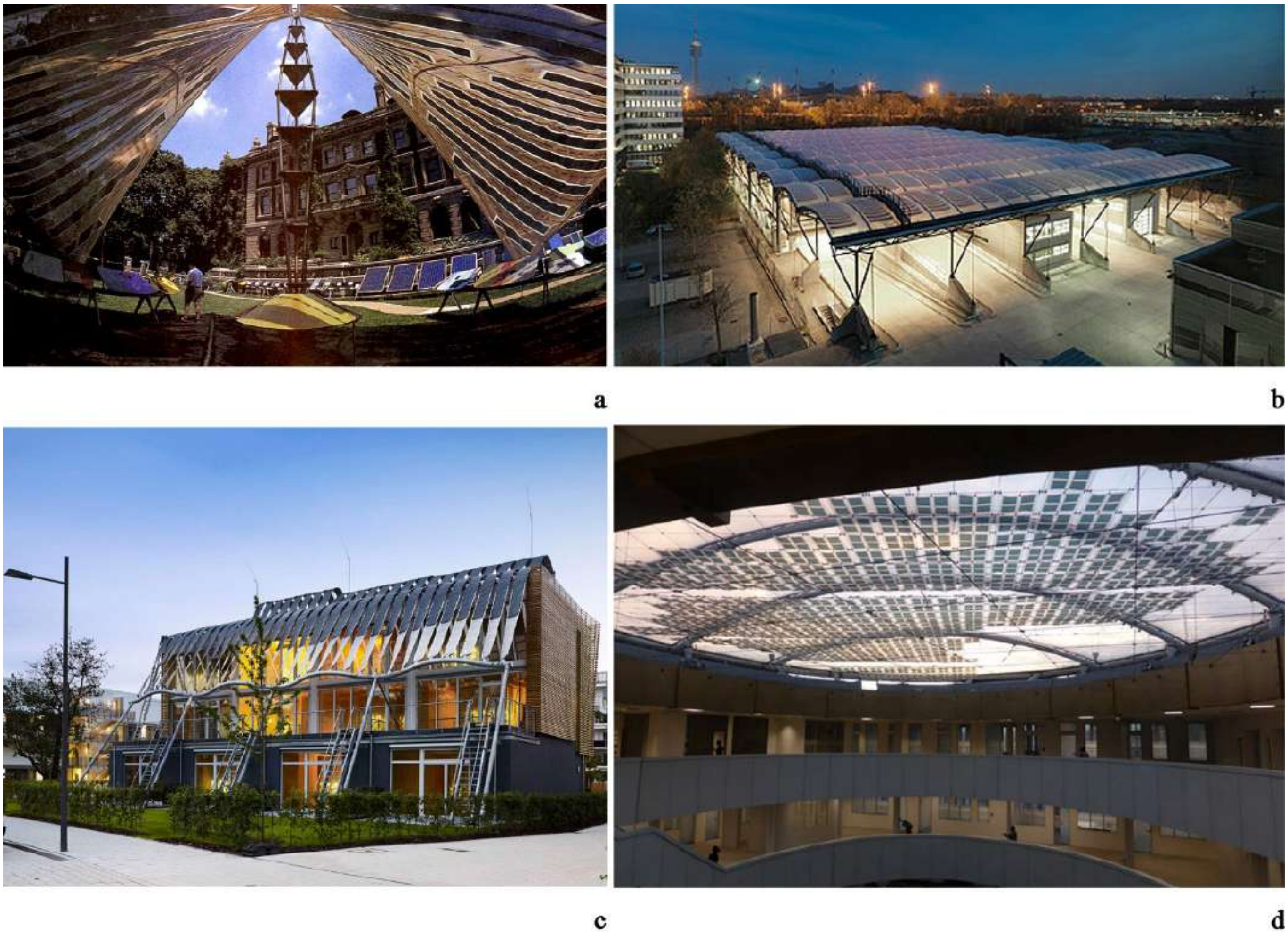


Fig. 1. *(a) Under the Sun Pavilion, Cooper-Hewitt National Design Museum, 1998 [4]; (b) Ackermann & Partner Architects, AWM Carport, 2013 [5]; (c) Kennedy & Violich Architecture, Soft House, 2013 [6]; (d) Carl Stahl Architektur, Peace and Security Building of the African Union Addis Abeba, 2015 [7].*

Among solutions of photovoltaic systems in the building, the so-called BIPV (Building Integrated Photo-Voltaic), there is the “textile solar system” developed for the prototype Soft House in Hamburg, designed by the Kennedy & Violich Architecture studio [8]. The building has a wooden load-bearing, which is characterized by a dynamic façade with solar shielding with vertical bands. These ones are made with a semi-transparent and highly reflective PTFE fabric which has been superimposed on eight thin-film photovoltaic cells (Fig. 1c). The responsive system generates the rotation of the bands to follow the solar path, thanks to the kinematics integrated into the anchoring systems of each band. The individual façade elements are able both to convert solar energy into electricity and regulate the luminous flux in indoor environments. To achieve this goal, the building is provided with a Building Management System (BMS). The shading level can also be controlled manually by users.

Another very interesting building is the work carried out by the Carl Stahl Architektur GmbH for the Peace and Security Building of the African Union Addis Ababa (2015). The building has a large central open space that is covered by a photovoltaic veil, created using a 25 m x 20 m shading system with 445 transparent blue organic photovoltaic (OPV) modules. It is capable of providing enough energy for the interior lighting of the building (Fig. 1d).

Within this framework, the research presented here aims to develop a responsive, intelligent component in flexible composite material for adaptive envelopes. SLICE (acronym of Solar Lightweight Intelligent Component for Envelopes) is capable of producing energy if connected to a charging and handling system; it would offer the opportunity to create dynamic building envelopes and innovative temporary architectures.

2. PREVIOUS STAGES OF THE SLICE RESEARCH AND STATE OF THE ART

The SLICE (Solar Lightweight Intelligent Component for Envelopes) research project started five years ago with an overview which drives the opportunity to develop innovative solutions on the use of foldable components, to get to the responsivity of architecture. In fact, foldability gives the shielding component a high degree of transformability connected to its kinematics; at the same time, it allows the increase of the mechanical performance because fold gives the material in the direction of the same a stiffening that takes the name of “resistance by shape” [9]. Moreover, through responsivity, it is possible to take into consideration the needs of the users. Through it, it is possible to reach different achievements, such as reducing energy costs, improving comfort, having accessibility, and so on.

The acquired knowledge suggested focusing our attention on the choice of the base material as well as the selection of the type of kinematics and the integration of photovoltaics into the foldable component in order to obtain a component capable of producing the energy necessary for its motion.

2.1. MATERIAL

The first phase of the research aims to create first samples of a small size composite material made by hand with a hot press, trying different fabric reinforcements (linen, carbon fibers and glass fibers) and two different matrices in thermoplastic elastomer, the styrene-ethylene-butylene-styrene (SEBS) and ethylene vinyl acetate (EVA) and testing different possible stratifications. The choice of the material to be used for the reinforcement was oriented towards natural fabrics and, in particular, the Biotex Flax fabric made up of flax fibers, and the fiberglass fabrics. Other fiber fabrics result in poor cohesion between the matrix and the reinforcement. The best performing stratigraphy is made up of a lower layer in EVA, a reinforcement fabric in Biotex, and an upper layer in EVA.

In collaboration with a local SME (Meridionale Impianti S.p.A.), who is a research project partner, production parameters (time and temperature of the lamination process) and stratigraphy composition (matrix and reinforcement layers) were defined, creating larger samples (about 20 cm x 40 cm making use of the vacuum production process in a single laminator.

For preliminary evaluations, the samples were subjected to visual and touch analyses and further analysis with the cross-section method. Finally, the samples that exceeded these analyses were subjected to a mechanical characterization process with a monoaxial tensile test [10, 11]. The results of the mechanical characterization tests show characteristics of the composite material comparable with those of the composite materials commonly used in Textile Architecture [12].

2.2. POST-PRODUCTION PROCESS

Once the lamination process was validated, the work was addressed to the definition of the folding procedure. The idea was to use a thermoforming post-production process to bring the material to the glass transition temperature (T_g) in order to re-melt the polymers present in it.

Preliminary, with the collaboration of another SME research partner (NTET S.p.A.), a sheet metal mold was made in order to define the folding process. It consists of two 90° V-shaped parts, obtained by pressing-bending two sheet metal sheets with a thickness of 0.8 mm, held in position with butterfly bolts, heated with four heated plates equipped with thermocouples, for temperature monitoring (Fig. 2a). This first solution was used to quickly analyse the definition of process parameters, as the thermocouples allowed precise control over the temperature trend in the parts of the mold. At the end of the experimentation, the definitive cycle parameters were set at 120°C of temperature and 15 min of duration. Based on these results, a multi-panel mold called "conformer" was designed for the pre-bending of large composite samples. It consists of stainless steel sheet plates (type 304b stainless steel). The composite is folded, alternating it with the panels characterizing the mold; the package obtained is tightened by means of stringent and subjected to heating in the oven (Fig. 2b). This pre-folding technique takes advantage of a considerable reduction in production times and costs. For the heating of this type mold, the same processing parameters previously identified were set [13].

2.3. PV TECHNOLOGY INTEGRATION

In order to make the component self-sufficient from the energy point of view, new samples in composite material were made integrating into it photovoltaic cells. Starting from the stratigraphy of the composite material developed, an experimental phase was carried out aimed at the implementation of the material through the integration of high-efficiency photovoltaic technology.

In recent years, this field of research has focused on the development of the exploitation of solar energy, to implement the structure of current solar cells and to search for new types in order to increase their efficiency, as well as pursuing the use of materials and technologies to break down the production costs. One of the most widespread and promising technologies in the sector is based on silicon photovoltaic cells or called first generation cells: photovoltaic panels based on monocrystalline and polycrystalline silicon cell modules dominate the market from the early years of the system's industrialization. The experimentation activity was focused on the possibility of increasing efficiency values, thanks to the use of new light-absorbing materials. In the cycle of only eight years, the efficiency increases from 4% in 2012 to the current higher theoretical value of 23%.

So, the choice fell on flexible monocrystalline silicon cells produced by SunPower, of the c60 type with proprietary Maxeon technology. They are cells with dimensions of 125 mm x 125 mm, with a thickness of only 165 μm ± 40 μm, with contacts placed at the inner layer (back contact).

For their integration in the foldable elements, the photovoltaic cells have been positioned in correspondence with the flat parts and not with the folds. The cells are however subjected to bending stresses because the composite has a certain flexibility. The greatest criticality consists in the electrical connection between the different cells, which must necessarily pass through the folds.

The use of PPE layer was also tested in order to optimize the integration of photovoltaic cells into the composite. PPE is a thermosetting polymer usually used in the production of photovoltaic panels as a coating layer, extremely waterproof, with excellent resistance to atmospheric agents and dirt, as well as to numerous chemical compounds.

The best performing stratigraphy is made up of a lower layer in EVA, a reinforcement fabric in Biotex, the interposition of the photovoltaic cells between two upper layers of EVA and final coverage, limited to the areas of the photovoltaic cells only, with PPE layer [14]. The

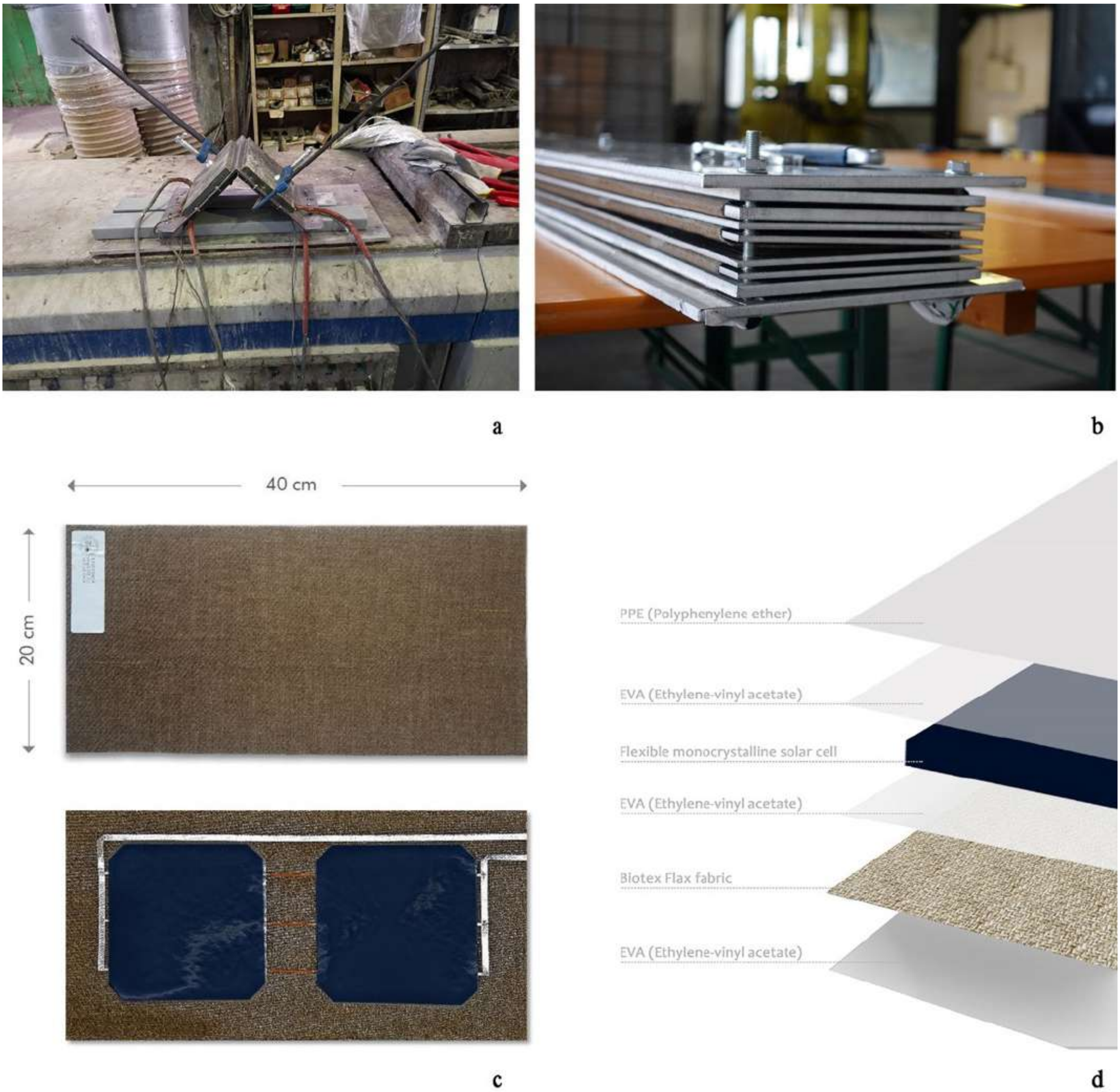
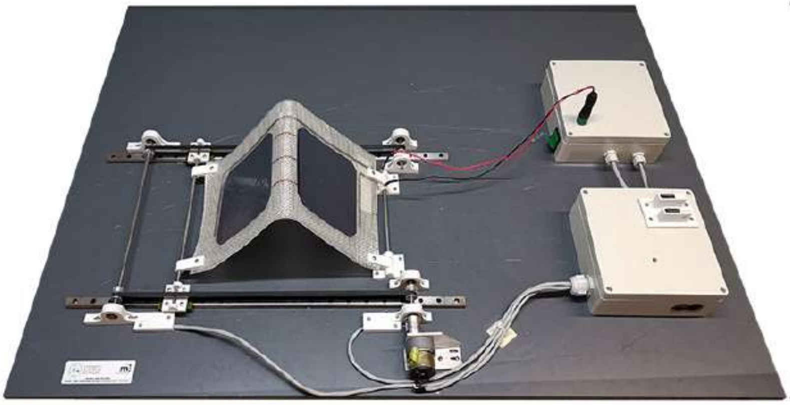


Fig. 2. *(a) Sheet metal mold consisting of two 90° V-shaped parts; (b) preparation of the "conformer" multi-panel mold; (c, d) sample of the material with integrated photovoltaic cells and relative stratification [13].*

photovoltaic cells were connected in series using flexible copper braid wires at the folding lines, spaced at least 3 cm apart and connected to the poles through the adoption of rigid dog bone tabbing wires (Figs. 2c and 2d).

2.4. PROTOTYPING

Two 1:1 scale prototypes have been developed aimed at simulating the operating cycles of the component. The first one (Fig. 3), called SLICE 1.0 was realized in order to test the system's charging and handling cycles, with simple bellows folding of dimensions 20 cm x 40 cm. It was equipped with two photovoltaic monocrystalline silicon cells SunPower Gen I and fiberglass reinforcement. The prototype was also tested with the use of a sunlight simulation lamp to verify the correct functioning of the electrical connections after the lamination and folding processes. The results were compatible with the sum of



Dimensions and weight	20 x 40 cm; 139 g
Matrix	EVA SKC Films EF2N
Reinforcement	glass fiber
Photovoltaic cells	SunPower Maxeon® Gen I
Charging circuit	ST Microelectronics ST SPV1040T
Battery	3.7V 2250 mAh 8.33Wh lithium
Microcontroller	Arduino Mega 2560

Fig. 3. *The first prototype equipped with fiberglass reinforcement and monocrystalline silicon solar cells [13].*

the voltage values from the technical data sheet of the individual cells, allowing the influence of the PPE coating layer adopted to be considered negligible.

The second prototype (Tab. 1), called SLICE 2.0was built for a test campaign in environmental conditions. In this case, the automation system was subjected to a profound upgrade to add a complete package of adaptive functions. A panel of dimensions comparable to a standard window for a standard room was adopted as the shielding element. SLICE 2.0 is equipped with no. 12 photovoltaic cells according to a circuit of 4 parallel branches, each of which is composed of 3 cells connected in series. This method of electrical connection was adopted to facilitate the arrangement of the cells in the layers and in such a way as to guarantee an output voltage value adequate to the values in which the charging board with ST Microelectronics SPV1040 chip adopted for the prototypes operates. In order to be applied to the prototype, the composite fabric was subjected to the defined thermoforming process with the metal conformer. The Arduino source code ha a list of instructions distributed in a hierarchical manner to obtain a finite state machine, usually known as a multitasking machine [15]. In this way, the prototype can recognize three different operating scenarios, called Comfort Mode, Energy Mode and Manual Mode, and react adaptively on the basis of predetermined cases, strictly connected to the need to ensure an adequate level of indoor comfort or optimize the production of energy from the incorporated photovoltaic cells.

The Comfort Mode has the purpose of privileging the comfort conditions within the rooms, ensuring an adequate level of lighting by moving the component, adjusting its position both in order to ensure good

Sample	100 cm × 68 cm; 1.5 kg
Composite	Biotex Flax, 400 g/m² Composites Evolution Ltd.
	EVA SKC Films EF2N
	DUN-SOLAR PPE
Silicon cells	SunPower Maxeon® Gen I
Linear guides	550 mm Mini MGN12H
Belts	Tiptiper 2GT-6
Pulleys	20 Teeth Bore 5 mm GT2 SIENOC
Gear motor	POLOLU-2205 150:1 Micro Metal Gearmotor LP 6 V
Lithium battery	4500 mA, 3.7 V
Charging circuit and additional module	ST SPV1040T battery by ST Microelectronics
	TC4056 IZOKEE 1A 5 V micro-USB
Control board	Arduino Mega 2560
Analogic light sensor	Adafruit GA1A12S202
Infrared proximity sensor	PIR HC-SR501
Rain or snow sensor	Raindrops Module MH-RD
Current sensor	ACS712-20 A
LCD display	HD44780

Tab. 1. *Components of SLICE 2.0. prototype.*

Fig. 4. *Example of SLICE 2.0 prototype installed on a window [16].*

lighting and to avoid potential glare situations. Energy Mode is activated when the proximity sensor does not detect the presence of users in the room. In this case, for maximizing the electrical energy production, the component movement to its complete extension. The Manual Mode is a maintenance mode, developed to allow complete control of the component by the user precisely for maintenance and/or cleaning activities on the frame or device.

The test campaign (Fig. 4) was preceded by a preliminary sensor calibration phase, performed to verify the right functioning of the code. The identification of the threshold values defined for opening and closing were checked, as well as the verify of the designed power and the capacity of the battery.

The tests highlighted some constraints of the SLICE 2.0 prototype because, in some cases, the values obtained did not correspond to the expected values. So, it was observed that the charging board did not have suitable dimensions, and as a consequence, it was not possible good store the energy produced by the PV cells. For this reason, the development of this research foresees the redesign of the recharging system and also the addition of an MPPT (Maximum Power Point Tracker) controller, which will allow the photovoltaic cells to operate at their point of maximum power [16].

The analysis of the technical data of the panel also suggested the prospective to use the surplus of energy produced to power the technological components of the environment where this is installed, so like as a BIPV solution.

3. ADVANCEMENT OF SLICE

SLICE project has undergone a further phase of development thanks to the synergy established with the eWAS project – An Early WArning System for culture heritage [17], already developed for some years by the University of Catania. One of the goals of EWAS project is the construction of a multipurpose architectural module for the valorization of cultural heritage. To this aim, an innovative technology called ICARO (Innovative Cardboard Responsive Object) was developed, based on the use of a panel consisting of corrugated cardboard boxes connected to a frame made of wooden elements. The combination gives rise to very light and sufficiently resistant elements to create sustainable architectures. The absence of foundations or other infrastructural works and the prevalence of dry building technologies makes the module suitable for use in fragile areas, such as archaeological sites, precisely.

This technology will be tested through the realization of a prototype pavilion. It will be placed in the coming months at the Megara Hyblaea test site; it is one of the oldest Greek colonies in Sicily, located near Augusta. The ICARO pavilion represents a micro-architecture to show the peculiarity of the site through multimedia capable of giving responses to the visitor's needs in sensory terms. Resting on the main north-south route, it divides two important monuments of the site: the south temple, dating from around the 7th century BC, and the prytaneum, from the 6th century BC, a place intended for city magistrates. The technology developed in the experiments illustrated so far, responding to the requirements of flexibility, lightness, low costs, high efficiency and durability, in fact, lends itself to application on energy self-sufficient temporary architectures.

In order to cover the energy needs of ICARO, the external cladding system of the pavilion will feature SLICE modules, used as a BIPV system for the production and storage of electricity for powering the technology. With this aim, a new prototype named SLICE4ICARO was designed.

4. METHODOLOGY

The SLICE4ICARO prototype is mainly characterised by the enhancement of the production chain as well as the electrical storage of the power generated.

In this specific case, an off-grid or stand-alone photovoltaic system was designed based on the installation of an inverter with MPPT and the connection of a battery pack to allow the pavilion to function during the opening hours for the archaeological park to visitors. The power of the batteries and the number of modules to be installed on the facade of the pavilion were designed by comparing different usage scenarios in relation to the expected loads for powering the technological services and the use of multimedia content.

The project of the electrical system represented the starting point for a test campaign aimed at obtaining useful data to validate the effectiveness of the proposed solution under real environmental conditions.

The tests were carried out at the University of Catania, on the premises of the DICAR (Department of Civil Engineering and Architecture). The two samples were placed on the terrace of a building of the University Campus of Catania, while the charge controller was placed inside an adjacent room. For the purposes of the tests, two different configurations were monitored: panels positioned vertically and horizontally.

The charge controller used for the tests is an MPPT Epeever Triron 1206N, which has a module that includes an RS485 port, which through a special USB to RS485 cable (CC-USB-RS485-150U) can be connected to a PC and monitored in real time through proprietary software.

The charge controller was instead connected to a 12V 24 AH / 10h "Prime AGM VRLA" battery. A 100W light bulb was used as the load to simulate the basic absorption of technological components serving an office environment. The PC was equipped with a remote management software and a webcam that made it possible to carry out a constant monitoring and check on the correct functioning of the load (switching on of the lamps) and on the instantaneous external light conditions.

5. RESULTS AND DISCUSSION

Two SLICE4ICARO samples were made with the stratigraphy already adopted in the previous steps [12]. The location of the embodied photovoltaic cells has been defined by considering the previous results. Specifically, each panel is equipped with 15 monocrystalline silicon photovoltaic cells, connected in series and distributed over three strings of five elements. Each one of them is connected and welded to the adjacent one through dedicated bus bars (dog bones). At the end of each group of five cells, a linear bus bar was applied to connect to the next string. The technical characteristics of each panel are shown in Table 2.

A set of tests were carried out on the prototype. According to this aim, it has been installed at the university campus of Catania. The Energy production was monitored for about three months. Figure 6 shows the two PV samples, which have an active surface of 0.469 m^2.

Figure 6 show the solar irradiance in Catania city, derived by the PVGIS database [18] for a horizontal and 90° tilted surface with azimuth 30°, in agreement with the panels installed.

Looking at this data is evident that the installation of the PV panels with a tilt angle of 90°, allows obtaining a more constant power production all year round, privileging the power production during the winter months.

Figure 7 shows the daily variation of the components of irradiance for a horizontal surface in February and a vertical surface in March.

Dimensions and weight of the single panel	105 cm x 65 cm; 1.8 kg
Single panel power	49.5 W
Single panel voltage	8.55 V
Current	5.8 A
Matrix	EVA SKC Films EF2N
Reinforcement	Biotex Flax, 400 g/m^2 Composites Evolution Ltd
Additional layer	DUN-SOLAR PPE
Photovoltaic cells	SunPower Maxeon® Gen I
Charging circuit	MPPT Epeever Triron 1206N
Battery	"Prime AGM VRLA" da 12V 24AH/10h

Tab. 2. *Datasheet of SLICE4ICARO prototype.*

Fig. 5. *Positioning of SLICE4ICARO panels for testing.*

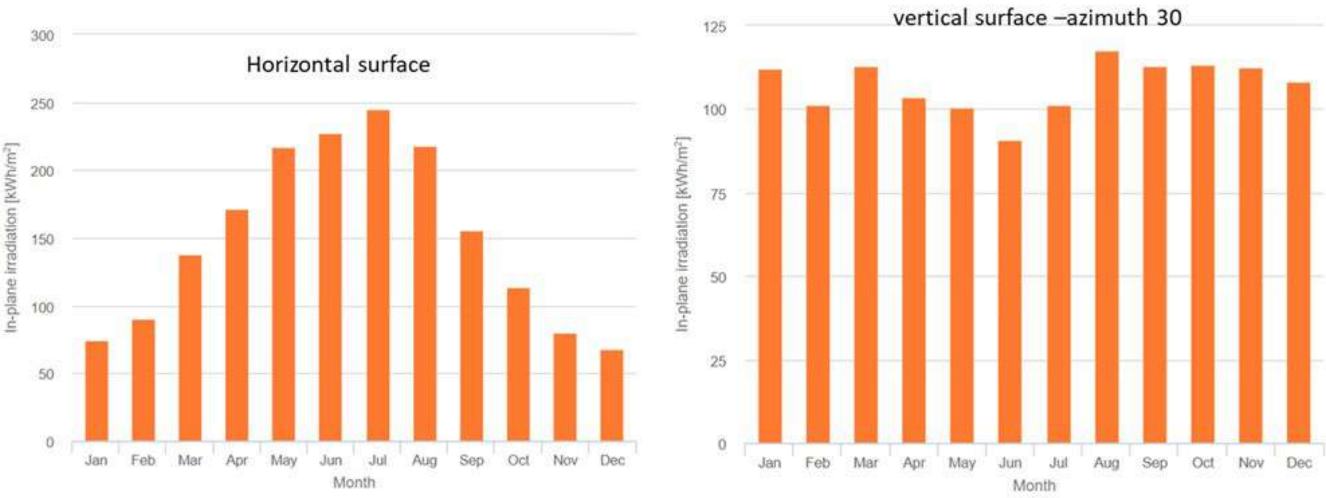


Fig. 6. *In-plane solar irradiation for a horizontal and vertical surface with azimuth 30°.*

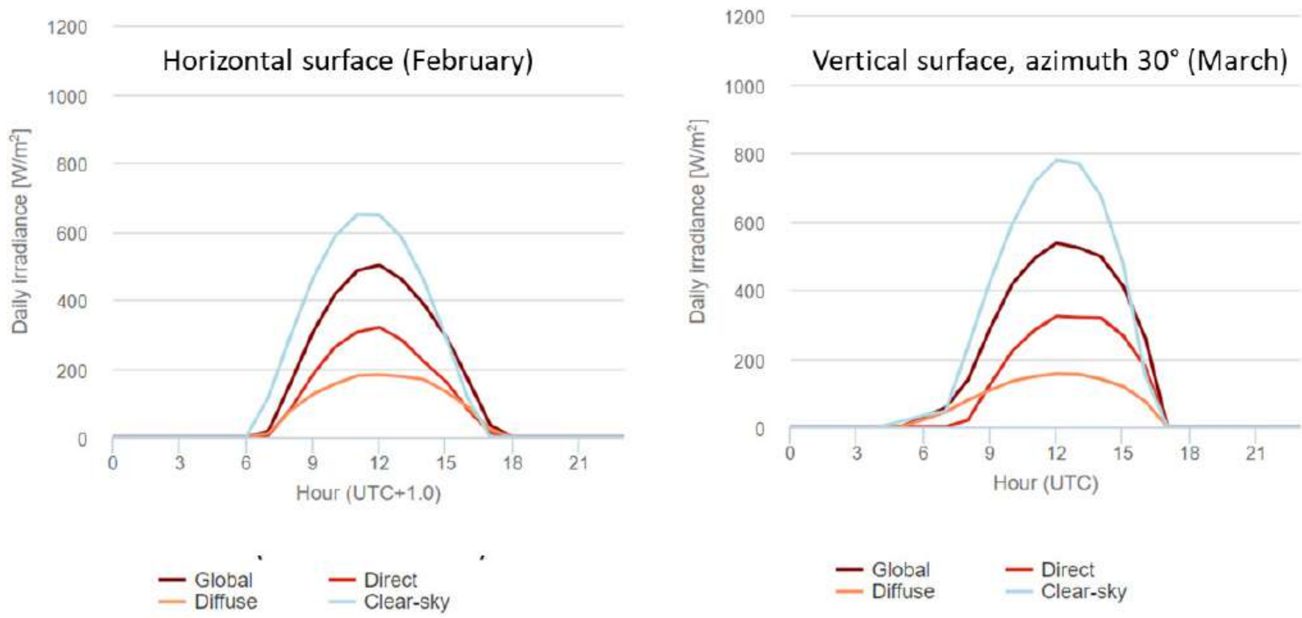


Fig. 7. *Global, Direct, Diffuse and Clear Sky irradiance for horizontal (February) and vertical surface (March).*

From the assumptions made during a preliminary analysis of the system, considering the various losses due to connections by welding, the type of installation and the prototype state of the entire components, the electrical efficiency of 14% was assumed for the whole system.

Figure 8 shows the observed power production during the period of the survey.

The power production with the panel installed horizontally has a maximum value of 268.46 Wh, and it is higher than 230 Wh for the other five days. For the remaining days, the less power production might indicate that those days were almost cloudy days.

Considering that during February, the average daily solar irradiation for a horizontal surface is about 3.21 kWh/m^2, the tested PV system might provide an energy production of about 210 Wh. This result indicates that during those days, the solar irradiation was slightly higher than the average value. Otherwise, assuming the solar irradiance clear sky conditions, that is 4.15 kWh/m^2, the tested PV system should give a power production of about 270 Wh which is in perfect agreement with the observed maximum power production.

Thus, it is possible to assert that the performances of the PV panel are quite in line with the design conditions.

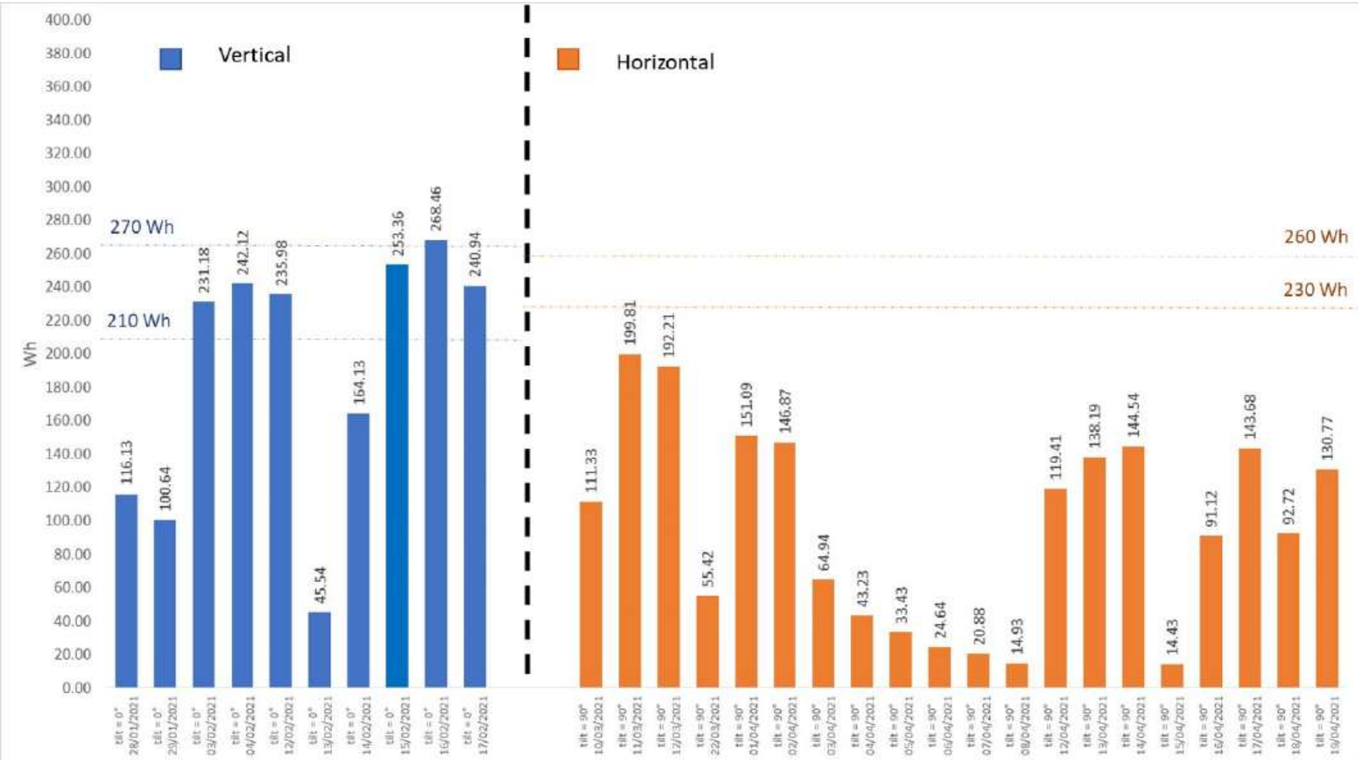


Fig. 8. *Power production for each of the investigated period.*

With the aim of evaluating the electrical performance of the whole system, the observed power production has been compared with the theoretical power production calculated using the solar irradiation data measured by the weather station installed at the laboratory of Environmental Technical Physics of the University of Catania [28, 29]. Such comparisons have confirmed the good agreement between expected and effective power production when the PV panel are installed horizontally.

Subsequently, the power production whit the PV panel installed vertically is commented.

The power production with the panel installed vertically is higher than 190 Wh for two days (March 11th and 12th), with a max value of 199.81 Wh, while for the remaining days, it is always lower than about 150 Wh.

Thus, considering that during March, the average daily solar irradiation for a vertical surface is about 3.55 kWh/m^2, thus the tested PV system should provide a power production of about 233 Wh. This result indicates that the system underperforms in comparison with the design conditions showing a loss of power production of about 30 Wh, which is about 15% of energy losses.

Such underperforming is even worst when the solar irradiance clear sky conditions are assumed as a reference, that is 4.00 kWh/m^2. In this case, the tested PV system should provide a power production of about 260 Wh, showing a loss of power production of about 60 Wh, which is about 30% of energy losses.

For the rest of the period, the system has power production that is in the range of 150 Wh, even when almost clear sky conditions were observed. This means a loss of production of about 40% in comparison with the design conditions.

The first justification for such loss of power production is certainly due to the partial shading of the PV cells, which of course, gives rise to a reduction in the performance of the PV panel.

In addition to this effect, other power losses emerge as the conversion efficiency declared by the MPPT manufacturer decreases for low production values.

In general, lower performance of the panel was detected for variable weather conditions and predominantly diffuse radiation. Further losses of efficiency are attributable to the higher temperatures compared to STC conditions. SunPower cell factory data indicate a 0.32% reduction in efficiency for degree centigrade deviations from STC (1000 W/m², AM 1.5g and cell temperature of 25°C).

6. CONCLUSIONS

In recent years, scientific research and production market focused their attention on adaptive, highly flexible and lightweight architecture components. The acquired knowledge suggested focusing the attention on the choice of the base material as well as the selection of the type of kinematics and the integration of photovoltaics into the foldable component. The most promising field of application of them seems to be that concerning small residential modules (the so-called "tiny houses"), exhibition pavilions and, in general, light flexible multipurpose architectures. In fact, in order to cover their energy needs, it is possible to image lightweight flexible photovoltaic panels used as a BIPV system for the production and storage of electricity for powering the technology.

Thanks to a synergy among two research projects which involve the University of Catania, called SLICE and ICARO, it was designed a new prototype, namely SLICE4ICARO. It consists of a module of composite materials with photovoltaic cells embodied in it. It will be used as part of the external cladding of a pavilion, as a BIPV solution, for the production and storage of electricity.

The prototype has been recently tested. On the base of the results, it is possible to assert that the performances of the PV panel are quite in line with the design conditions. Hence, the technology will be used in the real scale realization and the pavilion will be placed in the coming months at the Megara Hyblaea test site, that is one of the oldest Greek colonies in Sicily, located near Augusta.

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Authors contribution

Conceptualization, A.M. and G.R.; data curation, A.G.; formal analysis, A.M.; funding acquisition, V.S.; investigation, A.M. and G.R.; methodology, V.S. and A.G.; project administration, V.S. and G.R.; resources, V.S. and A.G.; supervision, V.S. and A.G.; validation, A.G.; visualization, A.M.; writing-original draft, A.M.; writing-review & and editing, G.R. and V.S. All authors have read and agreed to the published version of the manuscript.

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APPLICATION OF ADHESIVE TECHNOLOGY TO A NEW TYPE OF GLAZED PANEL FOR CURTAIN WALLS WITH AN INTEGRATED FRAME

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Abstract

The adhesive technology offers several advantages over traditional joints, allowing the assembly of construction elements with a reduced number of components. The use of large glazed surfaces is a distinctive feature of modern architecture and is reflected in the curtain walls. In traditional applications, glazed panels simply transfer the stress to the substructure (frame), not assuming a structural role. This article reports the results of an experimental campaign on a new type of wooden panels for windows and curtain walls (patent application No. 1020000023128 and European patent 3071775) which provides for the structural collaboration between the frame and glass panels using adhesives. This solution (glazed panels adhesively bonded to the wooden frame) adequately responds to the performance requirements of the highest class of resistance to wind load for windows (C5 – UNI EN 12207), limiting the maximum displacement within 1 mm (maximum deflection of the order of 1/1500).

Keywords

Timber-glass adhesive joint, Flexural tests, Adhesive bonding, Hybrid adhesive joint.

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Nomenclature

A_t	Application temperature
E_t	Young Modulus in tension
F	Applied load
k	Stiffness
s	Displacement
S_t	Service temperature
W_t	Working time
α	Thermal coefficient of expansion
ε_t	Tensile strain
σ_t	Tensile strength
σ_c	Compressive strength
τ	Shear strength

1. INTRODUCTION

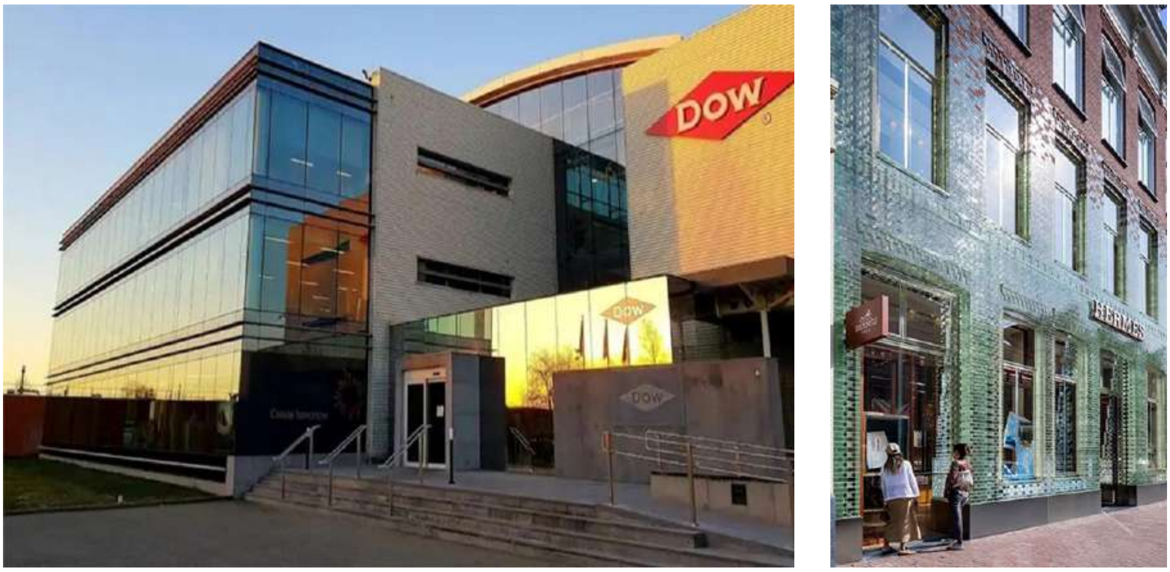
The latest regulatory developments have influenced the design of building components with increasingly demanding performance requirements for both materials and components. The current trend is the search for slender structures with high mechanical, acoustic, and energy performance while the present market demand is oriented towards large glass surfaces and transparent casings with low environmental impact [1, 2]. In these types of solutions, the glazed surfaces are usually carried by a metal frame (i.e., stainless steel or aluminum) to which the glass panels transfer the load.

Design and calculation need to take into account the interaction of the glass panels with the substructure. The connections are usually made with mechanical or adhesive splices. In the field of curtain walls, solutions involving the use of silicone adhesives are offered for example by Dow Corning. However, these are improperly defined as “structural” as the adhesives used to create a bond that cannot be entrusted with the mechanical collaboration between the glass paneling and the frame. This adhesive bond solution does not guarantee a satisfactory stiffness of the glass-frame junction and, for this reason, the glass panels require supports. Furthermore, the difference in thermal expansion coefficients between the glass and the substrates requires the use of a flexible structural adhesive, capable of effectively absorbing the differential deformations between the components. The impossibility of obtaining structural collaboration between glass and substrate with silicone adhesives leads to the use of considerable sections for the substructure elements.

The failure phenomena of silicone adhesives in building facades have been extensively studied by Chew [3] with in situ diagnostic studies comparing silicone to other polyurethane adhesives. The results highlight the lower adhesion of silicone to substrates compared to the other adhesives tested.

A couple of examples of silicone adhesive joints applied to curtain walls are the Dow Corning warehouse in Feluy, Belgium (Fig. 1a) and the Hermès flagship store in Amsterdam (Fig. 1b). In the first case, the stainless-steel connectors of the curtain wall are joined to the glazed panels by means of silicone; in the second building instead, a thin transparent adhesive was used, in which glass blocks are glued together in imitation of traditional masonry [4].

The results of the research on polymeric materials have highlighted the numerous advantages offered by the adhesive technology compared to the traditional joining methodologies (e.g., riveting, bolting, welding) [5, 6]. As a matter of fact, adhesive joint structures have high ultimate strengths and uniform distribution of stresses, with reduced peaks [7]. Thus, this technology has proven to be valid in hybrid joints for composite materials [8] (e.g., GFRP) which are sensitive to concentrated loads. In the field of civil engineering, adhesive technology is used in the construction of hybrid steel and glass structures [9, 10], structures in composite material [13], and facade cladding [11, 12]. Silvestru et al. [14] proposed new solutions for acrylic adhesive joints between glass and metal for curtain walls. The experimental in-plane and out-of-plane shear tests on full-scale specimens have shown that such structures have a high load-bearing capacity. Subsequent finite element analyses validated the experimental results.



(a) (b)

Fig. 1. *Real cases of application of structural adhesives for building facades.*

Richter et al. [15] studied the use of hyper-elastic adhesives to assemble facade panels by means of FE analysis on steel-glass joints. Laboratory tests were also performed on scaled components under different load conditions. Further studies [16–18] investigated the application of adhesive technology for curtain walls; however, bonding was not extended to all the perimeter surfaces of the glazed panels. In the works by Feldmann et al. [19] and Abeln et al. [20] experimental tests were carried out to investigate the ductility and strength of hybrid steel and glass adhesives joints. Bues et al. [21] investigated the bearing capacity of adhesive joints with different geometries, load directions, and temperatures by means of experimental campaigns on silicone adhesives for adhesive joints.

The use of adhesive wood-glass joints results in structures with high mechanical performance and, thanks to a major reduction in the frame size, great aesthetic value [22]. Piculin et al. [23] studied solutions for composite wood and glass panels joined with epoxy adhesives on scale samples obtaining encouraging results. Blyberg et al. [24–26] investigated the mechanical performance of silicone, acrylic, and polyurethane adhesives in applications on wood-glass joints with tensile and shear tests. Further experimental studies carried out by Kozlowski [27] on wood-glass structural elements assembled by means of an adhesive joint highlighted the improved mechanical performance offered by epoxy adhesives compared to traditional silicone adhesives.

Fig. 2. *Patent application No. 1020000023128, prototype.*

This study shows the results of an experimental campaign aimed at investigating the benefits of adhesive technology to the mechanical performance of new types of frames for doors, windows, and curtain walls. The performance of mahogany wood frames adhesively bonded to glass panels with float glass reinforcements is investigated in terms of global displacements, stiffness, and residual displacement. The used frame technology, shown in Fig. 2, refers to the patent application 1020000023128 «Frame for windows, doors and external perimeter panels made with profiles joined with structural adhesives – double glazing with spacer joined with structural adhesives (inventor: P. Munafò)».

2. MATERIALS AND METHODS

This section describes the mechanical characteristics of the materials and the test methodologies used in the experimental campaign.

2.1. ADHERENDS

Three different adherends were used: float glass panels (supplied by Vetreria Incicco, Italy), GFRP flat profiles (Fibrolux, Germany), and mahogany profiles (Dorica Legnami, Italy). The properties of the materials, provided by the manufacturers, are reported in Tables 1 and 2.

Adherends	Sapelli Mahogany
Category	Hardwood
Fresh density (kg/m^3)	780
Density after maturation (kg/m^3)	620
Histological structure	Fine texture
Fibration	Interwoven
Retire	Moderate
σ_c* (MPa)	55
Use	Structural

*along the fibres

Tab. 1. *Timber mechanical properties reported by manufacturers.*

GLASS*		
α (°C^{-1})	E_t (GPa)	σ_t (MPa)
9×10^{-6}	75	40

*according to CNR-DT 210/2013 [19]

Tab. 2. *Glass mechanical properties.*

2.2. ADHESIVES

A two-component epoxy structural adhesive (2K) EPX was used throughout the experimental campaign. This adhesive was chosen on the basis of the results obtained in previous experiments conducted by the same research group [28–32]. Tab. 3 shows the mechanical characteristics of the adhesive specified by the manufacturer in the technical data sheet.

Adhesive	EPX
Chemical base	Two-part epoxy
Viscosity	Thixotropic
W_t (min)	16
A_t (°C)	15÷25
T_g (°C)	66.87
S_t (°C)	-40÷80
τ*(MPa)	29.40*
E_t (MPa)	1500
ε_t **(%)	-
Use	Semi-Structural

* On aluminium-steel adherends
**At failure.

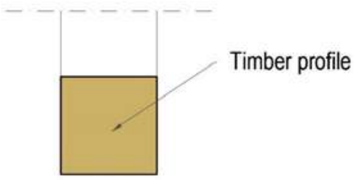
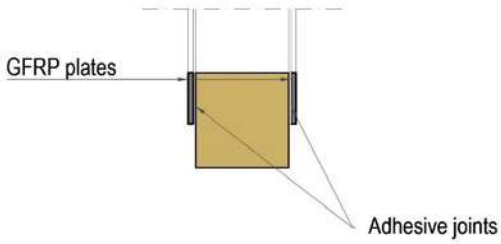
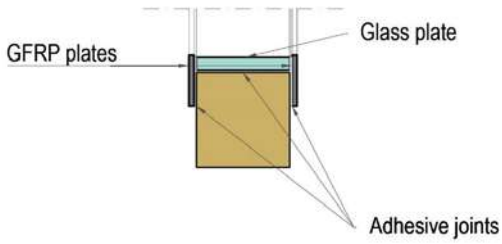
Tab. 3. *Mechanical characteristics of the adhesive reported by manufacturer.*

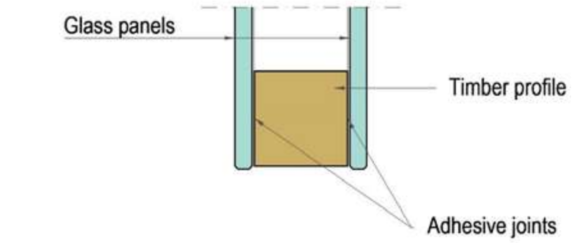
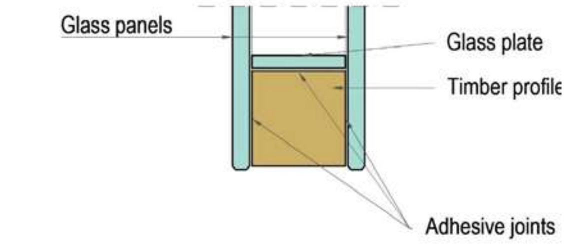
2.3. SPECIMENS: WINDOW AND DOOR FRAMES

Described materials have been used to assemble panels with the dimensions of 0.40 m x 1.24 m². In configurations (iv) and (v) panels are reinforced with float glass panels. Table 4 summarizes all tested configurations.

The cross section of the wooden frames has envelope dimensions of 47 x 45 mm². The external glazed panels to which the frame is adhesively bonded have a thickness of 6 mm. The GFRP and internal float glass reinforcement plates have sections of 2.40 x 24 mm² and 30 x 6 mm², respectively.

Glazed panels were bonded under laboratory conditions (21°C and RH 50%). All adhesive regions have a thickness of 1.10 mm, obtained through the use of spacers. Before the gluing phase, all the surfaces of the adhesives were manually cleaned with denatured isopropyl alcohol. The maturation of the frames lasted 28 days, in laboratory conditions (21 ± 2°C and RH 50 ± 8%), according to the specifications provided by the manufacturer of the adhesive used.

Acronym	Description	Cross-section
URM-M	Unreinforced mahogany wood frame	
RM-MG	Mahogany wood frame laterally reinforced with flat GFRP profiles	
RM-MGV	Mahogany wood frame reinforced with flat GFRP profiles laterally and glass profile in intermediate position (Patent Application n. 102020000023128)	

<table>
<tr><td>RM-MVV</td><td>Mahogany wood frame with float glass panels adhesively bonded to the wooden profile (European Patent n. 3071775)</td><td>
</td></tr>
<tr><td>RM-M2V</td><td>Mahogany wood frame with float glass panels adhesively bonded to the wooden profile, reinforced with glass profile in intermediate position (European Patent 3071775 Patent Application n. 102020000023128)</td><td>
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Tab. 4. *Tested panels.*

2.4. TEST SETUP

The experimental campaign consists of bending tests on frames for doors, windows, and curtain walls, to verify the structural collaboration between the components bonded together by means of an adhesive joint. Figure 3 shows the test setup.

Each load test was carried out by manually adding up the load with steps of 20 and 10 kgf, distributing the load on two points aligned on the center line, and simultaneously measuring the derived deformation. The purpose of this experimental setup is to statically simulate the action of the wind on the window frame. The applied load was gradually increased until reaching the limit value of the deformation for class C5 windows (i.e., maximum deformations contained within 1/200 of the height of the frame, equal to 6.20 mm), according to the UNI EN 12207 [33]. The maximum applied load is 1.47 kN, or a lower value when it led to the achievement of the maximum deflection.

Displacements were recorded at seven measurement points using vertical transducers (24 bit MAE LVDTs) located at the intrados of the profiles. The vertical transducers are analog potentiometers (model PY2C-50P) supplied by MAE (uncertainty of the instrument equal to ± 0.01 mm).

For each configuration, three specimens were tested, each of them subjected to three loading-unloading cycles, to reduce the influence of the rheological properties of the material and the uncertainty of the measurements on the experimental results.

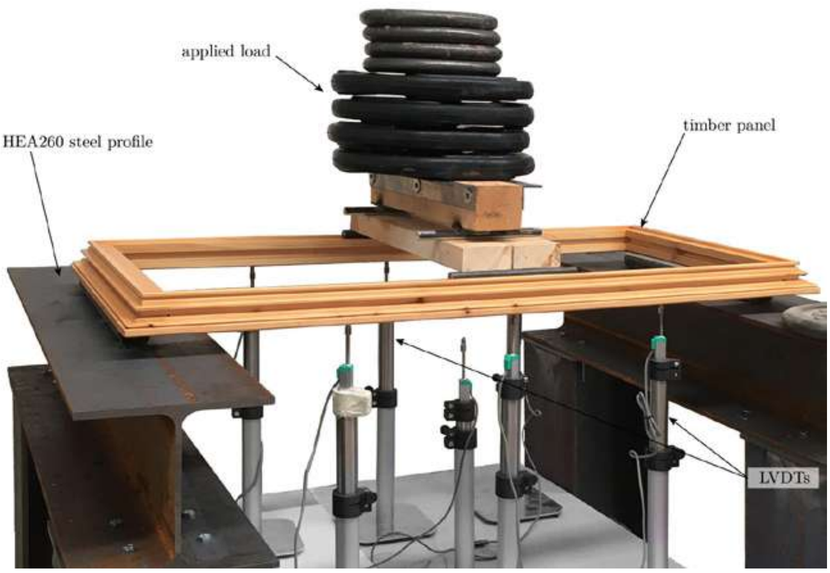


Fig. 3. *Test setup.*

3. RESULTS AND DISCUSSION

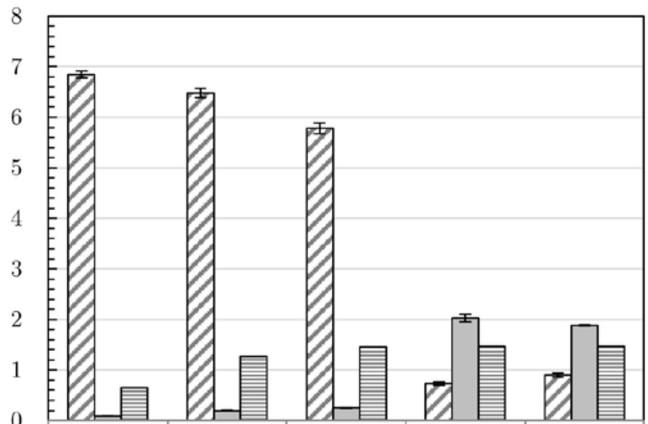
This section presents the results of the experimental campaign. Average values of maximum load, measured displacements, global stiffnesses, and maximum residual displacements are analyzed (Fig. 4 and Tab. 5).

The maximum deformations are registered for non-reinforced frames (6.84 mm) at low values of the load (0.66 kN). The addition of GFRP reinforcements adhesively bonded to the frames (RM-MG) allows for almost doubling the stiffness compared to non-reinforced ones. A further increase in stiffness is registered for frames reinforced with flat GFRP profiles and glass (RM-MGV), showing deformations compatible with those provided for by class C5 (≤ L/200 = 6.20 mm) when subjected to the maximum prefixed load (1.47 kN). Both the configurations with external glazed panels adhesively bonded to the mahogany frame (RM-MVV and RM-M2V) show the best performance in terms of stiffness (around 2 kN/mm) and maximum displacements (within 1 mm).

The maximum residual deformations (sres) are observed for GFRP reinforced frames (configurations RM-MG and RM-MGV), which also show the largest standard deviation. Configurations with external glass panels (RM-MVV and RM-M2V) have a residual displacement of an order of magnitude smaller, but the standard deviation is also in this case comparable with the deformation.

Figure 5 shows the response of the different configurations in terms of load-deformation. Each curve in diagrams a) to e) corresponds to a loading or unloading stage: it can be noted that the residual deformation remains constant after each unloading, not adding up to that of the previous cycle. Diagram f), instead, compares the first-load curve of each configuration.

All loads used were compatible with the elastic behavior of the materials involved in the specific test, so as



	URM-M	RM-MG	RM-MGV	RM-MVV	RM-M2V
Displacement (mm)	6.84	6.48	5.78	0.73	0.90
k (kN/mm)	0.09	0.20	0.25	2.03	1.88
Max Load (kN)	0.65	1.27	1.47	1.47	1.47

Fig. 4. *Mechanical properties of frame specimens.*

Frame	Configuration	F_{max} (kN)	s_{max} (mm)	f_{max} (s_{max}/L)	k (kN/mm)	s_{res} (mm)
Mahogany	URM-M	0.66	6.84 ±0.14	1/181	0.10 ± 0.00	0.12 ± 0.02
	RM-MG	1.30	6.48 ±0.18	1/191	0.20 ± 0.01	0.27 ± 0.24
	RM-MGV	1.47	5.78 ±0.21	1/215	0.26 ±0.01	0.28 ± 0.13
	RM-MVV	1.47	0.73 ±0.06	1/1700	2.07 ± 0.16	0.03 ± 0.02
	RM-M2V	1.47	0.79 ±0.08	1/1570	1.91 ± 0.20	0.03 ± 0.04

Tab. 5. *Mechanical parameters measured with standard deviations.* δ_{max} (L/200) = 6.20 mm.

no crisis modes or significant plastic deformations were found. However, the RM-MGV configuration recorded the failure of the glass reinforcement (Fig. 6), which was due to the incongruity between the deformations of the frame and those of the glass reinforcements. Figure 6a shows the triggering of the crisis in the glass reinforcement plate and Figure 6b its propagation in the material due to the subsequent load increase.

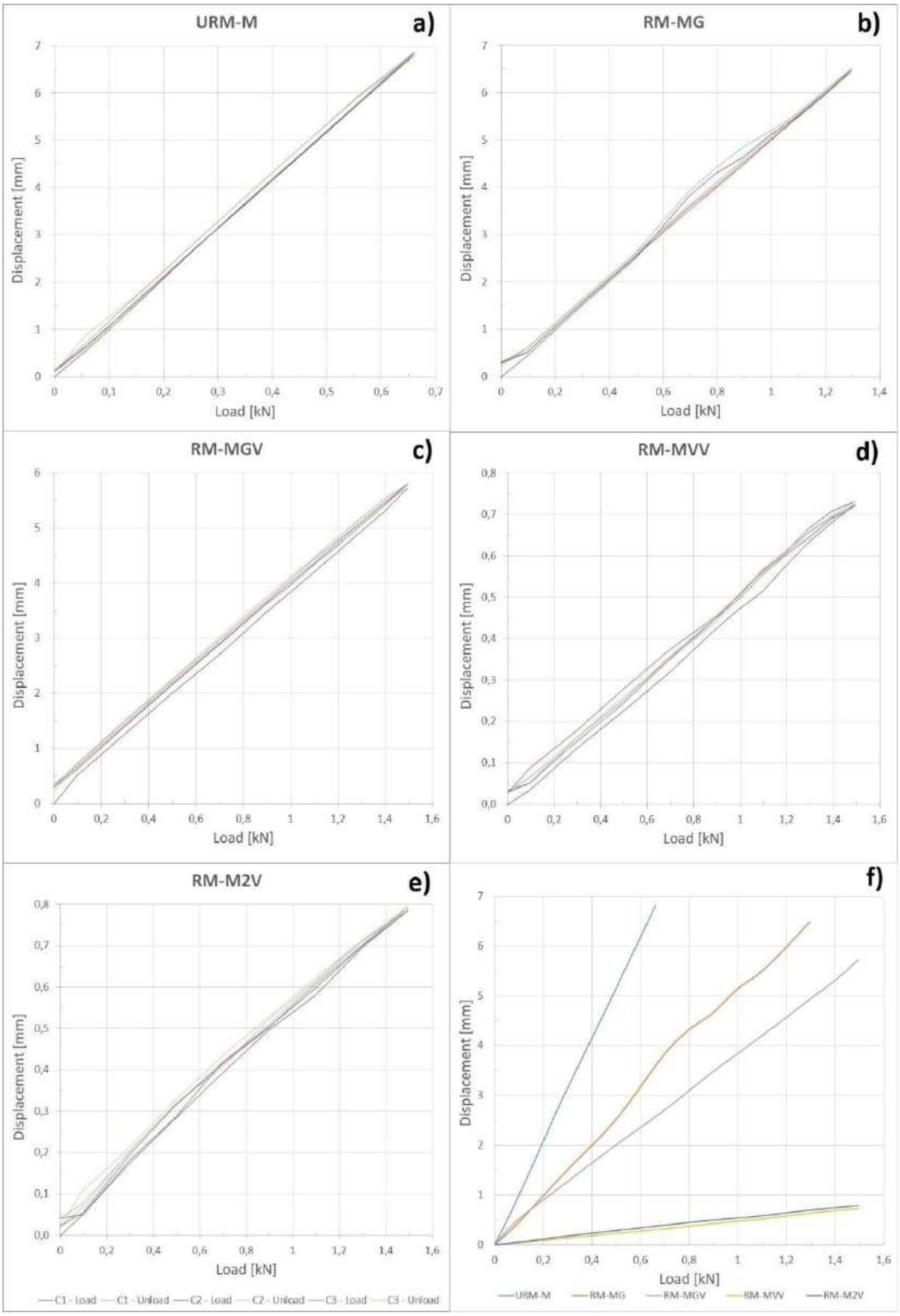


Fig. 5. *Each curve (blue: first load, light blue: first unload, red: second load, pink: second unload, dark green: last load, light green: last unload) in graphs (a) to (e) represents the displacement measured in each load or unload cycle averaged on the three samples investigated. In graph (f) each curve represents the first load cycle of a different typology of the frame.*

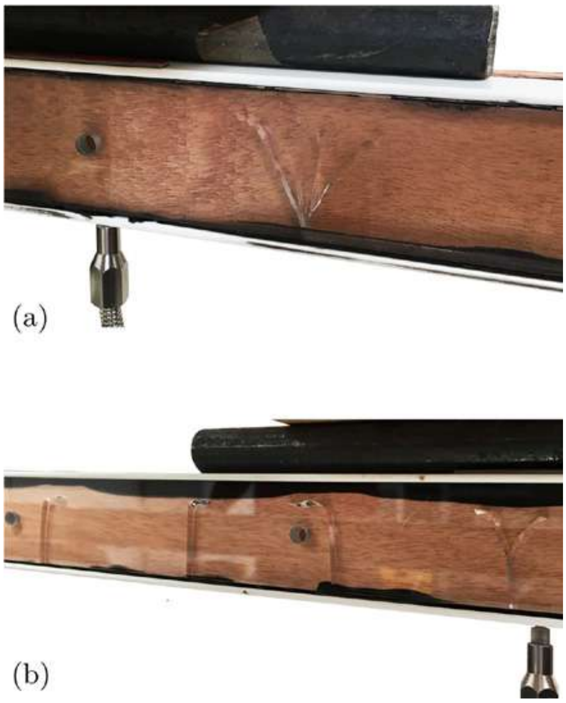


Fig. 6. *Failures in the glass reinforcement layer (RM-MGV): failure initiation (a); crack propagation (b).*

The results obtained for the unreinforced configuration reflect the characteristic stiffness of the material. The introduction of the adhesive joint between the frame and the glass panels and between the frame and the reinforcements (GFRP and internal glass plates) allows to obtain an improved structural collaboration between the components, leading to a structure with increased stiffness and maximum deformation within one millimetre.

4. CONCLUSIONS

This work presents the results of an experimental campaign carried out on an innovative type of frame for windows, doors, and curtain walls, in which the mahogany structure is adhesively bonded to the glazed panels using epoxy adhesive selected on the basis of previous research work. Several configurations were tested, including some of them with internal glass plates reinforcement. The results are analyzed in terms of maximum displacements, residual displacement, and global stiffness of the resulting element.

In light of the results obtained, the following conclusions can be drawn:

- the adhesive joints are able to realize an effective structural collaboration between the components adhesively joined together;
- the glass reinforcements plates cause a slight decrease in the maximum displacements, compared to the analogous non-reinforced configuration. In the case of GFRP reinforced frames, they also permit an increase in the ultimate load of 11.5%;
- the combination of the examined reinforcing techniques, applied on frames adhesively bonded to the glazed panels, leads to more rigid structures, showing maximum deformation within 1 mm and maximum deflections (f) within the C5 threshold (Tab. 4).

Results are promising about the application of adhesive technology in the civil engineering sector, and in particular for windows, doors, and curtain walls.

The registered increase in stiffness and decrease in the maximum displacement (especially for configurations RM-MVV and RM-M2V) envisages the possibility of using large glazing panels (e.g., 2.7 m x 3 m) with reduced size of the frame (30 mm x 30 mm).

Authors contribution

Experiments, writing, conceptualization and revision, F.M.; writing, revision, R.A.; supervision, conceptualization, P.M.

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