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Application potentials of a 3D exoskeleton technology combined with prefabricated panels to renovate the modern building stock

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1. ABSTRACT

A possible approach for seismic upgrading of existing reinforced concrete framed buildings consists in the creation of an additional structure connected to the existing one from outside. The installation of steel exoskeletons on the building façade is an application of this approach. This seismic upgrading technique provides several advantages: it can be realized without interrupting the building operativity, it allows a high level of prefabrication, it can be combined with energy efficiency solutions, and also used for the architectural restyling of the building. However, the availability of space around the building is a mandatory requirement for its installation.
In this framework, the paper investigates the potential application of a 3D exoskeleton technology based on the use of customizable three-dimensional steel trusses. The investigation is carried out with reference to a building selected as case study. It specifically involves a technical analysis of the proposed seismic upgrading intervention that is combined with an energy-efficiency solution based on prefabricated panels to be applied to the building façade. The potentialities of architectural integration of the retrofit intervention are also examined in compliance with a multidisciplinary design approach.

2. KEYWORDS

steel exoskeleton, seismic and energy renovation, architectural restyling, multidisciplinary approach, prefabrication

3. INTRODUCTION

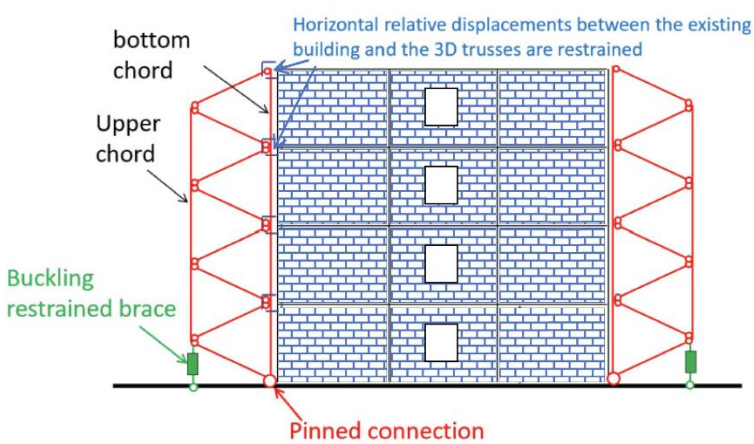
The renovation of the existing building stock is a current and comprehensive research topic because of its high energy and structural inefficiency. Indeed, building renovation is now a key priority to achieve the main targets of structural safety and environmental sustainability. However, focusing on the structural safety, the available techniques for seismic protection of existing buildings that do not require the interruption of the building operativity are very limited. These techniques include all the interventions that are carried out from the outside of the building through the addition of new structures connected to the existing building to improve its seismic performance. Among these, the addition of external steel braced structures, commonly named exoskeletons, is a smart and effective technique for the seismic upgrading of Reinforced Concrete (RC) framed buildings. Indeed, it is often used in buildings having public interest such as schools, hospitals, offices, etc. [1]. Steel exoskeletons may be used to improve the seismic response of the building enhancing one or more features of the structure: lateral stiffness, lateral strength, displacement capacity, as well as plastic deformation redistribution capacity [2]. These structural systems can be planar (2D) or three-dimensional (3D) with a wall-like or shell-like layout, and can be optionally equipped with additional energy dissipation devices to reduce the effect of the earthquake on the structure [3]. Overall, steel exoskeletons add minor mass to the existing structure compared to similar RC additional structures, and allow the geometry of the existing openings to remain unchanged. They also reduce implementation times on site thanks to the high level of prefabrication and dry installation, and provide a selective disassembly and the reuse or recycling of their components to reduce construction waste. These features well comply with the main principles of environmental sustainability in a Life Cycle perspective of building renovation [4]. However, as main drawbacks, the need of available space around the building, as well as the need of new foundations or enlargement and strengthening of the existing ones are mandatory requirements for the exoskeleton installation.

The research on the potential use of steel exoskeletons has been recently revived and expanded, in light of the chance to use them as holistic renovation strategy for the concurrent energy and architectural renovation of the buildings. Indeed, steel bracing systems can be used as support of a double-skin façade that aims at improving the energy performance of the building [5], and can also renew the architectural image of the building. Different shear walls and shell solutions to be coupled with energy-efficiency ones in the design of sustainable multi-skin exoskeletons have been examined [6-7]. External steel bracings have been investigated also as structural support for a newly energy-performing envelope made of pre-assembled components that also create additional and customized living spaces [8]. Moreover, the considerable potentility of architectural restyling of steel exoskeletons has been analysed by D'Urso and Cicero [9], who proposed the use of parametric design to generate multiple integrated retrofitting solutions for building façade. In fact, like the stone exoskeletons of Gothic cathedrals, the shapes and dimensions of the new structural elements could express a different image of the building. Nevertheless, the concern is that the renovated building does not present itself as a unitary and accomplished organism and appears to be, instead, a pre-existing construction that has been reinforced using structural elements that differ from its original appearance.

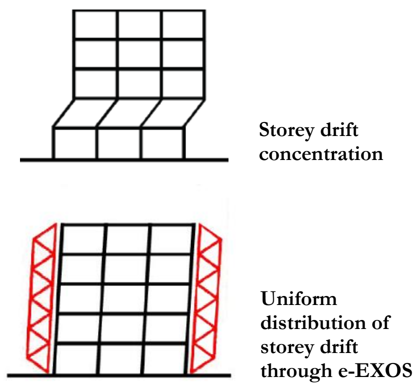
In this research context, this paper describes and reports an example of application of retrofit intervention based on the use of a 3D exoskeleton (named e-EXOS) combined with prefabricated insulating panels (named e-PANEL) to applied externally to the building façade. The steel exoskeleton proposed in this paper is similar to others available in literature, while the innovative feature of the analyzed retrofit solution should be searched in the design based on a multidisciplinary approach, which synergically involves both seismic, architectural, and technological aspects.

4. THE E-EXOS AND E-PANEL SYSTEMS: MAIN FEATURES AND USES

Figure 1a schematically shows the seismic upgrading intervention by e-EXOS. The e-EXOS system consists in a set of 3D steel trusses which are applied to the outer façade of the building. Each truss is pinned to a new foundation, and is fixed at each floor to the building decks through connections that constrain the nodes of the truss adjacent to the façade to have the same horizontal displacement of the decks. The connections between truss and decks do not exert any constraint on vertical displacements. Steel trusses are designed to remain elastic even in occurrence of strong ground motions. Hence, they force a uniform distribution of the storey drifts along the height of the building and avoid the formation of soft storey collapse mechanisms that would cause the localization of damage in one or few storeys (Figure 1b). Steel trusses do not provide additional lateral stiffness to the building, which otherwise would increase the seismic demand of the structure. Therefore, the e-EXOS reduces the drift demand of the existing structure caused by earthquake, and avoids the activation of the storey collapse mechanism. Furthermore, preventing drift concentration allows e-EXOS to increase the energy dissipation capacity of the structure, since structural members at all the storeys are forced by the trusses to participate to the dissipation of seismic energy after the yielding of the weakest structural members. Additionally, the trusses can be also equipped with Buckling Restrained Braces (BRBs) at the base, which provide a further increase of the dissipation capacity of the structure. The e-EXOS system improves the seismic response like the pinned RC wall proposed in [10], with the advantages that it requires dry installation, is a fully reversible upgrading technique and its components are recyclable.



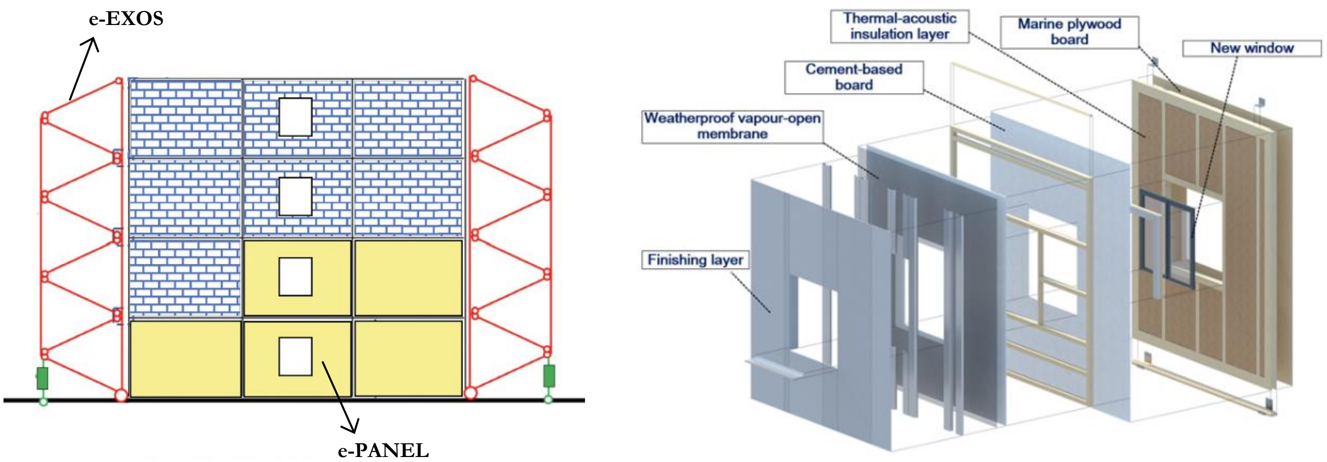
(a)



(b)

Fig. 1. Concept of the e-EXOS system: (a) steel trusses connected to the building; (b) seismic performance of the e-EXOS.

The e-EXOS system can be combined with the e-PANEL solution (Figure 2a), that is currently under investigation as energy efficiency solution within the e-SAFE project [11]. The e-PANEL consists of a prefabricated and insulating wood-based panel to be applied to the existing outer walls of the building as a double-skin façade. The new façade aims at increasing the thermal resistance of the walls, and thus the energy performance of the building. Additionally, it contributes to the renovation of the new building's architectural image.
Figure 2b shows the main stratification of the e-PANEL, according to the preliminary results that have been achieved within the project and have been already reported in [12-14]. This stratification is designed to ensure the panel: i) mechanical resistance against horizontal loads; ii) thermal resistance; iii) fire-protection ; iv) watertightness; v) airtightness; vi) vapour permeability and moisture resistance; vii) impact resistance, according to the European Construction Product Regulation. Basically, the e-PANEL is made of a lightweight wooden frame to which thermal-acoustic insulation material is interposed. The insulation layer is cladded by marine plywood boards, that are highly water-resistant compared to standard plywood boards. The external marine plywood board is replaced with a non-combustible cement-based board when the insulation material is not fireproof to ensure the panel suitable fire protection. The e-PANEL also integrates a weatherproof vapour-open membrane to prevent rainwater leakage and condensation problems, and the finishing layer, which is separated from the watertight layer by a ventilated air cavity to dry rainwater infiltrations or winter moisture.
The main features of the e-PANEL are the dry installation and the high level of prefabrication, which provides for the integration of windows, sun shading systems, and cladding materials during the manufacturing stage in order to reduce the implementation time compared to traditional external thermal insulation composite systems (ETICSs). The panels are also higly customizable according to the boudary conditions and customer's requirements. Overall, many cladding materials can be used, such as render, fiber-cement, wood, wood plastic composite (WPC), metal, ceramic, stone, glass, photovoltaic modules, etc.. The cladding layer may be fixed to the panel by means of a substructure made of load-bearing metal profiles and/or wooden studs, according to the type of cladding. Hence, the cladding layer can be fastened to the substructure using visible or hidden systems. The more efficient fastening systems include screws for wooden substructures, and screws, rivets, bolts or adhesives for metal ones. Instead, clamp fastening is less suitable for the e-PANEL since it would make the finishing layer less stable during transport and installation.



(a) (b)

Fig. 2. (a) The e-EXOS system in combination with the e-PANEL solution; (b) e-PANEL stratification.

The e-EXOS and e-PANEL solutions inevitably involve changing the originary configuration of the building, mainly due to the high architectural impact of the steel trusses. However, the architectural integration of these building components can be achieved by focusing on the structural expressiveness of the trusses as well as the finishing layer of the panels.
An application example of a retrofit intervention by the e-EXOS and e-PANEL is analysed in Section 5, with reference to a school building selected as case study.

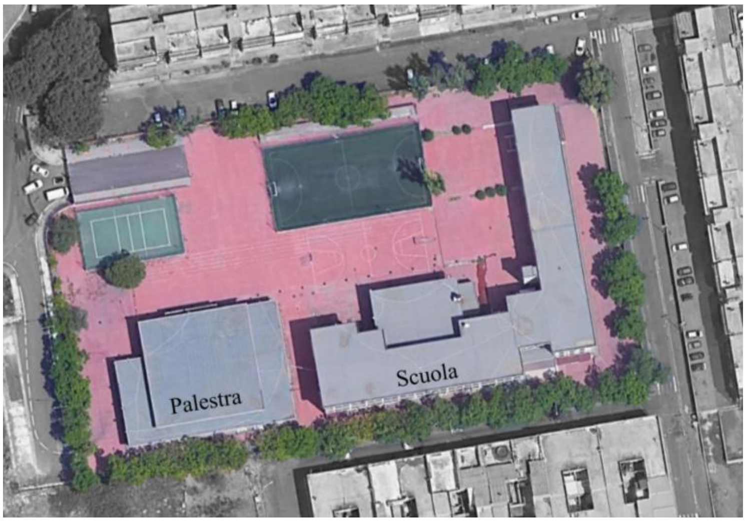
5. METHODOLOGY AND RESULTS

5.1 Case study

The case study (Figure 3) is a school building belonging to the school complex "Angelo Musco" in the city of Catania (Southern Italy), that offers an educational itinerary from nursery to high schools. It was built in the 1970s, and is representative of most Italian school buildings in terms of structural deficits, poor energy efficiency and architectural quality. Indeed, in Italy there are around 40.000 school buildings, mainly built between 1958 and 1983, i.e. before the issue of restrictive regulations on seismic resistance and energy efficiency. In that period over 800 new school buildings per year were recorded in Italy [15].

The case study has a L-shaped floor plan with an area of around 1600 m², has three storeys and a total height of 12 m. The building structure consists of RC frames, which are mainly oriented along a single direction, resulting in low strength and stiffness to seismic loads in the orthogonal direction. Indeed, the highly different lateral strength and stiffness of the structure in the two main directions is typical of buildings which have been designed without criteria for seismic resistance. Moreover, the architecture of the original building is quite anonymous and lacks the identity that would be required of a contemporary school building. It is an assemblage of functional blocks contained in plastered parallelepipeds with large windows. The only identity component is the color variation of the render on the different blocks. Finally, at the top, there is a small perimeter crown that is slightly projecting from the perimetral walls.

The external infill walls are 45-cm thick. Since there is no information about their stratigraphy, they are assumed made of two leaves of hollow clay bricks (12-cm thick) with an intermediate non-ventilated and non-insulated air cavity (16-cm thick), according to the construction techniques of that period. The intermediate floor and flat roof are characterized by RC and hollow tiles mixed slabs (23-cm thick), without thermal insulation too. The windows have steel frames without thermal break, and external roller shutters as sun shading systems. Overall, the above envelope components have high thermal transmittance values, which do not comply with the limits set by the current national regulation. Indeed, the U-values of the existing external walls and flat roof are 1,10 W/m² K and 1,33 W/m² K, respectively.



(a)

(b)

Fig. 3. The case study: (a) planimetric framework; (b) view from the inner court.

5.2 Retrofit intervention

The design of the retrofit intervention first involved defining the configurations of the e-EXOS and e-PANEL. Then, these components have been applied to the case study to analyse their potentialities of architectural integration.
Figure 4a shows the configuration proposed for the e-EXOS trusses. This configuration results from both structural, technical and architectural investigations. It consists of a set of rods and nodes manufactured off-site, and then assembled on-site. Specifically, rods are made by steel tubes (with a diameter of 177,8 mm and a thickness of 6,3 mm), while the nodes are made of steel solid spheres. Rods are bolted to each node through cone-shaped elements pre-welded to the rod edges. In this way, the rods transmit only tensile and compressive forces in case of earthquake. In particular, the proposed truss geometry ensures the uniform distribution of the forces in the rods, and low values of displacement and rotation of the nodes. The potential structural efficiency of this geometry has been verified through static analysis, by assuming to apply a horizontal load of 100 kN to a single node of the truss, in order to simulate the transmission of forces from the building structure to the truss in case of activation of storey collapse mechanisms under seismic events.
Each truss is fixed to both the building decks and a new foundation, which is separated from the existing one. The new foundation is assumed made of RC plinths on RC piles (i.e. 1 plinth and 4 piles for each truss, respectively) so that the forces can be transferred to deeper soil layers having better quality and strength compared to the topsoil layer that is clayey. Figures 4b and 4c show the details of the deck-truss connection and foundation-truss connection, respectively. Both are bolted connections made by combining rigid steel plates so that the e-EXOS works as described in Section 4. Specifically, the foundation-truss connection is conceived as a pinned connection which ensures each truss to rigidly rotate in the plane perpendicular to the building façade. On the other hand, the deck-truss connection is designed to restrain the horizontal relative displacements between the existing building and the truss, while the vertical ones are not constrained thanks to a vertical slotted hole in the anchor plate. In this way, each truss transmits a set of forces to the existing structure that reduces the concentration of drift in few storeys.

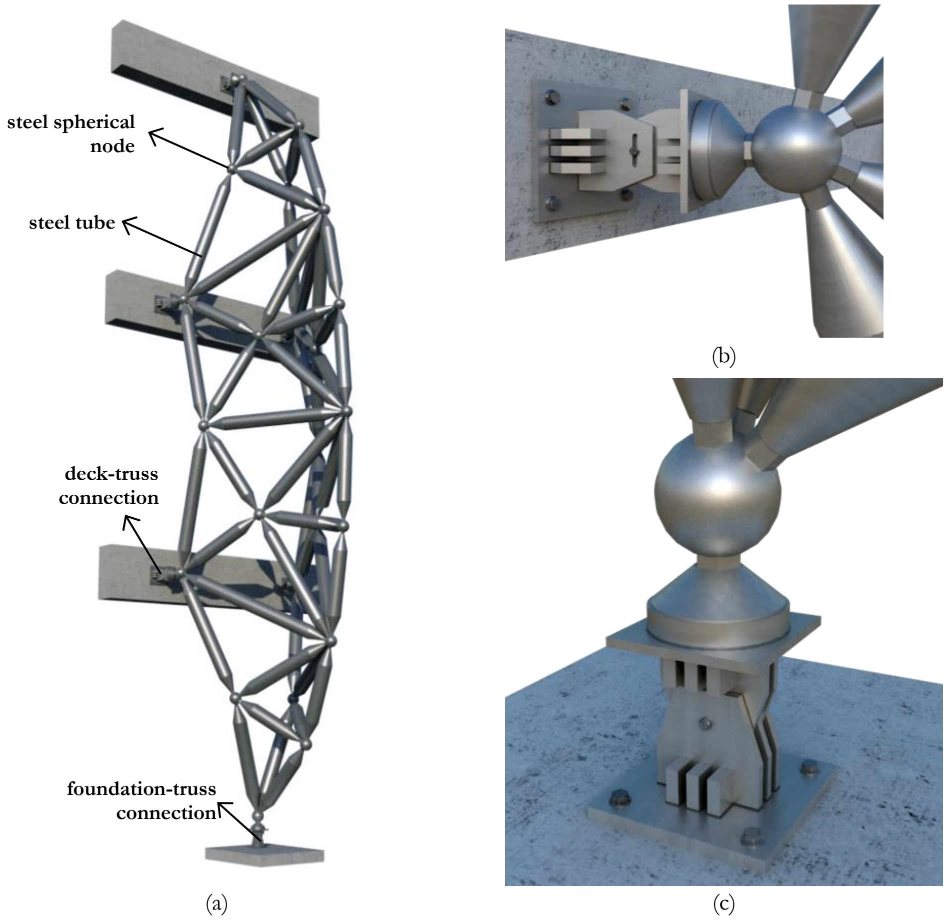
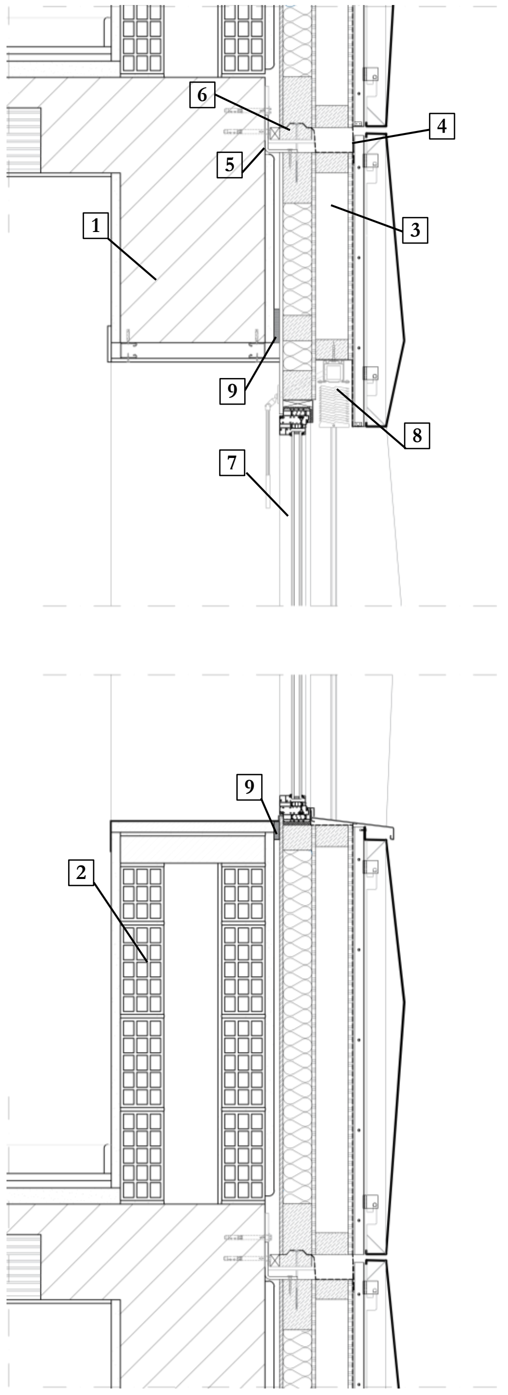
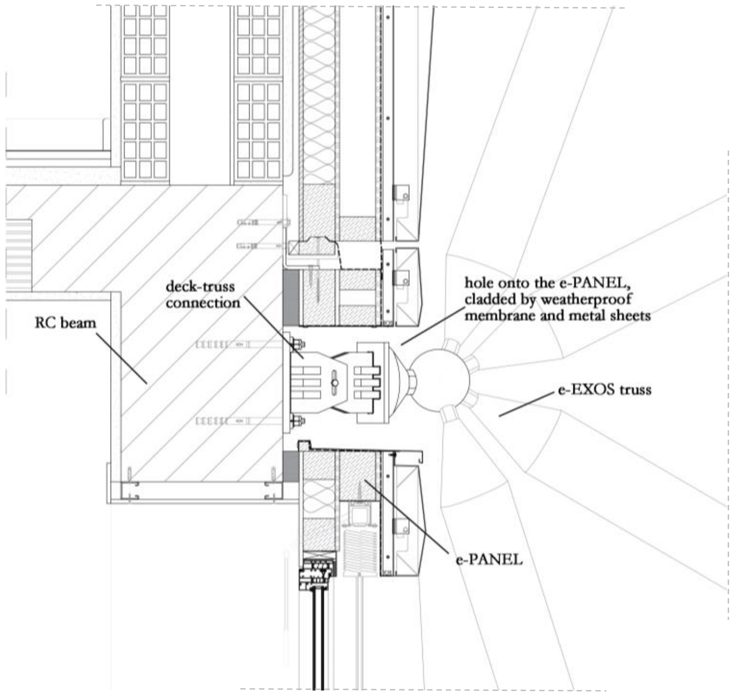


Fig. 4. Proposed e-EXOS configuration: (a) steel truss; (b) truss-deck connection; (c) truss-foundation connection.

As regards the e-PANEL, it is designed according to the main stratification reported in Section 4. Figure 5a shows a detail of the e-PANEL applied to the façade of the case study.





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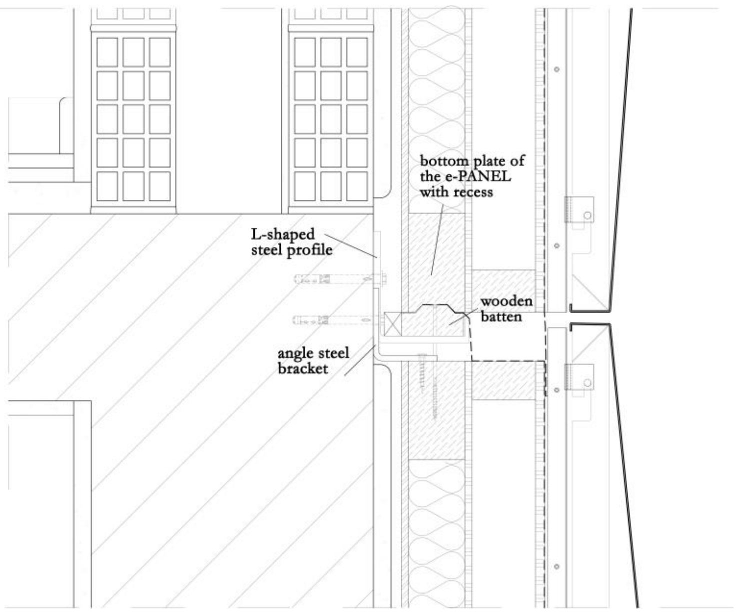

(c)

1. Existing RC beam
2. Existing outer wall
3. e-PANEL
4. Overlapping of the weatherproof membrane of the upper panel.
5. Angle steel bracket
6. Tongue and groove connection
7. New window
8. Venetian blind
9. Insulating polyurethane foam

(a)

Fig. 5. Details of the e-PANEL (vertical sections): (a) application to the building façade; (b) detail of the connection between the truss and the existing RC beam; (c) detail of the connection between the e-PANEL and the existing RC beam.

The panels are 320-mm thick and include: i) 80-mm thick rock wool insulation layer (λ= 0,035 W m^{-1} K^{-1}, ρ= 70 kg m^{-3}) that ensure the panel a thermal transmittance value (U) of 0,30 W m^{-2} K^{-1}, and also high fire-protection since it is a fireproofing material, thus complying with the current Italian regulations regarding the energy performance of the building and the fire performance of the façade components [16-17]; ii) double glazing windows with aluminum frame with thermal break (U= 1,7 W m^{-2} K^{-1}); iii) Venetian blinds as sun shading system; iv) 90-mm thick non-ventilated air cavity to allow the installation of sun shading devices like Venetian blinds; v) a cladding layer made of 3D metal sheets, which are fastened to a metal substructure through concealed bolts. A hole is also realized in some panels to allow the fixing of the e-EXOS trusses to the building structure (Figure 5b). These holes are protected by weatherproof membranes and metal sheets to prevent water infiltration.
The e-PANEL is anchored to the existing RC beams through the fixing system shown in Figure 5c [12]. This system provides the use of angle steel brackets on the top side of the panel, while a tongue and groove connection is foreseen at the bottom to facilitate installation and to allow horizontal sliding under seismic events. This connection is realized through L-shaped steel profiles on which a wooden batten is screwed. The L-shaped profiles are fixed to the RC beams of the bottom storey, while the e-PANEL is put on the batten by means of a recess in its bottom plate. In this way, in case of earthquake, the e-PANEL undergoes the same sliding movement of the upper RC beam thus preventing its damage. At the same time, its out-of-plane rotation is avoided.
Based on the above configuration of the e-EXOS and e-PANEL, the implementation of the proposed retrofit intervention involves the following steps:
1. Excavation of the pit around the building perimeter, and construction of the new foundations of the trusses by casting the RC piles and plinths, which include the anchor bolts for connection to the trusses.
2. Fastening of the anchor plates of the deck-truss connections to the existing RC beams through mechanical or chemical anchors, after render removal.
3. Removal of the existing windows and installation of the e-PANELs through lifting cranes. The vertical joints between the panels are protected through Ethylene-Propylene Diene Monomer (EPDM) softbands, which are pre-assembled on their lateral side. The horizontal joints between the panels are protected by overlapping the weatherproof membrane of the upper panel.
4. Fastening of the anchor plates of the foundation-truss connections.
5. Installation of the e-EXOS by assembling portions of trusses which are pre-mounted off-site and then anchored on-site to both the RC beams and the new foundations by bolting them to the pre-fixed anchor plates.
Figure 6 shows the architectural image of the proposed seismic and energy retrofitting solution. The intervention also includes the cladding of the steel trusses with triangular perforated aluminum panels, which are arranged to reveal the e-EXOS structure. Cladding the e-EXOS avoids that the trusses may become a source of danger, especially for students who use the outer spaces around the building. On the other hand, it aims at mostly enhancing the design of the trusses, considering their relevant architectural impact. In this regard, this intervention was based on the idea to give a symbolic value to the trusses, by comparing them to the massive columns of the ancient Greek temples, to which the school building refers in the meaning of "temple of knowledge". The symbolic connotation, derived from the structural and architectural choices, gives the building an identity that was missing in the original structure. A new wider cornice frames the building's image, incorporating the exoskeleton structures into a single complete architectural body. The cornice extends over the entrance, with a large canopy highlighting it. Finally, the foundations of the new exoskeleton were the pretext to redesign the base of the building as a stylobate. Along with the cornice, the trusses and stylobate refer to the temple's image. The new base also improves accessibility to the school by breaking down architectural barriers through the construction of ramps combined with stairs (Figure 6).

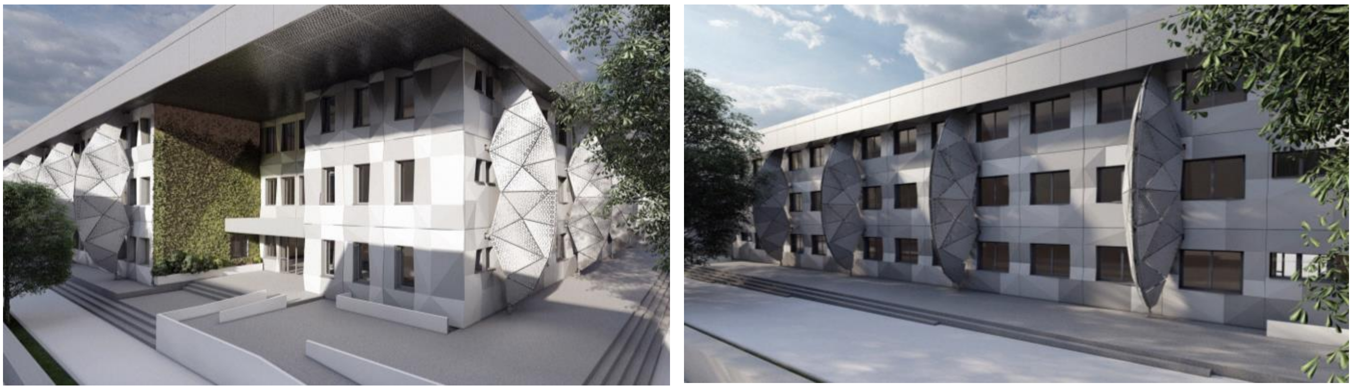

Fig. 6. South-east front of the case study at post-renovation state.

6. CONCLUSIONS

The paper reports a possible application of a retrofit intervention that combines a structural exoskeleton made of 3D steel trusses (called e-EXOS) with prefabricated, wood-based insulating panels (called e-PANEL), according to a multidisciplinary approach which synergically involves both seismic, architectural, and technological aspects. The proposed exoskeleton aims at reducing the seismic vulnerability of the building by avoiding the activation of the storey collapse mechanism, reducing the drift demand of the structure, and increasing its strength and dissipation capacity, meanwhile the insulating panels aim at increasing the thermal resistance of the outer walls to enhance the energy performance of the building. In particular, a construction analysis has been carried out to investigate the technical feasibility of combining the two retrofit systems.

The proposed intervention is implemented from the outside of the building, ensuring the maintenance of the building operativity. It requires dry installation, and is a fully reversible renovation intervention. It also ensures a high level of prefabrication and customization. Indeed, the e-EXOS is installed by assembling portions of trusses which are pre-mounted off-site through bolted connections. On the other hand, the e-PANELs integrate all the functional layers off-site, including cladding materials, high performing windows and sun shading devices, in order to reduce the implementation time compared to that of traditional ETICS systems. Proper technical solutions are required to ensure the watertightness of the new thermal wood-based envelope. The only invasive activities consist in excavating the pit for the new foundations of the trusses and removing the existing windows and shutter boxes.

The architectural integration of this solution has been achieved by focusing on the expressiveness of the structural components of the trusses and the cladding layer of the panels. It contributes to the building's architectural restyling and to some functional performance in terms of accessibility and identification of the access space.

Overall, the e-EXOS technology requires adequate space around the building, and involves changing the original configuration of the building façade. Hence, detached buildings with sufficient space around their perimeter and not subject to urban constraints that prevent the application of façade elements altering their appearance are the most suitable for this retrofit intervention.

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