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NEW LIFE TO OLD BUILDINGS IN SEISMIC AREA THROUGH STRUCTURAL STEELWORK

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ABSTRACT

In the present paper, additions in structural steelwork are utilised for extending the life of old buildings in regions characterized by medium/high seismic hazard. Two models are here proposed, i.e.: vertical addition for masonry buildings and lateral addition for r.c. buildings. For the model of vertical addition, the connection between the masonry and steel structures is realised by means of an intermediate isolation system (IIS). For the model of lateral addition, an exoskeleton (EXO) is rigidly connected to the existing building. Two buildings, representative of the heterogeneous Italian building stock, are selected as case studies. Parametric analyses are firstly performed on lumped mass models to explore the feasibility and effectiveness of the IIS and EXO systems in reducing the seismic response of the case studies; then, once selected the actual configurations of the new additions, more refined 3D FE models are adopted for the detailed analysis of the two solutions.

SOMMARIO

Nel presente articolo vengono utilizzate sopraelevazioni in acciaio per fornire nuova vita a edifici esistenti in regioni caratterizzate da pericolosità sismica medio/alta. Si propongono due tipi di modelli, ovvero: addizione verticale per edifici in muratura e addizione laterale per edifici in cemento armato. Per il modello relativo all'addizione verticale, la connessione tra strutture in mura-

tura e in acciaio è realizzata mediante isolamento sismico intermedio (IIS). Per il modello relativo all'addizione laterale, si connette rigidamente un esoscheletro (EXO) all'edificio esistente. Due edifici, rappresentativi dell'eterogeneità del patrimonio edilizio italiano, sono scelti come casi studio. Vengono dapprima effettuate analisi parametriche su modelli semplificati a masse concentrate al fine di esplorare la fattibilità e l'efficacia dei sistemi IIS e EXO nel ridurre la risposta sismica dei casi studio; successivamente, dopo aver selezionato le configurazioni di progetto delle nuove aggiunte, si adottano modelli raffinati 3D FE per un'analisi dettagliata delle due soluzioni.

1 INTRODUCTION

A sustainable model of urban growth should be based on the density increase and use/reuse of existing building stock, with no additional land consumption and saving the carbon burden that already exists in the built environment. In order to make feasible such strategy in regions of medium/high seismic hazard, a common approach is proposed, based on well-known principles of structural dynamics. Two models, both based on the concept of addition, are proposed: vertical addition for masonry buildings (Fig. 1a), and lateral addition (exoskeletons) for r.c. buildings (Fig. 1b). The design parameters are the dynamic properties of the structural addition (in structural steelwork) and of the connection between the existing and new structural parts. In the case of vertical extension (rooftop addition) the connection is realized by means of a seismic isolation system, located on the roof of the existing building and at the base of the new structure [1], [2], thus giving rise to an intermediate isolation system (IIS) for the structural complex; the isolation system should be designed for converting the vertical addition into a huge mass damper able to reduce the seismic demand on the structural complex with respect to the standalone existing building. The exoskeletons (EXO) are made by steel diagrid, hexagrid, or non-conventional structural patterns, which wrap the existing building [3]-[5]. They can also support ventilated or double skin façades, as well as satisfy solar shading/lighting requirements and integrate energy retrofit interventions [5], [6]. The connection between the existing building and the exoskeleton can be either "total" (rigid), by coupling in parallel the two structures, or "partial" (flexible and dissipative) [4], [5], [7], [8].
In this context, two case studies are selected for exploring the feasibility and effectiveness of steel additions for the seismic retrofit of existing buildings.

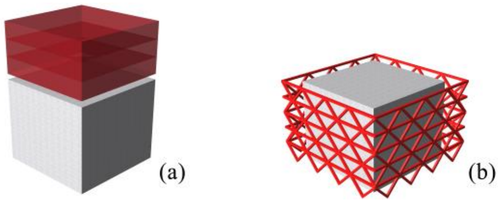


Fig. 1. Vertical addition, (b) lateral addition

2 SIMPLIFIED MODELS

Inter-story Isolation Systems and Exoskeleton Systems can be preliminary described through simplified lumped mass models. In the three-degree-of-freedom IIS model (3DOF IIS, Fig. 2a), m_i, k_i, c_i are the mass, stiffness and damping constant of the *i-th* DOF, with i = 1, 2, 3, i.e.: the lower structure (LS), the isolation system (ISO), and the upper structure (US), respectively. In the two-DOF model of the existing building (EB) connected to the exoskeleton (2DOF EB+EXO, Fig. 2b), m_1, k_1, c_1 and m_2, k_2, c_2 refer to the properties of the existing building and the exoskele-

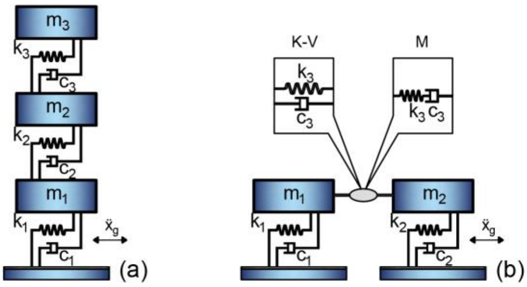


Fig. 2. Simplified lumped mass models: (a) 3DOF IIS; (b) 2DOF EB+EXO

ton, respectively. Instead, k_3 and c_3 are the stiffness and damping constant of the connection, which can be purely elastic ($c_3 = 0$), purely viscous ($k_3 = 0$), viscoelastic ($k_3 \neq 0$, $c_3 \neq 0$), by assuming either a Kelvin-Voigt (K-V) or a Maxwell (M) model [4], [7], [8].

3 THE CASE STUDIES

Two Italian buildings are selected as case studies (Fig. 3). After a brief description of the buildings, their capacity is assessed by means of push over analyses [9], developed on the relevant 3D FE models through the software SAP2000 [10]. Considering the contribution of the fundamental mode in the weakest (Y) direction, the dynamic properties of the reduced-order SDOF, i.e. the LS in the 3DOF IIS model (Fig. 2a) or the EB in the 2DOF EB+EXO model (Fig. 2b), are derived.

The *first case study* is a 16th century aggregate of four masonry buildings (Fig. 3a), located in Pozzuoli (Naples, Italy) [2], with residential and tertiary occupancy. It falls within a plan (P.U.A.), recently issued for the town, aimed at reconstructing some rooftop volumes, demolished in the 1980s. Plan dimensions and heights of the buildings are provided in Fig. 3a. The mechanical properties assumed for the tuff masonry material are: average weight of 16 kN/m^3, Young modulus of 1080 MPa, shear modulus of 360 MPa, compression strength of 3.0 MPa [9]. The dynamic properties of the SDOF LS are: m_1 = 2201 kNs^2/m, k_1 = 639883 kN/m, T_1 = 0.37 s.

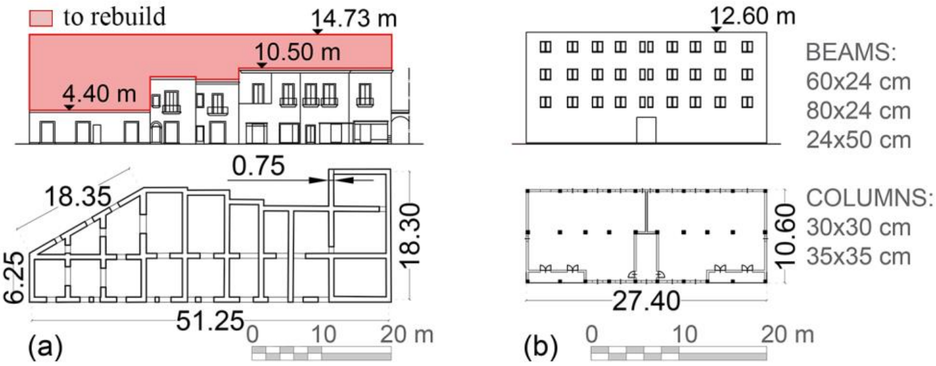


Fig. 3. First case study, (b) second case study

The *second case study* (Fig. 3b) is a four-storey residential building assumed to be located in L'Aquila (Italy), built in 1972 [5],[11]. Lacking some structural data of the existing building, a simulated design has been carried out for gravity loads according to the Italian building code in force at the time of construction [12]; then the assessment under seismic loads is carried out according to the current NTC 2018 [9]. The plan dimensions, height, and sections are provided in Fig. 3b. The building materials are steel FeB44k and concrete C 25/30. The dynamic properties of the SDOF EB are: m_1 = 575 kNs^2/m, k_1 = 27420 kN/m, T_1 = 0.91 s.

4 DESIGN SOLUTIONS

The solutions adopted for the seismic retrofit of the two case studies are realized by means of additions in structural steelworks (S275, f_{yk} = 275 MPa, f_{yd} = 261 MPa). The design solutions are firstly described; parametric analyses are then performed on the lumped mass models introduced in section 2, to explore the seismic behavior of such systems with response spectrum analyses; finally, spectrum-compatible time history analyses are performed on the relevant 3D FE models [10]. The design acceleration response spectrum is the elastic spectrum at the Life Safety Limit State (SLV, 475 years of return period) [9]. The set of spectrum-compatible acceleration records is defined with the software REXEL v 3.5 (PGA = 0.1 – 0.3 g in the period range 0.15 – 2 s) [13].

4.1 Vertical addition

The vertical addition is defined according to the P.U.A. of Pozzuoli in terms of floor area and storeys to rebuild (Fig. 3a). A "filling" steel structure has been preliminarily added on the left side of the aggregate in order to regularize the top edges of the buildings and to provide the floor level for the isolation system; then, a single-storey steel structure is realized on the top of the isolation devices. The idea is to design the isolation layer for converting the new isolated addition into a mass damper able to reduce the seismic demand with respect to the as-is configuration [2].

Parametric analysis. In the 3DOF IIS model (Fig. 2a) the design parameters are the mass ratio $\mu = (m_2 + m_3)/m_1 = 0.25$; the stiffness ratio $K = k_3/k_1 \in \{0.1, 0.5, 1.0, 1.25, 1.5, 2.0\}$; the isolation ratio $I = T_2/T_3 \in [0.1, 50]$. The damping constants c_1, c_2, c_3, are obtained from the values of the equivalent viscous damping ratios usually adopted for the corresponding structure types, i.e.: ξ_1 = 0.05 (masonry), ξ_2 = 0.15 (high damping rubber), ξ_2 = 0.02 (steel). The adoption of different values of damping ratios within the same structure leads to a system characterized by non-proportional damping and complex-valued natural modes [14]. The design spectrum is depicted in Fig. 4a for the site of Pozzuoli. The response spectrum analyses are carried out by considering the complex modal superposition method described by Sinha and Igusa [15]. The results are provided in Fig. 4b in terms of ratio between the base shear in the retrofitted ($V_{b,3DOF\ IIS}$) and as-is ($V_{b,\ SDOF\ LS}$) configurations: $v = V_{b,3DOF\ IIS}/V_{b,SDOF\ LS}$. The design solution ($K$ = 1.25, I = 4, T_2 = 0.5 s, v = 0.69) is selected in the shaded area of the chart that provides the minimum values of v.

Choice of the design configuration. The steel vertical addition is a single-storey Concentric Braced Frame (CBF), with two and four braced bays along the X and Y direction, respectively. The cross sections adopted for the structural members are: columns CHS 219.1x16; beams IPE 240 and 360; diagonals HEB 120 and 160; beam grillage on the roof of the existing building, RHS 900x450x40 mm, HEB 700 and 900, IPE 400 and 550. The isolation system consists of 10 high damping rubber bearings (ξ_{eq} = 0.15) placed at the intersections of the orthogonal walls of the lower structure (Fig. 5a). The steel structure, introduced to fill the height gap between the left building and the remaining aggregate, is a two- storey Moment Resisting Frame (MRF) designed for gravity loads only, with beams IPE 240 and 360 and columns CHS 219.1x16.

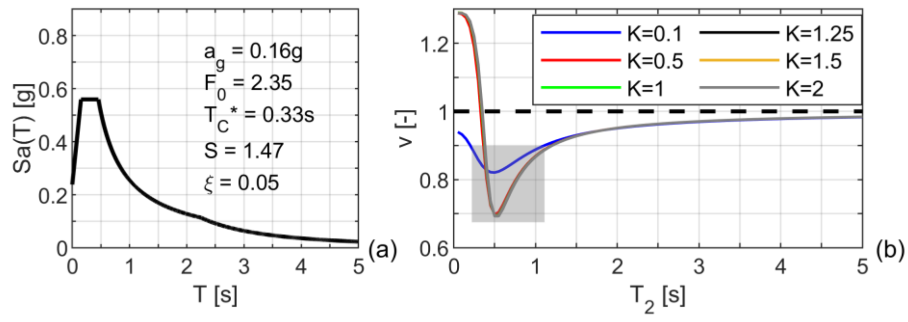


Fig. 4. (a) Elastic acceleration response spectrum (SLV, [9]), (b) v vs. T_2

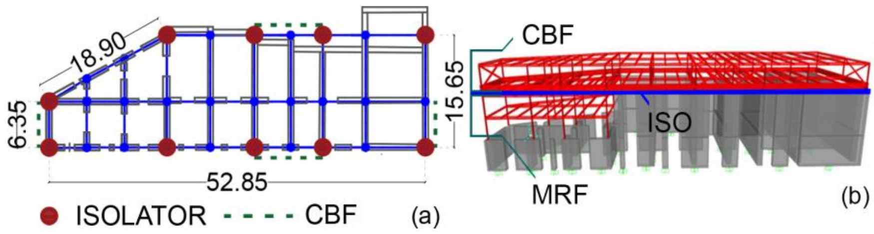


Fig. 5. (a) Isolation system, (b) 3D IIS model

3D Models and analyses. In the 3D FE model of the building with intermediate isolation IIS (Fig. 5b), lower and upper structures are considered elastic, as well as the isolation system that is modelled with linear springs. As previously discussed, the IIS system is characterized by non-proportional damping. Therefore, direct-integration time history analyses are developed in SAP2000 accounting for the full damping matrix [10]. The same analyses are also performed for the LS model. The Fig. 6a shows the peak displacement profiles for the seven input waves in the retrofitted configuration, and the average response for both retrofitted and existing buildings, while Fig. 6b provides the base shear ratios. The results of the analyses show that the displacements of the LS decrease in the IIS configuration, while the maximum shear ratios are smaller than, or equal to, one.

4.2 Lateral addition

The seismic retrofit of the r.c. building is achieved by means of a steel diagrid exoskeleton rigidly connected to the existing structure. The diagrid is configured as a narrow grid of diagonal members that guarantees high stiffness and strength against lateral actions [16]. The idea is to preserve the elastic behaviour of the retrofitted overall configuration, by transferring a great part of the base shear from the existing building to the diagrid [11].

Parametric analysis. In the 2DOF EB+EXO model (Fig. 2b) the design parameters are the mass ratio $\mu = m_2/m_1 = 0.05$ and the stiffness ratio $K = k_2/k_1 \in [1, 10]$. The spectrum is depicted in Fig. 7a for the site of L'Aquila. A constant damping ratio is assumed equal to 0.05. The results are provided in Fig. 7b in terms of shear ratios, namely:
$v = V_{2DOF\ EB+EXO}/V_{SDOF\ EB}$; $v_{EB} = V_{2DOF\ EB+EXO}^{(EB)}/V_{SDOF\ EB}$; $v_{yEB} = V_{2DOF\ EB+EXO}^{(EB)}/V_{y,EB}$.

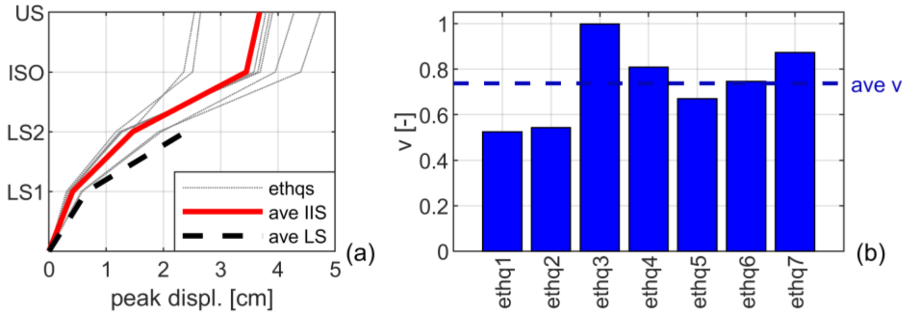


Fig. 6. (a) Peak storey displacement, (b) shear ratio v

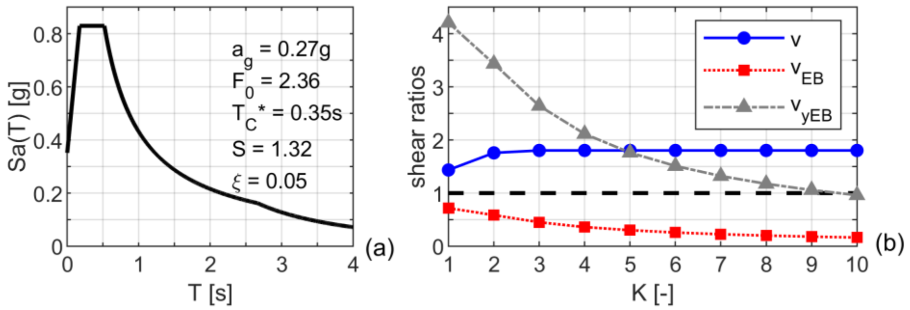
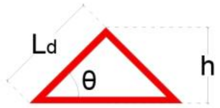


Fig. 7. (a) Elastic acceleration response spectrum (SLV, [9]), (b) v, v_{EB}, v_{yEB} vs. K

In particular, $V_{SDOF\ EB}$ and $V_{y,EB}$ are the base shear and the shear at the elastic limit in the as-is configuration, respectively; $V_{2DOF\ EB+EXO}$ and $V_{2DOF\ EB+EXO}^{(EB)}$ are the total base shear and the base shear of the existing building in the retrofitted configuration, respectively. From Fig. 7b it can be observed that, by increasing the stiffness of the exoskeleton, the base shear increases ($v > 1$), while the demand on the existing building is drastically reduced ($v_{EB} < 1$), with the r.c. elements remaining in the elastic field ($v_{yEB} < 1$) starting from $K = 9$.

Choice of the design configuration. The geometric characteristics of the triangular module are provided in Fig. 8a in terms of: diagonal angle (θ) and length (L_d), module height (h), number of diagonals on each façade (n), number of modules along the perimeter (n_k) and elevation (n_m). The diagrid is designed by adopting the procedure provided in Ref. [16] for tall buildings. As observed in Ref. [16], thanks to the high rigidity of the triangular module, particularly for this low-rise building, the local strength requirements (members sizing for strength and stability) prevail on global stiffness requirements. Hence, the members cross sections are derived to obtain $V_{2DOF\ EB+EXO}^{(EB)} \leq V_{yEB}$; then, the corresponding stiffness ratio is calculated, resulting in $K = 12$, which, being larger than 9, guarantees that the r.c. building is preserved from any damage. The profiles adopted for diagonal members are: SHS 140 mm x 8, 6.3 mm (X direction); SHS 180 x 20, 12.5, 8, 6.3 mm (Y direction).

3D Models and analyses. In the 3D FE model of the retrofitted building rigidly connected to the diagrid (3D EXO, Fig. 8b) both the existing building and the diagrid are considered elastic, checking *a posteriori* that the Demand to Capacity Ratio is smaller than one (DCR < 1). This configuration is characterized by almost the same mass and larger overall stiffness with respect to the standalone existing building (T_{EB} = 0.94 s, T_{EB+EXO} = 0.27 s). Analogously to the case of vertical addition, the results, provided in terms of peak storey displacements (Fig. 9a) and shear ratios v_{EB}, v_{yEB} (Fig. 9b), show a drastic reduction of the engagement of the EB, which remains in the elastic field.



Dir.	θ[°]	L_d[m]	h[m]	n[-]	n_k[-]	n_m[-]
X	48	2.12	1.58	10	40	8
Y	47	2.14	1.58	4	40	8

(a)

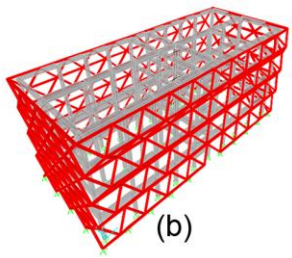


Fig. 8. (a) Geometrical characteristics of the diagrid triangular module, (b) 3D EB+EXO

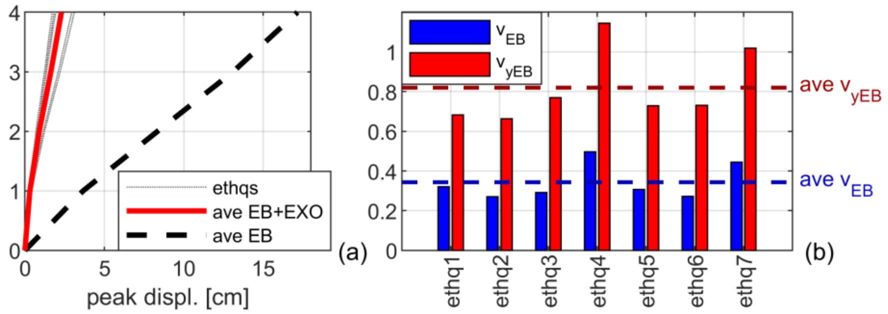


Fig. 9. (a) Peak storey displacement, (b) shear ratios

CONCLUSIONS

This paper deals with the seismic retrofit of old buildings in seismic areas. Two design solutions are developed by means of additions in structural steelworks. For the first case, a base isolated vertical extension is mounted on the roof of a masonry aggregate, thus realizing an intermediate isolation system. For the second case, a diagrid exoskeleton is rigidly connected to an existing r.c. building. Parametric analyses are firstly developed on the lumped mass models of the IIS and EXO systems, by means of response spectrum analyses to define the design configurations for the new additions. Then, spectrum-compatible time history analyses are carried out on the relevant 3D FE models of the design solutions. From the results of the dynamic analyses, it emerges that: (i) in the IIS solution, by carefully designing the isolation system, the new structure can be converted into a giant mass damper able to reduce the seismic response of the structural complex; (ii) in the EXO solution, the high rigidity of the diagrid, though increasing the global seismic response of the new configuration, preserves the elastic behaviour of the existing building.

The strategy suggested in this paper for the seismic retrofit of existing buildings, based on steel additions and proper design of the link between the old and new structural parts, appears effective and particularly feasible for a quick site assembly, with almost no disruptions of the activities that are hosted in the existing structures.

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KEYWORDS

seismic retrofit, vertical addition, lateral addition, intermediate isolation system, exoskeleton