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ON THE USE OF COLD-FORMED THIN WALLED MEMBERS FOR VERTICAL ADDITION OF EXISTING MASONRY BUILDINGS

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***Abstract**. According to the current trend for sustainable constructions in urban area, in this paper different constructive technologies for vertical addition of existing masonry buildings have been examined. Based on the analysis methodology of the new technical Italian code (M. D. 14/01/08) for assessing the behaviour of historical masonry buildings, a FEM model of a structural masonry unit has been implemented in order to allow for the comparison among different solutions for vertical addition, namely traditional technologies and innovative ones. A numerical campaign of linear dynamic analyses has been undertaken by changing both the number of floors (1, 2 and 3) and the strength (f_k=1, 3 and 6 MPa) of the base masonry structure. The seismic performance of the analysed structures, expressed in terms of PGA, has shown that cold-formed steel systems represent the best solution for vertical addition of existing masonry buildings.*

1 INTRODUCTION

In the last years the concept of sustainable development is emerged due to the apparent inadequacy of energy production to meet consumer demands without causing impact on the earth life quality. The construction field plays a major role in the environmental issue, since it represent the greatest impact source [1]. In this policy framework based on the reduction of energy consumption, the requalification of existing buildings has an important role, since it aims to improve their energetic behaviour. In this context, it was observed that acting on both the insulation grade and the service systems of the building, the management of the so-called smart home, which is able to reduce power consumption preserving the living comfort level, is allowed. Within such a scenario addressed to the energy saving, the difficulty to find living volumes in cities is recently appearing. This is relevant especially for Italian historic centres, where the exponential growth of population is remarkable. Therefore, economic and environmental structural solutions able to mediate the features of existing built heritage with the above new requirements are needed. Among these, the vertical addition is an alternative to the traditional solutions of growth of cities, it allowing for: a) the preservation of virgin land for future generations; b) the upgrading of building energy efficiency through the design of insulated roof; c) the optimization of local resources, which allows to increase the housing units while maintaining the soil resource; d) the urban renewal, since the increase of housing units in urban areas may be also the solution both for the overcrowding of neighbourhoods and the excessive daily mobility of workers towards the cities [2, 3]. On the other hand, as demonstrated by recent seismic events, vertical addition should be limited to buildings having a reduced vulnerability, such as good quality masonry structures with plan regularity and a limited number of stories. Moreover, the realization of added floors may be difficult in the historic centres due to problems related to the transportation, assembly and installation of the manufactured products [4]. In this contest, Italian legislation has drawn up new regulations, which are able to meet the new requirements. The study presented in this paper is related to this aspect. It deals with the assessment of structural behaviour of masonry buildings, which are the most common structural type in the South Italy constructive tradition, subjected to vertical addition by using both traditional and innovative technologies. The goal of the performed study is to establish, by means of the development of an extensive campaign of numerical analyses, the effectiveness of each solution adopted and the choice of the most effective one.

2 COLD FORMED SYSTEMS FOR VERTICAL ADDITION OF EXISTING BUILDINGS

Many manufacturing technologies could be used for vertical addition of existing masonry buildings. Besides the obvious solution involving the use of the masonry itself, added stories could be realized by using different construction technologies, which can be classified into traditional types and innovative ones (Table 1).

Table 1: Construction technologies for vertical addition of existing masonry buildings.

Traditional	Innovative
Timber	Glued laminated timber
Reinforced concrete	Composite materials with polymeric matrix
Hot - rolled steel	Cold formed and/or high-strength steel

In the first category the materials currently used in the Italian and European construction practice belong to. Glued Laminated Timber is preferred to timber, which was used in the past for erection of floors, since it allows to obtain sections of general shape with minimal defects and high structural performance. The possibility of reducing the dimensions of the vertical addition structure members has led in some cases to the use of reinforced concrete. The use of this technique is permitted by using a tie beam rigid enough to mitigate the local effects transmitted by columns to masonry walls. A strong reduction of actions transmitted to the substructure (from 4 to 10 times) can be obtained using high structural efficiency materials. Excluding structures made of composite materials with polymeric matrix because of their high costs, a solution widely used also for the retrofitting of existing buildings is the one based on hot-rolled steel elements [5], organized into either moment resisting frames or pinned ones. Finally an innovative solution that combines the use of light materials (structural incidence of the order of $0.15 \div 0.30$ kN/m^2) with structural types which distribute the vertical loads uniformly on all the masonry walls, is represented by the use of Cold-Formed systems (CF) [6]. Depending on the prefabrication level, three types of cold-formed constructive systems can be identified, namely stick-built constructions, panelised constructions and modular constructions. Among these, stick-built constructions are certainly the most suitable for vertical addition, mainly for technological reasons related to the easier installation and transportation, which are the most important requirements for super elevation within densely populated areas, as the city centres. This structural type, deriving from wood housing, is made by assembling vertical members (studs) placed each other at a distance ranging from 300 to 600 mm. In stick-built constructions the wall studs, which are the vertical load-bearing structural systems, have an important role. They allow to both transmit gravitational loads to foundations and sustain horizontal actions due to wind and/or earthquake. The way to transmit vertical loads allows to differentiate the structural types into balloon frames and platform frames, the studs being continued or interrupted, respectively. On the other hand, the way to absorb the horizontal actions allows to classify the structural types into sheathing braced system and x-braced one. In the first, the bracing function is provided by panels, normally made of wood, attached to the studs by means of special connection systems designed to ensure some dissipation capability through the screw-panel bearing mechanism [7]. Instead, in the second system, the bracing function is provided by steel diagonal members that, if properly designed by applying the capacity design philosophy, can ensure satisfied ductility. In this case the closing panels have protection function against the environmental actions only.

3 SEISMIC ASSESSMENT OF EXISTING MASONRY BUILDINGS ACCORDING TO THE NEW ITALIAN CODE (M.D. 08)

According to the provisions of the new technical Italian code (M.D. 14/01/08) [8], the structural safety evaluation of existing buildings, characterized by a level of uncertainty higher than the new ones, is carried out by means of analysis methods and checks depending on the levels of knowledge of buildings, which are related to their geometry, construction details and material properties. These knowledge levels are connected to particular confidence factors, which modify the capacity parameters and the safety factor to be used in the checks. M.D. 08 defines general criteria for safety assessment of building, providing in the explanatory circular recently approved [9] guidance on the identification of knowledge levels. Under this rules, building knowledge can be limited (LC1), adequate (LC2) and accurate (LC3). The analyses methods of masonry buildings can be either linear or nonlinear, both static and dynamic. With linear methods, seismic actions are determined on the basis of design spectra, obtained by reducing the elastic one through the behaviour factor q, which implicitly takes into account the system dissipation capability. The behaviour factor depends on the type of structure, on the design criteria adopted and on the material nonlinearity properties. The q factor values for existing ordinary masonry buildings are listed in Table 2 where the ones for new buildings are reported too.

Table 2: Behaviour factors for ordinary masonry buildings.

		Regular in elevation	Not regular in elevation
New building	α_u/α_1=1.4 (1 story)	2.80	2.24
	α_u/α_1=1.8 (2 or more stories)	3.60	2.88
Existing building	α_u/α_1=1.5	3.00	2.25

From the table it is apparent the penalty of the q factor because of the structural irregularity. This is due to the excessive concentration of plasticization in some structural elements, which reduces the overall dissipation capability. Therefore, the linear analysis methods take into account the structure nonlinear behaviour through behaviour factors but they are not able to adequately assess both the changes in the system response due to the plastic behaviour of components and the inelasticity distribution. Instead, these phenomena can be taken into account by adopting non-linear procedures, which consider the non-linearity of the material, the geometric non-linearity and the change of structure stiffness and strength, allowing also to know the location and the evolution of structural elements plasticity until the building collapse. Despite the difficulty in modelling the material and the geometry of components (piers, spandrels and nodal panels), the nonlinear static analysis are widely used for the study of masonry buildings, they allowing, within fixed limits, a more realistic and reliable evaluation of their structural response. It must be also noted that these procedures, despite push-over analyses are easily implemented into all computer programs, should be applied to both plan and in elevation regular building only. To this purpose, it is worth noticing that the change of stiffness in elevation, produced by vertical addition made of technologies different from masonry, should be considered by performing dynamic analyses.

4 SAFETY ASSESSMENT OF SUPERELEVATED MANSONRY BUILDINGS

4.1 Selection of the study sub-structures

According to the provisions of the section 8.7.1 of the M.D. 2008 [8], a single structural masonry unit extrapolated from a building in line, representative of the building heritage built in Naples at the beginning of '900, has been selected as a study case. The stories of the structural unit have been considered as variable from 1 to 3. Therefore, appropriate wall thicknesses have been considered, namely 40 cm for the 1-storey structure, 50 cm for the 2-storeys structure and 60 cm, 50 cm, 40 cm for the 1st, 2nd and 3rd floor, respectively, of the 3-storeys structure. 4.20m and 3.60m have been used as inter-story height of the ground floor and the other floors, respectively. As a consequence, the aspect ratio of lateral and central piers has been assumed equal to 1 and 0.5, respectively. The study structural unit have the potentiality to be superelevated due the following reasons. First of all, the unit was provided with 6 m spaced load-bearing shear walls (less than 7 m, which is the maximum limit for new buildings) having a percentage of masonry area, correlated to gross building area, suitable into the two main directions. Furthermore, the horizontal load-bearing system, made of steel profiles and hollow tiles, is completed with a slab anchored to the beams by appropriate connectors in order to have a rigid diaphragm. Also tie beams have been considered in order to both distribute the forces among shear walls and make a box behaviour building. For the purpose of vertical addition, the demolition of a significant part of the roof slope slab of the original structural unit has been foreseen, it producing a reduction of the permanent loads equal to 1.11 kN/m^2.

4.2 Parametric study

The possible use of cold-formed systems for vertical addition of existing masonry buildings has been investigated by means of a parametric study. The FEM models of the selected structural masonry units, provided with lateral restraints to reproduce the presence of adjacent buildings, have been implemented by means of the PRO_SAP structural program [10].

First, masonry, reinforced concrete, hot-rolled and cold-formed steels and glued laminated timber, have been selected as base materials for the one-story vertical addition structure. Later on, the masonry compressive (f_k = 1, 3 and 6 MPa) and shear (f_{vk0} = 0.10 and 0.15 MPa) resistance of the base material have been selected as variables for the masonry sub-structure. The main elements of the parametric study performed with the PRO-SAP software are illustrated in Figure 1 [11].

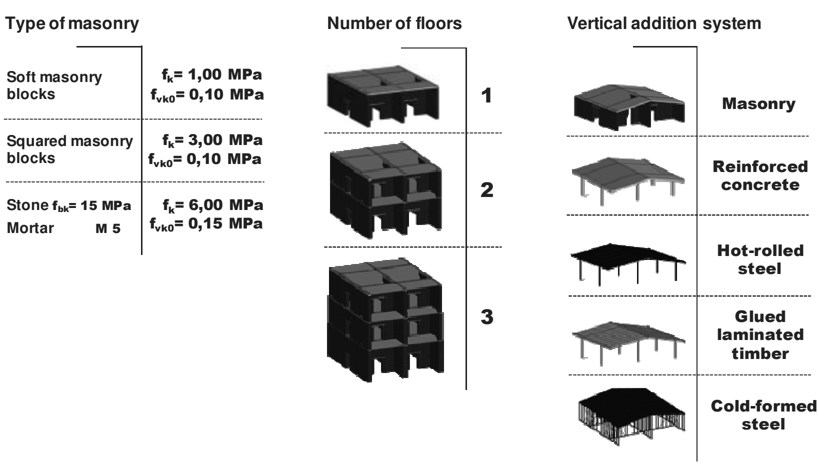

Figure 1: Base elements of the parametric study.

Once the geometric parameters of the substructure have been fixed, by varying the number of floors, the kind of vertical addition and the masonry mechanical properties, a numerical simulation program consisting of 18x3 models has been generated (Figure 2). The vulnerability of the base masonry buildings has been assessed towards both seismic actions (max PGA at Life Safety Limit State) and gravity loads (max vertical load at the Ultimate Limit State). In the first case, the seismic vulnerability has been determined by dynamic analyses with behaviour factor, assuming the earthquake applied along the direction of major vulnerability. Within this framework, it is apparent that, for buildings belonging to urban aggregates, the direction of greatest vulnerability is generally represented by the transversal one. In the second case, the vulnerability under vertical actions, that is the maximum vertical load sustainable by the superstructure roof when local failure at the interface between the masonry wall and the super elevation structure occurs, has been estimated.

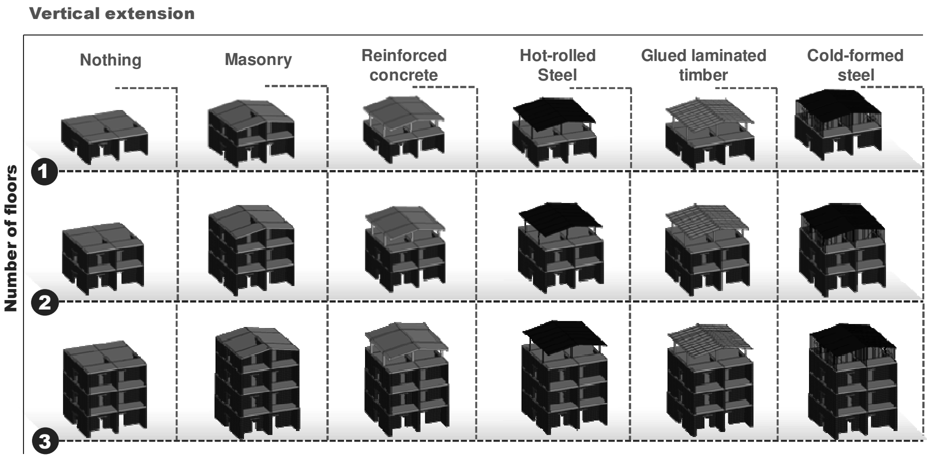

Figure 2: Typological matrix of the numerical simulation program.

4.3 Design of the vertical addition system by CF Steel

All the vertical addition structures listed in the Section 4.2 have been designed according to the prescriptions of M.D. 08 [8]. Omitting for brevity the design process details of traditional constructive solutions (masonry, reinforced concrete, rolled steel, timber), the design phases involving the CF solution are herein briefly discussed [12]. The structural type considered is the stick-built one, under form of the platform frame solution, braced with S235 steel thin strips. The resistant system towards horizontal actions is designed in accordance with the principles of capacity design: the full plastic behaviour of tension diagonals represents the system dissipation capability. The not dissipative structural elements of the system (studs, tracks, connections, shear anchors and hold-downs), are oversized in order to have an elastic behaviour until collapse. This is achieved by using S275 steel and an adequate thickness of both studs and tracks (Figure 3). In the numerical model the following actions were considered: a) permanent structural loads; b) permanent non-structural loads, represented by the insulated panels for coverage; c) variable load due to snow, equal to 1.00 kN/m^2. The earthquake has been represented by means of an elastic spectrum characterized by a PGA of 0.35 g and increased with a dynamic amplification factor (DAF) of 2 to take into account the dynamic amplification effect produced by the substructure. According to recent experimental studies performed on different configurations of x-braced panels [13], in the modelling of seismic actions the systems dissipative capacity has been considered assuming a behaviour factor equal to 3.

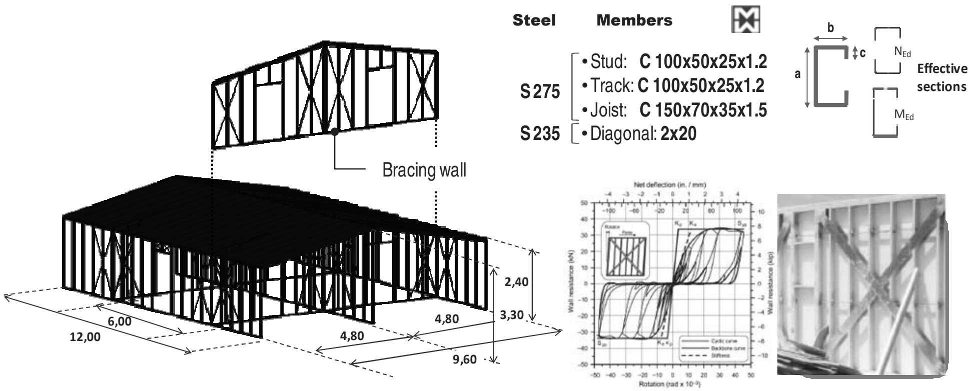

Figure 3: Main features of the CF steel vertical addition system.

4.4 Comparison among results

The vulnerability study performed by means of the modal analysis has shown that, except when the superstructure is made of masonry, all the techniques allow to increase from 7 to 26% the base building structural performances in terms of PGA (Figure 4). The reasons are double: 1) the removal of the slab tends to reduce the overall structural system weight. This is due to the fact that the weight reduction due to the slab removal, approximately equal to 1.10 kN/m^2, is higher than the superstructure incidence per unit area, considering the non-structural weight too, that ranges from 0.60 to 0.80 kN/m^2. 2) The added floor tend to load directly the shear walls of the building, improving their in plane structural performance in terms of bending-compression and shear behaviour. For masonry buildings characterized by low mechanical properties (f_k = 1MPa and f_{vk0} = 0.10 MPa), certainly representative of the Neapolitan area built up, the best solutions in terms of seismic performance are the low-weight ones (Figure 4). In fact, in this case, a combined bending –compression failure mechanism in lateral piers is occurred.

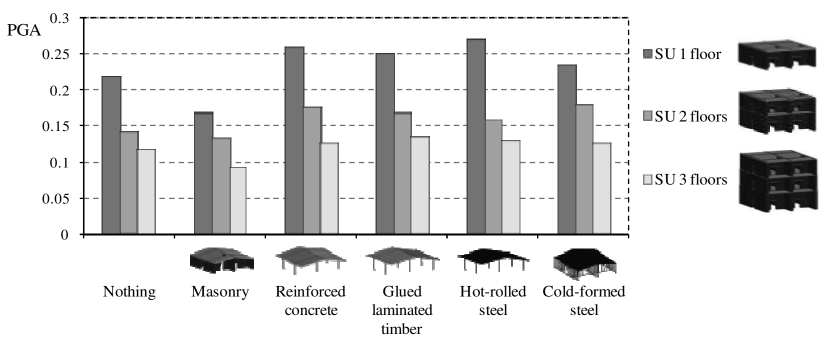

Figure 4: Max PGA at the Life Safety Limit State (f_k = 1 MPa and f_{vk0} = 0.10 MPa).

However, the dynamic analyses have not shown an unique optimal solution as the number of floors changes. Instead, if we consider the vulnerability under vertical loads (Figure 5), we can certainly say that when tie beams having a properly flexural stiffness are absent, the reinforced concrete solution provides clearly the worst result because of both its high-weight and the considerable stress concentration produced by the columns at the interface with the masonry structure. This concentration of loads is also apparent when other superstructures characterized by frame schemes are used. An exception is made for the cold-formed systems, which are composed of studs close each other realizing panel systems able to transmit uniform loads to the substructure. Therefore, these structures represent the most favourable solution for vertical addition of existing masonry buildings, since they restore the continuity of walls.

Finally the dynamic analyses have also allowed to estimate the dynamic amplification factors (DAFs) which the superstructure is subjected to when it is located on the building top instead of the ground floor. In fact, comparing the response of the superstructure with the same structure located at the ground level, we can observe that the former undergoes a base shear amplification with an increasing factor ranging from 1.08 to 4.10. In Table 3 the DAFs to be used for the design of the superstructures neglecting the presence of the base masonry building are shown.

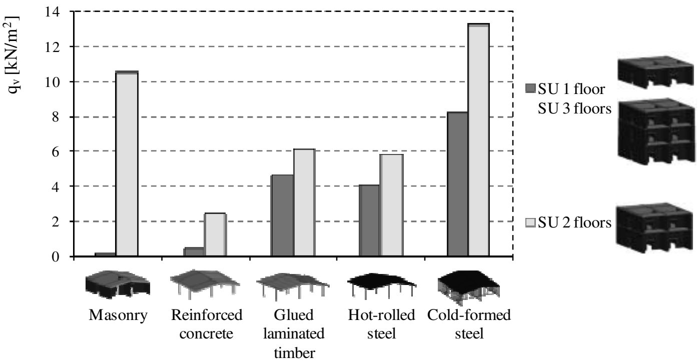

Figure 5: Max vertical load at the Ultimate Limit State (f_k = 1 MPa and f_{vk0}= 0.10 MPa).

Table 3: Dynamic amplification factors.

Vertical addition structure material	Base masonry structure		
	1 storey	2 storeys	3 storeys
Reinforced concrete	1.72	2.52	2.65
Glued laminated timber	2.53	3.47	2.66
Hot-rolled steel	2.94	3.07	2.69
Cold-formed steel	1.08	3.54	4.10

5 CONCLUSIONS

In this study the comparative analyses of different manufacturing technologies to be used for vertical addition of existing masonry buildings have been done. In particular, the potential use of cold-formed steel in spite of traditional solutions, such as masonry, reinforced concrete ordinary steel and glued laminated timber, has been proved. A single structural masonry unit extrapolated from a building in line representative of the building heritage built in Naples at the beginning of ‘900 has been selected as a study case. The stories of the structural unit have been considered as variable from 1 to 3. Once the geometric parameters of the substructure have been fixed, by varying the number of floors, the kind of vertical addition and the masonry mechanical properties, a numerical simulation program based on linear dynamic analyses has been generated. The vulnerability of the base masonry buildings has been assessed towards both seismic actions (max PGA at Life Safety Limit State) and gravity loads (max vertical load at the Ultimate Limit State). The achieved results have shown that the dynamic behaviour due to the difference of stiffness between substructure and superstructure cannot be neglected. In fact if the response of the superstructure is compared with that of the same structure positioned at the ground level, it is evident that the former is affected by larger forces with an amplification factor ranging from 1.08 to 4.10, depending on both the characteristics of the base building and the type of the vertical addition system. The results of linear dynamic analyses have also indicated that, except for the superstructure made of masonry, all other techniques allow to increase the structural performance of the base building. With regard to low-strength masonry buildings, the selection of the most effective solution as the number of floor of the masonry substructure changes is not so simple. If we consider the performance evaluation for vertical loads, we can certainly say that in all cases, without adequately rigid tie beams, the superstructures made of a framing scheme are certainly the worst solutions because of the considerable stress concentration at the columns-masonry structure interface. Instead, the use of cold-formed structures, realizing panel walls able to both restore the masonry continuity and transmit uniformly the loads to the base structure, is certainly preferable. As a result, these structures represent the most favourable solution for vertical addition of existing masonry buildings.

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