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Seismic performances and behavior factor of post-and-beam timber buildings braced with nailed shear walls

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ABSTRACT

A procedure to assess the behavior factor of post-and-beam timber structures based on the Capacity Spectrum Method is herein presented and the results of numerical simulations performed on three different building configurations, two and three storey buildings regular in plan and a two storey building non-regular in plan, are shown. The procedure assumes that the dissipative capacity of the structure is concentrated in the nailed connections of the components, whose non-linear behavior is derived by means of experimental tests. The results obtained, concerning the three types of buildings with three different proportioning criteria for the connections, are compared in terms of force–displacement capacity curves, global ductility, maximum resistant ground acceleration and behavior factor q. The global ductility ranges from 1.8 to 2.4. The values of the behavior factor q of the two storey buildings ranges from 2.4 to 3.8, depending on the shear redistribution amount among the shear walls; higher values (3.0–4.4) were obtained for the three storey buildings. Moreover, a nail distribution at each level according to the storey demand increases the dissipative capacity of the structure. The results of the study evidence that the maximum value of the behavior factor allowed in Eurocode 8 for timber structures with nailed shear walls and nailed diaphragms, connected with nails and bolts ($q = 5$) is in general not possible for post-and-beam timber buildings braced with nailed shear walls.

1. Introduction

A greater attention to timber constructions was devoted in the last decade in many countries, as Italy, in which for cultural reasons a very limited number of timber buildings are present. The main reasons for such a trend are the industrial production of the components, the speed in construction, the appreciable physical properties, the good performances under seismic excitation and the reduced energy consumption in the construction process and when in use. "Post-and-beam" is a timber structural system for multi-storey residential housing (Fig. 1) consisting in a main frame of continuous floor-to-roof posts, connected to the foundation by steel angles, sleeve footings or hold-downs, to which horizontal beams are frequently pin connected. As the main frame is able to support effectively vertical loads but has very low resistance to horizontal actions, the vertical bracing system is commonly provided by the introduction of mono-dimensional diagonal timber elements [1], timber shear walls or continuous floor-to-roof cantilevered timber walls [2,3]. The paper focuses on the bracing system made of timber shear walls, assembled from wood-based sheathing fixed to a timber light frame of studs and plates by nails or screws and connected to the main frame through mechanical fasteners; steel angle brackets or tie-downs are used to fix the foundation plate to the basement. Horizontal diaphragms are composed by timber frames with nailed wood-based sheathing or by a traditional structure of timber joists and nailed wooden planks, adequately braced (e.g. by means of nail plates connecting adjacent timber boards or diagonal carbon fiber (CFRP) strips glued to timber boarding [4]).

According to Eurocode 8 [5], in earthquake-resistant timber buildings designed in agreement with the concept of dissipative structural behavior, the seismic design may be done on the basis of a linear analysis of the structure, taking implicitly into account its dissipative capacity by using a design response spectrum equal to the elastic one reduced by the behavior factor q. The dissipative zones have to be located in joints and connections, whereas for the timber members an elastic behavior is assumed. The connections to the foundation have to be designed on the basis of a capacity design, considering an adequate overstrength [5] in order to avoid the premature collapse of the building induced by a local failure of a single concentrated connection and ensuring in such a way the development of cyclic yielding in the dissipative zones. Therefore, in a post-and-beam building braced with nailed shear

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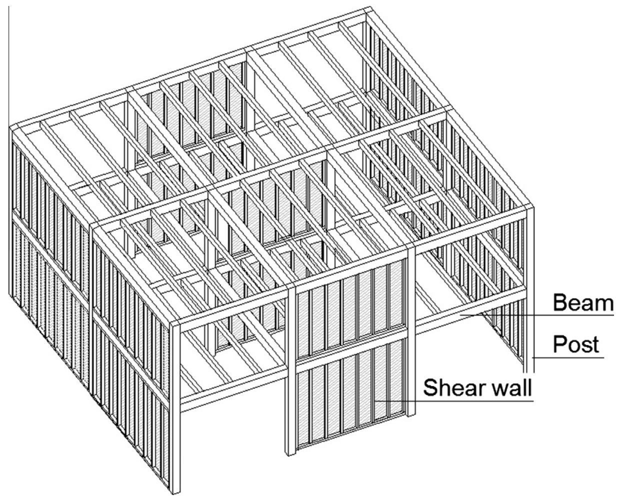

Fig. 1. Example of a timber post-and-and beam structure braced with shear walls.

walls, the connections between the sheathing and the light frame of shear walls and between the latter and the main frame characterize the overall dissipative capacity of the structure.

In Eurocode 8, the upper limit values of the behavior factors q to be assumed for the most common timber structures are indicated, depending on their ductile behavior and energy dissipation capacity under seismic actions, but no specific indications are reported for the post-and-beam timber buildings. Therefore there is the need to assess the ductility class and the actual values of the q-factor for these structures. In fact, the specific "timber structures made of nailed wall panels with nailed diaphragms, connected with nails and bolts" (section 8.3 of Eurocode 8 [5]), for which an upper limit equal to 5 for the behavior factor q is provided, refer only to Platform Frame buildings. As summarized in [6], the evaluation of the behavior factor can be conducted through experimental investigations, based on quasi-static cyclic tests or on full-scale shaking table tests, or through numerical simulations, adopting a static or a dynamic approach. The experimental approach based on full-scale testing (e.g. [7–13]) has the disadvantage of being expensive both in economic and time resources and the results are strictly related to the chosen earthquake and structural configuration. On the other hand, the q-values derived from cyclic tests on single shear wall specimens [14] cannot be directly used as a reduction factor for the global structure. Thus, hybrid approaches ([15–23]) have been proposed consisting in a numerical model of the whole building based on the experimental behavior of single shear walls. As non-linear dynamic analysis is performed, the method requires the assessment of the dissipative capacity of the wall elements when subjected to fully-reversed quasi-static cyclic loading. In these studies the q-factor is calculated as the ratio between the peak ground acceleration (PGA) at which the near collapse status is reached (e.g. interstorey drift for timber frame building, maximum uplift for X-lam structures) and the design PGA with $q = 1$.

The dissipative capacity of timber buildings may also be investigated by means of non-linear static analysis. Two nonlinear static procedures are nowadays mainly used for the seismic analysis of buildings: the N2 method, adopted in Eurocode 8 [5] and the Capacity Spectrum Method, reported in FEMA 440 [24] and adopted in the codes of many countries in the world. The differences among the methods mainly concern the approach adopted to find out the performance point (equivalence from the seismic demand and the structural capacity). In the former the seismic demand is represented by an inelastic spectrum based on the actual ductility of the system, in the latter the seismic demand is computed through an elastic spectrum that uses an effective damping to consider for dissipation capacity.

In [25], Fragiacomo et al. performed non-linear pushover analysis on X-lam buildings adopting the N2 procedure of Eurocode 8 with a modified bilinearisation procedure (Yasumura and Kawai [26]) so to calculate the maximum ground acceleration that a building can withstand. In that paper it was evidenced that the Eurocode 8 procedure do not properly include the case of systems with a pinching hysteretic behavior or larger stiffness degradation, which are typical for cross-lam structures and, in general, for timber shear walls.

In this paper, the estimation of the behavior factor for post-and-beam timber structures was conducted by performing pushover analysis. The Capacity Spectrum Method [27,28] was adopted so to determine the maximum response based on the displacement corresponding to the intersection of the capacity curve of the building and the spectral demand curve used to characterize the design seismic hazard. This method was preferred to that proposed in Eurocode 8 [5] as modifies the linear elastic response of the equivalent SDOF system accounting for the effective period and damping of the structure at ultimate displacement.

In [29] some experimental tests evidence that a large number of components (e.g. element dimensions, type of sheathing, nail type and spacing, connection to foundation) characterize the behavior of bracing shear walls, so in the numerical study all the single components are modelled distinctively. The non-linear behavior of each component was derived from experimental results available in the literature [30–32] and the numerical model was validated by comparison with experimental tests carried out on two different timber shear walls ([33,34]) subjected to in-plane horizontal cyclic loads. Some early results on the application of the numerical model to analyze multi-storey post-and-beam buildings braced with light frame shear walls were presented in [35,36].

Three typical configurations of post-and-beam residential timber housing were herein investigated: regular structures of two or three storeys and irregular in-plan structures of two storeys. The influence of the proportioning criteria adopted for the nailed connection was also taken into account.

2. Method

The procedure proposed in the paper to evaluate the seismic performance of a post-and beam timber building assumes the dissipative capacity of the structure concentrated in the nailed connections between the components (shear walls sheathing/light fame, light frame/main frame). According to the capacity-based design of Eurocode 8 [5], the other connections (e.g. connections of shear walls or posts to foundation, post-beam node connections, etc.) were designed with an adequate overstrength factor in order to ensure the development of cyclic yielding in the dissipative zones.

At first, a preliminary linear static analysis is performed to design the structural timber elements (post-and-beam main frame, shear walls), subjected to the design seismic combination of the area, and to proportionate the connections (steel angles, hold-down, anchor bolts, nails). In the analysis, the elastic stiffness of timber members and connections are considered and a tentatively value of the behavior factor $\overline{q}$ quite close to the expected one is assumed, so to have a ratio between horizontal and vertical forces on the elements approximately equal to that occurring in nonlinear analysis. A distribution of the lateral loads proportional to the fundamental mode shape was utilized. According to Eurocode 5 [37], the spacing of the sheathing nailed connections and of the fasteners connecting the shear walls to the main frame