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Seismic behavior of cross-laminated timber panel buildings equipped with traditional and innovative connectors

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ABSTRACT

The aim of this paper is to analyze the possibility to improve the seismic performance of cross-laminated timber (CLT) panel buildings introducing in the structure dissipative connectors in substitution of the classical hold-downs. In fact, as demonstrated by past experimental tests and numerical analyses, hold-downs exhibit a limited dissipation capacity. The proposed dissipative connector is called XL-stub and applies the concept usually adopted for ADAS devices.

In order to prove the effectiveness of the proposed system the results of an experimental program devoted to characterize the force–displacement response under cyclic loads and low fatigue behavior of the XL-stub are presented and compared to the results of cyclic tests of hold-downs with same resistance. Afterwards, the comparison is extended at the level of the building, evaluating the influence of the connection on the seismic performance of the whole CLT panel building. To this scope, a FE model of the three-storey building tested within the SOFIE project is calibrated and multiple transient dynamic analyses are performed both for the building with the classical layout of connections and for the building equipped with XL-stubs. The obtained results are compared and the values of the behavior factor for the two solutions are calculated.

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1. Introduction

Engineered timber such as Glu-Lam (Glued Laminated) or Cross-Lam (Cross-Laminated) is increasingly being used as a structural material. The sustainability and the technical advantages of modern wooden buildings are related to the fact that they are quick to erect, with high fire resistance and give the possibility to be easily integrated in energy efficient solutions. In addition, as already demonstrated in recent research programs [1–4] timber structures can exhibit also a satisfactory performance under seismic loading conditions, provided that members and connections are properly designed. From the seismic standpoint, timber buildings assembled with steel joints combine the advantages of the two materials. In fact, the high resistance/weight ratio of wood

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reduces the horizontal seismic actions, while the steel parts (fasteners, nail, screws, etc.), which are able to exhibit a ductile behavior, are employed to dissipate the input energy through their inelastic response.

Among the various timber structural systems, cross-laminated timber (CLT) panel buildings, despite their recent introduction, have rapidly spread on the European market, which for a long time has been oriented on structural solutions adopting masonry or concrete rather than lightweight materials such as timber. From the seismic standpoint, a CLT panel building is conceptually similar to a box structure in which walls and floors are rigid in their plane. Usually the structure is constituted by the assembly of prefabricated flat cross-laminated panels used for realizing both the vertical resistant system and slabs where the vertical panels are connected to each other by means of screws, nails and angle brackets. As far as the panels behave as rigid elements the deformation of the whole structure is usually lumped in the connections used to fasten the panel to the foundation and between each storey. Generally each panel at the ends possesses at least a couple of long nailed angles, namely hold-downs, able to prevent rocking and a number of smaller angles used to absorb shear forces.

Despite the recent applications and research efforts provided by some research groups worldwide, the seismic behavior of CLT panel buildings is still under investigation and, to date, also because CLT is a relatively young system, there is still a lack of codification. In fact, currently, Eurocode 5 [5] do not contain specific guidance on fabrication, design and procedures for inspection and maintenance. Furthermore, there are not satisfactory rules for the design of the dissipative and non-dissipative zones of the building and the behavior factors (q-factor) proposed by the Eurocode 8 [6] are not specifically devoted to CLT panel buildings which, in absence of more detailed information, have to be considered as low-ductility systems with a behavior factor equal to 2. Some years ago a great research effort has been devoted to this structural system in Italy by Ceccotti et al. [4,7], providing a wide experimental program including analyses of joints, sub-assemblies and to the shaking table tests on real scale buildings realized with the CLT panel system [7]. Within this work, the problem of evaluating the behavior factor of this structural typology has been examined, assessing the experimental results on real scale buildings and developing a set of multiple transient dynamic analyses (MTDA) with a FE model developed in DRAIN-3D [4]. The experimental and numerical analyses have revealed that, even though CLT panel buildings can exhibit a satisfactory performance under seismic loading conditions, with the current system of connections they should be designed using a maximum value of the behavior factor only equal to 3. Additional studies on CLT structures have also been performed more recently in [8–11].

Therefore, considering past experimental works, it is easy to understand that since the elements mainly devoted to the energy dissipation of CLT buildings are the hold-downs, the reasons of such a low value of the behavior factor can be searched in the response of these connectors under cyclic loading conditions. In fact, as already demonstrated in technical literature, hold-downs subjected to cyclic loads exhibit a response characterized by significant pinching phenomena and degradation of the hysteresis loops resulting in a low capacity to dissipate energy. In addition, in order to avoid brittle failures, hold-downs have to be oversized with respect to nails and screws in order to cover the random material variability of timber of the CLT panels. As already underlined in [12,13], this is not easy to perform and represents a very strong design condition for the hold-downs which, if not properly accounted for in design, may lead to the development of unexpected failure mechanisms of the connection.

As an alternative to the classical layout of connections of CLT buildings, recently, in [14] the possibility to substitute the hold-down with an innovative dissipative connector, called "XL-Stub", previously tested and applied to steel structures [15,16], has been examined and verified by developing numerical analyses on a single wall, alternatively equipped with hold-downs or XL-stubs, subjected to dynamic loading histories. The developed analyses have pointed out that the wall equipped with the XL-stubs is able to provide an improved response in terms of fatigue life, energy dissipation and displacement capacity leading to a significant reduction of the displacement demand which, depending on the considered accelerogram is reduced, with respect to the case of the wall equipped with the hold-downs, of a percentage contained between the 30% and the 78%. It is useful to note that also in other recent works it has been proposed to introduce dissipative elements in beam-to-column joints of concrete and engineered timber frames [17,18]. In particular, both these authors have proposed to insert at the top and bottom level of the beam two alternative angle details: one with a zone of the flange with reduced thickness and the another one with reduced thickness and circular holes. In addition, more recently, following these studies, solutions of dissipative connections for CLT systems have also been suggested by other authors [19–21].

Within this framework, in this paper, as a follow up of the previous work developed by the authors [22], the possibility to apply the XL-stub to CLT panel buildings is examined by extending the study to the analysis of the response of a three dimensional building alternatively equipped with XL-stubs or with hold-downs. In particular, starting from the results on the cyclic behavior and modeling of dissipative XL-stubs applied to CLT panels already presented in [22], the experimental monotonic and cyclic tests carried out at the University of Salerno on the XL-stub are compared with the results of cyclic tests on hold-downs with a similar resistance tested in [23]. Successively, in order to evaluate the influence of the connection on the seismic performance of the whole CLT panel building a FE model of the three-storey building tested within the SOFIE project [4] is calibrated and its accuracy is verified by comparing the numerical prediction with the time-history response observed in the shaking table tests performed in [4]. Finally, multiple transient dynamic analyses are performed both for the building with the classical layout of connections and for the building equipped with XL-stubs comparing the results in terms of behavior factor.

2. Cyclic behavior of typical connections of CLT panel buildings

Cross-laminated timber panel buildings are usually constituted by the assembly of panels made of cross-laminated wood,

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