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Seismic response of CFS shear walls sheathed with nailed gypsum panels: Numerical modelling

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A B S T R A C T

Building codes around the globe are in a transition to update their design guidelines to meet the objectives of performance based seismic design (PBSD). The fulfilment of the objectives of PBSD requires number of collapse simulations of a building equipped with certain type of seismic force resistant system. Numerical models with an ability to simulate post-peak deteriorating behaviour are essential for these collapse simulations. A European research project named ELISSA was carried out in recent years, to better understand the seismic behaviour of cold-formed steel shear walls sheathed with nailed gypsum based panels through experimental and numerical studies. Within the framework of project, numerical models were developed for single shear walls with an ability to simulate their nonlinear hysteretic behaviour and possessing the capability of being used in the collapse simulations of complete building models for meeting the PBSD objectives. These models are the focus of the study presented herein. Three types of models are presented, which differ with each other in terms of complexity, type of experimental results used in their calibration and the ability to simulate nonlinear monotonic or cyclic lateral static behaviour.

1. Introduction

High structural, technological and environmental performance of lightweight steel constructions has presented them as a better alternative for low to medium rise buildings located in seismic areas. Cold-Formed Steel (CFS) members are mainly used as the structural elements in these types of constructions. Shear walls, made of flat sheets of steel, wood, gypsum or fibreboard based panels attached to the CFS frame through screw or nail fastener systems, is one of the techniques to provide the seismic resistance in lightweight steel constructions. It has been evident from the previous research on these type of walls [1–4], that the interaction between sheathing panels and CFS frame represents the most significant nonlinear behaviour and strongly influences the lateral response of walls. Pin-connected horizontal and vertical elements of CFS frame cause it to deform into a parallelogram under the in-plane shear loads. The sheathing itself behaves as a rigid element and can only undergo rotation and translations. Inconsistent deformation of the steel frame into parallelogram and rigid body deformation of the sheathing produces tilting or bearing deformations in sheathing panel-to-steel frame connections, which is the key energy dissipation mechanism.

Regardless of the several benefits offered by lightweight steel construction in seismic areas, a lack of confidence exists in the European construction sector on use of this system, mainly due to the absence of proper design guidelines [5] and the existence of the very few applications [6,7]. In this regard, a European research project named ELISSA (Energy Efficient LIghtweight-Sustainable-SAfe-Steel Construction) [8] was conducted among different universities, research centres and material manufactures across Europe to promote the use of CFS systems. In particular, University of Naples Federico II, Italy, provided the seismic behaviour assessments of the wall constructions through several experimental and numerical studies. From structural point of view, the walls were sheathed-braced CFS shear walls made with impact resistant gypsum board panels (Diamant-X by Knauf) attached to the CFS frame through ballistic nails. Profiles in CFS frame were joined together using clinching techniques. The use of these connecting techniques in walls led to a more efficient level of prefabrication, thanks to their fast execution speed.

In order to evaluate the seismic behaviour of shear walls, a case study of a building representing a real-world application of lightweight steel construction was developed in the project. More details about the case study are provided in [9]. The performance of shear walls was investigated by means of experimental tests organized on three subsequent scale levels: micro-scale, meso-scale and macro-scale. At micro-scale level, monotonic and cyclic tests were conducted on sheathing connections made using ballistic nails [10]. Meso-scale tests included

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monotonic and cyclic tests on full-scale shear walls. Finally, macro-scale shaking table tests of complete two storey building [9] were conducted in order to evaluate its global seismic response.

Nowadays, modern earthquake standards are following a trend to integrate the performance based seismic design (PBSD) approaches in order to achieve a more rational design [11]. Development of PBSD requires to achieve a level of damage in structure, which can be simulated through nonlinear dynamic analysis of computational models having the capability to represent the deteriorating structural behaviour. Therefore, along with the experimental studies, nonlinear numerical models were also developed for the specimens tested at all three stages. Additionally, numerical modelling at each scale were also utilized to predict the response of subsequent experimental phases. This paper explains the three different approaches, which are adopted in the study presented herein for the development of numerical models of CFS shear walls sheathed with nailed gypsum boards to simulate their monotonic and cyclic response (meso-scale level). In the first approach, the experimental results of micro-scale sheathing connection tests were used to predict the monotonic or cyclic envelope response of shear walls using a detailed finite element (FE) model. In the second approach, an equivalent truss model was developed to simulate the wall hysteretic response using the experimental results of the meso-scale cyclic tests on shear walls. In the third approach, a procedure for simulating the cyclic response of shear walls through a unified FE-truss model was proposed, which only relies on test results on individual sheathing connection assemblies and is simplified enough to be used with complete building models. The experimental results used in the development of these models are presented in the companion paper [12].

2. Previous researches on the numerical modelling

The dynamic behaviour of CFS-sheathing-braced shear walls is characterized by a remarkable nonlinear response with a strong pinching of the hysteresis loops and degradation of the strength and stiffness in subsequent loops. In past, various researchers proposed numerical models to simulate this type of response. They can be broadly categorized into equivalent truss, equivalent shell and detailed finite element (FE) models based on the approach used in their development and the resulting inherent complexity. An equivalent truss model [13–18] relies on equivalent nonlinear truss elements or linear truss elements combined with nonlinear springs to simulate the behaviour of a shear wall. A shell model [19] uses shell elements with equivalent mechanical and physical properties, which are representative of complete wall behaviour, to simulate the nonlinear behaviour of a shear wall. Detailed FE models [20–24] follow a more realistic approach by simulating the nonlinear response of a complete shear wall through modelling of main structural elements, including all individual sheathing connections, which are the main energy dissipating mechanism in walls. Following paragraphs highlight the modelling approach used in different studies for developing the numerical models for CFS-sheathing braced shear walls.

Fülöp and Dubina [13] developed an equivalent truss model using DRAIN-3DX [25] software for CFS shear walls sheathed with corrugated steel sheets or OSB panels. They represented the nonlinear behaviour of the shear wall through pair of diagonal trusses having a fibre-hinge accommodating the desired hysteretic behaviour, which was calibrated using experimental results [26].

A similar modelling approach was followed by Shamim and Rogers [14] for CFS sheathed shear walls in OpenSees [27] software. They used nonlinear truss elements in a X configuration paired with an elastic wall frame, to represent the wall response under dynamic loading. In particular, they used *Pinching4 material* [28] for nonlinear truss elements, which possess the ability to simulate the pinched hysteretic response typical of CFS shear walls.

Very recently, North American cold formed research groups finished a project short named as CFS-NEES [29] aimed at better understanding of seismic behaviour and the improved design of CFS structures. In the project, a 2 storey CFS sheathed braced building was tested on shake table. Leng at al [15] developed the computational models for the tested structure. The models developed for shear walls were similar to the one developed by Shamim and Rogers [14]. In addition to using piching4 material for truss elements, they also tried to use an Elastic Perfectly Plastic material, which failed to provide better results than pinching4 material model. Moreover, for modelling the response of complete building they divided the shear walls in into sub panels. The lateral stiffness of each individual sub panel was modelled by pair of two diagonal truss elements having a picnhing4 material.

Kechidi and Bourahla [16] presented an equivalent truss model developed in Opensees [27] software for wood and steel sheathed CFS shear walls. They used a pair of rigid truss elements in a X configuration with an equivalent non-linear *Zero Length element* in the mid of truss elements having user-defined material to represent the wall behaviour. Additionally, they also developed a uniaxial material, which uses only the physical and mechanical characteristics of the wall as input to simulate the wall hysteretic response. The criteria governing the hysteretic behaviour of the uniaxial material was selected based on relevant experimental results.

Bourahla et al. [17] presented a simple model to account for the overall lateral stiffness and strength of the shear walls in the complete building models in SAP2000 software [30]. Model used a nonlinear equivalent shear link having a pivot hysteretic model connected to rigid triangular shell elements. They achieved a quite good match in terms of comparison of dynamic properties of numerical model of complete building with the results obtained from its ambient vibration testing.

The nonlinear hysteretic response of shear walls can also be represented by a set of differential equations which define the material rule for a nonlinear spring representing the behaviour of the shear wall. One such model was presented by Nithyadharan and Kalyanaraman [18], which used Bouc-Wen-Baber-Noori [31] smooth differential model in order to simulate the response of CFS shear walls braced with calcium silicate panels.

Martinez et al. [19] followed a more simplified modelling approach by simulating the behaviour of wood-sheathed CFS shear walls using an equivalent orthotropic shell elements in SAP2000 software [30]. The equivalent properties of shell elements were adjusted to account for the global behaviour of the shear wall.

Buonopane et al. [20] presented a detailed finite element model developed in OpenSees software [27] representing the main energy dissipating component (sheathing connections) in wood sheathed CFS shear walls through radially-symmetric nonlinear spring elements placed at each sheathing connection location. Rigid behaviour of OSB or gypsum sheathing panels was modelled through the *rigid diaphragm*, whereas the CFS frame was modelled using *elastic beam column elements. Pinching4 material* [28] was used for the nonlinear spring elements, which was calibrated based on the experimental results of sheathing connection tests.

Niari et al. [21] developed finite element models for steel-sheathed CFS shear walls in ABAQUS software [32] for simulating their monotonic response. *S4R shell element* with reduced integration was used to model the CFS frame and sheathing, whereas steel sheet-to-profile connections were modelled with *mesh independent fasteners*, which were calibrated on the basis of experimental results on individual connection tests.

Zhou et al. [22] developed a detailed finite element model for wood-sheathed CFS shear walls in ANSYS software [33] and compared their performance against the results of monotonic tests on shear walls. They modelled the frame and sheathing with the *Shell181 element* and used coupling methods to handle the panel-to-steel profile connections that allowed only rotation in connections, restricting any translation.

Telue and Mahendran [23] also developed detailed finite element models for wood-sheathed CFS shear walls for the evaluation of their monotonic response using ABAQUS [32] software. They used ABAQUS