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Shake table tests of a full-scale two-story sheathing-braced cold-formed steel building

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ABSTRACT

Shake table tests are particularly indicative to assess dynamic properties and seismic response under earthquakes in the case of a new building structure. In last years the University of Naples was involved in the research project named "Energy Efficient LIghtweight-Sustainable-SAfe-Steel Construction" (Project acronym: ELISSA), which was devoted to the development and demonstration of enhanced prefabricated lightweight CFS skeleton/dry wall constructions with improved antiseismic properties. Within the ELISSA project, in order to evaluate the global building seismic response, shake table tests on a full-scale two-storey building, named "ELISSA mockup", were carried out. The mockup was tested in two different conditions. In the first condition the mockup included mainly structural components of walls, floors and roof, whereas in the second condition it was completed with all nonstructural components. This paper presents the testing program and the obtained results in terms of dynamic identification (fundamental period and damping ratio) and earthquake performance (global lateral response, building drift, acceleration amplification, diaphragm response, and observed damage).

1. Introduction

It is well known that collect detailed information on the structural behaviour of a seismic-force-resisting system is necessary for reliable prediction of its seismic response. Among required information, a key rule is represented by test data deriving from experimental investigations. Particularly indicative in the case of a new building structure are shake table tests, which can be very useful to assess dynamic properties and seismic response under earthquakes, with the final goal to check assumed design criteria, calibrate models and validate structural analyses for the proposed seismic-force-resisting system [1].

In past years a lot experimental campaigns were carried out on seismic-force-resisting systems of Cold-formed Steel (CFS) framed buildings, on both sheathing-braced and strap-braced solutions. Most of these activities were focused on the static and cyclic behaviour of components, connections and structural assemblies, whereas dynamic shake table testing of complete structural system are very rare.

The lateral performance of CFS framed domestic structures subjected to earthquake loading was assessed by Gad et al. [2] with racking and shake table tests on both two- and three-dimensional framing configurations carried out on the two degree-of-freedom shaking table at the University of Melbourne. In particular, tests on the three-dimensional configuration were carried out on a 2.3 m × 2.4 m (plan dimensions) × 2.4 m (high) one-room one-story house, in which diagonal steel strap-braced walls (2.4 m long × 2.4 m high) represented the seismic-force-resisting system. The floor of the specimen was made of a concrete slab. The CFS structure was completed according the common solution for domestic house used in Australia, i.e. brick walls were used as exterior cladding and plasterboard was used as interior lining. The house was tested with racking cycles, swept sine wave and horizontal uniaxial simulated earthquakes in both plane directions and at different stages of construction in order to take into account the contribution of the various components on the seismic response. The El-Centro earthquake was selected as testing earthquake. It was applied with Scaling Factor (SF) from 100% to 300%. Authors concluded that for unlined frames the behaviour is governed by the strap bracing system, whereas for lined frames non-structural plasterboard combined with ceiling cornices, skirting-boards and set corner joints provided higher stiffness, load carrying capacity (about 60–70%) and damping than strap braces. In addition, for brick veneer walls there was no contribute to the

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lateral response of the system in the examined case, i.e. brick veneer walls attached to the frames with clip-on ties. Finally, natural period and damping ratio obtained at different stages of construction were in the range from 0.22 to 0.26 s and from 4.2 to 10.0%, respectively.

Horizontal uniaxial shake table tests of a full-scale two-story one-bay structure were carried out by Kim et al. [3,4] on the shake table, Tri-axial Earthquake and Shock Simulator (TESS) at the Engineer Research and Development Centre, Construction Engineering Research Laboratory (ERDC-CERL). In particular, the specimen consisted of two identical two-story one-bay structure, in which the lateral bracing was provided by two 2.8 m × 3.0 m (length × height) cross steel strap-braced walls, spaced at 3.9 m on centre, for each story. Both floors were made of a 200 mm thick reinforced concrete slab. The structure was designed with a response modification factor (R) equal to 4, but the specimen was designed to be significantly undersized, therefore the actual value of R was 5.47. The specimen was tested with random vibration tests and uniaxial natural earthquakes applied with different scaling factors. In particular, the SE 32 accelerogram provided by Somerville et al. [5] with SF from 2% to 100% (for 100% SF the input had the same spectral response acceleration as the design response spectrum). Authors obtained a fundamental period of 0.61 s and a damping ratio of 7.2%. They concluded that during the earthquake tests with higher scaling factor the cross-bracing straps showed very ductile but highly pinched hysteresis behaviour, whereas columns provided a contribution to the shear strength only where the braces provided no strength or stiffness.

Shamim et al. [6,7] carried out one directional shake table full scale tests on seven wood sheathed and ten steel sheathed CFS framed shear walls. The main objective of the study was to evaluate the seismic performance and to identify whether the shear-wall behaviour was consistent with past static tests. In addition, also the influence of the second story and floor detailing was investigated. Tests were carried out at the Ecole Polytechnique de Montréal structural laboratory. Tests of wood sheathed CFS framed shear walls included three single-story and four double-story walls, which were constructed of a typical CFS frame sheathed with either Douglas fir plywood (DFP) or Canadian softwood plywood (CSP) and gypsum panels, whereas tests of steel sheathed CFS framed shear walls included five single-story and five double-story walls. Each wall segment consisted of a CFS frame with 1.22 m length and 2.44 m height. In order to evaluate the contribution of non-structural components to the seismic performance of the walls, a gypsum panel was installed on one wood sheathed shear wall test specimen. Two of the wood sheathed and all the steel sheathed specimens were tested with a 12.5 kN gravity load on the top.

Wood sheathed walls were designed according to the Canadian provisions given in AISI S213 [8]. Therefore, a seismic force reduction factor equal to 4.25 was chosen and overstrength factor of 1.33 and 1.45 was selected for CSP and DFP sheathed walls, respectively. Steel sheathed walls were designed based on the data available from past static tests [9]. Each specimen was subjected to free vibration impact tests to measure the damping ratio, harmonic excitation to estimate the fundamental vibration period and ground motions representative of the seismic hazard in Canada. In particular, for wood sheathed walls, a simulated seismic time history closely matched to the 2005 NBCC elastic uniform hazard design spectrum representative of eastern Canada (an M7.0 event at 70 km in Quebec City) was used. For steel sheathed walls two records were considered for ground motion testing: the first was the same as one used for the wood sheathed walls and the second represented a simulated seismic time history closely matched to the 2005 NBCC (National Building Code of Canada) elastic uniform hazard design spectrum representative of western Canada (an M7.0 event at 70 km in Vancouver, BC). Authors concluded that the general behaviour of the walls in terms of strength-versus-drift hysteretic behaviour and failure modes did not differ significantly from that observed for nominally identical single story reversed-cyclic displacement-based tests. They noticed the importance to properly account for eccentric loads in the capacity design process for the chord-stud members. The measure of damping ratio depended on the analysis method used with values always greater than the 2% (6.0% and 7.6% in averaging for wood and steel sheathed walls, respectively).

Recently, a North American research project titled Enabling Performance-Based Seismic Design of Multi-Story Cold-Formed Steel Structures (CFS-NEES) funded by the U.S. National Science Foundation and the American Iron and Steel Institute was carried out by Schafer et al. [10]. Part of the work was the seismic response evaluation of a full-scale two-story 15.2 m × 7.0 m (plan dimensions) × 5.8 m (high) CFS-framed building (CFS-NEES archetype building) tested under a series of dynamic excitations during different phases of construction. The building was designed with a response modification factor (R) equal to 6.5 and an overstrength factor Ω equal to 3.0. Seismic testing was conducted using the twin shake tables at the University of Buffalo. The testing was carried out in two main phases. In the first phase the building was made of only structural elements, i.e. CFS shear walls sheathed with oriented strand board (OSB) panels, unsheathed CFS gravity walls, and CFS-framed floor and roof diaphragms sheathed with OSB. In the second phase, a second building was constructed with the same specifications of the first phase but including nonstructural components, i.e. exterior and interior sheathing, interior partition walls, ceilings, staircases. For the first phase, the specimen was tested through the three-axis Canoga Park record from the 1994 Northridge earthquake with SF from 16% to 100% (100% SF was equal to the Design Basis Earthquake per U.S. standards, i.e. a hazard level of 10%/50 years). For the second phase, the specimen was subjected to the 100% Canoga Park record, and then to the three-axis near-field Rinaldi record at 100% from the 1994 Northridge earthquake (100% Rinaldi record was equal to the Maximum Considered Earthquake (MCE) per U.S. standards, i.e. a hazard level of 2%/50 years). To identify the natural period of vibration and the damping ratio, white-noise tests were conducted after every earthquake test. Authors concluded that the characteristics of the building were significantly altered by the nonstructural systems, with a decreasing of fundamental period from 0.32 s to 0.15 s, which represents a 4.5 times increase in the building lateral stiffness. The measured damping ratio was 4% and 9% prior to first and second phase testing, respectively, whereas it was measured at 18% and 15% after first and second phase testing, respectively. The building experienced a modest damage, only occurred in the corner near the openings of interior non-structural walls, with small maximum story drift ratios (1.18% and 0.72% for first and second phase testing, respectively) and no residual drifts. Even if the building was designed as a series of independent shear walls and assuming a flexible diaphragm, the response was significantly affected by the coupling of shear walls and three-dimensional behaviour. Additional information on CFS-NEES Shake table tests can be found in Peterman [11] and Peterman et al. [12,13].

In past years, extensive studies were carried out at University of Naples "Federico II" in order to better understand seismic performance of CFS buildings [14–19]. More recently, the University of Naples was involved in the research project named "Energy Efficient LIghtweight-Sustainable-SAfe-Steel Construction" (Project acronym: ELISSA), which was funded by European Commission under the Seven Framework Programme (www.elissaproject.eu). The project was devoted to the development and demonstration of enhanced prefabricated lightweight CFS skeleton/dry wall constructions with improved thermal, seismic and fire performance,