IN-PLANE ASSESSMENT OF EXISTING TIMBER DIAPHRAGMS IN URM BUILDINGS VIA QUASI-STATIC AND DYNAMIC IN-SITU TESTS

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KEYWORDS:

Century old timber diaphragms, field testing, in-plane stiffness, wood diaphragm, natural period

ABSTRACT

Mechanical and dynamic in-plane properties of timber diaphragms are known to be key parameters when determining both the local and global seismic response of unreinforced masonry (URM) buildings. However, few data pertaining to experimental campaigns on performance of existing timber diaphragms are available in the literature. In the work presented here, the outcomes of a field-testing campaign conducted on full-scale 100-year-old timber diaphragms are presented. Two specimens, being 5.6 x 9.6 m2 and 4.7 x 9.6 m2, were obtained from a 17.0 x 9.6 m2 existing floor and were subjected to a series of cyclic and snap back tests in the direction orthogonal to the timber joists. Adhesive anchors were installed prior to testing due to the deficiencies of the original anchoring system to transfer shear forces. In order to reproduce the inertial load distribution, an ad hoc loading system was developed by means of wire ropes and steel pulleys.

Following testing of the diaphragms in the as-built condition, the effect of different refurbishment techniques was investigated. From the results, it seems that even "simple" and cost-effective solutions such as re-nailing of the flooring and the addition of thin plywood overlays are sufficient to achieve a significant increase in the equivalent shear stiffness.

INTRODUCTION

The in-plane properties of timber diaphragms influence the seismic response of a masonry building in different ways and at various levels. For example, an increase in diaphragm stiffness will increase the extent of collaboration between perimeter walls. This attribute is important in irregular ancient buildings (typical of Mediterranean countries) where massive torsional effects may be present. In addition, the diaphragm deformability has a governing role in determining both the typology and the activation threshold of the out-of-plane failure mechanisms, which represent one of the major sources of structural damage. Consequently, several experimental campaigns on unretrofitted/retrofitted timber diaphragms have been carried out by researchers from different countries [1, 2, 3]. However most of these works have considered laboratory-testing of newly constructed timber floors made on research purpose, which are characterised by better (and more homogeneous) mechanical properties compared to vintage floors. In addition, little information is available regarding diaphragm behaviour when the floors are subjected to loads in the direction orthogonal to the joist span [3].

The natural period of diaphragms is a basic parameter when determining the shear load that is transferred to the resisting wall elements as it has a direct influence on the magnitude of the horizontal load that has to be taken into account during the seismic assessment procedure. Therefore it is important to improve the evaluation accuracy of this parameter, through an experimental campaign, which also takes into account the period dependence associated with the target displacement.

EXPERIMENTAL CAMPAIGN ON 100 YEAR OLD TIMBER FLOORS

Tested building. The building chosen for the testing campaign was a two-story clay brick unreinforced masonry building located in Whanganui (New Zealand), which was constructed in 1913 (Fig. 1). The wall thickness is 350 mm (three leaves) at the ground floor and 220 mm (two leaves) at the first floor. The floor has a 9.7 m span and was centrally supported by a double timber beam that is supported on cast iron columns.

Floor sections. Two specimens, whose lengths were 5.6 m and 4.7 m, were obtained from an available 17.0 m floor length (joists were orientated in the 9.6 m direction). Due to the advanced state of decay of the floor adjacent to the North-West corner of the building, it was not possible to obtain more than two specimens. The difference in the specimen length is also related to the desire to test floors with different aspect ratios.

The specimens, from here on designated A (5.6 m x 9.6 m) and B (4.7 m x 9.6 m), were made of 50 mm x 300 mm NZ native timber rimu joists with an average spacing of 450 mm, covered by a layer of 130 mm x 22 mm NZ native timber matai floorboards. Timber cross bracing of the joists was present in the direction orthogonal to the joists, with a spacing of approximately 1.5 m. On the bottom surface of the joists a ceiling was attached. The ceiling was made of 85 mm x 13 mm NZ native timber kauri boards sheathed with metal sheets that were 0.3 mm thick (Fig. 1c).

In order to isolate the specimens from the supporting beam, each joist was lifted with a hydraulic jack to create sufficient space for a saw blade to be inserted in order to cut the nails connecting the joist to the beam. Subsequently, to minimise the effects of friction phenomena, greased, low-friction plates (polystone, 100 mm x 300 mm) were placed under each joist.

New anchors. It was identified that the original anchoring system was deficient, so new 16 mm epoxy-grouted anchors (maximum spacing = 2.0 m) were installed before starting the testing procedure (Fig. 2b). The thickness of the timber blocking elements was 50 mm, while the washers measured 80 mm x 80 mm x 5 mm. Because all the diaphragm tests were undertaken in the direction orthogonal to joists, no fasteners were applied to connect the blocking element to the adjacent joists. A shear unit load of 7.5 kN/m, which corresponds to a severe seismic condition, was adopted as the design load for the new anchors. The shear response of the adhesive anchors was determined through a series of cyclic tests conducted on walls located in the same building (Fig. 2).

Test setup. The loading system was constructed using pulleys, wire ropes and steel tubular elements, and was designed to reproduce the parabolic load distribution suggested by FEMA 356 [4]. Such a setup is characterised as being “lightweight”, “thin” and easy to relocate from one specimen to the next,

Fig. 1 Tested building (Whanganui – New Zealand): a) front view; b) floor top view; c) floor bottom view

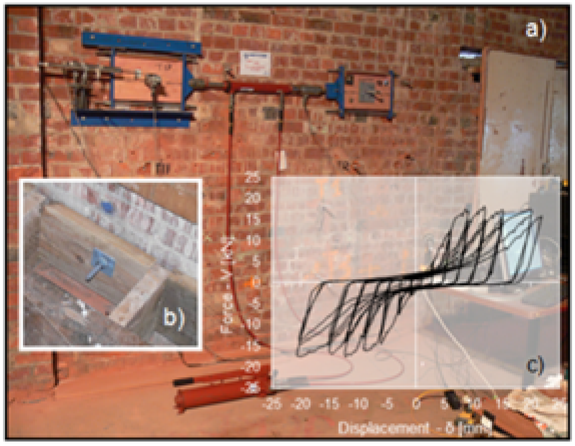

Fig. 2 New shear transferring anchoring system: a) anchor test setup; b) new anchor installation; c) cyclic test results

without the need to move the reaction points (Fig. 3a). In addition, the steel frame that keeps the pulleys in the correct position was able to be placed at any distance from the loading points (e.g. outside the tested specimen). Hence the setup did not affect the diaphragm response during the dynamic testing. However, the use of steel wire ropes to perform a cyclic test required two setups. The external force was applied by two hydraulic, single acting hollow cylinders positioned on each side of the specimen (Fig. 3c). During the snap back tests the load was instantaneously released by using a snap shackle borrowed from the "sailing world" (Fig. 3b). All the tests (both static and dynamic) were labelled with a progressive number followed by a letter representing the specimen (e.g. 4_A, 5_A, 6_A).

Cyclic tests. A total of 5 cyclic tests were conducted on the two floor specimens. The first cyclic test (5_A) was carried out on specimen A in the original condition, with both the ceiling and the metal sheathing in place. Then, the ceiling and the metal sheathing were removed and specimen A was re-tested with just the joists and the floorboards (8_A). This configuration can be considered representative of the common "as-built" condition. Subsequently, specimen A was strengthened by applying two new 2.85 mm x 75 mm nails into each board-to-joist intersection, with a spacing of approximately 100 mm (18_A).

In order to characterise the in-plane properties of the basic configuration in a way that was unaffected by any mechanical property degradation due to previous testing, specimen B was tested directly without the ceiling and the sheathing (26_B). Following test 26_B, the specimen was retrofitted using a layer of structural grade plywood panels placed directly on top of the existing floorboards (35_B). The plywood

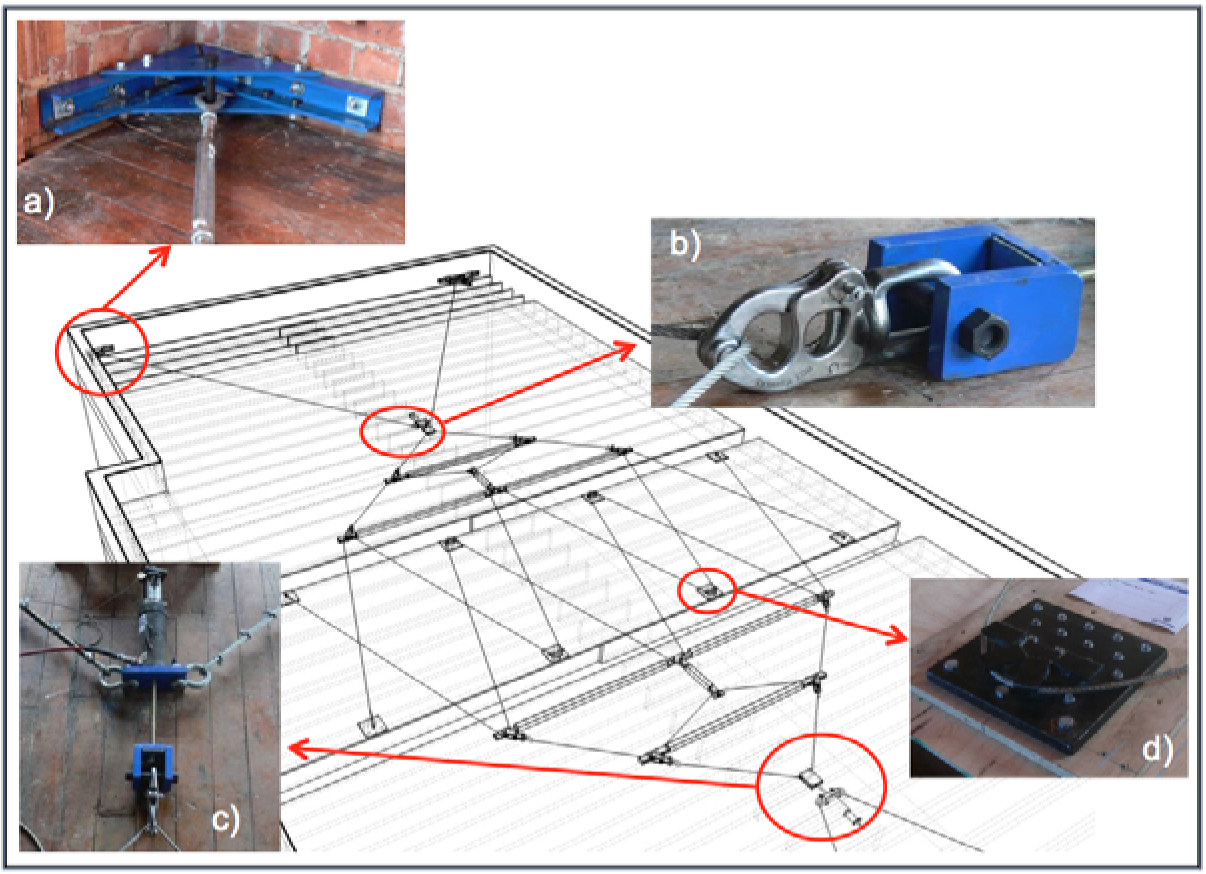

Fig. 3 Details: a) wall connection bracket; b) snap shackle for instantaneous load-release; c) hydraulic actuator; d) central loading plate

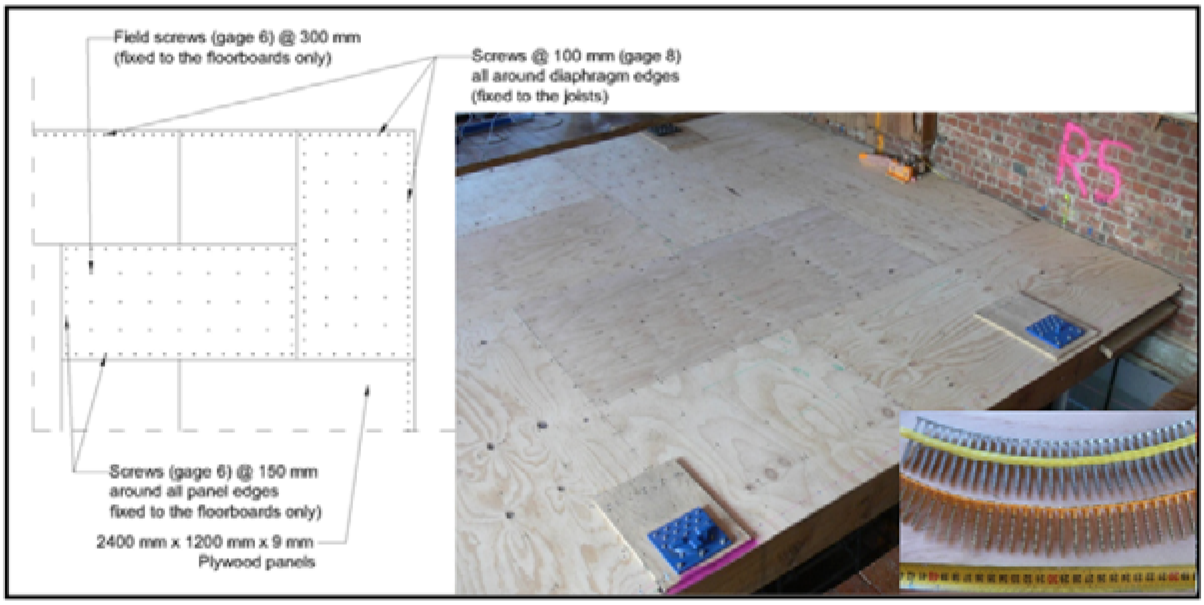

Fig. 4 Plywood overlay disposition

panels measured 9 mm x 1200 mm x 2400 mm [5] and were fixed to the flooring by means of gage 6 (30 mm long) screws inserted with a spacing of 150 mm around the edge of each panel and using a 300 mm by 300 mm grid in the "field region". On the perimeter of the specimen, gage 8 (60 mm long) screws were used at 100 mm centres in order to create a chord-like effect and to effectively transfer the shear forces to the lateral walls. The disposition of the joints in the plywood overlay (Fig. 4) was chosen to provide interlocking in both diaphragm directions and thus increase the diaphragm stiffness "homogeneously". In addition, recognising that gage 6 screws are not long enough to reach the joists, interlocking helps transfer the internal forces due to direct contact between panels and no real "solution of continuity". As a result, the on-site installation procedure was facilitated by the reduced need to cut the panels as it was unnecessary to match the screw lines and edges of the plywood panels with the centre of the joist, whose spacing was variable.

Snap back tests. Due to an expected nonlinearity of the floor response, the period of each diaphragm (as-built and retrofitted) was determined at different target displacements via a snap back test. An initial period was assessed through snap back tests carried out at a displacement approximating the nominal yield displacement, while an "ultimate" period was detected by imposing a displacement consistent with the critical displacement causing out-of-plane failure of the walls, which was defined to be equal to 70% of the wall thickness [6] (drift dr = 3.1%).

In particular, the initial period corresponded to a midspan displacement of approximately 2.5 mm for the specimen retrofitted using the plywood panels and of approximately 10 mm for all other tests. This type of snap back tests (hereafter referred to as "small") was also employed to check the decay of diaphragm properties induced by the repetition of different tests. Consequently, a small snap back test was performed before and after each cyclic test or "large" snap back test. It was decided not to rely on impact tests (with an instrumented hammer) or snap back tests at very small displacements, in order to minimize the influence of friction phenomena, which might vary during the testing phase.

TEST RESULT

Cyclic tests. The results of the cyclic tests in term of midspan displacement vs. applied load curves are reported in Fig. 5. From a first glimpse it is possible to notice a clearly nonlinear diaphragm behaviour. In order to compare the response of the two specimens in their different conditions, equivalent shear stiffness (Gd) values were determined at various displacement/drift levels (Table 1), assuming the ideal static scheme of a shear beam. The backbone curves were idealized through the second-order curve suggested by ABK [7].

The as-built floors, represented by tests 8_A and 26_B, showed in-plane shear stiffnesses that were slightly higher than the value (125 kN/m) suggested by NZSEE [8] for existing timber diaphragms loaded orthogonally to the joist direction. The value provided by FEMA and ASCE [9] (no distinction is made between diaphragms loaded in the joist direction and diaphragms loaded orthogonally to the joist direction) appears to overestimate the experimental stiffness.

For the retrofit solutions, the employment of the "re-nailing" technique resulted in a stiffness that was elevated by approximately 30% for both small and large displacements. A stiffness value 6 times the Gd values of the as-built condition was observed for the plywood panel overlay strengthening solution. Such a value was consistent with that given by FEMA and ASCE (1225 kN/m).

The contribution of the ceiling and metal sheathing to the diaphragm stiffness was observed to be undoubtedly significant. Test 5_A showed a shear stiffness approximately 3 times (for dr < 1%) that registered for the same specimen once the ceiling and the sheathing were removed. Therefore, neglecting to consider the ceiling and the sheathing (which has no structural purpose), when assessing old timber diaphragms, may lead to excessively conservative evaluations.

At critical drift values the as-built floors exhibited a unit shear resistance of 4.8 kN/m, which is lower than the design load assumed for the anchor system. The "re-nailing" strengthening technique proved to be a sufficiently valid intervention, as it permitted a shear capacity of 7 kN/m to be achieved, which is very close to the strength required in a severe seismic condition. If one considers the strength contribution of the ceiling and the sheathing, it is possible to satisfy the seismic demand within a drift of 1%.

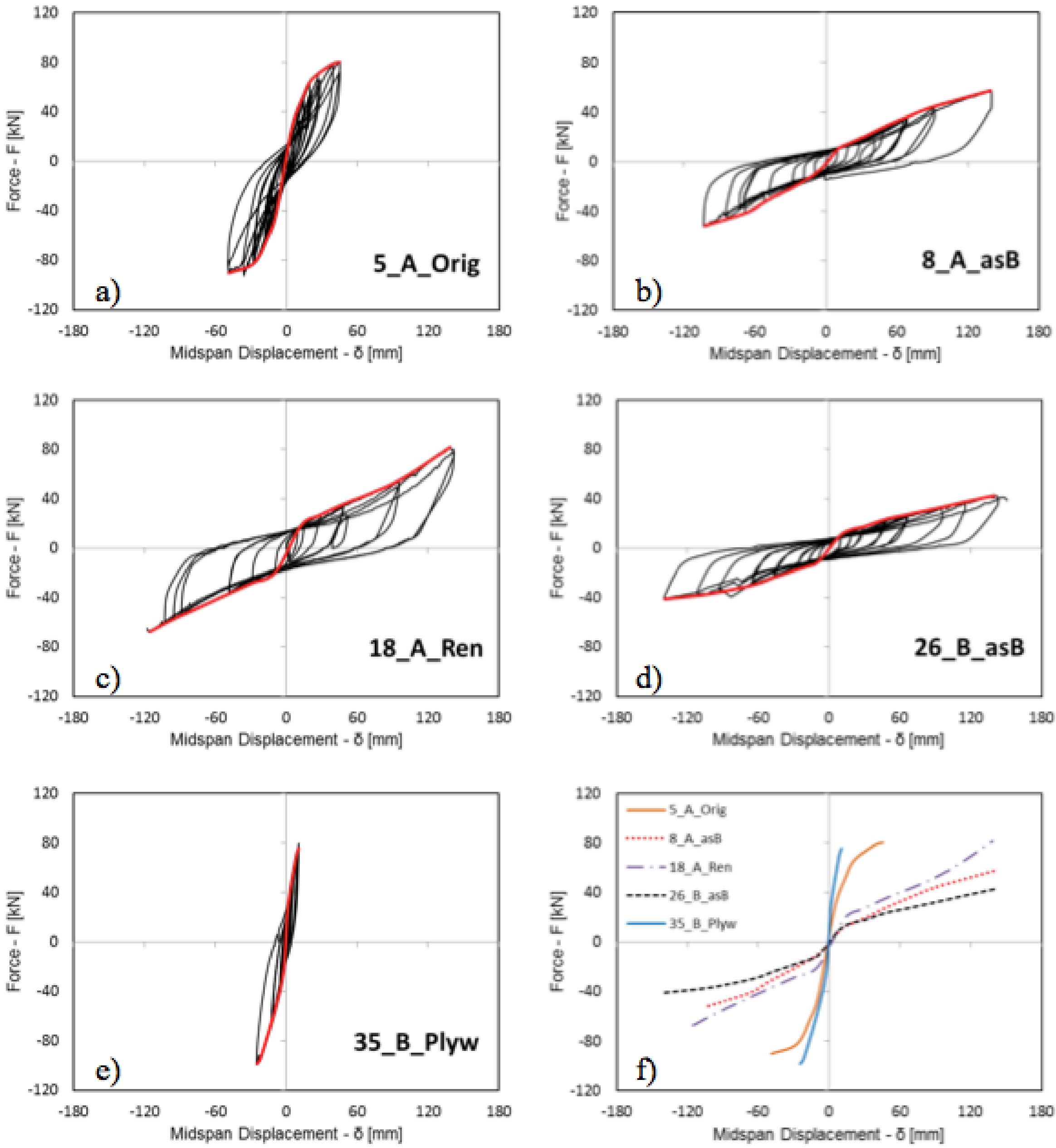

Fig. 5 Cyclic tests: a) specimen A - original condition (with ceiling and metal sheathing); b) specimen A - as-built; c) specimen A - re-nailed; d) specimen B - as-built; e) specimen B - retrofitted with a plywood panel overlay; f) backbone curves

Table 1. Equivalent shear stiffness [kN/m]

Mid. Displ. [mm]	Drift [%]	5_A	8_A	18_A	26_B	35_B	NZSEE (2011)	FEMA 356 ASCE/SEI 41-06
15	0.3	821	165	212	190	1343	125/95*	350
25	0.5	609	154	199	169	961		
50	1.0	371	133	172	126			
75	1.6		116	152	108			
100	2.1		104	136	91			
125	2.6		93	123	79			
150	3.1		85	112	70			

**Fair/Poor Conditions*

Dynamic tests. Table 2 gives the specimen fundamental periods determined from the snap back tests by means of a toolbox based on Matlab code and developed at the University of Auckland [10]. Various identification techniques (both frequency-domain based and time-domain based) were taken into consideration so as to obtain a more robust solution to the problem. Modal assurance criteria (MAC) values were also determined for each test. The minimum MAC value observed in the entire experimental campaign was 0.8, which is an excellent indicator of the good reliability of the results. In addition, a rough check of the diaphragm periods was conducted analysing the videos of the tests recorded using a high frame rate camera.

Table 2. Period values obtained from the snap back tests

Test nº	T [s]	Load [kN]	Displ. [mm]	Specimen Condition
2_A	0.09	21.00	2.40	Original (ceiling + sheathing)
3_A	0.07	14.50	1.90	“
4_A	0.12	40.50	10.00	“
6_A	0.25	77.03	61.82	“
7_A	0.25	76.21	60.68	“
10_A	0.48	11.00	10.87	As built (no ceiling and sheathing)
11_A	0.37	64.78	131.12	“
13_A	0.15	6.57	10.16	“
15_A	0.41	63.87	152.55	“
17_A	0.13	16.00	9.64	Retrofitted (new extra nails
19_A	0.34	65.22	120.97	“
21_A	0.14	10.21	9.78	“
23_A	0.34	54.38	101.57	“
25_B	0.16	11.73	10.27	As built (no ceiling and sheathing)
27_B	0.45	38.83	157.15	“
29_B	0.45	35.20	152.89	“
31_B	0.14	-	11.23	“
33_B	0.07	23.17	2.30	Retrofitted (plywood panels)
36_B	0.10	42.02	10.09	“
38_B	0.08	14.25	2.57	“
39_B	0.03	27.92	2.20	“

SUMMARY

From comparison between the experimental results and the relevant standards and guidelines on seismic assessment of existing vintage timber diaphragms, it appears that NZSEE suggests Gd values for single straight sheathed diaphragm that are very close to those registered experimentally, while FEMA and ASCE tend to overestimate the diaphragm stiffness. The reason might be related to the fact that all the tests were performed in the direction orthogonal to the joists. The orthotropic behaviour of single straight sheathed diaphragms, in fact, is an aspect contemplated only by NZSEE which also considers the flooring condition. Once the plywood layer is applied, the diaphragm response is governed by the plywood itself (significantly stiffer than the original flooring) whose behaviour is not affected by the loading direction, due to the particular panel disposition adopted. Consequently, the stiffness value provided in FEMA and ASCE is similar to that registered experimentally.

The "re-nailing" method proved to be a valid strengthening solution. In fact, with a very low cost-effectiveness ratio, it permitted an increase in stiffness of up to 30 %, which ensured that the tested floor section had the capacity to transfer shear loads corresponding to severe seismic events within acceptable drift levels. An extremely stiff response was achieved through the instalment of a plywood panel overlay directly onto the existing floorboards. Such behaviour was maximised by the peculiar panel disposition which also allowed a very fast installation procedure.

Considering the material property variability (e.g. conservation status, wood species, element dimensions), further testing need to be performed to make the outcomes of the campaign presented herein more representative. The test setup designed for this experimental campaign was shown to be non-invasive, easy to install and versatile (adaptable to different-sized specimens). Hence, additional testing will be performed if an opportunity presents itself.

A thorough processing of the snap back tests has been undertaken and the results will be published by the authors in the near future.

ACKNOWLEDGEMENTS

Funding for this project was provided by the New Zealand Natural Hazards Research Platform. Adolfo Preciado Quiroz and Kevin Walsh are thanked for their help with the test preparation. The authors thank Dave Corney from DML Builders (2003) Ltd for donating the building for the experimental campaign reported herein. The first author gratefully acknowledges the Italian RELUIS Consortium for partial financial support to this study, within the research program 2010-2012 carried out for the Italian Agency for Emergency Management.

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