Assessment of timber floor diaphragms in historic unreinforced masonry buildings

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Unreinforced masonry (URM) buildings outside of Europe were typically constructed with rigid clay brick perimeter walls, and comparatively flexible timber floor diaphragms. URM construction represents the predominant architectural heritage of many nations but the preservation of these buildings in seismically active regions is threatened due their well established inadequacy to withstand earthquakes. Timber floor diaphragms are widely recognized to have significant impact on the overall seismic response of URM structures, and the accurate assessment of diaphragms is therefore crucial during the seismic assessment and retrofit of URM buildings. *NZSEE (2006) - Assessment and improvement of the structural performance of buildings in earthquakes, and ASCE 41-06 (2007) – Seismic rehabilitation of existing buildings* represent the current state-of-the-art in seismic assessment but the validity of the procedures associated with timber diaphragm performance remains uncertain, and a review of their application and accuracy is required.

In order to generate much needed experimental data, a total of four diaphragm specimens labeled FS1a to FS4a were constructed with new pine timber and cyclically tested. Each specimen measured 10.4 x 5.535 m and was constructed with representative configuration. Diaphragms FS1a and FS2a were identical in configuration except for a 3.2 m x 1.08 m corner penetration in FS2a, and were both tested in the direction parallel to joists so that the diaphragm span to depth ratio was 1.88 to 1. Diaphragm FS3a comprised continuously spanning joists while diaphragm FS4a had discontinuous joists with a two-bolt lapped central connection. Both the FS3a and FS4a specimens were tested in the direction perpendicular to joists so that the diaphragm span to depth ratio was 1 to 1.88.

Overall the diaphragms displayed flexible and highly nonlinear characteristics with low levels of hysteretic pinching. No diaphragm failure was observed and all specimens appeared to remain completely serviceable at the conclusion of each test. Results indicated that the presence of the small corner opening in diaphragm FS2a, and the discontinuous joists with connections in diaphragm FS3a had little effect on diaphragm performance. Test results suggest that the hysteretic loops are larger in the direction parallel to joists, which is likely due to greater engagement of the yielding nail couples.

The conventional purpose of desktop assessment procedures in structural engineering are to transform complex loading and response mechanisms into quantifiable performance parameters that can be used in design. In the case of timber diaphragms, designers require strength, stiffness, shear stiffness and ductility values of each floor diaphragm to not only assess the capacity and deformation of the diaphragm, but to also determine in-plane and out-of-plane URM wall loads that rely on diaphragm

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period, which is a function of diaphragm stiffness. It is clear then that although these procedures should remain simple and transparent, they also need to be accurate. To verify the accuracy of the procedures published in NZSEE and ASCE 41-06 to assess timber diaphragm performance, the values predicted using these procedures were compared against experimentally determined parameters. Table 1 provides a summary of the performance parameters for comparison.

Table 1 – Diaphragm performance parameters

	Shear strength, R_n [kN/m]				***Stiffness K_d*** [kN/m]			***Shear stiffness, G_d*** [kN/m]			***Ductility, μ***		
	NZSEE (i)	NZSEE (ii)	ASCE	Exp	NZSEE	ASCE	Exp	NZSEE	ASCE	Exp	NZSEE	ASCE	Exp
FS1a	1.4	6.0	1.75	1.6	207	745	647	97	350	304	-	2.0	5.6
FS2a	1.4	6.0	1.75	1.6	207	745	606	97	350	284	-	2.0	5.2
FS3a	1.4	6.0	1.75	1.2	730	2630	1297	97	350	173	-	2.0	7.7
FS4a	1.4	6.0	1.75	1.2	730	2630	1842	97	350	245	-	2.0	10.8

Overall, the guidelines offered in both assessment documents poorly predict diaphragm performance. The values listed in Table 1 illustrate that diaphragm shear strength, stiffness, shear stiffness and ductility are either under predicted or over predicted using the NZSEE and ASCE 41-06 assessment procedures. Shear strength is the most accurately predicted parameter with approximately 10% discrepancy from experimentally determined values, with the exception of the alternative default value offered by NZSEE that grossly over estimates strength. The reason for this large discrepancy remains unknown. Diaphragm stiffness and shear stiffness is considerably under predicted using the methodology in NZSEE, while is over predicted using ASCE 41-06 guidelines. NZSEE offers no explicit guidance for diaphragm ductility while ASCE 41-06 provisions where shown to under estimate diaphragm ductility by up to five times.

An important observation from the experimental performance parameters listed in Table 1 is the highly orthotropic behavior demonstrated by the timber diaphragms. The shear strength and shear stiffness values, which are independent of diaphragm geometry, are significantly different in each principal direction of the diaphragm, yet the current assessment documents offer no provisions to address this behavior. In order to improve the transparency and accuracy of the assessment procedures, diaphragm performance parameters should be explicitly provided for in each principal direction.

It is recognized that heritage diaphragm performance may differ from the experimental performance values presented in Table 1 due to out-dated construction materials and the effects of age and decay. Test data from extracted floor sections and nail connections from ~ 100 year old timber floor diaphragms is anticipated to provide the necessary information to appropriately modify the performance parameters to ensure that they are representative for heritage construction. For the interim, the considerable difference observed between predicted and measured diaphragm performance suggests that the current assessment procedures published in NZSEE and ASCE 41-06 require updating with representative values, and in addition require provisions to address the highly orthotropic nature of timber diaphragms in each principal direction. As a final note, it is believed that the assessment documents should be harmonized to ensure that transparency and consistency exists between international assessment procedures.