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Seismic performance of flexible timber diaphragms: Damping, force–displacement and natural period

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ABSTRACT

Seismic performance of flexible timber diaphragms is examined using available test data. Damping–ductility and force–displacement relationships are quantified for numerous different types of diaphragm constructions. It has been observed that the damping–ductility relationship is significantly different than that for other types of structures, often exhibiting a decrease or relatively constant damping as ductility increases. Additionally, due to their highly inelastic behavior, even at low displacement amplitudes, the equivalent damping ratio of the diaphragm can be predicted from the hysteresis damping component only. This paper also tabulates force–displacement backbone curve parameters for both second-order curves and bi-linear models. Scaling of the elastic diaphragm stiffness based on theory is considered and determined to be reasonably accurate for plywood diaphragms. Natural periods calculated using several models, including those utilizing Timoshenko (shear) beam theory and ASCE7-10, have been compared to natural periods from recorded seismic motions of four prototype buildings with masonry shear walls and timber diaphragms. The model which achieved the lowest average error corresponds to a shear beam with lumped mass at the mid-span equal to half the total mass on the diaphragm.

1. Introduction

Timber diaphragm systems are classified as flexible according to the provisions of ASCE 7-10 [1] when used in conjunction with masonry shear walls. However, requirements on the analysis methods are not included in ASCE 7 for flexible diaphragms. In practice, this means that the seismic analysis is generally performed using simple beam approximations and a force-based approach from the Building Code. State-of-the-art approaches include various FEM non-linear methods with 2-D beam-spring models [2], considering the behavior of each nailed connection [3], linear and non-linear 3-D analysis using traditional shell elements [4,5], a specialized 2-D diaphragm finite element [6], and models considering the influence of beam pocket behavior [7,8].

Direct Displacement Based Seismic Design (DDBD) procedures are a less computationally intensive alternative to FEM non-linear analyses. Due to the smaller scale of these types of structures, in general, a non-linear time history analysis would not be performed in routine design practice. However, quantifying the seismic performance should still be a main concern of the designer and can be achieved through alternative means, such as a DDBD approach. This approach does not require 3-D finite element building models, and can performed using basic calculation tools. This has been recognized by previous researchers on performance based design for wood framed buildings [9,10]. However, their work focuses primarily on the behavior of the wood shear walls. Existing DDBD procedures focus on larger scale, rigid diaphragm structures and are not specifically applicable to flexible diaphragm buildings due to the dominance of the diaphragm in the dynamic behavior.

While flexible timber diaphragms are a common type of construction, and are particularly prevalent in existing and historic unreinforced masonry (URM) buildings, there are relatively few full-scale diaphragm component tests reported in the literature. Testing performed by Peralta [11], Wilson [12], and Agbabian, Barnes & Kariotis [13] are the notable exceptions, whose work applies to diaphragm construction typically found within the United States. The ABK testing is perhaps the most complete compendium as it features quasi-static and dynamic testing on nine different timber diaphragm types. The ABK 1981 test report does not include any interpretation of the test results; however, there was a draft document subsequently issued in 1982 which included this information. This document was never officially released and, as such, appears to have been lost to antiquity. The authors have contacted original authors of ABK 1981 and other researchers in the field, who have cited the ABK 1982 Draft paper, but were

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Table 1
ABK diaphragm types.

Type	Description
B	½″ Plywood unblocked chorded
C	½″ Plywood unblocked unchorded
D	½″ Plywood unblocked, unchorded built up roofing
E	1 × 6 Straight sheathing (planks) unchorded built up roofing
H	1 × 6 Straight with 5/16″ plywood overlay, chorded, unblocked
I	1 × 6 Diagonal sheathing (planks) unchorded built up roofing
K	1 × 6 Diagonal sheathing (planks), 1 × 6 diagonal overlay, chorded
N	½″ Plywood blocked chorded
P	¾″ Plywood with ¾″ plywood overlay blocked chorded

unsuccessful in obtaining a copy. Wilson [12] tested two different types of homogeneous construction and also investigated their orthotropic behavior due to a change in the load direction. Peralta [11] tested three distinct diaphragm constructions and investigated the effects of various retrofit attempts.

In addition to the diaphragm component tests, full-scale building testing with timber diaphragms is also available in the literature. This includes pseudo-dynamic testing on a single story URM building constructed by Paquette et al. [14,15] and the two story URM building constructed by Yi et al. [16]. Both of these works provide invaluable data on the response of the URM shear walls in addition to the diaphragms. They also compare the test results to numerical models and analytical methods of ASCE-41.

The objective of this paper is to quantify necessary parameters for direct displacement-based design and analysis of flexible timber diaphragms in URM buildings, however they may be useful for other performance based approaches. In particular, DDBD requires substantial knowledge of force–displacement and damping–ductility relationships along with accurate period calculation in order to be applied to these types of buildings. These three parameters are required to expand the method to flexible timber diaphragm structures and have not been fully addressed in the literature. While force–displacement relationships currently exist in ASCE-41 [17], they have been shown to exhibit significant error [11]. In this paper, we propose an approach to determine ductility–damping behavior and force–displacement relationships for flexible diaphragms from test results reported in the literature. Estimation of natural periods of buildings is generally done based on guidelines in ASCE-7 [1]. We have investigated six different models for the estimation of natural periods of buildings with timber flexible diaphragms and have determined their accuracy with respect to results based on recorded ground motions.

2. Interpretation of test results

Although there is limited test data on timber diaphragms, the testing presented in ABK [13] is the most comprehensive. Details of the ABK testing is fully detailed elsewhere [13], however a brief discussion is warranted here to understand the data and its interpretation and implementation. A series of nine 6.1 m × 18.3 m (20′ × 60′) diaphragms (Table 1) were constructed and tested under both quasi-static and dynamic loading. The displacements were recorded using string potentiometers at eleven locations, seven along the side with the actuators and four on the opposite side. For the quasi-static loading, four different maximum displacement amplitudes were tested, in general, for each diaphragm. During each test, the diaphragm underwent a number of hysteretic cycles before reaching the maximum displacement. Loading for ABK [13] was applied at each end of the diaphragm, see Fig. 1. Two reaction pillars were placed along the third-points of the span, emulating typical four-point beam loading. Reported results include hysteresis plot for each displacement amplitude, and a tabular report of the maximum and minimum forces and displacements recorded at each location during the test.

The hysteresis damping for each diaphragm type is calculated using Eq. (1) [18] for each of the displacement amplitudes, using the results from the quasi-static (QS) tests. Due to the lack of available digital data, the hysteresis area was determined graphically by manually digitizing the hysteresis plots using CAD software. Fig. 2 illustrates a sample of the hysteresis plots provided in [13] for each diaphragm type and displacement amplitude tested. The lowest displacement amplitude from ABK [13] is somewhat arbitrarily considered the “yield displacement” since the diaphragm behavior does not exhibit a well-defined yield point. For this reason, the term “pseudo-ductility” is used instead of ductility. When interpreting the data from Wilson [3], the “yield displacement” was assumed to be at the 25 mm displacement amplitude cycle.

$$\xi_h = \frac{A_h}{2\pi V\Delta_h} \tag{1}$$

In Eq. (1) above, the hysteresis damping ratio (ξ_h) depends on the area of the hysteresis loop (A_h), the peak shear force (V) and peak displacement (Δ_h). For each diaphragm, the hysteresis damping ratio is plotted against the pseudo-ductility in Fig. 3.

Typical damping–ductility curves for other structural systems are shown in Fig. 4. It is observed that the equivalent damping increases significantly with increase in ductility [18]. Comparing plots in Fig. 4 with those in Fig. 3, it is evident that timber diaphragms exhibit more erratic behavior. Some diaphragms exhibit a subtle increase in damping with ductility (K), while other remains nearly constant (P) or decrease (1A-PARA). Nevertheless, the change from the initial damping ratio is relatively small, for most diaphragm types, especially compared with the three or four-fold increase shown in Fig. 4 for some structure types. This behavior is primarily due to the fact that the diaphragm behavior is inelastic even at very low displacement amplitudes. The equivalent

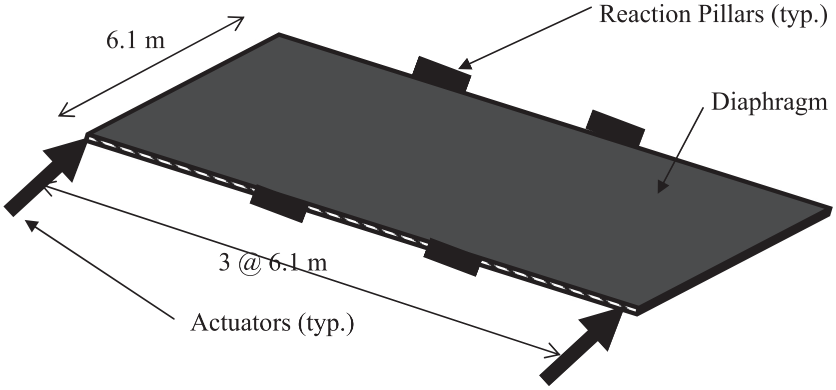

Fig. 1. Test schematic (adapted from [13]).