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Direct displacement based seismic design for timber flexible diaphragms in masonry shear wall buildings

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ABSTRACT

A method for analyzing the seismic performance of timber flexible diaphragms based on the direct displacement based seismic design (DDBD) principles has been developed. The method utilizes knowledge of timber diaphragm seismic behavior, such as natural period calculation, force–displacement and ductility–damping relationships, developed previously by the authors. Accuracy of the method is illustrated through analysis of four prototype buildings and comparison to recorded data and numerical results. All four prototype buildings have timber diaphragms in conjunction with either reinforced or unreinforced masonry shear walls. Excellent agreement is found between the results from the proposed DDBD approach, and those from both the recorded data and finite element analysis. The proposed method provides a rational and consistent design methodology for flexible diaphragm buildings, which is lacking in ASCE-7.

1. Introduction

While flexible timber diaphragms are a common type of construction, and are particularly prevalent in historic unreinforced masonry (URM) and reinforced masonry (RM) buildings, they lack a formalized method for analysis under Direct Displacement Based Seismic Design (DDBD) procedures. The DDBD method has been shown to be an accurate, less computationally intensive alternative to Non-Linear Time History (NLTH) analysis method, while maintaining the critical dynamic and non-linear behavior components [1]. It captures the non-linear behavior of an equivalent SDOF system through its force–displacement relationship, and relies on the secant stiffness to predict the effective period. Current research has shown the method to be accurate for a variety of building structures, with a focus on large scale rigid-diaphragm structures. Although Priestley et al. [1] covers myriad structural applications, additional research on the method has included studying P–Δ effects [2], buildings with torsion [3], asymmetric plan buildings [4], full-scale test verification [5], and wood shear wall buildings [6]. URM/RM buildings with timber flexible diaphragm structures are generally small scale and have not been included in the research on DDBD to date. In addition, their seismic design is commonly performed in practice by using the Equivalent Lateral Force (ELF) method in ASCE-7, owing to their smaller scale.

The objectives this paper are threefold: (i) illustrate the accuracy and applicability of the proposed Flexible Diaphragm DDBD methodology in analyzing buildings with the combination of timber diaphragms with URM/RM shear walls, (ii) discuss how the method is more accurate and rational than the existing ELF provisions in ASCE-7, which neglects the effects of diaphragm flexibility, and (iii) present a simplified approach which aligns within the parameters of the existing Code. To the authors' knowledge, this is the first paper in the literature to provide a displacement based approach to the seismic analysis of flexible diaphragms.

The proposed DDBD approach provides a logical procedure for determining the base shear and diaphragm displacement as compared to existing methodologies in ASCE-7 [7]. The ELF procedure in ASCE-7 for determining the base shear in a flexible diaphragm building is shown to be inconsistent with the results obtained through a FEM analysis. Further, the assignment of arbitrary response modification coefficients (R) in the ELF method does not reflect the diaphragm behavior at all, since it relies solely on the construction of the vertical lateral force resisting system. Timber diaphragms are generally non-linear, with no well-defined yield point [8–10], and therefore the use of R values is not representative of the expected performance. Estimation of the building's natural period is also calculated solely from the properties of the vertical lateral force resisting system [7]. Due to their significantly lower stiffness than the RM and URM shear walls, the horizontal dia-

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Nomenclature

Abbreviations

ABK	Agbabian, Barnes and Kariotis
CSMIP	California strong motion instrumentation program
DDBD	Direct Displacement Based Seismic Design
ELF	equivalent lateral force
FEM	finite element method
NLTH	non-linear time history
PGA	peak ground acceleration
RM	reinforced masonry
SA	spectral acceleration
SDOF	single degree of freedom
URM	unreinforced masonry

Symbols and variables

Δ_1	initial displacement
Δ_2	final displacement
Δ_y	yield displacement
μ	ductility
ξ_e	effective damping
B	building width or length, in direction of the shear wall length (L_w)
B_1	width of tested diaphragm
B_2	width of diaphragm to be analyzed
Fmax	maximum force recorded during diaphragm testing
Fu	ultimate force
Fy	yield force
$K1$	initial slope of force–displacement
$K2$	secondary slope of force–displacement
k_1	initial slope from testing [8]
k_e	effective (secant) stiffness
L_1	length of tested diaphragm
L_2	length of diaphragm to be analyzed
L_w	total length of shear wall along a support line
m_d	total diaphragm mass
m_e	effective mass
$m_{w,i}$	total mass of shear wall i
t_1	effective shear thickness of tested diaphragm
t_2	effective shear thickness of diaphragm to be analyzed
T_e	effective period

phragm systems dominate the lower modes and excite their mass at higher accelerations. Assigning the horizontal mass to the vertical elements with a lower acceleration provides a source of error and an inconsistency in the existing ELF procedure.

In this research, a proposed DDBD approach has been investigated through applications to four prototype building models available in the literature. These four structures are known as Paquette, Gilroy Firehouse, Palo Alto and Lancaster buildings. All four structures have either reinforced or unreinforced masonry shear walls with flexible timber diaphragms. The proposed analysis methods will be compared to both FEM analysis of these structures and available recorded structural responses for these buildings. Section 4 of this paper provides more detail on these buildings.

2. General DDBD methodology

The DDBD analysis procedure employs an iterative method [1] which can be summarized in the flowchart in Fig. 1.

The procedure, as described, assumes that the structural configurations are all known, as is the case in this work. This is detailed in Section 13.2 of [1], as the “displacement based assessment” procedure. A similar procedure can be employed for design, with an additional step at each iteration, where the diaphragm is designed for the forces and displacements from the first iteration and then simply analyzed and redesigned as necessary.

The equivalent damping ratio (ductility–damping behavior, Step 7), the force–displacement (Step 5) relationship, and period calculation (Step 4) are necessary in order to perform the analysis and are discussed in Whitney and Agrawal [8] among other sources. These steps become the main area of modification, in order to fit the method to this particular type of structure.

3. Analysis methods

3.1. Flexible diaphragm DDBD methodology

Whitney and Agrawal [8] have investigated the calculation of periods for diaphragms that is needed in Step 4 of the DDBD in the flowchart in Fig. 1. Based on the results presented in [8], the SDOF mid-span lumped mass model predicted the diaphragm period most accurately on average for the buildings studied under this work. Therefore, this SDOF model is used to characterize the diaphragm’s dynamic response. Accordingly, a force–displacement relationship is used which relates the mid-span displacement to total force on the diaphragm. It was also shown in [8] that the damping does not vary significantly with ductility for timber diaphragms, and therefore the damping has been held constant in this method. Modifications to the General DDBD Methodology are presented in the following step-by-step iterative method, performed for each diaphragm span:

Step 1: Determine the effective mass, m_e, one half the total diaphragm mass. Consider out-of-plane walls as lumped masses acting along the diaphragm length, in addition to the uniform diaphragm dead load mass. In a design scenario, include any code mandated minimum live loads in the effective mass, such as those in Section 12.7.2 of ASCE-7.
Step 2: Estimate an initial displacement, Δ_1.
Step 3: Calculate the effective stiffness, k_e based on the displacement Δ_1 and the force–displacement relationship for the diaphragm. The ABK [9] bi-linear mid-span displacement, total force relationships from [8] are used throughout this paper, and scaled according to shear beam deformation theory [8].
Step 4: Calculate the effective period.
Step 5: Determine the effective damping, ξ_e based on the diaphragm construction. The displacement ductility is not calculated, as discussed in [8], since the effective damping does not vary significantly with the ductility. Alternatively, a damping value could be selected based on the displacement magnitude for the diaphragm type, which is the approach taken for wood shear walls as discussed in [6]. However a limited database exists for timber diaphragms, as shown in [8], and therefore this is not recommended until a more substantial compendium of values are available.
Step 6: Develop the displacement response spectrum for ξ_e. The spectral reduction factor (R_ξ) is not used, and the displacement response spectrum does not need to be revised for successive iterations to account for change in effective damping.