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Evaluation of an alternative seismic design approach for rigid wall flexible wood roof diaphragm buildings through probabilistic loss estimation and disaggregation

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ABSTRACT

Rigid Wall Flexible roof Diaphragm (RWFD) buildings, commonly referred to as "big-box" buildings are the most prevalent type of construction for low-rise industrial and warehouse facilities in the United States (US). These buildings usually incorporate rigid-in plane concrete tilt-up walls and flexible wood roof diaphragms, which is a commonly seen construction technique in the Western United States. Due to their vulnerability in high seismic areas (e.g. California) observed in past earthquakes, an alternative design methodology was introduced in the FEMA P1026 document to account for the response of the flexible roof diaphragm. The FEMA P1026 design approach has been validated through numerical collapse assessment studies. In this study, the Performance-Based Earthquake Engineering framework, introduced by the Pacific Earthquake Engineering Research (PEER) center, is combined with Monte Carlo Simulation to evaluate, in a probabilistic sense, the earthquake-induced economic losses for these structures. The results are presented in terms of expected losses for two hazard intensities: Maximum Considered Earthquake (MCE) and Design Earthquake (DE), while loss disaggregation plots for collapse and no-collapse losses are also presented. The results demonstrate the ability of the FEMA P1026 design approach to reduce earthquake losses compared to current code-conforming RWFD buildings. Additionally, the results can provide damage and loss information for modeling of these types of buildings within a resilient community and other spatially focused analyses.

1. Introduction

Life safety associated with building failures has been extensively accounted for in structural design provisions and standards against extreme ground shaking. However, economic losses from earthquake-induced damage to structural and nonstructural components have not been incorporated into the evaluation of design methodologies and mitigation strategies. Next generation Performance-Based Earthquake Engineering (PBEE) framework introduced in the Unites States (US) by the Pacific Earthquake Engineering Research center (PEER) considers certain metrics to assess the seismic performance of buildings, which integrate economic losses into the design process [1–3]. The PBEE framework accounts for evaluation, design and construction of structures to satisfy seismic performance criteria expressed in terms of dollars, death, and downtime; metrics that are meaningful to stakeholders and building owners [4–6]. Site-specific hazard analysis (e.g. [7–11]), nonlinear structural modeling, damage assessment through fragility analysis (e.g. [12–16]), and economic loss assessment (e.g. [17–20]) are the main steps of such frameworks. A number of studies has been reported in the literature over the last decade focusing on economic loss assessment of building structures within the context of PBEE including, for example, studies on reinforced concrete [18,19,21–24], wood [25,26] and steel frame [20,27] buildings. Additional studies have focused on earthquake loss estimation methodologies, parameter sensitivity studies, or both for risk management and mitigation practices (e.g. [28–33]).

Rigid Wall Flexible wood roof Diaphragm (RWFD) buildings (commonly referred to as "big-box" structures) are one of the most prevalent construction types for warehouse, retail, and industrial facilities, in regions of high seismicity in the United States. Photos of typical RWFD building construction in the United States are shown in Fig. 1. These types of buildings have exhibited poor

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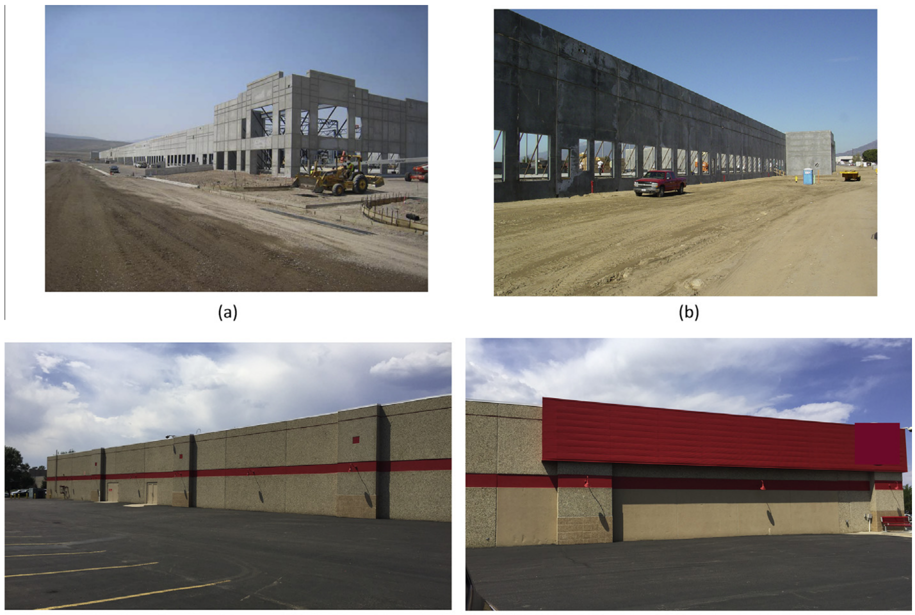

Fig. 1. (a) and (b) Photographs of typical RWFD building construction process in the US (photo credit: J. Lawson), (c) and (d) photographs of typical RWFD commercial buildings (photo credit: J.W. van de Lindt).

seismic performance during past earthquakes, including the 1964 Alaska, 1971 San Fernando, 1987 Whittier Narrows, 1989 Loma Prieta, and 1994 Northridge earthquakes [34–36], resulting in significant economic losses and operation disruptions. These types of buildings are characterized by rigid in-plane walls and flexible in-plane roof diaphragms. Studies by Koliou et al. [37] showed that current US code provisions do not satisfy collapse prevention objectives for RWFD structures under maximum considered earthquake ground motions. This is mainly because design provisions are based on assumed yielding of the walls rather than yielding of the flexible roof diaphragm. To address this issue, an alternative seismic design approach was introduced and evaluated under extreme ground shaking by Koliou et al. [38] and adopted as a FEMA design guideline [39] for RWFD buildings with wood roof diaphragms, which are typically encountered on the west coast of the US.

The scope of this study is to quantify the expected earthquake-induced economic losses in RWFD buildings through probabilistic loss estimation and disaggregation. The expected losses due to collapse and repair of the buildings were considered along with inventory losses accounting for the response of nonstructural components (i.e. steel storage racks), given their economic significance for the functionality of RWFD structures. Furthermore, the estimated economic impact of the proposed seismic design [38,39] was evaluated and compared with conventional US design provisions to demonstrate the efficiency of the proposed design approach. RWFD buildings that host steel storage racks are commonly used for commercial and retail products (e.g. Home Depot, Costco, and Walmart) are the primary focus of this study.

2. Overview of alternative seismic design approach

An alternative seismic design approach for RWFD buildings that incorporate rigid in-plane tilt-up walls and flexible wood roof diaphragms was adopted in the FEMA P1026 document [38,39] as an alternative design methodology to explicitly account for the roof diaphragm flexibility in the design procedure. The proposed approach introduces a specific response modification coefficient (R-factor) in the roof diaphragm design (R_{dia}) along with a separate R factor that is currently used in U.S. seismic provisions for the design of the vertical elements of the seismic force-resisting system (SFRS). Based on analytical studies by Koliou et al. [40] and previous post-earthquake observations, typical failure modes denote concentrated damage at the roof diaphragm edge, therefore the alternative seismic design approach facilitates the distribution of the roof diaphragm yielding towards the roof center/mid-span. In a force base design sense, this concept was introduced with a response modification factor R_{dia} of 4.5 for the design of the flexible roof diaphragm along with an amplification factor of 1.5 for the roof shear forces on a distance of 10% of the diaphragm span from both side edges (see Fig. 2). Furthermore, a semi-empirical fundamental period (T_1) that takes into account diaphragm response was introduced in this approach for RWFD buildings incorporating wood roof diaphragms and perimeter concrete shear walls as follows [38]:

$$T_1 = \frac{0.0019}{\sqrt{C_w}} h + 0.0020L \tag{1}$$

where L is the roof diaphragm span in ft. (1 m = 3.28 ft.), h is the height of the in-plane shear walls in ft. (1 m = 3.28 ft.), and C_w is calculated according to Eq. (2) [41].

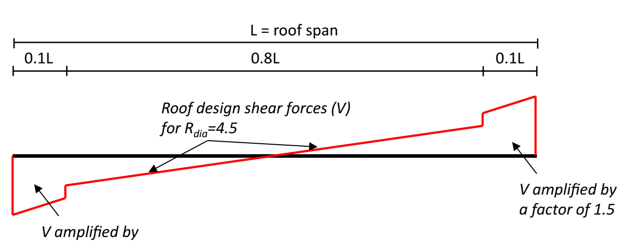

Fig. 2. Roof diaphragm design shear forces for alternative seismic design approach – FEMA P1026.