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Parameterized fragility functions for controlled rocking steel braced frames

Saber Moradi[a], Henry V. Burton[b,*], Ishaan Kumar[c]

[a] Department of Civil Engineering, Ryerson University, Ontario M5B 2K3, Canada
[b] Department of Civil and Environmental Engineering, University of California, Los Angeles, 5732 Boelter Hall, Los Angeles, CA 90095-1593, United States
[c] Department of Civil and Environmental Engineering, University of California, Los Angeles, CA 90095-1593, United States

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ABSTRACT

Parameterized fragility functions are developed for a controlled rocking steel braced frame (CRSBF) system, which link the probability of exceeding system-level limit states to ground motion intensity and design parameters such as frame aspect ratio, the initial post-tensioning force, the yield force in the fuse element and the dead load on the frame. The considered building performance levels include immediate occupancy (IO), repairability (RP), and collapse prevention (CP), which are achieved through non-exceedance of predefined response demand thresholds. Surrogate models are developed to predict the statistical distribution of global (peak transient and residual story drift) and local (posttensioned element strain and fuse deformation) response demand parameters using the ground motion intensity and CRSBF design variables as input parameters. The surrogate models are coupled with Monte Carlo simulations to develop the parameterized fragility functions, while incorporating model parameter uncertainty. The procedure is demonstrated using a 6-story CRSBF building. The results show that the IO and CP performance levels are controlled by the demand thresholds for peak transient story drifts. Among the four design parameters considered in this study, the aspect ratio had the greatest influence on the CRSBF performance. However, when measured in terms of the conditional probability of not meeting or exceeding the performance level at the maximum considered earthquake hazard level, the effect is significantly reduced for higher (better) performance levels.

1. Introduction

Steel buildings with conventional lateral force resisting systems (e.g. moment-resisting and concentrically braced frames) are typically designed to provide an adequate margin of safety against collapse by ensuring the ductile inelastic response in key structural elements. These systems are susceptible to excessive structural damage during moderate-to-severe earthquakes, which can lead to significant financial losses due to repair/replacement costs and downtime.

Controlled rocking steel braced frames (CRSBFs) have been developed to minimize the potential for structural damage in steel buildings. The key elements of the CRSBF system include the post-tensioned (PT) strands, replaceable fuse and the braced frame (Fig. 1). The PT strands contribute to the overturning resistance and provide self-centering capability. The fuse is the primary source of hysteretic energy dissipation and also provides overturning resistance. Note that it is possible to use other types of fuses besides the butterfly shaped elements [1] shown in Fig. 1. For example, buckling restrained braced frame fuses are sometimes used, which are subjected to axial deformations when the frame uplifts. The braced frame is designed to uplift under earthquake loading and its components (beams, columns and braces) are sized using capacity-design principles and are intended to undergo minimal damage under earthquake loading. The gravity loads acting directly on the rocking frame also contribute to the overturning resistance. Fig. 1 shows the PT and fuse at the center of the frame with the latter located at the ground level. Alternative configurations include having the same elements placed at the ends of the frame and multiple fuses placed along the height of the building (e.g. [2]).

Fragility functions describe the probability of exceeding a pre-defined component or system-level limit state conditioned on a loading control variable such as an intensity measure or engineering demand parameter. Useful for probabilistic vulnerability assessment, loss estimation, and performance-based design of structures, fragility functions can be categorized based on the source of data used for their development. For example, empirical fragility functions are developed from actual post-earthquake damage data (e.g. [3,4]) while heuristic curves rely on expert opinion (e.g. [5]). Analytical fragility functions couple the results from probabilistic seismic demand analysis with pre-determined demand-damage thresholds (e.g. [6,7]).

The goal of this study is to develop parameterized fragility functions

* Corresponding author.
E-mail addresses: s.moradi@ryerson.ca (S. Moradi), hvburton@seas.ucla.edu (H.V. Burton).

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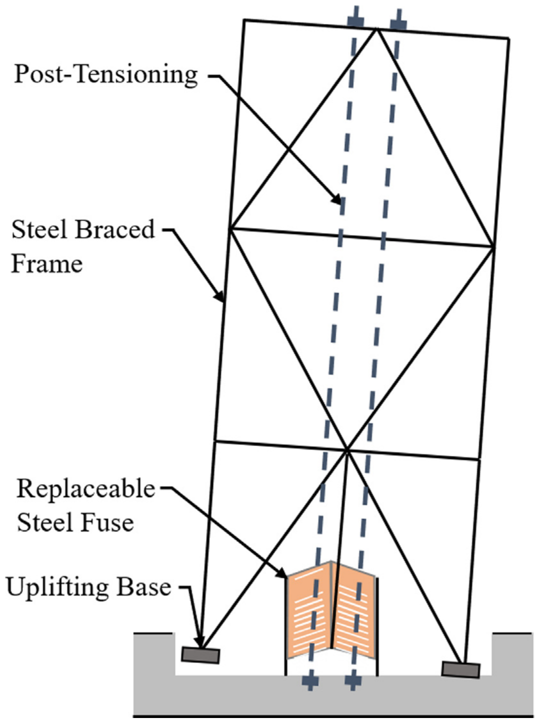

Fig. 1. Schematic of a CRSBF system.
(Adapted from [1,2]).

for CRSBFs, which link ground shaking intensity and multiple structural parameters (e.g. dead load on rocking frame, initial posttension force) to the probability of exceeding building-level damage states (e.g. immediate occupancy). Conventional analytical fragility curves relate the probability of limit-state-exceedance to a single demand variable (e.g. ground shaking intensity or engineering demand parameter). However, these univariate fragilities are unable to isolate the effect of multiple interactive factors on earthquake-induced damage. This feature can be incorporated in parameterized or multivariate fragility functions (e.g. [8,9,10,11]). Surrogate models utilizing the response surface methodology to approximate seismic response demands, are used to develop the fragility functions in this study. Structural parameters known to influence the CRSBF seismic response demands (e.g., the initial PT force), are used as predictors together with ground shaking intensity. The developed parameterized fragility functions can reduce the computational expense associated with performance-based assessment and design optimization of CRSBFs.

2. CRSBF system and component response

Fig. 2 shows the idealized cyclic and monotonic load-deflection relationship for the PT, fuse and the CRSBF system. The responses are described in terms of local forces in the PT and fuse as well as the base shear for the CRSBF system. The deflection is shown in terms of the roof drift in all three cases. The system behavior can be obtained from the superposition of the strength and restoring action of the fuse, PT and dead load on the frame. In Fig. 2, the points c_1 through c_4 correspond to the cyclic response. Prior to c_1, elastic straining of the frame and a reduction in the contact pressure of the tension column occurs. The point c_1 corresponds to frame uplift, elongation of PT and shear deformation of the fuse. Fuse yielding in the positive direction occurs at c_2, which represents the onset of inelastic response and permanent shear deformations. The load is reversed at c_3 and fuse yielding in the negative direction occurs at c_4. Prior to yielding of the PT (the limit state that follows fuse yielding) at m_3 in Fig. 2a, the CRSBF system provides immediate occupancy (IO) structural performance [1,2] if the frame self-centers and the ductility demand in the fuse is not high. Note that building-level performance can be compromised by damage to elements outside of the CRSBF (e.g. gravity system and non-structural damage). As described later in the paper, while the effect of damage to these other components are implicitly considered in the development of the fragility functions, the primary focus of the current study is on the performance of the CRSBF. The onset of strength loss leading to fracture of the fuse (m_4) and/or PT (m_5) will result in significant degradation in the lateral strength and stiffness of the CRSBF system and is considered a life safety threat. The developed parameterized fragility functions are described in terms of the aforementioned CRSBF limit states as well as damage to other parts of the building (e.g. damage to non-structural components and gravity framing).

3. Methodology

Fig. 3 summarizes the methodology used to develop the parameterized fragility functions for CRSBFs. Local and global seismic demand parameters including peak story drift ratio (*PSDR*) and peak residual story drift ratio (*PRDR*), PT strain (ε_{PT}) and fuse shear deformation (δ_f), are selected as the response variables. These demand parameters are selected based on their relationship to CRSBF damage and the system-level limit states. The immediate occupancy (*IO*), repairability (*RP*), and collapse prevention (*CP*) performance levels are defined by placing limits on response demands related to the CRSBF components (e.g. ε_{PT} and δ_f) as well as other parts of the building. Damage thresholds for the frame elements (beams, columns and braces) and drift sensitive non-structural components are defined using *PSDR* limits and the *RP* performance level is defined in terms of *PRDR*. Details of the limit states and associated fragility functions are described later in the paper.

Five structural design parameters (or factors) previously shown to have a significant influence on the seismic demand of rocking frames (e.g. [12,13,14]) are considered as the input parameters. They include the dead load on the rocking frame (P_D), initial PT force (F_{pt}), fuse yield strength (F_{yf}), the frame aspect ratio (i.e., the bay width-to-height ratio)

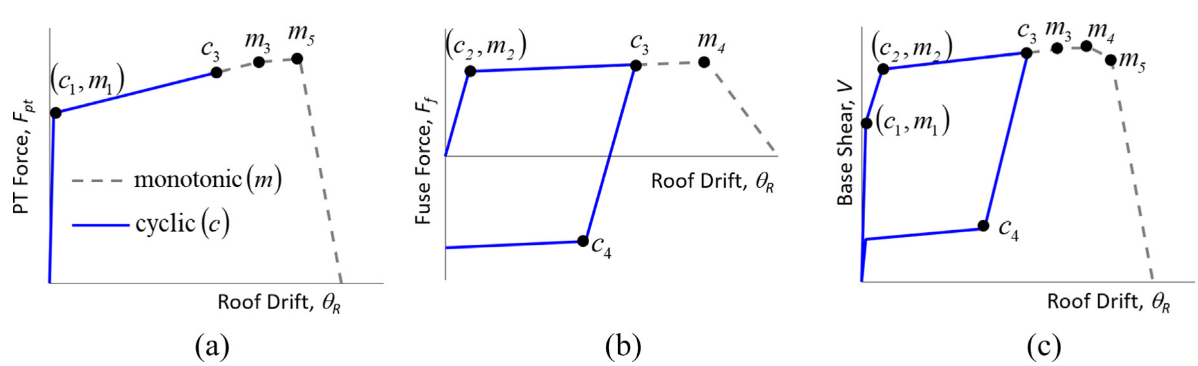

Fig. 2. Idealized cyclic and monotonic response of (a) posttensioning, (b) fuse and (c) combined CRSBF system.