Collapse-Consistent Protocols for Experimental Testing of Steel Columns under Multi-axial Cyclic Loading

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Extended Abstract

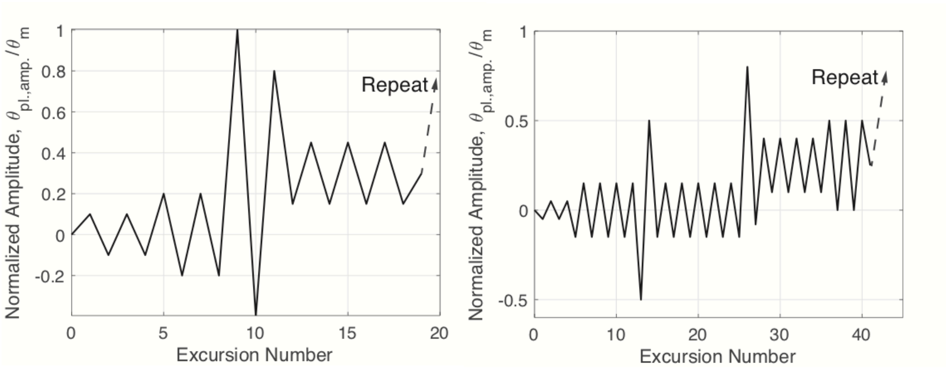
1.1 Introduction

Seismic performance assessment of structures necessitates the use of models idealizing the nonlinear behaviour of structural components under cyclic loading. The majority of these models have been calibrated to available experiments from structural components subjected to symmetric-cyclic loading histories (e.g., Krawinkler et al. [2000]). These were derived from concepts of cumulative damage (Krawinkler et al. [1983]) through the use of non-deteriorating single-degree-of-freedom systems. These aimed to describe the nonlinear behavior of buildings and their components with emphasis at design-basis seismic events. At these intensities, code-conforming steel moment-resisting frames (MRFs) that form the focus of the present paper, experience modest lateral drift demands (e.g., 1-2%). At such deformations, field reconnaissance and shake table experiments (Suita et al. [2008]) suggest that mean effects and cyclic deterioration in strength and stiffness of code-conforming structural components is negligible. Collapse experiments (Lignos et al. [2011; 2013]) and simulations (e.g., Elkady and Lignos [2014]) suggest that the behavior of steel MRFs prior to collapse is non-symmetric. It is typically characterized by few small amplitude inelastic cycles followed by monotonic pushes prior to incipient collapse. In the absence of such loading protocols, a common practice of the experimentalist is to simply use the symmetric cyclic loading protocol with lateral drift excursions larger than 2% till the structural component loses its load carrying capacity. While convenient, this practice imposes immoderate seismic demands to structural components (Krawinkler [2009], FEMA [2009]). This has a profound effect on nonlinear modelling of structural components as well as on acceptance criteria for collapse prevention (Suzuki and Lignos [2019], Maison and Speicer [2016]). To address this challenge, this paper proposes collapse-consistent loading protocols for experimental testing of steel components under cyclic loading.

The scope of this work is to develop a testing standard to produce physical data to (a) better inform deterioration models for collapse risk assessment; (b) to develop acceptance criteria associated with collapse prevention in future editions of assessment guidelines such as ASCE 41 (ASCE [2017]). Emphasis is placed on steel columns. These are subjected to lateral drift demands coupled with constant or variable axial load. The former is common in interior steel MRF columns, whereas the latter is typical for end (exterior) steel MRF columns. Therefore, the developed protocol, in the general case, consists of two parameters. The first one is associated with the lateral drift demand (typically in displacement control), while the second one is associated with the imposed axial load (typically in force control). The subsequent sections illustrate samples of such loading protocols along with data from experiments on steel columns subjected to those protocols.

1.2 PROPOSED LOADING HISTORIES FOR COLLAPSE ASSESSMENT

The proposed loading protocols are developed by means of nonlinear collapse simulations of more than 80 steel MRF archetypes (Suzuki and Lignos [2019]). The protocols, which are based on concepts of cumulative damage, reflect the seismic demands prior to collapse for both near fault (see Fig. 1a) and long duration (see Fig. 1b) earthquakes. Figure 1 shows such protocols for low-rise interior steel MRF columns. The lateral drift indexes are normalized with respect to the the chord rotation, θ_m, associated with 50% loss of the first order peak flexural resistance, M_{max} of the steel column based on a typical monotonic test. Alternatively, continuum finite element models (Elkady and Lignos [2018]) may be used to estimate θ_m or empirical equations for wide flange and hollow square sections (e.g., Lignos et al. [2019]). Full details of the proposed loading histories along with an automated matlab code to derive the protocols for a given column geometry can be found in Suzuki and Lignos [2019].

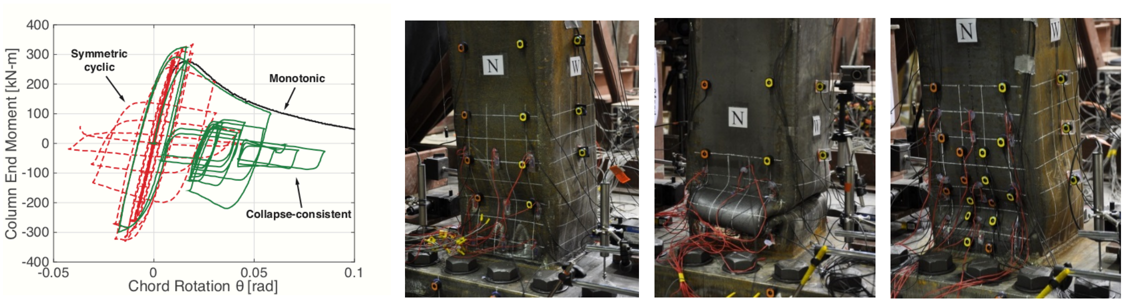


(a) (b)

Figure 1. Example of collapse-consistent loading protocols for steel columns in low rise steel MRF columns under (a) near-fault and (b) long duration ground motions

1.3 EXPERIMENTS UNDER COLLAPSE-CONSISTENT LOADING HISTORIES

Figure 2 presents the experimental results on three nominally identical specimens comprising cantilever steel columns with a seismically compact hollow square structural profile. The specimens were subjected to monotonic, symmetric cyclic and collapse-consistent loading protocols. From this figure, it is evident that at 4% lateral drift demand the steel column has lost its axial load carrying capacity when subjected to a symmetric cyclic loading history (see Fig. 2c). On the other hand, the corresponding one based on the collapse-consistent protocols indicate that there is at least 50% reserve capacity in the same member at 4% drift demand. Same observations hold true from full-scale shake table collapse tests (Lignos et al. [2013]). The above findings have direct implications into current seismic assessment guidelines of new and existing structures by means of nonlinear static procedures as well as derived component-based fragility curves for building specific seismic loss assessment (Elkady et al. [2018]).



(a) Moment rotation **(b) monotonic** **(c) symmetric cyclic** **(d) collapse-consistent**

Figure 2. Behaviour of steel columns with hollow structural sections under monotonic, symmetric cyclic and collapse-consistent loading protocols at 4% lateral drift demand

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