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Title: Capacity Limit States for Nonductile Bridge Columns

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Motivation: Caltrans currently employs the Shakecast software platform that retrieves USGS ground-shaking data and utilizes predictive seismic demand models and component/system capacity models to assess likely damage to bridges following an earthquake. While there has been significant progress in the development of demand models, the Shakecast platform has very limited models to correlate demands with capacity limit states, particularly for older California bridges. There is an urgent need to develop a range of capacity limit states (from minor damage up to collapse) for pre-1971 (also referred to as Era-1 columns) Caltrans bridge columns so as to enhance the capability of Caltrans to rapidly estimate damage to their bridge inventory following an earthquake and facilitate the planning, management, and mobilization of emergency response.

Objectives: Since the available experimental database of bridge column tests that are typical of Era-1 Caltrans columns is limited and the cost of initiating new experimental projects to test large-scale non-ductile columns can be time-consuming and cost prohibitive, the goal of the research was to develop the needed range of capacity limit states through modeling and comprehensive numerical simulations. Moreover, given the inability of ductility-based measures to characterize capacity limit states under random earthquake-induced loading histories, a major effort was dedicated to developing a damage-index based approach to classifying limit states for Era-1 columns. Following the validation of the proposed approach with observed experimental data, additional aspects of the seismic resistance of both single and multi-column bents are investigated.

Methodology:

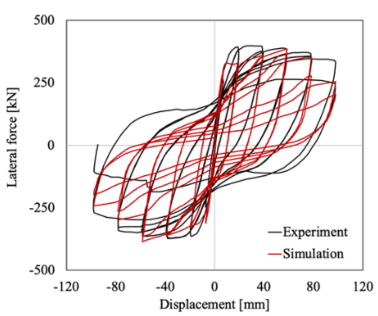
Given the overarching objective of the research to develop capacity limit states through modeling and simulation, it is imperative that the bridge column bents are modeled as accurately as possible to include the consideration of potential failure modes (flexure, shear and mixed flexure-shear), and incorporation of critical effects at the material level (such as confinement in concrete and bar buckling in reinforcing steel) and sectional level (such as bond-slip due to strain penetration). Given the prevalence of drift-based measures in seismic design and assessment, the first choice considered in the development of the limit-state models was ductility. Damage limit states, as a function of component ductility, was developed for a set of non-ductile columns using a strain-based approach. Both circular and wide rectangular sections, who cross-sectional properties were derived to represent typical Era-1 Caltrans columns, were considered in the simulations with loading protocols that included both cyclic loading and earthquake time histories. The drawback of using ductility-based measures to characterize limit states under random earthquake-induced loading histories led to the development of a damage-index based approach to classifying column limit states. Finally, the proposed damage-based approach was applied to two and three-column bents to assess the benefits of redundancy in limiting the damage experienced by non-ductile bridge columns.

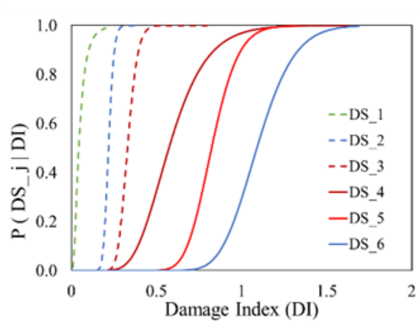
Results:

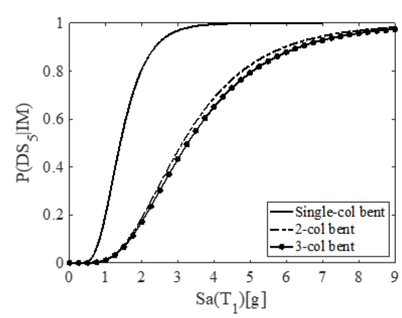
The overall modeling approach adopted in the study that encompassed both element and material modeling was shown to be effective in capturing both flexural and mixed shear-flexure failure modes through comparison with experiments reported in the literature. Strain-based calibration of damage limit states is an effective approach in the context of numerical simulations using a fiber-based discretization of the column element. When comparing numerically simulated ductility demands with estimates based on experimental data, it was found that the difference was larger for lower damage states than for extreme damage states. Based on the results of the numerical simulations under cyclic loading of both circular and wide rectangular sections, it was found that the ductility attained at damage states DS-1 through DS-5 is similar for all three loading protocols though the dispersion increases at higher damage states. However, at damage states DS-6 and DS-7, the ductility-based limits drop when more cycles are applied at each displacement level. A ductility-based limit-state definition becomes unreliable when applied to earthquake loading. The new damage-based methodology, irrespective of loading protocol, was successful in predicting the different capacity limit states, including cracking of the cover concrete, spalling of concrete, bar buckling, crushing of the core concrete and multi-bar rupture.

Conclusions:

The ability to estimate with reasonable accuracy the likelihood and extent of damage to bridges following an earthquake is crucial to post-earthquake mobilization of emergency response. Whereas modern bridges designed after 1990 are expected to perform well, older bridges, particularly those built before 1971, are vulnerable to damage during a severe seismic event. Findings from this study will contribute to improved prediction of damage to non-ductile bridge columns following an earthquake and also to ongoing efforts in prioritizing strengthening of such bridges.







Keywords: bridge columns, capacity limit states, inelastic modeling, non-ductile, seismic damage, seismic simulation