SEISMIC BEHAVIOR OF POLYURETHANE-ENHANCED BRIDGE COLUMNS

Nikoukalam, Mohammad T.\(^1\) and Sideris, Petros\(^2\)

**ABSTRACT**

In this study, the seismic performance of a novel bridge column design incorporating polyurethane (PU) damage-resistant segments, external replaceable energy dissipating (ED) links, and internal unbonded post-tensioning is investigated via computational studies. Polyurethanes are visco-elastic/visco-plastic polymeric materials, which, compared to concrete, exhibit large deformability, low stiffness and large strength, which increases with the loading rate, further preventing damage. As a result, under strong earthquakes, damage is mainly concentrated at the (external) ED links, which can be rapidly replaced without bridge operation disruptions, eliminating any residual deformations.

The mechanical properties of the selected polyurethane are quantified through compressive uniaxial tests at various strain rates. A uniaxial visco-elastic/visco-plastic parallel network constitutive model capable of capturing the observed response is developed, calibrated to the experimental data, and implemented in OpenSees. Using this model, analyses are conducted under monotonic loading for various PU-enhanced column designs. The obtained responses are compared with those of monolithic and rocking precast reinforced concrete columns. Using dynamic analysis, fragility curves are then generated for all columns. These analyses validated the effectiveness of PU-enhanced columns to mitigate seismic damage compared to conventional column designs.

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Seismic Behavior of Polyurethane-Enhanced Bridge Columns

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In this study the seismic performance of a novel bridge column design incorporating polyurethane (PU) damage-resistant segments, external replaceable energy dissipating (ED) links, and internal unbonded post-tensioning is investigated via computational studies. Polyurethanes are visco-elastic/visco-plastic polymeric materials, which, compared to concrete, exhibit large deformability, low stiffness and large strength, which increases with the loading rate, further preventing damage. As a result, under strong earthquakes, damage is mainly concentrated at the (external) ED links, which can be rapidly replaced without bridge operation disruptions, eliminating any residual deformations.

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Introduction

Conventional cast-in-place bridge columns, despite ensuring life safety and collapse prevention, sustain excessive damage in the form of plastic hinging at locations of high flexural demands under seismic loading. Such excessive damage affects the post-earthquake repairability of bridges, which often includes high repair costs and downtime. Over the past decades, various precast bridge substructure systems with emulative or jointed (rocking) end connectivity have been proposed with the objective of improving seismic performance and accelerate construction – a detailed review of which is provided in [1].

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This study assesses the seismic performance of an innovative rocking column design originally introduced by the authors [1]. The proposed rocking column design offers: (i) explicit damage control through polyurethane (PU) damage-resistant end segments, (ii) self-centering through internal unbonded post-tensioning, and (iii) energy dissipation and flexural stiffness/strength through external replaceable energy dissipating (ED) links in the form of buckling restrained yielding steel rebar. The replaceability of ED links offers low cost rapid post-earthquake retrofit without operation disruptions.

**PU Material Testing and Uniaxial Constitutive Model**

The selected PU is an amorphous thermosetting polyether polyl-based polymer, which is available from BASF [2] as ELASTOCAST. This material was investigated under uniaxial compression up to a peak nominal strain of 10% for three different compression strain rates: 0.001 s\(^{-1}\), 0.01 s\(^{-1}\), and 0.05 s\(^{-1}\). The stress relaxation properties of the material were investigated by inserting a number of holding periods into the loading strain history [1]. The elastic modulus and the peak compressive strength were found to increase by 20% and 44%, respectively, as the strain rate increases from 0.001 s\(^{-1}\) to 0.05 s\(^{-1}\) (Figure 1 (b-d)).

A simplified uniaxial visco-elastic softening visco-plastic constitutive model was developed to capture major material response properties at low computational time. The proposed constitutive model consists of a linear elastic spring \(A\) in parallel with a set of visco-elastic/plastic networks \(B_n\), with \(n = 1, 2, \ldots\), as shown in Figure 1(a). Each network \(B_n\) consists of an elastic spring in series with a softening elasto-plastic element that is in parallel with a nonlinear viscous dashpot. For the selected PU material, two \(B\) networks were found to be sufficient in simulating the observed response. Computationally predicted vs. experimentally measured stress vs. strain responses were in good agreement, as shown in Figure 1 (b-d), for all considered strain rates.

![Figure 1](image)

Figure 1. (a) Rheological representation of constitutive model; Predicted vs. measured compressive stress vs. strain at different strain rates: (b) 0.001 /sec; (c) 0.01 /sec; (d) 0.05 /sec.

**Column Designs and Modeling**

The reference column (Figure 2) is that of the single-column substructure of the Jack Tone Road Overcrossing, located in the city of Ripon, California [3]. The monolithic circular column of the bridge has a diameter of 5.51 ft with longitudinal reinforcement ratio of approximately 2%. Further details on the reference column may be found in [3]. A rocking column was obtained by cutting the mild longitudinal reinforcement at the interface of the column and footing and adding a post-tensioning bar at the center of the cross-section, designed so that the column exhibits similar lateral strength to the reference monolithic column. The proposed rocking PU column was obtained by replacing part of the bottom of the concrete rocking column with a PU segment of diameter and...
length equal to the diameter of the concrete columns (in accordance with the findings from [4]). Supplemental energy dissipation and the required flexural stiffness and strength was provided by external energy dissipating links in the form of buckling restrained yielding bars made of high performance steel and implemented in the vicinity of the PU segment. Two columns with re-centering ratios, $\Lambda_C$, of 0.25 and 0.5 were designed for a target drift ratio of 3% [4].

All column models were generated using OpenSees [5]. The RC and PU segments and the milled part of the ED links (Figure 2 (a)) were simulated using gradient inelastic force-based elements [6]. Elements and material models used to generate the column models are shown in Figure 2 (a). Monotonic analyses were conducted with a low drift ratio rate (0.0004 s$^{-1}$) and up to a drift ratio at which zero lateral resistance was reached. The monolithic and rocking columns exhibited similar strength (Figure 2(b)). The column with the PU segment achieved similar strength with the monolithic and rocking columns, but much lower stiffness. Addition of the ED links increased the stiffness and strength of the columns with PU segments – termed PUED columns herein – due to the contribution of the ED links to the total flexural stiffness and strength of the bottom joint.

| Figure 2. (a) Schematic representation of the structural analysis model of the PU column with ED links; (b) Monotonic response of the studied column systems |

| **Seismic Fragility Assessment** |

Fragility assessment is performed through incremental dynamic analysis (IDA)[7] using the far-field ground motion (GM) ensemble of FEMA P695 [8]. Scaling is performed with respect to the 5% damped geometric mean spectral acceleration of all GMs at the mean first mode period of all columns. Two damage states (DSs) are considered with respect to the residual drift ratio (RDR): (a) structural collapse, and (b) system demolition/replacement. The structural collapse DS is reached when the RDR of each column exceeds the lateral drift ratio at which its pushover curve crosses the zero-force axis (Figure 2(b)). The demolition/replacement DS is reached when the RDR exceed 1.5%, based on the newly adopted Japanese code for highway bridge design [9].

The generated fragility curves (Figure 3 (a) and (b)) show that, the PUED columns have the highest capacity against demolition/replacement and collapse, which increases with $\Lambda_C$. Per Figure 3 (c), the median capacity against collapse from the RC monolithic column to the PUED column increases by 7% and 17% for $\Lambda_C$ of 0.25 and 0.5, respectively. Similarly, the median capacity against replacement/demolition from the RC monolithic column to the PUED column increases by 107% and 125% for $\Lambda_C$ of 0.25 and 0.5, respectively. It is further observed that the median capacity of the PU column (without ED links) against demolition/replacement is larger than that of the monolithic and rocking RC columns, because of the low residual deformations of PU columns, driven by the large deformability of PUs.
The seismic performance of a novel rocking bridge column system, employing damage resistant end segments made of polyurethane (PU), energy dissipation (ED) links, and unbonded post-tensioning system, was investigated and compared to conventional reinforced concrete monolithic and rocking systems. A simplified phenomenological uniaxial visco-elastic softening visco-plastic material model is developed and calibrated to test results conducted by the authors. The analysis results showed that columns with flexible PU segments can accommodate lateral drift ratios up to 5% without damage and up to 15% with damage at the ED links. PU columns with ED links exhibited higher capacity against replacement and collapse, compared to the other column designs.

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