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# Seismic FRP retrofit of circular single-column bents using a ductility wrap envelope to alter failure modes

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#### 1. Introduction

Following the Sylmar earthquake in 1971, the California Department of Transportation (Caltrans) developed a bridge retrofit program to study single-column configurations and their susceptibility to seismic failure [1]. Since then, several investigations have focused on developing and implementing various retrofit methods to protect these columns. After the Loma Prieta Earthquake in 1989 and the Northridge Earthquake in 1994, the retrofit program was expanded having received supplemental economic support to further investigate seismic retrofit strategies. In this light, three retrofit techniques were developed to adequately protect seismically deficient columns. These techniques include steel jacketing, concrete jacketing, and composite jacketing for reinforced concrete (R/C) columns.

Various applications of Fiber Reinforced Polymers (FRP) with reinforced concrete structures have been investigated and tested for over a decade [2,3]. The outcomes of the investigations resulted in the use of carbon wrapped bridge columns as a retrofit strategy to protect against earthquakes [4,5]. Although the benefits of using steel jackets and concrete jackets are now well known, there remains a need to enhance R/C column retrofits by increasing efficiency, lowering maintenance costs, and increasing

### ABSTRACT

The target displacement ductility requirements for circular reinforced concrete (R/C) single-column bridge bents are considered using a proposed multi-failure mode algorithm to determine the required thickness of fiber reinforced polymer wraps (FRPs). The procedure is developed using two in-house computer algorithms, PACCC (Plastic Analysis of Circular Concrete Columns) and PACCC-FRP, to generate a moment-curvature analysis using circular segments and subsequent failure mode predictions in single-column bents for both FRP-wrapped and unwrapped circular R/C sections. The results of the study were verified against published experimental tests at the ultimate force-deflection states of R/C sections and also against three commercial "software test beds". The study uses PACCC-FRP to show that single-columns experiencing a brittle failure may be retrofitted with FRP wraps in order to increase the displacement ductility and satisfy target ductility values within the Ductility Wrap Envelope (DWE), or wrap-saturation level, as established herein.

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durability [4]. In experimental studies [4], several scaled bridge columns were wrapped with either glass or carbon-based fabrics and shown to adequately improve the columns' seismic resistance similar to that observed using steel jackets. The study by Seible et al. in 1997 [4] outlined procedures for retrofitting columns for shear enhancement, flexural hinge confinement, and lap splice confinement. Each scenario included specific guidelines and a prescribed methodology for determining the appropriate fabric thickness to resist the imposed demands. As research continued on the use of FRP wrapped columns, an increase in ductility became a prevalent point of investigation [6–9]. Nonetheless, a methodology that could be used to determine the required number and thickness of FRP layers to achieve a specified target displacement ductility had not been established although the need to optimize the use of FRP wraps for design practice implementation was apparent [3,10].

In the current study, a detailed methodology is developed for analyzing multiple failure modes in circular R/C single-column bents, including shear, longitudinal bar buckling, flexural hinge confinement, longitudinal bar rupture, and rupturing of the FRP wraps. Unlike other models, the proposed model utilizes an incremental approach to determine the appropriate FRP saturation level based on a target displacement ductility for the various failure modes as found from the derived moment–curvature and force–deflection relationships, whereas other approaches use an ultimate concrete strain to 'plug-in' to prescribed equations, thus limiting the type of failure modes subjected to a column. The proposed algorithms use circular finite elements to model the material constituents to expand on existing guidelines. Further, the





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