P-M INTERACTION DIAGRAMS FOR REINFORCED CONCRETE WALLS RETROFITTED WITH EXTERNALLY BONDED CARBON-FIBER REINFORCED POLYMER

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This research develops analytical axial load-bending moment (P-M) interaction diagrams for reinforced concrete (RC) walls retrofitted with carbon fiber reinforced polymer (CFRP). A 12-inch thick, 1-foot strip of RC wall section is considered with varying reinforcement ratios, varying axial compressive loading, and varying number of CFRP layers. The CFRP material is treated as externally bonded onto the tension face of the RC wall to investigate its impact on the flexural capacity of the section. Each P-M interaction diagram was generated considering a discretized compression zone and by satisfying principles of static equilibrium and strain compatibility. An elastic-plastic steel stress-strain relationship is used for Grade 60 reinforcement; a uniaxial nonlinear compressive stress-strain relationship is used for concrete; and a linear stress-strain relationship is used for CFRP in tension. The failure modes considered are steel yielding, concrete crushing, and CFRP debonding. The computed P-M interaction diagrams are normalized for their general use in the retrofit of existing RC walls using CFRP. Results show that as the axial compressive force on the RC wall increases, the less effective CFRP is. CFRP is more effective in sections with beam-like behavior, where the reinforcement ratio tends to be the smallest.

Keywords: CFRP, Compression, Bending, Retrofit.

1 INTRODUCTION

Historically, structures have been rehabilitated using traditional methods such as incorporating steel or concrete jackets, post-tensioning, steel plates, or replacement of deteriorated members. Although these traditional methods have proven to be functional solutions in increasing the strength capacities of structures, they substantially increase the dead load of the rehabilitated structure, are time consuming, and are labor-intensive solutions. Fortunately, with recent advancements in civil engineering, there is a wide range of alternative structural retrofitting methods using lighter-weight materials that have been studied and adopted into use for improving capacities such as Carbon Fiber Reinforced Polymer (CFRP) composite material. The goal of this study is to develop axial load-bending moment (P-M) interaction diagrams for a reinforced concrete (RC) wall retrofitted with CFRP. Slender RC wall behavior is not considered. Figure 1(a) shows the 12-inch vertical strip of wall considered under the action of combined axial compression and bending, with CFRP applied to the tensile face, depicted by the hatching on Figure 1(b).
2 MATERIALS

2.1 Carbon-Fiber Reinforced Polymer (CFRP)

This study focuses on manufacturer Fyfe® CFRP material, TYFO® SCH-41 Composite, which is made of Tyfo® S Epoxy and Tyfo® SCH-41 reinforcing fabric. The TYFO® SCH-41 composite material is considered a custom, unidirectional carbon fabric. This material is applied to the surface of a structure using the wet-layup method. The wet-layup method is a technique used to apply CFRP by applying the epoxy system as a liquid when the fabric is placed on the desired surface (Soudki and Alkhrdaji 2005). In this method, the epoxy resin (a two-part mix) is applied as a primer layer to ensure the composite FRP material can bond onto the concrete surface. Depending on available equipment at the time of installation, the composite fiber fabric could be placed on top of the primer layer and then coated by spreading the epoxy resin over that fabric layer or a mechanical impregnator can coat the composite fiber before application and then installed onto the surface as one consolidated piece (Lee 2011). Regardless, these methods require compaction of the layers by utilizing an Aluminum roller to help remove excess resin and voids in the fabric. Before installation of the composite material, the concrete surface must first be prepared in such a way that allows the CFRP to properly adhere to it. The surface must be clean and dry with no obstruction or cavities to prevent any tears of the Tyfo® system or voids being trapped underneath the Tyfo® system (FyfeFRP, LLC 2022). There will be discontinuous wrapping of the concrete surfaces since FRP shall only be studied for applying the material on the tensile section. Due to this discontinuous application, the manufacturer only requires a minimum Concrete Surface Profile Classification 2 (CSP2) profile to ensure proper bonding of the material and epoxy onto the concrete’s prepared surface. The CFRP selected for this research has a single-layer thickness, \( t_{\text{f1}} \) of 0.04 in., a modulus of elasticity, \( E_f \) of 12,600 ksi, an ultimate tensile stress, \( f_{\text{u1}} \) of 131 ksi, and an ultimate failure strain, \( \varepsilon_{\text{f1}} \) of 0.009 in./in. The debonding strains, \( \varepsilon_{\text{d1}} \), for one layer, two layers, and three layers of CFRP are 0.007394 in./in., 0.005229 in./in., and 0.004269 in./in., respectively.

2.2 Concrete

The concrete material model proposed by Mander was used to model the nonlinear uniaxial stress-strain behavior of concrete in compression (Mander et al. 1988). A 28-day concrete compressive
strength, $f'_{c}$ of 4,000 psi was selected with a maximum compressive strain, $\varepsilon_{cu}$ of 0.003 in./in. The tensile stress in the concrete was neglected.

### 2.3 Steel Reinforcement

A bilinear elastic-perfectly-plastic stress-strain relationship was used for the steel reinforcement. Grade 60 reinforcement was selected with a yield strength of 60 ksi and a corresponding yield strain of 0.00207 in./in.

### 3 PARAMETRIC STUDY

#### 3.1 Parameters

Table 1 summarizes the wall parameters considered in this study. Three reinforcement layouts were considered, resulting in different wall reinforcement ratios, $\rho$, computed using the total steel area ($A_s/\text{bd}$). For each reinforcement layout, a control case without any CFRP was considered (i.e., no layers of CFRP). In addition, cases involving one-, two-, and three layers of CFRP applied to the tensile face were considered (see Figure 1). Therefore, a total of 12 cases were considered in this study.

<table>
<thead>
<tr>
<th>Reinforcement (Each face)</th>
<th>$\rho$</th>
<th>CFRP Layers</th>
</tr>
</thead>
<tbody>
<tr>
<td>#5 @ 12” o.c.</td>
<td>0.0052</td>
<td>0, 1, 2, 3</td>
</tr>
<tr>
<td>#6 @ 12” o.c.</td>
<td>0.0073</td>
<td>0, 1, 2, 3</td>
</tr>
<tr>
<td>#7 @ 12” o.c.</td>
<td>0.0100</td>
<td>0, 1, 2, 3</td>
</tr>
</tbody>
</table>

#### 3.2 Analytical Approach

To determine the influence of the CFRP on the wall axial-flexural strength, various P-M interaction diagrams were produced by selecting an initial axial load upon the wall section and utilizing principles of equilibrium and strain compatibility to evaluate the section’s moment capacity. The P-M interaction diagrams represent all combinations of the axial forces and moments that result in column failure. The P-M interaction diagram is comprised of several key regions involving compression-controlled failure, tension-controlled failure, and a transition region between the two (McCormac and Brown 2016). The calculations used to develop the P-M interaction diagrams are based on failure modes such as steel yielding, concrete crushing, and the debonding of CFRP. Every case considered will vary on unique set of parameters such as cross-sectional dimensions, concrete strength, steel yield strength, and bar arrangement. Therefore, to avoid having unique diagrams for every possible column case, the calculations described herein are based on an approach that normalizes the P-M interaction diagrams. Additionally, the capacity reduction factor, $\phi$, from ACI 318-19 was applied to generate design strength P-M interaction diagrams for general use in retrofits (ACI Committee 318 2019). Each P-M diagram has a unique $\gamma$ term that represents the ratio of the center-to-center distance between the steel reinforcement on each face to the overall depth, $h$. 
Figure 2. Nonlinear stress distribution with discretized compressive fibers.

Each point on the P-M interaction diagrams was computed using an iterative approach where, for a given axial load, the depth to the neutral axis, $c$, was adjusted until tension-compression equilibrium was satisfied (see Figure 2). For cases where the CFRP experienced debonding failure, the maximum strain in the CFRP was limited to the debonding strain, $\varepsilon_d$, and the iteration proceeded by adjusting the neutral axis depth, $c$, until tension-compression equilibrium was satisfied. As part of the analysis, the concrete compression zone was discretized into 15 fibers. The curvature, $\psi$, was evaluated using the assumed neutral axis depth, $c$, and either the maximum concrete compressive strain $\varepsilon_c$ of 0.003 in./in. ($\psi = \varepsilon_c/c$) or the debonding strain in the CFRP ($\psi = \Delta_d / (h+0.5t_f - c)$), where $\Delta_d$ is the difference between the debonding strain, $\varepsilon_{d}$, and the initial compression strain on the wall due to axial load, $\varepsilon_c$. The compressive strain in each fiber was determined based on the distance of each fiber from the neutral axis of the wall section. The stress in each fiber was calculated using the uniaxial concrete compression stress-strain model proposed by Mander et al. (Mander et al. 1988). The compressive stress at the centroid of each fiber was converted to a compressive force by multiplying the fiber stress by the fiber cross-sectional area. The total compression force in the concrete, $C_c$, is the sum of all the fiber forces. The force in the tension- and compression steel reinforcement, $T_s$ and $C'_s$, respectively was computed in a similar manner using the steel constitutive model previously described. The tension in the CFRP was computed at the centerline of the CFRP thickness, $t_f$. The maximum nominal axial compressive strength in the P-M interaction diagrams was computed using Equation 22.4.2.2 in ACI 318-19 (ACI Committee 318 2019).

4 RESULTS

Figure 3 shows the P-M interaction diagrams of RC walls retrofitted with CFRP for the cases outlined in Table 1. Figures 3(a), 3(c), and 3(e) show the nominal strength P-M interaction diagrams and Figures 3(b), 3(d), and 3(f) show the design strength P-M interaction diagrams with the capacity reduction factor, $\phi$, applied for the given reinforcement and spacing cases specified.
Debonding failure is depicted with the “open circles”. The analyses reveal that the largest nominal- and design normalized moment capacities correspond to the walls with three layers of CFRP. The results obtained in this study reveal the greater the axial force applied to the RC section, the less effective CFRP becomes. A wall section subjected to lighter axial loads can have increases in bending capacity from 20% to 160% with increases in CFRP layers, while a wall section subjected to heavier axial loads can have increases in bending capacity from 1% to 14% with increases in CFRP layers. Debonding of the CFRP was observed only in the tension-controlled region.
5 CONCLUSIONS

The goal of this study was to analytically develop axial load-bending moment (P-M) interaction diagrams for reinforced concrete walls retrofitted with one-, two, and three layers of carbon fiber reinforced polymer (CFRP) using the wet layup technique. The wall has a 28-day compression strength of 4,000 psi, a thickness of 12 inches, and is reinforced with #5, #6, and #7 at 12 inches on-center along each face. The CFRP is applied only to the tension face. A total of 12 cases were considered. Nominal P-M interaction diagrams were generated, as well as design strength P-M interaction diagrams, incorporating the capacity reduction factor per ACI 318-19. Results showed that axial load on the wall plays a significant role in the effectiveness of CFRP as a retrofit option. Specifically, the greater the axial compression force on the wall, the less effective CFRP becomes. A wall section subjected to lighter axial loads can have increases in bending capacity from 20% to 160% with increases in CFRP layers, while a wall section subjected to heavier axial loads can have increases in bending capacity from 1% to 14% with increases in CFRP layers. Debonding of the CFRP was observed only in the tension-controlled region. The design P-M interaction diagrams are intended to assist engineers in the selection of CFRP layers for the retrofit of reinforced concrete walls meeting the specifications of the wall considered in this study.

References

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