The Effect of Preloading on the Strength of Jacketed R/C Bridge Piers

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SUMMARY:
The objective of this paper is to analytically investigate the influence of core preloading on the strength of jacketed R/C bridge pier sections. In this direction, a recently proposed method for arbitrary composite section analysis in biaxial bending and axial load is suitably extended to include preloading effects. A parametric evaluation of the preloading effect using quantitative indices is presented, considering the variance of several parameters such as section geometry, amount of reinforcement and various normalized axial and moment preloading levels. The analysis results are presented in the form of moment interaction curves and 3D failure surfaces. Specific cases where the preloading effect is more pronounced are finally highlighted.

Keywords: Preloading, Seismic retrofit, Flexural Strength, R/C Jackets, Bridge Piers

1. INTRODUCTION

Strengthening of reinforced concrete (R/C) columns, forming part of bridge piers using concrete jacketing, for enhancing their structural performance under seismic loading, is naturally applied on preloaded cores (i.e. the 'old' column) due to existing gravity loads. Unlike buildings, in the case of bridges it is practically difficult - if not impossible - to construct the concrete jacket after unloading the bridge pier from service loads. The preloading actions of the core may be in the form of axial compression with or without bending moment, depending on the structural system (pier/deck frame behavior in the transverse bridge direction). However, for the design or assessment of repaired or strengthened bridge piers, it is usually assumed, for simplicity, that the concrete jacket is applied on unloaded bridge piers (cores) considering a monolithic section during analysis, i.e. the concrete core and the jacket are sharing the same strain profile.

The effect of core preloading on the ultimate capacity of jacketed reinforced concrete columns has been already investigated, yet mainly on the basis of experimental testing. A common experimental procedure involves the axial preloading of the core to a certain amount of its ultimate axial capacity and the subsequent strengthening with concrete jacketing. In fewer cases (Ersoy et al., 1993), the loading of the core was continued until considerable crushing and buckling of the longitudinal reinforcement occurred, therefore the concrete jacket was introduced mainly for repair reasons. It is noted that the thickness as well as the longitudinal reinforcement of the jacket were kept constant during the experimental evaluation, however different concrete strengths for the core and the jacket were considered in all cases. Takeuti et al. (2007) axially loaded the concrete core from 44 % to 87 % of its ultimate core capacity. The preloaded specimen was subjected to an increasing compressive axial loading (without moment) and finally exhibited an increase of its strength up to 14 %, compared to its non-preloaded counterpart. Therefore, it was concluded that the preloading does not affect the strengthening process nor does it adversely affect the load bearing capacity of the retrofitted column. Ersoy et al. (1993) applied axial preloading on the core of jacketed reinforced concrete columns up to 75 % and 70 % of its ultimate axial capacity, and tested the performance of the preloaded specimens under uniaxial and combined axial and bending loading respectively. The specimen subjected to uniaxial loading exhibited 5 % to 10 % decrease of its strength compared to its non-preloaded counterpart, while in the case of combined axial and moment loading the strength capacity of the preloaded and non-preloaded specimens turned up to be almost identical. Finally, Vandoros and Dritsos (2008) compared the performance of axially preloaded and non-preloaded jacketed reinforced concrete columns under combined axial loading and bending moment. The comparison on the basis of flexural capacity revealed an increase in strength up to 35 % when axial preloading of the core was considered.

As described above, the effect of core preloading has been experimentally investigated only for the case of uniaxial compressive preloading (without bending moment). Analytical investigation involving preloading effects on jacketed reinforced concrete sections is, generally, lacking. Analytical modeling can be found in Ong and Kang (2004), concerning composite sections with preloading on the steel core. The key objective of the present paper is to analytically investigate the effect of combined axial and moment preloading of the core on the ultimate strength of jacketed sections. In the following sections, a recently introduced numerical method for arbitrary composite section analysis under biaxial bending and axial load is suitably extended to account for preloading effects. A parametric evaluation of the preloading effect using quantitative factors is presented, considering a range of values for several parameters i.e. section geometry, amount of reinforcement, and various normalized axial and moment preloading levels. The analysis results are presented in the form of biaxial moment interaction curves and 3D failure surfaces. Specific cases where the preloading effect is more pronounced are finally highlighted.

2. THEORETICAL BACKGROUND

The present analytical procedure is based on a recently proposed numerical method for the analysis of arbitrary composite sections under biaxial bending and axial load (Papanikolaou, 2012). According to this method, the section under consideration may consist of an unlimited number of individual components, namely surfaces (S_i), multi-segment lines (L_i) and fiber groups (FG_i), for simulating various section elements e.g. concrete or steel areas, distributed reinforcement or fiber-reinforced polymer strips, and reinforcement bars or tendons, respectively (Fig. 1, left). These components can also be ‘negatively’ defined, in order to explicitly simulate voids or multi-nested materials, which is a requisite feature for compiling R/C jacketed sections (Fig. 1, right), without resorting to complicated fictitious cuts (Fafitis, 2001).

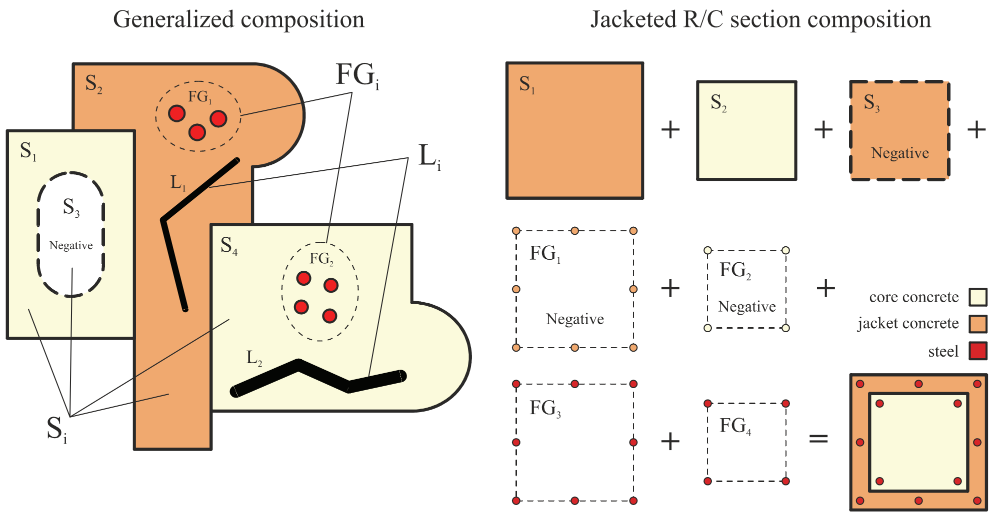

Figure 1. Generalized (left) and jacketed R/C section composition (right)

Each section component may be associated with a different material constitutive law, i.e. a series of stress-strain arbitrary functions in piecewise form (Fig. 2, left), which are integrated by applying a numerical, adaptive strain-mapped integration scheme, based on Gaussian sampling on a Green path integral. In order to perform stress integration, the ultimate strain profile (ε_{ou}, φ_u) is imposed on the section, following the Bernoulli-Euler assumption (Fig. 2, right). This ultimate strain profile is defined using multicriteria limit states, which are preset for each material model, usually according to Code regulations (e.g. EN1992-1-1, 2004). Following derivative-free solution strategies, the axial and moment capacity values (N, M_X, M_Y) in the form of plane strength interaction curves or 3D failure surfaces are calculated. Moreover, the complete moment-curvature response of the section can also be derived. An in-depth presentation of the aforementioned numerical procedures is provided in Papanikolaou (2012).

The limitation of the existing method is that the same ultimate strain profile is shared among all section components (Fig. 2, right); however, if the effect of preloading is taken into account, the section core already exhibits initial strains due to preloading actions (N_p, M_p), which should be considered during the stress integration of the jacketed section. In order to derive this initial strain profile, a 'preparative' moment-curvature analysis of the core subsection is performed using the existing method. The analysis parameters are the section orientation (θ, see Fig. 2, left) and preloading axial load (N_p). The preloading strain profile (ε_{op}, φ_p) is extracted at the moment when the target preloading moment (M_p) is reached during the analysis. For the special case where only axial preloading is considered ($M_p = 0$), the resulting strain profile (ε_{op}) corresponds to initial equilibrium state for zero curvature (Fig. 3).

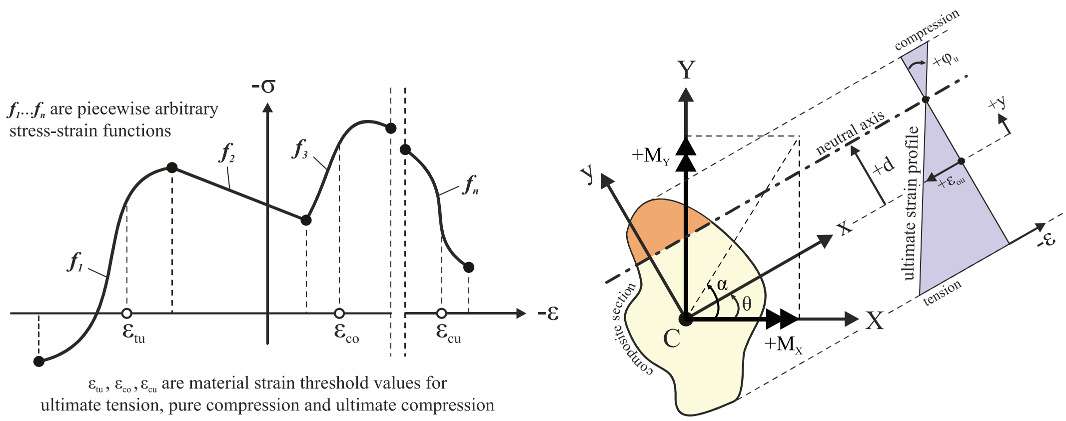

Figure 2. Material definition (left), section strain profile and loading parameters (right)

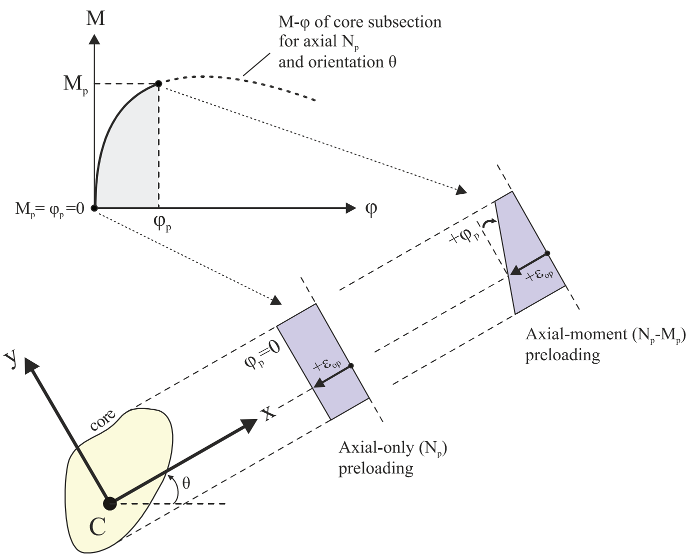

Figure 3. Core subsection initial strain profile due to preloading

After the calculation of the initial strain profile of the core subsection, the section analysis method is extended as follows: for each section component that participates in the preloaded core subsection (i.e. concrete, reinforcing steel etc.), the elementary strain-to-coordinate transformation equation is modified to include the initial profile parameters (see also eqs. 14 and 22 in Papanikolaou, 2012).

$$y = \varepsilon_{ou} - \varphi_u \, y \rightarrow y = \left(\varepsilon_{ou} - \varphi_u \, y\right) + \left(\varepsilon_{op} - \varphi_p \, y\right) \tag{2.1}$$

With the above modification, the resulting total strain profile for the core subsection reflects the addition of the strains due to preloading and those due to the considered global ultimate limit state (Fig. 4). The mathematical formulations for the rest of the section (jacket) remain unmodified. A very important aspect that has to be noted here, is that the core subsection components are a-priori excluded from the multicriteria limit state procedure that derives the ultimate strain profile. In other words, the ultimate limit state of the composite section is assumed to depend only on the jacket material. This assumption is justified by the fact that since the core has already been damaged due to preloading, it will probably fail before the jacket reaches its ultimate capacity; hence it can be no longer considered as a reliable criterion (threshold) for the entire section to reach its ultimate limit state. On the contrary, when no preloading is considered (common strain profile, see Fig. 2, left), the above assumption is not needed, since the jacket ultimate limit state is always reached first, due to section geometry. Furthermore, it is also assumed that perfect connection exists between old and new concrete (monolithic behavior), i.e. possible interface slip is ignored.

Figure 5 depicts the ultimate strain and stress profiles of a common rectangular jacketed R/C section for three cases: without preloading, preloading with axial load only (N_p), and preloading with both axial and moment actions (N_p, M_p). Two different concrete materials are assigned to the core (f_{cc}) and the jacket (f_{cj}) respectively, following the Eurocode 2 parabolic-linear model (EN1992-1-1, 2004), while reinforcement bars are not shown for clarity. It is again shown that the ultimate strain profile of the section is always defined from the jacket material response (here: concrete compressive failure), while the core stress contribution diminishes, especially when moment preloading is imposed. However, apart from preloading actions, the influence of preloading on the section capacity may depend on other parameters such as geometry and amount of reinforcement, which will be further investigated in the subsequent sections by a parametric evaluation.

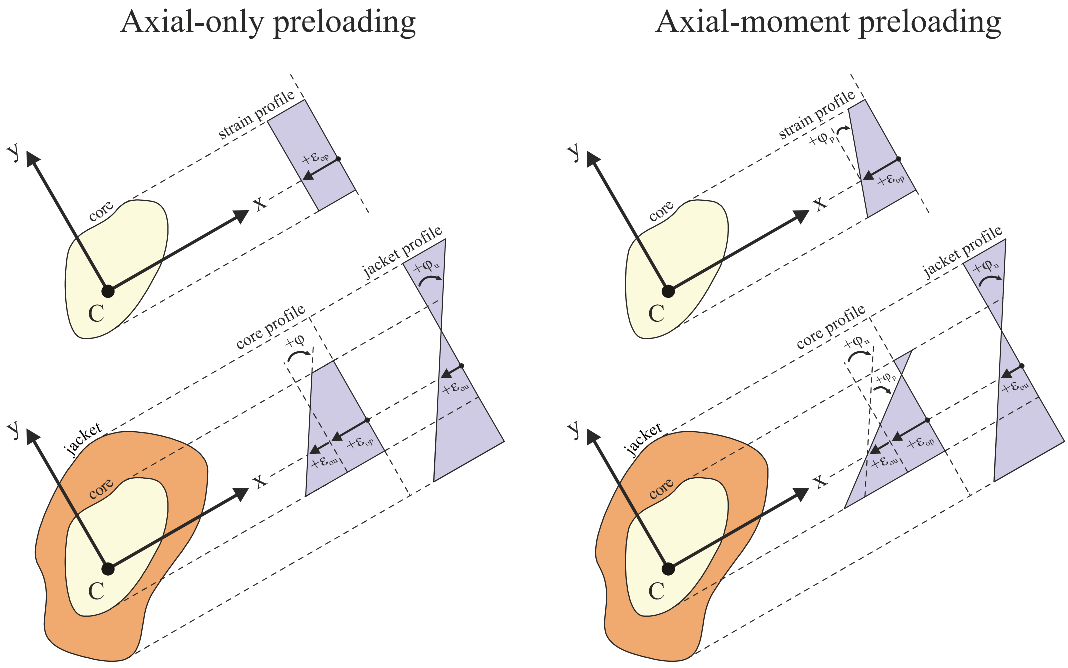

Figure 4. Jacketed section ultimate strain profiles including preloading effects

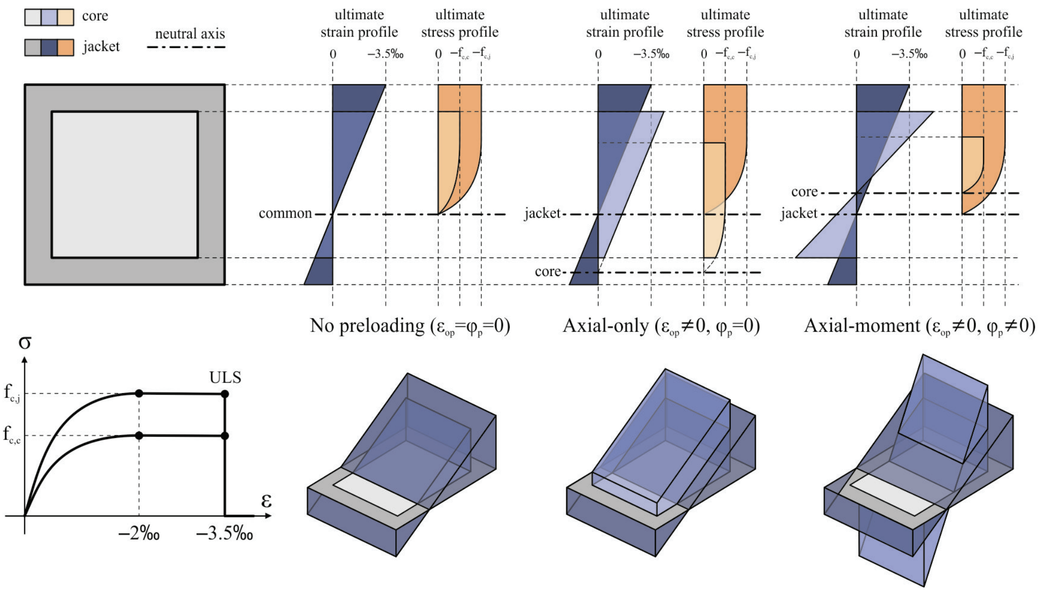

Figure 5. Jacketed section strain/stress profiles including preloading effects

3. ANALYTICAL SETUP

The numerical method outlined in the previous section will be applied to a series of parametric analyses for an old circular R/C bridge column, strengthened by R/C jacketing. The selected column belongs to a three-column deck-supporting frame (Fig. 6, left), hence it is subjected to preloading not only due to axial load but also to bending moment due to gravity loads. The pier diameter is 1.2 m, with low strength C12 type concrete ($f_{c,c}$ = 12 MPa) and it is reinforced with 36Ø20 bars (using fiber representation) of low strength C220 steel grade ($f_{y,c}$ = 220 MPa), which corresponds to a Code minimum ratio of approximately ρ_c = 10 ‰. The preloaded core was strengthened with three different jackets of 10, 15 and 20 cm thickness respectively, using C20 type concrete ($f_{c,j}$ = 20 MPa) and for each jacket, three different reinforcement ratios of 5, 10 and 20 ‰ (calculated on the jacket area) of B500C steel grade ($f_{y,j}$ = 500) MPa were applied as linearly distributed reinforcement, resulting to a total of 9 different strengthening cases (Fig. 6, right). All material constitutive laws follow the Eurocode 2 (EN1992-1-1, 2004) recommendations, i.e. parabolic-linear model for concrete, with $\varepsilon_{co} = -0.002$ and $\varepsilon_{cu} = -0.0035$ (see Fig. 2, left and Fig. 5, bottom-left) and elastoplastic bilinear model for steel.

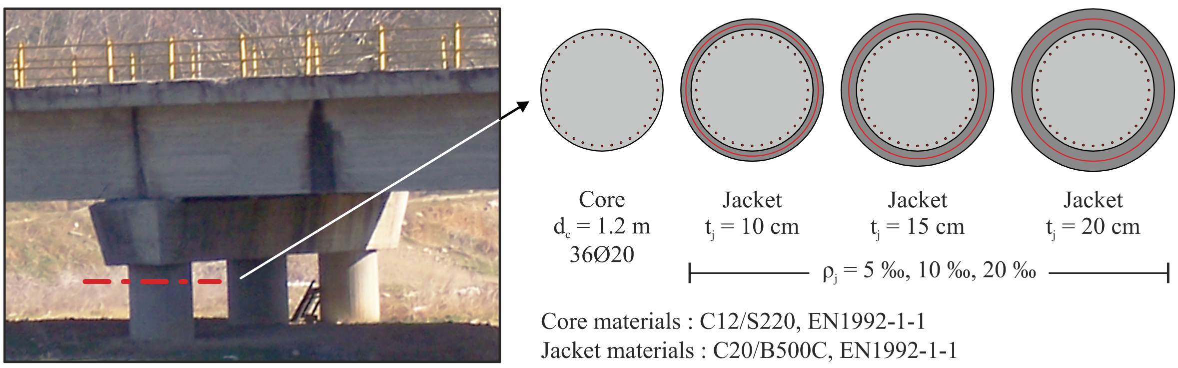

Figure 6. Jacketed sections considered in the parametric analysis

For each of the above nine strengthening cases, nine combinations of normalized axial and moment preloading levels for the core subsection were considered (ν = −0.1, −0.3, −0.5 combined with μ = 0.00, 0.05, 0.1) together with the trivial, non-preloaded case for $\nu = \mu = 0$ (total 90 analyses). (N_p, M_p) were calculated from:

$$N_p = \nu \cdot \frac{\pi d_c^2}{4} \cdot f_{c,c} \tag{3.1}$$

$$M_p = \mu \cdot \frac{\pi d_c^3}{4} \cdot f_{c,c} \tag{3.2}$$

It is noted that the resulting preloading actions (N_p, M_p) are kept below the core capacity, i.e. concrete jacketing is used for strengthening (not repair) of the pier section. Furthermore, in order to completely isolate and investigate the effect of preloading, any material-level manipulating factors such as design partial factors or confinement factors were ignored in the parametric analysis. For the evaluation of the strength of composite sections in general, it is herein introduced a new capacity index, named *volumetric capacity* (VC), which corresponds to the 3D failure surface volume of the section, expressed in N^3m^2 units. It is believed that the volume of the complete failure surface reflects the section capacity in an elaborate and straightforward manner, taking into account the full range of admissible axial loading, contrary to a simpler evaluation based on plane moment interaction curves that correspond to a constant axial load. Figure 7 shows a 3D failure surface of adequate mesh density (half, for clarity) that was calculated using the software implementation of the present method.

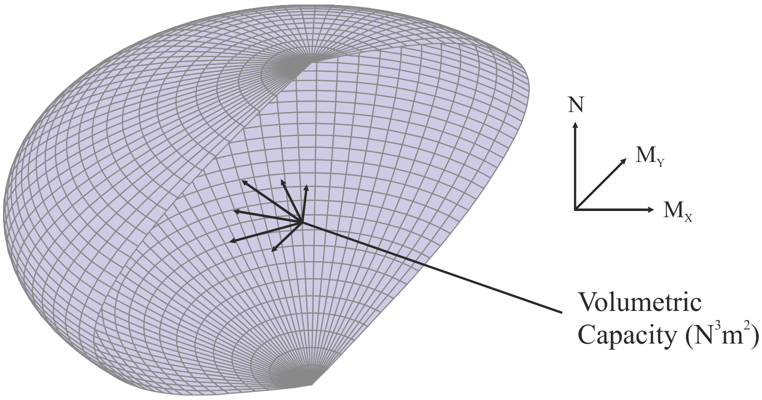

Figure 7. The volumetric capacity index (VC)

4. ANALYSIS RESULTS

Following the parametric setup described in the previous section, 90 different jacketed circular R/C piers, with and without preloading effects were analyzed using the ad-hoc developed software. From each analysis, the full 3D failure surface was extracted, together with the calculated volumetric capacity (VC). For the 81 preloaded sections, the percentile difference compared to the respective non-preloaded model (i.e. same jacket thickness and reinforcement) was derived, and the results in histogram form are depicted in figure 8.

It is observed that the effect of preloading on the flexural strength is marginally favorable (up to +2.5 %) when only axial preloading is considered. This favorable influence has been also reported in various experimental studies (Takeuti et al., 2007; Vandoros and Dritsos, 2008) and can be explained by the fact that the augmented core strain profile (ε_u+ε_{op}) due to axial preloading (see Figs. 4-5), maps generally on higher material stresses, which are subsequently integrated into higher section capacity. On the contrary, with increasing moment preloading levels, the preloading effect becomes significantly adverse, up to −38.6 %. This is justified as follows: when moment preloading is introduced, the corresponding preloading curvature (φ_p) significantly distorts the core ultimate strain profile, resulting to overstraining of large parts of the core (beyond material ultimate limits) thus the corresponding stresses drop to zero and lead to significantly lower section capacity.

Furthermore, it is also observed that preloading becomes more favorable when, primarily, the jacket thickness and, secondarily, the reinforcement ratio is increased; this is justified by the fact that with increasing jacket thickness and reinforcement, the contribution of the jacket to the strength of the entire section becomes dominant, compared to that of the - damaged - core section. Nevertheless, the relative variation between different preloading combinations appears to be stable, irrespective of the jacket geometry and reinforcement.

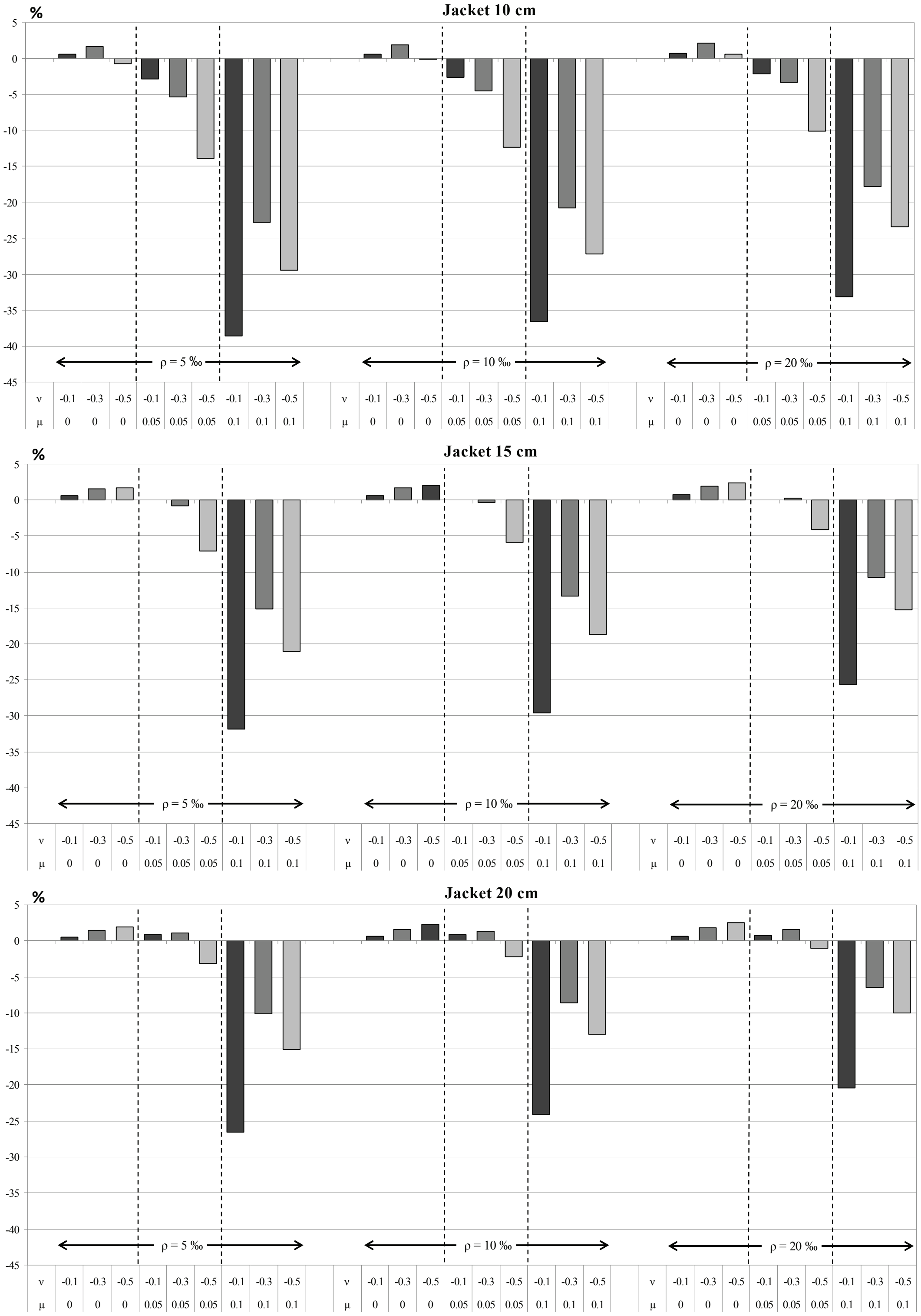

Figure 8. Section ultimate strength variations due to preloading effects

A more in-depth evaluation of the analysis results also shows when large moment preloading is applied ($\mu = 0.1$), its adverse effect is unexpectedly minimized for medium preloading ($\nu = -0.3$), which implies that, for this case, the stress contribution of core materials is maximized. However, this can be explained because, considering the same (large) preloading curvature (φ_p), a significant region of the core concrete fails in tension ($\varepsilon > 0 \rightarrow \sigma = 0$) for low compressive preloading ($\nu = -0.1$) and in compression ($\varepsilon < -0.0035 = \varepsilon_{cu} \rightarrow \sigma = 0$) for large compressive preloading ($\nu = -0.5$). Consequently, it can be concluded that a certain level of axial compression may counteract the always negative influence of core moment preloading on jacketed R/C sections.

Figures 9 and 10 show comparisons between 3D failure surfaces with jacketed R/C sections of different geometry, reinforcement and preloading parameters. Specifically, figure 9 shows the enhancement of section capacity with (a) increasing jacket thickness for the same jacket reinforcement ratio ($\rho_j = 10$ ‰) and (b) with increasing jacket reinforcement ratio for the same jacket thickness (d_j = 15 cm). This comparison was performed without considering core preloading, in order to focus only on material variations (geometry, reinforcement) as well as the robustness of the solution procedure. It is observed that, for the former case (a), the strength gain is localized in the compressive region (−N) due to the presence of increasing concrete areas (contributing only in compression), while for the latter case (b), the strength gain is almost equal both in the tension and compression region due to the presence of increasing steel areas (equally contributing both in compression and tension). By analogy, the above cases could be referred as ‘kinematic’ and ‘isotropic’ strength gain, respectively.

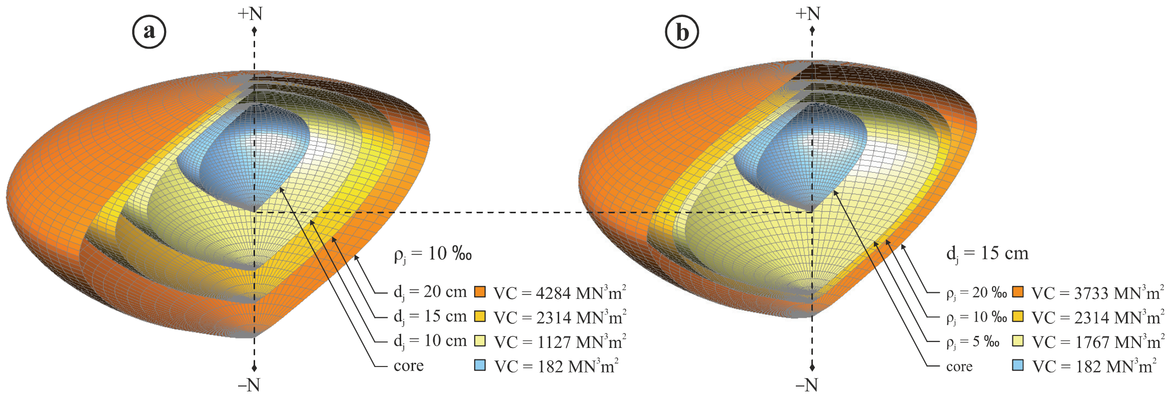

Figure 9. Effect of jacket geometry and reinforcement on ultimate strength

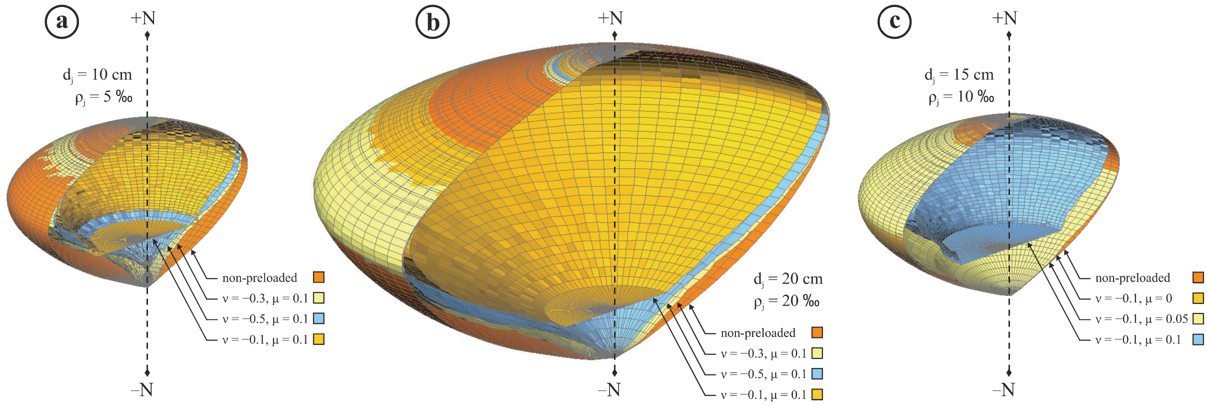

Figure 10. Effect of preloading on ultimate strength for various loading levels

In figure 10, the depicted comparisons between failure surfaces include the effects of core preloading as well. It is generally observed that the preloading effect becomes more pronounced for medium to higher compression levels, while it is not influential for lower compression. More specifically, subfigures (a) and (b) show the two geometry / reinforcement extremes (i.e. d_j = 10 cm / $\rho_j = 5$ ‰ and

d_j = 20 cm / ρ_j = 20 ‰, respectively) for all considered axial preloading levels ($\nu = -0.1, -0.3, -0.5$) and large constant moment preloading ($\mu = 0.1$), in order to examine the cases where the preloading effects are more pronounced, as already indicated in figure 8. It is again confirmed that medium axial preloading ($\nu = -0.3$) best counteracts the unfavorable moment preloading actions, exhibiting the lowest strength loss. However, it is shown again that for larger jacket dimensions and reinforcement (case b), the above differences are diminishing. Furthermore, subfigure (c) shows a failure surface comparison for a typical jacketed pier (d_j = 15 cm, ρ_j = 10 ‰) with low axial preloading ($\nu = -0.1$) and all considered moment preloading levels (μ = 0, 0.05, 0.1). It is observed that differences between non-preloaded and preloaded cases are marginal, except for the largest moment preloading level ($\mu = 0.1$), which is manifested as a shrunk failure surface towards higher compression with a noticeable compression cutoff ‘cap’. This cutoff is present on the tensile region as well (less significant, hence not clearly visible) and is justified by the fact that when the jacket material reaches its uniaxial limit state, a substantial region of the preloaded core has already failed (zero stresses).

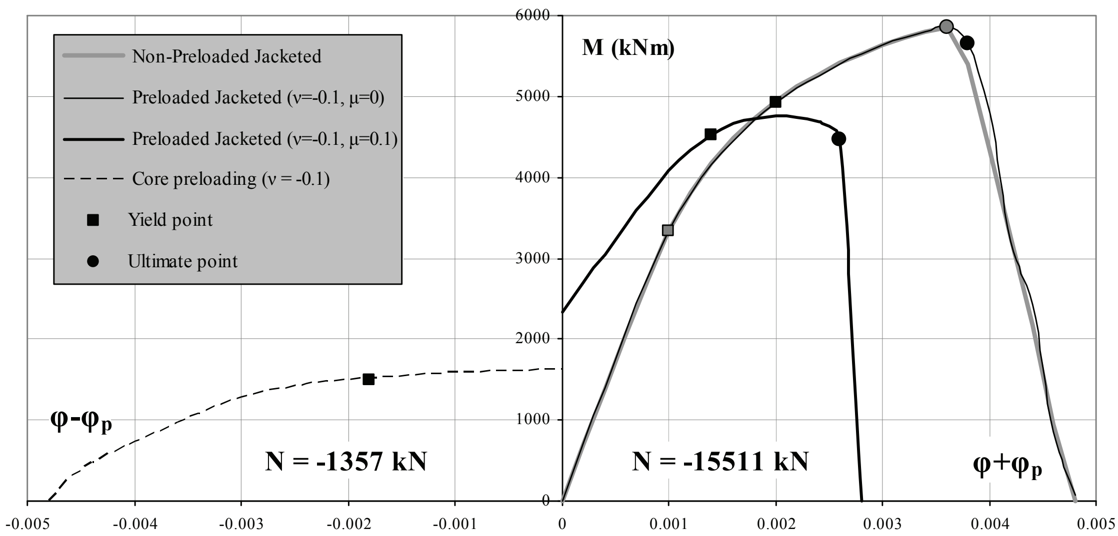

Figure 11. Moment-curvature response of jacketed R/C section with and without preloading

The response of a typical jacketed R/C section (d_j = 15 cm, ρ_j = 10 ‰) in moment-curvature terms is depicted in figure 11, for zero excitation angle (θ=0) and high compression ($\nu_{tot} = -0.5 \rightarrow N = -15511$ kN), selected in order to better highlight the differences between preloaded and non-preloaded cases. Specifically, it is observed that for axial-only preloading ($\nu = -0.1$), the difference in strength is marginal, however, when large moment preloading is introduced ($\nu = -0.1$, $\mu = 0.1$), a strength drop of approximately 20 % is observed, with similar reduction in ultimate curvature (corresponding to the first attainment of the ultimate strain among jacket materials - circular points on Fig. 11 curves). As far as the curvature ductility is concerned (ultimate over yield curvature), there is a reduction from 3.60 for the non-preloaded case down to 1.90 for axial-only preloading and 1.85 for axial/moment preloading. However, this significant curvature ductility reduction is only attributed to the delayed yielding of the jacket reinforcement bars due to axial preloading and hence it cannot be considered an alerting issue.

5. CONCLUSIONS

In this paper, the effect of core preloading on the ultimate strength and moment-curvature response of jacketed R/C bridge pier sections was investigated, using a robust section analysis method and performing an extended parametric analysis for several geometric, reinforcement and preloading parameters. The most important conclusions from the present study can be summarized as follows:

a) The effect of preloading on the ultimate strength is marginally favorable when only axial preloading is considered.
b) When axial preloading is combined with moment, the effect on the ultimate strength becomes significantly adverse.
c) Preloading becomes more favorable when jacket thickness and reinforcement ratio is increased.
d) Preloading effects become more pronounced for medium to higher compression levels, while it is not so influential for lower compression.
e) Medium axial preloading was found to best counteract the unfavorable moment preloading actions, exhibiting the lowest strength loss.
f) Strength loss under large moment preloading levels is manifested as a shrunk failure surface towards higher compression, with a 'cap' style cutoff. This cutoff is also present, on the tensile region, at a smaller scale.
g) Comparisons of moment-curvature response showed that for axial-only preloading, the difference in strength is marginal. However, when large moment preloading is introduced, both strength and ultimate curvature are noticeably reduced, under large axial compression levels.

The final objective of the present study is attempting to answer the vital question whether preloading effects should be accounted for, when applying section analysis for jacketed R/C bridge piers and generally for jacketed R/C vertical members, under biaxial bending with axial load. It is deemed that the answer to the above question is negative; notwithstanding the important differences that were observed (in terms of volumetric capacity), especially for large moment preloading levels, the inspection of the actual failure surfaces showed that these strength reductions are localized in higher compression regions, which are generally not expected or even allowed in modern seismic design. Therefore, for acceptable bridge column axial compression levels (e.g. $\nu_{tot} \leq 0.3$), the effect of core preloading can be safely ignored.

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