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# **The Effect of Preloading on the Strength of Jacketed R/C Columns**

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## **Abstract**

The influence of core preloading on the strength of jacketed reinforced concrete (R/C) columns is analytically investigated. A recently proposed method for arbitrary composite section analysis in biaxial bending and axial load is extended to include preloading actions. A parametric evaluation of the preloading effect using quantitative indices is performed, considering the variability of several parameters such as section geometry, amount of reinforcement, and various axial and moment preloading levels. Results are presented in the form of 3D failure surfaces and moment-curvature curves. Specific cases where the preloading effect is more pronounced are finally highlighted.

Keywords: Preloading, R/C jackets, Seismic retrofit, Flexural strength, Section analysis

## **1. INTRODUCTION**

Strengthening of R/C columns for enhancing their structural performance under seismic loading is naturally applied on preloaded cores (i.e. the ‘old’ column), due to existing gravity loads. In columns with high axial loading, it is practically difficult - if not impossible - to construct the concrete jacket after unloading the column 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 (e.g. corner columns in buildings or monolithic pier to deck connections in bridges). However, for the design or assessment of repaired or strengthened columns, it is usually assumed, for simplicity, that the concrete jacket is constructed on an unloaded core, considering a monolithic section during analysis [1], i.e. the concrete core and the jacket are assumed to share the same strain profile.

The effect of core preloading on the flexural capacity of jacketed R/C columns has been addressed in some studies, yet mainly on the basis of experimental testing. The common experimental procedure involves the axial preloading of the core to a certain amount of its axial capacity and the subsequent strengthening with concrete jacketing. In fewer cases, core preloading is continued until considerable crushing and buckling of the longitudinal reinforcement occurs, therefore the concrete jacket is introduced mainly for repair reasons. In the study by Takeuti et al. [2] the concrete core was axially loaded from 44 % to 87 % of its 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 preloading does neither affect the strengthening process nor does it adversely affect the load bearing capacity of the retrofitted column. Ersoy et al. [3] applied axial preloading on the core of jacketed R/C columns up to 75 % of its 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 a 5 % to 10 % decrease in 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, Vadoros and Dritsos [4,5] compared the performance of axially preloaded and non-preloaded jacketed R/C columns under combined axial loading and bending moment. Comparison on the basis of flexural capacity revealed a significant increase in strength up to

35 % when axial preloading of the core was considered. It is noted that in the above cases, the thickness, as well as the longitudinal reinforcement, of the jacket were kept constant in all test specimens, however different concrete strengths for the core and the jacket were 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 R/C sections is generally lacking; a somewhat relevant studies by Ong and Kang [6] and Liew and Xiong [7] are concerning steel-concrete composite sections with preloading on the steel core. The key objective of the present study is to analytically investigate the effect of combined axial and moment preloading of the core on the strength of jacketed R/C columns. In the following sections, a recently suggested numerical method [8] 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 normalised axial and moment preloading levels. The analysis results are presented in the form of 3D failure surfaces and moment-curvature curves. 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 [8]. 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 fibre groups ( $FG_i$ ), for simulating various section elements e.g. concrete or structural steel areas, distributed

reinforcement or fibre-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 [9], which is a requisite feature for compiling R/C jacketed sections (Fig. 1, right), without resorting to complicated fictitious cuts [10].

Each section component can 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 ( $\varepsilon_{ou}$ ,  $\varphi_u$ ) is imposed on the section, following the Bernoulli-Euler assumption (Fig. 2, right). This ultimate strain profile is derived using multicriteria limit states, which are preset for each material model, usually according to Code regulations (e.g. [11,12]). Following derivative-free solution strategies, the axial and moment capacity values ( $N$ ,  $M_x$ ,  $M_y$ ) in the form of biaxial moment or axial-moment interaction plane curves or 3D failure surfaces are calculated. Moreover, the complete moment-curvature response of the section can also be extracted. An in-depth presentation of the aforementioned numerical procedures is provided in Papanikolaou [8].

The limitation of the existing method is that the same ultimate strain profile is attributed to all section components (see 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 included in 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 first performed. The analysis constants are the neutral axis orientation ( $\theta$ ) and the preloading axial load ( $N_p$ ). The requisite preloading strain profile ( $\varepsilon_{op}$ ,  $\varphi_p$ ) is extracted when the target preloading moment ( $M_p$ ) is reached during curvature incrementation. For the special case

where only axial preloading is considered ( $M_p = 0$ ), the resulting strain profile ( $\varepsilon_{op}, \varphi_p = 0$ ) corresponds to initial stress equilibrium state for zero curvature (Fig. 3).

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 eq. 14 for areas/lines and eq. 22 for fibre groups, in [8]).

$$y = \varepsilon_{ou} - \varphi_u y \rightarrow y = (\varepsilon_{ou} - \varphi_u y) + (\varepsilon_{op} - \varphi_p y) \quad (1)$$

With the above modification, the resulting total strain profile for the core subsection reflects the addition of strains due to preloading to those due to the considered global ultimate limit state (Fig. 4). The mathematical formulations for the remaining section components (i.e. jacket concrete/reinforcement) remain unmodified. An 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 materials. This assumption is justified by the fact that since the core has already been damaged due to preloading, it is expected to fail before the jacket reaches its full 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 no longer 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, i.e. possible interface slip [13] is ignored.

Fig. 5 depicts the ultimate strain and stress profiles of a common rectangular jacketed R/C

section for three distinct cases: without preloading, preloading with only axial load ( $N_p$ ), 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 parabolic-linear model [12], while reinforcement is not shown for clarity. It is again shown that the ultimate strain profile of the section is always defined in terms of jacket material criteria (here: concrete compressive failure), while the core stress contribution reduces, especially when moment preloading is imposed. However, apart from the preloading actions themselves, the effect of preloading may also depend on other parameters such as section geometry and amount of reinforcement, which will be further investigated in the subsequent sections by a parametric study.

### 3. ANALYTICAL SETUP

The numerical method outlined in the previous section will be applied to a series of parametric analyses covering a rather broad range of structural behaviour expected in practice and focusing on: (a) an old circular R/C bridge column, and (b) a square R/C structural column, both strengthened by R/C jacketing. The selected bridge column belongs to a three-column frame pier (Fig. 6, top), hence it is subjected to both axial and moment preloading actions, due to gravity loads (more pronounced in the transverse bridge direction). The column diameter is 1.2 m, with low strength C12 type concrete ( $f_{c,c} = 12$  MPa), reinforced with 36 $\varnothing$ 20 bars, modelled as fibres, of low strength C220 steel grade ( $f_{y,c} = 220$  MPa), which corresponds to a Code minimum ratio of approximately  $\rho_c = 10$  ‰. 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 ‰ (with respect to the jacket area) of grade B500C steel ( $f_{y,j} = 500$  MPa) were

considered as linearly distributed reinforcement, resulting in a total of 9 different strengthening cases. For each of the above nine strengthening cases, nine combinations of normalised axial and moment preloading levels for the core subsection were considered ( $v = -0.1, -0.3, -0.5$ , combined with  $\mu = 0.00, 0.05, 0.10$ ) together with the trivial, non-preloaded case for  $v = \mu = 0$  (a total of 90 analyses). The R/C building column selected is a typical square jacketed column, experimentally tested by Bousias et al. [14] (column Q-RCR), with a width of  $\alpha = 25$  cm and a jacket thickness of 7.5 cm. The concrete strengths were  $f_{c,c} = 27.7$  MPa and  $f_{c,j} = 55.3$  MPa for the core and the jacket, respectively, and the reinforcement was 4Ø14 bars with  $f_{y,c} = 313$  MPa for the core and 4Ø20 bars with  $f_{y,c} = 487$  MPa for the jacket (Fig. 6, bottom). For this column, higher compressive axial preloading was imposed, which is more likely to be encountered in multi-storey buildings, with a total of nine combinations ( $v = -0.3, -0.5, -0.7$  combined with  $\mu = 0.00, 0.05, 0.10$ ), together with the non-preloaded case. All material constitutive laws are adopted from Eurocode 2 [12], 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. The set of preloading actions for each column ( $N_p, M_p$ ) were calculated from:

$$N_p = v \cdot \frac{\pi d_c^2}{4} \cdot f_{c,c} \quad M_p = \mu \cdot \frac{\pi d_c^3}{4} \cdot f_{c,c} \quad (\text{circular column}) \quad (2)$$

$$N_p = v \cdot \alpha^2 \cdot f_{c,c} \quad M_p = \mu \cdot \alpha^3 \cdot f_{c,c} \quad (\text{square column}) \quad (3)$$

It is noted that the imposed preloading actions ( $N_p, M_p$ ) are always kept below the core capacity (ultimate flexural resistance), i.e. concrete jacketing is used for strengthening rather than repair of damaged columns. Furthermore, in order to completely isolate and investigate the effect of preloading, any material-related ‘manipulating’ factors, such as safety or

confinement factors were ignored in the parametric analysis.

For the quantitative evaluation of section ultimate strength, it is herein introduced a new capacity index, namely *volumetric capacity* (VC), which corresponds to the section 3D failure surface volume, expressed in  $\text{N}^3\text{m}^2$  units (Fig. 7). 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 level (horizontal cross-section on the 3D surface).

#### **4. ANALYSIS RESULTS**

Following the parametric setup described in the previous section, 90 different jacketed circular R/C bridge columns and 10 square R/C building columns, with and without preloading effects were analyzed using an ad-hoc developed software (Fig. 8). From each analysis, the full 3D failure surface was extracted, along with the calculated volumetric capacity (VC).

For the 81 preloaded circular columns, the percentage difference compared to the respective non-preloaded section (i.e. same jacket thickness and reinforcement) was derived, and the results, in histogram form, are depicted in Fig. 9. It is observed that the effect of preloading on flexural strength is marginally favourable (up to +2.5 %) when only axial preloading is considered. This favourable influence has been also reported in various experimental studies (e.g. [2,5]) and can be explained by the fact that the augmented core strain profile ( $\epsilon_u + \epsilon_{op}$ ) due to axial preloading (see Figs. 4 and 5), is generally mapping on higher material stresses, which are subsequently integrated into higher section capacity. On the contrary, for increasing moment preloading levels, the preloading effect becomes

significantly adverse (down to  $-38.6\%$ ). This is justified as follows: when moment preloading is introduced, the corresponding preloading curvature ( $\phi_p$ ) distorts the core ultimate strain profile, resulting to overstraining of large parts of the core (beyond material ultimate limits) thus the corresponding stresses are zeroed, leading to a significantly lower section capacity.

Furthermore, it is also observed that preloading becomes less adverse 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 jacket contribution to the strength of the entire section becomes dominant, as 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.

A more in-depth evaluation of the analysis results also shows that 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. Nevertheless, this can be explained because for the same high preloading curvature ( $\phi_p$ ), a significant region of the core concrete fails in tension ( $\epsilon > 0 \rightarrow \sigma = 0$ ) for low compressive preloading ( $\nu = -0.1$ ) and in compression ( $\epsilon < -0.0035 = \epsilon_{cu} \rightarrow \sigma = 0$ ) for high compressive preloading ( $\nu = -0.5$ ). Consequently, it can be concluded that a moderate level of axial compression may counteract the normally negative influence of core moment preloading on jacketed R/C sections.

Figs. 10 and 11 show comparisons between 3D failure surfaces with jacketed R/C sections of different geometry, reinforcement and preloading parameters. Specifically, Fig. 10 shows the enhancement of section capacity for (a) increasing jacket thickness while keeping the same jacket reinforcement ratio ( $\rho_j = 10\%$ ) and (b) increasing jacket reinforcement ratio, keeping the same jacket thickness ( $d_j = 15\text{ cm}$ ). This comparison was performed without

considering core preloading, in order to focus 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 equidistant 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.

In Fig. 11, 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 high compression levels, while it is not so influential for lower compression. More specifically, subfigures (a) and (b) show the two geometry / reinforcement extremes (i.e.  $d_j = 10 \text{ cm} / \rho_j = 5 \text{ ‰}$  and  $d_j = 20 \text{ cm} / \rho_j = 20 \text{ ‰}$ , respectively) for all considered axial preloading levels ( $v = -0.1, -0.3, -0.5$ ) and for large moment preloading ( $\mu = 0.1$ ), in order to examine the cases where the preloading effects are more pronounced, as already indicated in Fig. 9. It is confirmed that medium axial preloading ( $v = -0.3$ ) best counteracts the unfavourable moment preloading actions, leading to the lowest strength loss. However, it is shown again that for the largest jacket thickness and reinforcement (case b), the above differences are smaller. Furthermore, subfigure (c) shows a failure surface comparison for a typical jacketed bridge column ( $d_j = 15 \text{ cm}, \rho_j = 10 \text{ ‰}$ ) with low axial preloading ( $v = -0.1$ ) and all considered moment preloading levels ( $\mu = 0, 0.05, 0.1$ ). 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 cut-off ‘cap’. This cut-off is present in 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 part of the preloaded core has already failed (zero stresses).

The response of a typical jacketed R/C circular section ( $d_j = 15$  cm,  $\rho_j = 10$  ‰) in moment-curvature terms is depicted in Fig. 12, for zero excitation angle ( $\theta=0$ ) and high compression ( $v_{tot} = -0.5 \rightarrow N = -15511$  kN), selected in order to better highlight the differences between preloaded and non-preloaded cases. It is observed that for axial-only preloading ( $v = -0.1$ ), the difference in strength is marginal, however, when large moment preloading is introduced ( $v = -0.1, \mu = 0.1$ ), a strength drop of approximately 20 % is observed, with similar reduction in ultimate curvature (corresponding to the first attainment of the ultimate strain of jacket materials - circular points). As far as 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 as an alerting issue, in the sense that the energy absorption capacity of the member is not jeopardised.

For the square columns analyzed, which is not only a different type of section but also a smaller one than that of the bridge column, the main trends, discussed in the previous paragraphs, concerning the effect of preloading on the section flexural strength are similar. Fig. 13 shows the percentage difference for the 9 preloaded sections compared to the respective non-preloaded case (left), together with a failure surface comparison for the highest compressive axial preloading ( $v = -0.7$ ) and between various moment preloading levels (right). It is again noted that when only axial preloading is taken into account, its effect is marginally favourable (up to +2.0 ‰) and becomes adverse (down to -12.8 ‰) when moment preloading is introduced. However, preloading is now considerably less influential for the

considered square columns, even for the now higher levels of axial preloading, compared to the bridge circular columns. This can be attributed to the fact that for the jacketed square columns, the contribution of the jacket is clearly more significant ( $t_j/\alpha = 7.5/25 = 0.3$  compared to the thickest circular jacket  $t_j/d_c = 20/120 = 0.167$ ). Finally, the shrunk view of the failure surface in the high compression region is again apparent, yet in a non-smooth shape, due to the lack of axial symmetry.

## 5. CONCLUSIONS

This study addressed the effect of core preloading on the flexural strength and moment-curvature response of jacketed R/C column sections, using a robust section analysis method and performing an extended parametric analysis for several geometric, reinforcement, and preloading parameters. The most important conclusions can be summarized as follows:

- a) The effect of preloading on flexural strength is marginally favourable when only axial preloading is considered.
- b) When axial preloading is combined with bending moment, the effect on the flexural strength may become significantly adverse.
- c) Preloading becomes more favourable when jacket thickness and reinforcement is increased, which is normally the case with small columns.
- d) Preloading effects become more pronounced from medium to high axial compression levels, while it is not so influential for lower compression.
- e) In circular columns, a medium axial preloading was found to best counteract the unfavourable moment preloading actions, exhibiting the lowest strength loss.
- f) In circular columns, the strength loss under high moment preloading levels is manifested as a shrunk failure surface towards higher compression, with a 'cap' style cut-off.

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 larger axial compression levels.

The final objective of the present study is to provide an answer to the vital question whether preloading effects should be accounted for, when applying section analysis for jacketed R/C columns, under biaxial bending and 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 column axial compression levels (e.g.  $v_{tot} \leq 0.55$ -0.65 for building columns [15]), the effect of core preloading can be safely ignored.

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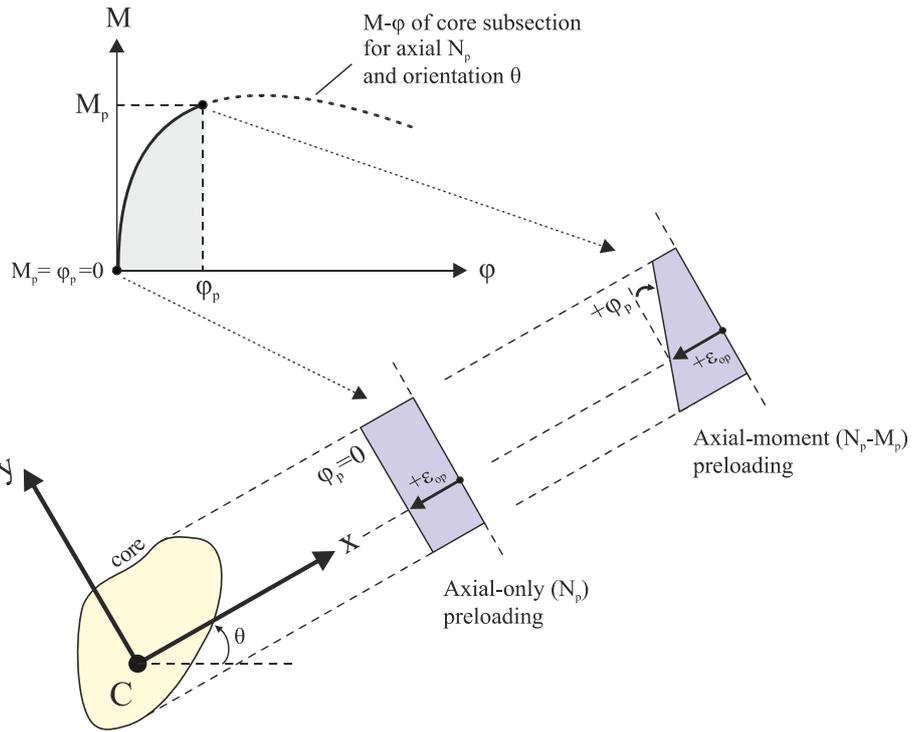


Fig. 3 Core subsection initial strain profile due to preloading

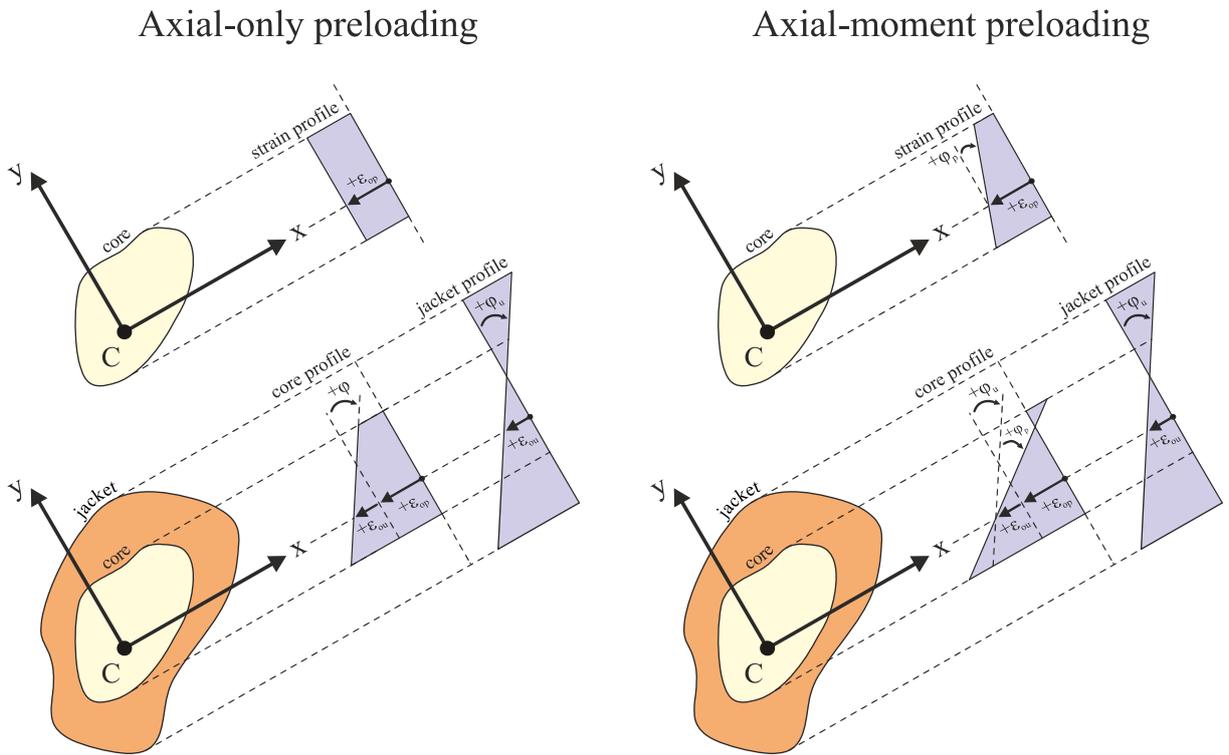


Fig. 4 Jacketed section ultimate strain profiles including preloading effects

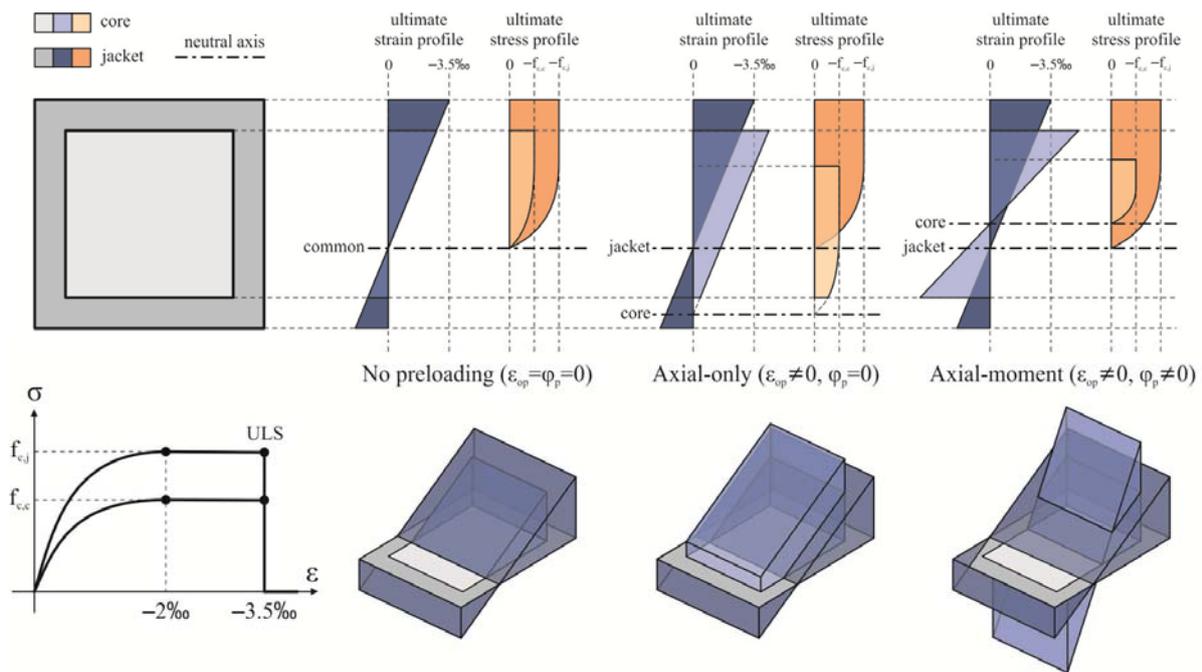


Fig. 5 Jacketed section strain/stress profiles including preloading effects

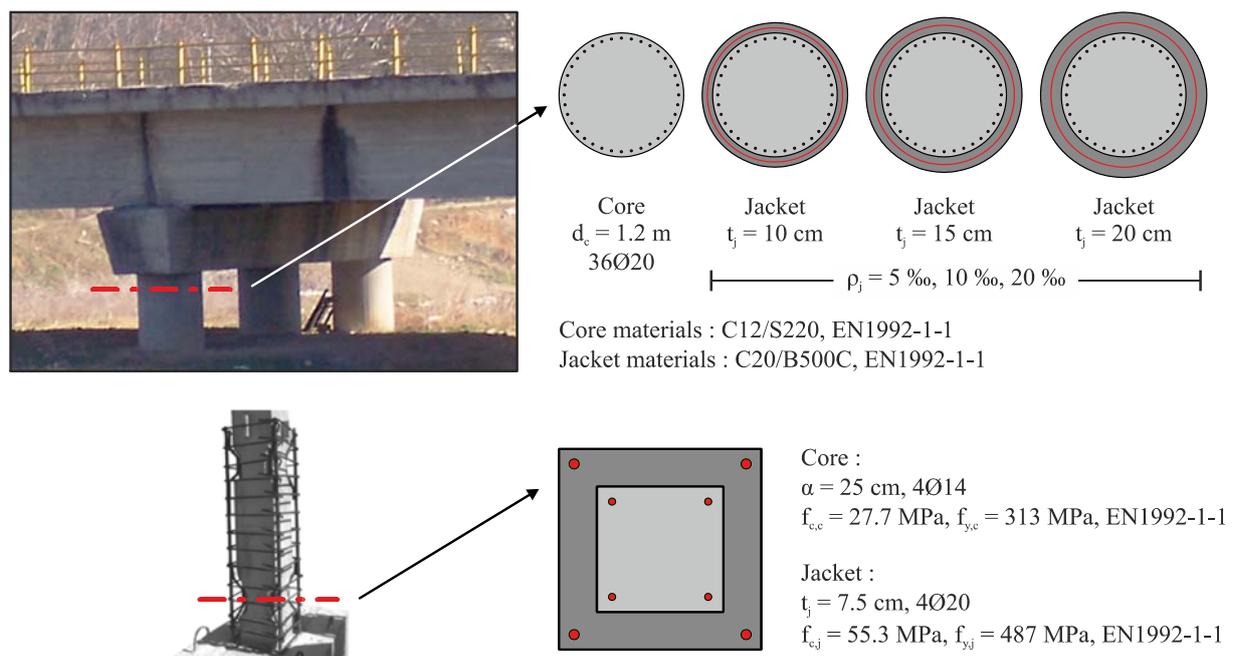


Fig. 6 Jacketed sections considered in the parametric analysis

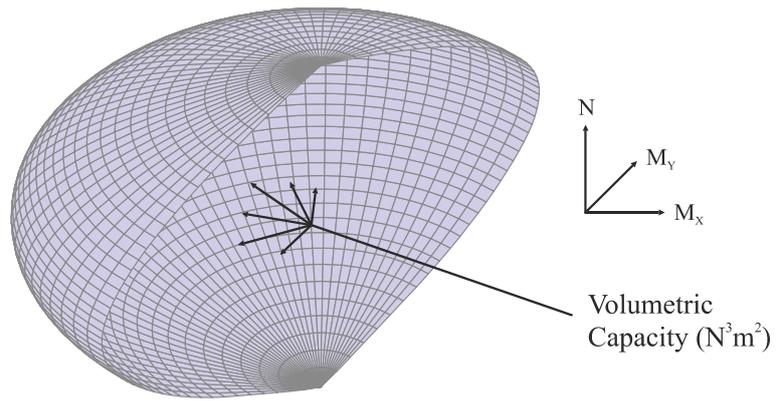


Fig. 7 Definition of the volumetric capacity index (VC)

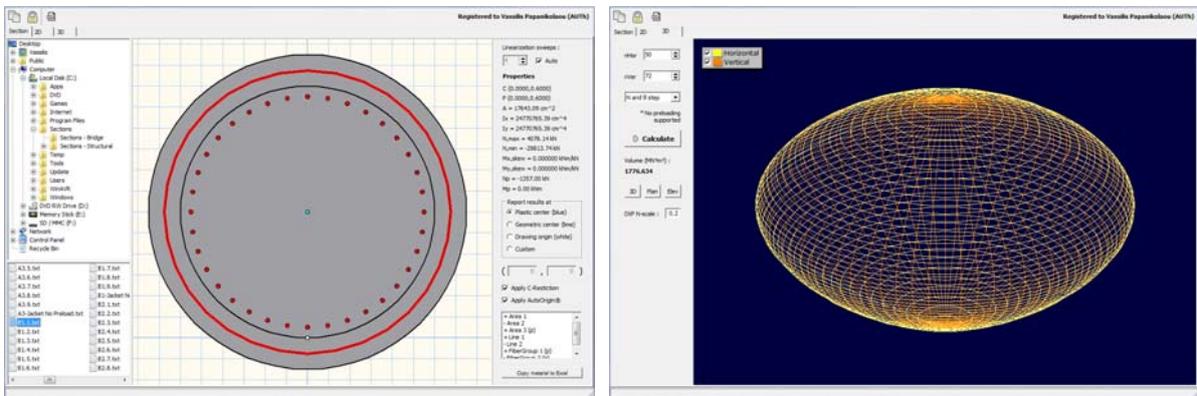


Fig. 8 Ad-hoc developed software for section analysis

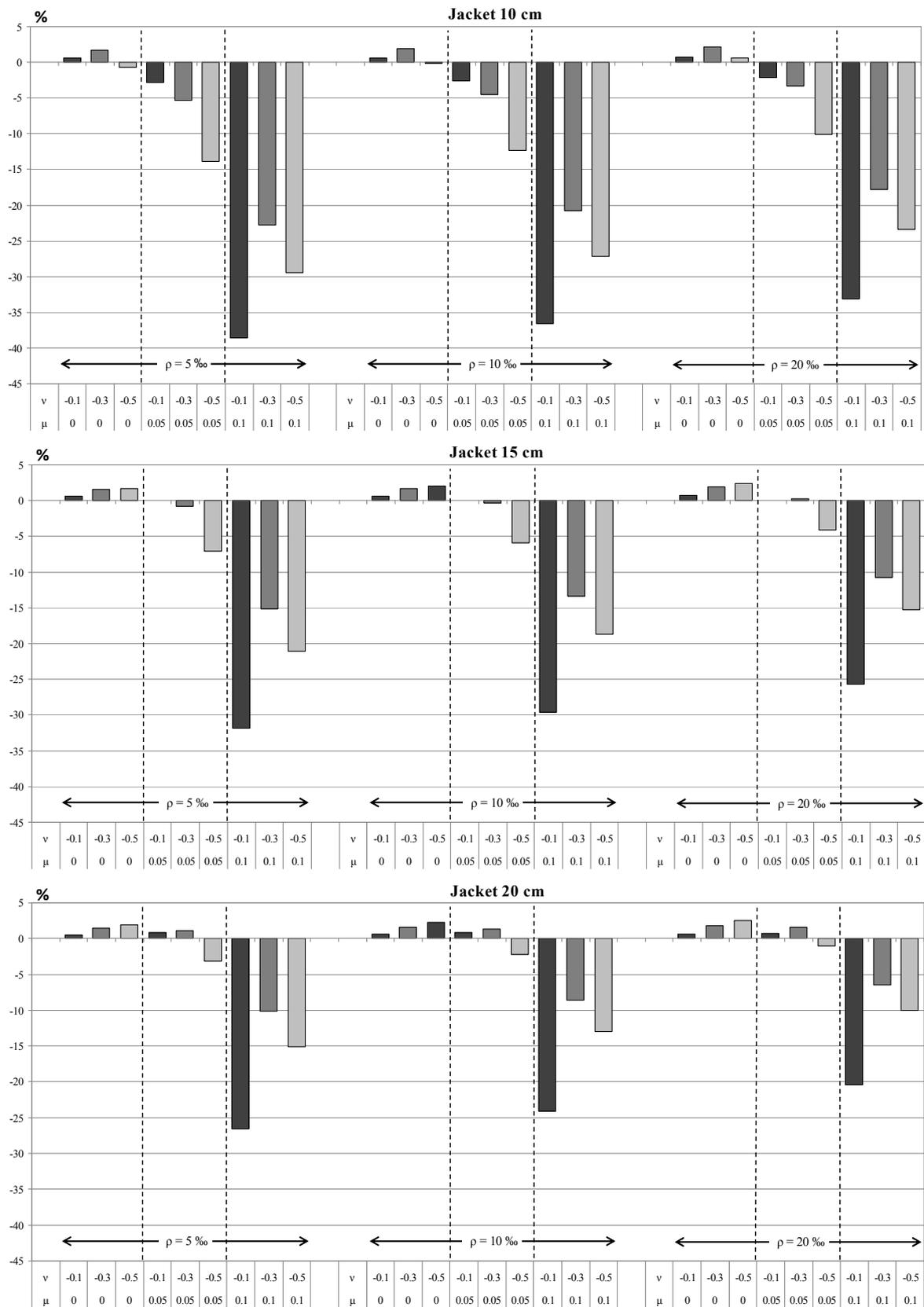


Fig. 9 Percentage differences in volumetric capacity due to preloading for circular columns

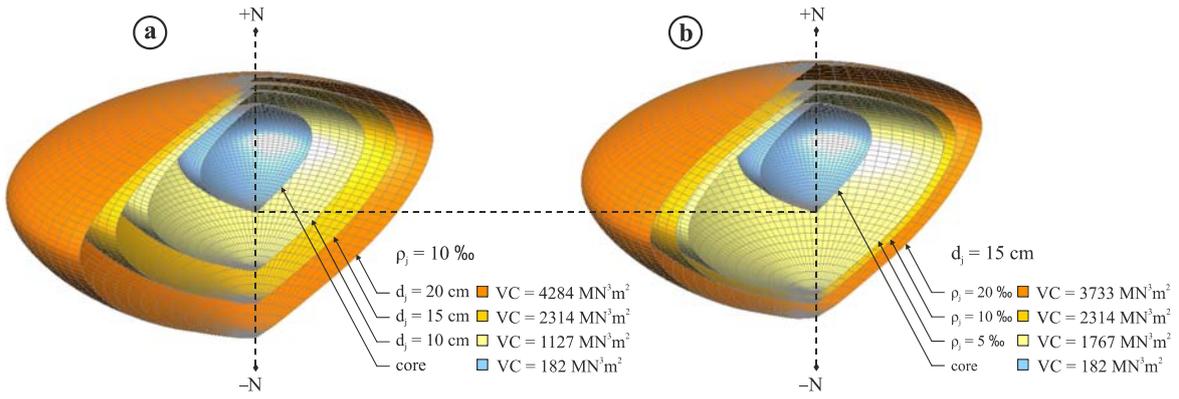


Fig. 10 Effect of jacket geometry and reinforcement on circular column strength

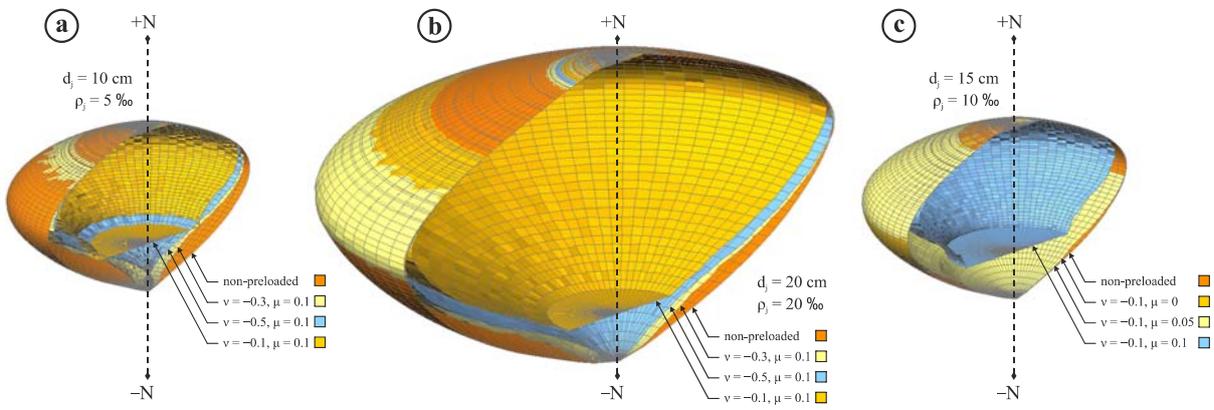


Fig. 11 Effect of preloading for various preloading levels on circular column strength

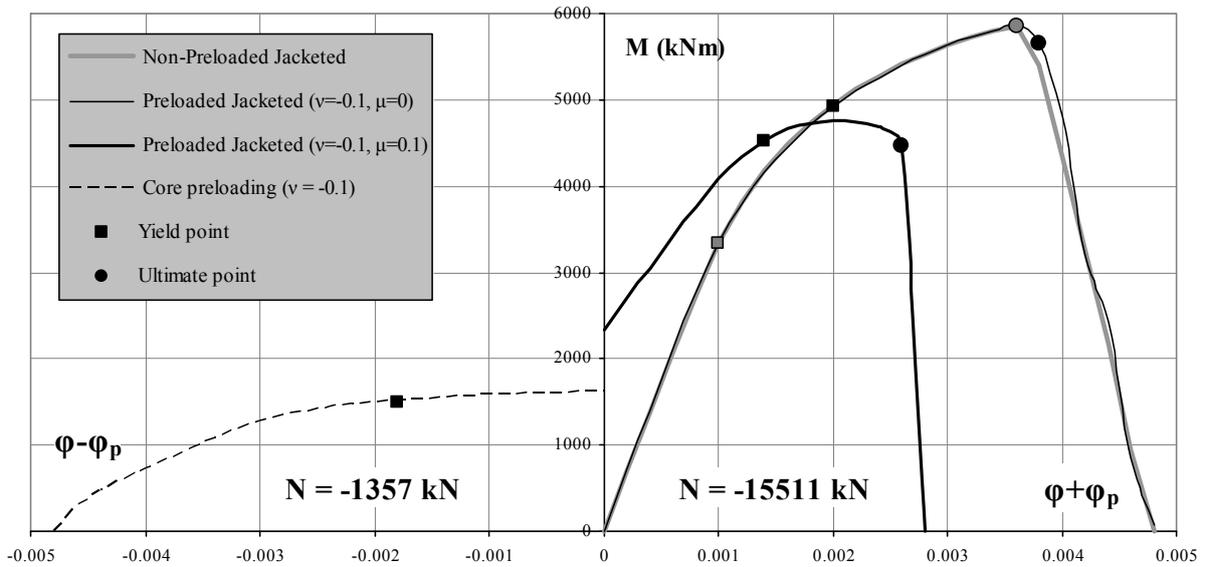


Fig. 12 Moment-curvature response of circular column with and without preloading

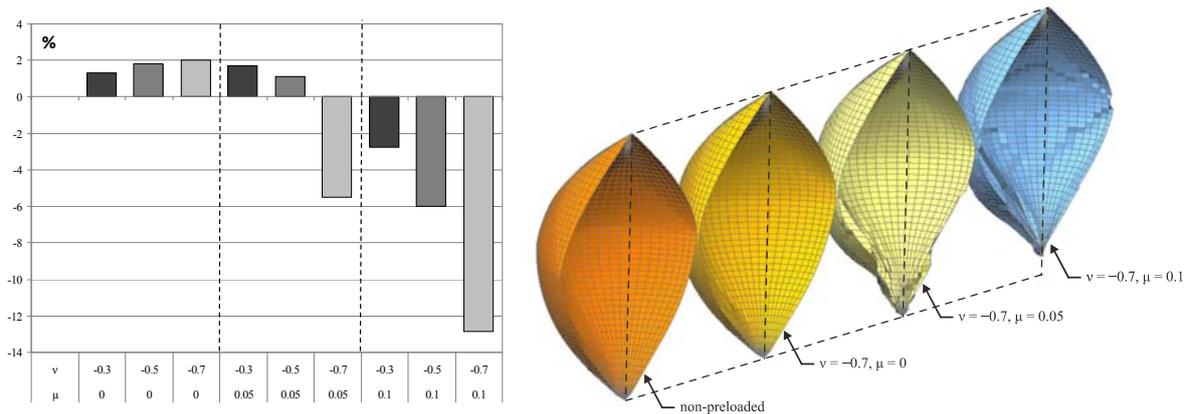


Fig. 13 Percentage differences in volumetric capacity due to preloading for square columns (left) and comparison of 3D failure surfaces for high axial preloading (right)