Concrete Cover Influence on Inelastic Buckling of Longitudinal Reinforcing Bars

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Abstract. The paper presents the results of numerical analyses of post yielding behaviour of compressed reinforcing bars, taking into account the impact of concrete cover on static equilibrium path. Concrete cover was modelled as a transverse ties with characteristics like for the tensioned concrete. The calculations were performed for various parameters of concrete cover and bar slenderness, with the use commercial system Abaqus/CAE. The results of analysis showed that the concrete cover has a significant impact on inelastic buckling of reinforcing bars.

1. Introduction

The impact of seismic loads, exceptional loads or overloads on structures may lead to postcritical states in various elements of the structure. While analysing the behaviour of reinforced concrete elements in the state of postcritical deformations, and when the ultimate deformations of a concrete cover are exceeded, it is necessary to consider inelastic buckling of compressed longitudinal bars.

The existing models of compressed bars, inter alia [3,4,6], which take into account their possible inelastic buckling have been elaborated on the basis of the analysis of behaviour of bars (both ends fixed) compressed in a laboratory (figure 1a). The carried out experimental tests and numerical analysis [1,3,7,10,11] imply that the geometry of the bars (slenderness), as well as the mechanical features of steel that the bars are made of (i.e. yield strength, the length of the plasticity plateau, the relation between strength and yield strength and the course of strengthen curve) influence the inelastic buckling of bars.

Figure 1. (a) Buckling bar during test. Buckling mode: (b) local buckling, (c) global buckling
However, the behaviour of compressed bars placed in reinforce concrete elements differs from their behaviour in laboratory environment. Most frequently, longitudinal bars placed in reinforce concrete beams and columns experience buckling between two neighbouring ties – local buckling (figure 1b). In this case, the critical force in the bar is influenced by (apart from the bar slenderness) both the reinforce concrete cover and the forces of adhesion between the concrete and the longitudinal bar. Buckling of bars in a reinforced concrete element takes place not until the detachment of the cover. Therefore, the cover contributes to delaying the buckling process in reinforcement bars. The buckling process may also occur in a compressed bar in a reinforced concrete element along a section longer than the span between the ties, e.g. a bar may buckle between the first and the fifth ties – a global buckling (figure 1c). Then, the behaviour of a compressed bar is conditioned not only by the reinforcement concrete cover but also by the ties placed along the bar. Additionally, the behaviour of the compressed bars in a reinforced concrete element is influenced by the method in which the element is loaded and the geometrical imperfections of the bars and the element, as well as the strains and deformations of reinforced concrete elements.

Due to the above factors, it is necessary to modify the known models of compressed reinforcing bars. The models should include the above mentioned factors which influence their behaviour. It will enable more precise prognosis of the behaviour of reinforced concrete elements while operating within the range of postcritical deformations.

The paper presents the results of numerical analysis of postcritical behaviour of compressed longitudinal reinforcement bars. The objective of the carried out analyses was to determine the influence of the cover of longitudinal reinforcement bars on the equilibrium path of the bars. The cover was modelled with transverse bonds with characteristics as for concrete subject to tension. Calculations were carried out for various parameters of concrete cover and for various options of bar slenderness. The calculations were carried out with the use of ABAQUS/CEA application.

2. Inelastic buckling of reinforcing bars

The task of inelastic buckling of reinforcement bars was the subject of numerous papers, which presented both the results of experimental tests and numerical simulations. The presented research include extensive investigation into the influence of geometrical parameters of the bars but their mechanical parameters have been examined insufficiently. Their testing has been restricted to few types of steel manufactured in the authors' countries.

![Figure 2. (a) Relation stress - longitudinal strain, (b) Relation stress - lateral strain [7]](image_url)
Figure 2 presents relations between stress ($\sigma_s=F/As$) normalised in terms of yield strength ($\sigma_s/f_{sy}$), and a relative shortening of the bar, and a relative transverse displacement $\Delta t/\phi$ of the central section of the bar (figure 2b) obtained in numerical analyses. As can be noticed, the bearing load capacity depends on the bar slenderness. Maximum stresses in the bar $\sigma_s$ are greater than the yield strength $f_{sy}$, if the bar slenderness $s/\phi<8$. For greater slenderness, maximum stresses in the bar are equal to the yield strength. The compressed bar loses its straight form immediately after it has reached the yield strength. When stresses in the bar are equal to the yield strength, the bar undergoes transverse deformations.

The task of the influence of the cover on buckling of bars was referred to in, inter alia [4,5,15]. With the use of analytic methods, the authors of these works tried to determine the value of ultimate stress in the cover of reinforcement at the moment of bar buckling [5], the value of the ultimate force in a longitudinal bar acting on the reinforcement cover at the moment of bar buckling [15], or else transverse ultimate stresses resulting from the cover bending at the moment of bar buckling [4]. The authors did not consider the issue of critical force in bars of longitudinal reinforcement at the moment of their buckling.

There are much more works referring the influence of ties on global inelastic buckling of bars of longitudinal reinforcement [4,9,12]. With the use of analytic and numerical methods, the authors tried to find the influence of the rigidity of ties on inelastic buckling of bars. Some authors also determined simultaneous impact of reinforcement cover on bar buckling.

Interesting results were obtained in numerical analyses of the influence of external spiral reinforcement attached to a reinforced concrete column (of a circular cross-section) with a FRP composite strips on buckling of a bar [2]. In the case of a considerable span between the ties (bar slenderness $s/\phi=15$), the composite spiral reinforcement increases essentially the critical force in reinforcement bars and accompanying strains. In this case, the static equilibrium path gets closer to the material curve.

3. Description of the model concept
Figure 3 presents a physical calculation model for the behaviour of a bar of longitudinal reinforcement placed in a compressed reinforced concrete column. The impact of individual bars of longitudinal reinforcement on the concrete cover was assumed to be limited to the span between the bars in the cross-section. The cover detached when stresses in concrete, in a vertical cross-section which runs through the centre of gravity of the bars in the middle of the section between the ties, reached its strength to tension. As experiments reveal, the detachment of the cover was a rapid process which spread quickly along the whole section between neighbouring ties. Local buckling of a bar, i.e. buckling between neighbouring ties, has been assumed. The reinforcement bars, along the section between the ties, were fixed in their both ends. In the physical model, the cover was replaced by side bars (of a concrete nature) holding a bar of longitudinal reinforcement.
A bar (16 mm diameter) fixed in its both ends was analyzed. The calculations were carried out for eight options of the bar slenderness. The ratio of the distance between the supportive points $s$ and the diameter of the bars $\varnothing$ equaled: $s/\varnothing = 5, 6, 7, 8, 9, 10, 12, 15$. Mander's nonlinear steel model [1] was assumed with plasticity plateau and strengthen curve.

The analysis was carried out with the use of Abaqus/CAE system. The task was modelled with 25-beam elements (BEAM 2D) of an elasto-plastic nature. For a steel bar, the yield strength was assumed $f_{sy} = 400$MPa, and the strain at yielding equalled 2‰. Strains at reinforcement $\varepsilon_{sh}$ equalled 1‰, Young modulus at strengthen $E_{sh} = 10$GPa, whereas strength $f_{su} = 600$MPa. The concrete cover was reduced to a transverse bar (of cross-section $s \times 32$ mm and elastic characteristics with concrete damaged plasticity. The vertical bar made of reinforcing steel was subject to axial compression of 1 N.

The calculations were divided into two stages. In the first stage, the forms of buckling of the model were determined with the use of Linear perturbation/Buckle analysis. Then, the form of buckling, resulting from the first mode (Eigenvalue) was recorded in a global system of coordinates using displacements in the input file. In the second stage of the analysis, static analysis (Static, Riks) was carried, applying formerly recorded geometrical imperfections of the model. The analysis allowed the transition through the bifurcation point and simulation of the model's behaviour after it has lost stability.

4. Results and discussions
Figure 4 presents selected equilibrium paths for bars with and without a cover, including three options of bar slenderness $s/\varnothing = 5, 8, 15$. The figure also includes the material curve. As can be seen, the reinforcement cover has a positive influence of the compressed bar. The cover contributes to the increase in the load-bearing capacity, expressed by maximum stress $\sigma_{sf}^*$, and also to the increase in strains $\varepsilon_{sf}$ at the moment of buckling in relation to load-bearing capacity $\sigma_{sf}$ and strains $\varepsilon_{sf}$ without the cover. The increments in load-bearing capacity and strains depend essentially on bar slenderness.
Figure 4. Relation stress – strain for various options of bar slenderness

Figure 5 presents the impact of the reinforcement cover on maximum stresses in the bar, $\sigma_{sf^*}$, in the function of bar slenderness $s/\phi$ (figure 5a) and the impact of the reinforcement cover on bar strains for maximum stress $\varepsilon_{sf^*}$ in the function of bar slenderness $s/\phi$ (figure 5b). The results of the analysis were compared with results obtained for bars without a cover, values $\sigma_{sf}$, $\varepsilon_{sf}$, and the comparison was presented in the figure.

As can be seen in graphs in figure 5, reinforcement cover contributes to a noticeable increase in the load-bearing capacity of compressed bars compared to bars without a cover only for slenderness $s/\phi<10$ (figure 5a). The greatest increase in load-bearing capacity is observed for bars of slenderness $s/\phi=10$ and equals just under 10% and then decreases linearly to zero for slenderness $s/\phi=10$. On the other hand, the impact of the reinforcement cover on strains at the moment of bar buckling is considerable (figure 5b). The presence of the reinforcement cover increases strains at buckling $\varepsilon_{sf^*}$ by app. 50%, within the bar slenderness of $s/\phi$ from 5 to 9. The reinforcement cover does not influence considerably strains at bar buckling, for bars $s/\phi\geq10$. The strains are similar in both cases.

Ductility is the ability of materials, elements of structures or structures to transmit elastic deformations without considerable deterioration in load-bearing capacity. Material ductility is measured by a strain ductility coefficient which was defined as a quotient of strain $\varepsilon_{so}$ at the moment of formal loss of load-bearing capacity $0.9\sigma_{sy}$ and strain at the moment of yielding $\varepsilon_{sy}$. Figure 6
presents alterations of the ductility coefficient for bars with the cover \( \mu_{\varepsilon}^* \), and bars without the cover \( \mu_{\varepsilon} \) in the function of longitudinal bars' slenderness.

![Figure 6. Alterations in ductility of bars with and without a cover in the function of bar slenderness](image)

Figure 6. Alterations in ductility of bars with and without a cover in the function of bar slenderness

An essential impact of the cover on the ductility of compressed reinforcing bars, similar to the formerly presented cases, may be noticed for bar slenderness \( s/\phi < 10 \). When the slenderness exceeds ultimate value \( s/\phi = 10 \), the influence of the reinforcement cover on the behaviour of compressed bars is inconsiderable. Above this value of slenderness, the presence or the absence of the reinforcement cover does not result in any alterations to the elasticity of the compressed bars. The ductility of bars with cover \( \mu_{\varepsilon}^* \) is greater than the ductility of bars without one \( \mu_{\varepsilon} \) by app. 50% if the value of bar slenderness \( s/\phi \) is less than 10.

5. Conclusion

The existing normative physical and mathematical models for reinforcing bars do not take into account possible inelastic buckling in compressed bars. It is assumed that the behaviour of the compressed and tensioned bars is the same in both case. The presented results of experimental and numerical research indicate it to be wrong. The longitudinal reinforcing bars buckle. Additionally, the presented results of the analysis show that their concrete cover influences considerably their behaviour. The cover influences inconsiderably the buckling capacity. However, the reinforcement cover contributes to the increase in ductility of the compressed bars, which directly translates into the increased ductility of cross-sections and bent elements.

The presented results of numerical analysis require to be further confirmed in experimental tests.

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