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Review article

Experimental research and analysis of load capacity and deformability of slender high strength concrete columns in biaxial bending

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ABSTRACT

The paper shows results of experimental research and a comparative analysis of load-bearing capacity and deformability of sixteen reinforced concrete columns made of HSC in bi-axial bending. The computational analysis was conducted on the basis of approaches commonly used in EC2 (2004) and ACI (2008) standards, and the results were compared with the results of own experimental research. The described tests were carried out on elements similar to columns at a natural scale, whose slenderness ratio in main planes was: 1.0, 2.0, 3.0 and 4.0. All elements were made of concrete of a mean cylindrical strength amounting, on the test day, of 155 MPa.

The paper attempts to answer the question whether the approaches to column design according to ACI (2008) and EC2 (2004) codes can be applied to concrete of higher classes than the ones recommended in these codes. The laboratory tests and comparative calculations carried out proved that guidelines presented in ACI (2008) and EC2 (2004) concerning analysis of columns in bi-axial bending are safe for elements made of HSC. Application of simplified code methods resulted in obtaining significantly lower load-bearing capacity in comparison to the outcome of experimental research, which, above all, was related to the inaccuracy of the simplified methods of analysis of second order effects. The results of the experimental research were closest to the ACI (2008) guidelines.

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1. Introduction

Columns in bi-axial bending are very often used in designed RC (reinforced concrete) structures. Despite of the fact that the topic is well known and has been analysed by many researchers over several dozen years, there are still a lot of unknowns is in this respect. Tests carried out so far have mainly been concentrated on columns made of ordinary concrete. Currently, designers are using HSC more and more often, especially in RC columns used in high-rise buildings.

The paper shows results of experimental research and an analysis of load-bearing capacity and deformability of sixteen reinforced concrete columns in bi-axial bending. The tested elements were made of HSC in a scale similar to the natural one. The columns differed with respect to their side proportion, the size of the load eccentricity and the deviation angle of the load plane. The paper shows a complete analysis of load-bearing capacity and deformability, on the basis of approaches commonly used in ACI [2] and EC2 [1] standards, and the results were compared with the results of experimental studies.

Methods for the determination of load-bearing capacity columns in bi-axial bending included, inter alia, in the following standards: ACI [2], EC2 [1], are based on an analysis of load-bearing capacity and deformability separately for each main direction, which enables the definition of an approximate load-capacity for the oblique plane.

Theoretical approaches analyse two problems separately:

– Problem No. I:

Checking the load-bearing capacity of the cross-section in bi-axial bending for preset values of N_{Ed}, M_{Edx}, M_{Edy}. There is a number of papers that quote numerical methods to build interaction surfaces (limit load-bearing capacity) at the cross-section level. The use of such an approach in design practice requires that suitable computer software should be available. In order to facilitate designing works, a number of simplified methods was proposed, based on the load-bearing capacity of cross-section in the main planes. The two methods proposed in 1960 by Bresler [3]: "reciprocal load method" (Eq. (1)) adopted by standard ACI [2] and "load contour equation" (Eq. (2)) in the version adopted by the EC2 [1] are especially popular.

– Problem No. II:

Checking the load-bearing capacity of a slender element in bi-axial bending. In this case, for the proper estimation of M_{Edx} and M_{Edy} moments, in the most critical cross-sections of slender columns, it is necessary to know second order effects. Simplified approaches included in standards to determine second order effects are usually based on the nominal curvature method (NC)-EC2 [1] or nominal stiffness (NS)-EC2 [1] and ACI [2]. Most of the simplified approaches assume a separate calculation of second order effects for both the main column planes – EC2 [1] and ACI [2]; however, there are few papers estimating second order effects directly in the oblique deflection plane [4,5].

The method included in ACI [2] ("reciprocal load method") allows one the specification of columns capacity in bi-axial bending, using Eq. (1).

$$\frac{1}{N_{Ed}} \geqslant \frac{1}{N_{Rdx}} + \frac{1}{N_{Rdy}} - \frac{1}{N_{Rd0}} \tag{1}$$

where: N_{Rdx}, N_{Rdy} – the design ultimate loads for each plane as for uniaxially compressed elements, taking the second order effects into account, N_{Rd0} – the design ultimate load for cross-section under axial compression, N_{Ed} – the design value of axial force.

According to the commentary to ACI [2], Eq. (1) is the best suited if the load-bearing capacities of N_{Rdx} and N_{Rdy} are higher than the corresponding forces at the point of limit balance (i.e. axial forces designated for the limit value of the compressed zone range $\xi_{eff} = \xi_{eff.lim}$).

According to EC2 [1], the exploitation degree of load-bearing capacity for columns in bi-axial bending may be obtained in a simplified way, using the following expression:

$$\left(\frac{M_{Edx}}{M_{Rdx}}\right)^{a} + \left(\frac{M_{Edy}}{M_{Rdy}}\right)^{a} \leqslant 1.0 \tag{2}$$

where: M_{Edx}, M_{Edy} – the design moments around the respective axes, including nominal second order moments, M_{Rdx}, M_{Rdy} – the moment resistances in the respective directions, a – the exponent depending on N_{Ed}/N_{Rd0}.

According to Bonet [5], the column load capacity calculated on the basis of Eq. (2) may be overestimated if the cross-section is bent mainly in the plane with a higher stiffness and the applied force is approximately equal to the limit load-bearing capacity of the cross-section. This is due to the fact that in EC2 [1], the method does not take into account mutual interaction of the curvature in one and in the other direction. Tests carried out by Pallarés et al. [6,7] and a numerical analysis made by Cortés-Moreno [8] confirmed that in the analysis of slender reinforced concrete columns, the load-bearing capacity in relation to the weaker axis is important. In slender elements, buckling is possible in a plane with lower stiffness, despite of the fact that the load is applied mainly in the higher stiffness plane.

Simplified methods defining the load-bearing capacity for columns in bi-axial bending are based on a load-bearing analysis carried out separately for each direction. Apart from the above, the load-bearing capacity of such columns can also be analysed in an accurate manner. Design of bi-axial bending cross-sections using the accurate method is a complex issue, given the need to take into account non-linear σ–ε relations for concrete and steel (physical nonlinearities) and additionally, with respect to slender elements, second order effects (geometric nonlinearities). The issue is more complicated because of the characteristics of concrete, which is quasi-brittle material and may be cracked, which leads to a reduction of column stiffness, which, in turn, increases second order effects.

The literature contains papers that analyse the load-bearing capacity of elements in bi-axial bending at a cross-section level, taking into account only physical nonlinearities: CEB/FIB [9], Barros and Ferreira [10], Bonet et al. [11,12], Cedolin et al. [13], Falitis [14], Gil-Martin et al. [15], Helgason [16], Ludovico et al. [17], Marmo et al. [18], Pallarés et al. [19], Resheidat et al. [20], Rodriguez-Gutierrez and Aristizabal-Ochoa [21], Sfakianakis [22], Silva et al. [23,24], Vivo and Rosati [25].

The cited papers enable, in a numerical manner, the creation of an interaction (or limit load-bearing capacity) surface in N_{Rd} – M_{Rdx} – M_{Rdy} space, at the cross-section level. Its use in the design process or when checking the load-bearing capacity of reinforced concrete columns can be twofold:

- For short columns, where second order effects are negligible, one can use it to determine directly the element load-bearing capacity.
- For slender columns, where second order effects must be taken into account, its use must be preceded by a correct estimation of total eccentricities.

There are few papers at a level of the entire element, which take into account the combination of geometric and physical nonlinearities: Ahmad and Weerakoon [26], Furlong and Hsu [27],