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FE analysis of failure behaviour of reinforced concrete columns under eccentric compression

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Abstract

Paper presents results of FE modelling of failure behaviour of reinforced concrete columns under eccentric compression. Concrete was described with an elasto-plastic model using isotropic hardening and softening. A Drucker–Prager criterion with a nonassociated flow rule was defined in a compressive regime and a Rankine criterion with an associated flow rule adopted in a tensile regime. To ensure the mesh-independence and to capture strain localization in concrete, both criteria were extended by a characteristic length of microstructure in a softening regime with the aid of a non-local theory. The reinforcement was described with an elastic-ideally plastic constitutive law by von Mises. Two-dimensional plane strain and three-dimensional simulations were performed. The FE-calculations were carried out with a different characteristic length of micro-structure, reinforcement ratio, column slenderness, load eccentricity, distribution of the tensile strength, bond-slip between concrete and reinforcement and fracture energy. The FE results were quantitatively compared with those from laboratory experiments performed by Kim and Yang [Kim J, Yang J. Buckling behaviour of slender high-strength concrete columns. Engineering Structures 1995;17(1):39–51]. A satisfactory agreement was achieved.

Keywords: Bond-slip; Buckling; Column; Concrete; Cracks; Elasto-plasticity; FEM; Non-locality; Reinforcement

1. Introduction

Reinforced concrete columns supporting slabs and beams and subject to eccentric compression belong to the most important structure elements. Their role still grows due to the increasing size of multistorey high buildings. In particular, nowadays the use of high-strength concrete columns and concrete-filled steel tubular columns (Kim and Yang [1], Kilpatrick and Rangan [2]) is becoming very popular worldwide.

The buckling behaviour of reinforced concrete columns depends upon many different factors as: column slenderness, load eccentricity, boundary conditions at ends, area and shape of the cross-section of concrete, area and spacing of the vertical and horizontal reinforcement, reinforcement ratio, compressive and tensile strength of concrete, strength of reinforcement, type and character of load (short- or long-term, monotonic or cycling), concrete shrinkage and creep. To calculate the optimum concrete and reinforcement area, and thus to decrease building costs and increase net floor space, a realistic prediction of the effect of these factors on stresses in the entire column element is needed. However, the buckling behaviour of reinforced concrete columns is a complex phenomenon due to cracks in concrete.

The intention of the paper is to numerically predict the behaviour of reinforced concrete columns subject to eccentric compression with consideration of cracks. The analysis was carried out with a finite element method based on elasto-plasticity with non-local softening. To describe plain concrete for monotonic loading, a continuum elastic–plastic crack model was used. A linear Drucker–Prager criterion with an isotropic hardening and softening and a non-associated flow rule was defined in a compressive regime, and a Rankine criterion with an isotropic softening and an associated flow rule was adopted in a tensile regime. To ensure the mesh-independence, to capture properly localized zones and to

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investigate a deterministic size effect, both criteria were enhanced in a softening regime by a characteristic length of microstructure with the aid of a non-local theory. Through that, the well-posedness of the underlying incremental boundary value problem was preserved, and the width and spacing of localized zones were properly described. In turn, the behaviour of reinforcement was modelled by an elasto-perfect plastic constitutive law by von Mises. The effect of the load eccentricity, column slenderness, area of the vertical longitudinal reinforcement, bond between concrete and reinforcement, fracture energy, distribution of the tensile strength and characteristic length of microstructure on the failure strength of columns was studied. Two-dimensional plane strain and three- dimensional FE simulations were carried out. The theoretical results of failure forces were compared with corresponding comprehensive experiments carried out by Kim and Yang [1].

There have been many experimental studies on reinforced concrete columns. The effect of the load eccentricity was investigated on columns by Makovi [3], Gruber and Menn [4], Kiedroń [5], Billinger and Symons [6] and Lloyd and Rangan [7]. In turn, Billinger and Symons [6], and Kim and Yiang [1] studied the effect of the slenderness of columns. Szuchnicki [8] analysed the influence of the cross-section area. In turn, the effect of creep was investigated by Kordina et al. [9], the effect of lateral prestressing by Gardner et al. [10], the effect of the vertical reinforcement by Lloyd and Rangan [7], Saenz and Martin [11], Martin and Olivieri [12] and Kim and Yang [1], and the effect the horizontal reinforcement by Oleszkiewicz et al. [13], Korzeniowski [14] and Nemecek and Bittnar [15]. In turn, the influence of the concrete strength was shown in tests by Kiedroń [5], Billinger and Symons [6], Lloyd and Rangan [7], Saenz and Martin [11], and Kim and Yang [1]. The size effect was investigated by Bazant and Kwon [16]. The results of experiments have evidently shown that bearing capacity of columns decreases with increasing load eccentricity, slenderness, ratio of the end fixing and creep. The increase of concrete strength influences significantly the bearing capacity for small eccentricities. The lateral prestressing and horizontal reinforcement increase the bearing capacity of cylindrical elements. The failure load exhibits a strong size effect (the bearing capacity decreases as the column size increases).

There exist several theoretical models to calculate the bearing capacity of elements under eccentric compression on the basis of analytical assumptions and FEM [1,17–25] which provide satisfactory results as compared to experiments. The novelties of our comprehensive analysis as compared to other theoretical solutions dealing with columns are following: (a) consideration of a characteristic length of micro-structure in concrete, (b) comparative 2D and 3D-calculations and (c) application of bond-slip between concrete and reinforcement.

The paper is organized as follows. At the beginning, buckling experiments by Kim and Yang [1] are briefly described. Next, basic assumptions incorporated in the formulation of a constitutive model for concrete are outlined. Later, the details of finite element implementation are given. Next, the numerical 2D and 3D results on reinforced concrete columns subject to eccentric load are described and compared to experimental data [1] to demonstrate the validity of the model. Finally, general conclusions from the numerical research are provided.

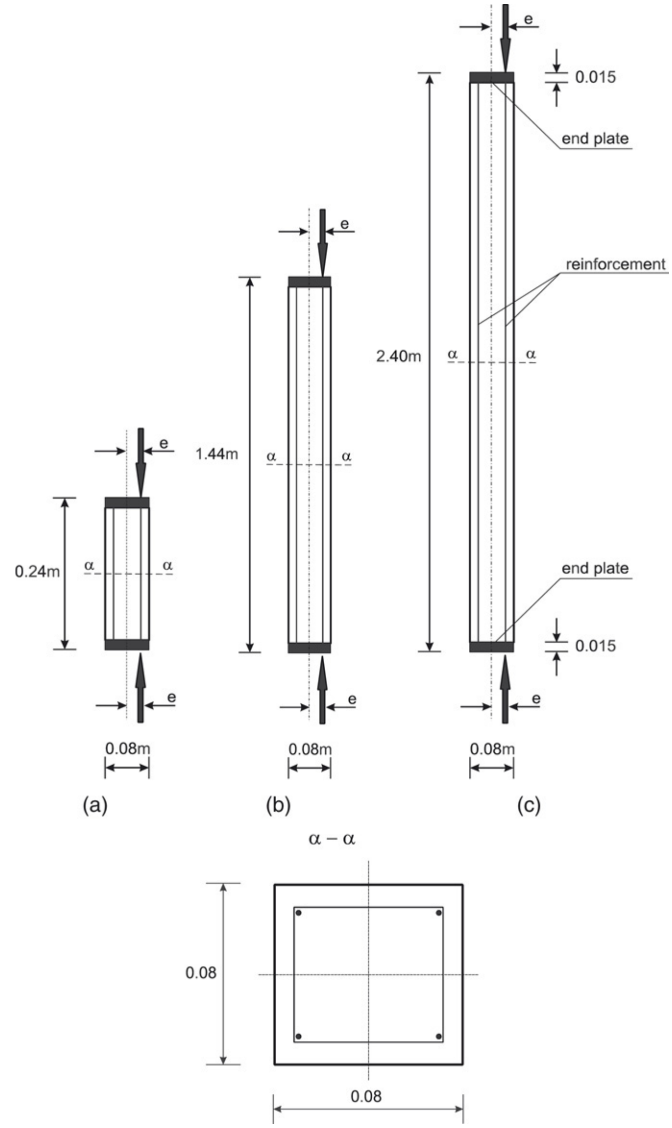

Fig. 1. Geometry of reinforced concrete columns in experiments by Kim and Yang [1]: (a) λ = 10, (b) λ = 60, (c) λ = 100.

2. Experiments on columns by Kim and Yang [1]

A series of laboratory tests was carried out for 30 tied reinforced columns with a square cross-section of $b \times h = 80 \times 80$ mm^2 and three slenderness ratios λ of 10, 60 and 100 (Fig. 1). The corresponding column lengths were $l = 0.24$ m, $l = 1.44$ m and $l = 2.40$ m, respectively. Three different concrete compressive strengths of 25.5 MPa, 63.5 MPa and 86.2 MPa and two different longitudinal steel ratios of 1.98% (4ϕ6) and 3.95% (8ϕ6) using a symmetric reinforcement were applied. The splitting tensile strength of concrete was 3.4 MPa, 5.5 MPa and 6.2 MPa, respectively. The maximum size of the aggregate in concrete was $d_{max} = 13$ mm. The concrete