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Deformation capacity of non-conforming r.c. columns under compressive axial load and biaxial bending

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ABSTRACT

In a performance based approach, the knowledge of ultimate capacity of reinforced concrete (r.c.) columns subjected to simultaneous compressive axial load and biaxial bending becomes essential to correctly assess the seismic capacity of existing structures. In the present work, the reduction of ultimate deformation (i.e. rotational) capacity of r.c. members due to the two components of bending moment is analysed by using a specific simplified numerical model. The influence of axial load, geometry, amount of longitudinal reinforcement and mechanical properties on the ultimate chord rotation of r.c. columns is investigated on a dataset of 780 numerical tests on non-conforming columns with plain bars governed by flexural mode. Then, a practice-oriented formulation for the ultimate rotation domain, based on the Load Contour method extended to the chord rotations, is proposed and discussed.

1. Introduction

The seismic assessment of reinforced concrete (r.c.) existing building is, nowadays, a topic widely investigated since recent earthquakes underlined the high vulnerability of those structures to seismic events. During an earthquake, r.c. structures exhibit a complex three-dimensional dynamic behaviour; the seismic excitation and the angle of incidence α of ground motion are not always predictable. The traditional approach for the evaluation of structural capacity under seismic actions is based on the analysis of the two independent components of ground motions in NS and WE direction. According to the current seismic codes provisions [1,2], the structures could be analysed assuming two unidirectional seismic actions in both longitudinal and transversal directions and then combining their effects. This assumption is suitable for structures with a regular layout. Under this distribution of unidirectional lateral loads, the structural elements (i.e. columns) are mainly subjected to compressive axial load and uniaxial bending. Therefore, structures characterized by an irregular in-plan configuration generally develop torsional responses that imply biaxial bending moment on the columns even under unidirectional excitation. Furthermore, the existing structures are commonly not perfectly regular (both in plant and elevation) and thus they could experience small torsional responses even if loaded along the principal directions.

In a performance based design approach, an accurate prediction of the structural capacity, in terms of both strength and deformation, should take into account the two simultaneous components of seismic excitation and the biaxial bending moment acting on the columns.

The strength capacity of r.c. members subjected to compressive axial load and biaxial bending has been widely investigated in literature, by developing specific numerical or analytical models [3–6]. The Eurocode 2 [7] suggests an analytic formulation for the strength failure surface N-M_x-M_y, according to the Load Contour method [8], which provides the strength domain M_x-M_y for square/rectangular cross-sections as a function of the two uniaxial flexural strengths, $M_{x,Rd}$ and $M_{y,Rd}$:

$$\left(\frac{M_x}{M_{x,Rd}}\right)^{\alpha_1} + \left(\frac{M_y}{M_{y,Rd}}\right)^{\alpha_2} = 1 \quad (1)$$

The accuracy of the analytic formulation is related to the exponents $\alpha_1 = \alpha_2$, which may be derived as a function of the cross-section geometric and mechanical properties and of the axial load (i.e. Eurocode 2 provides a proper formulation for $\alpha_1 = \alpha_2$ as a function of the axial load acting on the column). Many researchers focussed on the definition of proper formulations for the calibration

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Notation

The following symbols are used in this paper:

α	angle of incidence of imposed displacements
δ	imposed displacement
n	neutral axis
f	inflection axis
$\phi_{u,x0} - \phi_{u,y0}$	uniaxial ultimate curvature
ϕ_u	biaxial ultimate curvature
$\phi_{u,x} - \phi_{u,y}$	components of biaxial ultimate curvature along x-y axis
$\theta_{u,x0} - \theta_{u,y0}$	uniaxial ultimate chord rotation
θ_u	biaxial ultimate chord rotation
$\theta_{u,x} - \theta_{u,y}$	components of biaxial ultimate chord rotation along x-y axis
η	reduction of ultimate chord rotation with respect to the uniaxial ones
Δ	variation of η
N_{Ed}	external axial load
ν	dimensionless axial load
A_c	gross section area
A_s	reinforcement area
ρ	geometric reinforcement ratio
ω	mechanical reinforcement ratio
f_c	concrete compressive strength
f_y	reinforcement yielding strength
h	cross-section height
b	cross-section base
h/b	cross-section aspect ratio
θ_u^{LC}	simplified ultimate chord rotation according to Load Contour method
$\theta_{u,x}^{LC} - \theta_{u,y}^{LC}$	components of simplified ultimate chord rotation along x-y axis
$\overline{\alpha}$	exponent of LC method extended to the chord rotation
$\overline{\alpha}(\nu, \omega)$	simplified function for the exponent $\overline{\alpha}$
$\theta_{u,x0(EC8)} - \theta_{u,y0(EC8)}$	uniaxial chord rotations according to EC8-3 Eq. A4

of the exponents α_1 and α_2, based on numerical analysis results or derived by experimental data [9–11].

In spite of the strong effort in the field of the strength capacity of existing r.c. columns subjected to axial load and biaxial bending, a lack of investigation has been recognised on the deformation (i.e. chord rotation) capacity of r.c. members subjected to the two components of bending moment. Several studies investigated the experimental behaviour of r.c. members under uniaxial actions [12–20]. Analytical formulations or numerical values for the uniaxial chord rotation at ultimate conditions are provided by codes [1,21], based on theoretical or experimental evidences. Much less investigated is the behaviour of r.c. members subjected to oblique loading paths (i.e. biaxial bending) [22–27]. According to experimental results, ultimate chord rotation domains $\theta_{u,x} - \theta_{u,y}$ are proposed in [25,28] as an extension of the Load Contour method to the chord rotation capacity. Numerical procedures able to theoretically predict the Load-Deflection curve of biaxially loaded r.c. members have been developed and implemented in computer codes [29,30]; non-linear finite element models to simulate the behaviour of r.c. members subjected to biaxial excitations have been utilized in [31–36].

In this study, the ultimate capacity of r.c. members under simultaneous axial load and biaxial bending is analysed, focusing on the reduction of chord rotation capacity due to the two components of bending moment. A dataset of 780 numerical tests on non-conforming r.c. columns representative of existing buildings has been obtained by using a simplified numerical model [30], which extends the theoretical approach adopted by European code [21] for the prediction of ultimate chord rotation under uniaxial bending to the ultimate chord rotation under biaxial load conditions. The influence of axial load, geometry and mechanical properties on the ultimate deformation capacity has been investigated. Then, a practice-oriented formulation for the ultimate chord rotation domain $\nu - \theta_{u,x} - \theta_{u,y}$ is proposed, in order to easily and reliably evaluate the theoretical rotational capacity of members subjected to biaxial bending. The comparison between theoretical results and experimental capacity of r.c. members under biaxial bending is out of the scope of this work.

2. Research significance

The influence of bi-directional seismic excitations on the inelastic response of r.c. members is a key factor in order to correctly predict the structural capacity. Indeed, taking into account the two components of ground motion, the columns are subjected to combined compressive axial load and biaxial bending. Experimental results on r.c. columns pointed out that the member deformation capacity is strongly affected by oblique loading paths. However, common theoretical approaches accounts for ultimate chord rotation under unidirectional loads only. Thus, to fill such gap, a simple analytical approach able to relate biaxial bending and axial load for the evaluation of the member deformation (i.e. chord rotation) capacity in needed. The present study aims to define a simplified analytical practice-oriented formulation, in agreement with Eurocode approach under uniaxial bending, able to reliably predict the ultimate chord rotation of r.c. members under biaxial bending, without performing time-consuming analyses.

3. Ultimate deformation capacity of r.c. members

The response of r.c. members subjected to compressive axial load and biaxial bending could be evaluated following two possible approaches. The first, commonly applied to theoretically determine the strength capacity, assumes the two components of external bending moment $M_x - M_y$ to be proportional each other during the entire load history. By this, the inclination of the bending axis, given by the ratio of external actions, is constant but the deformed configuration cannot be captured in a plane since it is three-dimensional, see Fig. 1a. The second approach, commonly adopted in experimental tests, consists in imposing the angle of incidence α of the loading path, that is the two components of external displacement $\delta_x - \delta_y$ to be proportional each other during the entire load history, see Fig. 1b.

Under this condition, the inclination of the members' axis of inflection, f, is fixed during the entire load history and the deformed configuration will be plane along the plane of inflection. Thus, assuming a fixed direction of the axis of inflection, the inclination angle of the cross-section neutral axis n is constant during the load history (i.e. n is orthogonal to f) and equal to α (i.e. the inclination of the neutral axis is equal to the inclination of the imposed loading path, α).

In the present study, a simplified numerical model, which evaluates the response of r.c. members for a fixed inclination α of the neutral axis has been used [30]. According to the most common