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Strength and ductility of R.C. columns strengthened with steel angles and battens

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HIGHLIGHTS

- ▶ Flexural behaviour of strengthened columns with steel angels and strips.
- ▶ Extensive comparison with available experimental data referred to member under compression and flexure.
- ▶ Numerical comparison with existing codes in terms of moment axial force domains.
- ▶ Parametric analyses in term of available ductility and moment–curvature diagrams.

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ABSTRACT

In this paper the behaviour of R.C. members externally strengthened with steel angles and battens subjected to axial force and bending moment is analysed. A fibre model was utilised to predict the moment–curvature diagrams of the strengthened members on the basis of stress–strain curves of the constituent materials (confined concrete, steel bars and angles) recently derived by the author. The stress–strain curves utilised for compressed concrete were able to take into account the confinement effects induced by longitudinal (bars and steel angles) and transverse (stirrups and battens) steel reinforcements. Constitutive laws in compression for confined concrete and steel bars and angles were utilised for a preliminary calibration of the compressive response of axially loaded columns strengthened with steel cages. Therefore axial force and bending moment diagrams and moment curvature diagrams were derived and verified against experimental data available in the literature. Finally, a parametric analysis showing the influence of the main parameters governing the problems (angle and strip geometry and mechanical properties of constituent material) was carried out, mainly referring to moment axial force domains, moment curvature diagrams. The analysis showed the effectiveness of this reinforcing technique in improving both the strength and the ductility of R.C. columns.

1. Introduction

Steel jackets around square or rectangular R.C. columns are usually made up of four corner steel angles to which either continuous steel plates or thicker discrete horizontal steel battens are welded. This reinforcing technique, if properly designed, increases both the load-carrying capacity and the ductility of R.C. columns.

Referring to the calculation of the load carrying-capacity or the flexural response of R.C. members retrofitted with this reinforcing technique, many studies have made contributions [1–15].

Several design prescriptions are also given [1,16,17]. However, most of these studies separately link the increase in load-carrying capacity to concrete core confinement [2,17] or to the composite action if angles are directly loaded [16].

In the case of directly or indirectly loaded angles, it has been demonstrated experimentally [8] and theoretically [13] that the increase in load-carrying capacity is due both to the confinement and composite action and contributions present when this reinforcing technique is applied. Recent studies [11] have also stressed the importance of this reinforcing technique for R.C. members subjected to compressive loads or to monotonic and cyclic flexural actions in the case of both flexural and shear failure. Most models separately consider the composite action or the confinement effects induced while only few models consider both effects and refers mainly to the compressive behaviour of strengthened columns.

In this context the paper investigated on the response of R.C members externally strengthened with steel angles and battens subjected to axial force and bending moment and the original contribution of the paper was the study of the effect of steel angles and strips externally welded to the R.C. columns both in term of moment axial forces increments and available ductility. Extensive comparison with available experimental data and with models given in the codes [16,17] was made. Finally parametric analyses in term of available ductility and moment–curvature diagrams were carried out to highlights the effectiveness of this reinforcing technique.

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Nomenclature

b	side of square cross-section b
d_b	diameter of longitudinal bars
e	eccentricity ($e = M/N$)
f'_c	strength of the unconfined concrete.
$f_{l\max}$	equivalent maximum confinement pressure
f_y	the yield stress of longitudinal bars
f_{ya}	yield stress of the steel angles
f_{yb}	yield stress of the steel battens
f_{yl}	yield stress of the longitudinal bars and
f_{yst}	yield stress of the stirrups.
f_{cc}	strength of the confined concrete.
f_u	the ultimate stress of longitudinal bars
L	whole length of the column
L_1	side of steel angles
M	bending moment acting in the column
M_{sd}	bending moment on angle
M_u	ultimate moment
N	axial force acting in the column
N_{sd}	axial force on angle
N_u	ultimate axial force
n	number of longitudinal bars
s	pitch of steel battens
s_2	height of steel battens
t_1	thickness of steel angles
t_2	thickness of steel battens
s_{st}	pitch of steel stirrups
χ	curvature of cross-section
ε_{c0}	strain of the unconfined concrete
ε_{cu}	ultimate strain of the confined concrete
ε_y	the yield strain of longitudinal bars
ε_{sh}	the strain corresponding to the beginning of strain hardening
ε_{su}	the ultimate strain of longitudinal bars
ε_{cc}	strain of the confined concrete
ϕ_{st}	diameter of transverse stirrups
$q_{l\max}$	the maximum lateral load
σ_c	critical stress

2. Study case

The case examined here is that of a concrete member with a square cross-section with side b (Fig. 1) strengthened with steel angles with side L_1, and thickness t_1 and with steel battens with height s_2 and thickness t_2 placed at pitch s. The whole length of the column is L. f_{yb} is the yield stress of the steel battens and f_{ya} is the yield stress of the steel angles. The columns were subjected to the coupled effects of axial load N and bending moment M giving eccentricity $e = M/N$. Failure in the welded sections of steel battens and steel angles was not considered. Cases of directly loaded angles were considered, also including second order effects. The angles were assumed not to be bonded to the concrete and only made to adhere to it without gaps along the entire height. The presence of pre-existing of n longitudinal bars of diameter d_b and transverse stirrups of diameter ϕ_{st} placed at pitch s_{st} was also considered. f_{yl} is the yield stress of the longitudinal bars and f_{yst} is the yield stress of the stirrups. The effects of the steel cage were analysed separately from the effect of pre-existing steel reinforcements and the superposition principle was applied to consider both the effects.

Detailed and useful geometrical rules for the design of steel caging are those derived from Cirtek [2], which are: $-L_1 \geqslant 0.2 \cdot b; -t_1 \geqslant 0.1 \cdot L_1 = 0.02 \cdot b$. Analogously for steel strips, it should be: $-0.4 \leqslant \frac{s}{b} \leqslant 0.75; -t_2 \leqslant t_1; -s_2 \geqslant \frac{0.004 \cdot b^2}{t_2}$. Eurocode 8 [17] prescribes that the spacing between two successive steel strips should be at least b/2. For minimum thickness t_1 and minimum side L_1 Cirtek [2] suggests values of 5 and 50 mm, respectively.

3. Theoretical model for constituent materials

3.1. Modelling of concrete behaviour

The concrete model adopted here was the well-known model of Mander et al. [18] leading to stress–strain curves for effectively confined and unconfined concrete. It is based on the following relationship:

$$\sigma_c = \frac{\frac{\varepsilon}{\varepsilon_{cc}} \cdot f_{cc} \cdot r}{r - 1 + \left(\frac{\varepsilon}{\varepsilon_{cc}}\right)^r} \tag{1}$$

with

$$r = \frac{E_c}{E_c - E_{\text{sec}}} \tag{2}$$

where $E_c = 5000 \cdot \sqrt{f_{co}}$ in MPa and $E_{\text{sec}} = \frac{f_{cc}}{\varepsilon_{cc}}$, with f_{cc}, ε_{cc} the strength and the strain of the confined concrete.

The strength f_{cc} is determined, as suggested by Eurocode 8 [17] for strengthened columns, in the following form:

$$f_{cc} = f'_c \left[1 + 3.7 \cdot \left(\frac{f_{l\max}}{f'_c}\right)^{0.87}\right] \tag{3}$$

with f'_c and ε_{c0} the strength and the strain of the unconfined concrete and ε_{cc} evaluated, according to Mander et al. [18] as follows:

$$\varepsilon_{cc} = \varepsilon_{co} \cdot \left[1 + 5 \cdot \left(\frac{f_{cc}}{f'_c} - 1\right)\right] \tag{4}$$

The ultimate strain ε_{cu} of the confined concrete was assumed as in Monturi and Piluso [11] in the following form:

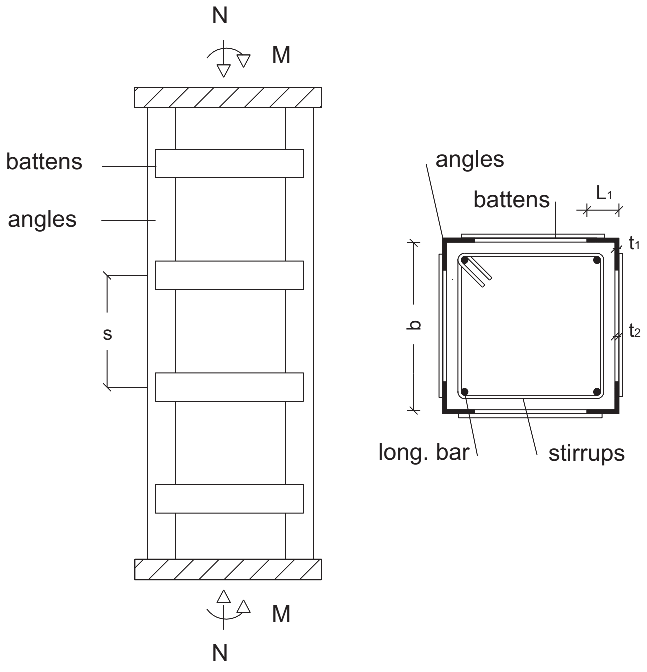

Fig. 1. Study cases.