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PROPOSED MODEL OF PREDICTING THE REDUCED YIELD AXIAL LOAD OF REINFORCED CONCRETE COLUMNS DUE TO CASTING DEFICIENCY EFFECT

Abstract

The study deals with the investigation of the effect of casting deficiencies- both experimentally and analytically on axial yield load or reinforced concrete columns. It includes 6 specimens of square section (150x150x500 mm) of 24.37 MPa nominal concrete strength with 4 longitudinal steel bars of 8 mm (500 MPa nominal strength) with confinement ratio ω_c=0.15. Through casting procedure the necessary provisions defined by International Standards were not applied strictly in order to create construction deficiencies. These deficiencies are quantified geometrically without the use of expensive and expertise non-destructive methods and their effect on the axial load capacity of the concrete columns is calibrated trough a novel and simplified prediction model extracted by an experimental and analytical investigation that included 6 specimens. It is concluded that: a) even with suitable repair, load reduction up to 22% is the outcome of the initial construction damage presence, b) the lower dispersion is noted for the section damage index proposed, c) extended damage alters the failure mode to brittle accompanied with longitudinal bars buckling, d) the proposed model presents more than satisfying results to the load capacity prediction of repaired columns.

Keywords

RC columns, construction damages, repair; fiber reinforced thixotropic mortar, capacity prediction model.

1 INTRODUCTION

Damages in structures are caused by various phenomena such as:

1. Construction imperfections ([1], [2], [3]).
2. Seismic loads ([7], [14])
3. Exposure to environmental effects: temperature, ice and froze effects ([13], [15])
4. Corrosion ([16])
5. Fire ([17], [18])
6. Time- change of use ([11]).

Repair techniques and suitable materials have been developed and are widely applied for the rehabilitation of the load and deformation capacity of RC columns.

International guidelines of repair and strengthening of RC structures and elements ([4], [10], [16]) do not include quantifications of the capacity of repaired elements with each method. The initial construction damage or deficiencies are not extensively examined in all studies. In order to

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investigate the rehabilitation of concrete columns with this kind of damages, thixotropic high strength mortar was used as a repair material due to the easy application, the high cohesion level and the lack of the cracking effect due to slight expansion ([6], [12]). This kind of mortars is produced for application in structural rehabilitation fulfilling the requirements of the R4 category of EN1504-3 standard and the EN1504-6 for steel anchors [9].

The current study adds useful information to previous investigation through extensive analytical study: numerical analysis of the influence of construction damages to the bearing capacity of RC columns.

2 EXPERIMENTAL INVESTIGATION

2.1 Specimens' Characteristics

Six specimens were built to simulate reinforced concrete columns in scale 1:2 of rectangular section 150x150 mm and height 500 mm. Concrete of approximately 24 MPa nominal strength, 500 MPa nominal yield stress of steel for longitudinal reinforcement and 220 MPa for stirrups were used achieving the minimum confinement ratio defined by modern codes for medium ductility concrete columns. Specimens were symmetrically reinforced with two bars of 8mm diameter at each face. Transverse reinforcement consisted of 5.5 mm diameter spaced at 50 mm (Figure 1). All steel bars were adequately anchored. During casting consolidation of concrete was incomplete in order to create initial construction imperfections in 5 columns (Figure 2). Casting was not performed according to the provisions set by EN 206-1 (2000) [9] and ACI 309R-06 (2006) [5] as in real construction sites where it is common to ignore the standards set. According to international standards of concrete consolidation through internal vibration for application of plastic concrete in thin members and confined areas the use of a 20-40mm (3/4-1 in) head diameter vibrator is suggested. In this way, the radius of action is 80-150mm (3-6 in). What is more, the rate of concrete placement is assumed to be within 100-500 cm in the current study, a 20 mm (3/4 in) head diameter vibrator was used and concrete was being placed in higher frequency than predicted. What is more, large aggregate size was used (d_{gr}=32 mm). One specimen was constructed without damages and considered as reference model. Damaged specimens were repaired using high strength thixotropic pseudo plastic mortar according to EN 1504 [8] and were subjected to axial compression repeatedly with cycles of 1‰ axial strain up to 10 ‰. This pre-loading procedure created overloading cracks of 2 mm maximum width which does not affect their capacity in bearing vertical loads. The axial deformation was measured from the relative displacements between two loading platens with the use of Displacement Transducers (D.T.). The axial load is applied in a compression machine with a capacity of 3000 kN maximum load.

2.2 Quantification of Construction Deficiencies

The construction damages were quantified by the indexes proposed by [2]. The expansion deficiencies along the element axis and section was measured (Figure 3). The percentages of those damages to the designed dimensions are extracted through three different indexes (Table 1), representing the percentages of the deficiency area compared to the designed area:

1. f_{tot}: nominal section area (Equation 1)
2. d_s : Section index is the deficiency ratio of the section (Equation 1)
3. d_h : Axial index which quantifies the expansion axially (Equation 2) and,
4. d_v : Volumetric index (Equation 3) as a combination of the above-mentioned indexes resulting to the volumetric ratio of imperfect areas.

$$d_s=f_1/f_{tot} \quad (1)$$

$$d_h=h_1/h_{tot} \quad (2)$$

$$d_v=1-[(1-d_s)\times(1-d_h)] \quad (3)$$

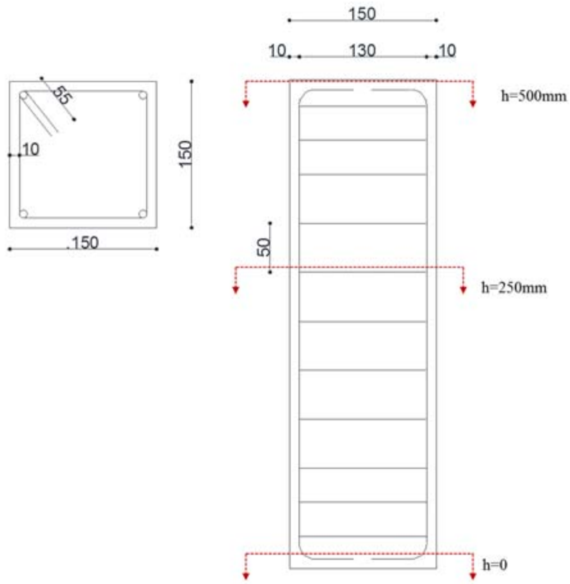

Fig. 1: Cores' reinforcement details (mm)

Fig. 2: Construction Damages D_mR_c-6

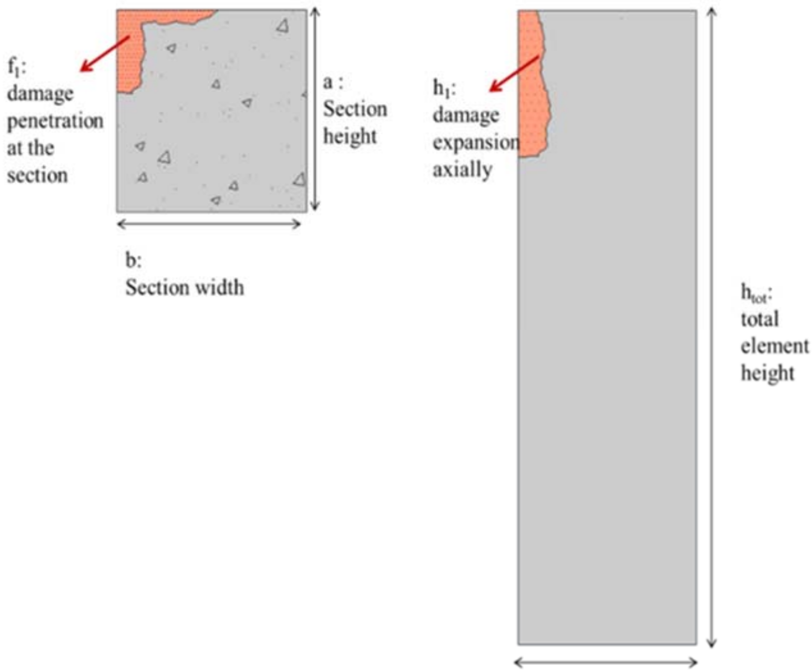

Fig. 3: Schematic damage indexes parameters definition

Tab. 1: Damage indexes of specimens (cores)

Specimen	d_s (%)	d_h (%)	d_v (%)
R_c-1	-	-	-
D_m-R_c-1	25	20	40
D_m-R_c-3	13	24	34
D_m-R_c-4	25	28	46
D_m-R_c-5	37	26	54
D_m-R_c-6	31	22	46
All specimens contain confinement ratio of ω_{wc}=0.15			

3 RESULTS

3.1 Experimental Results

The stress strain curve and the dissipation of energy of the repaired specimens are presented (Figure 4, 5, 6 and 7). It is observed that the maximum stress is presented in values of axial strain close 5-6 ‰ for all levels of imperfections. It is evident that in high levels of damaged section (D_mR_c-5) the peak stress is more reduced (22 %). It should be noted that when the impairment of the section exceeds 17% (d_s>25) (D_mR_c-5) the failure happens after 5 ‰ axial strain with abrupt reduction due to early buckling of the longitudinal reinforcement and deboning of repair material (Figure 5,8). The dissipation of energy, both up to peak and totally of the repeated loading, is lower than the non-damaged one. Speaking of the same levels of section impairment, specimens with stirrups of minimum levels of modern design code for medium ductility performance (D_mR_c-1, D_mR_c-4) dissipate slightly higher ratio of energy, but 25 % and 8 % respectively higher energy on the whole

(Figure 6). The tendency of highly damaged specimens (d_s index) to present resistance in lower normalized yield load is illustrated graphically in order to examine the dispersion. It's sure enough that the declination is in tolerable limits since the dispersion factor (R^2) for this level of ductility, is quite satisfactory (0.63), but also the second degree polynomial dispersion factor is in excellent levels (0.89). The tendency in dissipating lower energy according to the damaged section area is also depicted for both up to the peak stress and the failure stress (Figure 7).

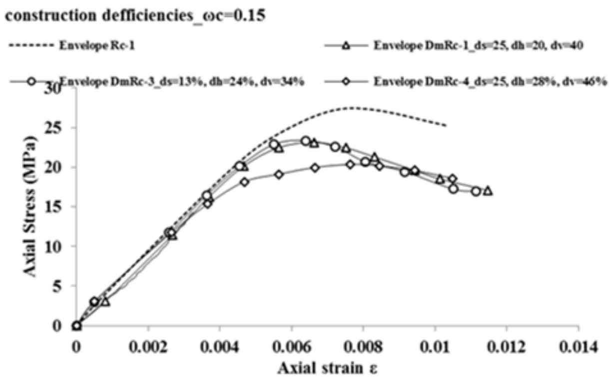

Fig. 4: Axial stress- strain curves of experimental results for specimens R_c, D_mR_c-1, D_mR_c-3, D_mR_c-4

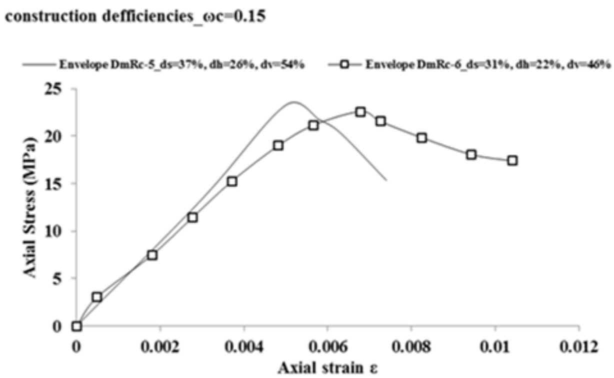

Fig. 5: Axial stress- strain curves of experimental results for specimens D_mR_c-5, D_mR_c-6

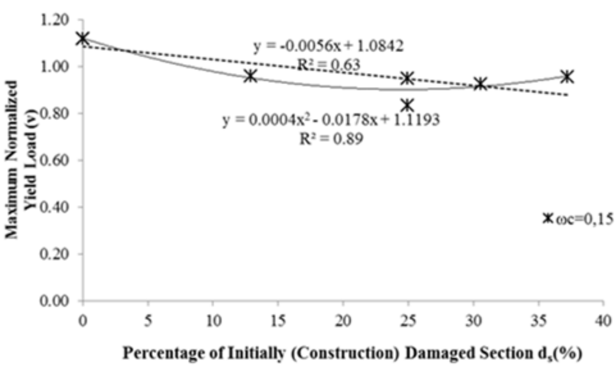

Fig. 6: Normalized axial yield load as a function of the damaged section ratio (d_s)

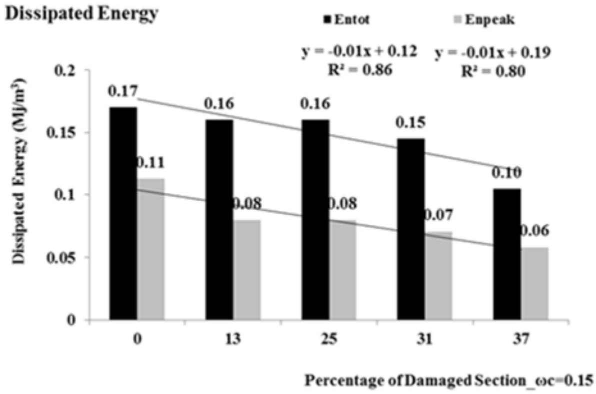

Fig. 7: Dissipated Energy as a function of the damaged section ratio (d_s)

Fig. 7: Buckling of longitudinal bar of D_mR_c-5 ω_c=0.15 after failure

3.2 Proposed Model

A novel proposed model of prediction of load and yield strain capacity of elements with initial construction deficiencies ([1]). The repaired gap volumes created by inadequate casting are considered as imperfections cause the reduction in axial load capacity. The yield strain, though, is augmented. The capacity of elements as a function of the confinement ratio and the section damage index (d_s) is given by Equation 4:

$$\frac{f_{cdm}}{f_{co}} = a + b \times \left(\frac{f_{cc}}{d_s}\right)^{3/4}, \ d_h \leq 0.40 \ \& \ d_v \leq 0.55 \quad (4)$$

where:

a, b - correlation/calibration coefficients to reduce error

f_{cdm} - stress capacity of repaired specimen with construction damages

f_{co} - unconfined compressive strength

f_{cc} - confined compressive strength

The above equation is suitable only for ductile elements, that is for construction deficiencies axially up to 200 mm ($d_h \leq 0.40$) and volumetrically up to 55 % ($d_v \leq 0.55$). Out of these limits the model is presented very sensitive to the change of d_h index since it cannot foresee the buckling of the longitudinal reinforcement bars and as a result the axial load. For the current confinement ratio the equation is transformed to Equation 5:

$$\frac{f_{cdm}}{f_{co}} = 0.91 - 1.03 \cdot \left(\frac{f_{cc}}{d_s}\right)^{\frac{3}{4}} \cdot \omega_{cc} = 0.15 \rightarrow \frac{f_{cdm}}{f_{co}} = \left[1.01 - \left(\frac{f_{cc}}{d_s}\right)^{\frac{3}{4}}\right] \cdot 1.13 - 0.11 \rightarrow \frac{f_{cdm}}{f_{co}} = 1.03 - 1.13 \cdot \left(\frac{f_{cc}}{d_s}\right)^{\frac{3}{4}} \quad (5)$$

For the augmented axial yield strain of damages elements a similar analytical model is proposed (Equation 6):

$$\frac{\varepsilon_{cydm}}{\varepsilon_{co}} = c + d \cdot \left[1 + \frac{\left(\frac{0.85 \cdot d_v \cdot \varepsilon_{ccy}}{1000}\right)^{\frac{2}{3}}}{\varepsilon_{co}}\right], d_h \leq 40\% \,\&\, d_v \leq 55\% \quad (6)$$

where:

c, d - calibration factors

ε_{cydm} - axial yield strain of repaired concrete

ε_{cy} - axial yield strain of unconfined concrete

ε_{ccy} - axial yield strain of confined concrete

For the current confinement ratio the proposed yield strain of damaged elements is given by Equation 7:

$$\omega_{cc} = 0.15 \rightarrow \frac{\varepsilon_{cydm}}{\varepsilon_{co}} = 0.50 + 1.47 \cdot \left[\frac{\left(\frac{0.85 \cdot d_v \cdot \varepsilon_{ccy}}{1000}\right)^{\frac{2}{3}}}{\varepsilon_{co}}\right] \quad (7)$$

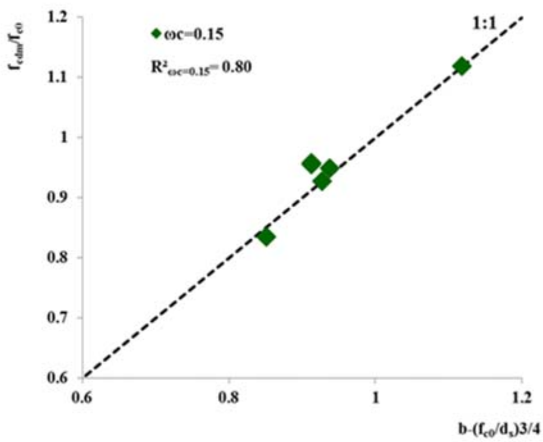

Fig. 8: Evaluation of the analytical model concerning the prediction of stress capacity of repaired RC columns

4 DISCUSSION

The analytical and experimental results come in remarkable agreement presenting low dispersion (R^2=0.80, Figure 9). In the case of the prediction of the corresponding yield strain the comparison of analytical and experimental results present satisfactory levels of dispersion (R^2=0.51, Figure 10). The model seem to be more sensitive in the aspect of predicting the yield strain since the longitudinal bars' buckling at higher damaged section ratios affect the total response of the specimens, as mentioned before. To summarize, the proposed model can be used for the prediction of the stress capacity of columns with section impairment.

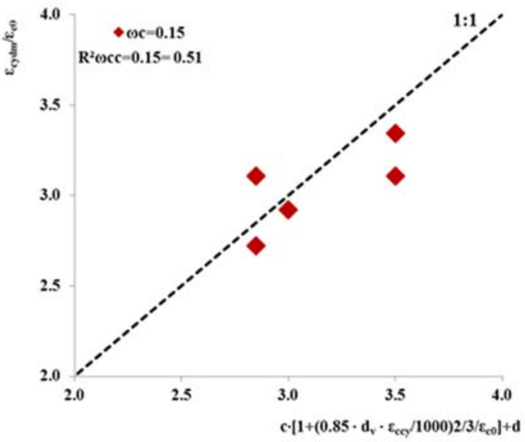

Fig. 9: Evaluation of the proposed model concerning the yield axial strain of repaired RC columns

5 CONCLUSIONS

Based on the results of the experimental and analytical investigation, the following conclusions are drawn:

1. Initial deficiencies affect the final behavior of the repaired specimen achieving lower values of load especially after yield.
2. Damage index ds seem to reflect better the reduction of maximum resistance load.
3. The proposed model is very sensitive and cannot be considered as accurate when deficiencies exceed the 26-28 % of the length of the element and cannot foresee the reinforcement longitudinal bars' buckling. The model presents high accuracy in predicting the reduced normalized yield load.
4. The reduced normalized load can be described even as a function of the deficiency index d_s.

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