Concrete Shrinkage Effect on Columns Strengthened with Concrete Jackets

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Abstract

Placing reinforced concrete (RC) jackets around RC columns is a common strengthening technique, particularly in seismic regions. The influence of concrete shrinkage on columns strengthened with a RC jacket has not been investigated yet. This paper presents an analytical procedure to calculate the stresses induced by shrinkage of the new concrete. A variable modulus of elasticity with time and relaxation due to creep are taken into consideration in the procedure. Finite element analysis method is used to perform parametric numerical simulations. From the results, it is found that jacket concrete shrinkage reduces the strength of composite columns. This strength reduction increases as the shrinkage strain values increase. For example, a value as low as 0,6 of monolithic behaviour was found for a normalised axial load of 0,4 and a concrete free shrinkage strain of 1600 microstrains. It is concluded that the effect of concrete shrinkage must be considered when strengthening RC columns, as it induces slip at the interface between the old and the new concrete and tensile stresses in the jacket concrete.

Keywords: shrinkage; concrete; columns; strengthening; jackets; finite element.

Introduction

The continual improvement in design codes means that the majority of old buildings require upgradation as a result of increased load and strength demands. To this end, placing reinforced concrete (RC) jackets around the existing RC columns is a common retrofit technique. Additionally, in seismic regions, the method is used to strengthen deficient columns before an earthquake or to repair; or repair and strengthen columns after an earthquake. A significant amount of relevant experimental work has been published.[1–10] The results demonstrate that interface roughening and placing dowels between the old and the new concrete are essential to prevent the concrete jacket from debonding. Nevertheless, the effect of new concrete shrinkage on the composite column strength has not been investigated. Codes and design recommendations, such as Part 3 of EC 8[11] and fib Bulletin 24,[12] propose correlation factors between strengthened and monolithic behaviour. However, values are mostly empirical. The Greek retrofitting code (GRECO)[13] proposes values for the ratio of composite column capacity to monolithic capacity based on experimental results where the effect of jacket concrete shrinkage was not taken into account. This paper investigates the influence of shrinkage on such factors.

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Several research papers have been presented that deal with the effect of concrete shrinkage on RC elements and composite concrete layers.[14–18] It has been found that shrinkage can significantly reduce cracking resistance and the stiffness of reinforced concrete elements.[14] In the case of composite layers, the new concrete cannot freely shrink because it is connected to the substrate, and tensile stresses are induced in the new layer. This results in interface shear stress, which may lead to sliding and the additional layer debonding.

The aim of the present work is to investigate the effect of concrete shrinkage on the behaviour of RC columns strengthened by placing RC jackets. This paper presents an analytical procedure that estimates stresses produced by the restrained concrete shrinkage of the jacket. The variation of the modulus of elasticity of concrete with time and creep relaxation are taken into account in the procedure. Results from a parametric investigation using the finite element analysis method are presented and discussed.

Analytical Investigation of the Effect of Concrete Shrinkage in Composite Layers

When considering unrestrained concrete shrinkage, additional stresses do not develop, as the new concrete can freely shrink. However, when strengthening, there is a connection between the old and the new concrete, which may induce tensile stresses. These can be calculated from Eq. (1) when considering uncracked concrete. Restrained strain values can be determined by subtracting the final measured strain values from the free shrinkage strain values.

$$\sigma = E_c \times \varepsilon_r \text{ and } \varepsilon_r = \varepsilon_{sh} - \varepsilon_a \qquad (1)$$

where σ is the tensile stress due to restrained concrete shrinkage, E_c is the modulus of elasticity of concrete, ε_r is the strain value due to restrained concrete shrinkage, ε_{sh} is the strain value due to free concrete shrinkage and ε_a is the actual concrete shrinkage.

In the case of unrestrained concrete shrinkage, the actual concrete strain equals the free concrete shrinkage strain and stresses are not generated in the new concrete. In the case where the new concrete is fully restrained due to being connected to the old concrete, stresses can be calculated using the free shrinkage value. When strengthening using RC jackets, the restrained strain values of the jacket concrete are similar to free shrinkage strain values because of the strong connection between the old and the new concrete.

When calculating the effect of shrinkage using the finite element method, a volumetric strain equal to the free shrinkage value can be applied to the jacket concrete. Depending on the connection to the original column, tensile stresses are induced. The simulation of concrete shrinkage using this method is approximate because E_c is considered equal to its 28-day value

	Days							Years	
	3	7	14	21	28	56	91	1	10
f_c/f_{c28}	0,46	0,7	0,88	0,96	1	1,08	1,12	1,16	1,17
E_c/E_{c28}	0,77	0,89	0,96	0,99	1	1,03	1,04	1,05	1,05

Table 1: Normalised development of f_c and E_c with time

and relaxation due to creep is ignored. Alternatively, a variable E_c with time and relaxation due to creep are considered in the present paper.

Development of Modulus of Elasticity and Shrinkage Strain With Time

Concrete strength increases with time. *Table 1*[19] presents concrete strength values f_c normalised by their 28-day value f_{c28}. *Table 1* also presents the development of E_c with time, determined from the following equation[20]:

$$E_c = 9500\left(f_c\right)^{1/3} \tag{2}$$

where f_c is the average concrete strength.

Shrinkage strain also increases with time. Equation (3) from ACI 209R-92[19] can be used to estimate the shrinkage strain:

$$\varepsilon_{sh}(t) = \left(\frac{t}{35+t}\right)\times\varepsilon_{shu} \tag{3}$$

where $\varepsilon_{sh}(t)$ is the shrinkage strain value for t, the age in days and ε_{shu} is the limit shrinkage strain value.

The value of the limit shrinkage strain depends on the type of concrete. According to EC 2,[20] the limit shrinkage strain for normal concrete is 600 microstrains. For shotcrete (which is commonly used when jacketing existing RC columns), this strain value is much larger and can be in the range of 1000 to 1600 microstrains.[21,22]

Stress Relaxation due to Creep

According to ACI 209R-92,[19] stress relaxation due to creep occurs when concrete is subjected to sustained loading. This can be taken into account when calculating stresses simply by using a decreased E_c value, as follows:

$$E_{ct} = \frac{E_c}{1+x\times C_t},\quad 0{,}774 < x < 0{,}996 \text{ and}$$

$$C_t = 2{,}35\times\left(\frac{t^{0,6}}{10+t^{0,6}}\right) \tag{4}$$

where E_{ct} is the reduced value of E_c taking into account stress relaxation and x is an ageing coefficient that can be considered as 0,8.[23]

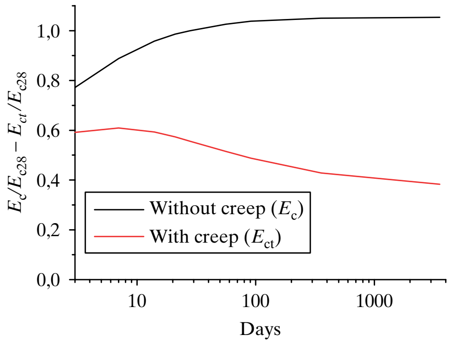


Fig. 1: Variation of E_c with time with and without creep relaxation

The variation of E_c with time, with and without creep relaxation, is presented in *Fig. 1*.

From *Fig. 1*, it is obvious that E_c significantly reduces when stress relaxation due to creep is taken into account.

Tensile Stress Calculation

Equation (1) can be used to estimate the tensile stresses. By considering the variation of E_c with time, the following equation can be derived:

$$\sigma_t = \int_{t=t_0}^{t=t} E_{ct}\times\varepsilon_{rt}\,dt \tag{5}$$

where σ_t is the tensile stress with time and $d\varepsilon_{rt}$ is the incremental restrained shrinkage strain value.

By considering Eq. (5), it can be seen that jacket concrete tensile stresses due to shrinkage continuously increase with time. When also considering the effect of stress relaxation due to creep, induced stresses significantly reduce with time. In order to take this reduction into account and for the purposes of finite element analysis, the use of a reduced restrained shrinkage strain value is proposed rather than reducing E_c during the analysis. Reduced strain values can be determined from the following equations:

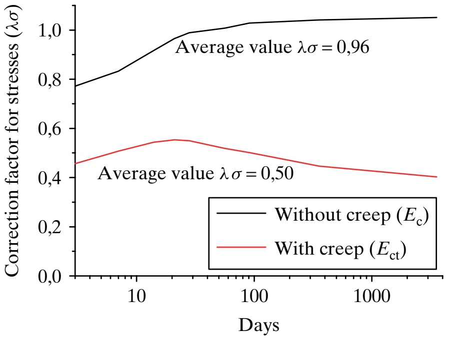


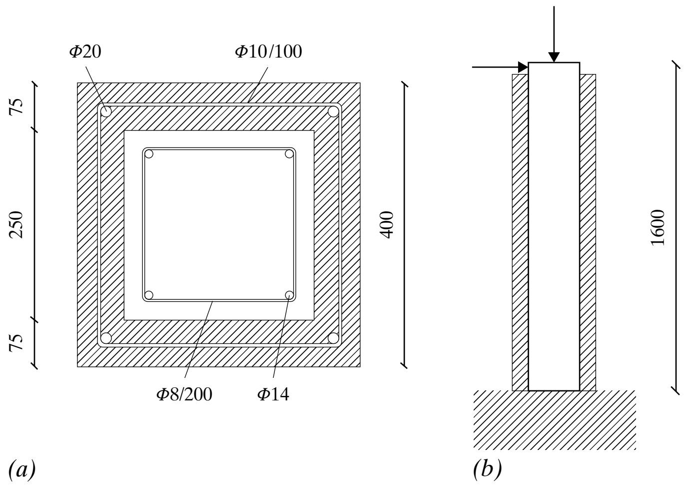
Fig. 2: Variation of correction factor λ_σ with time

$$\varepsilon_r' = \lambda_\sigma\times\varepsilon_r \text{ and } \lambda_\sigma = \frac{\sigma_t\left(E_{ct}\right)}{\sigma_t\left(E_{c28}\right)} \tag{6}$$

where ε_r' is the reduced restrained shrinkage strain value and λ_σ is a correction factor that takes into account the effect of the variation of E_c with the time on stress values induced by restrained shrinkage.

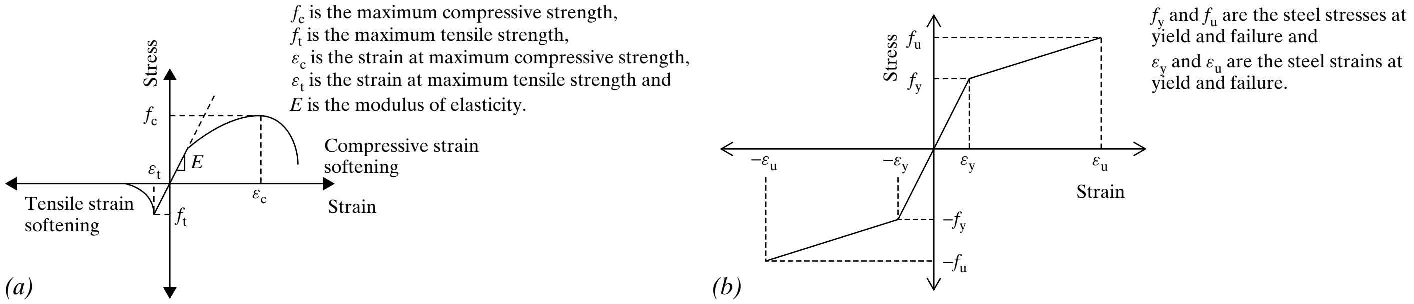
During analyses, ε_r' can be used while considering E_c to be constant. This procedure is used for simplification purposes when modelling the effects of relaxation and the variation of E_c with time.

The variation of λ_σ with time, with and without considering relaxation due to creep, is presented in *Fig. 2*. Average λ_σ values have also been calculated.



(a) (b)

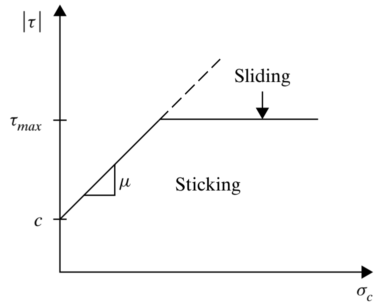
Fig. 3: (a) Cross section and (b) vertical section of the strengthened column (Units: mm)



f_c is the maximum compressive strength,
f_t is the maximum tensile strength,
ε_c is the strain at maximum compressive strength,
ε_t is the strain at maximum tensile strength and
E is the modulus of elasticity.

f_y and f_u are the steel stresses at yield and failure and
ε_y and ε_u are the steel strains at yield and failure.

Fig. 4: Stress against strain model (a) for concrete and (b) for steel



$\tau_{max} = \mu\sigma_c + c$ and $|\tau_{shear}| \le \tau_{max}$
where:
τ_{max} is the maximum friction stress,
$|\tau_{shear}|$ is the shear stress,
μ is the coefficient of friction,
c is the coefficient of cohesion and
σ_c is the normal stress at the interface

Fig. 5: Shear stress against normal stress distribution at the interface

From the average values of *Fig. 2*, ε'_r equals $0{,}96 \times \varepsilon_r$ or $0{,}50 \times \varepsilon_r$ when considering a variable E_c or relaxation due to creep, respectively.

Numerical Investigation on the Effect of Concrete Shrinkage in Columns Strengthened With Jackets

The finite element software ATENA[24] was used for the numerical investigation. The effect of concrete shrinkage was taken into account by applying an initial volumetric strain to the jacket concrete.

Specimen Geometry and Material Properties

For this investigation, square RC columns strengthened with RC jackets were examined. In order to validate the model, cantilever columns, as shown in *Fig. 3*, which were experimentally investigated in the past,[9,10] were considered. The cross-sectional dimensions of the original columns were 250 × 250 mm and their height was 1600 mm. The longitudinal reinforcement was four bars of 14 mm diameter. Stirrups were 8 mm in diameter and were placed at every 200 mm. The steel grade was S220. The thickness of the jacket was 75 mm and its longitudinal reinforcement was four bars of 20 mm diameter. Jacket stirrups were 10 mm in diameter and were placed at every 100 mm. The grade of the jacket steel was S500. Each jacket was placed to a height of 1550 mm. The compressive strengths of the concrete columns and jackets were 20 and 30 MPa, respectively. The strengthened columns were fully fixed at their base. The surface of each initial column was considered well roughened in order to provide sufficient connection with the new concrete. A well-roughened interface is achieved when there is full amplitude of approximately 6 mm as defined in ACI 318.[25] An axial load and a horizontal incremental load were applied to the top of each original column. The investigated columns were intended to represent strengthened half height full-scale ground floor columns subjected to seismic loading. Applying a horizontal load to the top of the cantilever column induced a moment that linearly increased from zero at the point of load application to a maximum at the base of the column. Therefore, shear stresses developed at the interface.

Numerical Work and Assumptions

An eight-node three-dimensional finite element was used to simulate the concrete. The stress against strain curve used to define concrete behaviour was multi-linear in compression and linear in tension up to the maximum strength values. After these points, there were softening branches in both tension and compression,[24,26] as shown in *Fig. 4a*.

To simulate the steel reinforcement, linear finite elements with bilinear stress against strain behaviour and strain hardening were used, as demonstrated in *Fig. 4b*.

The relative slip between concrete and steel was also simulated using the model proposed by the CEB-FIP Model Code, 1990.[26]

Special two-dimensional contact finite elements were used to simulate the interface between the old and the new concrete. Coefficient of friction and cohesion values of 1,5 and 1,9 MPa, respectively, were used to define the behaviour of the contact elements, as shown in *Fig. 5*. These values represent a well-roughened interface according to CEB Bulletin No. 162.[27]

The numerical model used in this investigation is presented in *Fig. 6*. Three hundred and eighty-four 3D (three-dimensional) elements were used to simulate the concrete (*Fig. 6a*), 616 linear elements were used to model the steel reinforcement (*Fig. 6b*) and 180 two-dimensional elements were used to simulate the interface (*Fig. 6c*).

To simulate concrete shrinkage, a negative strain value was applied to the jacket concrete in order to represent free shrinkage. As already stated, in the case of strengthening using RC jackets, free shrinkage strain values are similar to the restrained shrinkage values because of the connection to the initial column. In this investigation, a full connection was considered and, therefore, the restrained shrinkage strain value equalled the free shrinkage strain value.

A parametric investigation was performed for applied strain values of 200, 400, 600 and 800 microstrains in order to investigate the effect of concrete shrinkage on the behaviour of strengthened columns. It is important to note that these values correspond to free shrinkage values of 400, 800,

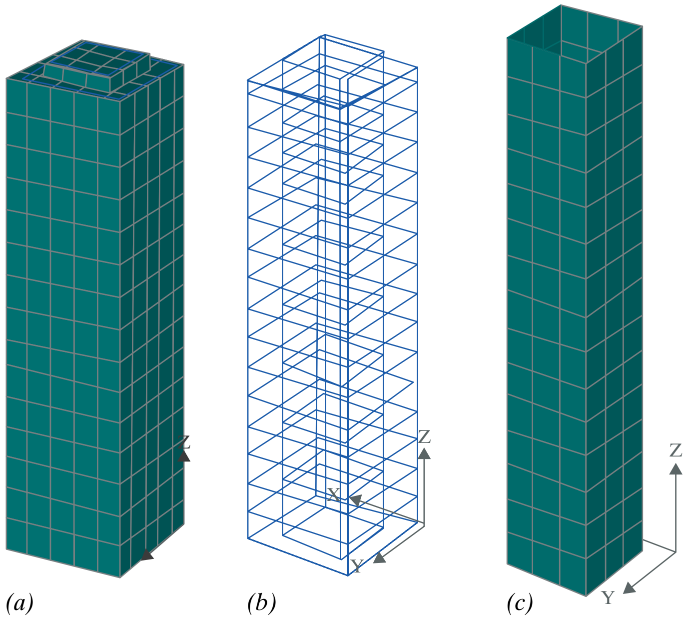


Fig. 6: Finite element model used for the simulation of (a) the concrete, (b) the steel reinforcement and (c) the interface

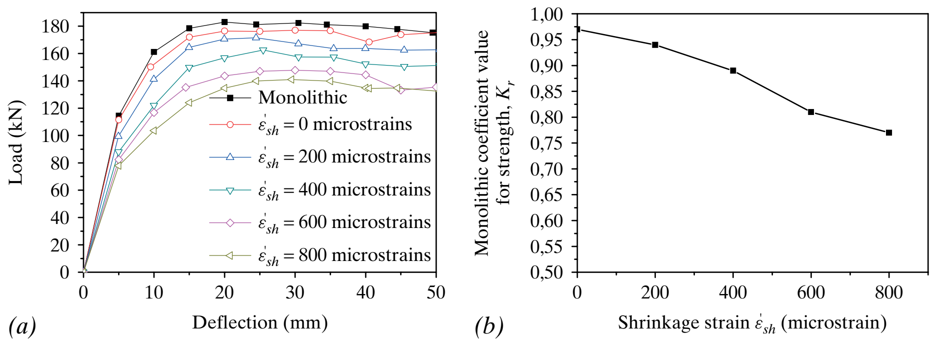


Fig. 7: (a) Load against deflection curves and (b) variation of monolithic coefficient value with the strain due to concrete shrinkage for a normalised axial load of 0,2

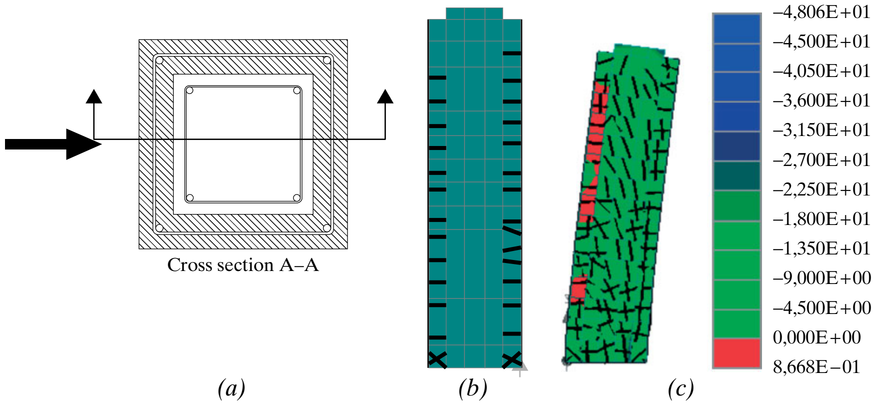


Fig. 8: (a) Cross section A–A, (b) cracks due to concrete shrinkage and (c) vertical stress (MPa) distribution at failure

1200 and 1600 microstrains, respectively, when considering a reduction due to creep effects and the variation of E_c with time (λ_σ equal to 0,50). For purposes of comparison, other simulations ignoring the concrete shrinkage effect were also performed. In addition, a parametric study using a constant ε_r' value of 800 microstrains and normalised axial load values of 0,05, 0,2 and 0,4 was carried out. The normalised axial load for the strengthened columns was calculated using Eq. (7).

$$\nu = \frac{N}{A_{co} \times f_{co} + A_{cj} \times f_{cj}} \qquad (7)$$

where N is the initial applied load, A_{co} is the cross sectional area of original concrete, f_{co} is the concrete strength of the original concrete, A_{cj} is the cross sectional area of the concrete jacket and f_{cj} is the concrete strength of the jacket.

In this investigation, failure was deemed to have occurred when there was a 3% rotational angle at the base of the columns.[28] This corresponded to a horizontal deflection at the top of the columns of 48 mm. The effect of jacket concrete shrinkage was evaluated by comparing strength results with the respective value from a monolithic column. A monolithic column can be defined as an ideal specimen with exactly the same geometry, reinforcing steel and material properties as a strengthened column. The only difference is that there is a perfect monolithic connection between the old and the new concrete.

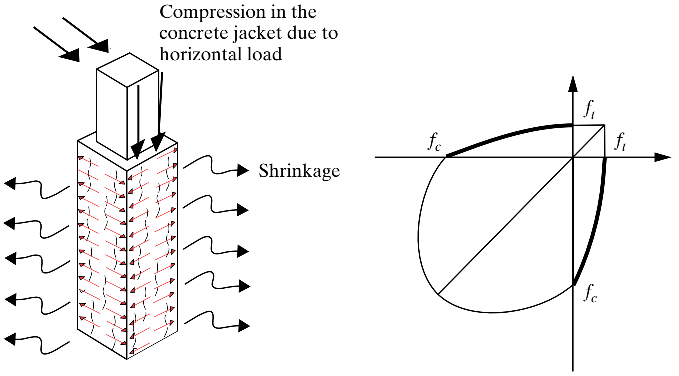
Results

It was found that, when determining the jacket concrete shrinkage, an initial slip at the interface between the old and the new concrete was induced. This occurred at the top of the column and its value was less than 0,2 mm.

Figure 7a presents load against deflection curves for different strain values due to concrete shrinkage for a constant normalised axial load ν of 0,2. Results from analyses ignoring concrete shrinkage and the respective monolithic specimen are also presented. By defining a monolithic strength coefficient K_r as the ratio of the strength of a strengthened specimen to that of a corresponding monolithic specimen, the variation of K_r for different shrinkage strain values can be determined, as presented in *Fig. 7b*.

From *Fig. 7a and b*, it can be seen that ignoring shrinkage gives a slight reduction in strength when compared to monolithic behaviour. As the strain due to shrinkage increases, specimen strengths considerably reduce.

For cross section A–A presented in *Fig. 8a*, the cracks formed in the numerical model due to 400 microstrains concrete shrinkage is presented in *Fig. 8b*. The vertical stress distribution at the failure is presented in *Fig. 8c*. It must be mentioned that in all the examined models a flexure failure was observed without delamination between the concrete jacket and the column because a well-roughened interface was used.



(a) Tensile stresses due to concrete shrinkage and concrete cracking

(b) Where f_t is the tensile strength of the concrete

Fig. 9: (a) Stress state of jacket concrete and (b) biaxial strength of concrete[29]

The influence of concrete shrinkage is significant because of the induction of tensile stresses in the jacket concrete, as it cannot shrink freely. This leads to a biaxial stress state in the jacket concrete as it is compressed in the vertical direction, as shown in *Fig. 9a*. According to Kupfer *et al.*,[29] f_c is reduced when compared to the respective value under uniaxial loading, as shown in *Fig. 9b*.

Figure 10a presents load against deflection curves from the parametric study where $\varepsilon_r^{'}$ was held constant while ν was varied. *Figure 10b* presents the variation of K_r values.

It can be seen from *Fig. 10a* that when shrinkage is modelled, there is a significant reduction in the strength of the strengthened column, especially for large ν values. The transverse tensile stresses in the concrete of the jacket, due to the restrained shrinkage and the axial load, are increased as the axial load value is increased. The compressive strength of the concrete of the jacket is further reduced because of the biaxial stress state. As a result, the strength of the jacketed column is also reduced. From *Fig. 10b* it can be seen that K_r values also significantly reduce when the jacket concrete shrinkage is simulated, particularly as ν increases. It must be noted that a K_r value as low as 0,6 was found for a v value of 0,4. By considering that the reduction of K_r values with the concrete shrinkage strain (presented in *Fig. 7b*) are valid for different values of v, K_r values for different strains can be got. *Table 2* presents K_r values for various ε_{sh} and $\varepsilon_{sh}^{'}$ values.

From *Table 2*, it can be seen that K_r values are significantly lower than those proposed in GRECO[13] for a ε_{sh} value of 1600 microstrains, which is a value typical for shotcrete.[21,22] The monolithic coefficient value proposed in GRECO[13] is 0,85 and is not dependent on the boundary conditions of the columns. This value is based on a number of experimental results of cantilever columns with v values in the range of 0,1 to 0,2.[30] From the results presented in *Table 2*, it can be observed that the numerical results are very close to the experimental ones for a reasonable shrinkage strain value.

From the results presented in this paper, it can be stated that concrete shrinkage significantly influences the behaviour of the RC columns strengthened with RC jackets. There is considerable reduction due to the biaxial stress state of the jacket concrete. The reduction of K_r values proposed in this paper can be used to estimate the strength of retrofitted RC columns when the interface between the old and the new concrete has been well roughened. However, more research is required in this area and an experimental validation of the effect of restrained concrete shrinkage on the compressive strength of concrete is essential.

	$\varepsilon_{sh}(\times10^{-6})$	**$\varepsilon'_{sh}(\times10^{-6})$**	**v**			**GRECO[13]**
			0,1	**0,2**	**0,4**	
K_r	400	200	0,94	0,94	0,88	0,85
	800	400	0,9	0,89	0,8	0,85
	1600	800	0,8	0,77	0,6	0,85

Table 2: K_r values for different strains

Conclusions

The following can be concluded from the results presented in this work:

- The effect of concrete shrinkage must be considered when strengthening RC columns, as it induces slip

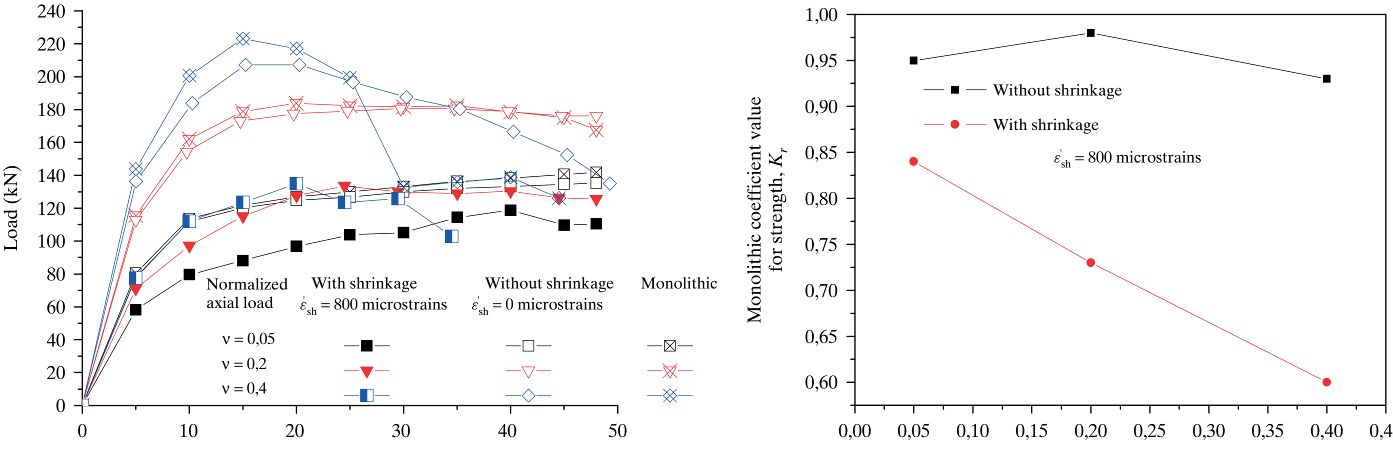


Fig. 10: (a) Load against deflection curves and (b) variation of K_r with the normalised axial load

at the interface between the old and the new concrete and tensile stresses in the jacket concrete.

- For RC columns strengthened with RC jackets, the effect of additional tensile stresses in the jacket concrete significantly reduces its compressive strength as a result of a biaxial stress state.
- The modulus of elasticity of concrete is low at the early stages when shrinkage takes place. This results in reduced tensile stresses due to concrete shrinkage. This reduction was found to be negligible.
- Creep relaxation was found to significantly reduce induced stress values due to concrete shrinkage. Stress values including the effect of creep were found to be 50% lower than those determined when ignoring it.
- The results of a parametric investigation of different values of concrete shrinkage using the finite element method show, for composite columns, a significant reduction of strength with increasing shrinkage strain.
- Monolithic correction factor values for strength were found to be significantly lower than those proposed in GRECO[13] for large values of normalised axial load. For example, values were found to be as low as 0,6 for a normalised axial load of 0,4 and a concrete free shrinkage strain of 1600 microstrains.
- The use of concrete with reduced shrinkage strain values can significantly contribute to increased strength of composite columns, and their behaviour can be considered to be similar to the respective monolithic columns when considering a well-roughened interface.

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