Theoretical calculation method for crack resistance of jacketed RC columns

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Abstract. Theoretical method of crack width calculation in jacketed reinforced concrete columns is described and validated in this paper. The total number of tested columns was 12. The initial load applied to the column before strengthening was the main variable parameter in this test. Columns were strengthened by reinforced concrete jacketing after loading. Two RC columns were tested without strengthening to serve as reference samples. Two RC columns were strengthened with RC jacketing without any initial loading to determine maximum strengthening effect. Loading was applied in steps. This study is the calculation of the crack resistance parameters RC columns, strengthened by RC jacketing under the influence of various initial loads. Crack width and pattern were checked after each step. The maximum allowed crack width for test samples was adopted as \( w_{\text{max}} = 0.3 \text{ mm} \). The rest eight samples were preliminarily loaded to 0.3; 0.5; 0.7 and 0.9 of reference columns bearing capacity, strengthened and tested to failure. The results of theoretical calculation deviate from test results by 13.6...27.9%.

1. Introduction
Reinforced concrete is one of the most widespread materials in industrial, civil and transport construction [1-4]. Studies of reinforced concrete structures are being carried out nowadays by many researchers. Recently, many works have been devoted to the development of the combinations of concrete materials, sheet steel, composite materials and reinforced concrete [5-13]. The direction of the works is devoted to increasing the durability, efficiency and reliability of such structures. However, there are still many structures in operation that are likely to be restored and, if necessary, strengthened rather than changed with the new ones. During operation, reinforced concrete, like any material, wears out and receives various damages [14,15].

That is why, to date, much work is devoted to strengthening and restoration of reinforced concrete structures. Strengthening of RC structures requires careful calculation considering various stresses including shear [15, 16].

One of the modern strengthening methods for reinforced concrete structure is the use of various composite materials [19, 20]. Although in some cases the traditional methods of strengthening with the use of concrete and reinforced concrete jackets is still relevant today [20-24], however, not enough work is devoted to the study of structures strengthened under the initial load level, which would simulate the real conditions of strengthening during operation.

Therefore, the purpose of this study is the calculation of the crack resistance parameters RC columns, strengthened by RC jacketing under the influence of various initial loads.
2. Test program
The total number of tested columns was 12. The initial load applied to the column before strengthening was the main variable parameter in this test. Columns were strengthened by reinforced concrete jacketing after loading to 0; 0.3; 0.5; 0.7 and 0.9 of reference columns bearing capacity. All samples were tested to failure as compressed-bent elements.

Loading was applied in steps. Crack width and pattern were checked after each step. The maximum allowed crack width for test samples was adopted as \( w_{\text{max}} = 0.3 \text{ mm} \). The Detailed test results are given in [20].

3. Calculation method
The calculation principle is based on the current Ukrainian standards. This type of calculation is for unchanged (undamaged or unstrengthened) structures and is mainly used for design.

Crack width is calculated from the equation:

\[ w = s_{r,\text{max}} \left( e_{\text{re}} - e_{\text{co}} \right) \]  

(1)

where \( s_{r,\text{max}} \) – maximum spacing between cracks; \( e_{\text{re}} \) – average rebar strain; \( e_{\text{co}} \) – average concrete strain between cracks.

For determine values of deformation rebar and concrete between cracks using equation (2).

\[ (e_{\text{re}} - e_{\text{co}}) = \frac{\sigma - 0.6f_{\text{co}} \left( 1 - \alpha \rho_{\text{eff}} \right)}{P_{\text{eff}}} \]  

(2)

where \( \sigma \) – rebar stress in section with crack (taken from bearing capacity calculation);
\( \alpha = E_s/E_{\text{co}} \) – coefficient of relation between modulus of elasticity for rebar and concrete;
\( \rho_{\text{eff}} = A_s/A_{\text{eff}} \) – coefficient of relation between area of tensile rebar and area of tensile concrete zone;
\( A_{\text{eff}} = b \cdot h_{\text{eff}} ; h_{\text{eff}} = \min \left[ 2.5 \cdot (h - d) ; (h - x) / 3 ; h / 2 \right] \) – method of calculation tensile concrete zone and height of tensile concrete zone.

Maximum spacing between cracks determine from next two relationships:

\[ s_{r,\text{max}} = 3.4c + 0.17 \frac{\Omega}{P_{\text{eff}}} , \quad \left( \text{Stirrups spacing} \leq 5(c + \Omega/2) \right) \]  

(3)

\[ s_{r,\text{max}} = 1.3(h - x) , \quad \left( \text{Stirrups spacing} > 5(c + \Omega/2) \right) \]  

(4)

where: \( c \) – longitudinal rebar concrete cover; \( \Omega \) – longitudinal rebar diameter; \( h, x \) – general height of cross section and height of compressed zone respectively.

4. Main assumptions and results
The average rebar and concrete strain of RC jacket was considered in the calculation. Strain in the materials of core section were ignored since jacketing is considered to be included to the design with zero initial strain.

Main results are presented in Figures 1-6 by "\( N(M) - w \)" curves for both theoretical and test results.

Maximum calculated crack width for all samples equaled: \( N_{w(0)}^{\text{teor}} = 134.19 \text{ kN}, N_{w(0.5)}^{\text{teor}} = 334.55 \text{ kN}, N_{w(0.3)}^{\text{teor}} = 345.00 \text{ kN}, N_{w(0.5)}^{\text{teor}} = 350.42 \text{ kN}, N_{w(0.7)}^{\text{teor}} = 348.86 \text{ kN}, N_{w(0.9)}^{\text{teor}} = 321.73 \text{ kN}. \)
Figure 1. "N(M) – w" curves for reference columns.

Figure 2. "N(M) – w" curves for column strengthened with 0.0 initial load.
Figure 3. "N(M) – w" curves for column strengthened with 0.3 initial load.

Figure 4. "N(M) – w" curves for column strengthened with 0.5 initial load.
Figure 5. "N(M) – w" curves for column strengthened with 0.7 initial load.

Figure 6. "N(M) – w" curves for column strengthened with 0.9 initial load.
Comparison of theoretical and test results are given in table 1.

Table 1. Serviceability according to maximum crack width.

| Column     | $N_u^{teor}$, (kN) | $N_w^{teor}$, (kN) | Strengthening effect | $N_w^{teor} / N_u^{teor}$ | $N_w$, (kN) | $(N_w - N_w^{teor}) / N_w \times 100\%$ |
|------------|---------------------|---------------------|----------------------|---------------------------|-------------|----------------------------------------|
| Reference  | 161.05              | 134.19              | -                    | 0.83                      | 165.73      | 19.0%                                   |
| 0.0-$N_u(K)$ | 419.77              | 334.55              | 149%                 | 0.80                      | 464.02      | 27.9%                                   |
| 0.3-$N_u(K)$ | 414.39              | 345.00              | 157%                 | 0.83                      | 444.73      | 22.4%                                   |
| 0.5-$N_u(K)$ | 402.62              | 350.52              | 161%                 | 0.87                      | 427.19      | 17.9%                                   |
| 0.7-$N_u(K)$ | 384.36              | 348.86              | 160%                 | 0.91                      | 403.98      | 13.6%                                   |
| 0.9-$N_u(K)$ | 362.23              | 321.73              | 140%                 | 0.89                      | 387.91      | 17.1%                                   |

Maximum effect of serviceability increase was reached by 0.5-$N_u(K)$ samples (161%), minimum – 0.9-$N_u(K)$ samples (140%). The difference between theoretical and test results is within range of 13.6–27.9%. In all cases experimental values are higher than theoretical which is satisfactory considering the archived deviations.

“$N(M) – w$” curves show us that jacketing cracks appear first in 0.0-$N_u(K)$ samples and latest in 0.9-$N_u(K)$ samples.

Considering the relation between $N_w^{teor} / N_u^{teor}$ we can come to the conclusion that in all cases columns have additional 10-20% reserve of bearing capacity after ultimate cracks appear. In the same time, the test shows us the appearance of ultimate cracks right before failure of columns.

Relation $N_w^{teor} / N_u^{teor}$ for all testing samples are within 0.80–0.91. This means, after finishing column serviceability with criteria limit width of cracks, structure still had margin of carrying capacity 10-20%. But results of the experiment show, that limit cracks appeared directly before exhaustion carrying capacity.

5. Conclusion

Calculated values of serviceability according to maximum crack width deviate from experimental in range of 13.6…27.9%. Experimental values are higher than theoretical. Test shows us that serviceability limit drops with the increase of initial loading but it is not resembled in theoretical results.

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