論文

ULTIMATE STRENGTH OF RC COLUMN MEMBERS RETROFITTED BY PC ROD PRESTRESSING

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ABSTRACT: The behavior of RC columns with wing-walls, analytically and in adaptation to test results is investigated. Three specimens retrofitted by PC bar prestressing and the standard one under constant axial force are conducted to cyclic lateral load and the test results are compared to the calculated ones derived through nonlinear section analysis. Shear strength is calculated by AIJ guidelines using a new realistic yield drift angle, thus the performance of such retrofit method is evaluated. Finally a simplified method to calculate the flexural strength for wing-wall section has been established.
KEYWORDS: RC column, seismic retrofit, wing-walls, shear strength, flexural strength, section analysis

1. INTRODUCTION

Adding wing-walls to original square section can considerably enhance the strength of RC member if section has been supplied with adequate amount of transverse reinforcement. By means of this shape, both the moment lever and compression area of section are improved and accordingly, the flexural capacity increases. The geometry of section also provides considerable improvement in shear strength. In the case of poor lateral transverse reinforcement, particularly in short columns, undesirable brittle shear failure tends to take place. The shear strength of RC columns is obtained from combination of truss and arch mechanism. Basically shear failure mechanism is a complicated behavior. If transverse reinforcement of the truss mechanism yielded, flexure-shear crack widths increase rapidly, reducing the strength of the concrete shear-resisting mechanism. As a consequence, shear failure is brittle and involves rapid strength degradation and inductile failure. Since wing-wall section is popular among RC buildings in Japan, particularly for external column besides the windows, it is necessary to assess the ductile behavior of wing-wall RC section and, as well as, the requirement of shear enhancement must be accounted for. To recover the flexure-dominated failure and take advantage of ductile response, confinement enhancement utilizing prestessed steel bar was suggested by Yamakawa et al. (2002) [6)], as a new high effective solution to protect the section against arising the shear crack before flexural one and change the failure mode.

The objectives of analytical and experimental assessments of this paper are as follows:

1- Performance evaluation of application of the high strength steel rod prestressing methods for RC wing-wall column and detection of practical specifications.

2- Proposal and fulfillment of simplified nonlinear analysis and finding out the proper method to realize the adopted value for yield drift angle (Ry) corresponding to start point of plastic hinge formation.

3- Calculation of shear strength due to truss-arch analogy suggested by AIJ using the new method to calculate plastic hinge rotation and evaluation of accuracy of this method to predict the actual shear behavior observed through experimental tests.

4- Establishment of simplified method to calculate flexural strength and comparison to exact value.

2. MATERIAL MODELS

Proper representation of material behavior for steel and concrete has significant effect on result reliability. Although the local failure prediction by proposed section analysis could not be captured, but to evaluate such simplified analysis, selection of the adequate material model is very important. In order to predict the strength degradation of structural concrete component suitable representation of compression strain-softening, considering passive confinement from transverse reinforcement and prestressed steel bar is necessary. To achieve this object the confined concrete model proposed by Mander et al. [2)] (1988) is

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adopted by authors. The selected model for steel has significantly influenced the nonlinear section analysis result. However to capture the exact behavior, modeling of buckling is essential, but for such proposed method in this study is not possible. As a simplified assumption, the enhancement effect of strain hardening is ignored to neutralize the effect of buckling. As a result, the elastic perfectly plastic model is selected to represent the effect of buckling and strain hardening of reinforcement. The strength of confined concrete is calculated by Mander method considering the active confinement imparted by prestressed steel bar through Richart's formula [4)]. As a matter of fact, the adopted value for concrete strength was taken as 85% of the result of cylinder compression test.

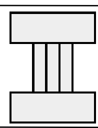
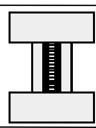
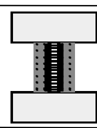
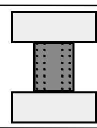
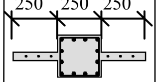
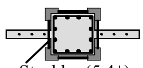
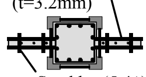
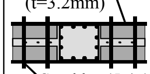
3. SECTION DATA AND TEST RESULTS

Cyclic loading tests for four test specimens were carried out under constant axial force ($N/(bD\sigma_B)=0.2$). **Table 1** contains the material properties. **Table 2** includes section information and specifications of various retrofit techniques. **Fig. 1** shows the shear load (V) against drift angle (R) through the tests for all specimens. The standard specimen R02WC-P0 has poor arrangement of shear reinforcement and because of shear span to depth ratio of 0.67 including wings, this specimen is shear critical one and as shown in **Fig. 1** the hysteretic response represents a brittle shear failure. In this kind of failures, before forming the flexural crack the diagonal-shear cracks are rapidly spreading in member and section reaches to failure without substantial energy absorbing. The aim of this study is evaluation of effectiveness of proposed retrofit techniques through an experimental program and an assessment by analytical approach. The proposed retrofit techniques using steel bar prestressing, which are applied in this study, are including of, retrofit on main square section (R02WC-P65), retrofit on both square section and wing-walls (R02WC-P65S), and retrofit of all section after converting to rectangular one by filling the four sides of section by adding mortar. As shown in **Table 2** in the cases of R02WC-P65S and R02WC-S, the wings and transformed section were enforced by steel rod prestressing through two embedded plates (t =3.2 mm). Comparing to standard specimen, results indicate that by applying the proposed retrofit techniques, in the cases of R02WC-P65 and R02WC-P65S the largeness of flexural strength does not change but the amount of energy absorbing over the wide range of ductility significantly increases. As a result the shear failure changes to flexural one. Through out the tests it has been seen that the connection between wing-walls and square section in high ductility totally has been vanished and when section reaches to larger drift angle, three individual columns sustaining the total axial load, in proportion to section area, are formed. The flexural strength of these two sub-columns corresponding to the wing-walls is less than shear one, so the failure mode switched to flexural one. Consequently because of very low flexural strength of wings, the retrofit of wings in R02WC-P65S seems to be worthless. The analytical result which will be discussed more in next parts also implies that the calculated flexural strength for R02WC-P65S could have not achieved and in larger drift angle the behavior of wing-wall section tends to be adapted to behavior of square section. The fact can be attributed to the separation of the unified section in large drift angles to three individual columns including the main square section, left wing and right one. Because R02WC-S is converted to rectangular one, both shear strength and flexural strength increase and

Table 1 Material properties

	Area (cm^2)	σ_y (MPa)	ε_y (%)	E_s (GPa)
Rebar(D10)	0.71	365	0.2	183
Hoops & reinforcement of wing-walls (3.7ϕ)	0.11	391	0.19	205
Steel rod (5.4ϕ)	0.23	1202	0.61	200
Steel plate (t=0.32)	7.36	276	0.33	208

Table 2 Specimens and retrofit

	R02WC-P0	R02WC-P65	R02WC-P65S	R02WC-S
Elevation (mm)				
Cross section (mm)				
Steel bar	-	5.4ϕ-@65		5.4ϕ-@123
Prestress	-	2450μ		
Common details	Rebar: 12-D10 (pg=1.36%) Hoop: 3.7ϕ @105 (pw=0.08%), Wall thickness: 50mm M/(VD) : 2.0 , σB : 25.7MPa , N/(bDσB) : 0.2			

section can resist against excessive seismic attacks. The result shows that the suggested retrofit technique for specimen R02WC-S can be deserved for highly critical cases as a reliable retrofit technique. The more details of test results are presented in reference number 6.

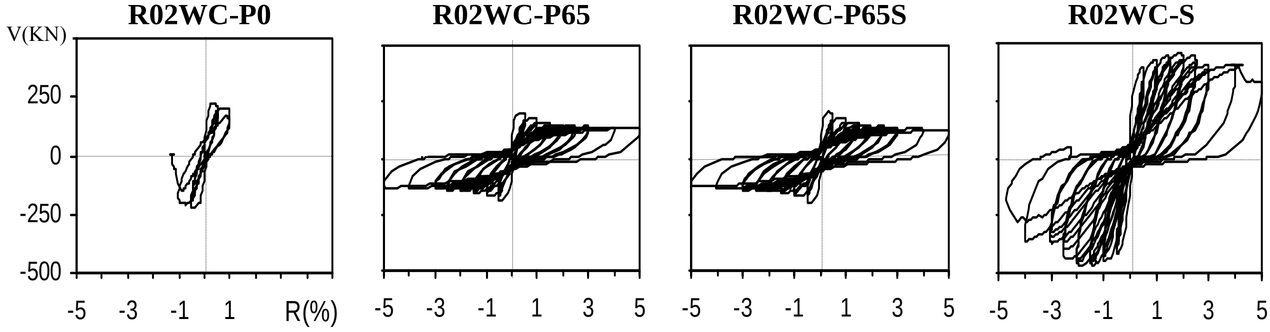


Fig. 1 Measured lateral force V versus drift angle R by experimental tests

4. ANALYSIS PROCEDURE FOR FLEXURAL STRENGTH

To calculate the displacement ductility, it is necessary to calculate the curvature ductility. The ductility capacity depends on section geometry, the amount and distribution of transverse reinforcement within plastic hinge region. Confinement provided by hoops and steel rods enhances the compressive strength. However, hoops protect longitudinal reinforcement against buckling, but the external steel bar cannot provide buckling protection. The details of the section analysis, as well known method are available in literature [5)]. Hereafter some new key points, being proposed in this paper, are pointed out. Since the shear span to depth ratio is 0.67 including wing-walls, the shear deflection is considerable and to calculate the deflection prior to yield point, both shear and bending displacement are taken into account. Eq. (1) is used in this regard. In **Fig. 2**, Θ_y represents the rotation of top and bottom of column, before formation of plastic hinge.

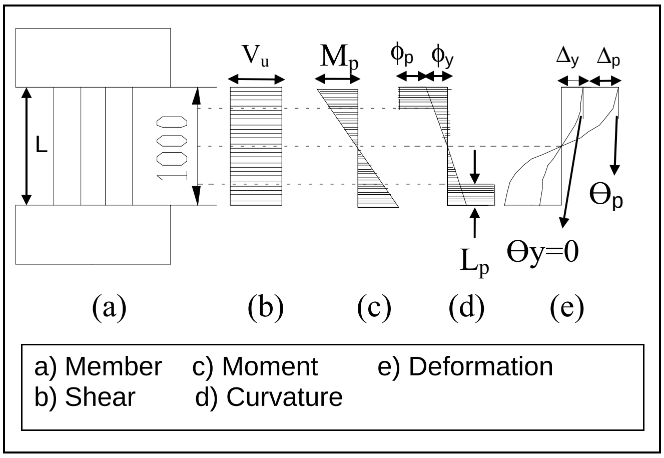


Fig. 2 Plastic deflection in hinge region

$$\Delta = \frac{\phi L^2}{6} + \int_0^L \frac{V}{GA_{ve}} \quad , \qquad (\phi \le \phi_y) \tag{1}$$

In Eq. (1) ϕ_y is equivalent yield curvature which is being found by extrapolating the line joining the origin and condition at first yield to the nominal moment capacity, M_n determined according to flexural strength at condition in which either extreme fiber compression strain of concrete reaches 0.004 or extreme tension reinforcement reaches 0.015. Effective shear stiffness GA_{ve} rather than the shear stiffness based on the shear area should be employed to reflect the increased shear deformation in flexural cracked concrete member [5)]. In this study it is assumed that the effective stiffness reduction in shear can be considered proportional to effective stiffness in flexure as Eq. (2):

$$GA_{ve} = GA_v \frac{EI_e}{EI_g} \tag{2}$$

$$EI_e = \frac{M_n}{\phi_y} \tag{3}$$

Where, E and G are Young's modulus of elasticity and shear modulus of elasticity respectively. I_e and I_g represent the effective and gross moment of inertia respectively. A_v represents shear area and ϕ_y equals to yield curvature. Paying attention to **Fig. 2**, the procedure of calculation of flexural capacity, corresponding to drift angle which gives the trend of shear force, before and after formation of plastic hinge, is being illustrated.

5. ANALYTICAL PROCEDURE AND DISCUSSION

Because of poor arrangement of transverse reinforcement, the shear strength of R02WC-P0 is less than flexural capacity and substantially the shear failure mode is expected. After applying above-mentioned retrofit techniques, the shear capacity increases. As a result, the shear strength is higher than flexural strength and higher ductility can be gained. In this study to predict the shear strength, the AIJ method [1)] is employed. AIJ formula has two main components reflecting truss action and arch mechanism. The cracks pattern and observed failure modes in specimens represent the obvious individual acting of truss and arch action mechanism in wings and square section. As shown in **Fig. 3** in the case of R02WC-P0, R02WC-P65 and R02WC-P65S, it is proposed to calculate truss and arch mechanism within two separate parts. Actually in the main square section both truss and arch components are taken into account but for wing-walls only arch component across the section is considered (see **Fig. 3**). Although the overlap part of square and wings is counted twice, since the concrete of wing-walls is unconfined, result is not affected considerably. In the case of R02WC-S, in addition to prerstressing force, by adding filling mortar embedded by two plates, section is converted to rectangular one whereas prestressing force is applied to section through these plates. In R02WC-S, similar to wing-walls for other specimens, to calculate shear strength only arch action is accounted for. In calculation, the arch component of AIJ formula in which ν_0 is taken 0.7 for transformed section is employed. Moreover, the concrete strength of main section is represented for all converted rectangular section. In AIJ formula, it is necessary to calculate plastic hinge rotation. As a new solution, by assumption of rigid body motion between midpoints of two plastic hinges located at ends, in addition to the exact solution method described above, the Eq. (4) can adequately represent plastic hinge rotation, particularly when curvature data is not available.

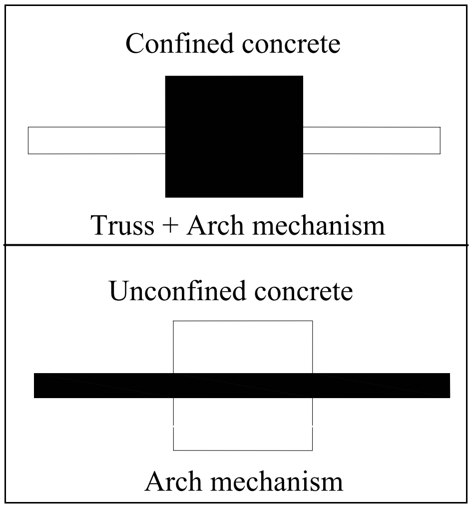


Fig. 3 Truss and arch components

$$R_p = \theta_p = \frac{\Delta - \Delta_y}{L - L_p} \tag{4}$$

$$L_p = 0.08L + 0.022 f_{ye} d_{bl} \geq 0.44 f_{ye} d_{bl} \quad (f_{ye} \text{ in MPa}) \tag{5}$$

Where R_p=Θ_p is plastic hinge rotation, Δ is total displacement, Δ_y is displacement corresponding to yield point, L is height of column and L_p is plastic hinge length that is calculated by Eq. (5) [3)] ,where f_{ye} is yield strength of longitudinal reinforcement, d_{bl} the diameter of longitudinal reinforcement.

The shear strength and flexural strength derived through described analytical method, in comparison to measured skeleton curve are shown in **Fig. 4**. In the case of R02WC-P0 as notified before, the failure mode is shear one. In analytical procedure, wing-walls of R02WC-P65 are considered to be unconfined and that of R02WC-P65S is considered to be confined. As a result, when calculating the flexural strength by the fiber model, the wings of R02WC-P65 in larger drift angle are getting spalled and eventually the unified wing-wall section is converted to square one. Comparing the measured skeleton curve of R02WC-P65S to fiber model result indicates that the analytical flexural strength of unified section is not adopted to test result and the same skeleton curve of unconfined wings (the same as R02WC-P65) can be seen. As a matter of fact, during experimental tests of R02WC-P65 and R02WC-P65S it was observed that wing-walls and the middle square column were separated by forming depth cracks along the conjunction lines and finally the three individual columns were sustaining loads proportionally. Actually in lower level of ductility the wings and square section act as a unified section but in higher level there are totally separate sections. As shown in **Fig. 4**, because of very low amount of shear and flexural strength of wings in high ductility, the dominant behavior is adapted to square section. One of the main reasons for connection tearing could be the effect of holes which must be made at connection line to pass the steel bars. In **Fig. 4** for R02WC-P65S the expected flexural strength calculated for unified section is not adapted to skeleton curve and meanwhile the skeleton curve in high ductility matches to square one. As it is notified before, the enhancement of concrete strength of wings by introducing the steel rod prestressing through embedded plate does not change the flexural strength of wing-wall section in high ductility and as a principal conclusion, the retrofit of wings is meaningless and seems to be uneconomic. On the other hand, the applying such retrofit method on main square section significantly changes the failure mode from shear to flexural one and absorbing more energy due to ductile hysteretic loop. Actually, if the shear strength of wing-wall sections is being less than flexural one, before separating the wings and main square column shear failure is observed and there is no opportunity to switch the failure from shear to flexure. As a result, retrofit of main square column is essential to preserve the column under high seismic attack.

As an alternative, in spite of using the exact method to calculate the flexural strength, a simplified method is employed too. In this method the place of neutral axis is assumed at center of square column section in ultimate stage and the flexural component of wing-wall must be added to the calculated flexural strength by simplified method for square section (Eqs. (6) and (7)) [5]:

$$N_C = (tl_c\sigma_B + \sum A_{sw}\sigma_y) \quad \text{, (In turn of moment: } M_C=N_c\times 0.5\times(D+l_c)) \qquad (6)$$

$$N_T = \sum A_{sw}\sigma_y \quad \text{, (In turn of moment: } M_T=N_T\times 0.5\times(D+l_c)) \qquad (7)$$

Where t is thickness of wing-walls, lc is length of one wing, A_{sw} is total longitudinal steel area in one wing and D is square column depth. **Fig. 6** shows the flexural component of wings as a vector. The ultimate stage is the situation in which the compression strain in extreme fiber reaches to 0.004. Consequently the derived vector will be added to flexural strength of rectangular main column. **Fig. 5** shows the results of exact N-M interaction curve in comparison to those by simplified method for specimens R02WC-65 and R02WC-65S. As shown in **Fig. 5**, the flexural strength of R02WC-P0 and R02WC-P65 are predicted by simplified method in good level of accuracy. As a general result, there is a good agreement between simplified method and exact one; however the result for all cases seems to be larger, but in lower axial force the calculated moment can be used for prediction of flexural strength of sections which is applicable to calculation of displacement ductility and also could be used for design aspects. It must be considered that simplified method is reliable in integrated wing-wall section in which wings and square sections are unified. In large drift angles flexural strength of R02WC-P65 equals to that of square column.

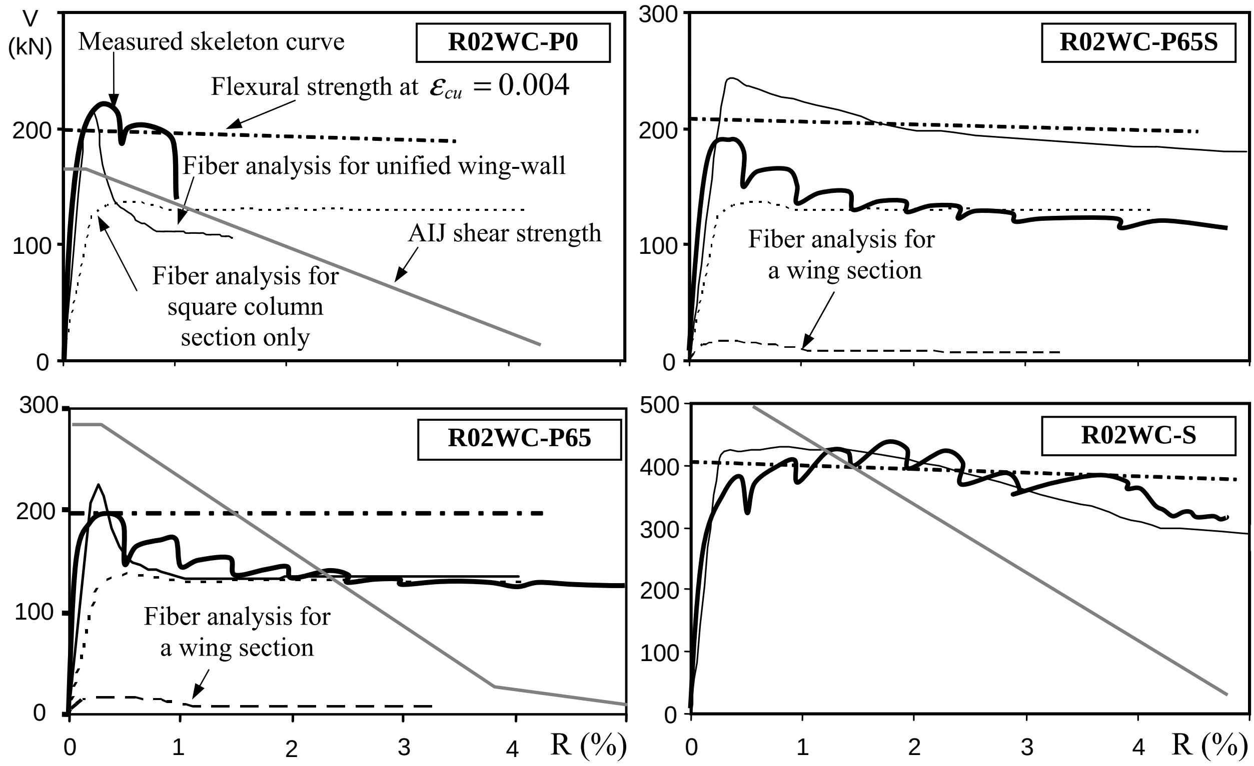


Fig. 4 Comparison between experimental and calculated results

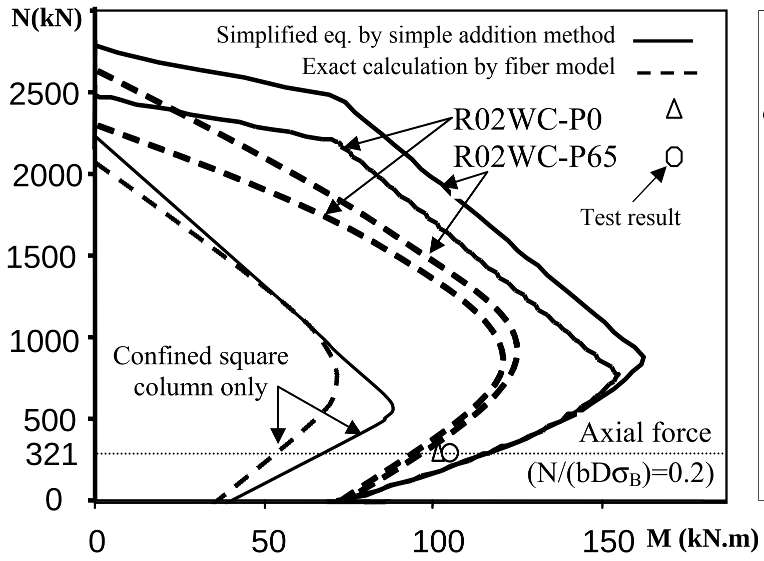


Fig. 5 N-M interaction curves

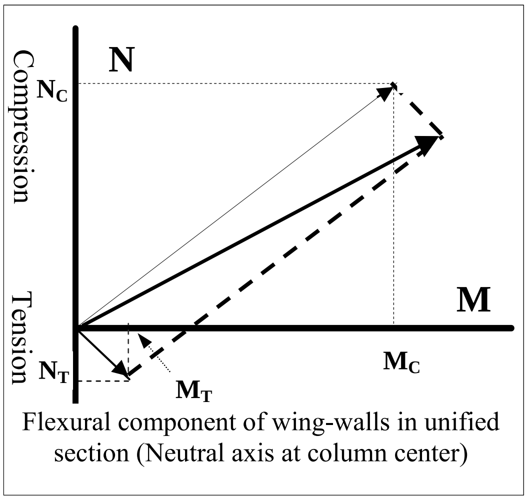


Fig. 6 Wing-wall flexural component

6. CONCLUSIONS

1- Comparison of experimental data and the results of proposed analytical model indicates that retrofit of main square column can improve the shear capacity and ductility adequately.
2- The result shows that in the case of applying such retrofit technique in both square column and wings, because of tearing of wing connection to square columns, applying retrofit in wings is meaningless.
3- Utilizing the prestressed steel bar and transforming the section to rectangular one by adding mortar embedded between two steel plates can significantly improve the flexural and shear strength including considerable ductility enhancement of original section and is easily applicable in highly critical situation.
4- Because of tearing of wing connection in large drift angle, the flexural strength of specimens is dominated by main square column section.
5- As an alternative for unified wing-wall sections the simplified method to calculate the flexural strength is reliable in occasions of design and assessment.

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