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Behaviour of Reinforced Concrete of Structural Walls: A New Interpretation

Comportement des parois de cisaillement en béton armé: une nouvelle interprétation

Bruchverhalten von Stahlbetonscheiben: eine neue Interpretation

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SUMMARY
The work forms part of a comprehensive research programme which has been aimed at developing a sound theoretical basis for the design of reinforced concrete structures in shear. Finite element analysis is used to verify that the 'shear' capacity of reinforced concrete structural walls is associated with the strength of the compressive zone. Experimental evidence is presented with indicates that current code provisions are not safe; it is shown that shear capacity can be improved by strengthening the compressive zone rather than the portion of the wall below the neutral axis as specified by these provisions.

RÉSUMÉ
L'étude constitue une partie d'un programme de recherche qui tente de formuler une base théorique solide pour le calcul au cisaillement des structures en béton armé. Des analyses par éléments finis sont utilisées pour vérifier que la résistance au cisaillement des murs en béton armé est associée à la résistance de la zone comprimée. Les résultats expérimentaux présentés montrent que les règlements actuels ne sont pas sûrs. La résistance au cisaillement peut être améliorée par un renforcement de la zone comprimée plutôt que de la zone située sous l'axe neutre comme cela est normalement recommandé.

ZUSAMMENFASSUNG
Die vorliegende Arbeit fasst Teile eines umfassenden Forschungsprogrammes zusammen, das auf die Entwicklung einer soliden theoretischen Basis für die Schubbemessung von Stahlbetonbauteilen hinzielt. Ein Finite Elemente Modell wird angewandt, um den direkten Zusammenhang von Schubspannungskapazität von Stahlbetonscheiden und Festigkeit der Druckzone zu verifizieren. Durch Experimente erhaltene Aussagen werden benutzt, um auf die Unsicherheit aktueller Normen hinzuweisen. Es wird gezeigt, dass die Schubspannungskapazität eher durch Verstärkung der Druckzone als des Bereiches unterhalb der neutralen Faser verbessert werden kann.

1. INTRODUCTION

Reinforced concrete structural walls are widely considered to provide an efficient economic bracing system, not only for high-rise, but also for low-rise buildings in areas of high or moderate seismicity. Such walls are designed as cantilever beams with concrete, above the neutral axis, and longitudinal reinforcement resisting the combined action of gravity loads and bending moment, whereas the region of the wall below the neutral axis provides shear resistance to the action of the horizontal forces, with horizontal reinforcement sustaining the portion of the shear force in excess of that which can be sustained by concrete alone. The horizontal reinforcement is assessed by using one of a number of methods invariably based on the "truss analogy" concept which stipulates that, once inclined cracking occurs, the beam behaves as a truss with concrete between the inclined cracks forming compression struts and the horizontal reinforcement forming the tension ties.

It has been recently found, however, that the above design method is not always safe since the wall shear capacity as predicted on the basis of the "truss analogy" concept often overestimates considerably that established by experiment [1,2]. The reason for this appears to be compatible with recent experimental evidence indicating that the "truss analogy" does not provide a realistic description of the mechanism of shear resistance [3]. In fact, it has been demonstrated that shear resistance is associated with the strength of concrete in the region of the path along which the compressive force is transmitted to the supports, with the portion of the beam below the neutral axis making an insignificant, if any, contribution [4].

It would appear from the above, shear resistance of the wall can only be improved by strengthening the compressive force path, rather than the portion of the wall below the neutral axis. The present work, therefore, has been aimed at verifying the validity of the above concept by means of finite element analysis (FEA). FEA is used to, first indicate that the method yields realistic predictions of R.C. wall behaviour and then, investigate whether strengthening the compression force path does indeed improve the structural behaviour of the walls.

2. NONLINEAR FINITE ELEMENT ANALYSIS

The nonlinear finite element system used in the programme is fully described elsewhere [5] and thus is only discussed briefly here. Essentially it is an iterative procedure which incorporates a linear solution technique. This is based on the Newton-Raphson method and the residual force concept. The procedure has been incorporated into a Choleski linear solution FE system and its application to the analysis of R.C. structures requires the use of "constitutive" laws describing the strength and deformation properties of concrete and steel as well as the interaction between concrete and steel.

The constitutive laws are fully described elsewhere [6,7] and their discussion is beyond the scope of this paper. It should be noted, however, that these laws for concrete include a description of the cracking process of concrete based on the smeared crack approach.

The finite elements used to model concrete and steel have been 8-node isoparametric and 3-node bar (possessing axial stiffness only) elements, respectively, with a steel element always coinciding with the boundaries of the adjacent concrete elements.

3. STRUCTURAL FORMS INVESTIGATED

The NLFEA system has ben validated by comparing analytical predictions with published information obtained experimentally for a wide range of R.C. structural walls [1,2,8,9]. The walls investigated represent the critical storey element of a structural wall system with rectangular, barbell or flanged cross-section. The height to width ratio of the elements analysed varied from 0.5 to 2.4, whereas their thickness to width ratio varied from 0.04 to 0.10. Vertical and horizontal reinforcement was distributed over the whole width of the wall. The ultimate strength of the reinforcement varied from 510 to 765 MPa, while the uniaxial compressive strength of concrete varied from 28 to 50 MPa.

The full design details of a typical wall are given in Figure 1, whereas Figure 2 shows the finite element mesh adopted for the analysis. The latter figure also indicates the boundary conditions and loading history of the wall.

Of the walls investigated, those which failed below the predicted design level were re-analysed after modification of their reinforcement details. The modification involved strengthening the compressive zone, by increasing the amount of the compression reinforcement, as well as weakening the region below the neutral axis, by reducing the horizontal reinforcement by more than half the original amount. These modifications have been made in order to demonstrate, not only that the compressive zone makes a significant contribution to shear capacity, but also that, in contrast to widely held views, the wall does not have to behave as a truss in order to sustain shear forces after inclined cracking occurs.

An indication of the modification to the reinforcement details of the typical wall shown in Figure 1, is given in Figure 3. It is interesting to note that the compressive zone at the critical section has a significantly smaller size than that of the overall wall cross-section.

4. RESULTS

The main results of the investigation are shown in Figures 4 to 8. Figure 4 shows the correlation between predicted and experimental values of the load-carrying capacity for a wide range of R.C. structural walls subjected to various combinations of vertical and horizontal loading, whereas Figure 5 illustrates the predicted and experimental load-displacement curves for the typical wall of Figure 1.

Figure 6 shows a typical mode of failure established by experiment [2] together with that predicted by analysis in the present work, whereas Figure 7 shows the predicted crack pattern and deformed shape of the wall at characteristic load stages corresponding to (i) crack initiation, (ii) significant inclined crack formation and (iii) maximum load-carrying capacity.

Finally, Figure 8 shows the relationship between shear capacity and amount of horizontal reinforcement predicted by current Code provisions for walls investigated into two different experimental programmes. The Figure also shows for comparison the values predicted by the analysis and those from experiments.

5. DISCUSSION OF THE RESULTS

Figures 4 to 7 demonstrate a satisfactory correlation between prediction and experiment for all aspects of structural behaviour investigated in the present work i.e., load-carrying capacity, deformational characteristics and mode of failure. Similar correlations have also been obtained for a wide range of R.C. structural forms [10,11]. The apparent successful application of the FEA system to all cases investigated to date, is attributed to the constitutive model of concrete behaviour which the system incorporates.

From Figures 6 and 7, it may be noted that the predicted mode of failure is characterised by longitudinal cracking within the compressive zone near the base of the wall where the flexural moment attains its maximum value. The modes of failure of R.C. beams in both flexure and combined flexure and shear have also been found to be characterised by similar cracking [12]. Such behaviour is considered to indicate a common underlying cause of failure, fully described by the concept of the compressive force path [13]. It is interesting to note in Figure 6 that the mode of failure established experimentally is also characterised by longitudinal cracking of the compressive zone near the base of the wall.

Figure 8 indicates, that the Code provisions [14] predict a linear increase in shear capacity with increasing percentage of horizontal reinforcement, from a lower level representing the contribution of concrete to shear resistance, to an upper level corresponding to "crushing" of the concrete struts of the "truss" model. Beyond this level, it predicts that shear capacity remains constant. From the Figure, it is apparent that while the Code predictions are conservative for the lower range of values of the percentage of horizontal reinforcement, they overestimate considerably the wall capacity, for the upper range of these values. On the basis of the "truss analogy", predictions can only improve by adjusting current design methods so as to provide a lower bound failure envelope to published experimental data such as those included in Figure 8.

In contrast to the "truss" analogy, the concept of the compressive force path suggests that shear capacity can increase by strengthening the compressive zone of the concrete in the region of the critical section. Vertical and horizontal reinforcement is considered to have no purpose other than safeguarding against out-of-plane instability due to the heterogeneity of concrete.

The validity of the above view is supported by the analytical evidence obtained in the present work. Figure 8 shows that the inclusion, near the extreme compression and tension fibres, of additional reinforcement in both the compression and tension zones of the wall, results in a significant increase of load-carrying capacity; this happens in spite of the considerable reduction of horizontal reinforcement to near nominal levels. An experimental verification of the above predictions forms part of an on-going experimental programme, and the results obtained to date have been found to correlate closely with the predictions [15].

6. CONCLUSIONS

(1) The results obtained in the present work indicate that "truss analogy" does not form a suitable basis for the design of R.C. structural walls.

(2) It is shown that the shear capacity of the walls is associated with the strength of concrete in the compressive zone in the region where the maximum bending moment develops and not, as widely believed, in the region of the wall below the neutral axis.

(3) It has been demonstrated that strengthening of the compressive zone can lead to a significant increase in load-carrying capacity, in spite of the considerable reduction of horizontal reinforcement.

(4) The above evidence is compatible with the concept of the compressive force path and it appears that this concept can form the basis for the development of a method suitable for the design of walls.

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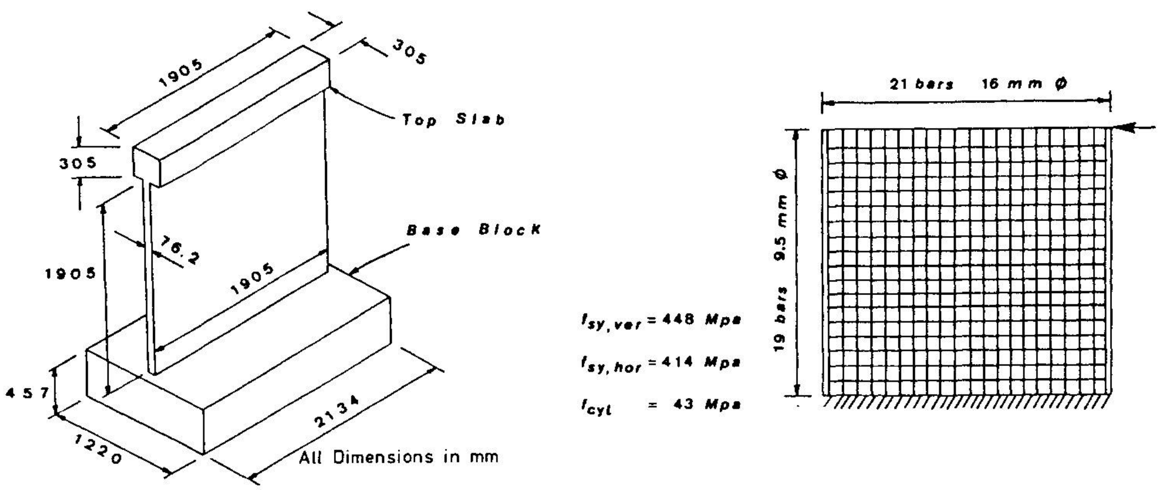

Fig. 1 Design details of a wall typical of those investigated (ref. [1])

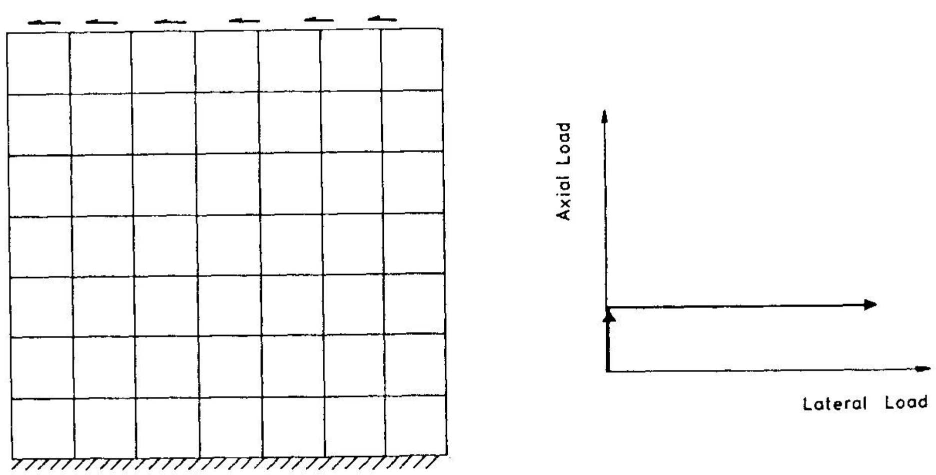

Fig. 2 Finite element mesh adopted for the wall shown in Fig. 1

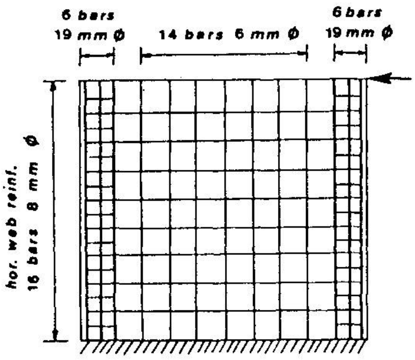

Fig. 3 Reinforcement details of wall with strengthened compressive zone

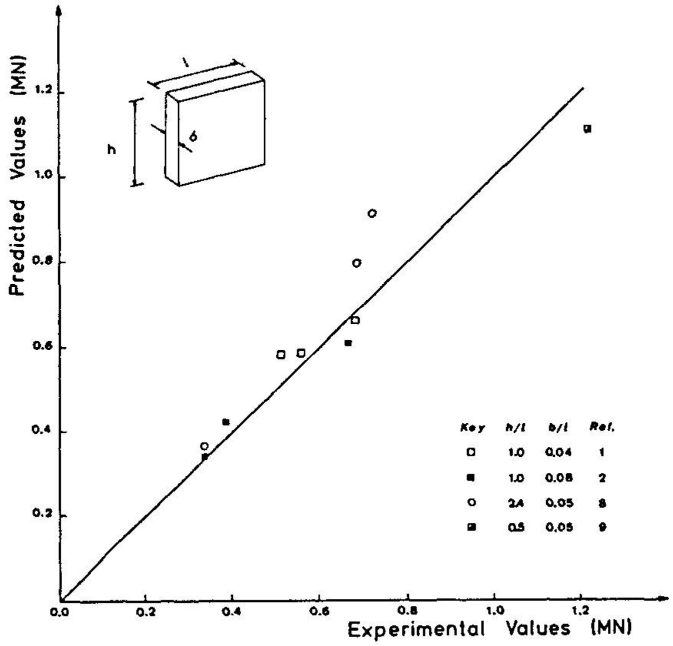

Fig. 4 Correlation of predicted load-carrying capacity of walls with experimental values

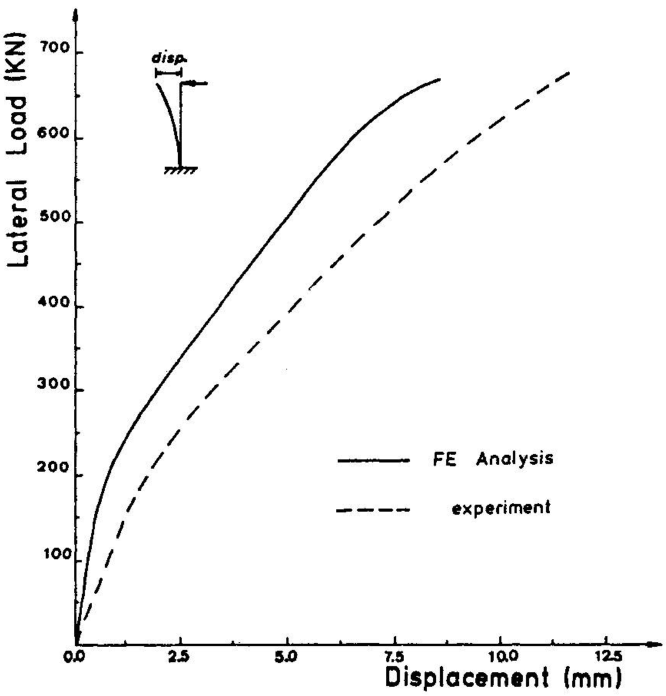

Fig. 5 Typical load-displacement curve of wall

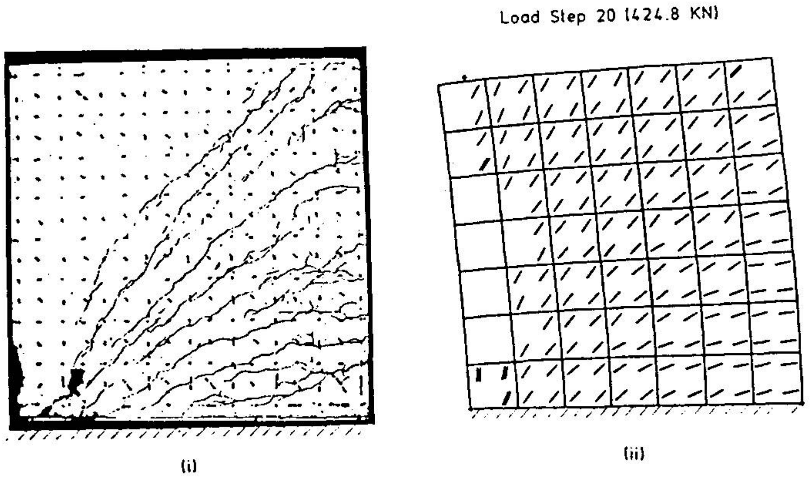

Fig. 6 Typical mode of failure (i) established by experiment (ii) predicted by analysis

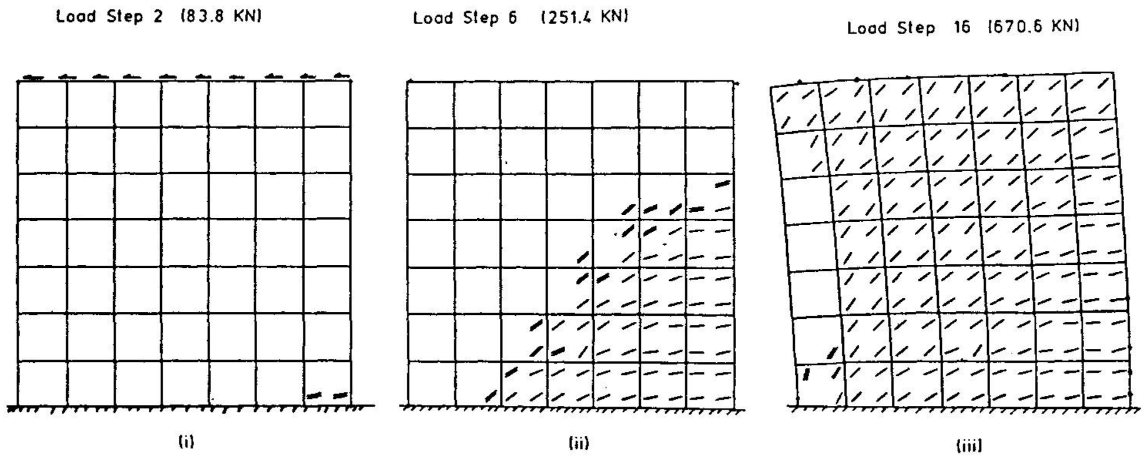

Fig. 7 Crack pattern and deformed shape of a typical wall at load stages corresponding to (i) crack initiation (ii) significant inclined crack formation and (iii) maximum lateral load capacity

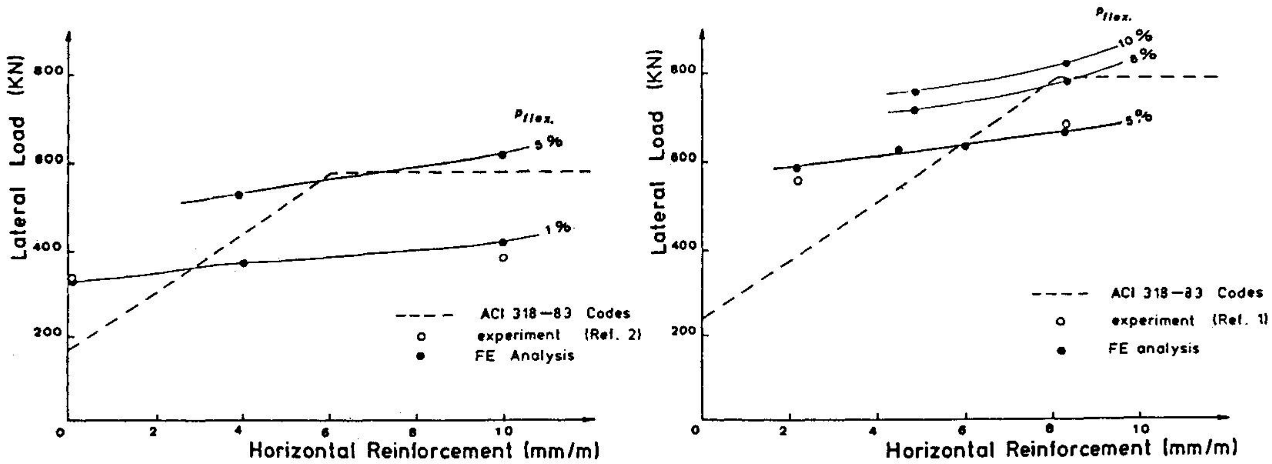

Fig. 8 Relation between shear capacity and amount of horizontal reinforcement predicted for two different experimental programmes