Finite Element Analysis of Reinforced Concrete Shear Walls

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ABSTRACT

A conceptual model is described for predicting the response of reinforced concrete under general membrane stresses. The model includes realistic constitutive relations for cracked reinforced concrete, derived from extensive test data. A nonlinear finite element procedure, incorporating the model, is presented. The analysis procedure is utilized in modelling the response of a series of large-scale shear walls tested. Good correlation is found between predicted and observed response. The details and results of the wall tests, and of the analyses, are discussed.

1 INTRODUCTION

In reinforced concrete nuclear structures, shear walls often represent the major component providing lateral load resistance. In such cases, the shear walls are heavily reinforced and typically exhibit complex theoretical behaviour governed by the performance of the concrete.

Shear walls have thus been the subject of intensive experimental and analytical investigation. At the tenth SMIRT conference, several papers were presented describing comprehensive research programs undertaken (eg. Iizuka et al, 1989; Watabe et al, 1989). Included were discussions of various analytical procedures used to predict the behaviour of shear walls under monotonic or cyclic loading. In general, these procedures were not adequately corroborated with test data or, if so, in some cases did not provide accurate modelling of response.

In this paper, a simple nonlinear analysis procedure is described by which shear walls can be modelled. The procedure's primary distinction is its incorporation of realistic constitutive models for cracked reinforced concrete. By comparing the predicted and observed responses for an extensive series of walls tested, an indication of the accuracy of the procedure will be sought.

2 MODIFIED COMPRESSION FIELD THEORY

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Cracked reinforced concrete elements, under load, typically respond in a complex nonlinear manner. The constitutive response of the concrete and reinforcement, working together, can be substantially different from that determined for the materials acting alone. Analysis procedures using the behaviour models of plain concrete, for example, have typically led to poor results. To better model the response of reinforced concrete under general two-dimensional stress conditions, the Modified Compression Field Theory (MCFT) was formulated (Vecchio and Collins, 1986).

The MCFT treats cracked reinforced concrete as an orthotropic nonlinear elastic material based on a smeared, rotating crack model. Conditions of equilibrium and compatibility are treated in terms of average stresses and average strains. Local stress conditions at crack locations are also examined. Realistic constitutive relations are given for the concrete and reinforcement, derived from extensive test data. Of particular importance in the constitutive modelling are the effects of softening of concrete in compression due to co-acting transverse tensile strains, and the effects of post-cracking tensile stresses in the concrete.

3 CORROBORATION OF THEORY

To corroborate and refine the theoretical model, several test programs were undertaken involving membrane element specimens. The conditions investigated encompassed a wide range of specimen construction details and loading conditions. Included were panels with perforations, panels with pre-defined shear planes, uniaxially reinforced panels, panels with partial prestressing, panels of varying sizes (ie. to study scale effects), panels constructed from high strength concrete, and panels subjected to reversed cyclic loads. Shell element specimens were also tested to study behaviour under conditions involving combined membrane stresses, bending, and out-of-plane shear. In total, over one hundred membrane type specimens have been tested since the theory's formulation.

The MCFT, in essentially its original form, was found to model accurately the behaviours observed in these tests. Aspects of response relating to crack patterns, deformations, reinforcement stresses, ultimate strengths, and failure modes were predicted well in all cases (Vecchio, 1991).

4 FINITE ELEMENT IMPLEMENTATION

The concepts and formulations of the MCFT were incorporated into nonlinear finite element analysis algorithms, using several alternative approaches. In particular, program TRIX was developed using a secant-stiffness based algorithm. Linear displacement finite elements were formulated and incorporated into an iterative linear elastic procedure (Vecchio, 1989). The resulting nonlinear procedure demonstrated good numerical stability and good convergence characteristics. Extensions to the formulations were later developed which permitted the consideration of prestrain effects in the component materials (Vecchio, 1990). Prestressing of the reinforcement, shrinkage or expansion of the concrete, or other types of strain offset effects could then be considered.

The accuracy of the finite element analyses was examined by predicting the response of the various membrane elements tested, as well as by modelling several 'benchmark' tests reported in the literature. In general, very good correlation was found between theoretical and observed response (eg. Vecchio, 1989). Strength, load-deformation response, reinforcement stresses and failure modes were all predicted with good accuracy.

5 TEST PROGRAM

The shear walls chosen for analytical study were walls recently tested by Lefas, Kotsovos and Ambraseys (1990). The test program comprised of a total of thirteen large-scale walls, of rectangular cross section, tested under various conditions of axial load and monotonically increasing lateral load. The test parameters included wall geometry, strength of concrete, reinforcement ratios, and axial load.

The wall geometries were of two types, differing in their height-to-width ratio. The Type I walls were relatively squat, having a height-to-width of 1.0. The Type II walls were more slender, with a height-to-width of 2.0. In both cases, the walls were of constant thickness. The integrated top spreader beam and base structure were thickened and heavily reinforced. In both wall types, concealed columns were effectively formed at the outer edges of the walls by the inclusion of horizontal closed ties placed around the vertical reinforcement.

The walls were subjected to a constant axial load combined with horizontal load that was monotonically increased until failure. The loads were applied through the top spreader beam. The loading rate, for the horizontal load, was 0.04 kN/s.

The walls exhibited a strong, ductile behaviour developing strengths higher than expected. The concrete at the base of the walls, and within the concealed columns, was well confined. Lefas et. al (1990) reported the development of tri-axial compressive stress conditions in these zones, and attributed the high shear resistance of the walls to this state of stress.

6 ANALYTICAL MODELLING OF WALLS

Finite element models were developed for each of the walls tested. The walls were modelled for membrane stress analysis using low-powered linear displacement rectangular elements. A 94-element mesh was used to represent the Type I walls, and a 124-element mesh was used for the Type II walls. Considering the type of element being used, the meshes employed were relatively coarse.

The wall reinforcement was modelled in a smeared manner. Allowances were made for the extra horizontal reinforcement, at the edges of the walls, due to the presence of the ties. However, the out-of-plane reinforcement provided by the ties was not modelled. Loads acting on the wall structures were applied as nodal forces along the top spreader beam. The nodes along the lower edge of the base structure were assumed fixed.

Nonlinear finite element analyses were conducted using program TRIX. Incorporated into the program were the constitutive models of the Modified Compression Field Theory, which have been shown to model accurately the response of cracked reinforced concrete (ie. concrete under tension-compression biaxial stress conditions). To provide more realistic modelling for uncracked concrete under biaxial compression, a relationship describing strength increases according to the Kupfer model was implemented. This allowed for increases in the compressive strength of concrete of up to 25%. No attempt was made to implement a model to account for strength increases due to tri-axial compression.

7 ANALYSIS RESULTS

In all the walls analyzed, the predicted sequence of failure involved flexural-shear cracking, followed by yielding of the vertical reinforcement on the tension side, ending with crushing of concrete near the base on the compression side. In no wall did the stresses in the horizontal reinforcement approach yield. All these aspects agreed well with the experimentally observed behaviour.

The ultimate loads obtained from the theoretical analyses are compared to the experimental values in Table I. It can be seen that the strengths of both the Type I and Type II walls were predicted fairly accurately. For the thirteen walls analyzed, the ratio of the experimental to predicted strength had a mean of 1.07 and a coefficient of variation of 7.2%. The general tendency, however, was for the strengths to be slightly under-estimated, particularly for the Type II (ie. slender) walls.

Table I: Lateral Load Capacities

Specimen	Experimental (kN)	Predicted (kN)	Experimental / Predicted
SW11	260	260	1.00
SW12	340	326	1.04
SW13	330	279	1.18
SW14	265	258	1.03
SW15	320	293	1.09
SW16	355	340	1.04
SW17	247	250	0.99
SW21	127	118	1.07
SW22	150	145	1.03
SW23	180	150	1.20
SW24	120	122	0.98
SW25	150	143	1.04
SW26	123	102	1.20

The predicted load-deformation responses were also compared to the experimental values. Shown in Figure 1, as examples, are the theoretical and experimental deflections at the top of walls SW16 and SW22. The reasonably good agreement shown was typical for both series of walls. Generally, the deflections were predicted well at all stages of loading. However, there was a tendency to slightly under-estimate deflections at intermediate load levels. As well, at ultimate loads, the experimental results demonstrated a more ductile response whereas the force-controlled analyses reflected a sudden crushing failure.

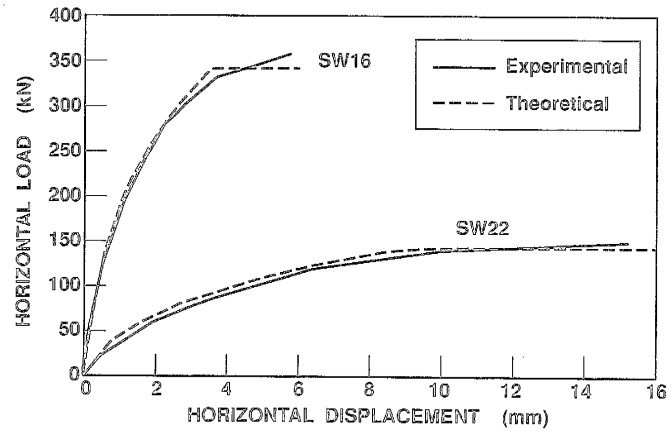

Figure 1: Comparison of experimental and theoretical load-deformation curves.

Other aspects of behaviour were also examined, including crack patterns, stresses in the reinforcement, surface strains, and failure modes. Again, good correlation was found between the experimental and analytical results.

To obtain an indication of the importance of the concrete strength increases due to biaxial compression, analyses were repeated in which biaxial compression effects were ignored. It was found that, while there was little influence at low and intermediate load levels, the ultimate load capacity was decreased by 5 to 15%. As well, the ductility at ultimate load was reduced to a significant degree.

8 DISCUSSION

The theoretical analyses provided an accurate modelling of the nonlinear response of the test walls. This was due largely to the nature of the constitutive models incorporated into the analysis procedure.

The strain softening of concrete in compression, due to co-acting transverse tensile strains, impacted heavily on the behaviour of elements in the large cracked regions of the walls. Neglecting this effect would have resulted, in some cases (particularly the Type I walls), in significantly overestimated strengths. Tension stiffening effects, on the other hand, were of major influence in accurately predicting deflections. Ignoring tension stiffening effects would have led to substantially over-predicted deflections.

The tendency, in the theoretical analyses, to slightly under-estimate ultimate strength was largely related to the inability to account for increases in concrete strength due to confinement. As noted by Lefas et al (1990), the higher shear resistances of the walls arose from the development of tri-axial compressive stresses in the confined concrete. This occurred in the regions in which the concrete was effectively confined by ties. As well, the confinement of concrete may have been responsible for the more ductile response noted at ultimate load. As for the slightly under-estimated deflections at intermediate load levels, the influence of shrinkage stresses or base rotation may have been a factor.

9 CONCLUSIONS

The response of the shear walls studied was heavily influenced by the complex behaviour of concrete. In cracked regions, compression strain softening and tension stiffening effects were predominant factors. In uncracked regions, strength enhancements due to biaxial compression, and more so due to confinement, were significant.

The nonlinear finite element procedure described, incorporating the formulations of the Modified Compression Field Theory, was found to accurately model the response of the shear walls. Strength, deformation response, and failure mode were all predicted reasonably well. The accuracy of the analyses was derived primarily from the attention paid to the constitutive modelling of concrete. Improvements in modelling could be achieved by incorporating a model for confinement effects.

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