Earthquake Engineering, Tenth World Conference © 1992 Balkema, Rotterdam. ISBN 90 5410 060 5

Use of wall macroscopic models in the nonlinear analysis of RC frame-wall structures

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ABSTRACT: In this paper attention is focused on RC shear-wall models which, based on a macroscopic approach, can be efficiently incorporated in a practical nonlinear analysis of multistorey RC frame-wall structures. An overview of the above models is given. In order to evaluate the effectiveness and reliability of selected wall models, analytical and experimental results with reference to isolated walls and to a frame-wall structure are shown.

1 INTRODUCTION

Well-designed RC frame-wall structures prove to be very effective during strong ground motions. Considerable improvement in the understanding of the hysteretic behaviour of these structures has been attained, within the framework of a joint U.S.-Japan research project, by Kabeyasawa & al. (1984) and Bertero & al. (1984), who carried out testings on a 7-storey RC frame wall structure. Prior to testings the base shear capacity of the structure was calculated by using a two-dimensional model in which all the structural members were idealized as line (beam) elements. The calculated value of the shear capacity was considerably less than the corresponding measured value. Apart from the strain hardening of the reinforcement, there have been two main reasons for the low computed strength: (a) the contribution of slab reinforcement was significantly underestimated (e.g., the effective flange width was greater than that currently assumed in building codes); (b) some aspects of the three-dimensional behaviour of the structure (e.g., wall rocking and consequent restraint provided by the outriggering frames surrounding the wall, etc.), which were ignored in the two-dimensional model, were found to contribute greatly to the lateral load capacity.

The reliability of a frame-wall model depends on the accuracy in describing the hysteretic behaviour of single structural members and their interaction. In particular, the use of a suitable wall model is considered crucial. Very sophisticated wall models (i.e., microscopic FE models) are unpractical to analyze multistorey structures; nevertheless, their use is not justified due to uncertain data about expected earthquake loading.

Therefore, in this paper the attention is focused on relatively simple, yet reasonably accurate, wall models based on the macroscopic approach. After synthetically discussing main features of these models, a pseudo-three-dimensional model of a frame-wall structure is considered. Finally, analytical results for walls and a frame-wall structure, respectively tested by Vallenas & al. (1979) and Bertero & al. (1984), are compared with experimental results.

2 RC WALL MACROSCOPIC MODELS

2.1 Equivalent beam and truss models

A current modeling considers the generic wall member replaced by an equivalent beam or a truss system.

The main limitation of a beam model is that rotations occur around points of the wall centroidal axis. Thus, important observed phenomena (i.e., fluctuation of the cross-section neutral axis, rocking, etc.) are disregarded and consequent effects in a frame-wall structure (i.e., outriggering interaction with frames surrounding the wall, etc.) are not accounted for adequately.

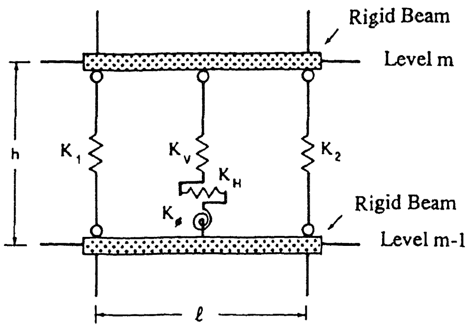
The use of truss models is at the present limited to monotonic loading, because of difficulties in defining structural topology and properties of the truss elements under cyclic loading.

2.2 Multiple-vertical-line-element models

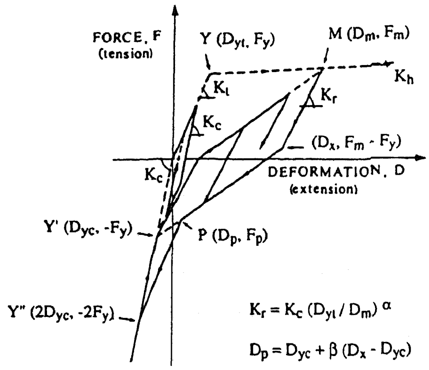
Unlike the equivalent beam model, these models account for the fluctuation of the neutral axis of the cross-section and permit an adequate simulation of the observed phenomena (e.g., the outriggering effect).

After full-scale pseudo-dynamic testing of a 7-storey RC frame-wall structure, Kabeyasawa & al. (1984) proposed the three-vertical-line-element model (TVLEM) in Fig. 1a. The model idealized a wall member under uniform bending as three vertical line elements with infinitely rigid beams at the top and bottom floor levels: two outside truss elements represented the axial stiffnesses K_1 and K_2 of the boundary columns, while the central element was a one-component model consisting of vertical, horizontal and rotational springs at the base with stiffnesses K_v, K_H and K_ϕ, respectively.

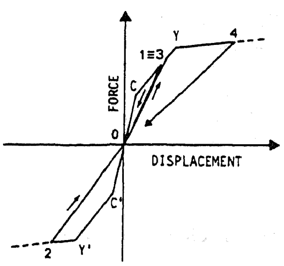
The axial-stiffness hysteresis model (ASHM) in Fig. 1b was proposed to simulate the response of the truss elements. The origin-oriented hysteresis model (OOHM) in Fig. 1c was used for both the rotational and horizontal springs.



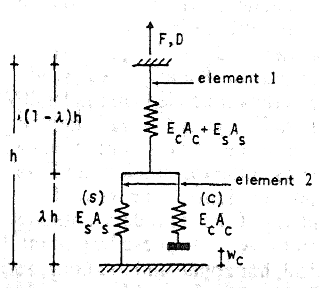
(a) Wall member model.



(b) ASHM for truss elements.



(c) OOHM for horizontal and rotational springs.



(d) Modified ASHM (Vulcano & Bertero 1986, 1987).

Fig. 1 - Three-vertical-line-element model (Kabeyasawa & al. 1984) and its modification.

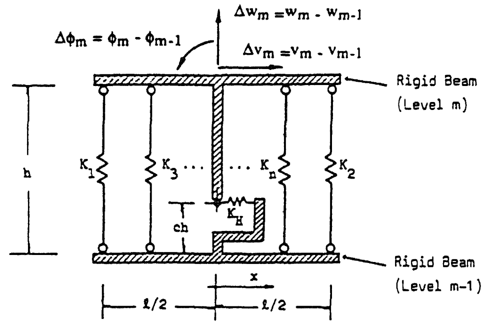


Fig. 2 - Multi-component-in-parallel model (Vulcano & al. 1988).

In order to limit as much as possible the empirical assumptions, Vulcano & Bertero (1986, 1987) modified the TVLEM by replacing the ASHM with the two-axial-element-in-series model (AESM) shown in Fig. 1d: the element 1 was a one-component model to represent as a whole the axial stiffness of the column segments in which the bond was still active, while the element 2 was a two-component model to represent the axial stiffness of the remaining segments of steel (S) and cracked concrete (C) for which the bond was almost completely deteriorated. Even though refined constitutive laws could be considered for the element components, at first schematic laws were assumed in order to check effectiveness and reliability of the AESM.

Subsequently, in order to attain a more refined description of the wall flexural behaviour, Vulcano & al. (1988) proposed the multi-component-in-parallel model (MCPM) in Fig. 2, whose basic idea is similar to that followed for a fiber model (Park & al. 1987). The relative rotation $\Delta\phi_m$ was intended around the point placed on the central axis of the wall member at height ch. A suitable value of the parameter c could be selected on the basis of the expected curvature distribution along the inter-storey height h.

Moreover, the AESM in Fig. 1d was modified by assuming also the element 1 as a two-component model to account for the mechanical behaviour of uncracked concrete and steel separately; a suitable law for the dimensionless parameter λ defining the length of the two elements provided with an accurate description of the measured tension-stiffening effect. Refined constitutive laws were adopted to idealize the hysteretic behaviour of the materials and the tension-stiffening effect.

To improve effectiveness of the MCPM without renouncing reasonable accuracy, schematic constitutive laws could be suitable as well. This is confirmed in recent studies conducted by Fajfar & Fischinger (1990), who introduced simplified hysteretic rules to describe the response of the vertical and horizontal springs.

3 MODELING OF RC FRAME-WALL STRUCTURE

With reference to the 7-storey RC frame-wall structure (Fig. 3) tested by Bertero & al. (1984), the pseudo-three-dimensional model (PTDM) shown in Fig. 4 is adopted.

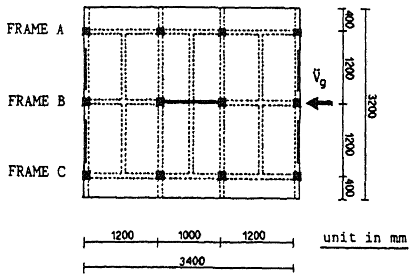


Fig. 3 - Test structure (Bertero & al. 1984).

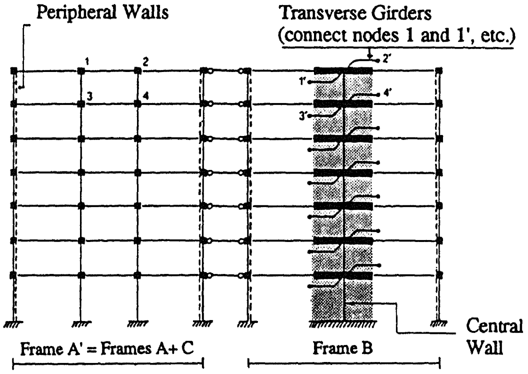


Fig. 4 - Pseudo-three-dimensional model of the test structure in Fig. 3.

Because of the symmetry, the two side frames A and C are lumped together in the resulting frame A'. Frame A' and wall-frame B are constrained by rigid horizontal truss elements to have identical lateral displacement at each floor. Unlike two-dimensional model, in PTDM the transverse girder-slab system is assumed to be effective in relating vertical displacements of the frames A' and B.

The four peripheral walls are modeled as truss elements in parallel with the exterior beam-column elements. The joint zones are assumed to be rigid, while the deformable part of the structural members (apart from the central wall) is idealized as a beam element. The central wall could be idealized by adopting any one of the wall models described in the previous section. In the next section the two-component beam model or, alternatively, the MCPM will be considered.

4 RESPONSE OF ANALYTICAL MODELS

In order to check effectiveness and reliability of macroscopic wall models, in the course of previous studies (Vulcano & Bertero 1986 and 1987, Vulcano & al. 1988, Vulcano & Colotti 1990) an extensive numerical investigation was carried out with reference to isolated walls tested by Vallenas & al. (1979) and to the 7-storey RC frame wall structure already mentioned. Herein meaningful results are shown and discussed.

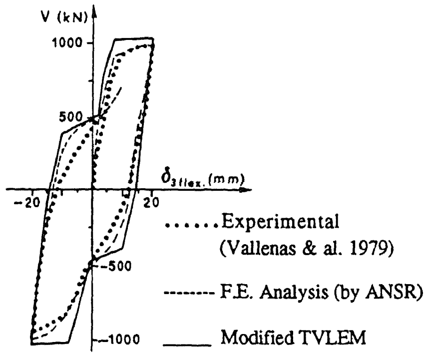


Fig. 5 - Analytical and experimental curves for framed-wall specimen .

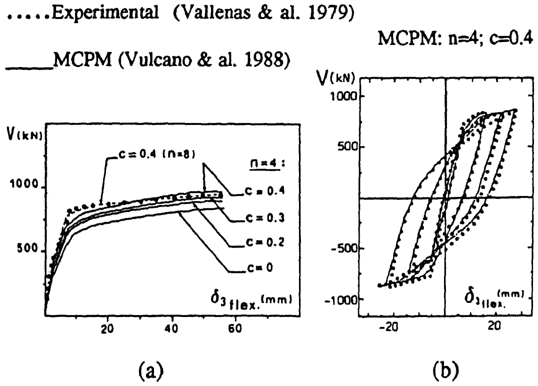


Fig. 6 - Analytical and experimental curves for rectangular-wall specimens .

As shown in Fig. 5 for a framed-wall specimen, a satisfying prediction of the experimental curve is obtained by the modified TVLEM, even by assuming schematic laws for the AESM components in Fig. 1d. The accuracy level attained by the modified TVLEM is comparable to that by a F.E. analysis, which of course requires an higher computational effort .

As shown in Figs. 6a and 6b for rectangular-wall specimens under monotonic and cyclic loadings, respectively, considerable improvement in predicting the wall flexural behaviour can be attained by MCPM. In Fig. 6a a good agreement with the experimental curve is shown when assuming c=0.4 and 4 vertical uniaxial elements (n=4) for MCPM; the agreement becomes excellent for c=0.4 and n=8 (see dashed line). A very good agreement is also shown in Fig. 6b, where the analytical curve represents the displacement-controlled flexural response.

Analogous results, which are omitted for sake of brevity, have been obtained by using MCPM for framed-wall specimens. However, it was noted that under high shear stresses, as previously found for the TVLEM and corresponding modified model (Vulcano & Bertero 1986, 1987), difficulties are met for accurately predicting flexural and shear displacement components.

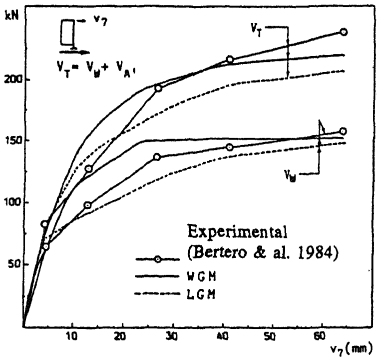


Fig. 7 - Analytical and experimental curves for the frame-wall structure in Fig. 3.

Finally, in order to check the suitability of the MCPM for incorporation in the nonlinear analysis of multistorey structures, in Fig. 7 results are shown with reference to the structure in Fig. 3. Exactly, the base shears V_T and V_w of the overall structure and central wall, respectively, are shown against the roof horizontal displacement v_7. The experimental curves were obtained by Bertero & al. (1984) as envelope of the results of dynamic testings. The analytical curves have been obtained by PTDM in Fig. 4 by idealizing all the structural members as line beam elements (LGM model) or, alternatively, the central wall only by the MCPM (WGM model); a static nonlinear analysis was carried out by assuming a uniform loading distribution and a suitably reduced value of the initial and strain-hardening flexural-stiffnesses of the beam elements, idealized by a two-component model (see Vulcano & Colotti 1990).

As it can be observed, both the analytical models, but particularly LGM, underestimated the ultimate strength of the structure, even though a uniform loading distribution has been assumed for both of them: this should have implied some overestimation of the ultimate strength, because of the actual loading distribution in the dynamic testing and some mechanical degradation due to cyclic loading. On the other hand, the underestimation of the ultimate strength by both the analytical models can be mostly ascribed to the fact that the strain rate to obtain the constitutive curves of the materials, on which mechanical characteristics of the analytical models have been settled, was considerably lower than that recorded during the dynamic testing.

5 CONCLUSIONS

The PDTM is suitable for nonlinear analysis of multistorey RC frame-wall structures. The following conclusions about incorporation of wall models can be drawn.

Wall models based on a macroscopic approach are more effective than microscopic FE models.

Equivalent beam models fail to simulate the fluctuation of the cross-section neutral axis, leading to a wrong description of the interaction of the wall with the surrounding frames. The implementation of a truss model meets with difficulties in defining properties of the truss elements, particularly under cyclic loading.

Multiple-vertical-line-element models prove to be the most suitable for the above incorporation, particularly because they are capable of accounting for fluctuation of the cross-section neutral axis. When a suitable value of the parameter c and refined constitutive laws are assumed, the MCPM accurately predicts the flexural response, even assuming the minimum of uniaxial elements (n=4), with a limited computational effort.

In order to improve the effectiveness of the MCPM, simplified, yet reasonably accurate, constitutive laws can be adequate as well. Accuracy improvement of the MCPM can be attained: by revising the OOHM which, under high shear stresses, gives only approximate description of the shear hysteretic response, by simulating other observed phenomena at the present ignored (e.g., fixed-end-rotation at the base of the wall, etc.) and by a better calibration of the parameters (e.g., c, etc.) affecting the response of the models.

ACKNOWLEDGEMENTS

This work was partially financed by a grant from C.N.R. (Italian Research Council).

REFERENCES

Bertero V.V., Aktan A.E., Charney F.A. & Sause R., "U.S.-Japan cooperative research program: earthquake simulation tests and associated studies of a 1/5th-scale model of a 7-story reinforced concrete test structure", *Report UCB/EERC-84/05*, Univ. of California, Berkeley, 1984.

Fajfar P. & Fischinger M., "Mathematical modeling of reinforced concrete structural walls for nonlinear seismic analysis", *Procs. EURODYN'90, Euro. Conf. on Struct. Dyn.*, Bochum, Germany, 1990.

Kabeyasawa T., Shioara H. & Otani S., "U.S.-Japan cooperative research on R/C full-scale building test - Part 5: discussion on dynamic response system", *Procs. 8th W.C.E.E.*, Vol. 6, S. Francisco, 1984.

Park Y.J., Reinhorn A.M. & Kunnath S.K., "IDARC: inelastic damage analysis of reinforced concrete frame-shear-wall structures", *Report NCEER-87-0008*, State Univ of New York, Buffalo, July, 1987.

Vallenas J.M., Bertero V.V. & Popov E.P., "Hysteretic behaviour of reinforced concrete structural walls", *Report UCB/EERC-79/20*, Earthquake Engineering Research Center, University of California, Berkeley, 1979.

Vulcano A. & Bertero V.V., "Nonlinear analysis of R/C structural walls", *Procs. 8th E.C.E.E.*, Vol. 3, Lisbon, Portugal, 1986.

Vulcano A., & Bertero V.V., "Analytical models for predicting the lateral response of RC shear walls: evaluation of their reliability", *Report UCB/EERC-87/19*, Univ. of California, Berkeley, 1987.

Vulcano A., Bertero V.V. & Colotti V., "Analytical modeling of R/C structural walls", *Procs. 9th W.C.E.E.*, Vol. VI, Tokyo-Kyoto, Japan, 1988.

Vulcano A. & Colotti V., "Analytical modeling of RC frame-wall structural systems", *Procs. 9th E.C.E.E.*, Vol. 10-B, Moscow, 1990.