ON PRACTICAL METHOD FOR EVALUATING LATERAL STIFFNESS OF R/C SHEAR WALLS ARRANGED IRREGULARLY INTO DUCTILE MOMENT-RESISTING FRAMES

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SUMMARY

In the current earthquake-resistant code provisions for ordinary building structures, it is required to determine the fundamental elastic period of vibration as well as story drifts and member forces. In case when R/C shear walls are provided into ductile moment-resisting space frames, it is necessary to evaluate the lateral stiffness of those walls as precisely as possible, because analysis results are remarkably affected by the different techniques in evaluating the lateral stiffness of the walls. This paper examines the practical methods for evaluating the elastic lateral stiffness of the R/C shear walls, especially arranged irregularly into low-rise building frames.

INTRODUCTION

It has been recognized that the reinforced concrete shear walls which are provided into ductile moment-resisting space frames have a large lateral load-carrying capacity as well as giving a large effect on the structural behavior of the whole structure during the earthquake. Because of being very difficult to evaluate their lateral stiffness precisely and quantitatively, especially for shear walls arranged irregularly, most of the structural engineers usually determine the horizontal rigidity of those walls by their own engineering judgements. In accordance with the aseismic code provisions in earthquake countries including Japan and USA, it is required to determine the fundamental period of vibration, interstory drifts and an eccentricity between the center of mass and that of lateral rigidity in each story of the building frames. In order to evaluate those quantities precisely, it is necessary to establish the practical method for evaluating the lateral stiffness of those walls because the earthquake behavior of the whole structure is largely affected by the different techniques in evaluating the shear wall stiffness.

Although a number of methods for determining the lateral stiffness of the shear walls have been proposed by many authors, emphasis of most of those works is placed upon the horizontal rigidity of the shear walls arranged regularly or continuously through the height of the structures, and there are quite few studies that deal with irregularly arranged shear walls. In recent years it has been possible to make more precise structural analyses by using direct stiffness method, finite element method and so on, and also some of the analytical solutions or methods are available to be used for determining the shear wall stiffness (Refs. 1 and 2). In most of those solutions and methods, however, high speed electric computers are assumed to be used. While in structural analysis for ordinary medium- and low-rise building frames, practical evaluation method for shear wall stiffness is needed to be established because those types of structural analyses are usually done by using small computers and/or handiworks.

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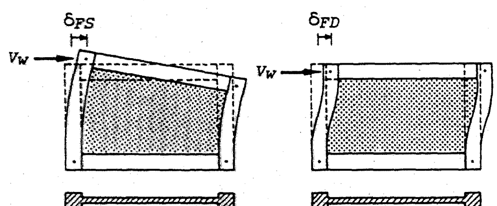
Main objective of the present study is to examine the practical methods for evaluating the elastic lateral stiffness of R/C shear walls having edge members which are arranged irregularly into low-rise building frames. Since the pattern of arrangement of the shear walls into a building frame has a large effect on fundamental periods of vibration, lateral deflections and member forces, a total of thirty-eight R/C model structures in which shear walls are irregularly arranged in various patterns are selected as analytical models. By using the exact stiffness matrices of all members and shear walls where the shear walls are represented as four-node elements with three-degree-of-freedom at each node, and whose stiffness matrices are derived through techniques of established accuracy, both eigenvalue and static analyses are conducted against lateral forces. All of the deformations of the shear walls obtained are separated into three components - flexural deformation, shear distortion and rigid-body rotation. Based on the relation between those three components of the deformation and lateral shears carried by the walls, values of lateral stiffness - flexural, shear and rotational rigidities - of all shear walls are calculated. Results obtained are compared with those determined by simple practical methods.

SELECTION OF MODEL STRUCTURES

Three-bay-six-story R/C ductile moment-resisting plane frames in which shear walls are irregularly provided in various patterns are adopted as analytical model structures. These model frames shown on the left sides of Figs. 4(a) through (g) are almost the same as those adopted in Ref. 3, where the effect of different manner of shear wall arrangements on static and dynamic behavior of building frames was examined by using the same analytical models. Those of thirty-eight building frames selected are the minimum-scale low-rise buildings having at least the upper, lower and intermediate stories along the height of the frames, and also having the exterior and interior bays in their horizontal directions. According to their shear wall arrangements, model frames are classified into eight groups, such as "TYPE A", "TYPE B" and so on, as shown in Fig. 4. All of the size and shape of those frames and shear walls are the same as those in Ref. 3.



(a) (b)

Fig. 1 Flexural Deformation

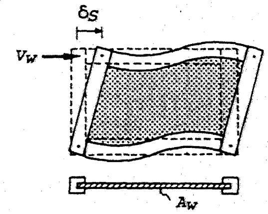


Fig. 2 Shear Distortion

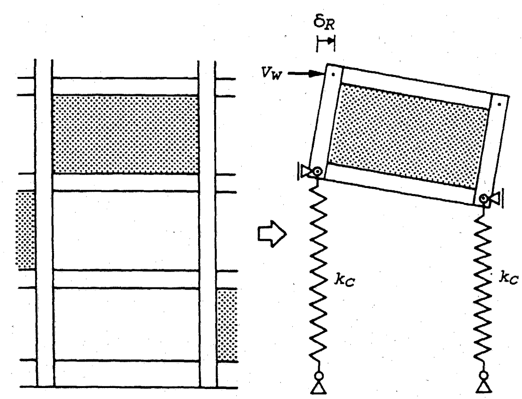


Fig. 3 Practical Evaluation for Shear Wall Rotation

DEFORMATION CHARACTERISTICS OF INDIVIDUAL SHEAR WALLS

Exact Structural Analysis. In order to examine the deformation characteristics of the shear walls located in the building frames, elastic structural analysis was conducted for all of the model frames shown in Fig. 4, in case when those frames are subjected to lateral earthquake forces. Stiffness matrices of all the beam and column elements are determined by taking into account of the flexural and shear deformations. Since each floor is assumed to act as a rigid horizontal diaphragm in its own plane, beams have no axial deformations, although the axial deformation of each column is considered. Presence of rigid zone within the beam-to-column connection is also taken into consideration. While in shear walls, stiffness matrices proposed by Tomii et al. (Refs. 1 and 2) are used to evaluate the stiffness of the individual shear walls, in which the shear walls are represented as four-node elements with three-degree-of-freedom at each node.

Since the distribution of equivalent static lateral forces over the height of the building frames varies widely from the triangular-shape (as specified in the Uniform Building Code in USA) to the rectangular one (in the old Japanese Building Standard Law) in accordance with the different manner of arrangement of the shear walls (Ref. 3), both of the triangular and rectangular distributions having the same base shear coefficient of 0.2 are used. The same distribution of the weights as in Ref. 4 is assumed in the analysis. Based on the direct stiffness method, unknown displacements of all nodes and member forces were determined. Material constants assumed are that the values of Young's modulus and Poisson's ratio of the structural elements are $E = 210$ ton/cm^2 and $\nu = 1/6$, respectively, and a factor depending on the form of the cross sections for the shear distortion is taken as 1.2 for the column and beam elements.

Separation of Shear Wall Deformation. By using the technique presented in Refs. 2 and 5, arbitrary deformation of a shear wall (represented by the nodal displacements with three-degree-of-freedom at each node) can be separated into three components - flexural deformation, shear distortion and rigid-body rotation - the strict definition of which is given in Ref. 5 and is schematically illustrated in Figs. 1, 2 and 3, respectively. From these three components of the deformation, corresponding lateral displacements (designated by symbols, δ_F, δ_S and δ_R in Figs. 1, 2 and 3) between top and bottom of each individual shear wall can be determined. In addition, since the lateral shear carried by the shear wall, Vw, has been also obtained from the exact analysis as described previously, corresponding lateral stiffness of the shear wall can be calculated. In equation form,

$$K_F = Vw/\delta_F, \qquad K_S = Vw/\delta_S \quad \text{and} \quad K_R = Vw/\delta_R \qquad \text{..........(1)}$$

where K_F, K_S and K_R represent the lateral stiffness due to flexural deformation, shear distortion and rigid-body rotation occurred in the shear wall, respectively.

Deformation Characteristics of Shear Walls. Based on the exact structural analysis, values of lateral stiffness due to flexure, shear and rigid-body rotation given by Eq. 1 were calculated for all of the shear walls located in each story of the model frames. Results in case when the model frames are subjected to triangular-shape lateral forces are given in Figs. 4(a) through (g). In the figures, values of $1/K_F$, $1/K_S$ and $1/K_R$, which represent the interstory displacements due to flexural deformation, shear distortion and rigid-body rotation caused by unit lateral shear force, are respectively plotted against the location of each shear wall. As is seen from those figures, flexural and shear displacements caused by unit shear force, given by the values of $1/K_F$ and $1/K_S$ respectively, are almost constant through the height of the model frames except for a few walls, and have relatively smaller values than those caused by the rigid-body rotation. On the contrary, it can be understood that the lateral displacements caused by the rigid-body rotation, represented as $1/K_R$, are widely scattered depending upon the manner of arrangement and location of the shear walls, although the values in the upper story shear walls are larger than those in the lower story shear walls. Deformation characteristics of the shear walls obtained by using the rectangular-shape static lateral forces had also the similar tendency to those in Fig. 4.

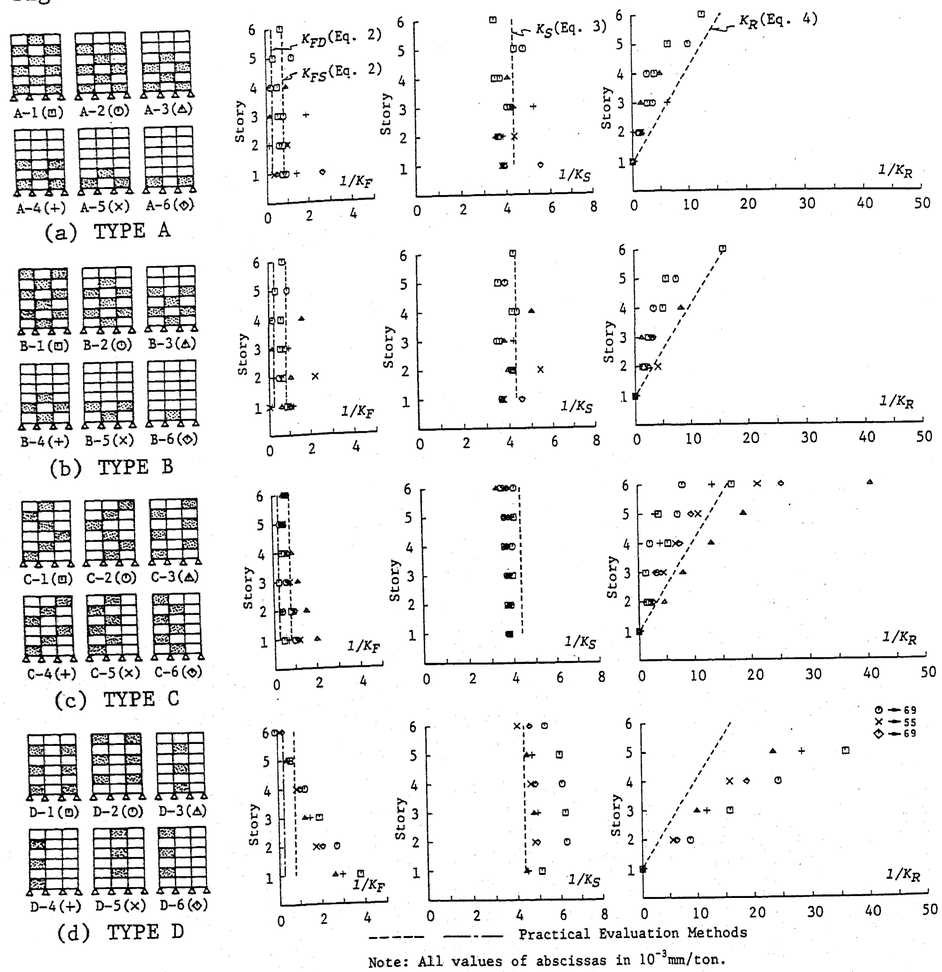


Fig. 4 Separation of Shear Wall Deformation

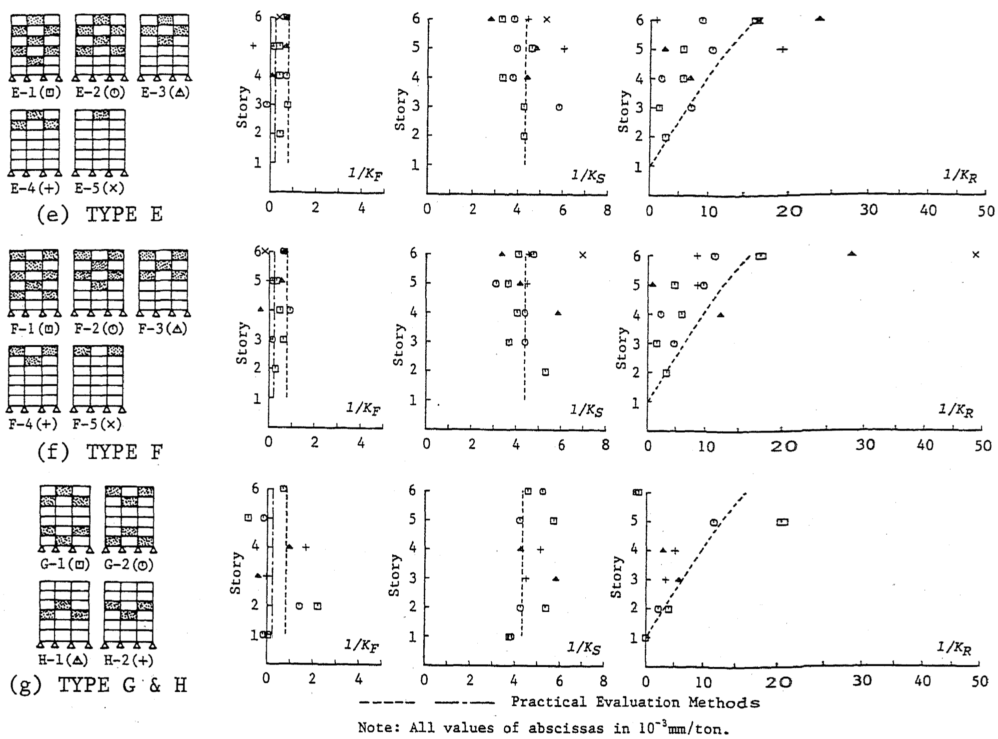


Fig. 4 Separation of Shear Wall Deformation (continued)

INVESTIGATION OF PRACTICAL STIFFNESS EVALUATION

Practical Evaluation Methods for Lateral Stiffness of Shear Wall. In order to examine the accuracy of lateral stiffness of the shear walls determined by the practical evaluation methods, horizontal rigidities for flexure, shear and rotation of the shear wall were respectively calculated by using the simple equations. In determining the lateral stiffness of the shear wall due to flexural deformation, two cases of deformations - single curvature deformation as shown in Fig. 1(a) and double curvature one in Fig. 1(b) – were taken into consideration. When the shear wall acts as line model with I-shape horizontal cross section, corresponding values of lateral stiffness can be respectively evaluated by the following simple equations.

$$K_{FS} = 3EI_W/h^3 \quad \text{and} \quad K_{FD} = 12EI_W/h^3 \qquad \text{(2)}$$

in which K_{FS} and K_{FD} represent the lateral stiffness in case when the single and double curvature deformations occur in the shear wall, respectively, and I_W and h denote the moment of inertia of the horizontal wall cross section and vertical distance from center-to-center of edge beams. Lateral stiffness of the shear wall caused by the shear distortion as shown in Fig. 2 can be evaluated by the popular equation;

$$K_S = GA_W/\alpha h \qquad \text{(3)}$$

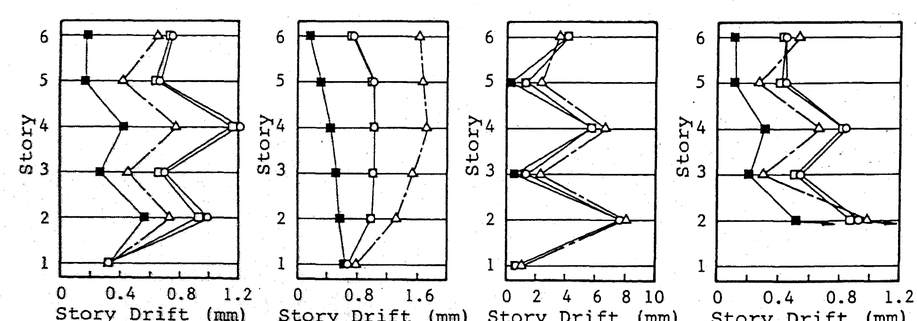
where G denotes the modulus of shear of the wall material and A_W is the horizontal cross-sectional area of the shear wall (Fig. 2). The value of α is taken as 1.2. While in determining the rotational rigidity of the shear wall due to rigid-body rotation, only the axial deformations of columns located under the shear wall are taken into account. This quite simple evaluation method is schematically shown in Fig. 3, and its lateral stiffness is given by

$$K_R = k_C(l^2/2h^2) \qquad \text{...} (4)$$

where k_C represents the axial spring constant of the left and right columns located under the shear wall and l denotes the horizontal distance from center-to-center of edge columns of the shear wall.

The values of lateral stiffness of the shear wall given by Eqs. 2, 3 and 4 are respectively shown in Fig. 4 by using the dashed lines, where those quantities are represented in the forms of $1/K_{FS}$, $1/K_S$ and $1/K_R$, respectively. In addition, the values determined by K_{FD} in Eq. 2 are also shown by dashed-and-dotted lines in $1/K_F$ versus story relations in Fig. 4. It can be seen from Fig. 4 that the flexural and shear deformations of the shear walls which are calculated simply by Eqs. 2 and 3 show the average of those determined from the exact structural analysis. While except for several model frames such as Type D, rotational displacement, $1/K_R$, caused by unit shear force which is determined by Eq. 4 gives larger evaluation than the values obtained from the exact analysis. This fact means that the lateral displacements of the shear walls determined by using Eq. 4 are conservative against the actual elastic deformation behavior of most of the shear walls arranged in the building frames.

Story Drifts. All of the story drifts of the model frames which are obtained from the direct stiffness method were compared with those determined by using the practical method of seismic analysis proposed by Muto (Ref. 6), in which lateral stiffness of each shear wall was evaluated by considering the following three cases. In the first and second cases designated by "CASE 1" and "CASE 2" (the results of which are represented by the symbols ○ and □ ,



(a) TYPE A-1 (b) TYPE C-3 (c) TYPE D-3 (d) TYPE E-1

---△- Exact Analysis
—○— (CASE 1), —□— (CASE 2), —■— (CASE 3) in Practical Methods

Note: Story drifts in Figs. (a), (b) and (c) are caused by triangular-shape static lateral forces and those in Fig. (d) are by rectangular one.

Fig. 5 Story Drifts due to Static Lateral Forces respectively, in Figs. 5 and 6), K_{FS} and K_{FD} in Eq. 2 are respectively used for evaluating the flexural displacements of the shear walls. Shear and rotational rigidities are evaluated by Eqs. 3 and 4 for both of those two cases. While in the third case, "CASE 3" (■), rigid-body rotations of all the shear walls are restrained although flexural and shear deformations calculated by K_{FD} and K_S in Eqs. 2 and 3 are incorporated. In determining the lateral stiffness of the individual columns, flexural and shear deformations of beam and column elements and the presence of rigid zones within the beam-to-column connections are taken into account in all the cases. Some of the typical story drifts obtained are given in Fig. 5. From the results obtained, it can be seen that the story drifts in the upper stories determined practically are considerably underestimated if rotational deformations of the shear walls are restrained (CASE 3 in Fig. 5). Difference of results between CASE 1 and CASE 2 is quite small, in other words, the effect of flexural deformation of the shear walls on story drifts can be neglected. In addition, results in CASE 1 and CASE 2 give better agreements with those of the exact analysis than CASE 3.

Eigenvalues. By using the mass and stiffness matrices used in the direct stiffness method, fundamental periods of vibration and modal participation functions of all the model frames were calculated, and the results obtained were compared with those determined from the practical evaluation methods. Comparison of fundamental periods of vibration is shown in Fig. 6, where exact values, ${}_ET_1$ (Ref.4), are compared with those , ${}_pT_1$, determined practically in

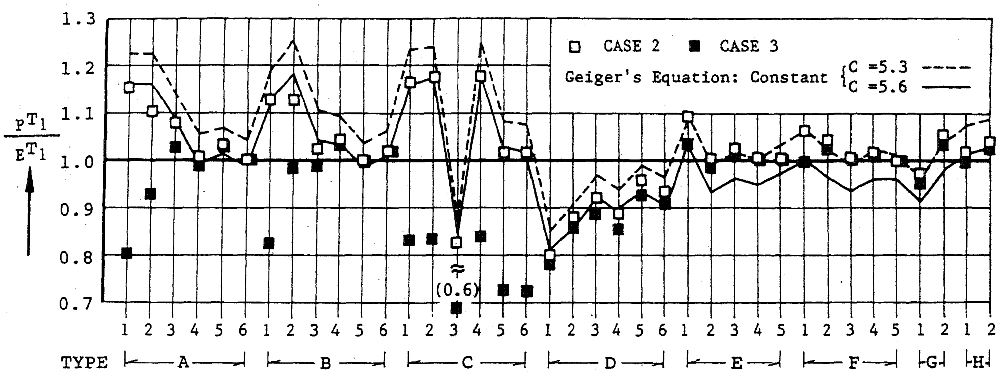


Fig. 6 Accuracy of Fundamental Periods of Vibration Determined by Practical Evaluation Methods

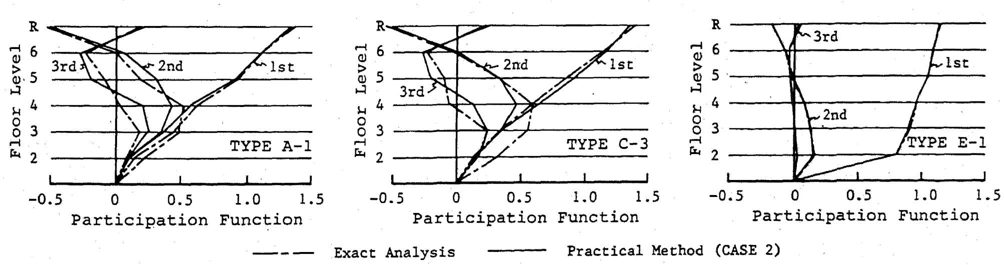


Fig. 7 Modal Participation Functions

CASE 2 and CASE 3. In the same figure, fundamental periods determined by Geiger's equation (Ref. 3), in which lateral stiffness in CASE 2 were used, are also compared with those of the exact analysis by solid lines and dashed lines. It can be understood from the figure that the fundamental periods of vibration of most of the model frames can be practically evaluated within the error of 15 percent, and also Geiger's equation is excellent to determine the fundamental periods of vibration of those frames if the constant in the equation is appropriately choosen. Such a good agreement is also seen in the comparison of the modal participation functions as shown in Fig. 7 and member forces (Ref. 7).

CONCLUDING REMARKS

(1). Shear and flexural rigidities of the shear walls are not widely affected by the different manner of shear wall arrangement into building frames. Those values are nearly constant through the height of the building and can be approximately evaluated by the simple practical equations.

(2). Pattern of arrangement of the shear walls into the building frame has a large effect on rotational deformation of those walls.

(3). Rotational rigidity of the shear walls, which is practically determined by considering the axial deformation of columns located under the walls, gives a conservative evaluation against the actual deformation behavior of most of those walls.

(4). Lateral displacements, member forces including lateral shears carried by the shear walls, fundamental periods of vibration and modal participation functions of those low-rise building frames in which shear walls are irregularly provided can be approximately evaluated by using the lateral stiffness of the walls determined from the simple practical evaluation methods.

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