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Nonlinear FEM analysis of 3-D RC shear walls under cyclic loading

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ABSTRACT: A simple model for nonlinear analysis of 3-Dimensional(3-D) Reinforced Concrete(RC) shear walls under cyclic loading by finite element method(FEM) is proposed in this study. The analysis and the comparison with the experimental results demonstrated that the model had good accuracy.

1 INTRODUCTION

Many research works have been done for RC finite element method during the last decade. One of these famous works is the modified compression field theory for RC, which was developed by Collins and Vecchio(1982), and its application was made by Inoue(1985) et. al. and Vecchio(1989) to nonlinear finite element analysis of RC shear wall. Another one of these works is to develop a rational simple model available for nonlinear analysis under cyclic loading or dynamic loading. A simple model to analyse RC membrane by means of rod element was proposed by Inoue and Suzuki(1989), and it was applied to dynamic analysis of shear walls in a nuclear power plant by Sakai(1993) et. al. recently. To focus on the 3-D RC shear wall structures, a laminated layer model, considering the out-of-plane bending effect, was proposed by Ueda(1983) et. al. for FEM analysis of 3-D RC shear wall under monotonic loading. This model was used for the analysis of cylindrical and box walls and the reliable results were obtained.

Based on the above studies, a simple model under cyclic loading is proposed in this paper toward formulating a more rational model which can be used in dynamical nonlinear FEM analysis of 3-D RC shear wall.

2 FINITE ELEMENT MODEL

To simplify the complex 3-D RC wall-slab structures with the nonlinearity of RC material, the proposed model is developed by assembling the iso-parametric plane elements with 4-node for walls and iso-parametric 3-D solid elements with 8-node for slab on the walls. The link nodes, which tie a wall to its orthogonal wall and the slab, are defined to be 3-D nodes in order to model the 3-D shear wall structures (see

Fig. 1). The RC wall is considered as inelastic material, while the slab is considered as relatively rigid elastic material. The Newton-Raphson method is employed to solve the nonlinear equations, and the iteration is performed until the error vector meets accuracy requirments.

The constitutive model is formulated on the basis of the nonlinearity of concrete and reinforcement. The nonlinear RC model is based on the smeared appoach for both the concrete cracks and the reinforcements in an element.

3 STRESS-STRAIN RELATIONSHIP

3.1 Concrete

The constitutive equations of concrete under biaxial stresses are defined for two different concrete states as follows:
1) Uncracked concrete
The isotropic material stiffness matrix is used before concrete cracking, where the tangential isotropic modulus Ei is determined by the curve (Fig. 2) of the larger absolute value of the principal stresses in uncracked Gauss point of every element.

$$[D]_c = \frac{E_i}{1-\nu^2}\begin{pmatrix} 1 & \nu & 0 \\ \nu & 1 & 0 \\ 0 & 0 & (1-\nu)/2 \end{pmatrix} \tag{1}$$

2) Cracked concrete
Based on the Collins' theory, cracked concrete is treated as a kind of new material with modified stress-strain characteristics. Thus, the cracked concrete material stiffness matrix is as follows

$$[D]_c = \begin{pmatrix} E_{c1} & 0 & 0 \\ 0 & E_{c2} & 0 \\ 0 & 0 & G_c \end{pmatrix} \tag{2}$$

where the E_{c1} and E_{c2} are the moduli as evaluated using the stress- strain curve of Fig. 2.

After cracking, the material was assumed to be orthotropic characterists with respect to the crack direction and its orthogonal direction. The tension stiffening

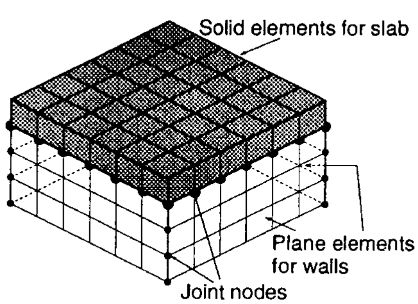


Fig. 1 FEM mesh layout of specimens B-00 and B-45

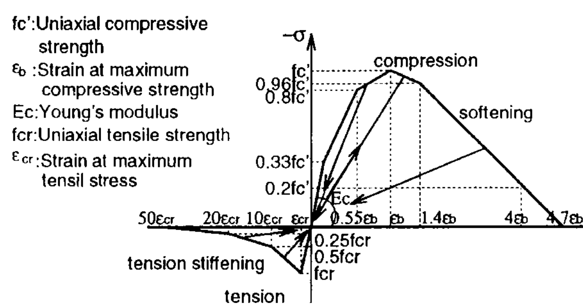


Fig. 2 The stress-strain curve for concrete under cyclic loading

effects in tension and the degradation of stiffness and strength in compression were considered in the stress-strain relationship. The degradation ratio of strength is assumed to be a constant value of 0.75 which is considered to be an average value in the web panel subjected to shear. If the structure is under cyclic loading, the principal stress-strain curve is assumed to simply return to original point linearly (see Fig. 2). The new crack direction under the negative load was assumed to be orthogonal to the direction of the old crack under the positive load.

As to shear stiffness
$$G_c = \beta G \tag{3}$$
$$\beta G = a/\varepsilon_1 \tag{4}$$

where ε_1 is the tensile principal strain.
a is the constant coefficient using $0.036(tf/cm^2)$ according to the experimental study by Aoyagi(1982).

3.2 Reinforcement

Reinforcement is modeled by a bi-linear relationship. The material stiffness matrix of reinforcement $[D]_s$ is evaluated as follows

$$[D]_s = \begin{bmatrix} \rho_x E_s & 0 & 0 \\ 0 & \rho_y E_s & 0 \\ 0 & 0 & 0 \end{bmatrix} \tag{5}$$

where ρ_x, ρ_y are the reinforcement ratios in direction x and y respectively, and E_s is the tangential modulus of steel which is determined by the stress-strain relationship of steel shown in Fig. 3.

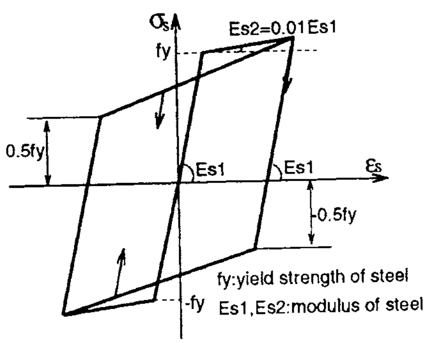


Fig. 3 Uniaxial stress-strain relationship of steel under cyclic loading

Tab. 1 Parameters of specimens

Parameters	B-00	B-45
reinforcement ratio (%)	1.2	1.2
thickness of wall (cm)	8.0	8.0
length of wall (cm)	150.0	150.0
height of load point(cm)	90.0	90.0
shear span ratio M/QD	0.600	0.425
compressive strength of concrete (kgf/cm²)	304	293
tensile strength of concrete (kgf/cm²)	17.4	17.1
Young's modulus of concrete (kgf/cm²)	2.76×10^5	2.67×10^5
yield strength of steel (kgf/cm²)	4540	4540
Young's modulus of steel (kgf/cm²)	1.95×10^6	1.95×10^6

4 ANALYTICAL PROCEDURE

To correct the error caused by the overshoot at modulus-changing points of stress-strain curve in one incremental step and to deal with the downword sloping portion of stress-strain curve as tension stiffening part in tension and softening part in compression shown in Fig. 2, the Newton-Raphson iterative method is employed to solve the nonlinear equations. The iterative procedure can be described as following equations.

The equilibrium equation in each load incremental step n can be written as

$$[K]_n^1\{\Delta u\}_n^1 = \{\Delta F\}_n \tag{6}$$

where

$[K]_n^1$ is the total tangential stiffness matrix in the first iterative step

$\{\Delta u\}_n^1$ is the incremental vector of displacement in the first iterative step

$\{\Delta F\}_n$ is the incremental vector of load

The iterative equation in the following iterative step i $(i > 1)$ can be written as

$$[K]_n^i\{\Delta u\}_n^i = \{R\}_n^i \tag{7}$$

$$\{R\}_n^i = \sum_{step}\{\Delta F\}_n - \sum_{element}\int\int\int[B]^T\{\sigma\}_n^i dV \tag{8}$$

where $[K]_n^i$ is the total tangential stiffness matrix in iterative i step

$\{\Delta u\}_n^i$ is the incremental vector of displacement in iterative i step

$\{R\}_n^i$ is the error vector in iterative i step

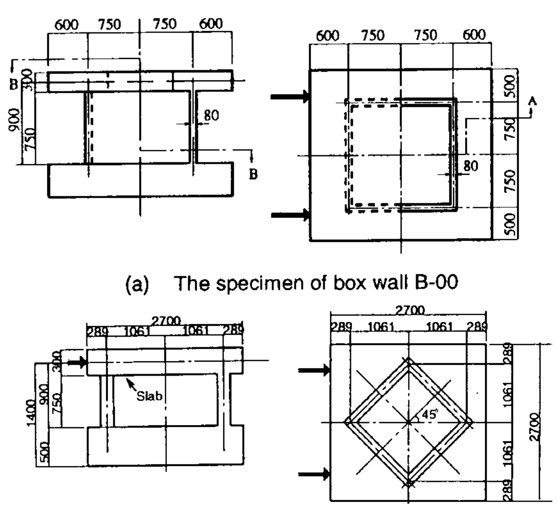
$\{\sigma\}_n^i$ is the element stress vector in iterative i step

This iteration is performed until a given error criteria is satisfied. The merit of this approach is that it can restrain accumulated error during analysis because equilibrium equation is checked at every incremental step.

5 ANALYSIS OF RC SPECIMENS

5.1 Description of the test

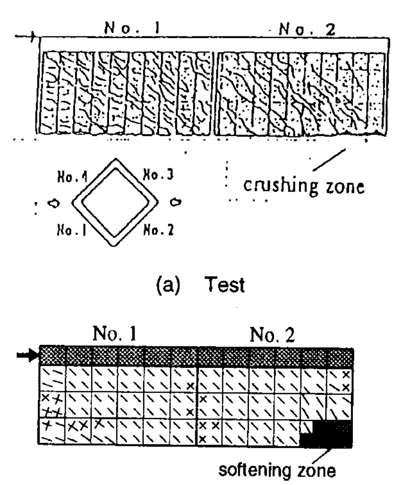
Experimental studies on the seismic behavior of RC box walls under cyclic loading



(a) The specimen of box wall B-00

(b) The specimen of box wall B-45

Fig. 4 The specimens



(a) Test

(b) Analysis

Fig. 5 Cracking pattern and softening zone were carried out by Miyauti(1985) et. al. The specimen of box wall B-00 and B-45 is shown in Fig. 4. The cyclic horizontal loading are at 0° and 45° angle with the direction of web respectively. The material properties of the specimen are given in Tab. 1

Tab. 2 The comparison with the results of test B-45

	test	analysis
bending cracking	35.8	27.72
shear cracking	47.9	48.50
yield of vertical steel in flange	136.8	128.87
maximum strength	193.5	182.92

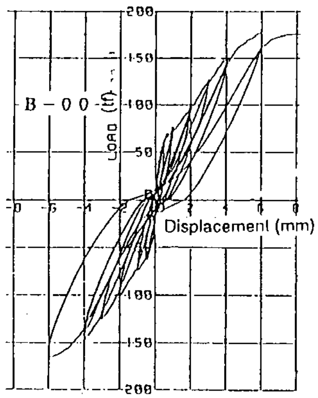
unit(tf)

5.2 Results of analysis

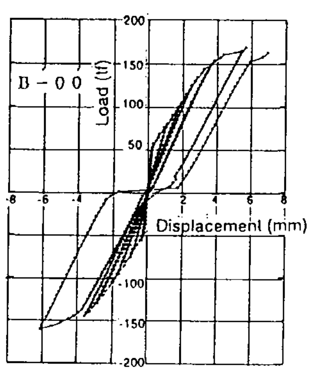
Tab. 2 gives the loads at cracking, yielding of vertical steel in flange, and maximum strength compared with the experiment of B-45.

Fig. 5 shows the crack patterns and softening zone of concrete of the test specimen B-45 observed after the test and those obtained with analytical model at the maximent load. The pattern of cracking and softening obtained from analysis agree well with those in the test.

Fig. 6-Fig. 7 show the comparison with experiment about the relationship between the load and the displacement under cyclic loading, which demonstrated that the analytical results by simple model proposed herein can give a preliminary simu-

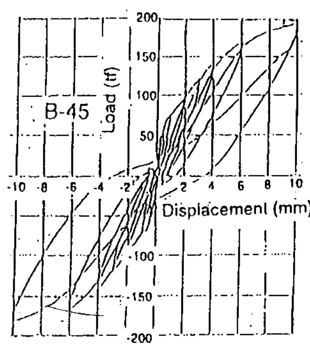


(a) Test

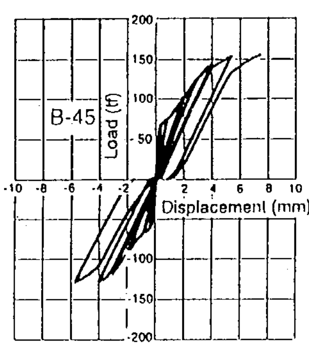


(b) Analysis

Fig. 6 Load-Displacement relationship under cyclic loading of B-00



(a) Test



(b) Analysis

Fig. 7 Load-Displacement relationship under cyclic loading of B-45 lation of test under cyclic loading and the overall comparison with the experimental results can be obtained.

The areas surrounded by the hysteretic loop are comparatively smaller in the proposed model than those of the test results. This difference was caused by the assumption of unloading hysteretic rule in the stress-strain relationship as Fig. 2. However, this disadvantage will be compensated by using the equivalent viscous damping in dynamical analysis.

6 CONCLUSION

A computer program for nonlinear FEM analysis of 3-D RC shear walls was developed based on the proposed model. The model proposed herein is effective for nonlinear analysis of 3-D RC shear wall structures subjected to not only one-directional but also two-directional loads. It is applicable to the nonlinear analysis of both reactor buildings and the other structures such as 3-D shear walls with L-shaped section or H-shaped section and the shear core walls of buildings.

The detail analysis was given for specimens of box walls subjected to horizontal cyclic loading, which is an experiment to simulate a reactor building under seismic loads. The comparisons with the experimental results of load-displacement relation, crack pattern and softening zone of concrete show that the model had good accuracy.

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