Numerical Analysis of Cyclic Loading Test of Shear Walls based on OpenSEES

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ABSTRACT :

Neither the original structure nor the altered structure of the Garden Hotel in Guangzhou accords with the ductile details of seismic design based on current Chinese codes. In order to explore the seismic performance of the original shear wall structure and the altered shear wall structure, the cyclic loading testes of the shear walls with different reinforcement ratio and constructional details are carried out. This paper presents the numerical analysis of the cyclic loading testes of shear walls with SWNA (Shear Wall Nonlinear Analysis) program. SWNA program is secondary developed based on OpenSEES and MVLEM. Compare with the testes, the numerical results confirmed the accuracy of this analysis procedure in representing the nonlinear behavior of the shear wall, such as the shifting of natural axis, shear deformation, local collapse and collapse mechanism. The analysis procedure based on MVLEM, which saves the calculating cost due to fewer DOFs, can stimulate the nonlinear behavior of the shear wall, and fit for global inelastic analysis and performance based design of tall building structure.

KEYWORDS: Shear wall, Cyclic loading test, OpenSEES, MVLEM, Nonlinear analysis

1. FOREWORD

Reinforced concrete shear wall structure is one of the most important forms in industrial and civil structures. Nonlinear analysis of shear wall structure is the focus and difficulty point. There are mainly two models which are usually used in nonlinear analysis: microcosmic and macrocosmic model. The former simulate shear walls with solid and shell element which have distinct and accurate theory but is not applicable due to large amount of calculation and difficulty in experiment analytical correction. The latter simulate shear walls with multiple vertical springs which has a better description of nonlinear behavior for the whole structure. It is suitable for nonlinear analysis of the whole structure due to small amount of calculation and simple analytical correction.

A program for nonlinear analysis of shear walls (SWNA) based on further development of OpenSEES and MVLEM is put forward in this paper. Compared to the cyclic loading test results of shear walls from the Garden Hotel, the numerical analysis results validated that the nonlinear behavior of shear wall can be simulated well in macro-scale by MVLEM.

2. BACKGROUND

Nonlinear model of shear wall includes two models: microcosmic model and macrocosmic model. There are mainly three models included in microcosmic model: integrated model, separate model and composite model[1].

Macrocosmic model is suitable for nonlinear analysis for the whole structure due to fewer DOFs. The main macrocosmic models are as follows: A pseudo-dynamic test of a 7-story full-scale moment frame was carried out by Kebeysasawa[2] and shear wall was simplified to three vertical line element model (TVLEM), as shown in Fig.1(a). Four vertical line element model was suggested by Linda[3] based on improvement of TVLEM, as shown in Fig.1(b). Two-dimension plate model was suggested by Milev[4] based modification of TVLEM, as shown in Fig.1(c). In order to solve the coordination problem of flex springs and two side-bars, Vulcano and Bertero[5] proposed a modified model in which multiple vertical springs are used to replace rotation springs representing compression bending stiffness and a horizontal spring is used to represent shear stiffness, as shown in Fig.1(d).

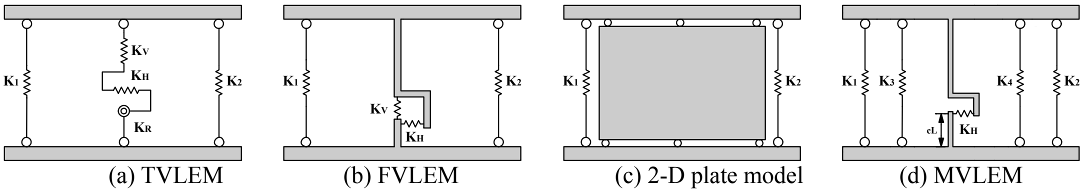


Fig.1 Macro model of shear wall

3. THEORY OF MVELM

The coordinative relation of flex springs and two side-bars is ambiguous in TVLEM, which is avoided in MVLEM. By given hysteretic relation of tension-compression and shear behavior, the shift of the neutral axis during the seismic response could be taken into account.

The entire shear wall is modeled as a stack of n MVLEM wall elements which are placed one upon each other. The cross-section of shear wall is divided to several parts which are simulated by springs. The tension-compression behavior of springs can be gained form material constitutive model. The constitutive model form the program DRAIN-2D[6] is taken as the restoring force model of the springs, as shown in Fig.2.

As to general shear walls, the parameters of restoring force model can be taken as follows: α =1.0, β =1.5, γ =1.05, δ =0.5[7]. The solving equation of the force and deformation of the key points in spring constitutive model curve are list in Table 1.

There is a shear spring which has a distance of cL from the bottom representing shear deformation of the 2-D MVLEM which has 3 DOFs together. There are three horizontal springs including two-way shear springs and a rotation spring in 3-D MVLEM which has 6 DOFs in general. The 3-D MVLEM is shown in Fig. 3.

Table 1 Formulas of parameters of restoring force modelof vertical spring

parameter	description	function
k_1	Initial elastic stiffness	$k_1 = A_c E_c / L$
F_{cr}	Cracked tensile force of concrete	$F_{cr} = f_{ct} A_c$
F_y	Yield force of steel bar	$F_y = f_y A_s$
Δ_y	Yield deformation of steel bar	$\Delta_y = A_s E_s / L$
k_3	Hardening stiffness of steel bar	$k_3 = f_{hard} k_s$
F_c	Limit pressure force of concrete	$F_c = f_{ck} A_c$
Δ_c	Limit deformation of concrete	$\Delta_c = \varepsilon_c L$
F_{cu}	Residual force after concrete crushing	$F_{cu} = f_{cu} A_c$
Δ_{cu}	Residual deformation after concrete crushing	$\Delta_{cu} = \varepsilon_{cu} L$

Either the linear elastic constitutive model or the shear constitutive model in DRAIN-2D could be adopted as the restoring force model of horizontal shear spring, as shown in Fig.4. The height coefficient c is determined by curvature distribution of the element. The trial calculation with different value of c(c=0,0.2,0.3,0.4) was carried out by Vulcano and the best result was gained when c=0.4 which was taken in this paper.

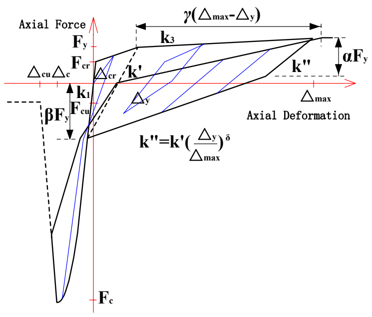


Fig.2 Restoring force model of vertical spring

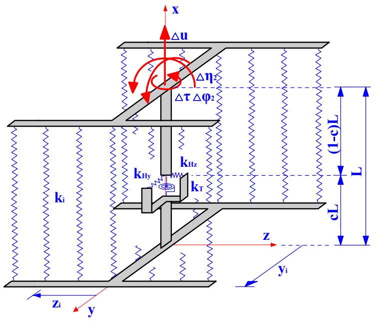


Fig.3 Sketch of MVLEM3D element

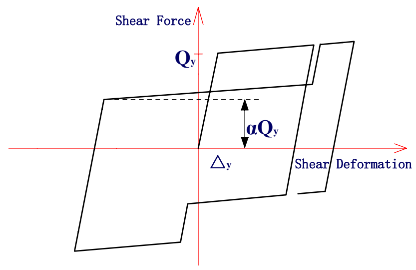


Fig.4 Restoring force model of horizontal shear spring

4. INTRODUCTION TO OPENSEES

OpenSEES stands for Open System For Earthquake Engineering Simulation[8]. It is an open-source system of earthquake simulation and allows the customers add new material constitutions and new types of elements to the system by programming. OpenSEES is mainly applied to analysis the seismic response of the structure. And it has a large library of materials and elements.

The 2-D MVLEM based on unaxial constitutive model was added to OpenSEES by Kutay Orakcal[9] according theories above. Shear walls can be well simulated by this element after analytical correction of cyclic loading test. Based on the 2-D MVLEM, the 3-D MVLEM was added by Matej Fichinger[10] according to constitutive model of spring. The dynamic characteristic of shear walls could be reflected well by the 3-D MVELEM. Numerical analysis of cyclic loading test of shear walls from the Garden Hotel in this paper is based on the 3-D MVLEM.

OpenSEES is an analysis program based on Tcl/Tk script language. Nonlinear solving is realized by adaptive transition program which modify the step size automatically until a convergent solution is gained.

5. LOW CYCLIC LOADING TEST OF SHEAR WALLS

There are 12 shear wall specimens in the low cyclic loading test of the Garden Hotel[11]. And the first 4 specimens are numerical simulated in this paper. The height of the specimen is 1.9m, and the parameters such as reinforcement, construction measure and axial compression ratio are listed in Table.2. The sectional reinforcement are shown in Fig.5~Fig.6.

The strength of concrete taken as fcu,m=34.43MPa is determined by block samples test. The strength of steel bar taken in the model is determined by material test, as listed inTable.3.

The loading equipment is shown in Fig.8. NC tension-compression actuating cylinder from MTS. US. and hydraulic jack (50T) is taken as horizontal and vertical loading device respectively.

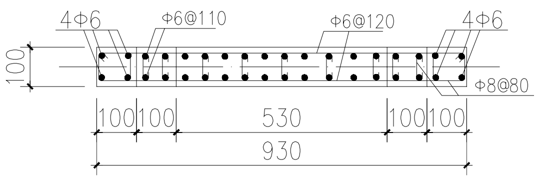


Fig.5 Dimension and details of Spec.1 and Spec.2

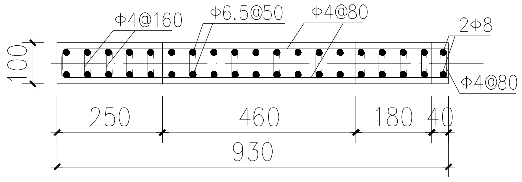


Fig.6 Dimension and details of Spec.3 and Spec.4

Table 2 Parameters of specimens

Specimen number	No.1	No.2	No.3	No.4
Design code	Current code	Current code	Former code	Former code
Axial compression ratio	0.24	0.36	0.24	0.36
Vertical reinforcement	Ø6@110	Ø6@110	Ø6.5@50	Ø6.5@50
Horizontal reinforcement	Ø6@120	Ø6@120	Ø4@80	Ø6@120
Tie bar (end)	Ø8@110×80	Ø8@110×80	Ø4@160×50	Ø4@160×50
Tie bar (middle)	Ø8@110×120	Ø8@110×120	0	Ø4@160×100

Table 3 Parameters of reinforcement

The type of steel bar	Yield sress (MPa)	Limit stress (MPa)	Yield strain (με)	Limit strain (με)	Elastic modules (N/mm^2)
Ø 4	345	442	1560	2000	2.21×10^5
Ø 6	429	533	2000	2460	2.15×10^5
Ø 8	425	530	2000	2460	2.14×10^5

Complete loading to axial compression ratio required in vertical direction is adopted and keep the same during the test. Horizontal low cyclic load is applied with actuating cylinder. Force control mode which keeps the load increment of each step in 10% of structural bearing capacity is adopted until the specimen yield. When the specimen yield, displacement control mode is taken as the load mode. Yield displacement of the specimen is taken as the cyclic displacement increment for three times of each step. It is suggested that the test should be ended when the bearing capacity of the specimen drop to 60%~70% of the limit capacity or the specimen is obviously failed.

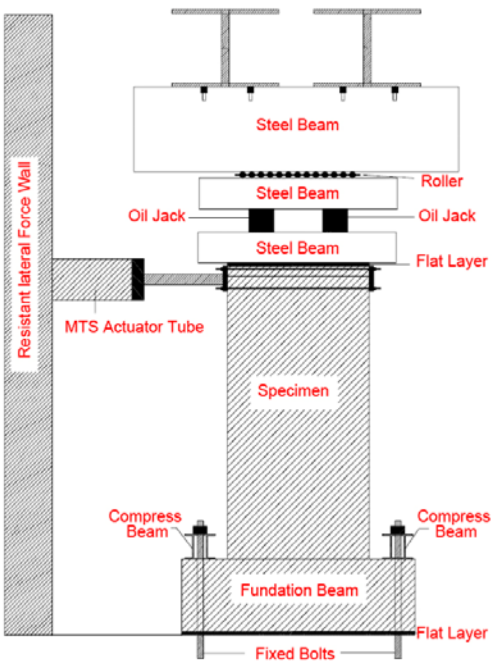


Fig.7 Figure of experiment device

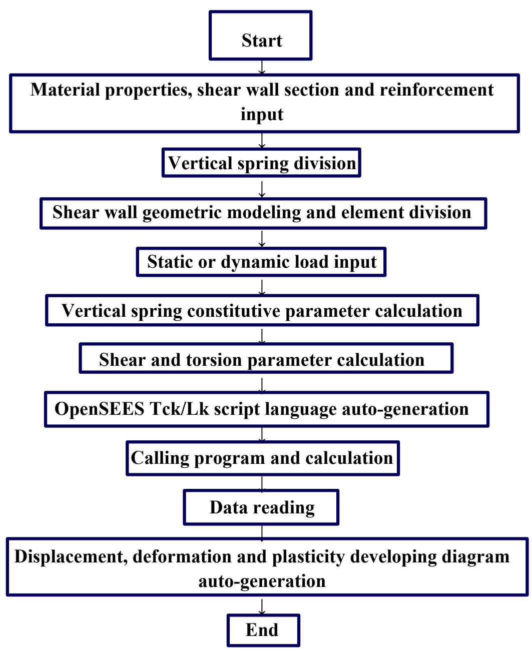


Fig.8 Flow chart of SWMA program

6. NUMERICAL ANALYSIS

OpenSEES is a nonlinear finite element analytical program with high performance. But there is no visual operation interface currently. And the location and constitutive model of each spring should be text input, which cause pre-process with a large amount of work. In order to solve the problem above, a nonlinear analysis program of shear walls (SWNA) is programmed by further development of OpenSEES based on object-oriented language. The calculation flow is shown in Fig.8.

The modified Kent-Scott-Park constitutive mode[12],[13] is adopted as the constitution of the concrete in the paper, as shown in Fig.9. The strength and ductility of concrete in restraint area can be taken into account in this model. According to the sectional reinforcement, the stress-strain relation can be calculated by the program based on Eqn.1~Eqn.4. The bilinear model is adopted for steel bar, taking hardening coefficient as 1/1000. Elastic modules and yield stress are listed in Table 3. According to functions listed in Table.2, restoring force model of vertical spring is generalized by constitutive model parameters which could be gained from the program.

In order to study the effects of different divisions, shear walls simulated with different amount of springs, horizontal and vertical divisions are carried out in this paper. There are generally 16 examples whose properties are listed in Table.4. The connection of 3D MVLEM in horizontal divisions is realized by hinges of rigid arm. Then the plane section assumption of overall section could not be obeyed and local deformation of shear walls can be taken into account, as shown in Fig.10. Vertical divisions of TestB are carried out in 1/4 parts at the bottom. The skeleton curve gained by the results of OpenSEES is shown in Fig.11. Only the positive values of skeleton curve are proposed due to its symmetric shape.

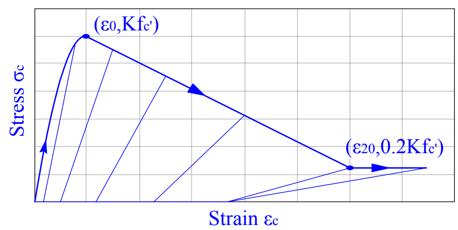


Fig.9 Kent Park modified concrete model(1982)

$$\sigma_c = \begin{cases} Kf_c'\left[2\left(\frac{\varepsilon_c}{\varepsilon_0}\right)-\left(\frac{\varepsilon_c}{\varepsilon_0}\right)^2\right] & \varepsilon_c \le \varepsilon_0 \\ Kf_c'\left[1-Z(\varepsilon_c-\varepsilon_0)\right] & \varepsilon_0 \le \varepsilon_c \le \varepsilon_{20} \\ 0.2Kf_c' & \varepsilon_c > \varepsilon_{20} \end{cases} \tag{1}$$

$$\varepsilon_0 = 0.002K \tag{2}$$

$$K = 1+\frac{\rho_s f_{yh}}{f_c'} \tag{3}$$

$$Z = \frac{0.5}{\frac{3+0.29f_c'}{145f_c'-1000}+0.75\rho_s\sqrt{\frac{h'}{s_h}}-0.002K} \tag{4}$$

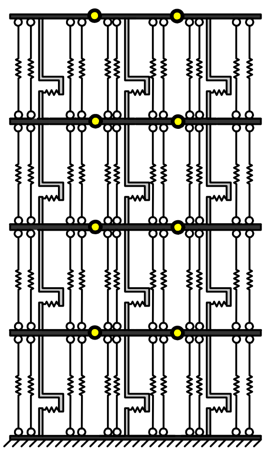


Fig.10 Finite element model of specimen

Table 4 Parameters of element divisions

Division	Model	Horizontal Elements	Vertical Elements	Springs of each element	Amount of springs
Spring divisions	TestA-1	1	4	24	96
	TestA-2	1	4	36	144
	TestA-3	1	4	60	240
	TestA-4	1	4	180	720
Veridical Divisions	TestB-1	1	4	24	96
	TestB-2	1	5	24	120
	TestB-3	1	6	24	144
	TestB-4	1	7	24	168
Horizontal Divisions	TestC-1	2	4	16	128
	TestC-2	3	4	16	192
	TestC-3	4	4	16	256
	TestC-4	5	4	16	320

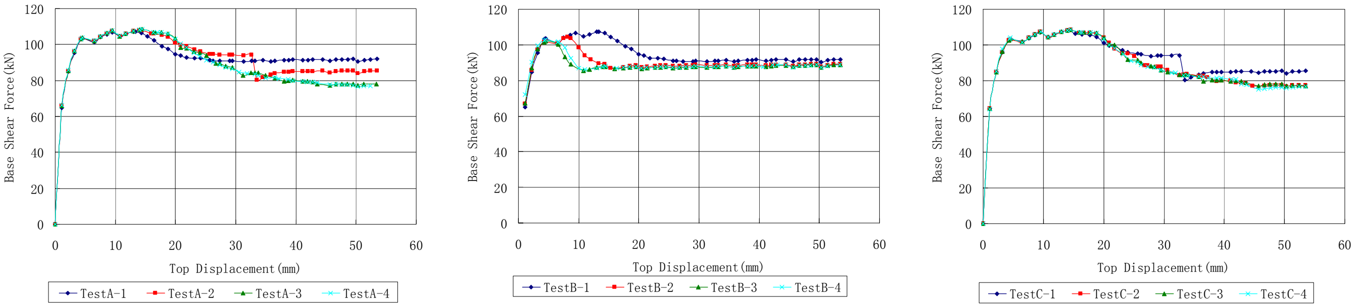


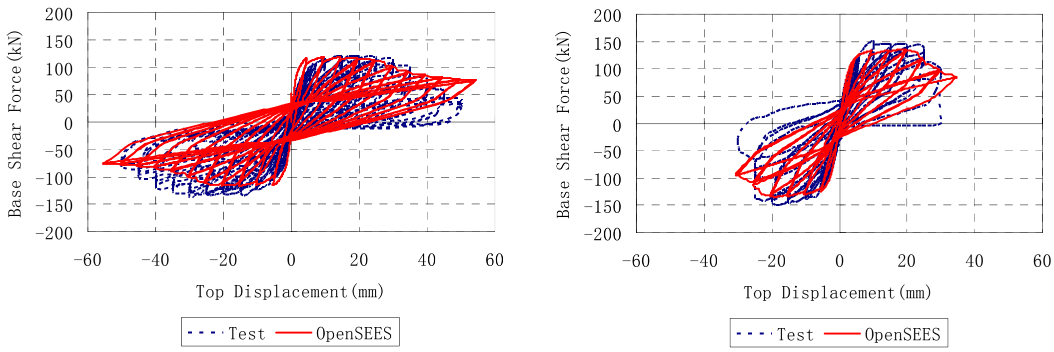
Fig.11 Comparison of force-deformation skeleton curve between the results of different divisions

It can be known from Fig.11(a), spring divisions have a direct influence on the accuracy of calculation. The results become stable when the amount of springs reaches about 60. It is seen from Fig.11(b), the more divisions along vertical direction, the bigger deviation from the experiment results. So the length of vertical division should be longer than the length of plastic region. It can be seen from Fig.11(c), horizontal division could help to gain a reasonable result. When there are more than 3 divisions along horizontal direction, a smooth curve of descend segment could be gained without abrupt change.

Numerical simulation of shear wall model is divided into 4 parts along model height, and the section is divided into 48 springs. There are 5 nodes, 4 elements and 30 DOFs. If analysis method anticipating do not satisfy the plane section assumption, element could be divided along horizontal direction. Parameters of springs restoring force model are input as defaulted without adjustment. A convergent solution is gained by adaptive adjustment of step size and iterative method.

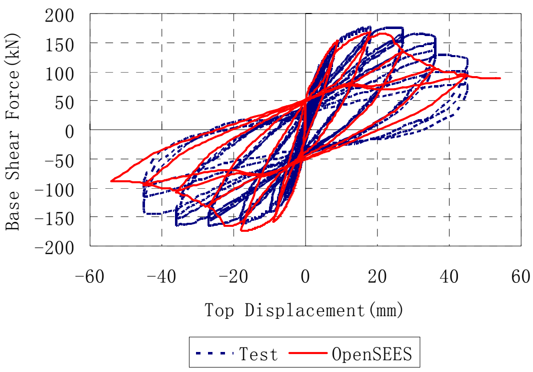
Calculation description: Take specimen 1 as a sample. The number of analysis step is 5410. The PC used for calculation is described as following: CPU: AMD Athlon (tm)64 Processor 3200+(2.1GHz); Ram: 1GB. It costs 34 seconds to finish the calculation. The analysis results from numerical simulation of 4 shear walls are compared to the results gained from the low cyclic loading test. The comparisons of hysteretic loops are shown in Fig.12.

According to the comparison, hysteretic loops and skeleton curve could generally match well, especially the hysteretic loops of specimen 1 and 2 designed according with current code. And the result of specimen 3 and 4 gained by numerical simulation is a little precipitate during the descend part, but still match well in strength and ductility. The results match well in inelastic because that plane section assumption is satisfied in the individual EVLEM. So it can not be simulated when strongly nonlinear occurred. This could be improved by horizontal division. Life safety and collapse avoiding are required for shear wall in performance based seismic design and no strongly nonlinear behavior should occur[14]. So MVLEM is suitable for performance based analysis and design.

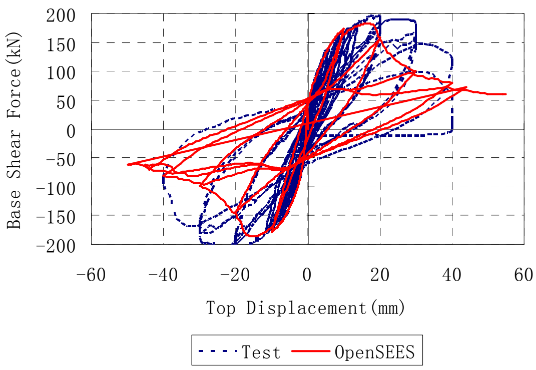


(a)specimen 1

(b)specimen 2



(c)specimen 3



(d)specimen 4

Fig.12 Comparison of force-deformation curve between experiment results and OpenSEES

The animation of deformation of shear wall structure of the whole process can be gained by the program SWNA, as well as the deformation and nonlinear states of springs. Take specimen 1 as an example, as shown in Fig.13~14. Nature axis shifts continuously under cyclic loading, which can be seen from Fig.13.

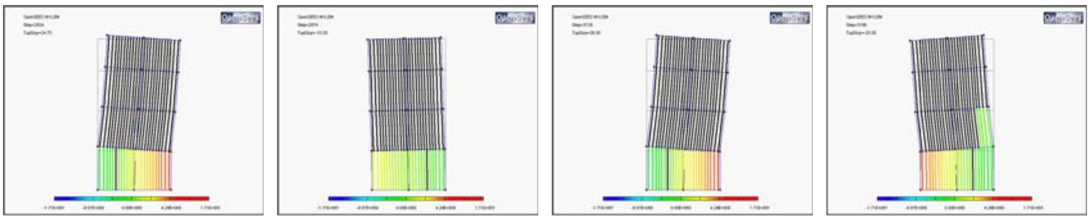


Fig.13 Deformation of vertical springs of shear-wall elements

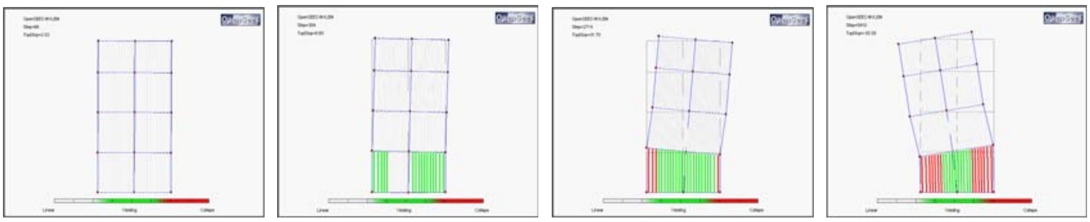
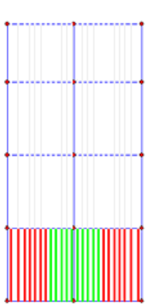


Fig.14 Collapse process of shear-wall elements shown in SWNA

The yield mechanism of shear wall described by MVLEM is shown in Fig.14. Plastic deformation is mainly occurred at the bottom. Steel bar yield firstly, then the concrete of two sides are crushed and out of work. The part crushed extend from edge to middle. The whole shear wall is failed at last due to descend of the resistance capacity of lateral load after most concretes are crushed and steel bars are yield. The failure mode comparison of specimen 1 is shown in Fig.15~16.


(a)Opensees Result

(b)Test Result

Fig.15 Comparison of collapse status of specimen 1 between FEA and experiment

Fig.16 Local collapse of specimen 1

7. CONCULSION AND PROSPECT

Low cyclic loading test and shaking table test are the most visual and reliable measure to value seismic performance of shear wall structure. But there are several limitations due to lots of human and material resources. Numerical simulation of cyclic loading test of shear walls based on OpenSEES in this paper show that the nonlinear behavior of shear walls including shifts of nature axis, influence of shear deformation, local plastic status and failure mechanism could be well reflected by the macrocosmic element of adjusted MVLEM in some extent. And because of fewer DOFs and less computing time, this numerical model and OpenSEES are applicable to tall building structures with shear wall.

According to the analysis of shear wall, further development based on OpenSEES aiming at reducing the work of modeling and providing visible analysis results is programmed. The program SWNA can be applied to shear walls with different reinforcement. The static and dynamic nonlinear analysis can be realized. And the quantitative seismic performance index of shear wall which has a great significance for performance based seismic design can be gained regress analysis.

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