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Research on Deformation Limit State of Reinforced Concrete Shear-Walls

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The limit state of shear-walls deformation is the key factor to performance-based seismic design of RC shear-wall structures. A structural nonlinear analysis program named MESAP (Macro Element based Structural Analysis Program), is developed by object-oriented technology to simulate the nonlinear behavior of shear-walls which are designed according to Chinese codes. In the MESAP, two types of elements MVLE (multiple-vertical-line-element) and MCFT (modified compression-field theory) are proposed. Several shear-wall-component-experiments were used to verify the rationality and reliability of two nonlinear finite element models. In considering of different reinforcement ratios, axial force level and section dimensions, series models of high and low RC shear-walls are used to obtain the deformation limit state of different earthquake levels. Moreover the calculation approach of the deformation limit state of shear-walls of frequent, medium and rare earthquake level are presented, which can be applied to evaluate the plastic deformation of shear-walls of RC building under different earthquake level.

Keywords: Reinforced Concrete Structure, Shear-Wall, Nonlinear Analysis, Limit State, Cyclic Loading Test, Performance-Based Seismic Design.

1. INTRODUCTION

With the development of economy, linear elastic method cannot meet the requirement for seismic analysis of structure. Accurate simulation of the nonlinear behavior of structures under severe earthquake has become the most important part of performance-based seismic design. Extensive research on nonlinear analysis of structures' seismic behavior has been proposed in recent years, however, the correctness and effectiveness of the analysis has yet to be confirmed. Meanwhile, performance-based seismic design method has been becoming increasingly accepted by structural engineers in China, which not only proposes the capacity requirements, but also sets a desired deformation limit state according to different earthquake levels. Well development of this method in China still has a long way to go.

2. DEVELOPMENT OF MACRO ELEMENT BASED ON STRUCTURAL ANALYSIS PROGRAM MESAP

MESAP is developed by the authors, using the OOP (Object Oriented Programming) Technology.[1] By using this technology, the source code can be packaged as DLL (Dynamic Linking Library) files which can be provide for secondary development, and developer's intellectual property is protected. The program framework of MESAP is shown in Figure 1.

The Newton-Raphson method is used to solve the nonlinear equations in MESAP and structural load applying method is load control method and displacement control method. Complete force-displacement curve and hysteretic loops can be obtained by displacement control method, including simulating the strength degradation behavior. The GUI (Graphic User Interface) of MESAP is shown in Figure 2.

3. THE MACRO-ELEMENT THEORY OF SHEAR-WALL AND DEVELOPMENT OF ANALYSIS PROGRAM

The MVLEM (Multiple vertical line element model):[2] The basic principle of MVLEM theory is to divide the shear-wall component into several elements along its height, and the flexure-compression deformation and shear deformation of the element were independent. The cross-section of shear-wall is divided into several parts which were simulated by tension-compression springs for the simulation of the flexure and compression deformation. A horizontal spring which has a distance from the bottom is used to simulate the shear deformation. The sketch of the element model is shown in Figure 3.

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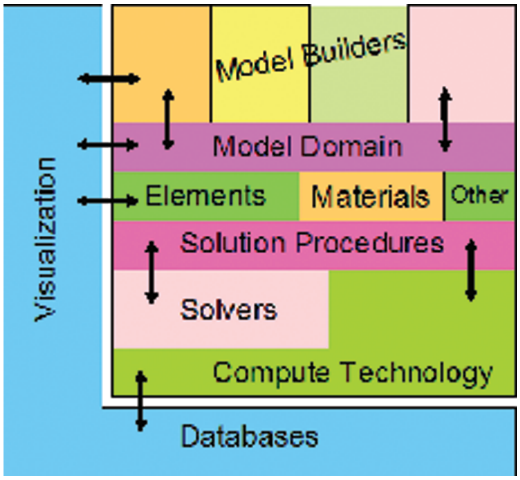

Fig. 1. Program Framework of MESAP.

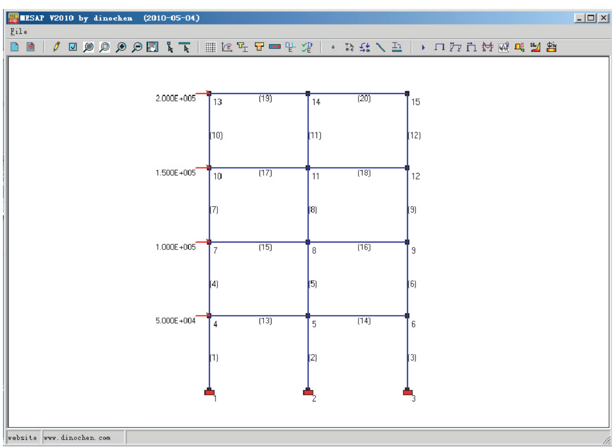

Fig. 2. GUI of MESAP.

Development of the shear-wall element: According to the MVLEM, MVLE is added into the element library of MESAP. To analyze the nonlinear behavior of shear-walls, the modified Kent-Park concrete model,[3] Pinto steel model,[4] Fischinger hysteretic model[5] and the origin-oriented shear spring model were added into the material library of MESAP. The material model is verified by comparing the cyclic loading test result with the corresponding material in OpenSEES,[6] as shown in Figures 4 to 6.

Shear-walls example analysis: To study the nonlinear behavior of shear-wall, Thomsen and Wallace (1995)[7] conducted a series of low cyclic loading tests of shear-walls. The results can be adopted as the benchmark of the shear-wall element verification. The analysis of specimen RW2 and TW2 were completed by

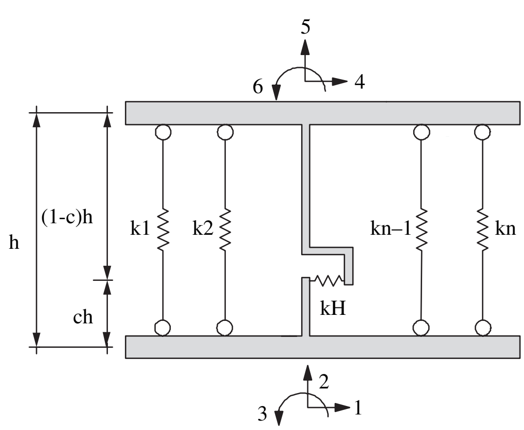

Fig. 3. Sketch of MVLEM.

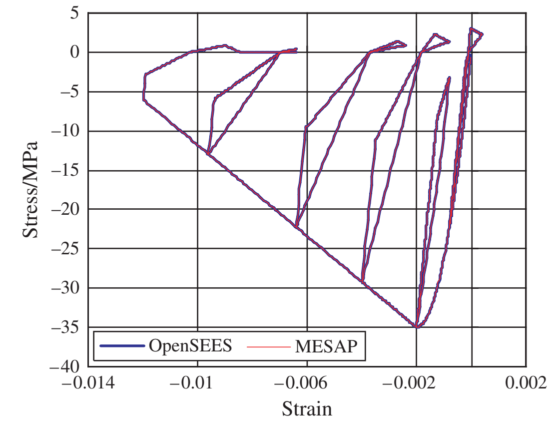

Fig. 4. Kent-Park concrete model.

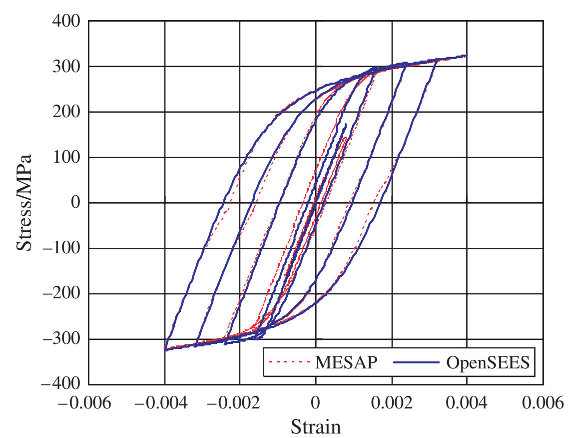

Fig. 5. Pinto Steel model.

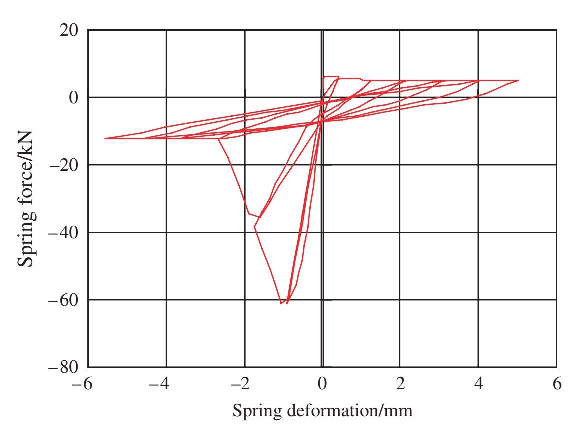

Fig. 6. Hysteretic loops of Fischinger spring mode.

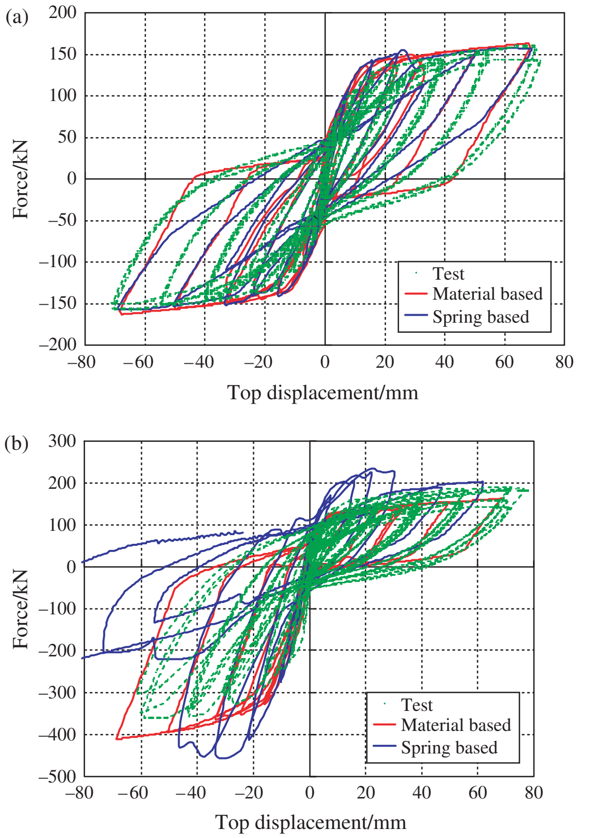

Fig. 7. Comparison of hysteretic loops between shear-wall test results and MESAP obtained by two analysis models. (a) Specimen RW2. (b) Specimen TW2.

MESAP in this paper. Material model and spring model were used separately to find difference between these two methods. The hysteretic loops obtained by two analysis models were compared with test results in Figure 7.

Errors were found in the analysis based on the Fischinger model, as shown in Figure 7(b), for the flange of T-shape wall, the exact position of reinforcement affects the analysis result directly. The reinforcement and the concrete were required to disperse together in the spring model where the center of spring is also the center of concrete and reinforcement bar, which results in the great difference between the test and the analysis results of T-shape shear-wall. In general, both the two models can be used for the hysteretic analysis of shear-walls. For its higher accuracy and convenience to observe the strain of the concrete and steel bars, material model for MVLE is more suitable to determinate the deformation limit state of shear-walls. In this paper, the MVLE is adopted in the research of limit state of flexure control shear-walls.

4. THE MODIFIED COMPRESSION-FIELD THEORY AND DEVELOPMENT OF ELEMENT

The MCFT (Modified Compression-Field Theory): The MCFT is proposed by Vecchio and Collins,[8] based on the Modified Compression-Field, which is predicting the force-deformation response of reinforced concrete elements subjected to in-plane shear stress and normal stresses. In the MCFT, the following additional assumptions will be made:

(1) For each strain state there exists only one corresponding stress state; situations in which the influence of loading history is significant will not be treated.
(2) Stresses and strains can be considered in terms of average values over areas or distances large enough to include several cracks.
(3) The concrete and the reinforcing bars are perfectly bonded together at the boundaries of the element.
(4) The longitudinal and transverse reinforcing bars are uniformly distributed over the element.

The sketch of element model is shown in Figure 8.

Development of MCFT element: Hongestad Parabola concrete model is used in the classic example, and concrete model given in Chinese code is used in the shear-wall element designed according to Chinese code. Bi-linear steel model is used for steel bars. Hongestad Parabola concrete model is shown in Figure 9.

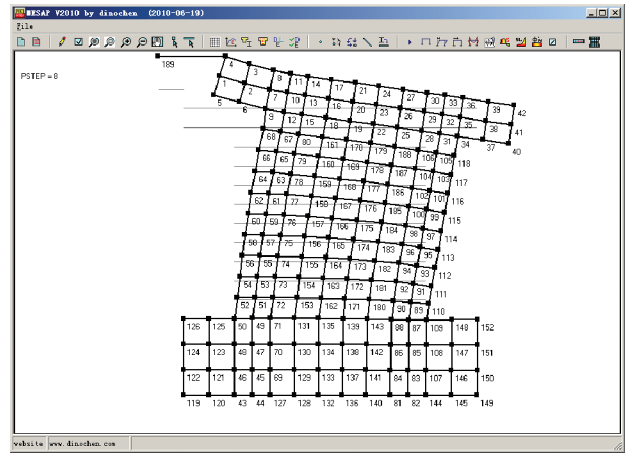

Fig. 8. MCFT model of shear-wall concrete model.

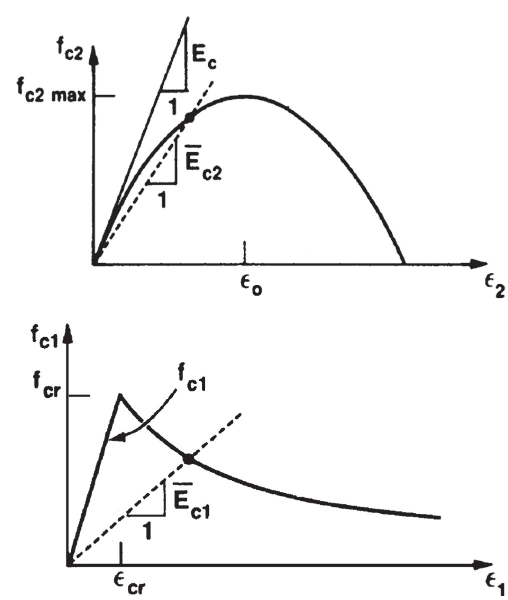

Fig. 9. Hongestad Parabola concrete model.

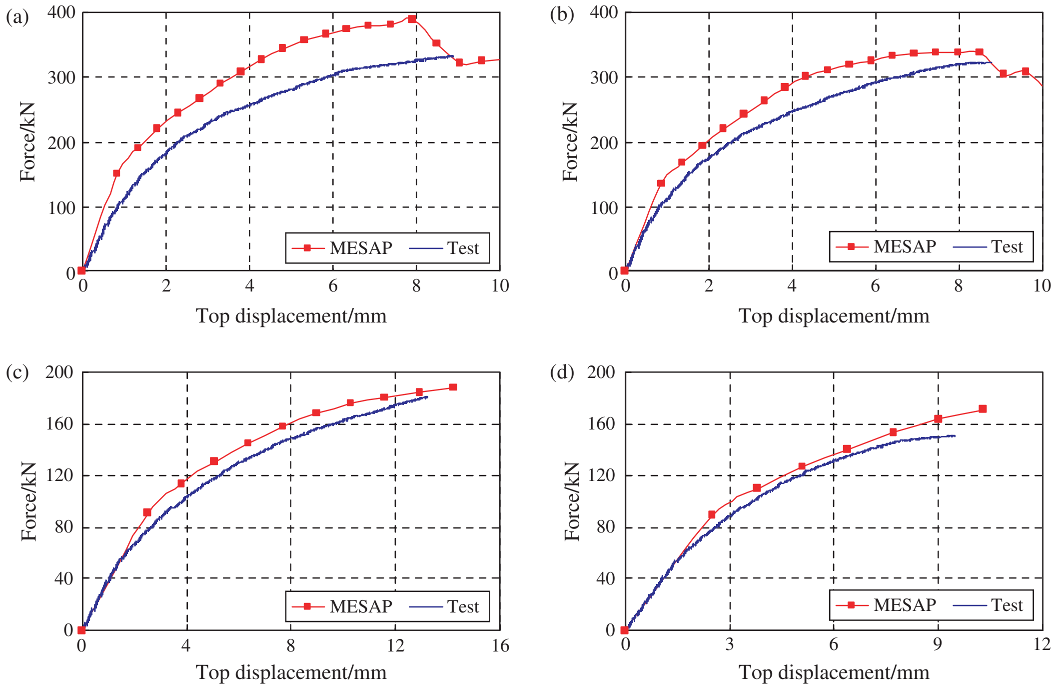

Fig. 10. Comparison of the force-deformation curve between test results and MESAP. (a) Specimen SW13. (b) Specimen SW15. (c) Specimen SW23. (d) Specimen SW25.

MCFT element was added in the element library of MESAP, and the corresponding material models were also added in material library. Nonlinear iterative method based on secant stiffness iteration is developed for MCFT element computation.

Shear-wall examples analysis: In order to study the numerical analysis function of MESAP to simulation the nonlinear behavior of compression-flexure-shear interaction component such as low shear-walls, the monotonic loading test of shear-wall conducted by Lefas[9] is chosen to verify the MCFT element.

The comparison between test results and MESAP of the force-deformation curve for a several examples is shown in Figure 10. It was concluded that the MCFT element in MESAP can simulate the shear-flexure-axial interaction nonlinear behavior of shear-walls with different height-to-width ratios well. The relative error of capacity was within 13%, and the deformation was 4%, which were both meet the requirement of accuracy.

5. NUMERICAL ANALYSIS OF TESTS FOR SHEAR-WALLS (CHINESE CODE) UNDER LOW-CYCLIC LOADING

In order to study the relationship between the edge reinforcement strain and CP (collapse prevention) state of component, the tests of shear-walls with bi-directional single row of steel bars conducted by Prof. Wanlin Cao and Xingmin Yang[10–12] and the tests of shear-walls with concealed truss conducted by Prof. Wanlin Cao and Yanfei Fan[13–15] were chosen. To obtain the relationship between the reinforcement strain and CP state, 30 shear-wall elements were simulated by MESAP. The comparison of force-deformation between test results and MESAP are shown in Figure 11. As shown in figure, the relative error of capacity was within 15%, and the stiffness was predicted well.

Edge reinforcement strain time-history is proposed in MESAP. The rotation of shear-walls of CP state in the skeleton curve of 30 shear-walls elements were confirmed refer to FEMA356, rotation of CP state are shown in Figure 12, and strain values of edge reinforcement of CP state are shown in Figure 13.

For the assumption that Axial force level φ_N and reinforcement compression strain limit ε_{scu} are both follow to the linear rule. To obtain a conservative CP state, the limit of edge reinforcement compressive strain ε_{scu} can be listed as follow:

Where $\varphi_N \le 0.3$, $\varepsilon_{\text{scu}} = 0.01$

Where $0.3 < \varphi_N \le 0.5$, $\varepsilon_{\text{scu}} = 0.01 + 0.075 \times (\varphi_N - 0.3)$

Where $\varphi_N > 0.5$, $\varepsilon_{\text{scu}} = 0.025$

From the hysteretic analysis for the large sample of shear-walls, it was concluded that

(1) rotation of shear-walls under CP state is 0.007 to 0.014, while is 0.005 to 0.015 in FEMA 356.

(2) rotation under CP state is related to edge reinforcement compression strain, and compression strain is related to axial force level.

6. RESEARCH ON THE DEFORMATION LIMIT STATE OF SHEAR-WALS WITH FLEXURE CONTROL

Definition of the deformation performance limit state: Through the numerical analysis and low-cyclic loading test of shear-walls elements, it can be concluded that the whole deformation process includes crack, start yield, yielding, close to collapse and collapse. In the FEMA 356 code,[16] the performance limit state of element is divided into four levels: OP, IO, LS, and CP.

The performance state of four levels in FEMA356 are not meet the requirement of three levels of in Chinese seismic code, therefore the performance state of three levels is proposed in this paper, which are defined as frequent earthquake limit state, medium earthquake limit state, and rare earthquake limit

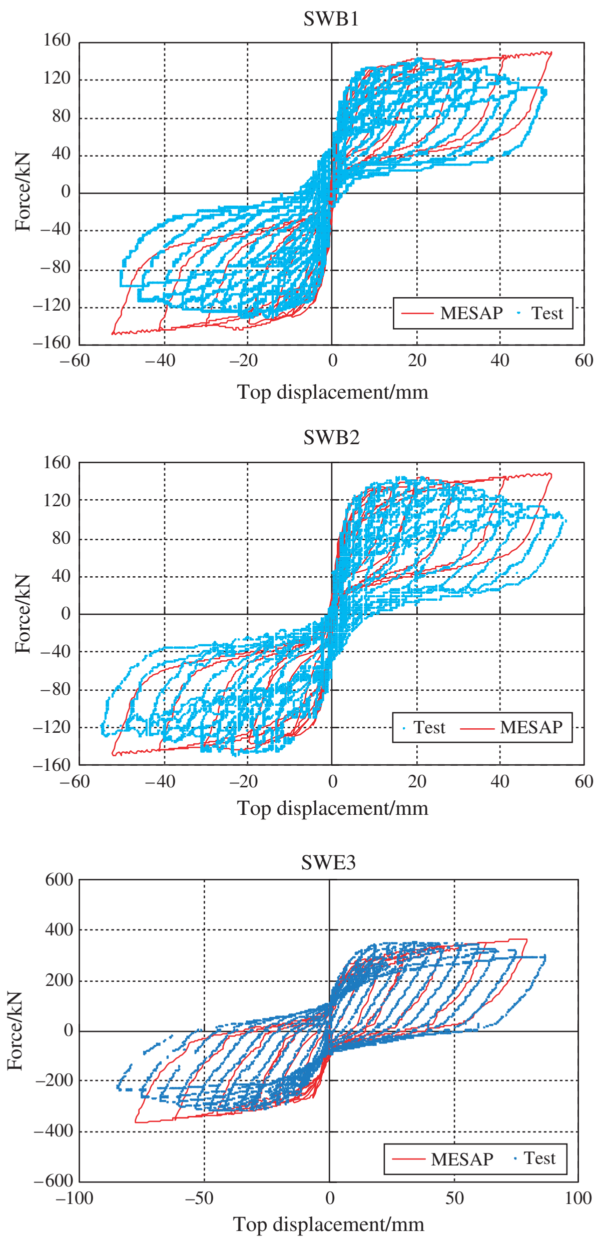

Fig. 11. Comparison of force-deformation curve between test results and MESAP.

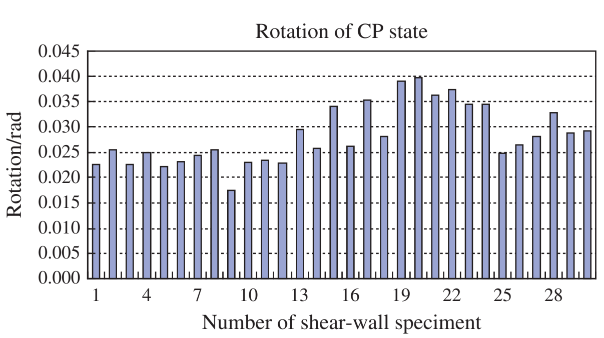

Fig. 12. Rotation of shear-walls of CP state.

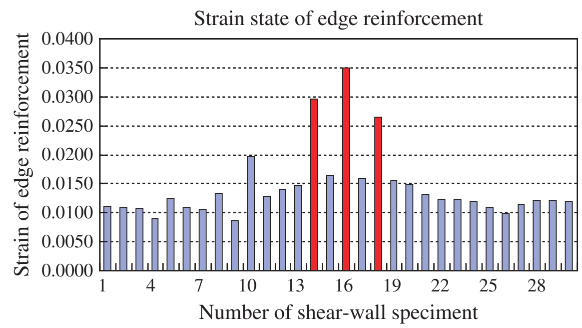

Fig. 13. Strain of edge reinforcement of CP state.

state corresponding to "no damage under frequent earthquake, repairable under moderate earthquake, no collapse under severe earthquake."

Ensured that the element deformation is not yield, frequent earthquake limit state is defined from O to IO state, and medium earthquake state is from IO state to LS state. As there is no obvious structural deformation characteristic at the LS state, a coefficient α_{LS} is proposed to control the relationship between the element deformation of the IO and CP state. The equation is as follow:

$$\delta_{\mathrm{LS}} = \delta_{\mathrm{IO}} + \alpha_{\mathrm{LS}} \times (\delta_{\mathrm{CP}} - \delta_{\mathrm{IO}}) \tag{1}$$

Where δ_{IO}, δ_{LS}, δ_{CP} is the element deformation limit state at each IO, LS, CP state. Frequent earthquake limit state, medium earthquake limit state, and rare earthquake limit state are according with the three levels of seismic level in Chinese code.

Research on the Deformation Limit State: In this paper, the shear-wall analysis model file (∗.inp script file) according to main parameters of element is programmed in MESAP, and the law of ultimate deformation limit state is obtained by the regression of large-sample analysis results. As the examples were generated in batches, total cross-section reinforcement is used. The parameters of model were: concrete material, steel material, depth and width of section, height of specimen, reinforcement ratio, and axial force level. The number of samples is $4^5 \times 2 = 2048$, the detail of the parameters are shown in Table I.

Table I. Parameters of samples.

Concrete material	Steel material	h/mm	b/mm	ρ_s/%	φ_{N}
C30	HRB335	2000	200	0.6	0.1
C40		4000	400	0.8	0.2
C50	HRB400	6000	500	1.0	0.4
C60		8000	600	1.2	0.6

Table II. Deformation limit states of shear-walls with flexure control (rotation θ/rad).

Limit state	Frequent earthquake limit state θ_{IO}	Medium earthquake limit state θ_{LS}	Rare earthquake limit state θ_{CP}
Equation	$\theta_{\mathrm{IO}} = 0.00175\beta_{\mathrm{IO}}^{0.28}$	$\theta_{\mathrm{LS}} = \theta_{\mathrm{IO}} + (\theta_{\mathrm{LS}} - \theta_{\mathrm{IO}}) \times 0.5$	$\theta_{\mathrm{CP}} = 0.0063\beta_{\mathrm{CP}}^{-0.187}$

*Where $\beta_{\mathrm{IO}} = (\rho_s f_y / \varphi_N f_{\mathrm{ck}})$, $\beta_{\mathrm{CP}} = \rho_s \varphi_N f_{\mathrm{ck}}$, and ρ_s is total cross-section reinforcement ratio; φ_{N} is axial force level, and $\varphi_{\mathrm{N}} \le 0.6$.

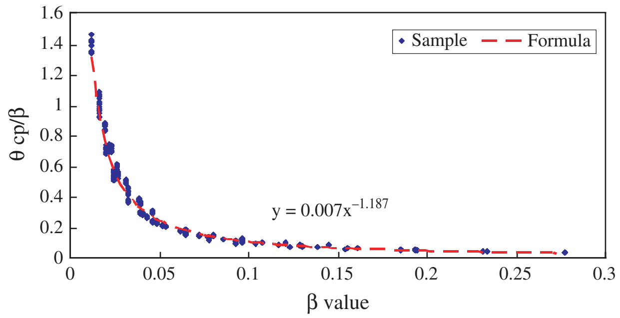

Fig. 14. Comparison of rotation values of the shear-wall sample and the formula.

According to the relationship of CP limit state and edge reinforcement compression strain, the CP limit state of shear-walls is captured. With the equal-dissipate-energy approach and the skelecton curve, the deformation of IO limit state is captured. By the Eq. (1), LS limit state is captured. Finally, the equation of frequent earthquake limit state, medium earthquake limit state, and rare earthquake limit state is shown in Table II. The comparison of rotation of shear-wall-samples which are computed by MVLEM and the equation (Table II) proposed by this paper is shown in Figure 14.

7. RESEARCH ON THE DEFORMATION LIMIT STATE OF SHEAR-WALL WITH SHEAR CONTROL

The difference between non-ductility and ductility element's curve is that deformation form yield to collapse of non-ductility element is less than that of ductility element. The yield deformation is close to collapse deformation for on-ductility element, so ductility coefficient $\mu = \Delta_u/\Delta_y$ is smaller.

For the assumption that the element is linear, the deformation is in direct proportion to the force level, and the force is also in direct proportion to peak ground acceleration. Through peak ground acceleration at different levels in the Chinese Code for seismic design of buildings, it was calculated that the ratio of frequent earthquake to rare earthquake is 0.19, and the ratio of medium earthquake to rare earthquake is 0.53. Frequent earthquake limit state, and medium limit earthquake state can be obtained by rare earthquake limit state directly, and the equations are as follow:

$$\delta_{\mathrm{LS}} = \alpha_{\mathrm{LS}} \times \delta_{\mathrm{CP}} = 0.53 \times \delta_{\mathrm{CP}} \tag{2}$$

$$\delta_{\mathrm{IO}} = \alpha_{\mathrm{IO}} \times \delta_{\mathrm{CP}} = 0.19 \times \delta_{\mathrm{CP}} \tag{3}$$

In order to capture the CP limit state of low shear-walls, a large sample of low shear-walls is made. The detail of the parameters of low shear-walls are shown in Table III. the number of samples is $3^7 = 2187$.

Table III. Parameters of sample.

Concrete material	Steel material	λ	h/mm	b/mm	ρ_{sy}/%	ρ_{sx}/%	φ_{N}
C30	HRB335	1.5	4000	300	0.6	0.2	0.1
C40		1.25	6000	500	1.2	0.5	0.3
C60		1	8000	700	2	1	0.6

Table IV. Deformation limit states of shear-walls with shear control (Rotation θ/rad).

Limit state	Frequent earthquake limit state θ_{IO}	Medium earthquake limit state θ_{LS}	Rare earthquake limit state θ_{CP}
Equation	$\theta_{\mathrm{IO}} = 0.0114\beta^{-0.35}$	$\theta_{\mathrm{LS}} = 0.0318\beta^{-0.35}$	$\theta_{\mathrm{CP}} = 0.06\beta^{-0.35}$

*Where $\beta_{\mathrm{CP}} = (f_{\mathrm{cu},k} b\lambda/\varphi_{\mathrm{N}})$, and λ is height-to-width ratio, $\lambda \le 1.5$; φ_{N} is axial force level, $\varphi_{\mathrm{N}} \le 0.6$.

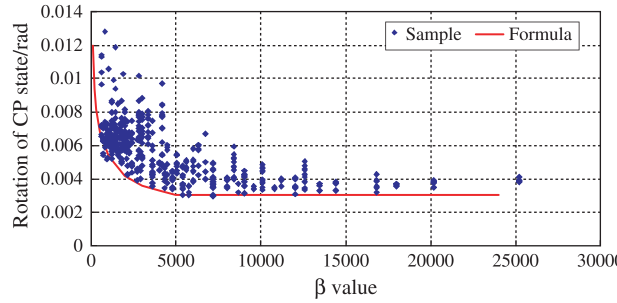

Fig. 15. Comparison of rotation values of the shear-wall sample and the formula.

With the skelecton curve, the drop point, which is regarded as CP limit state of the non-ductility component, is captured. The deformation of IO and LSlimit state is captured. By the Eqs. (2) and (3), LS limit state is captured. Finally, the equation of frequent earthquake limit state, medium earthquake limit state, and rare earthquake limit state is shown in Table IV. The comparison of rotation values of shear-wall samples which are computed by MCFT method and the formula (Table IV) proposed by this paper is shown in Figure 15.

8. CONCLUSIONS

In this paper, a macro element based on structural analysis program MESAP was developed to simulate the low-cyclic loading test of high and low RC shear-walls, and the applicability of the program was verified by the comparison between simulation results and test results. MVLEM and MCFT element were used to simulate the nonlinear behavior of shear-walls with flexural control and shear control, and the deformation limit state of shear-walls is also presented. It can be used as a tool for evaluation of shear-walls seismic performance and performance-based seismic design of shear-walls structures.

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