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Numerical Modeling of Slender RC Shear Walls Subjected to Monotonic and Cyclic Loadings

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Abstract

Reinforced concrete (RC) shear walls are used to provide lateral stiffness and strength in RC structures as well as steel structures. There are different approaches to model shear walls for both linear and nonlinear analyses. Proper modeling of shear walls depends on the type of loading, on the geometry of the wall as well as on the failure state expected. However, due to the complex behavior of concrete and reinforcing steel often a detailed nonlinear model is required which yield compatible results with those of the experiments. In this paper, two fiber modelsare presented and verified that the modelsare capable to simulate results of the monotonic and cyclic wall tests with an acceptable accuracy. It is shown that the presented fiber modeling of RC walls provides an adequate representation of stiffness and strength behavior of the walls which had been tested by previous researchers. Moreover, due to easy application the presented fiber modeling, it can be used by engineers in practice as well in detailed analysis. Monotonic and cyclic test of the walls are simulated by using the flexure-shear interaction fiber model and the fiber beam column element, respectively, where the aspect ratio of the walls is not less than two. Constitutive material laws with hysteretic rules are implemented for concrete and steel fibers. Numerical results illustrated graphically show good agreement with the experiments.

Keywords:cyclic test; fiber element; flexure-shear interaction; reinforced concrete shear wall modeling

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1. Introduction

Shear walls that are resisting in-plane forces can be divided into two groups as slender and squat walls depending whether bending moment or shear force is dominant. Squat walls, which resist shear forces dominantly, are subjected to diagonal tensile and compression stresses, where shear yielding is acceptable. On the contrary, expected behavior of slender walls is like flexural cantilever where the nonlinear behavior is governed by ductile flexural yielding, without shear failure.

There are different modeling techniques that have been used by researchers to reveal inelastic response of reinforced concrete shear walls. These techniques can be classified in two groups. The first one is micro modeling, which is the application of solid mechanics and is depended on discretization of the continuum through finite element procedures [1]. These models are based on the theory of plasticity, which takes into account criterion of yielding, rule of plastic flow, and strain hardening to display behavior beyond the elastic limit. On the other hand, reinforcing steel can be modeled as discrete embedded or smeared [2].

The second modeling technique is employed by using macro models, such as, beam-column element, equivalent truss element, four-nodeisoparametric element and multiple vertical line element (MVLE). The author in [3] stated, the main goal of the macro models is to simulate the global behavior of wall segments. Beam-column elements are generally used with a lumped plasticity model including hysteresis behavior, where other parts of the element remain elastic. Another type of beam-column element employs fibers in their longitudinal direction which are capable to simulate distributed plasticity [4]. Truss models are used to determine the behavior of RC shear walls as well [5]. Four-node isoparametric element consisting of one panel element for wall web, two vertical elements for boundary zones and two horizontal elements for top and bottom girders where the element represented by a finite element having nine integration points [6]. MVLE model was first introduced by [7] as a simple and reasonably accurate slender wall model. In this model rotational spring in the center was removed by at least four axial springs to develop an enhanced estimation of flexural behavior. MVLE model was extended by the authors in [8]and they implemented hysteretic uni-axial strain-stress laws instead of arbitrary force-deformation rules. The authors in [9] proposed a new MVLE model which incorporates panel behavior and takes into account shear-flexure interaction.

This study focuses on nonlinear modeling of slender walls subjected to monotonic and cyclic loadings. Models of the walls which are subjected to monotonic loading, are expected that they should sophisticated enough to include M-N-V interaction, neutral axis migration, tension stiffening of concrete, confinement effects, bond deterioration, slip, bar fracture and bar buckling, dowel action, shear friction response, time dependency effect, apparent yield stress of rebars, rocking effect, effect of shear reinforcement on strength, stiffness and deformation capacity, out of plane buckling of the wall. In addition to these effects, it is expected that following effects should be taken into account for cyclic loadings: progressive crack closure, opening and closing of cracks with recovery of stiffness, strength degradation. However, for performance assessment of a whole engineering structure, it is not necessary to take into account all of the above-mentioned effects. In this paper, it is shown that the wall models selected are capable to predict some of the experimental results of walls and also suitable to be used in a large number of DOFs thanks to its relatively practical structure comparing with solid models.In addition, it should be also noted that wall models which are used in this study have some constraints and limitations. Plane section remains plane assumption is considered in the wall models. It is known that this assumption is not valid in large inelastic deformations. Another limitation of the wall models which are used in this study is the lack of ability of prediction of the shear failure due to the steel material model.

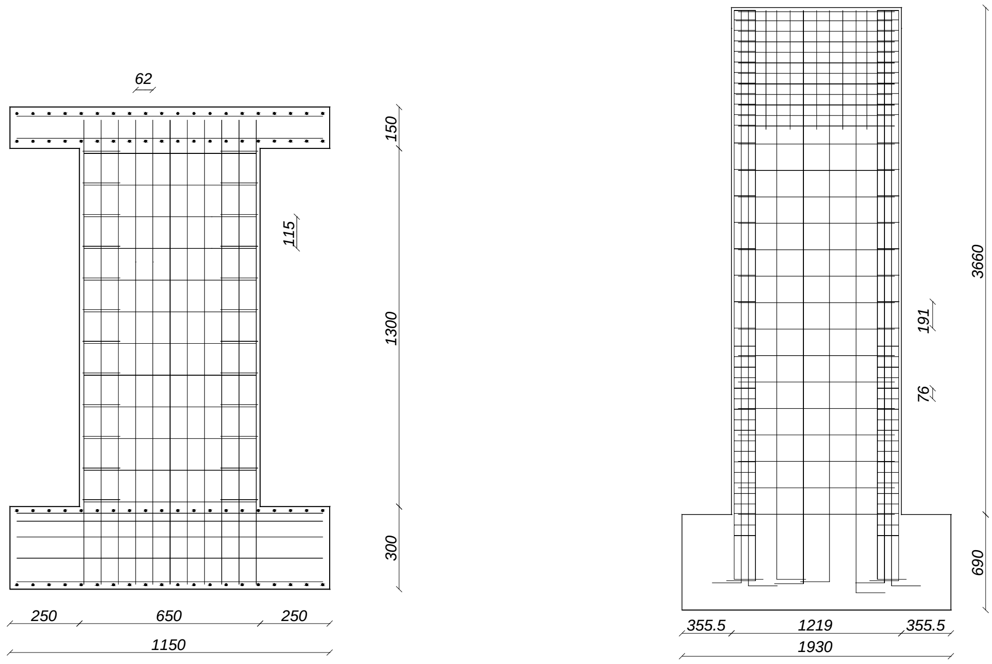
2. Summary of Tests

2.1. SW21, SW22 Walls Tested by Lefas, Kotsovos and Ambraseys

The authors in [10] tested 13 different structural walls under monotonic loading and six of them have an aspect ratio of two and rest of them with an aspect ratio as one. The walls are of rectangular shape having boundary zones and they are supported at the bottom for which a stiff support is provided and they are loaded horizontally at the top. Differences between these walls are concrete strength, axial force ratio, and horizontal reinforcement ratio. In this paper SW21 and SW22 are studied in order to make numerical verification of the analysis results. The corresponding experimental data are summarized in Table 1 where; ρ_{flex},ρ_{hor},ρ_{ver}represent ratio of the main flexural reinforcement to the gross concrete area of the boundary zone, ratio of the horizontal reinforcement to the gross concrete area of vertical section of the web element, ratio of the vertical web reinforcement to the gross concrete area of the horizontal section of the wall web, respectively. Moreover, $f_c^{'}$, f_{sy}, and f_{su} denote cylindrical compressive strength of concrete, yield stress and ultimate strength of reinforcing steel, respectively. Elevation view and longitudinal section of the wall is given in the Fig. 1 and cross sections of SW21 and SW22 walls are shown in Fig. 2. These tests were force-controlled and loading is stopped at the ultimate strength level.

Table 1 - Experimental data of SW21 & SW22

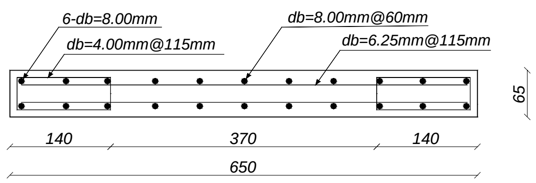
properties of specimen	SW21	SW22
ρ_{hor},%	0.80	0.80
ρ_{ver},%	2.50	2.50
ρ_{flex},%	3.00	3.00
$f_c^{'}$ (MPa)	46.4	43.0
f_{sy}-f_{su} of horizontal (MPa)	520-610	520-610
f_{sy}-f_{su} of vertical & flexural (MPa)	470-565	470-565
f_{sy}-f_{su} of confinement (MPa)	420-490	420-490
axial force ratio	0.00	0.10



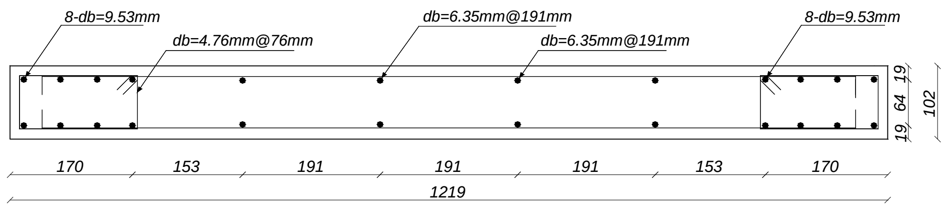
a) SW21 & SW22

b) RW2

Fig.1. Elevation view of the walls (dimensions are in mm)



a)SW21 & SW22



b) RW2

Fig.2. Cross-section and reinforcement details of the walls (dimensions are in mm)

2.2. RW2 Wall Tested by Thomsen and Wallace

The authors in [11]tested different structural walls under cyclic loading. RW2 is one of these four walls which have an aspect ratio greater than two. As it is well known, the aspect ratio is an important parameter which shows slenderness of the wall and indirectly points whether shear (squat wall) or bending (slender wall) is dominant. Elevation view and longitudinal section of the rectangular wall is given in the Fig.1. Cross section of RW2 wall is shown in Fig. 2 and the corresponding test data are summarized in Table 2 and a cyclic displacement controlled loading is applied. The first loading is carried out up to a drift of 0.10, then the direction of the loading is reversed and loading is continued. The loading is stopped in the 20th cycle, when the drift is reached 0.025 in the 20th cycle.

Table 2 - Experimental data of RW2

properties of specimen	RW21
ρ_{hor},%	0.33
ρ_{ver},%	0.33
ρ_{flex},%	3.30
f_c' (MPa)	42.8
f_{sy}-f_{su} of horizontal (MPa)	448
f_{sy}-f_{su} of vertical & flexural (MPa)	414
f_{sy}-f_{su} of confinement (MPa)	448
axial force ratio	0.075

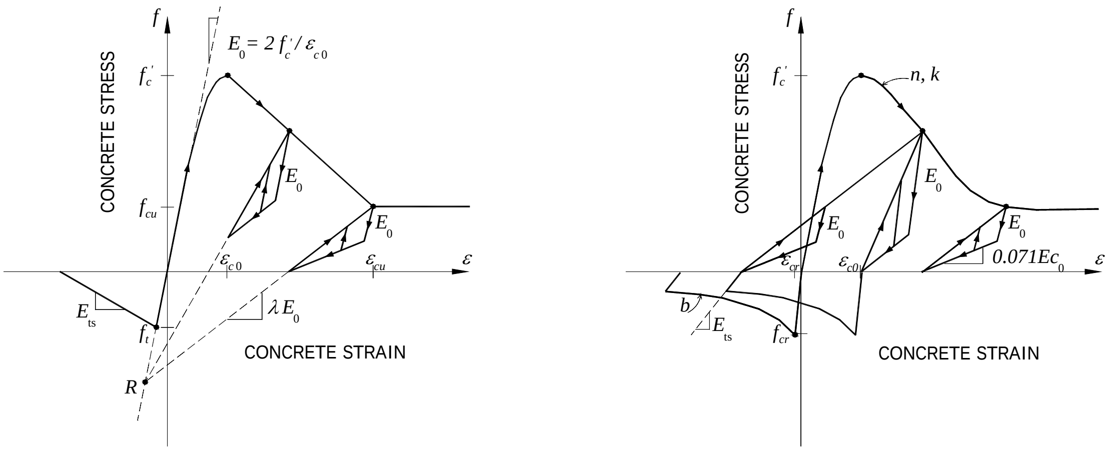
3. Mathematical Models

3.1. Material Models

Two different uniaxial concrete models are used. First one is a uniaxial concrete material model where tensile strength and linear tension softening is considered. The material model follows the loading, unloading and reloading rules of [12] as extended by [13] having a monotonic envelope curve of concrete in compression.

In the model cyclic unloading and reloading behavior is represented by a set of straight lines whereas hysteretic behavior is taken into consideration for both tensile and compressive stresses. Degradation of the stiffness is assumed in a way that all reloading lines intersect at a common point R as shown in Fig. 3(a). The tensile behavior of the model takes into account the tension stiffening and degradation of the unloading and the reloading stiffnesses for increasing values of the maximum tensile strain after initial cracking [14].

In Fig. 3, ε_{c0} is concrete strain at the maximum stress, f_c' is concrete compressive cylinder strength, ε_{cu} is concrete strain at the crushing strength, f_{cu} is concrete crushing strength, λ is ratio between the unloading slope at the crushing strain and the initial slope, f_t and f_{cr} represent concrete tensile strength and E_{ts} is tension softening stiffness. In addition to these parameters, to define model with tension stiffening, *n*, *k*, *b*, ε_{cr}andα is necessary which represent compressive shape factor, post-peak compressive shape factor, exponent of the tension stiffening curve, tensile strain at the peak stress and parameter for the plastic strain.



a) model with linear tension softening b) model with tension stiffening

Fig.3. Strain-stress relationships of the uniaxial concrete models

The second concrete model considers the tension stiffening in which the envelope curves are adopted to simulate the concrete behavior in membrane elements where Thorenfeldt-base curve is used for compressive behavior. Tension stiffening equation of [15] is taken into consideration for the tensile envelope. In the model linear unloading and reloading paths are used for compressive hysteretic rules. Plastic strains are considered in the hysteretic rule for concrete in tension to model the gap closure effect which enhances the dissipating characteristics of the hysteretic rule.

In the paper a uniaxial steel material model is adopted for reinforcing steel that considers [16] hysteretic model with an isotropic strain hardening which is included by [17]. Beyond the elastic part, this steel model consists of a stress-strain relationship for branches between two subsequent reversal points and uses an explicit algebraic stress-strain relationship, as opposed to the Ramberg-Osgood model. In this model, an asymptote is used as a transition curve between two straight-lines with a slope E_0 and E_1=bE_0 as shown in Fig. 4, where σ_y, *b*, and *R* represent yield stress, strain hardening ratio, monotonic curvature parameter, respectively. Bar buckling and failure resulting from low-cycle fatigue are excluded in that model.

3.2. Wall element Models

Two different fiber element models are considered in the analyses here. In the first one, the walls in the monotonic test are modeled by fiber wall elements referring to the research by [18]. In these analyses, concrete model with the tension stiffening and reinforcing steel model with the[16]steel model are considered. This wall model is based on linear interpolation of the curvature and constant axial strain with shear flexibility. Biaxial response has been taken into account by employing the uniaxial strain-stress relationships for concrete and steelin the two orthogonal directions separately. Only linear geometric transformation and in-plane analysis are possible with this element). Center of rotation is specified as 0.4 in these analyses as it is recommended in the analysis results of the wall tests by [7].

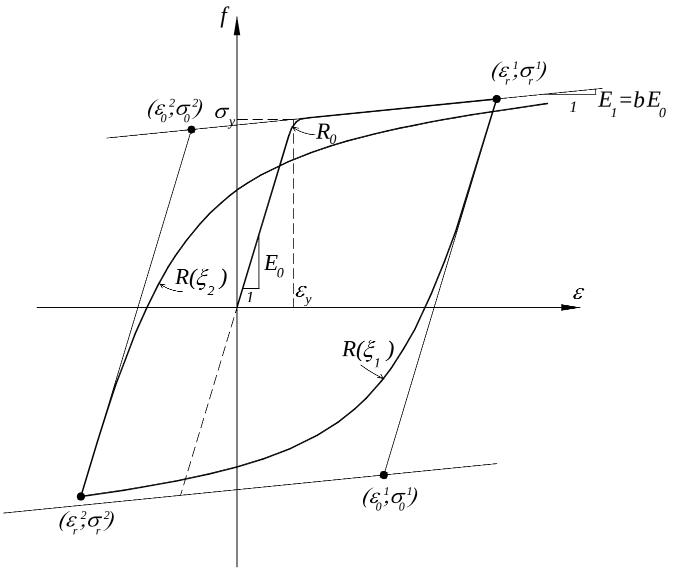
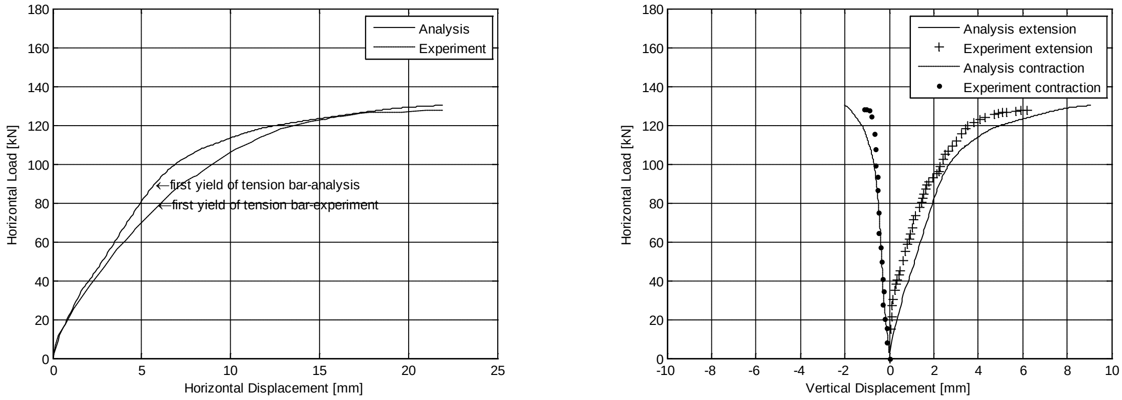


Fig. 4.Strain-stress relationships of the steel model

The second wall model is force-based fiber element which is used to model cyclic test of the authors in[11]. In these cyclic analyses, for concrete the model with linear tension softening andfor reinforcing steel the [16]steel model is employed. Plane sections remain plane and small deformations assumptions leads to a simple relation between fiber strains and generalized deformations. This fiber element model permits yielding at any point of the element and spread of plasticity within the element as well[4]. All analyses are performed in OpenSees software [19].

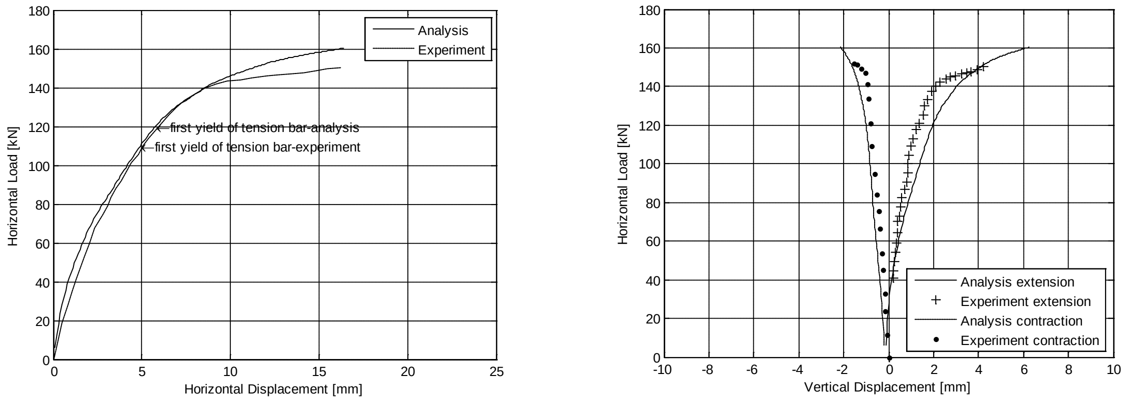
4. Comparison of the Test Results and the Analytical Results

Numerical results are presented in Figs. 5-7. As it is seen, the overall trend of the force displacement curve of SW21 and SW22 is estimated by the wall model of [18] where the concrete model with tension stiffening and the steel model of [16]are considered. There is no axial force on SW21, whereas SW22 has an axial load of 10% of its compression capacity. as given in Table 1. Figure 5 shows that the ultimate load capacity of SW21 structural wall is predicted accurately. However, the analysis curve seems to display a slightly larger stiffness at the medium stresses and lower stiffness at the higher stiffness compared to its experimental counterpart which correspond to cracking of concrete and hardening of steel regions.



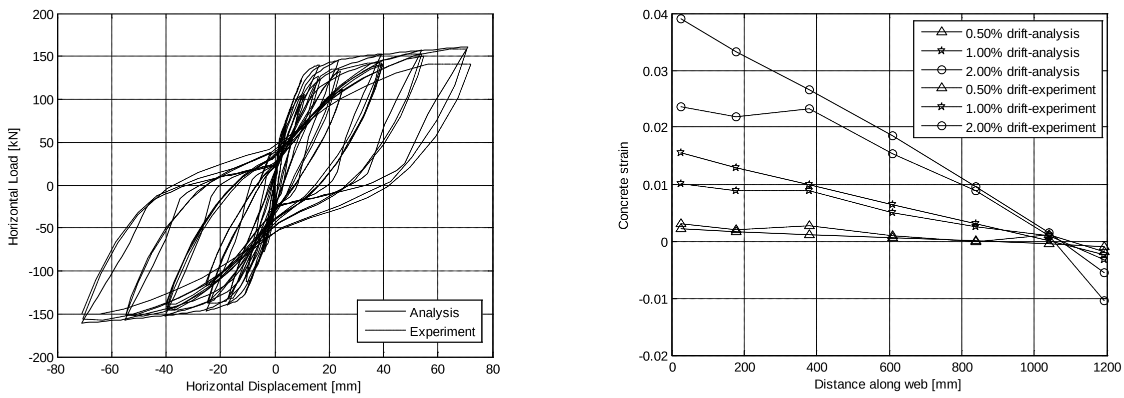
a) Horizontal load versus horizontal top displacement b) Horizontal load versus top vertical displacement

Fig.5. Comparison of the test and the analysis results of SW21



a) Horizontal load versus horizontal top displacement b) Horizontal load versus top vertical displacement

Fig.6. Comparison of the test and the analysis results of SW22



a) Horizontal load versus top displacement b) Concrete strains at the base level

Fig. 7. Comparison of the test and the analysis results of RW2

Vertical displacements measured at the top of the walls on the tensile and compressive edges are given, as axial extension and axial contraction separately in Fig. 5(b). Predicted vertical displacement is larger than the experimental result especially for the extension zone. In the loading curves of Fig. 5 and Fig. 6 the yielding load levels of the main reinforcement and the corresponding horizontal displacement are shown. As seen, the analysis curve and the experimental results are close to each other for SW22 as well; except the strain hardening region of the reinforcing steel. There is also good agreement between the vertical displacements which present the rotation of the top cross section and the axial extension of the fiber in the wall axis.

The force displacement curve of RW2 is obtained by using the wall model of [4] where the concrete model with a linear tension softening and the steel model of [16]are considered as concrete fiber material and steel fiber material, respectively. In order to make a comparison, the calculated horizontal load versus the top displacement curves of RW2 structural wall are plotted together with the experimental cyclic response curve in Fig. 7. The figure yields that there is a very good agreement between the analysis and the experimental results. Since the constitutive model of concrete includes the pinching effect, the same effect is obtained in the global behavior of the wall as well as it is seen in Fig. 7. Comparison of the predicted strains and the average measured concrete strains at the base of the wall for the selected drift levels are given in Fig. 7(b). As the figure shows very clearly, that the analytical model predicts reasonably well the tensile strain profile except at the tensile region for the drift level of 2.00%.

5. Conclusion

In this study, fiber beam column element, which is developed by [9],is used for biaxial behavior of the wall elements material model which is obtained as anextension of uniaxial material model for concrete and steel to predict experiment results of the structural walls subjected to monotonic loadings. Moreover, forced based fiber beam column element, which is proposed by [4],is used to predict experiment results of the structural walls subjected to cyclic loadings. Various numerical results are obtained by using the material model adopted and the results are given comparatively together with the experimental results. A close agreement is found between the numerical prediction developed in the present study and the experimental results. The authors anticipate that this model can be used to investigate the seismic behavior of structural walls which are essential elements of the lateral resisting structural system. It is shown that the modelsare able to predict elastic and plastic deformations of concrete and reinforcing steel, as well as, monotonic and cyclic loadings with acceptable accuracy. Since structural walls are expected to experience inelastic deformations even under moderate seismic loads, their nonlinear behavior is of prime importance. The presented model promises to yield results which can be even useful to develop some simplified guides for design of structural walls as well.

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