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EVALUATION OF FINITE AND FIBER ELEMENTS RC MODELS FOR NONLINEAR CYCLIC ANALYSIS OF U SHAPED SHEAR WALL

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Abstract

Reinforced concrete (RC) shear wall buildings are a very common type of construction worldwide. Nonlinear dynamic analyses of this type of structural systems are used more and more by the engineering profession in the context of performance based design or safety assessment of existing buildings designed using older codes/standards. Researchers are also working to improve advanced RC cyclic constitutive models especially under three dimensional (3D) excitations involving axial, moment, shear and torsional interactions. Several computer programs are available to perform nonlinear seismic analysis of reinforced concrete structures. Detailed solid finite elements (FE) models (i.e. ANSYS, ABAQUS) using built-in constitutive models are able to capture the local stress-strain responses, quantify low cycle fatigue, steel reinforcement bond slip in addition to the global force-displacement responses. These programs require the definition of several material parameters according to the constitutive model and failure envelope used (i.e. smeared vs discrete steel reinforcement, concrete confinement). Additional parameters to drive the nonlinear solution algorithms to convergence are also of major importance. FE models are also often used to calibrate the nonlinear stiffness and strength properties of fiber elements (i.e. OpenSees, SeismoStruct) that could be used in a computationally effective way to assess global nonlinear response of a complete building structures (i.e. formation of plastic hinges). The predictions of both FE and fiber elements models need to be compared to experimental data to validate their performance for both ductile (flexural) and brittle (shear) failure mechanisms.

This study describes the developments of FE (ANSYS, ABAQUS) and fiber element (OpenSees, SeismoStruct, SAP2000) models of U shaped shear walls (2.72m high, 1.30m x 1.05m footprint and 100 mm thick) tested by other researchers under axial and reversed cyclic bi-directional flexural loading. Guidelines are provided for a proper definition of the FE and fiber elements modeling parameters using five different computer programs to satisfactorily reproduce the given experimental results, up to a drift percentage of 2.5%. The capabilities of the different models to predict failure mechanisms are also investigated. The advantages and limitations of the different computational tools are discussed. The results of this study are very useful for researchers and practitioners working in the field of seismic safety evaluation of RC shear wall buildings using predictive computational tools.

Keywords: Finite Element, Fiber Element, U-shaped Shear Wall

1. Introduction

In a Reinforced Concrete (RC) building, the seismic force-resisting system is often concentrated in relatively few walls that are distributed around floors, or within non-planar RC wall systems, to provide desirable shear resistance and limit lateral deformations of the building to acceptable levels. Coupled RC U-shaped walls (hereinafter referred to as core walls) can efficiently resist the majority of seismic lateral forces and improve the design flexibility of RC buildings. Substantial lateral strength and stiffness, in addition to deformation capacity to meet the demands of strong seismic excitations, make core walls a desired option for seismic force-resisting system of RC buildings. In general, structural walls are designed to prevent collapse and loss of life under severe earthquakes. The reason for adopting such a strategy is that it is extremely expensive to design structures to respond elastically under such severe events, which may not occur during their expected life; therefore, inelastic wall deformations are expected.

The seismic behavior of shear walls in buildings can be affected by many variables such as shear span ratio, interacting nonlinear axial-shear-flexural behavior, boundary elements, and the interaction with other structural members. Since structural walls are the primary, and in some cases the only, seismic-force resisting elements, robust analytical tools for nonlinear analysis of multi-story buildings are essential for reliable seismic performance design or assessment. These tools must include models capable of estimating the global seismic demands of the building and capturing the hysteretic behavior of structural walls. Moreover, multi-storey core walls are sensitive to 3D seismic effects, thus requiring modeling tools that can account for these phenomena while providing results with an acceptable accuracy and within a reasonable computational time [1].

A large number of computer programs have been developed for nonlinear modeling and analysis of building structures. These tools are becoming more and more popular in engineering offices thanks to the growing performance of material constitutive laws and efficiency of numerical formulations. Different modeling approaches can be used, ranging from macro-scale models such as concentrated inelasticity, multi-axial spring models, truss models and combined models, up to micro-models such as finite element (FE) models and fiber models.

Although RC micro modeling using solid FE models (e.g. ANSYS, ABAQUS) can generally provide more detailed and precise results, the relevant expertise required to build such models and to ensure analysis convergence and good quality of the results is still rather highly specialized. In addition, micro modeling is practically inapplicable to large building systems. The need for implementing several material parameters required by selected constitutive laws and/or failure envelopes can be another limitation imposed by built-in material laws in many of the tools available for nonlinear analyses of RC buildings. Understanding of these limitations is crucial for critical assessment of the results of numerical calculations, especially for the cyclic response of the structure.

Macro modeling is more convenient and generally easier than micro modeling and also has rather less calculation process. However, the efficiency of both FE and fiber element models needs to be validated against the experimental data to ensure their reliability for predicting both the global and local behavior of RC shear walls. Clough et al. [2] proposed the first nonlinear macro model for numerical modeling of RC elements. Afterward, the first application of the finite element method of analysis in RC elements was proposed Ngo and Scordelis [3]. Since then several advancements were done in the area of modeling of RC elements including shear walls.

In comparison with planar walls, very little experimental research has been carried out on the performance of U shaped RC walls subjected to lateral loads. In one of the first attempts, Ile and Reynouard [4] examined three full scale U-shaped RC walls subjected to uniaxial and biaxial cyclic lateral loading. The tests aimed at studying the behavior of U-shaped wall in uniaxial and biaxial bending and shear, and compared the alternative design requirements of two versions of EC8. Beyer et al. [5] performed bi-directional quasi-static cyclic testing of two U-shaped walls with different thickness, built at half-scale and designed for high ductility. The tests mainly focused on the flexural behavior of walls, considering different directions of loading (two orthogonal as well as diagonal). Results showed that the most critical direction was the diagonal one, in which the maximum attained moment was less than what plastic hinge analysis would predict. Moreover, the displacement capacity of the wall in diagonal direction is smaller than the other two orthogonal directions.

In this study, numerical models of an RC core wall are developed using different micro and macro modeling approaches, including fiber element-based concentrated and distributed inelasticity models, as well as finite elements. Different computer programs implementing these approaches are used to model a U shaped shear wall tested by Constantin and Beyer [6] under axial and reversed cyclic bi-directional flexural loading. The predictions of the numerical models are compared to available experimental data to highlight the advantages and disadvantages of each modeling approach.

2. Review of numerical approaches for seismic safety assessment of RC shear walls

2.1 Concentrated and distributed inelasticity models

Concentrated inelasticity models, i.e. lumped plastic hinges, are among the simplest and earliest nonlinear formulations for building seismic analyses [2]. They assume that most significant inelastic deformations occur at the critical zones, such as the ends of beam-column members, while the other parts of the structure remain elastic. Plastic hinges can be accounted for through discrete- or fiber-based formulations [7]. The fiber-based approach, generally considered as more accurate, is used herein. It consists of using fiber elements which are beams composed of multiple fibers discretized within a certain number of integration sections located along the whole length of a structural member. When applied in a concentrated inelasticity model, this approach directly takes account of the geometry of the structure and material properties. The length of the plastic hinge and its position should be determined prior to analysis [8]. Fiber-based formulations can be split into: displacement-based (DB) or force-based (FB) techniques [9]. A DB-based simulation uses an interpolation of displacements or curvatures along each fiber element, which may fail to adequately represent highly nonlinear behavior. DB solutions can be improved by increasing the mesh density, but at the expense of higher computational cost. The FB approach is generally preferred as it uses interpolation functions that are chosen to correspond to the exact solution of the internal forces in the elements [10]. It is then possible to represent a structural member using a single FB element without the need for refinement, except for the number of integration sections which can enhance convergence and solution quality. However, FB simulation assumes that plane sections remain plane, which prevents from appropriately accounting for the effects of shear deformations and flexure-shear interactions.

As opposed to concentrated inelasticity models, distributed inelasticity models do not localize inelastic deformations in critical zones, but rather account for their spreading along beam-column members [11]. In this work, the distributed inelasticity approach is combined with the Wide Column Model (WCM) Analogy [5] to simulate the nonlinear response of the core wall. As for lumped hinges, fiber-based elements are available either as DB or FB formulations. Due to the multiple segments of the WCM of the studied core wall, only DB elements are used to avoid localization effects, i.e. strong dependence of the obtained nonlinear response on finer mesh discretization and does not converge into one single solution [10]. The same limitations of fiber elements discussed above apply to the WCM, i.e. fiber elements are infinitely rigid in shear and torsion as they account only for compression and flexure. To attenuate this limitation and partially account for the effect of horizontal steel rebars on the shear resistance of the core wall, springs with rigidities determined in a way to simulate shear deformations at these locations, can be assigned between the multiple members of the WCM.

2.2 Finite elements

In FE analysis of RC shear walls, both shell and solid elements can be used in combination with nonlinear material constitutive laws available in the numerical tool. The main benefits of shell elements are relatively accurate consideration of 3D stress states and internal forces, simplicity and low computational costs. In some cases however, shell finite elements do not allow adequate consideration of steel rebars in RC structures. Modeling such structures using 3D-solid finite elements is more straightforward, and detailed models of the rebars can be developed regardless of the bar geometry and direction (e.g. longitudinal bars, hoops, and transverse bars in a RC wall). This can lead to more accurate account of local effects such as rebar buckling. However, the associated computational cost can be prohibitive for large scale problems. Convergence of the analysis is always an issue that needs to be addressed appropriately in FE analysis of concrete members. Static and Dynamic/Implicit or Explicit analyses can be used depending on the software and type of loading applied [12, 13]. Implicit static and dynamic analyses sometimes suffer from the low rate of convergence because of contact or material complexities, resulting in a large number of iterations. This is one of the most drawbacks of these FE analyses, which usually happens in nonlinear analysis of RC members with large inelastic displacements corresponding to the concrete cracking [13].

4. RC constitutive models and used software

4.1 Software used for concentrated and distributed inelasticity models

Three software packages were used to build the concentrated and distributed inelasticity models: SeismoStruct [14], SAP2000 [15] and OpenSees [16]. SeismoStruct is a fiber element-based software, allowing both DB or FB modeling approaches, as well as concentrated or distributed inelasticity modeling [14]. The program was developed mainly for nonlinear analyses under static or dynamic loads, including conventional time-history response, pushover, incremental dynamic and modal response analyses. It can account for both large displacements and material inelasticity. Gauss-Legendre and Gauss-Lobatto numerical integration quadrature rules are used for DB and FB elements, respectively. Four concrete and four steel constitutive laws are available, e.g. Trilinear constitutive law and Mander et al. [17] for concrete, and bilinear and Menegotto-Pinto [18] for steel rebars.

SAP2000 [15] is widely used for the design and analysis of any kind of structures, such as buildings and bridges. It is particularly suited for linear analyses, but can also account for geometric nonlinearity through P-delta effects and for material nonlinearity by using plastic hinges or nonlinear link elements [15]. Static and dynamic analyses are implemented into the software, including pushover nonlinear static analysis, response spectrum analysis, time-history linear and nonlinear modal analysis, and time-history linear and nonlinear direct integration analysis. Gauss-Legendre numerical integration quadrature is used. Stress-strain curves can be defined as Simple and Park models for steel rebars, and Simple and Mander models for concrete material [15, 17]. Hysteresis types for nonlinear cyclic analysis are somewhat limited as only a select few are available in the software, including kinematic [15] for steel rebars, and Takeda [19] for concrete material.

OpenSees is an open source program for seismic response analysis of structural and geotechnical problems [16]. It contains, among others, elastic and inelastic fiber-based beam-column elements and continuum elements for structural and geotechnical models. Both DB and FB formulations are available for fiber-based beam-column elements. OpenSees provides nonlinear static and dynamic methods, equation solvers, and various methods for handling constraints. The default numerical integration quadrature rules are Gauss-Legendre and Gauss-Lobatto for DB and FB elements, respectively. A wide range of uniaxial materials and section models are available for beam-columns, such as bilinear and Giuffré-Menegotto-Pinto [18] for steel rebars, and Kent-Scott-Park [16] and Linear Tension Softening [16] for concrete material. Nonlinear analysis requires a wide range of algorithms and solution methods.

4.2 Finite Elements

Finite element modeling is carried out herein using two software packages: ANSYS [12] and ABAQUS [13]. ANSYS offers a specific solid element for RC members, i.e. SOLID65, which is an eight-noded solid element with three translational degrees of freedom at each node. The element is capable of modeling cracking in tension and crushing in compression and it is well suited for the 3D modeling of solids with or without reinforcement materials [12]. Cracking is supported at any surface along any direction by means of the angle between the normal of the crack surface to the global directions. Steel reinforcement can be considered as smeared throughout the concrete element or using discrete steel rebar elements bonded to the concrete elements. The material constitutive law provided in ANSYS for considering the cyclic response of the concrete medium include smeared cracking and crushing model to add a certain cracking and crushing limit under tensile and compressive stresses respectively. Also, shear transfer coefficients β_t and β_c are provided for crack openings and closures respectively, which represent the shear strength reduction factors for those subsequent loads which induce sliding (shear) across the crack face. These parameters can have significant effects on the cyclic response of RC members with subjected to severe shear demands.

ABAQUS has a variety of elements that can be used to model concrete, including both continuum and structural elements. Standard solid elements, i.e. 8-node linear solid (C3S8R) or 20-node quadratic solid (C3D20) elements, which both have three degrees of freedom per node, are widely used to simulate the nonlinear response of RC members. Three different constitutive laws for the concrete material including Brittle Cracking (BC), Smeared Cracking (SC) and Concrete Damage Plasticity (CDP) can be employed. The latter appears to be the most comprehensive model for RC structures, as it can represent all compressive crushing, tensile cracking and tension stiffening behaviors. Moreover, CDP is the only constitutive model that can be used in both Implicit and Explicit analysis. Though the SC constitutive model in ABAQUS uses the same theory as ANSYS does, there is no feature available in ABAQUS to consider the shear reduction because of crack opening/closing. As for the steel reinforcement, there is no smeared reinforcement option provided in the solid elements in ABAQUS. However, discretized reinforcement modeled using truss or beam elements can be effortlessly embedded into the concrete medium.

Although the ABAQUS/Explicit is the usual choice for a seismic analysis, it can be used for certain static or quasi-static problems. Typically, these are problems that would be solved with ABAQUS/Standard but may have difficulty converging, making them computationally expensive. ABAQUS/Explicit determines the solution without iterating by explicitly advancing the kinematic state from the previous increment [13], results in a more efficient analysis depending on the case. Substantial disk space and memory savings of ABAQUS/Explicit are other advantages which make it more practical. However, specific considerations such as smooth stepping and loading rate should be taken into account to achieve reasonable results using the Explicit solver.

5. Experimental data for comparisons of RC constitutive models

To evaluate the performance of RC models, validation of numerical predictions against the data from experimental tests by Constantin and Beyer [6] are performed. For the sake of brevity, only an overview of these tests is provided herein, detailed information can be found in Constantin and Beyer [6]. The tests were carried to evaluate the lateral capacity of RC core walls subjected to bi-directional loading. One of the tested U shaped RC core walls, denoted as TUC, is considered here for validation of the numerical approaches described above. Three actuators, two acting along the NS (flanges) direction, and one along the EW (web) direction, were attached to the collar at the top of the wall. Three types of steel rebars, i.e. D6, D8 and D12, having 6, 8 and 12 mm diameters, respectively, were used. To assess the effects of reinforcement distribution on the response, the vertical reinforcement of one flange was uniformly distributed, while it was concentrated in the boundary elements of the other flange. The core wall was subjected to an axial load kept constant during cyclic tests, and to various protocols of bidirectional loads applied through cycles corresponding to different drift ratios from 0.1% to 3.0%.

6. Hysteretic cyclic responses

The numerical strategies presented in the previous sections are applied next to evaluate the response of the core wall tested by Constantin and Beyer [6]. The results obtained are compared to their experimental findings to highlight the advantages and limitations of each modeling approach.

6.1 Predictions using concentrated inelasticity models

This section describes the concentrated inelasticity models developed using SeismoStruct and SAP2000. The core wall is modeled as a single beam element with a plastic hinge located at the base. The length of the plastic hinge is determined as proposed in the Canadian code CSA A23.3-14 [20]

$$L_p = 0.5L_w + 0.1h \tag{1}$$

where L_w denotes the length of the wall in the studied direction and h the total height of the building in the studied direction, considered as the distance between the base of the wall and the location of the actuators in the present case. Eq. (1) yields plastic hinge lengths of 985 mm and 820 mm along the EW and NS directions, respectively, obtained using L_w = 1.3 m and h = 3.35 m in the EW direction, and L_w = 1.05 m and h = 2.95 m in the NS direction. For the sake of simplicity, a mean value of 900 mm is used as plastic hinge length. The collar is modeled using elastic elements that also serve to connect the actuators to the wall. Considering that only concentrated loads are applied to the core wall, internal forces are interpolated linearly in the FB elements.

In the current version of SeismoStruct, it is not possible to model steel rebars with different mechanical properties in a single section. To circumvent this limitation, the mechanical properties of the rebars are defined in proportion to the actual quantity of each rebar type in the section. The constitutive laws of Menegotto-Pinto [18] and Mander et al. [17] are used to model steel and concrete, respectively. For practical purposes, the NS actuators are merged into a single one. The cyclic displacements imposed by actuators are applied to the wall through a static time history analysis.

In SAP2000, each rebar is assigned its own mechanical properties, including a nonlinear stress-strain curve with kinematic hardening, including an elastic, a perfectly plastic (which has been removed in our case), an empirical strain hardening, and a softening region. Mander et al. [17] and Park constitutive laws are used respectively for the concrete and the steel materials. The hysteresis behaviors used for the materials are Takeda et al. [19] for concrete and kinematic for steel, since they are the only ones available that are nonlinear. Confinement has been added manually to the section of the model. Cyclic displacements are applied as a Nonlinear Direct Integration History load case. No mass is assigned to the model and a small stiffness proportional damping is considered to enhance convergence. The Hilber-Hughes-Taylor method [21] with the parameters γ=0.5, β=0.25 and α= – 0,0005 is used with time increments of 10 s.

Figure 1(a) illustrates the concentrated inelasticity models built using SeismoStruct and SAP2000. The fiber discretization of the wall cross-section using SeismoStruct is presented in Fig.2 (b), as well as the directions used for the bidirectional cyclic loading protocol.

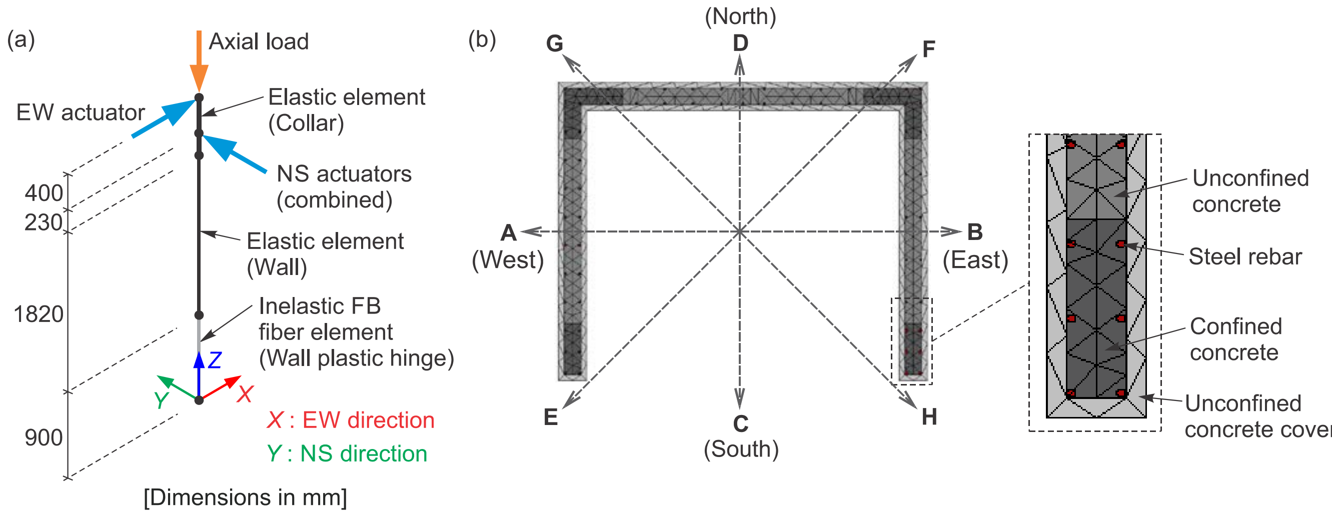

Fig. 1. Concentrated inelasticity model: (a) Model components in SeismoStruct [14] and SAP2000 [15]; (b) Fiber discretization of the wall cross-section using SeismoStruct [14].

The hysteretic cyclic response of the core wall along E-F direction obtained using concentrated inelasticity models in SeismoStruct [14] and SAP2000 [15] are illustrated in Fig. 2 along with experimental data from Constantin and Beyer [6]. A smoothing technique was applied to the SAP2000 results to reduce jagged effects on the graph data. The initial stiffness predicted by SeismoStruct is slightly higher than measured, which can be attributed to shear deformations not being fully accounted for in the model. This effect could be attenuated partially by using link elements assigned a stiffness corresponding to the shear stiffness of the wall along each direction. However, this would increase the computational effort and lessen the attractive feature of using a single FB element per structural member. This procedure is also limited depending on the plastic hinge length, since the hinge can only be placed on a single member.

The model seem to reproduce the slight strength-hardening observed in experimental results. However, it does not account for 3D local behavior along the wall cross-section, i.e. warping effects, which might contribute to the predicted overstrength of the wall, especially at position E along both principal directions. Two other reasons for the discrepancies between predictions and experimental results in Figs. 2(a) and (b) are: (i) that a single set of mean mechanical properties had to be used to represent the three different steel rebars, i.e. D6, D8 and D12, and (ii) that confinement zones had to be predefined as being equal for certain regions of the wall section which is not always the case in the actual wall.

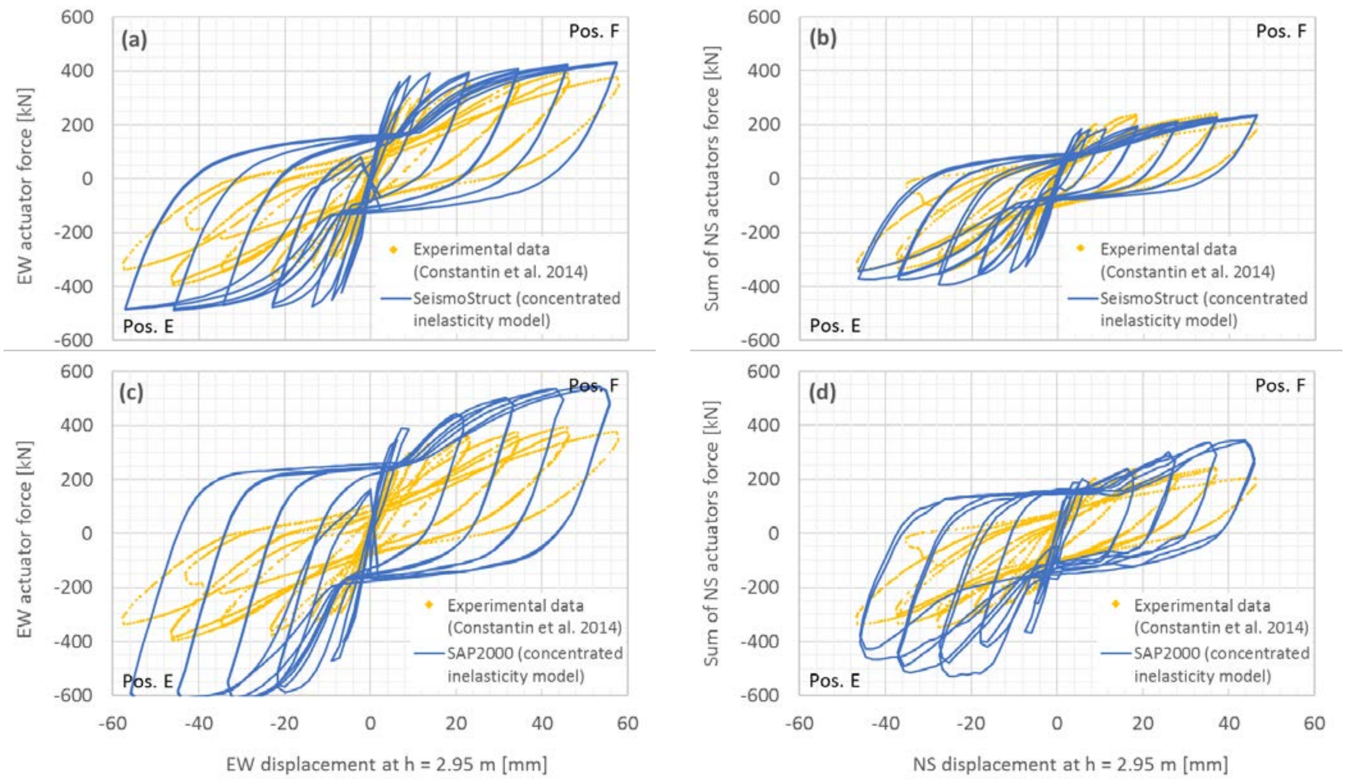

Fig. 2. Predictions of hysteretic cyclic response of the core wall along E-F direction using concentrated inelasticity models vs experimental data: (a) and (b) SeismoStruct [14]; (c) and (d) SAP2000 [15].

For the SAP2000 model, a similar behavior to the SeismoStruct predictions is observed, but in a more amplified way; i.e. the initial stiffness is too high, and an increased overstrength is observed for both directions (Figs. 2(c) and (d)) compared to the predictions of SeismoStruct and experimental data. The in-cycle strength degradation observed are mainly caused by the smoothing technique used along both EW and NS actuators.

6.2 Predictions using distributed inelasticity models

The distributed inelasticity models are built using SeismoStruct and OpenSees (Fig.3). In both cases, the wall is modelled according to the Wide Column Model Analogy (WCM) [5] and steel and concrete materials are modeled using Menegotto-Pinto [18] and Mander et al. [17], respectively. In SeismoStruct, the mechanical properties of the rebars are defined in proportion to the actual quantity of each rebar type in a given cross-section as previously, while these properties are assigned individually to each rebar in OpenSees. The vertical elements defining each wall panel are modeled using inelastic DB fiber elements. The collar is modeled using elastic elements as before. Zero-length link elements with elastic concrete properties corresponding to a fraction of the gross section of the wall are used between every two vertical elements to approximately account for shear deformations of the wall [5]. Horizontal link elements are included to connect the three wall panels. These elements have elastic concrete properties of a fraction of the wall gross section and are only flexible in torsion and out-of-plane flexure [5, 23]. The collar and wall parts of the model are connected using rigid links located at the three top nodes of the core wall. The cyclic displacements imposed by actuators are applied to the wall through a static time history analysis. The analysis is run as a static analysis. The algorithm used is Krylov-Newton [24]. The hysteretic cyclic response of the core wall along E-F direction obtained using a Wide Column Model approach with distributed inelasticity models in SeismoStruct [14] and OpenSees [16] are illustrated in Fig. 4 along with experimental data from Constantin and Beyer [6].

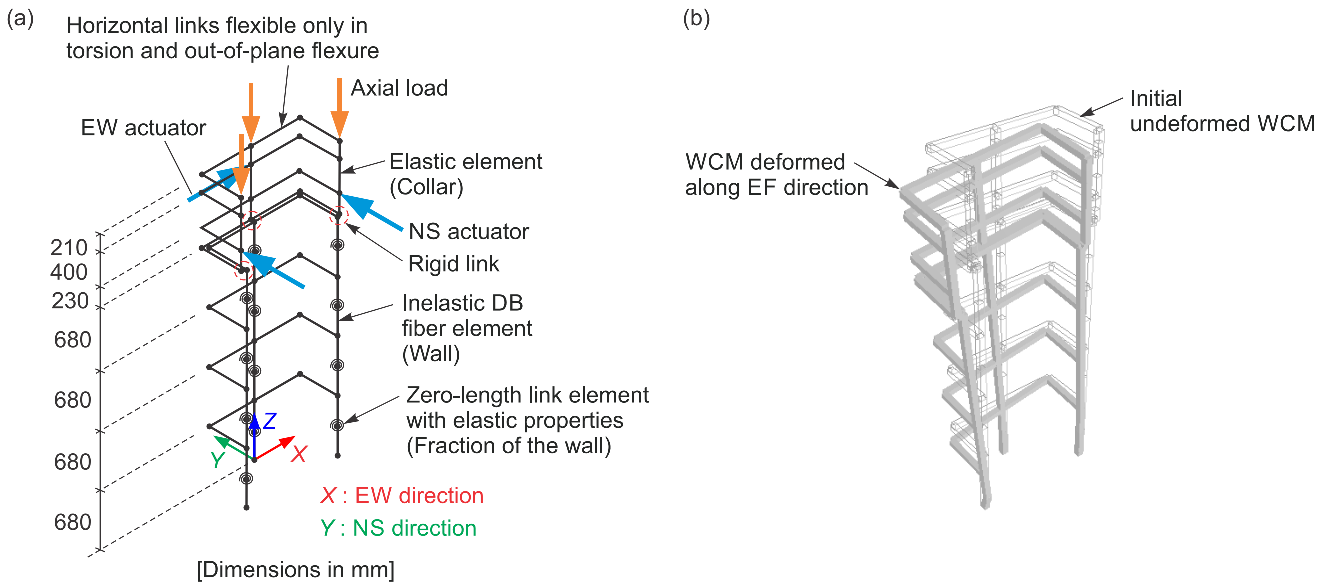

Fig. 3. Fiber element-based WCM model: (a) Components of the WCM used in SeismoStruct and OpenSees; (b) Undeformed WCM and deformed configuration along EF direction obtained using SeismoStruct [14].

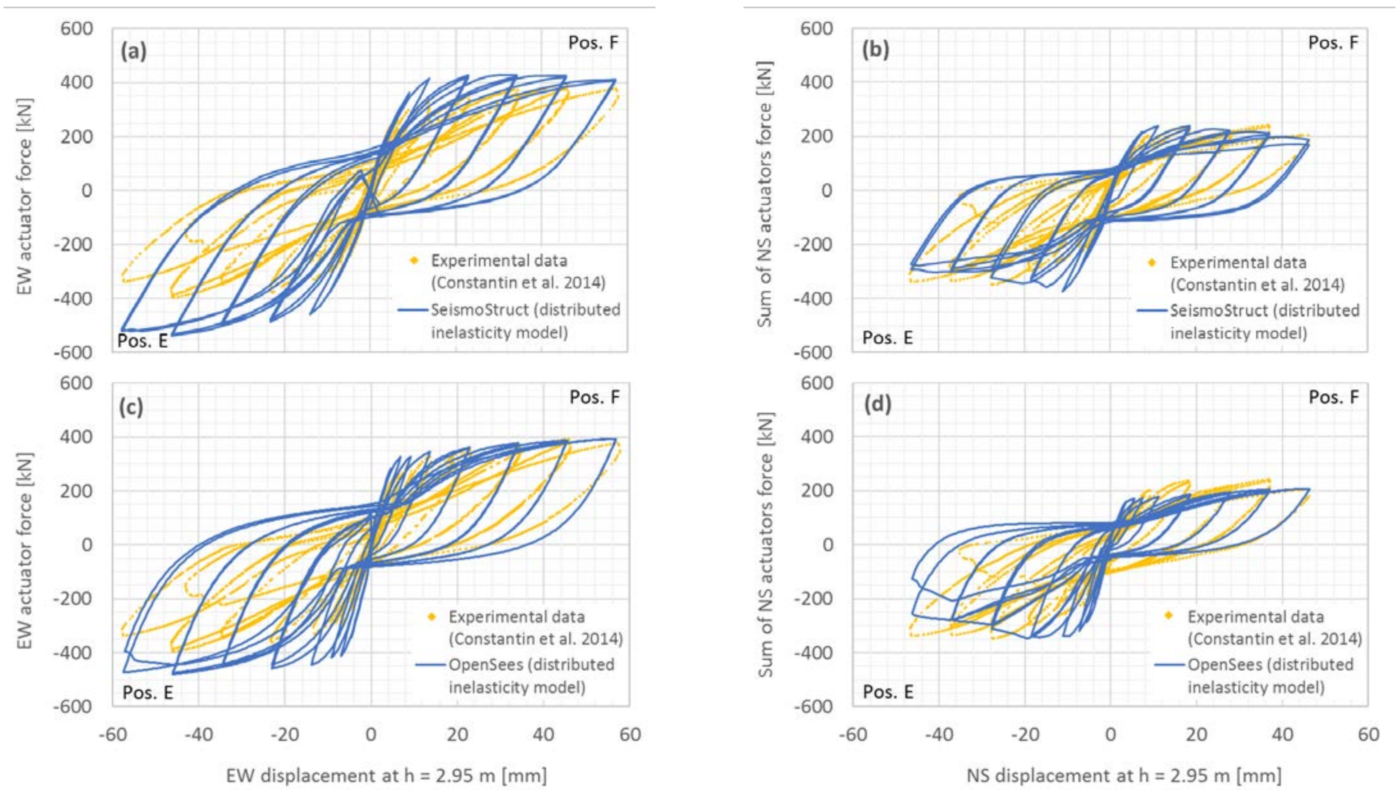

Fig. 4. Predictions of hysteretic cyclic response of the core wall along E-F direction using distributed inelasticity elements and wide column models vs experimental data: (a) and (b) SeismoStruct; (c) and (d) OpenSees.

Figures 4(a) and (b) show that the initial stiffness is well predicted by the SeismoStruct distributed inelasticity elements models. The initial overstrength at the E position on the graph for both actuators can be at least partly explained by the fact that a mean value of mechanical properties had to be used for the west flange (composed of 3 different rebars sizes). Still, the general behavior is somewhat well represented by the model.

For the EW direction, a slight hardening is observed in later stages of the nonlinear cycles at the E position. This behavior can be attributed to multiple factors, such as definitions of materials and confinement areas, i.e. they must be specified as symmetric in rectangular shapes in SeismoStruct and a compromise has to be made. In-cycle strength degradation and cyclic strength degradation seem to describe better the behavior of the core wall in NS direction. This kind of response can happen because of concrete crushing at the ends of the flanges. As was the case in the EW direction, approximations of confinement regions could play a role in this behavior. The OpenSees models seem to give reasonable results for the F position, while the prediction in the E position is again less accurate. Definitions of the mechanical properties and confinement regions are more precise in this case. The results seem to confirm the overstrength in the E position, but it is less obvious than predicted by SeismoStruct model. The model globally reproduces the behavior of the wall relatively well. Limited in-cycle strength degradation and cyclic strength degradation are also observed for the E position along the NS direction.

6.3 Predictions using finite element models

Figure 5 shows 3D views of FE mesh used in ANSYS and ABAQUS models. In ANSYS, SOLID65 elements are used to model the concrete, while BEAM188 elements are used to model discretized steel rebars. SC model and a plastic regime with isotropic hardening are assigned for concrete and steel materials, respectively. Similar configurations are used for model implementation in ABAQUS, i.e. C3D8R solids and beam elements, except the SC model, which is replaced by CDP model. Full bond interaction between the concrete and steel rebars is considered in the numerical models. The deformed shape of the core wall FE models and the stress distributions are presented in Figs.5 (c) and (d). The force-displacement curves for both NS and EW actuators obtained using FE analyses are compared to experimental results in Fig.6. As it is depicted in Figs. 6(a) and (b), the observed responses from the ANSYS FE model are in acceptable agreement with the test data in both loading and unloading parts of the cycles. The initial stiffness of the curves match well for both NS and EW directions, and the FE models showed a reasonable precision in predicting core wall capacity and maximum displacements at failure. Possible reasons for the observed discrepancies could be the loss of tension stiffening effects under reversed cyclic load conditions, and the degradation in the bond and anchorage of the reinforcement, particularly at the base.

Figures 6(c) and (d) shows that though the ABAQUS FE model closely predicts the initial stiffness in both directions, it fails in reproducing the cyclic response of the core wall. First, the model overestimates the lateral capacity of the wall. Moreover, while the calculated unloading stiffness of the model is close to the elastic stiffness, the degradation of the unloading stiffness could not be captured. In fact, the model is unable to capture sliding between the already cracked concrete surfaces. Little effects on the hysteretic force-displacement response were observed by adjusting the stiffness recovery parameter available in CDP model. The numerical model exhibits fat hysteresis loops with very low pinching, due to the lack of a proper shear reduction algorithm, which induce shear sliding across crack faces. Shear sliding effects at the time of crack closure upon load reversal can significantly affect cyclic loops and lead to pinching effects in the cyclic response of the core wall.

Figures 6(e) and (f) present a comparison between the results of pushover analysis of the core wall using both implicit and explicit solvers implemented in ABAQUS. For the explicit analysis, smooth stepping feature in ABAQUS is used to avoid the waving effects in the response of the core wall. A slow loading rate of 0.1 mm/s is also adopted in explicit analysis to simulate quasi-static loads and satisfy the recommendations in ACI 374.2R [25]. A mass scaling technique is used with a scaling factor of 16 to expedite the computations, after performing sensitivity analyses. Both implicit and explicit analyses result in reasonable prediction of the monotonic response of the core wall. However, the explicit solver decreases computational time up to 60% in the investigated case. This difference can be even higher in cases when a relatively fine mesh and significantly small time increments are required to address convergence difficulties.

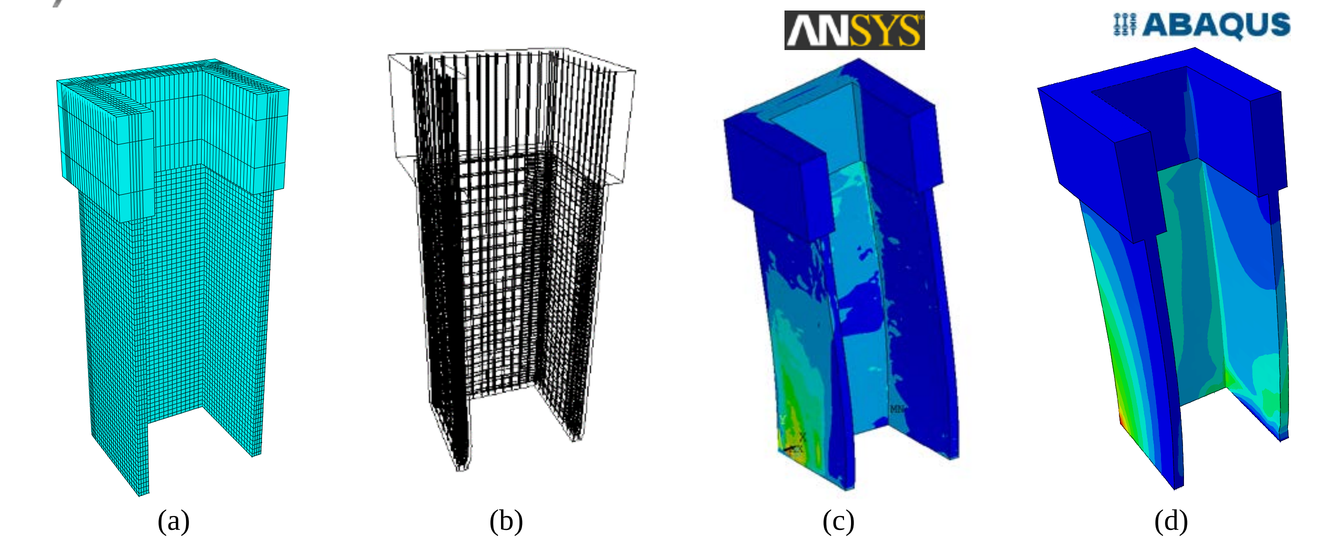

Fig. 5. View of the 3D FE models for specimen TUC: (a) FE mesh, (b) Rebars disposition, (c) Deformed shape extracted from ANSYS, (d) Deformed shape extracted from ABAQUS.

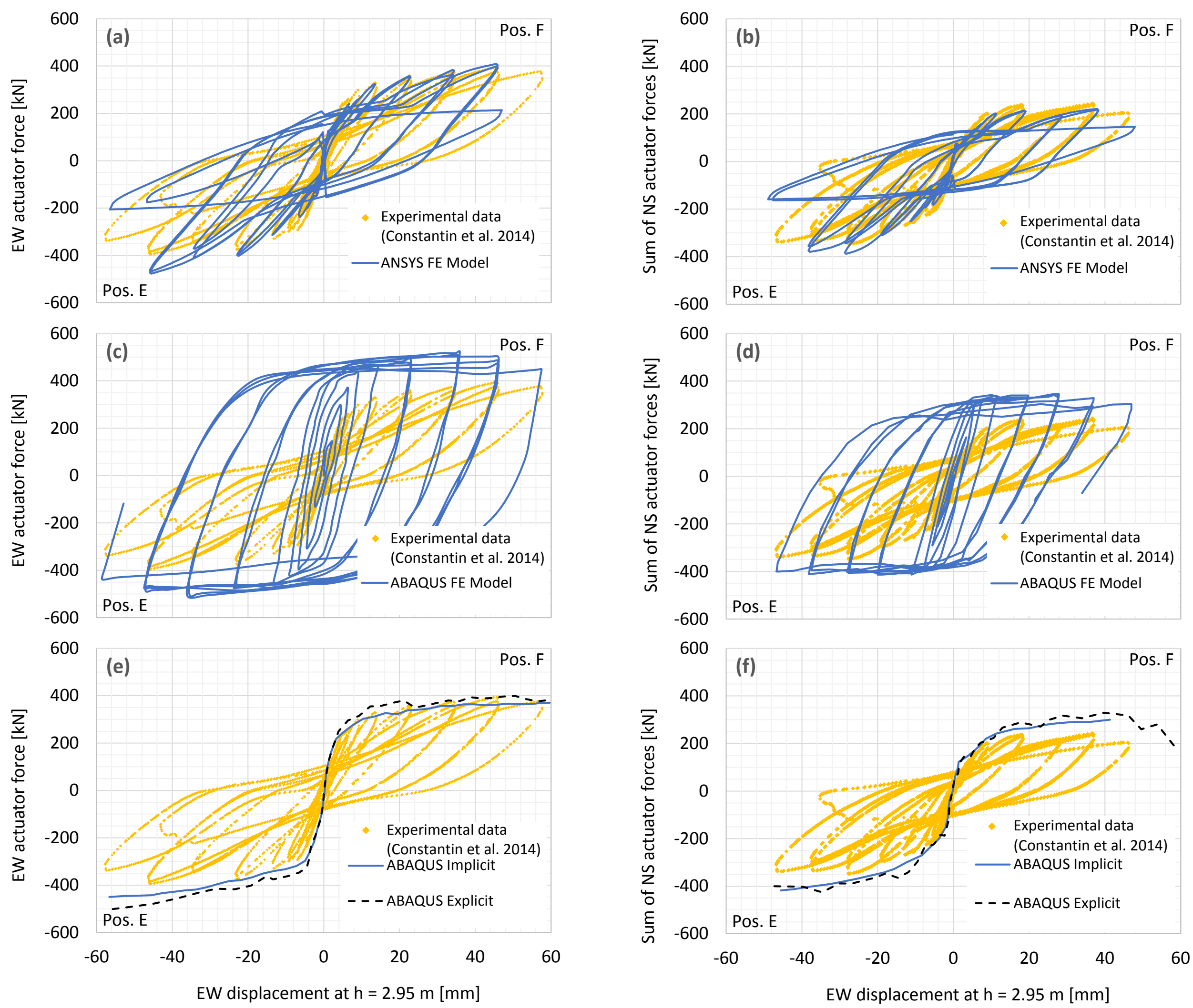

Fig. 6. (a) to (d) Hysteretic cyclic response of the FE models: ANSYS and ABAQUS; (e) to (f) Comparison between the monotonic results of ABAQUS/Implicit and ABAQUS/Explicit (EF direction)

7. Ongoing experimental testing program – Multiaxial loading of U shape walls

An experimental testing program is currently being prepared at the Structures Laboratory of Polytechnique Montréal. The main objectives of this program is to develop enhanced numerical models to account for 3D seismic effects on U shaped walls. The models will be validated against new experimental data obtained from planned cyclic tests of U shaped walls subjected to multidirectional loads including torsional effects. A High-Performance Multiaxial Loading System available at the Structures Laboratory of Polytechnique Montréal will be used for this purpose. The tested core walls will be retrofitted using FRP (Fiber Reinforced Polymers) sheets, and then re-tested under multiaxial cyclic loads. Numerical models of the retrofitted core walls will also be validated against experimental data.

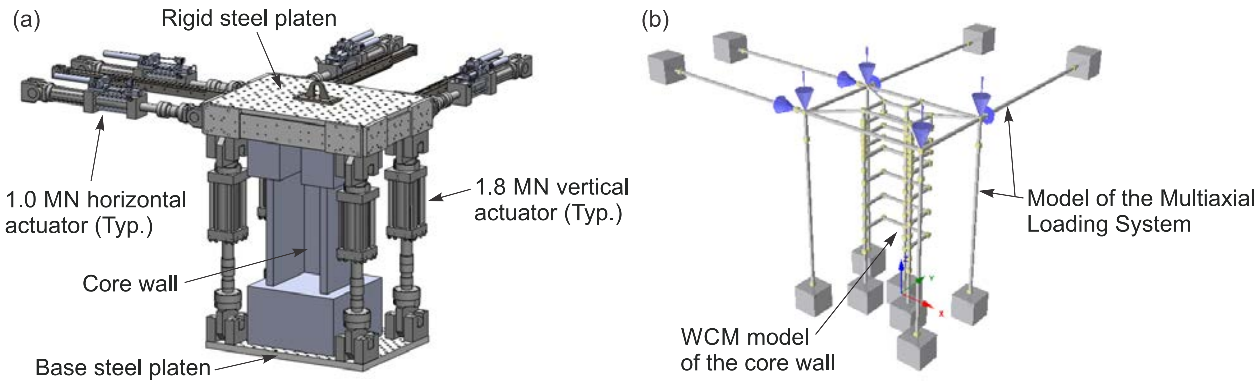

Fig. 7. Ongoing experimental testing program: (a) U shaped shear wall to be tested using the Multiaxial Loading System available at Polytechnique Montréal, (d) Simulation of the tests using SeismoStruct.

8. Conclusions

A variety of finite and fiber element RC models for nonlinear cyclic analysis of RC core walls were evaluated in this paper, using different computer programs. The main results are summarized as follows:

- The concentrated plasticity models, created herein using SeismoStruct and SAP2000, have the advantage of being very simple to create. This type of analysis requires a shorter amount of time than the others in terms of building the models and running the analyses. This economy can be to the cost of precision however; i.e. warping and shear deformations are not taken into account.
- The distributed plasticity models combined with the WCM analogy, created herein using SeismoStruct and OpenSees, are relatively simple to use including features to enhance precision such as shear flexibility.
- FE modelling using the software such as ANSYS and ABAQUS could be as an accurate tool for structural analysis. However, calibration/validation of the results is necessary because of the probable uncertainties.
- By using the shear reduction feature provided by ANSYS, it can perform well in predicting the cyclic behavior of the RC U-shaped wall, as well as its capacity and the maximum displacement at failure. On the contrary, though it is claimed that CDP model in ABAQUS can capture the cyclic response of RC elements, this seems to be true only in well detailed concrete elements with no pinching. In any case that pinching behavior is not expected, CDP model can be used.
- In contrast to cyclic loading, results of the CDP model under monotonic loads from both Implicit and Explicit analyses are well in agreement with experimental ones. Hence, Explicit analysis can be successfully used in quasi-static analysis of RC members.

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