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PRACTICAL NONLINEAR MODELING OF U-SHAPED REINFORCED CONCRETE WALLS UNDER BI-DIRECTIONAL LOADING

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Abstract

Reinforced concrete (RC) structural walls are the most commonly used structural elements in buildings to resist lateral load imposed by earthquakes. Therefore, analytical models capable of capturing important nonlinear response characteristics of RC walls at global and local response levels are essential for engineering design and evaluation, particularly for practicing performance-based methodologies. Although various analytical models for nonlinear analysis of RC walls are available in the literature, the majority of computer models have been validated for planar walls only, as experimental data on RC flanged walls are sparse. Furthermore, very limited number of nonlinear modeling approaches is implemented in commercial simulation platforms to be used in practice. Currently, Perform 3D (Computers and Structures Inc.) is the most commonly used in the US, and one of the only commercial structural analysis software for nonlinear analysis of RC structural walls. While being widely used, analytical models for walls available in this software have not been validated in details, particularly for flanged wall specimens subjected to multi-directional loading.

This paper provides detailed information about sensitivity of predicted wall responses to modeling parameters, calibration, and validation of analytical models available in Perform 3D against experimental results obtained for U-shaped wall specimen tested under bi-directional quasi-static cyclic loading regime. The U-shaped wall was tested at ETH Zurich and represented the lower two levels of a six-story building. The wall was subjected to a constant axial force and cycles of horizontal displacements. These cycles were applied along the two principal horizontal axes, along one diagonal axis and using a sweep pattern. The cycles were applied with increasing displacement amplitudes. During the test, the forces applied by the actuators and global and local deformations were recorded. The wall failed due to crushing of the compression diagonal in the web. At the point of failure, two bars of one flange had buckled but not fractured.

The behavior of the U-shaped wall was simulated using two conceptually different analytical models available in Perform 3D: shear wall element and general wall element. Material models for steel and concrete were calibrated to match as tested material properties. Lateral displacement history at the top of the wall (bi-directional loading) was applied in the analysis to simulate experimental loading conditions. Sensitivity of analytical results to model geometry discretization and material modeling parameters was investigated. In addition, detailed comparison between experimentally measured and analytically predicted wall responses is conducted at both global (force-deformation) and local (strain) levels. It has been observed that general wall element captures experimentally measured load-deformation behavior of the wall specimen more accurately than the shear wall element, as well as that predicted wall responses are less accurate in diagonal loading direction for both models. Plastic hinge length of the wall was predicted reasonably well regardless of geometry discretization, whereas magnitudes of vertical axial strains within the plastic hinge region are considerably sensitive to mesh size. Based on results of analytical studies presented, capabilities of analytical models available in Perform 3D are assessed and recommendations for practical applications are provided.

Keywords: Reinforced concrete walls; Analytical modeling; Perform 3D; Performance-based earthquake engineering;

1. Introduction

1.1 Background

Reinforced concrete (RC) structural walls are the most commonly used structural components in buildings to resist lateral load imposed by earthquakes, and analytical models capable of capturing important nonlinear response characteristics of RC walls at global and local response levels are essential for performance-based seismic structural engineering. The majority of computer models available in the literature have been validated for planar walls only since experimental data on RC core walls are sparse. In addition, very limited number of nonlinear modeling approaches is implemented in commercial software, where Perform 3D (CSI) is currently the most commonly used software in US engineering practice. Even though somewhat simplified material models are available in Perform 3D, this computational platform provides the opportunity to simulate important responses of the three-dimensional nonlinear RC wall behavior. Although widely used, analytical models for RC walls available in this software have not been validated in details, particularly for flanged wall specimens subjected to multi-directional loading.

1.2 Scope and Objectives

This paper discusses calibration and validation of analytical models for RC walls available in Perform 3D against experimental data obtained from a heavily-instrumented U-shaped wall specimen subjected to multi-directional loading. The main objective of the paper is to investigate the sensitivity and accuracy of the modeling procedures commonly employed in engineering practice for the purpose of Performance-Based Seismic Design (PBSD) and to provide comments and modeling recommendations that could improve practical methods for nonlinear modeling of RC walls. In addition to information about calibration of material models and wall geometry, sensitivity of predicted wall behavior with respect to important modeling parameters is presented. As well, analytical results are compared with experimentally measured wall responses and global (load-deformation) and local (strain) levels.

2. Experimental Studies

Four U-shaped walls built at half-scale were tested under a quasi-static cyclic loading regime. The first two walls (TUA and TUB [1]) tested the effect of wall thickness and were subjected to cycles in the two principal directions, along one diagonal and were also subjected to a sweep. The third and fourth test unit (TUC and TUD, [2]) differed with regard to the axial load ratio and were subjected to loading in the diagonal directions. The model presented in this paper is validated against TUB and in the following we give a brief description of test unit geometry and test setup. The walls represented the lower two levels of a six-story building. Three actuators were used to control the movement of the wall head (Fig. 1a,c): the EW-actuator which loaded the web and the two NS-actuators which loaded the flanges (Fig. 1c). They were connected to the "collar" at the top of the wall which had an increased wall thickness of 300 mm. The shear span ratios were 2.6 and 2.8 for loading parallel to the web and parallel to the flanges respectively. Basic characteristics of wall specimen TUB are presented in Table 1. The test unit was instrumented with linear variable displacement transducers (LVDTs), string pots and Demec points; the average strain measurements obtained from the LVDTs are used in the following to validate the model not only with regard to the global force-displacement response but also with regard to local strain demands.

The applied loading history was a bi-directional loading history (Fig. 1b, Fig. 6b) which comprised at each ductility level a cycle parallel to the web (O→A→B→O), a cycle parallel to the flanges (O→C→D→O), a cycle in diagonal direction (O→E→F→O) and a "sweep" (O→A→G→D→C→H→O). During these cycles the rotation of the wall head was restrained by the two actuators loading the flanges (actuators NS-E and NS-W). The load pattern was repeated at displacement ductility levels of μ = 1, 2, 3, 4 and 6 when failure occurred. Prior to nominal yield a slightly different load pattern was applied which only consisted of cycles in EW, NS, and diagonal direction. The axial force was maintained constant throughout the test.

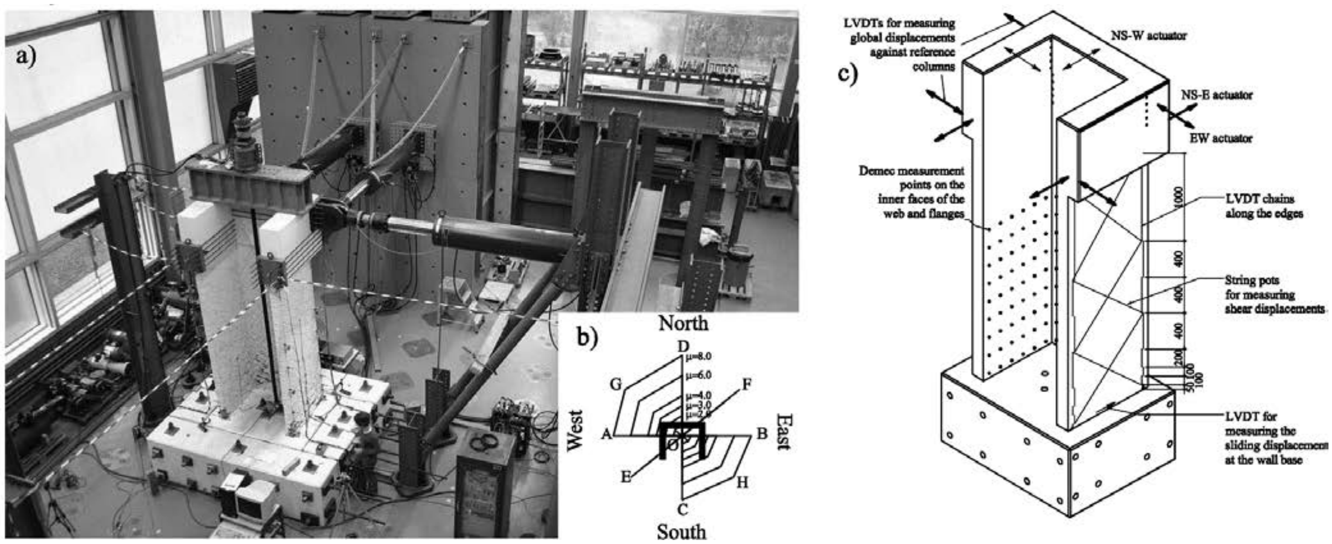
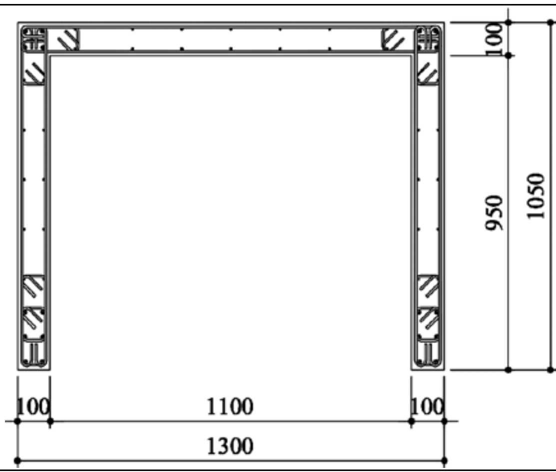


Fig. 1 Quasi-static cyclic tests on U-shaped walls at the ETH: Photo of the test setup (a), bi-directional loading history (b) and instrumentation of the test units (c) (Beyer et al., 2008)

Table 1 Characteristic values of TUB (Beyer et al., 2008)

	TUB
Scale	1:2
Shear span for loading parallel to the web *M/V*	3.35 m
Shear span for loading parallel to the flanges *M/V*	2.95 m
Axial load	780 kN
Compactness ratios: t_w/l_{web} / t_w/l_{fl}	0.08 / 0.10
Longitudinal reinforcement ratio ρ_{tot}	1.01%
Shear reinforcement ratio ρ_h	0.45%



3. Analytical Modeling

Analytical model of test specimen TUB was generated in Perform 3D [3], one of the most commonly used structural analysis platform for PBSD in the United States. Two types of wall elements available in Perform 3D are used to model the behavior of specimen TUB: 1) shear wall element (SW), and 2) general wall element (GW). Brief description of element formulations is provided in the following section, whereas detail description of model characteristics can be found in Perform 3D User Manual.

3.1 Shear Wall and General Wall Element

The behavior of four-node SW and GW elements is governed by a number of layers connected in parallel to the nodes that are capable of capturing different modes of behavior, as shown in Fig. 2. SW elements consist of two layers: a horizontal fiber section used to represent axial/bending behavior in vertical direction (Fig. 2a), and layer used to represent conventional shear behavior (Fig. 2c), whereas GW elements consist of five layers: two fiber sections for axial/bending behavior in vertical and horizontal directions (Fig. 2a,b), conventional shear behavior (Fig. 2c) and two diagonal compression layers used to represent the diagonal strut action (Fig. 2d,e). In both SW and GW elements, in-plane shear and flexural behavior are uncoupled while out-of-plane shear and bending are defined as linear-elastic. Although formulation of GW element is advantageous comparing to SW element, SW element is the most commonly used in engineering practice to simulate the behavior of structural walls due to its simplicity and reduced computational effort.

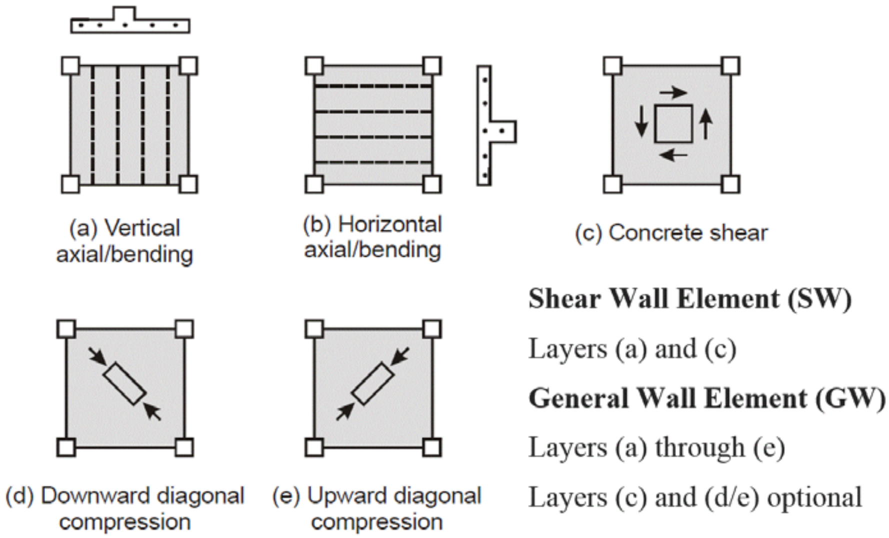


Fig. 2 – Modeling approach: Layers of SW and GW elements (Perform 3D User Manual, CSI)

3.2 Description of Analytical Model

Analytical model of TUB specimen was generated using both SW and GW elements available in Perform 3D. Following sections provide information about model geometry, material calibration and bi-direction load application.

3.2.1 Model Geometry

Structural model of specimen TUB is presented in Fig. 3 including wall cross-section (Fig. 3a) and wall isometric view for two considered discretizations (Fig. 3b, c). Wall discretization shown in Fig. 3b ("dense" discretization) consisted of seven and eight elements along the length of flanges and web, respectively, where element height was determined to match instrumentation provided along the height of the specimen, as well as to maintain aspect ratio of wall specimens within the acceptable range (i.e., < 5.0). Wall discretization shown in Fig. 3c ("sparse" discretization) consisted of four and five elements along the length of flanges and web, respectively, and four elements along the wall height, which corresponds approximately to two elements per story - a discretization commonly used in practice. Each of the wall elements, in dense and sparse discretizations, consisted of four steel and concrete fibers to represent axial/bending behavior of a wall. To simplify the modeling procedure, AUTO SIZE option is used, which distributed steel reinforcement uniformly over the element thickness; reinforcement is assigned as a percent of concrete thickness based on the actual reinforcement layout. Additional steel reinforcement in wall corners was assigned using Steel Tie/Bar/Strut elements to represent four ϕ12mm bars as shown in Fig. 3a. Fig. 3a also provides information about type of materials assigned to different elements in the wall cross-section used to represent the actual reinforcement layout and to capture effect of confinement in the flange ends of the wall. Support spring elements (Fig. 3b) are assigned at locations of actuators to enable application of a relatively complex loading pattern, as described in Section 3.2.3. Large stiffness is assigned to these elements in the directions of applied actuator forces, and zero stiffness in all other directions.

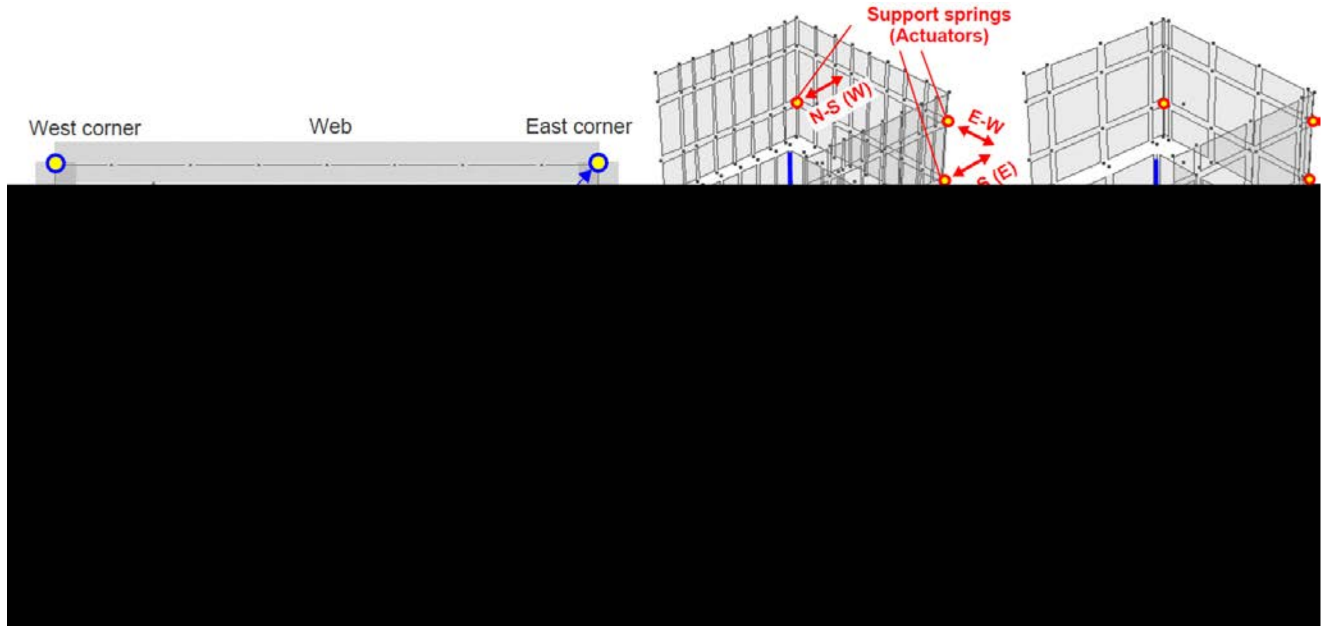


Fig. 3 – Modeling approach: a) Model cross-section, b) Dense discretization, c) Sparse discretization

3.2.2 Calibration of Material Models

Material models for steel and concrete are calibrated to match as-tested material properties. Comparison between sample experimentally obtained material strain-stress relationships and analytical models used in Perform 3D is presented in Fig. 4. For steel material (Fig. 4a), tri-linear relationship is applied to reasonably fit experimentally measured material behavior of steel coupons in tension tests. Tension capacity of concrete is modeled using strain stiffening model by Belarbi and Hsu [4]. Concrete material with zero tension capacity was also considered to investigate sensitivity of model results to this modeling parameter, as common engineering practice typically disregards concrete capacity in tension. Pre-peak of concrete compression envelope is defined based on peak stress and corresponding strain measured from test cylinders at day of testing, whereas post-peak slope was obtained from theoretical model by Saatcioglu and Razvi [5]. In addition, the effect of confinement was accounted according to model by Mander et al. [6]; the comparison of unconfined and confined concrete compression envelopes can be observed in Fig. 4b.

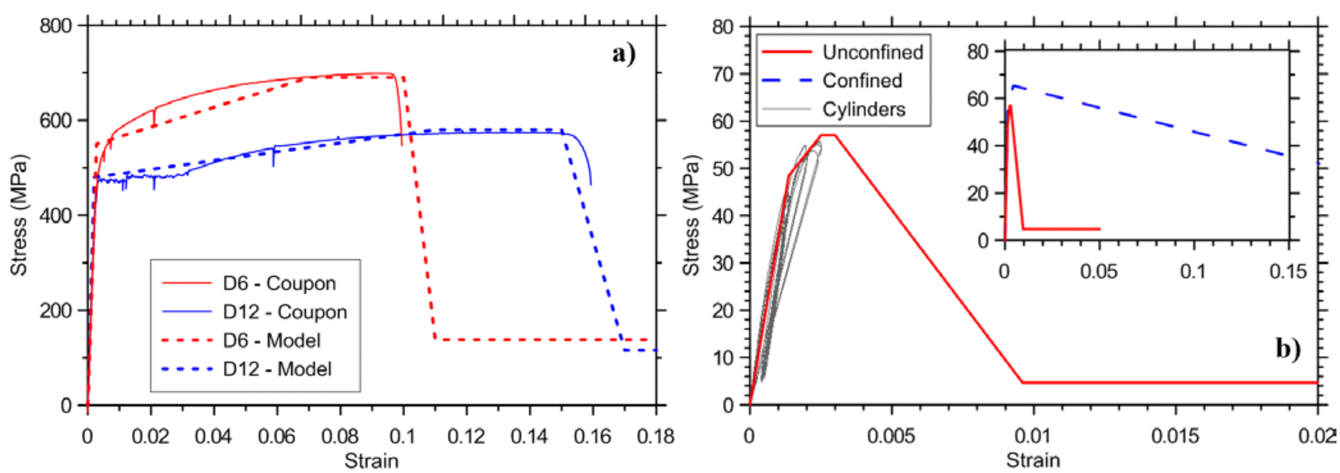


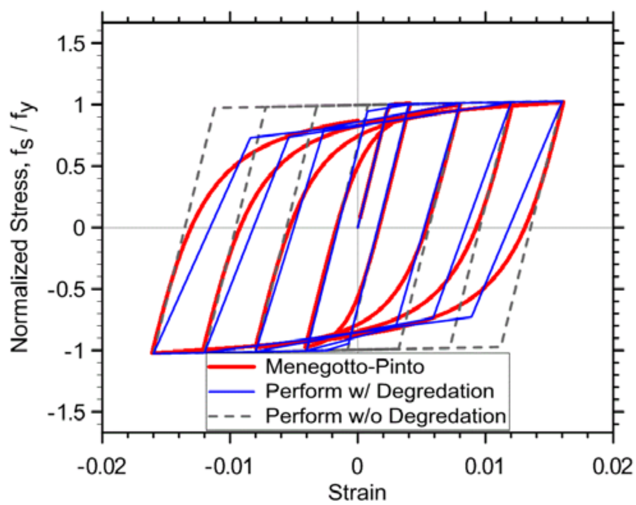
Fig. 4 – Calibrated material models for: a) Steel, b) Concrete

Perform 3D offers some flexibility in terms of controlling cyclic behavior of material models by prescribing cyclic degradation parameters. For this study, cyclic degradation is included via YX+3 option available in Perform 3D. The parameters are adopted to match reasonably well more sophisticated material models for concrete [7] and reinforcing steel [8]. Values of cyclic degradation parameters are presented in Table 2, whereas illustration of the calibration for steel material is presented in Fig. 5. It should be mentioned that common engineering practice disregards calibration of material cyclic degradation parameters. To illustrate the effect of considering material cyclic degradation, sensitivity of analytical responses to cyclic degradation parameters (i.e., with and without cyclic degradation) is presented in Section 4.3.

Table 2 Material Cyclic Degradation Parameters

Cyclic Degradation Parameters	**Unconfined Concrete**	**Confined Concrete**	**Steel D6 & D12**
Deformation			
1	0.0014	0.0019	0.01
2	0.003	0.003	0.03
3	0.004	0.004	0.03
Energy Factor			
Y	0.001	0.001	1.00
1	0.001	0.001	0.75
2	0.001	0.001	0.75
3	0.001	0.001	0.75
X	0.001	0.001	0.75

Fig. 5 Calibration of Steel Material



3.2.3 Load Application

Wall specimen TUB was subjected to a relatively complex biaxial loading pattern at the top of the wall presented in Fig. 6b. As mentioned earlier, loading pattern included cycles in E-W (A-B), N-S (C-D) and diagonal (E-F) directions, as well as complex O-A-G-D-O-C-H-B-O cycle (sweep). Peak displacements for each level of deformation corresponded to displacement ductility levels of 1.0, 2.0, 3.0, 4.0, and 6.0.

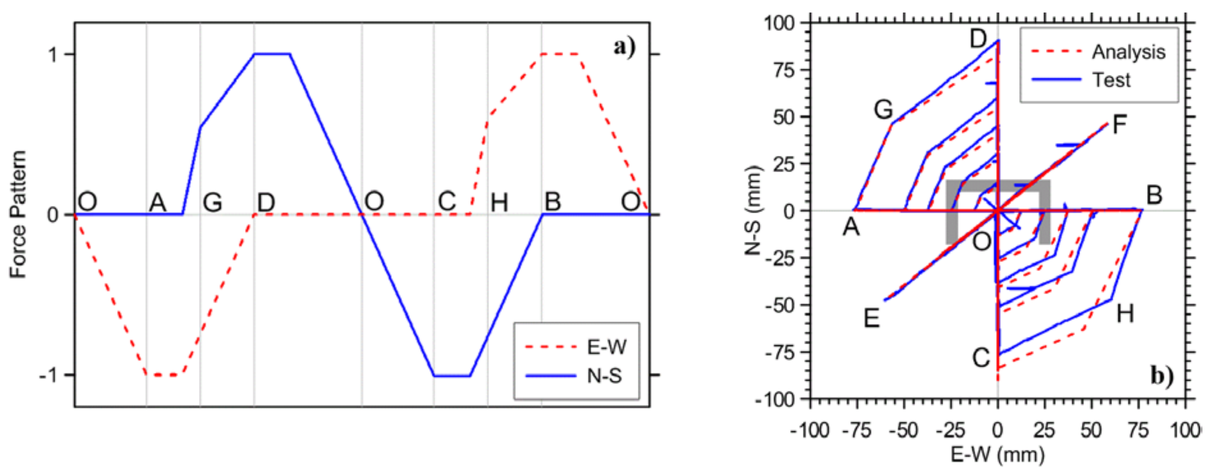


Fig. 6 – Application of loading history: a) load patterns for O-A-G-D-O-C-H-B-O cycle, b) experimental and analytical displacement history at height of 2950 mm.

Several options are available in Perform 3D to apply cyclic (quasi-static) loading to a structural component. The most commonly used approach includes application of series of pushover analyses at the top of the wall in desired direction. The loading is defined by the means of load (or displacement) pattern that is used to apply force to achieve prescribed level of deformation, i.e., the analysis is force controlled. However, in cases where the center of stiffness does not correspond with the point of load application (typically center of mass), or where the analyzed structure is torsionally irregular, this approach would cause torsional deformations and displacements out-of-direction of the applied force, which can produce undesirable results. Given that TUB specimen is characterized with U-shaped cross-section, alternative approach had to be used in this study to apply complex displacement pattern. The approach involved application of large forces at the support springs (actuators, Fig. 3b) in the direction of actual actuator forces. Loading patterns were defined for each of the actuators in E-W and N-S directions, such that their combination produces the wall top displacement measured during the experiment; E-W and N-S loading patterns applied for the "sweep" cycles are presented in Fig. 6a. Therefore, analysis performed in this study was a dynamic (time-history) analysis, instead of displacement-controlled (static), via application of appropriate scaling factors to the prescribed force patterns. Fig. 6b compares experimental and analytical displacement history at wall height of 2950 mm.

4. Sensitivity of Model Results to Modeling Parameters

This section presents the sensitivity of predicted wall responses to model discretization and material cyclic degradation. The sensitivity is investigated at global (load-deformation) and local (vertical strains) response levels. Load-deformation responses are presented for cycles in N-S and E-W direction only; observations are similar for diagonal cycles.

4.1 Model Discretization

Sensitivity of analytical predicted wall behavior to model discretization is investigated by considering models with "dense" discretization (Fig. 3b) and "sparse" discretization (Fig. 3c) described in Section 3.2.1. Fig. 7 plots load-deformation response of the wall for the two considered cases. It can be observed that load-deformation response is modestly sensitive to model geometry discretization. For the E-W cycles (Fig. 7a), where wall load-deformation is symmetric, wall capacity predicted using model with dense discretization is approximately 10% large than model with sparse discretization at all levels of lateral displacements for both loading directions. For the N-S cycles (Fig. 7b), where wall behavior is not symmetric, almost identical capacity is predicted for loading direction in which web is in compression, whereas wall capacity is approximately 15% larger for loading direction that imposes tension on the wall web. Model with sparse discretization predicts smaller wall neutral axis depth than in the case of dense discretization, where more elements along the flanges allow nonlinear strain distributions to be captured more appropriately, resulting in lower wall capacity. It should be mentioned that material models should be properly regularized [9] to avoid effects of mesh size to predicted wall responses. However, since material regularization is not common engineering practice, this procedure is disregarded here to illustrate mesh size effect in practical applications.

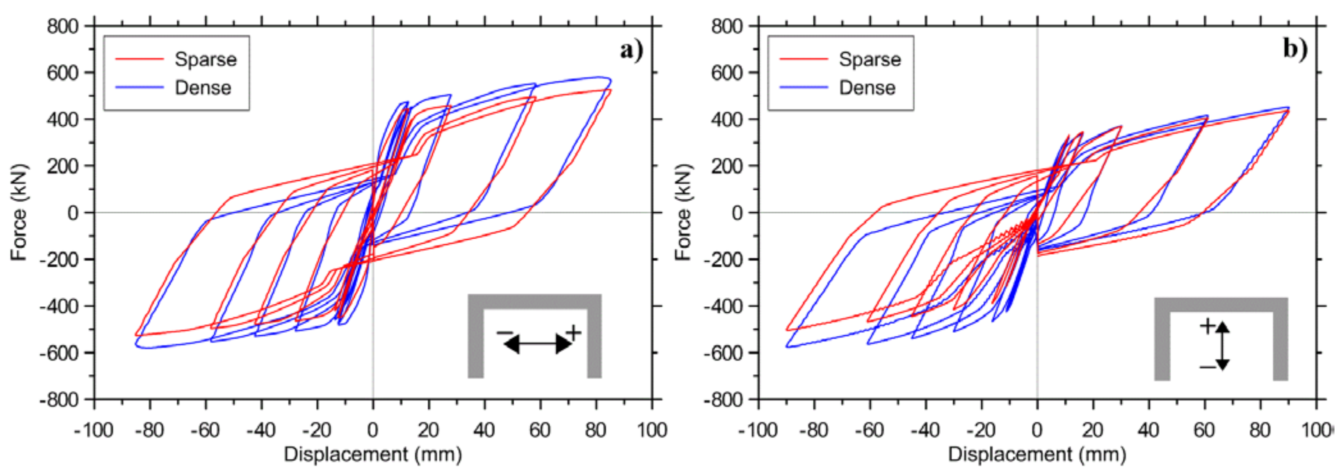


Fig. 7 – Sensitivity of SW element to wall discretization: a) E-W direction, b) N-S direction

Furthermore, Fig. 8 compares histories of vertical strains for two considered wall discretizations obtained for bottom elements at west flange end (Fig. 8a) and east wall corner (Fig. 8b) for loading cycles corresponding to displacement ductility of μ = 3, 4, and 6; strains shown in the figure represent average strains over the element heights of 250 mm for dense discretization and 900 mm for sparse discretization. Although comparing strain predictions obtained from two elements of significantly different sizes might not represent one-to-one comparison (strains are not averaged over the same length), it is important to observe that strains predicted using dense wall discretization are approximately three times larger at the wall base than strains obtained with the sparse discretization, which is representative of the model discretization used in engineering practice. When PBSD is applied, the strain profiles obtained from relatively large elements (e.g., two elements per story height) are typically compared with prescribed strain limits. It can be further observed from Fig. 8 that tensile strains predicted by SW element (regardless of discretization) are typically by approximately 50% larger than tensile strains obtained using GW elements, as well as that sensitivity of compressive strains to model formulation is also considerable. Comparison between experimentally measured and analytically predicted strain profiles is presented in Section 5.2.

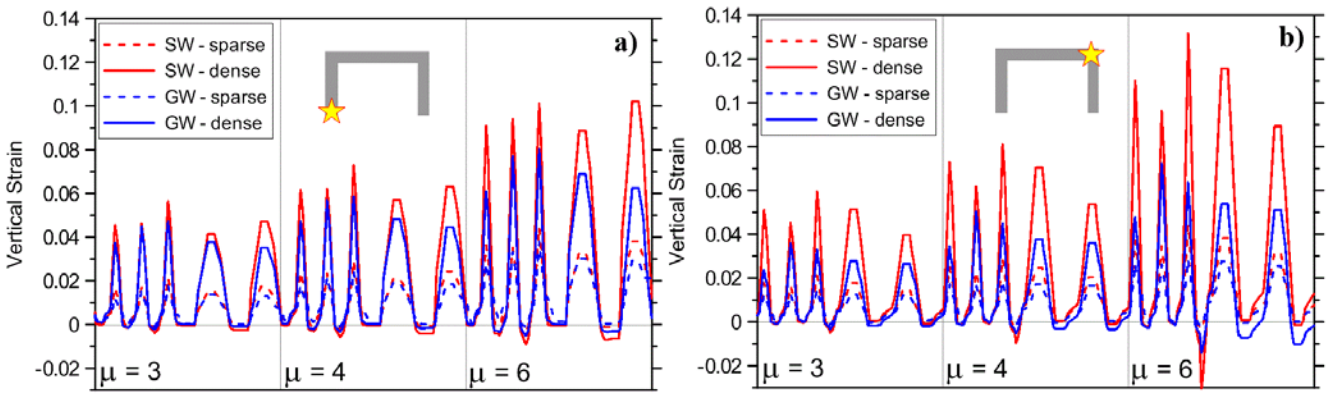


Fig. 8 – Sensitivity of vertical strains: a) S-W corner, b) N-E corner

4.3 Material Modeling Parameters

Although Perform 3D software offers opportunity to account for cyclic degradation of uniaxial materials used in structural models, these modeling parameters are rarely implemented in engineering practice. In this study, cyclic degradation is considered for steel and concrete uniaxial materials as described in Section 3.2.2. Fig. 9 compares predicted load-deformation responses for models with (calibrated) and without (default values) implemented material cyclic degradation. As shown in the figure, although overall wall capacity is not sensitive to modeling material cyclic degradation, wall unloading and re-loading stiffness is considerably sensitive to material cyclic degradation, which could have an impact on predicted force distributions within the structural system in nonlinear time-history analysis results and energy dissipation. In addition, Fig. 9 also reveals that disregarding tension capacity of concrete has minor effect on the overall response.

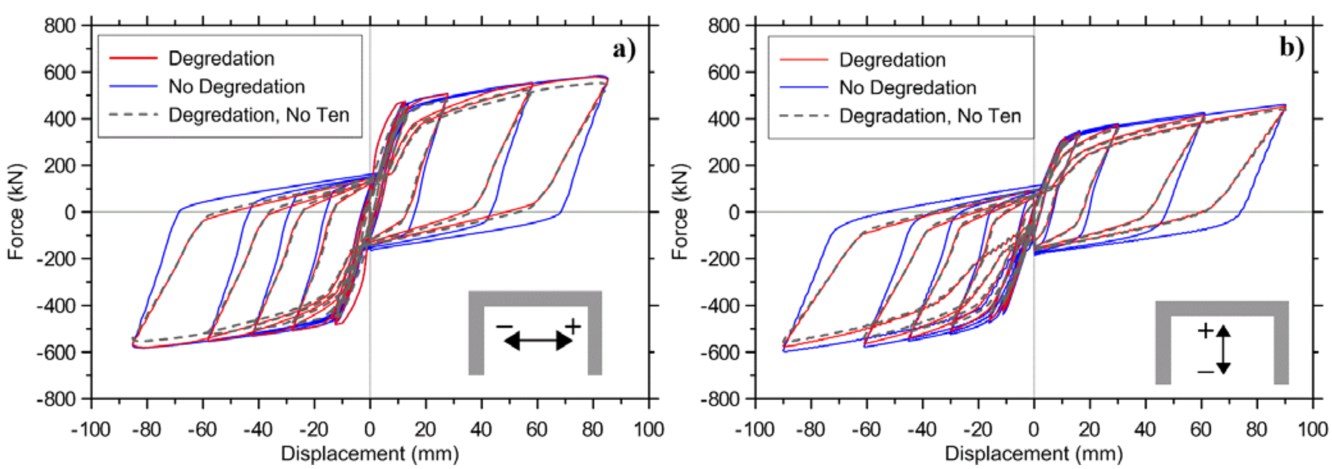


Fig. 9 – Sensitivity of analytical results to material cyclic degradation: a) E-W direction, b) N-S direction

5. Experimental Validation of Perform 3D Models

This section provides information about validation of wall models available in Perform 3D against experimentally measured global (force-deformation) and local (vertical strains) responses. Responses are presented for both SW and GW wall elements.

5.1 Load-Deformation Responses

Lateral load versus wall top displacement responses are compared in Fig. 10a-d for each loading direction individually, Fig. 10e compares total (SRSS) moment at the base of the wall, while Fig. 10f plots analytically predicted distribution of shear forces within east and west flanges for the GW element.

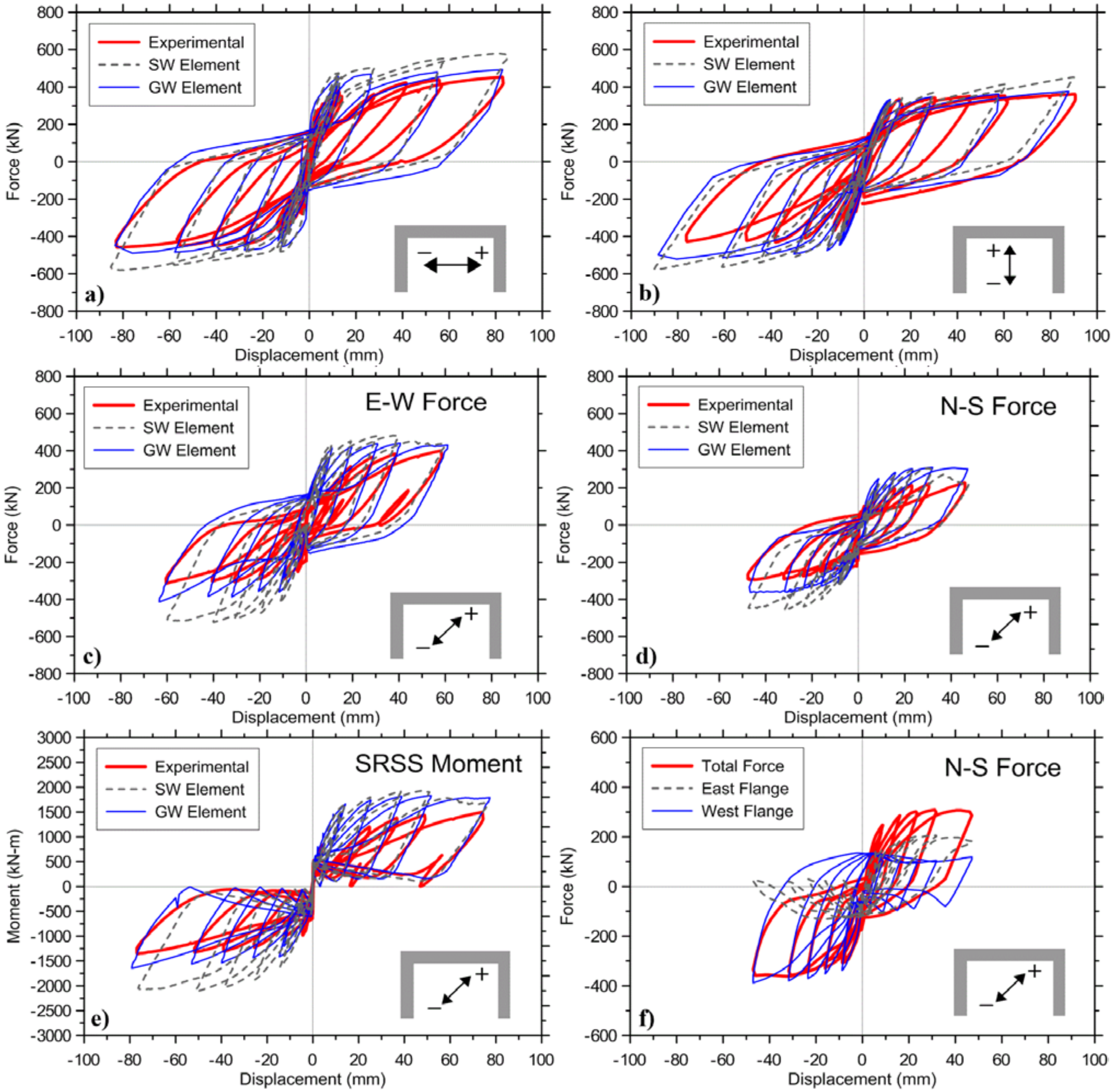


Fig. 10 – Load-deformation responses: a) E-W Dir., b) N-S Dir., c) Diagonal Dir.: E-W Component, d) Diagonal Dir.: N-S Component, e) Diagonal Dir.: SRSS Moment, f) Diagonal Dir.: Flange Forces

It can be observed from Fig. 10a that for cycles in the E-W direction, both model formulations (SW and GW) capture reasonably well the experimentally measured load-deformation responses in terms of wall strength, stiffness and stiffness degradation. GW element captures closely shear wall capacity, whereas SW elements overestimate wall lateral strength by approximately 15% at lower level of lateral displacement (μ = 1.0-2.0) and about 20% at larger displacement ductility demands (μ = 4.0-6.0). For the cycles in N-S direction (Fig. 10b), the discrepancy between the two modeling approaches is smaller. Both SW and GW model predict well lateral load capacity for loading direction that imposes tension on the wall web, while when the load is reversed and the web is subjected to compression wall capacity is overestimated approximately 40% using both modeling approaches. Furthermore, Fig. 10c and Fig. 10d plot forces in N-S and E-W directions, respectively, for diagonal loading cycles. Both models generally overestimate the lateral load capacity of the wall by approximately 20% for positive loading direction (compression on N-E corner), while when the load is reversed and the majority of wall web is in tension, SW overestimated wall lateral capacity by approximately 50% and GW by approximately 20%. Predictions of total moment (SRSS) at the wall base are characterized with similar behavior as illustrated in Fig. 10e. One possible reason for the discrepancy between analytical and experimental results is related to the inability of the models to capture accurately nonlinear strain distributions along the wall flange/web (shear-lag effect) under complex displacement history (that could be caused by earthquake). In addition, models do not incorporate interaction between shear and flexural behavior, which could have significant impact for diagonal loading direction. Finally, Fig. 10f shows analytically obtained shear force distribution within each of the wall flanges for the cycles in diagonal direction, illustrating that shear force is not resisted equally by both flanges.

5.2 Vertical Strain Profiles

To investigate the capability of the wall models available in Perform 3D to capture local responses, analytically obtained vertical strains over the height of the wall for the two considered geometry discretizations (dense and sparse) are compared with experimentally measured strain profiles. Fig. 11 and Fig. 12 show strain comparisons for SW and GW elements, respectively, at positions A (E-W cycles), C and D (N-S) cycles corresponding to displacement ductility of μ = 3.0 (intermediate cycles) and μ = 6.0 (at failure).

Based on comparisons of results presented in Fig. 11 and Fig. 12, it can be observed that strain profiles predicted using both model formulations (SW and GW) and both discretizations (dense and sparse) suggest that analytical models are capable of capturing height of the wall over which strain concentration occurs (plastic hinge length) reasonable well; both experimental and analytical results suggest that plastic hinge length of approximately 900 mm. It can be further observed that models with sparse wall discretization generally predicts reasonably well average tensile strains over the plastic hinge region, although with considerable dispersion at some locations, whereas models with dense discretization typically overestimate significantly wall tensile strains at the wall base. In addition, compressive strains are generally underestimated at the base of the wall by significant amount, which is consistent with observations from prior studies [10] regarding fiber-based (P/M and V uncoupled) wall models.

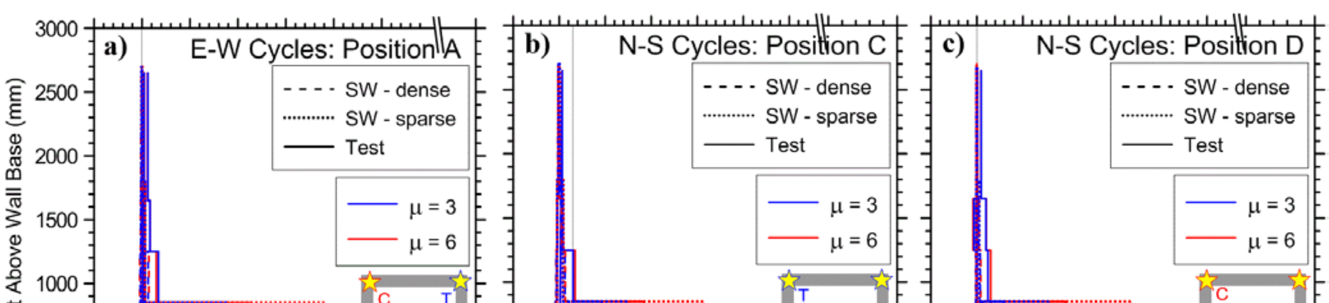


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Fig. 11 – Experimental and Analytical (SW) Strain Profiles: a) E-W Dir. (A), b) N-S Dir. (C), c) E-W Dir. (D)

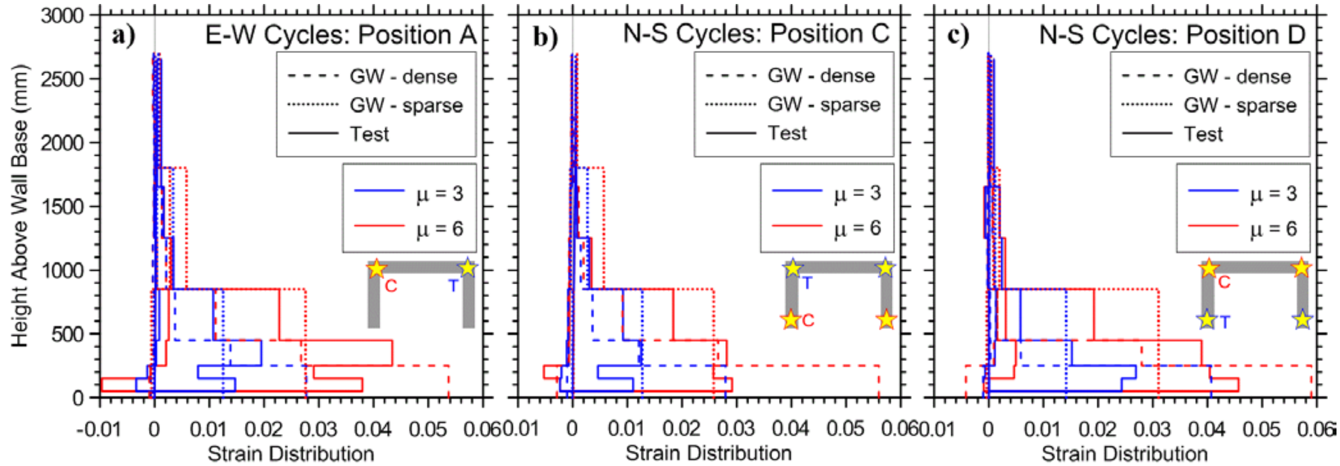

Fig. 12 – Experimental and Analytical (GW) Strain Profiles: a) E-W Dir. (A), b) N-S Dir. (C), c) E-W Dir. (D)

6. Summary and Conclusions

Nonlinear modeling of reinforced concrete structural walls has become a common practice in the past 15 years with the implementation of Performance-Based Design methodologies for seismic design and evaluation, where computational platform Perform 3D is the most commonly used software in the U.S. for this purpose. Although widely used, wall models available in Perform 3D are validated against relatively small number of experimental results, particularly for flanged (e.g., U-shaped) test specimens that are subjected to multi-directional loading. This paper provides information about calibration, sensitivity and validation of analytical models for simulation of structural wall elements available software Perform 3D Experimental results obtained from test on well-instrumented U-shaped wall specimen tested under constant axial load and multi-direction lateral loading regime. Particular emphasize is given to investigation of modeling procedures commonly employed in engineering practice for the purpose of Performance-Based Seismic Design and to providing comments and modeling recommendations that could improve practical methods for nonlinear modeling of RC walls.

Analytical model of a considered wall specimen was created using shear wall (vertical axial/bending and shear behavior) and general wall (vertical and horizontal axial/bending, shear behavior and diagonal strut action) elements available in Perform 3D. Sensitivity of material model to geometry discretization was examined by considering relatively detailed and sparse discretization of wall geometry. Material models were calibrated to match as-tested material properties. Material parameters related to cyclic degradation and concrete tension capacity were varied to investigate sensitivity of the model results to these modeling parameters. Sensitivity studies revealed modest sensitivity of predicted analytical results to mesh size. Predictions of wall lateral capacity using denser element mesh are approximately 10% larger than when sparse model discretization is used; note that comparison between the two model discretizations was conducted without performing material regularization, as this procedure is not commonly done in practice. In addition, model sensitivity with respect to material cyclic degradation showed that wall capacity is not affected by changes in these modeling parameters, while unloading/reloading stiffness and shape of the hysteretic loops are modestly affected. Recommendations for cyclic degradation parameters for concrete and steel are presented in the paper. Finally, modeling of concrete tension capacity had minor effect on predicted force-deformation response.

Comparison of experimental and analytical wall responses revealed that both shear wall and general wall elements capture global load-deformation responses of the wall reasonably well, where general wall element typically yields more accurate predictions of wall lateral stiffness and capacity. In the loading directions parallel to the wall web (E-W), predicted wall load-deformation response is in good agreement with experimental results. For loading directions parallel to the wall flanges (N-S), lateral load is generally better predicted by loading direction that imposes compression on wall web, whereas in the opposite loading direction, in which web is in tension, wall capacity is overestimated by approximately 20-40%. Analytical predictions of wall capacity for diagonal cycles generally overestimate wall lateral strength by 50% for the shear wall element and 20% for the general wall element. Furthermore, analytical models considered capture reasonable well concentration of vertical tensile strains over the bottom 900 mm of the wall (i.e., plastic hinge length). Vertical tensile strain predictions obtained using sparse wall discretizations showed to be in reasonable agreement with average strains measured during the experiment, whereas use of dense wall discretization typically overestimated tensile strains at the bottom wall element. Compression strains are underestimated by the analytical models regardless of wall discretization and modeling approach.

Overall, analytical models for nonlinear modeling of reinforced concrete structural walls available in Perform 3D software capture wall global and local behavior reasonably well. General wall element showed to be capable of predicting more accurately load-deformation responses of the wall specimen than shear wall element. However, given its more cumbersome formulation, general wall element is less popular among practicing engineers, which creates a bias in predictions of shear force demands under seismic actions. In addition, material calibration should include cyclic degradation of material models, as default material properties not necessarily represent well actual material hysteretic responses. Finally, prediction of average vertical strains over the plastic hinge region are generally in good agreement with experimental results (in average sense), while using relatively small elements could lead to strain localization if material regularization is not performed properly. Future studies will focus on evaluation of wall models against detail experimental results from test programs mentioned in Section 2 (or others), investigation of sensitivity of predicted wall responses to choice of modeling parameters used to simulate shear behavior, as well as model evaluation against experimental results obtained from dynamic tests on structural wall systems.

7. Acknowledgements

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