Experimental, numerical, and analytical studies on the seismic response of steel-plate concrete composite shear walls and squat RC shear walls

Siamak Epackachi, PhD
Assistant Professor
Amirkabir University of Technology - Tehran Polytechnic

Iranian Society of Steel Structures—October 22, 2017
OUTLINES

1. INTRODUCTION
2. SC WALL APPLICATIONS
3. PRELIMINARY DESIGN AND ANALYSIS OF SC WALLS
4. EXPERIMENTAL PROGRAM
5. EXPERIMENTAL RESULTS
6. NUMERICAL ANALYSIS OF SC WALLS
7. NUMERICAL ANALYSIS RESULTS
8. A PARAMETRIC STUDY: DESIGN OF SC WALLS
9. ANALYTICAL MODELING OF RECTANGULAR SC WALL PANELS
10. MODELING SQUAT REINFORCED CONCRETE SHEAR WALLS FOR SEISMIC ANALYSIS
11. CONCLUSIONS AND FUTURE RESEARCH
1. INTRODUCTION

Different types of SC walls

1 – SC modular box units proposed by Fukumoto et al.
2 - SC shear wall composed of two corrugated steel faceplates and infill concrete proposed by Wright et al.
3 - SC faceplates with infill reinforced concrete proposed by Astaneh-Asl et al.
4 - Bi-Steel construction proposed by British Steel (later Corus)
Focus of the research is flexure- and flexure-shear critical SC wall piers. Only loading in the plane of the wall is considered.

The SC wall piers studied in this research consist of:

- Two steel faceplates
- Infill concrete
- Headed steel studs anchoring the faceplates to the infill
- Tie rods connecting the two faceplates through the infill
Advantages of SC construction

- General construction
  - Elimination of formwork
  - Enables large-scale modularization
  - Penetrations easily accommodated
  - Superior strength and ductility
  - Improved quality of placed concrete (SCC)
  - Increased construction speed and economy

- Nuclear construction
  - Increased shielding capability
  - Superior missile/blast resistance
2. SC WALL APPLICATIONS

SC walls used in multi-story buildings
Forty Spring Garden Manchester's Financial District, Corus (2006)
Dundrum Cinema Lift Core, Corus (2004)
AP1000, Sanmen, China
AP1000, Sanmen, China
3. PRELIMINARY DESIGN AND ANALYSIS OF SC WALLS

Preliminary design of test specimens

- Design of specimens based on a draft version of AISC N690s1

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Wall dimension ((H \times L \times T)) (in. × in. × in.)</th>
<th>Stud spacing (in.)</th>
<th>Tie rod spacing (in.)</th>
<th>Reinforcement ratio (%)</th>
<th>Faceplate slenderness ratio</th>
<th>Day-of-test wall concrete strength (ksi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SC1</td>
<td>60×60×12</td>
<td>4</td>
<td>12</td>
<td>3.1</td>
<td>21</td>
<td>4.5</td>
</tr>
<tr>
<td>SC2</td>
<td>60×60×12</td>
<td>-</td>
<td>6</td>
<td>3.1</td>
<td>32</td>
<td>4.5</td>
</tr>
<tr>
<td>SC3</td>
<td>60×60×9</td>
<td>4.5</td>
<td>9</td>
<td>4.2</td>
<td>24</td>
<td>5.3</td>
</tr>
<tr>
<td>SC4</td>
<td>60×60×9</td>
<td>-</td>
<td>4.5</td>
<td>4.2</td>
<td>24</td>
<td>5.3</td>
</tr>
</tbody>
</table>

- Two 3/16-in. thick steel faceplates were used for all four SC walls.
- The diameter of the studs and tie rods was 0.375 in. for all walls.
- Reinforcement ratio: \(2t_s / T\)
- Slenderness ratio: \(S / t_s\)
XTRACT Analysis of SC walls

- The shear strengths of SC1 and SC3 corresponding to these flexural strengths were 344 kips and 328 kips, respectively.
- The maximum shear resistance of the walls per the draft Appendix N9 to AISC N690s1, Ozaki et al., and Varma et al. is 870/855/815 kips for SC1/SC2 and 840/855/780 kips for SC3/SC4. The SC walls were identified to be flexure-critical since the shear strength associated to the flexural strength of the walls was less than their maximum shear resistance.
ABAQUS Analysis of SC walls

- Infill concrete
- SC wall model
- Loading plate and post-tensioning bars
- Steel faceplate
- Baseplate, threaded bars, studs, and tie rods
ABAQUS Analysis of SC walls

Drift ratio [%]

Shearing force [kips]

Lateral displacement [in.]

XTRACT-predicted shearing strength for SC1/SC2=344 kips

XTRACT-predicted shearing strength for SC3/SC4=328 kips
4. EXPERIMENTAL PROGRAM

Construction of the steel shells

Foundation construction

Constructed SC walls
Material testing

- **Studs and tie rods:**
  - The 3/8-in. and 5/8-in. diameter Nelson studs and tie rods were fabricated from carbon steel.
  - Nominal yield and ultimate stresses were 50 and 75 ksi, respectively.

- **Steel faceplates:**
  - Three coupons were tested per ASTM A370.

- **Infill concrete and foundation:**
  - Concrete cylinder were tested per ASTM C39-02 at 7, 14, 21, 28 days after concrete casting and on the days of the SC wall tests.

This image shows a stress-strain relationship graph with the following labels:

- Test#1
- Test#2
- Test#3

The stress values for SC1/SC2 are:
- $f'_c = 4.4$ ksi

The stress values for SC3/SC4 are:
- $f'_c = 5.3$ ksi
# Test setup and loading protocol

<table>
<thead>
<tr>
<th>Load step</th>
<th>Peak displacement (in.)</th>
<th>Drift ratio (%)</th>
<th>Number of cycles</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>LS1</td>
<td>±0.014</td>
<td>0.02</td>
<td>2</td>
<td>0.18(\delta_y)</td>
</tr>
<tr>
<td>LS2</td>
<td>±0.070</td>
<td>0.12</td>
<td>2</td>
<td>0.5(\delta_y)</td>
</tr>
<tr>
<td>LS3</td>
<td>±0.105</td>
<td>0.18</td>
<td>2</td>
<td>0.75(\delta_y)</td>
</tr>
<tr>
<td>LS4</td>
<td>±0.142</td>
<td>0.23</td>
<td>2</td>
<td>(\delta_y)</td>
</tr>
<tr>
<td>LS5</td>
<td>±0.283</td>
<td>0.47</td>
<td>2</td>
<td>2(\delta_y)</td>
</tr>
<tr>
<td>LS6</td>
<td>±0.425</td>
<td>0.70</td>
<td>2</td>
<td>3(\delta_y)</td>
</tr>
<tr>
<td>LS7</td>
<td>±0.567</td>
<td>0.93</td>
<td>2</td>
<td>4(\delta_y)</td>
</tr>
<tr>
<td>LS8</td>
<td>±0.709</td>
<td>1.17</td>
<td>2</td>
<td>5(\delta_y)</td>
</tr>
<tr>
<td>LS9</td>
<td>±0.850</td>
<td>1.40</td>
<td>2</td>
<td>6(\delta_y)</td>
</tr>
<tr>
<td>LS10</td>
<td>±0.992</td>
<td>1.63</td>
<td>2</td>
<td>7(\delta_y)</td>
</tr>
<tr>
<td>LS11</td>
<td>±1.134</td>
<td>1.87</td>
<td>2</td>
<td>8(\delta_y)</td>
</tr>
<tr>
<td>LS12</td>
<td>±1.276</td>
<td>2.10</td>
<td>2</td>
<td>9(\delta_y)</td>
</tr>
<tr>
<td>LS13</td>
<td>±1.417</td>
<td>2.33</td>
<td>2</td>
<td>10(\delta_y)</td>
</tr>
<tr>
<td>LS14</td>
<td>±1.701</td>
<td>2.80</td>
<td>2</td>
<td>11(\delta_y)</td>
</tr>
<tr>
<td>LS15</td>
<td>±1.984</td>
<td>3.27</td>
<td>2</td>
<td>12(\delta_y)</td>
</tr>
</tbody>
</table>

**Loading protocol**
Instrumentation of test specimens

LVDTs, Temposonic Displacement Transducers, and String Potentiometers

Potentiometers and Temposonics were attached to the ends of the walls to measure in-plane displacement. Potentiometers measured also the out-of-plane displacements of the walls. The movement of the foundation block relative to the strong floor was monitored using potentiometers.

Layout of the string potentiometers (SP), Temposonic displacement transducers (TP), and linear variable displacement transducers (LPH and LPV)
## 5. EXPERIMENTAL RESULTS

### Test results

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Initial stiffness (kips/in.)</th>
<th>Onset of steel plate buckling</th>
<th>Onset of steel plate yielding</th>
<th>Peak load</th>
<th>Test termination at 3.3% drift ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>SC1</td>
<td>1680</td>
<td>245 (kip) 0.48</td>
<td>240 (kip) 0.48</td>
<td>317/320</td>
<td>1.18/1.18</td>
</tr>
<tr>
<td>SC2</td>
<td>1420</td>
<td>200 (kip) 0.48</td>
<td>200 (kip) 0.48</td>
<td>314/319</td>
<td>1.18/1.18</td>
</tr>
<tr>
<td>SC3</td>
<td>1380</td>
<td>240 (kip) 0.70</td>
<td>185 (kip) 0.48</td>
<td>265/275</td>
<td>1.40/1.18</td>
</tr>
<tr>
<td>SC4</td>
<td>1310</td>
<td>240 (kip) 0.70</td>
<td>200 (kip) 0.48</td>
<td>270/275</td>
<td>1.18/1.18</td>
</tr>
</tbody>
</table>
Damage to SC walls

Concrete crushing

Buckling of the steel faceplates

Tearing of the steel faceplate

Concrete crushing

Tearing of the steel faceplate

Buckling of the steel faceplates

Concrete crushing

Concrete crushing
A: Concrete cracking
B: Yielding of the steel faceplates
C: Buckling of the steel faceplates
D: Concrete crushing

E: Fracture of the steel faceplates at their connection to the headed studs
F: Tearing of the steel faceplate above the welded connection of the faceplates to the baseplate
G: Fracture of tie rod
The energy dissipated in each cycle was calculated as the area enclosed by the hysteresis loop in that cycle.

The equivalent viscous damping in the SC walls was calculated using:

\[ \xi_{eq} = \frac{1}{4\pi} \frac{E_D}{E_s} \]
Normal and shear strains in each square panel were calculated using:

- In-plane displacements measured by Krypton LEDs
- An isoparametric quadrilateral formulation.

The values of the plane stress components were calculated using:

- The calculated strain field in the steel faceplates
- The elastic properties of the steel faceplates.

### Strain and stress fields in steel faceplates

#### Von-Mises stress

- 0.12% drift ratio
- 0.47% drift ratio
- 1.17% drift ratio

#### Stress fields

- 0.47% Drift ratio
- 1.17% Drift ratio
- 1.87% Drift ratio
Components of the lateral displacement at top of the wall

Definition of the horizontal strips for the shear displacement calculation

SC1 SC2

SC3 SC4

Displacement components

SC1

SC2

SC3

SC4
6. NUMERICAL ANALYSIS OF SC WALLS
LS-DYNA model

Springs connecting two baseplates
Studs attached to the base plate
Studs attached to the faceplates
Steel faceplates

Tie rods connecting two faceplates

Base plate
Infill concrete
Plate embedded in the foundation block
The smeared crack Winfrith model (MAT085) in LS-DYNA, developed by Broadhouse, was used to model the infill concrete. The Broadhouse model
• provides information on the orientation of the cracking planes (up to three orthogonal cracks for each element) and the width of the cracks.
• assumes elastic-perfectly plastic behavior in compression and its yield surface is based on the four-parameter plastic surface of Ottosen model.
• considers shear stress across the crack due to the aggregate interlock.
• smears the rebar.
• The Winfrith model can incorporate strain-rate effects.

Concrete material model

Crack Analysis in the Winfrith Model

The cracking formulation used in the Winfrith model is based on Wittmann et al.

<table>
<thead>
<tr>
<th>Model</th>
<th>Mass density (\frac{\text{lbf} \cdot \text{sec}^2}{\text{in}^4})</th>
<th>Young’s modulus (ksi)</th>
<th>Poisson’s ratio</th>
<th>Uniaxial compressive strength (ksi)</th>
<th>Uniaxial tensile strength (ksi)</th>
<th>Crack width (in.)</th>
<th>Agg. Size (in.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SC1/SC2</td>
<td>(2.25 \times 10^{-4})</td>
<td>3000</td>
<td>0.18</td>
<td>4.40</td>
<td>0.35</td>
<td>0.0025</td>
<td>0.75</td>
</tr>
<tr>
<td>SC3/SC4</td>
<td>(2.25 \times 10^{-4})</td>
<td>3300</td>
<td>0.18</td>
<td>5.30</td>
<td>0.40</td>
<td>0.0025</td>
<td>0.75</td>
</tr>
</tbody>
</table>
A plastic-damage model, Mat-Plasticity-With-Damage (MAT081) with isotropic hardening, was used to simulate the nonlinear behavior of the steel faceplates and the connectors.

- The average stress-strain relationship, derived from coupon tests, was used to model the steel faceplates.

### Steel material properties input to the DYNA model

<table>
<thead>
<tr>
<th>Material</th>
<th>Mass density $\frac{\text{lbf.sec}^2}{\text{in}^4}$</th>
<th>Young’s modulus (ksi)</th>
<th>Poisson’s ratio</th>
<th>Yield strength (ksi)</th>
<th>Ultimate strength (ksi)</th>
<th>Failure strain (%)</th>
<th>Fracture strain (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Faceplate</td>
<td>$7.34 \times 10^{-4}$</td>
<td>29000</td>
<td>0.30</td>
<td>38</td>
<td>55</td>
<td>30</td>
<td>40</td>
</tr>
<tr>
<td>Connectors</td>
<td>$7.34 \times 10^{-4}$</td>
<td>29000</td>
<td>0.30</td>
<td>50</td>
<td>75</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
Contact and constraint modeling

- Contact-Automatic-Surface-To-Surface formulation was used to model friction between:
  - the infill concrete and the steel faceplates,
  - the infill concrete and the baseplate, and
  - the baseplate and the steel plate embedded in the foundation block
- The coefficient of friction for steel on concrete = 0.5
  - Rabbat et al. showed that the coefficient of friction between a steel plate and cast-in-place concrete varied between 0.57 and 0.7.
- The steel faceplates were tied to the baseplate using the kinematic constraint Contact-Tied-Shell-Edge-To-Surface.
- The studs and tie rods were coupled to the infill concrete elements using the Constrained-Lagrange-In-Solid formulation.
7. LS-DYNA ANALYSIS RESULTS

Load-displacement cyclic response

![Graphs of load-displacement cyclic response for SC1 to SC4]
Hysteretic damping

SC1 and SC2
- Equivalent viscous damping ratio [%]
- Drift ratio [%]
- Pre-peak strength
- Post-peak strength

SC3 and SC4
- Equivalent viscous damping ratio [%]
- Drift ratio [%]
- Pre-peak strength
- Post-peak strength

Test vs. DYNA
Steel faceplate contribution to the total load

- SC1: Yielding of the steel faceplates, DYNA-total, DYNA-faceplate, Rosette-faceplate, Krypton-faceplate
- SC2: Same as SC1
- SC3: Same as SC1
- SC4: Same as SC1
Steel faceplate contribution to the total load

- 0.23% drift ratio
- 0.47% drift ratio
- 0.70% drift ratio
Damage to SC walls

Steel faceplate buckling
Cracking and crushing of infill concrete
Steel faceplate fracture

Damage to specimen; test (left panel) and analysis (right panel)

Concrete cracking and crushing

Damage to infill concrete; test (left panel) and analysis (right panel)
8. A PARAMETRIC STUDY: DESIGN OF SC WALLS

DYNA modeling of SC walls and design variables

- Six design parameters were considered:

<table>
<thead>
<tr>
<th>Variable</th>
<th>Low</th>
<th>Intermediate</th>
<th>High</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aspect ratio</td>
<td>0.5 (-1)</td>
<td>1.25 (0)</td>
<td>2.0 (+1)</td>
</tr>
<tr>
<td>Reinforcement ratio (%)</td>
<td>1.67 (-1)</td>
<td>3.33 (0)</td>
<td>5.0 (+1)</td>
</tr>
<tr>
<td>Slenderness ratio</td>
<td>10 (-1)</td>
<td>25 (0)</td>
<td>40 (+1)</td>
</tr>
<tr>
<td>Axial load ratio</td>
<td>0 (-1)</td>
<td>0.1 (0)</td>
<td>0.2 (+1)</td>
</tr>
<tr>
<td>Yield strength of the steel faceplates (MPa)</td>
<td>235 (-1)</td>
<td>350 (0)</td>
<td>460 (+1)</td>
</tr>
<tr>
<td>Concrete compressive strength (MPa)</td>
<td>27.6 (-1)</td>
<td>41.4 (0)</td>
<td>55.2 (+1)</td>
</tr>
</tbody>
</table>
8. A PARAMETRIC STUDY: DESIGN OF SC WALLS

DYNA modeling of SC walls and design variables

Low-aspect ratio wall
Intermediate-aspect ratio wall
High-aspect ratio wall

Steel faceplates
Infill concrete
Connectors attached to the faceplates
Analysis results

10-in. thick wall with normal-strength concrete

20-in. thick wall with normal-strength concrete

30-in. thick wall with normal-strength concrete

10-in. thick wall with intermediate-strength concrete

20-in. thick wall with intermediate-strength concrete

30-in. thick wall with intermediate-strength concrete
Design of Experiments (DOE)
Mechanics-based Equations for Predicting Peak Flexural Strength

\[ \varepsilon_c = \varepsilon_y (1 - \lambda_1) + \lambda_4 \varepsilon_{cu} \]

(a) \[ L \]

(b) \[ \frac{1}{\lambda_3 \kappa} \]

(c) \[ f_t^* \]

(d) \[ f_t^* \]

[Diagram showing the equations and variables related to flexural strength and strain.]
A numerical model for calculating the monotonic response of SC wall panels was developed and verified for the preliminary analysis and design of structures including these walls.

The key components of the numerical model for monotonic analysis of rectangular SC walls are:

- moment-curvature for each wall panel.
- shearing force-shearing strain relationships for each wall panel.

Assumptions are:

- axial load effects are ignored
- perfect bond between the faceplates and the infill concrete.

Simplified monotonic analysis of SC walls

\[ M_i = V_i y_i \]

\[ V_i = V_f \]

\[ V_{f}^{\text{max}} \]

\[ V_{s}^{\text{max}} \]

\[ V_{t}^{\text{max}} \]

\[ \Delta_f \]

\[ \Delta_s \]

\[ \Delta_t = \Delta_s + \Delta_f \]

Simplified monotonic analysis of SC walls
Shearing force-shearing strain relationship

In-plane shear response of SC walls

45° cracking of infill concrete

Yielding of steel faceplates

Crushing of infill concrete

Shearing force, $V$

Elastic behavior

$V_{u}$

$V_{y}$

$V_{cr}$

$K_{cr}$

$K_{e}$

$\gamma_{cr}$

$\gamma_{y}$

$\gamma_{u}$

Shearing strain, $\gamma$

A: Concrete cracking

B: Yielding of steel faceplates

C: Concrete crushing
at the onset of concrete cracking
at the onset of the steel faceplate yielding
on the compression side of the wall
at maximum concrete compressive strain equals to
the strain corresponding to peak concrete stress
at the onset of the steel faceplate yielding on
the tension side of the wall

Moment-curvature relationship of SC wall
Validation of the simplified monotonic analysis

Force-displacement relationship for 10-in. thick walls with 3.8% reinforcement ratio

Force-displacement relationship for 20-in. thick walls with 1.9% reinforcement ratio

Force-displacement relationship for 30-in. thick walls with 2.1% reinforcement ratio

Force-displacement relationship for 30-in. thick walls with 5.0% reinforcement ratio
Force-displacement response of multi-story SC walls

Elevation view of three-story SC walls subject to uniform and triangular loadings

Analytically- and numerically-predicted responses of three story SC wall
Simulation of cyclic response

Cyclic loop of the IKP model

Cyclic loop of the MIKP model
Simulation of the cyclic analysis of SC walls

LAN10-5
LAN20-2
IAN10-5
LAH10-5
LAH20-2
IAH10-5
10. MODELING SQUAT REINFORCED CONCRETE SHEAR WALLS FOR SEISMIC ANALYSIS

ASCE 41-13 cyclic backbone curves

Table 1. Modelling parameters and acceptance criteria for nonlinear procedures—R/C shear walls and wall segments controlled by shear [11]

<table>
<thead>
<tr>
<th>Conditions</th>
<th>Total drift ratio (%)</th>
<th>Strength ratio</th>
<th>Acceptable total drift ratio (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>d</td>
<td>e</td>
<td>g</td>
</tr>
<tr>
<td>( \frac{(A_s - A_s')f_y + P}{t_w l_w f_c'} ) \leq 0.05</td>
<td>1.0</td>
<td>2.0</td>
<td>0.4</td>
</tr>
<tr>
<td>( \frac{(A_s - A_s')f_y + P}{t_w l_w f_c'} ) &gt; 0.05</td>
<td>0.75</td>
<td>1.0</td>
<td>0.4</td>
</tr>
</tbody>
</table>

\( \frac{\Delta}{h} \)
Database development

Data from the cyclic testing of 240 low-aspect ratio RC walls was assembled to evaluate the utility of the ASCE 41-13 backbone curve.

- wall aspect (moment-to-shear) ratio ($M / V l_w$)
- vertical web reinforcement ratio ($\rho_v f_{yw}$)
- horizontal web reinforcement ratio ($\rho_h f_{yh}$)
- vertical reinforcement ratio in the boundary element ($\rho_{vb} f_{yvb}$)
- normalized axial compressive load ($P / A_g f'_c$)
- concrete uniaxial compressive strength ($f'_c$)
Database development
Database development

\[ \frac{M}{VL_w} : \text{rectangular walls (left panel), and barbell and flanged walls (right panel)} \]
Database development

ACI 318-14 Chapter 11; rectangular walls (left panel) and barbell and flanged walls (right panel)
5. Tie rods instead of shear studs are recommended near the base of an SC wall, where the faceplates are likely to buckle and high tensile forces are imposed on the connectors, to improve the seismic response of SC walls.

6. The initial stiffness of SC walls constructed with a baseplate connection to an RC foundation may be substantially affected by the flexibility of the connection, with a potential significant impact on the dynamic response of the supported structure.

7. The contribution of the steel faceplates to the total lateral strength increases as the reinforcement ratio and/or the wall aspect ratio increases.
FUTURE RESEARCH

3. Research on the response of SC walls subjected to both in-plane and out-of-plane loadings.
4. Development of macro model which can be easily implemented in an engineering computational platform for practical analyses of SC walls.
5. Identification of the response modification factor, R, for SC walls.
7. Comparison studies on SC and RC walls with identical shear span-to-depth ratios and reinforcement ratios.
References

Journal articles:


References

Conference proceedings:


References


Thank you