MODULAR CONNECTION TECHNOLOGIES FOR COMPOSITE WALLS IN SMRs: DEVELOPMENT AND EXPERIMENTAL VERIFICATION

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DOE NEUP – AMM Presentation
Goal: The goal of the project was to develop and verify connection technologies for steel-plate composite (SC) walls.

Specifics:
1. The verified connection technologies and data etc. should be available in the public domain for easy access by industry, regulators, DOE
2. Include SC wall-to-basemat anchorage, SC wall-to-wall joints, and SC wall-to-slab connections
3. Consider different connection design and performance philosophies
PROJECT OBJECTIVES

1. Develop modular SC wall connection strategies, and evaluate their structural behavior, fabrication efficiency, and construction economy.

2. Develop and benchmark numerical modeling and analysis techniques that can be used to investigate the structural behavior, performance and failure of SC wall connections.

3. Conduct experimental investigations to verify SC wall connection performance.

4. Develop standardized connection details and design guidelines that can be used to expedite the design, review, licensing, and construction processes for SMRs.
PROJECT TASKS

- Task 1 - Selection of connection configurations for the project is complete.
- Task 2 – Computational simulation and benchmarking analysis work is complete. Expanded state-of-the-art numerical techniques, concrete material models etc.
- Task 3 – Design and experimental evaluation of:
  1. SC wall-to-basemat anchorage
  2. SC wall-to-wall T-connections
  3. SC wall-to-wall L-connections
  4. SC wall-to-slab connections
  5. SC wall-to-basemat anchorage
- Task 4 - Design guidelines for SC wall-to-wall connections, and full strength SC wall-to-basemat anchorage
MAJOR ACCOMPLISHMENT - 1

- Development, review, balloting, and publication of a consensus standard for steel-plate composite (SC) walls:
  - AISC N690-12s1 (2015) - Specification for Safety-Related Steel Structures for Nuclear Facilities Including Supplement No. 1 - Published in August 2015
  - Appendix N9 - Specification for steel-plate composite SC walls in safety-related nuclear facilities
  - Instead of ACI 349 code for concrete structures for nuclear facilities
  - Specification for SC walls and associated connections

- Cumulative Meeting Man-Hours from November 2006 to May 2013:
Specification for Safety-Related Steel Structures for Nuclear Facilities

Including Supplement No. 1

January 31, 2012 (ANSI/AISC N690-12)
August 11, 2015 (ANSI/AISC N690s1-15)

Supersedes the Specification for Safety-Related Steel Structures for Nuclear Facilities dated September 20, 2006 and all previous versions of this specification

Approved by the AISC Committee on Specifications
APPENDIX N9
STEEL-PLATE COMPOSITE (SC) WALLS

This appendix addresses the requirements for steel-plate composite (SC) walls in safety-related structures for nuclear facilities. The provisions of this appendix are limited to SC walls consisting of two steel plates (faceplates) composite with structural concrete between them, where the faceplates are anchored to concrete using steel anchors and connected to each other using ties.

The appendix is organized as follows:

N9.1. Design Requirements
N9.2. Analysis Requirements
N9.3. Design of SC Walls
N9.4. Design of SC Wall Connections

User Note: A flowchart to facilitate the use of the appendix has been provided in the Commentary.

N9.1. DESIGN REQUIREMENTS


The following provisions apply to SC walls:
# Organization of Appendix N9

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<td>N9.3.6 Strength Under Combined Forces</td>
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</table>
2. Required Strength

The required strength for the connections shall be determined as:

(a) 125% of the smaller of the corresponding nominal strengths of the connected parts, or

(b) 200% of the required strength due to seismic loads plus 100% of the required strength due to nonseismic loads (including thermal loads)

**User Note:** Connections designed for required strength as per option (a) develop the expected capacity of the weaker of the connected parts. Connections designed for required strength as per option (b) develop overstrength with respect to the connection design demands, while ensuring that ductile limit states govern the connection strength. Option (a) is preferred. Where option (a) is not practical, option (b) may be used.
For option (a) (full-strength connections), a load increase factor ($LIF$) of 1.25 has been selected to be consistent with ACI 349 (ACI, 2006) requirements, which is the prevalent code for design of safety-related nuclear concrete facilities. The regulatory agency also considers the precedence established by ACI 349 to be the relevant rubric for evaluating and accepting SC structures currently being built in the United States, which are primarily replacements for RC structures. This factor also takes into consideration the strain hardening and overstrength that will be expected in SC walls. Because a full strength connection is designed for 1.25 times the nominal strength of the connected SC walls, the connection is always adequate, provided the wall is safe for the load combinations considered.

For option (b) (overstrength connections), an $LIF$ of 2.0 is applied to the seismic demands with the intention to achieve the minimum high-confidence-of-low-probability-of-failure margin of safety equal to 1.67, while utilizing the approach specified in ACI 349 Appendix D for the connection design.
3. **Available Strength**

The available strength shall be calculated using the applicable force transfer mechanism and the available strength of the connectors contributing to the force transfer mechanism. The available strength for connectors shall be determined as follows:

(a) For steel headed stud anchors, the available strength is determined in accordance with *Specification* Section I8.3.

(b) For welds and bolts, the available strength is determined in accordance with *Specification* Chapter J.

(c) For compression transfer via direct bearing on concrete, the available strength is determined in accordance with *Specification* Section I6.3a.

(d) For a shear friction load transfer mechanism, the available strength is determined in accordance with ACI 349, Section 11.7.

(e) For embedded shear lugs and shapes, the available strength is determined in accordance with ACI 349, Appendix D.

(f) For anchor rods, the available strength is determined from ACI 349, Appendix D.
3. **Available Strength**

The connection available strength for each demand type should be calculated using the applicable force transfer mechanism and the available strength of its contributing connectors. Figure C-A-N9.4.2 lays out the procedure to be followed in calculating the available strength for the connection.
Peer review is recommended to determine the connection adequacy for combinations of demands, that is, combined in-plane and out-of-plane forces. If deemed necessary by the peer review, the connection adequacy for combinations of demands should be verified by the results of a nonlinear inelastic finite element analyses conducted using benchmarked nonlinear finite element models. This verification should also be reviewed. Figure C-A-N9.4.3 lays out the procedure for connection qualification.
MAJOR ACCOMPLISHMENT - 2

- Development, review, balloting, and publication of an AISC Design Guide for steel-plate composite walls and connections.

- AISC Design Guide No. XX (2016). This design guide has completed two review cycles, and has been accepted by AISC for publication. Typesetting is ongoing right now.

- It includes design examples for both SC walls and connections based on the findings of this DOE project.
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SC Wall-to-Basemat Anchorage Connection

Can be designed either as full-strength or over-strength anchorage. Full-strength design is preferred and convenient.
FORCE TRANSFER MECHANISMS

Bending due to uniform reaction

Cantilever

$M_{cp}$
RESEARCH NEEDED TO COMPLETE DESIGN

1. Direct shear strength of rebar-coupler anchor systems. This information is not available in any existing design codes / standards, and must be verified through large-scale tests before adoption.

2. Cyclic performance of SC walls designed with full-strength connections. Focus on in-plane shear behavior of SC wall piers and flanged walls.
DIRECT SHEAR STRENGTH OF REBAR-COUPLER ANCHOR SYSTEMS FOR
STEEL-PLATE COMPOSITE (SC) WALLS

Efe G. Kurt¹, Amit H. Varma², and Young M. Sohn³

ABSTRACT

This paper focuses on the direct shear behavior of rebar-coupler anchor systems, and their use for anchorage of steel-plate composite (SC) walls to the concrete basemat of safety-related nuclear facilities. Large-scale rebar-coupler anchor specimens were tested under direct shear loading until failure. The results included the applied load-slip displacement responses of the specimens, the direct shear strength, and the observed failure mode. The American Concrete Institute (ACI) 349 code equation for calculating the direct shear strength of embedded anchors was compared with the direct shear strengths from the tests. The code equation underestimated the direct shear strength of the anchor system, because it was based on the assumption that shear failure occurs in the rebars, whereas experimental observations indicated that shear fracture failure occurred in the coupler rather than the rebars. The design equation was updated to utilize the net shear area of the coupler instead of the rebars, after which the direct shear strengths from the tests could be calculated with reasonable accuracy. The experimental results were also used to propose an empirical model for the shear force-slip displacement response of rebar-coupler anchor systems.

Keywords: Composite, steel-plate composite, steel-concrete, direct shear strength, rebar-coupler anchor.

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The direct shear strengths calculated using the updated design equation were within 1% of the corresponding failure loads from the tests. The load-slip relationships measured from the tested specimens could be modeled empirically using a modified version of the empirical model proposed for the behavior of shear studs embedded in concrete.

This paper presents the cyclic in-plane shear behavior of SC wall piers with full-strength basemat anchorage. The anchorage is achieved using rebar-coupler anchor systems designed as mentioned before. The cyclic in-plane shear behavior was evaluated for SC wall piers with different reinforcement ratio, stud and tie spacing, and wall aspect ratios ranging from 0.60 – 1.0.
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<table>
<thead>
<tr>
<th>Sp.</th>
<th>SC1</th>
<th>SC2</th>
<th>SC3</th>
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<th>SC6</th>
<th>SC7</th>
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<td>305</td>
<td>102</td>
<td>305</td>
<td>3.1</td>
<td>21</td>
<td>40</td>
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</table>

- **Sp.** Spacing
- **SCx** Specimen Number
- **h/l_w** Height to Width Ratio
- **Lateral load [kips]**
- **Lateral displacement [in.]**
- **Drift ratio [%]**

![Diagrams](image)

- **1:** Initial flexural crack
- **2:** Initiation of yielding of faceplates
- **3:** Initiation of local buckling
- **6:** Weld fracture
- **4:** Crushing of concrete
- **5:** Fracture of faceplate

**$F_y$ (MPa):**

- 262
- 262
- 262
- 393
- 393
- 393
- 393
MAJOR RESEARCH PRODUCTS

- Event 1. Concrete flexural cracking
- Event 2. Concrete crushing initiation
- Event 3. Faceplate local buckling
- Event 4. Concrete crushing
- Event 5. Faceplate fracture

Graph showing:
- Drift ratio [%]
- Lateral load [kN]
- Lateral displacement [mm]

Plot details:
- SC7 with $h/l_0 = 0.75$
- Events:
  1. Flexural cracking
  2. Faceplate yielding
  3. Local buckling
  4. Concrete crushing
  5. Faceplate fracture

Specimen SC6

Images:
- (a) Specimen SC6
- (b) Event 1. Concrete flexural cracking
- (c) Drift ratio vs. Lateral load for SC7
- (d) Event 4. Concrete crushing initiation
- (e) Event 4. Concrete crushing final
- (f) Event 5. Faceplate fracture
MAJOR RESEARCH PRODUCTS


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In-Plane Seismic Behavior of Rectangular Steel-Plate Composite Wall Piers

Siamek Epackachi, A.MASCE¹; Nam H. Nguyen²; Efe G. Kurt³; Andrew S. Whittaker, MASCE⁴; and Amit H. Varma, MASCE⁵

Abstract: An experimental study investigated the behavior of large-scale steel-plate composite (SC) walls subjected to cyclic lateral loading. The testing program involved four rectangular SC wall specimens with an aspect ratio (height-to-length) of 1.0. The specimens were anchored to a concrete base and a pinned terminal connection that was designed to be stronger than the walls. The design parameters considered in the investigation were wall thickness, reinforcement ratio, stud spacing, and tie bar spacing. The present analysis, global force-displacement responses, contributions of the steel facades and infill concrete to the lateral resistance load transfer between the facades and infill concrete, and damage to the face plates and infill, were documented. The four SC walls failed in a flexural mode characterized by tensile cracking of the concrete, tensile yielding of the steel plates, crushing of concrete at the toes of the wall, outward local buckling of the steel facades, and fracture of the steel facades. The walls achieved the peak shear strength estimated using simplified procedures and ABAQUS. Pinching of the force-displacement response was observed at displacements greater than those associated with peak load. The connection between the baseplate and the first row of connectors affected the post-shear peak strength and fracture of the facades. The connection of the SC wall to the foundation block had a significant influence on the initial stiffness of the walls. DOI: 10.1061/(ASCE)ST.1943-541X.0001148 © 2014 American Society of Civil Engineers.

Author keywords: Steel-plate composite shear wall; Safety-related nuclear structure; Flexure-critical wall; Cyclic loading; Hysteresis loops; Metal and composite structures.

Introduction and Background

Steel-plate composite (SC) walls, consisting of steel facades, infill concrete, built-up steel studs anchoring the facades to the infill, and tie rods connecting the two facades through the infill, have potential advantages over conventional reinforced concrete walls due to their relatively high shear strength, deformation capacity, and ease of construction. To date, design of SC walls has been based on proprietary test data and limited data available in the literature. Most of these tests were conducted at small scales and have focused on the essentially elastic range of response. Although SC wall construction is not new, it has yet to see widespread use in the building industry. In the last four decades, a number of research projects have investigated the performance of SC walls for use in tunnels, blast resistant shelters, and liquid and gas retaining structures. The use of SC wall construction in nuclear power plants has been studied for nearly 20 years, with an emphasis on elastic response in design basis shaking. Application of SC walls to contain internal structures and shield buildings in nuclear power plants has begun in the United States and China (e.g., Vama et al., 2014; Zhang et al., 2014).

The use of seismically resisting SC walls for offshore construction was proposed in the late 1970s by the Hitachi Shipbuilding and Engineering Company (Adams et al., 1987), which prompted further studies (e.g., Gerwick and Dale 1987; Murotsu and Isata 1987; O’Flynn and MacGregor 1987; Smith and McLeish 1987; Link and Elwi 1995). Double skin composite construction was proposed in 1987 for submersible tunnels. Pilot tests were performed and design guidelines were drafted by Wright and his coworkers (e.g., Oddy and Wright 1989; Wright et al., 1991).

The use of SC walls in safety-related nuclear structures in Korea, Japan, and the United States has been studied for the past 20 years. Small-scale tests were performed to develop data on the in-plane shear, out-of-plane shear, and thermal performance of SC walls for different reinforcement ratios and concrete strengths (e.g., Akiyama et al., 1998; Sanaki et al., 1999; Takeishi et al., 1996; Usami et al., 1996; Akita et al., 2001; Kanzaki et al., 2001; Oraki et al., 2001, 2004). The Japanese data were used to develop the Japanese code on SC wall construction: H31-488 (JEA 2005). Korean researchers followed the Japanese lead and conducted companion experiments, also at a small scale. The proprietary Korean data were used to aid the design of the APR 1400+ power plant and the development of the Kona code for design of SC walls in nuclear facilities. A design code for SC walls in nuclear structures is currently in preparation in the United States: AISC N690r (2014). This draft standard under public review is based on recent tests performed in the United States (e.g., Booth et al., 2007; Nemer and Vama, 2014; Vama et al., 2011, 2012, 2013, 2014), available Korean and Japanese data,
Kurt et al. (2016) includes design equations for calculating the lateral load capacity of SC wall piers with full-strength anchorage connections.


Seo et al. (2016) develop design equations for calculating the in-plane shear strength of SC walls with boundary elements and full-strength anchorage connections.
SC Wall-to-Basemat Anchorage Connection

Can only be designed as over-strength anchorage. Preferred due to ease and pace of construction.
FORCE TRANSFER MECHANISMS

Axial Tension

In-Plane Shear

Out-of-Plane Moment
RESEARCH NEEDED TO COMPLETE DESIGN

1. Design and detailing of non-contact lap splice between steel faceplates of SC walls and rebar from concrete foundation. This information is not available in any codes / standards, and must be verified using large-scale tests before adoption.

2. Cyclic performance of SC walls designed with over-strength connection. Focus on in-plane shear behavior of SC wall piers.
ST5213

Experimental Behavior and Design of Steel-Plate Composite-to-Reinforced Concrete (SC-to-RC) Lap Splice Connections

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ABSTRACT

Steel-plate composite (SC) walls can be anchored to reinforced concrete (RC) foundations or connected to RC walls using lap-splice connections. These lap-splice connections consist of steel rebars or dowels that are fully developed (Lw) in the RC portion and embedded (Lw) in the SC wall. Tension forces are transferred from the steel faceplates of the SC wall to the steel rebars or dowels using stud anchors and ties welded to the steel faceplates. The efficiency of force transfer depends on the dowel embedment length (Lw), the number of stud anchors and ties engaged (n), the eccentricity or distance between the steel faceplates and dowel bars (α), and the tie bar reinforcement ratio (ρ). This paper presents the results of experimental investigations conducted in Japan and in the US to evaluate the pullout (tension) strength and ductility of these lap-splice connections. The parameters included in the tests were Lw, n, α, and ρ. The effects of eccentricity (offset distance between dowel bars and steel faceplates) on the axial tension behavior of SC-to-RC lap-splice connections were also investigated. Detailed numerical models were developed to gain additional insight into the behavior and force transfer in lap-splice connections. The results from the experimental and numerical investigations were used to propose design and detailing recommendations for lap-splice connections.

Keywords: Steel-plate composite shear wall; Safety-related nuclear structure; Lap-splice connections.
PRIMARY FINDINGS

- Force transfer from the steel faceplates (of the SC portion) to the steel dowels (of the RC portion) can be accomplished using stud anchors.
- The number \( (n) \) and strength \( (Q_n) \) of these stud anchors and ties should be designed and detailed to develop the expected strength \( (N_r) \) of the weaker of the connected parts.
- The embedment length \( (L_{emb}) \) of the steel dowels within the SC portion will depend directly on the number \( (n) \) and spacing \( (s) \) of stud anchors and ties, but it is not recommended to be less than the corresponding development length \( (L_d) \) of the dowel bars in the RC portion.
- Shear reinforcement \( (\rho_w) \) ratio greater than 0.5% can provide ductility. The steel dowel bars have to be placed at least 1.0x \( d_{b,dowel} \) so that concrete struts can be anchored adequately.
Cyclic in-plane shear behavior of SC walls designed with overstrength connection achieved using non-contact spliced rebars.

Tested two specimens SCRC1 and SCRC2 with aspect ratio of 0.6. The non-contact lap splices between the steel plates and rebars were designed using Seo et al. (2016).
MAJOR RESEARCH PRODUCTS – 5

SCRC1 designed to be governed by flexural capacity of RC portion at base

SCRC2 designed to be governed by shear strength of RC portion at base
Cyclic behavior of SCRC1 governed by flexural yielding of the RC portion at the base. Does not develop SC wall strength. Overstrength connection demonstrated.

Cyclic behavior of SCRC2 also governed by flexural yielding of the RC portion at the base. Does not develop SC wall strength. Overstrength connection demonstrated.
Published in Ph.D. Dissertation of Efe Kurt. The corresponding journal article is still being prepared.
SC WALL-TO-WALL CONNECTIONS

- Wall-to-wall T-joints and L-joints are common in plant layout configurations. See plan view below.
**SC Wall-to-Wall Joints**

- **Full-strength connection design philosophy**
  - Develops the expected strength of the weaker of the two connected walls.
  - Failure mode: flexural yielding (ductile) with formation of plastic hinges in SC walls.

- **Over-strength connection design philosophy**
  - Develops failure in the joint, but the strength is greater than the calculated required strengths (twice the seismic load).

- In order to implement either philosophy, need to calculate **joint shear strength** to either prevent it (for full-strength) or have over strength with respect to it.
FORCE TRANSFER MECHANISMS

Axial Tension in Discontinuous Wall

Resulting Joint Shear Force to Achieve Flexural Yielding in Cont. Walls

\[ V_{js} = \max\left(\frac{N_r}{2}, \frac{M_r}{jT}\right) \]
FORCE TRANSFER MECHANISMS

For In-Plane Shear Demand

For Out-of-Plane Shear Demand

Resulting Joint Shear Force

\[ V = V_n e^{-\exp -dc/2} \]
RESEARCH NEEDED TO COMPLETE DESIGN

1. Joint shear strength for SC walls with T-joints, L-joints, etc. There are no codes / standards that provide this information. ACI 349 includes joint shear strength for RC joints, but large-scale experimental verification is needed to extend to SC joints.

2. Joint shear strength for T-joints and L-joints can be different, and need further evaluation.
MAJOR RESEARCH PRODUCTS - 6


- Ph.D. Dissertation of Jungil Seo, Purdue Univ.
The major research finding is that the joint shear strength can be calculated conservatively, and with reasonable accuracy using ACI 349 joint shear strength equation for RC joints.

\[ V_n = \gamma \sqrt{f'_c A_j} \]

- $\gamma = 12$ for SC wall T-joints
- $\gamma = 8$ for SC wall L-joints

Another major finding is that the presence of tie bars, or additional shear studs does not have a significant influence on joint shear behavior or strength.
MAJOR RESEARCH PRODUCTS - 6

Details of T-Joint Specimens

Details of L-Joint Specimen
MAJOR RESEARCH PRODUCTS - 6

Test-Setup for T-Joint Specimens

Test-Setup for L-Joint Specimens
Cyclic Loading Protocol

Specimen JS-T1-F
Specimen JS-T0-F
Specimen JS-T0-P
Specimen JS-T2-F

ACI 349-06

Shear Force-Displacement Behavior of T-Joint Specimens

Shear Force-Displacement Behavior of L-Joint Specimen

$H_n = \text{Lateral load at the expected joint shear strength, } V_n$

$\Delta_y = \text{Projected displacement at } V_n$
Crack pattern at the ultimate joint shear: all specimens

JS-T1-F

JS-T0-F

JS-T0-P

JS-T2-F
SC Wall-to-Slab Connections

Typical SC Wall-to-RC Slab Connection
FORCE TRANSFER MECHANISMS
RESEARCH NEEDED TO COMPLETE DESIGN

- Out-of-plane shear and moment transfer mechanism need experimental validation. There are no codes / standards for estimating the out-of-plane shear strength of the wall-to-slab joint region.

- Experimental verification of the wall-to-slab out-of-plane shear strength is needed.
Two large-scale SC wall-to-RC slab specimens were tested to evaluate the out-of-plane moment transfer mechanism, and out-of-plane shear strength.

Specimens were designed to develop the flexural capacity of the RC slab (using rebars).
**Test Setup**

**Force-Displacement**

- **Graph:**
  - **Y-axis:** Applied Force, kips
  - **X-axis:** Displacement, in
  - **Graphs:**
    - Test
    - Flexural Strength

- **Graph:**
  - **Y-axis:** Applied Force, kips
  - **X-axis:** Microstrain
  - **Graphs:**
    - Test
    - Flexural Strength
COMPLETE DESIGN EXAMPLE

Appendix 1 of the Design Guide includes a complete design example with calculations, drawings, details etc. for an SC wall and corresponding basemat anchorage connection.
CONCLUSIONS

- Project Goal and Objectives were achieved
- All project tasks were completed successfully
- Several major research products in terms of journal articles, conference papers and presentation etc.
- Major outcomes include Ph.D. dissertations of two students. One working in INL now with structural engineering and seismic group.
CONCLUSIONS

- Published consensus code / standard from AISC N690s1 (2015), and AISC Design Guide (2016) for SC walls

- Developed two different connection design philosophies

- Developed SC wall-to-basemat anchorage connections that could achieve difference performance, and verified them experimentally

- Developed design equations and approaches for anchor strength needed to complete design
CONCLUSIONS

- Developed design approaches for SC wall-to-wall connections including T-joints and L-joints

- Developed and verified equations for estimating the joint shear strength of SC wall-to-wall joints

- Developed and verified SC wall-to-RC slab connection

- Developed and published a complete design example for SC walls and connections
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