Modular Connection Technologies for Composite Walls in SMRs: Development and Experimental Verification

Amit H. Varma, Efe G. Kurt, Jungil Seo

October 18, 2016

DOE NEUP – AMM Presentation

PROJECT GOAL

- 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

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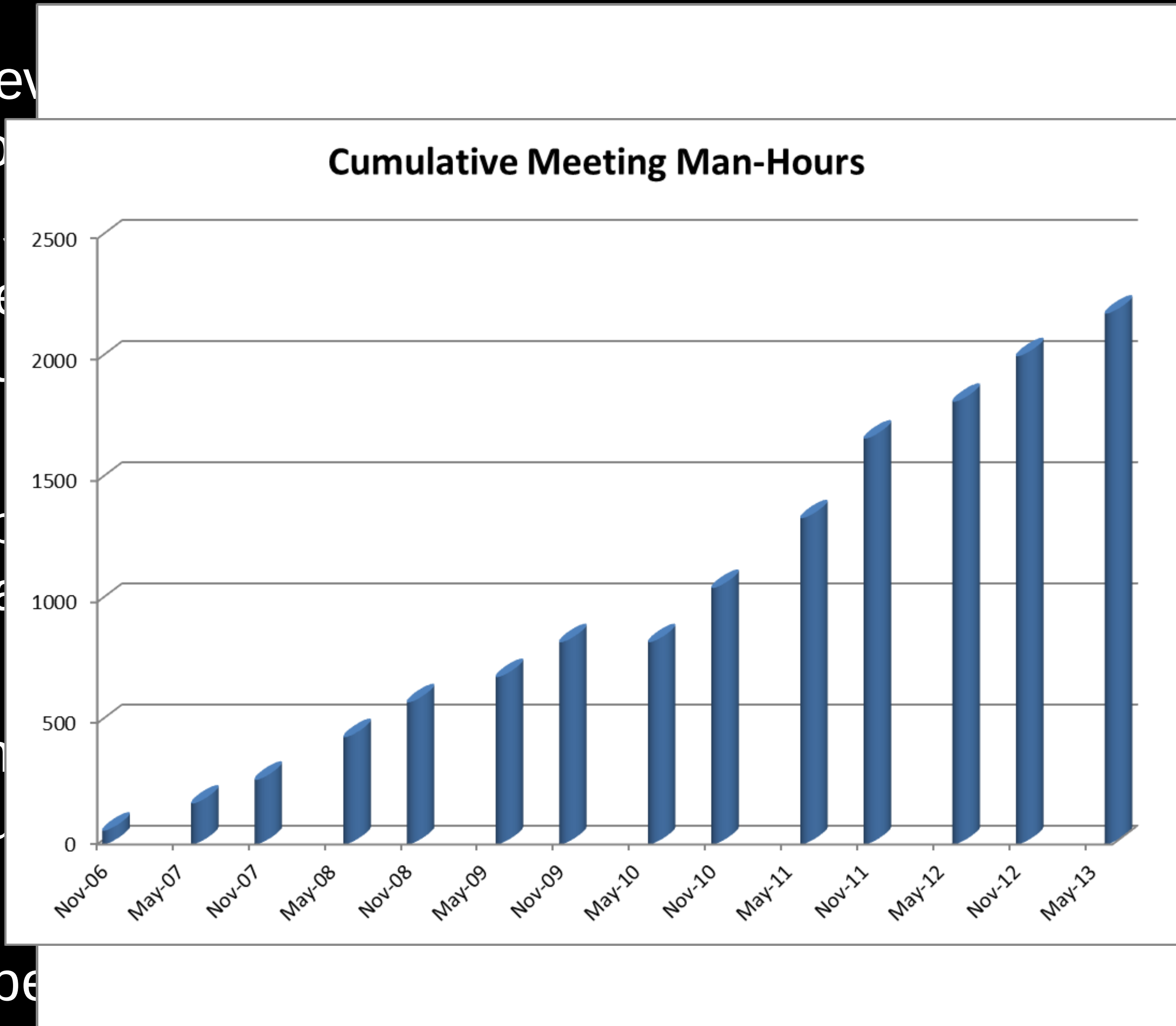

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ANSI/AISC N690-12
ANSI/AISC N690s1-15
An American National Standard

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

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CONSENSUS STANDARD

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:

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

N9.1. DESIGN REQUIREMENTS

1. General Provisions

The following provisions apply to SC walls:

ORGANIZATION OF APPENDIX N9

- N9.3 Design of SC Walls
  - N9.3.1 Tensile Strength
  - N9.3.2 Compressive Strength
  - N9.3.3 Out-of-Plane Flexural Strength
  - N9.3.4 In-Plane Shear Strength
  - N9.3.5 Out-of-Plane Shear Strength
  - N9.3.6 Strength Under Combined Forces

N9.4 Design of SC Wall Connections

- N9.4.1 General Provisions
- N9.4.2 Required Strength
- N9.4.3 Available Strength

AISC N690s1: Appendix N9.4.2 Connection Design Philosophy

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.

AISC N690s1: Appendix N9.4 Connection Design Philosophy

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.

all other demands

for Each Demand Type (N9.4.2)

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.

N9.4.2: Calculate Connection Required Strength

AISC N690s1: Appendix N9.4.3 Connection Design

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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.

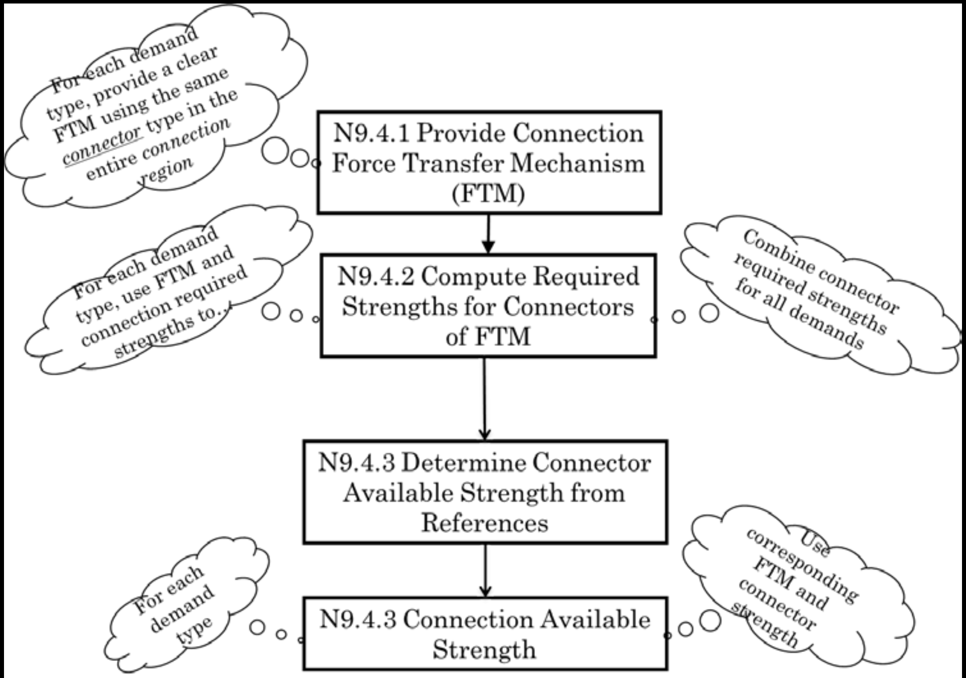
(c) For compression transfer via direct bearing on concrete, the available strength is determined in accordance with *Specification* Section I6.3a.

(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.

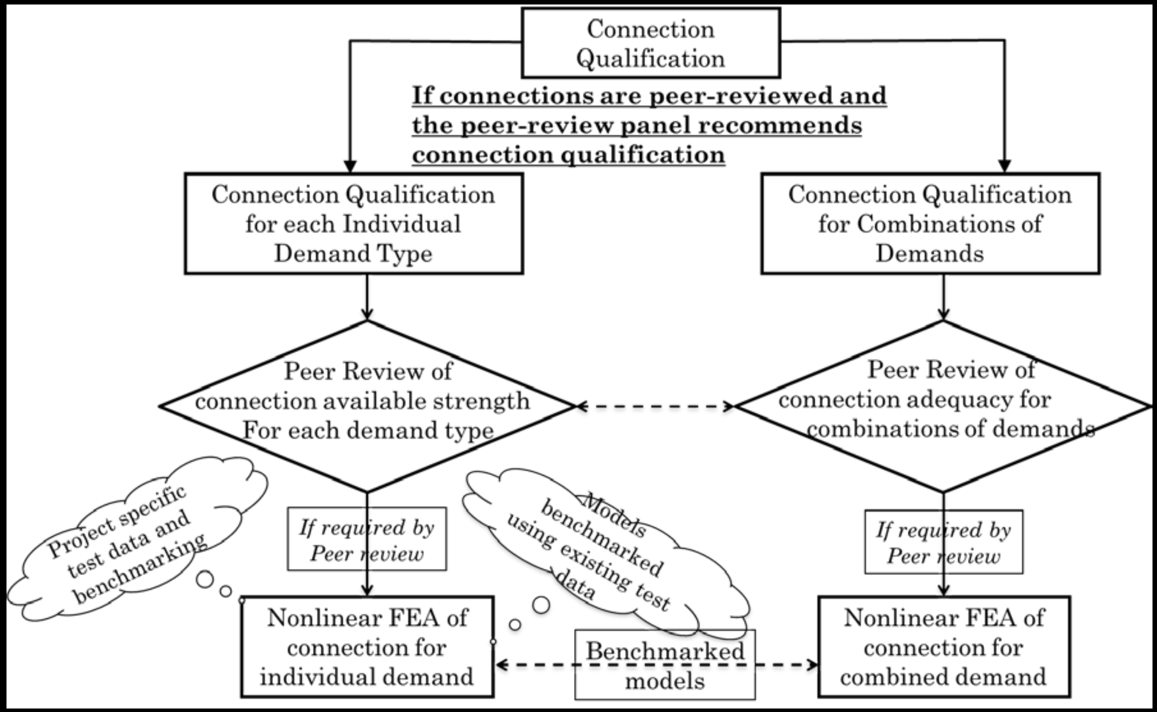
AISC N690s1: Appendix N9.4.3 Connection Design



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.

AISC N690s1: Appendix N9.4.3 Connection Design



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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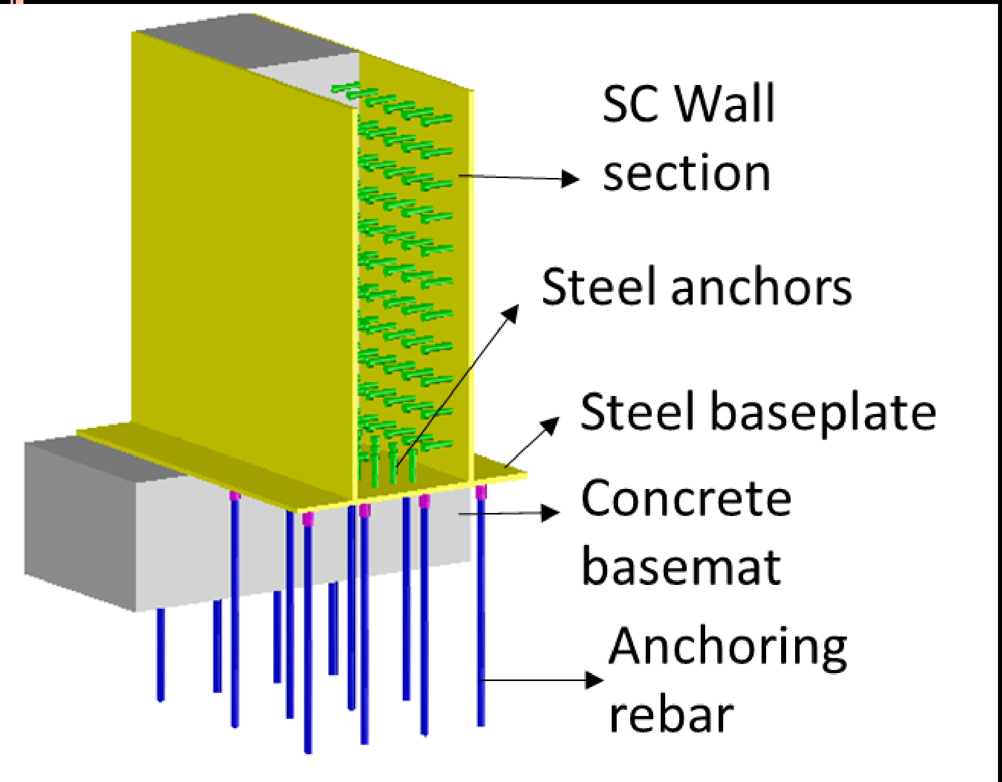
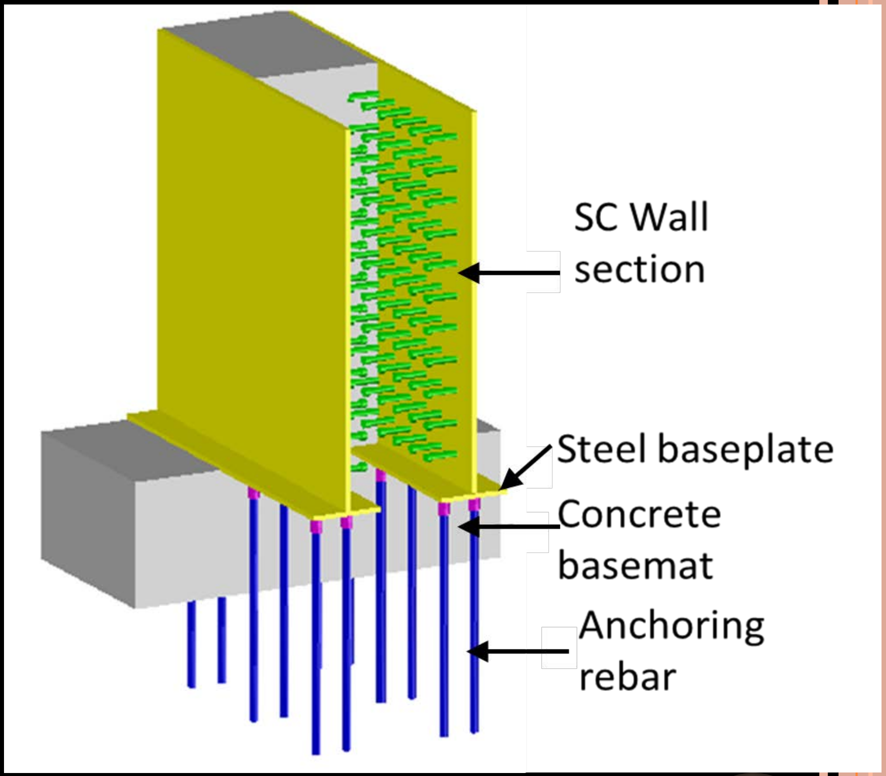
CONNECTIONS

Table of Contents

SC Wall-to-Basemat Anchorage Connection

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

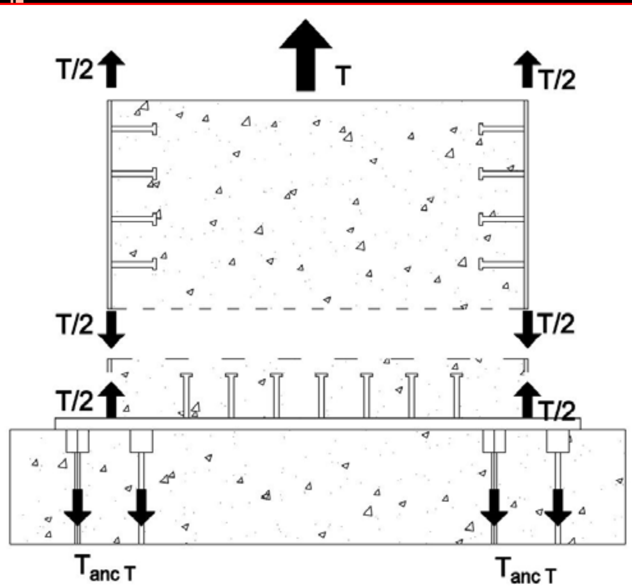


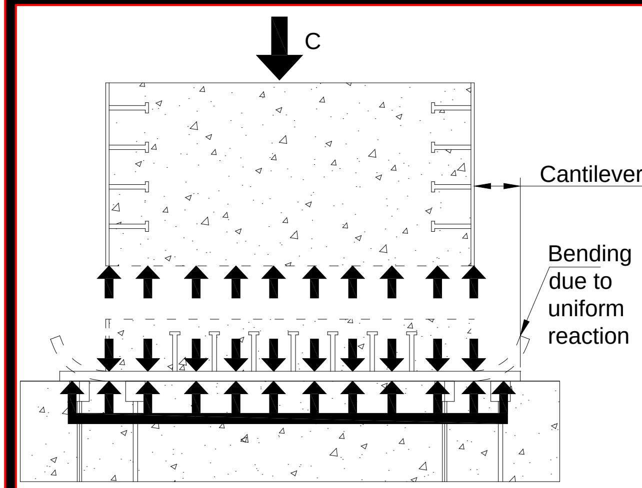


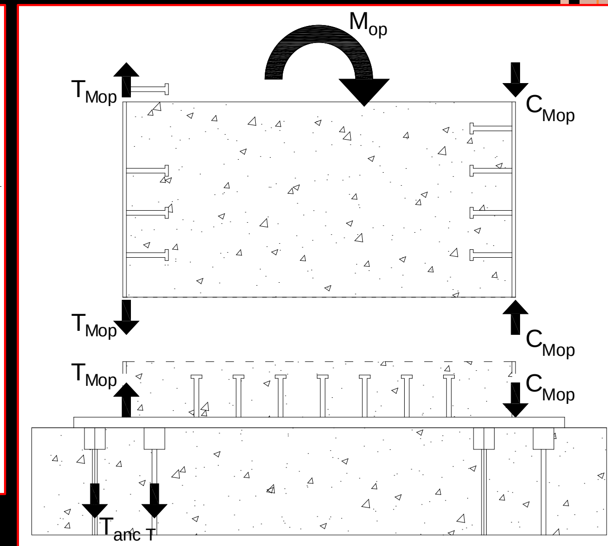
Single baseplate SC Wall-to-Basemat Connection

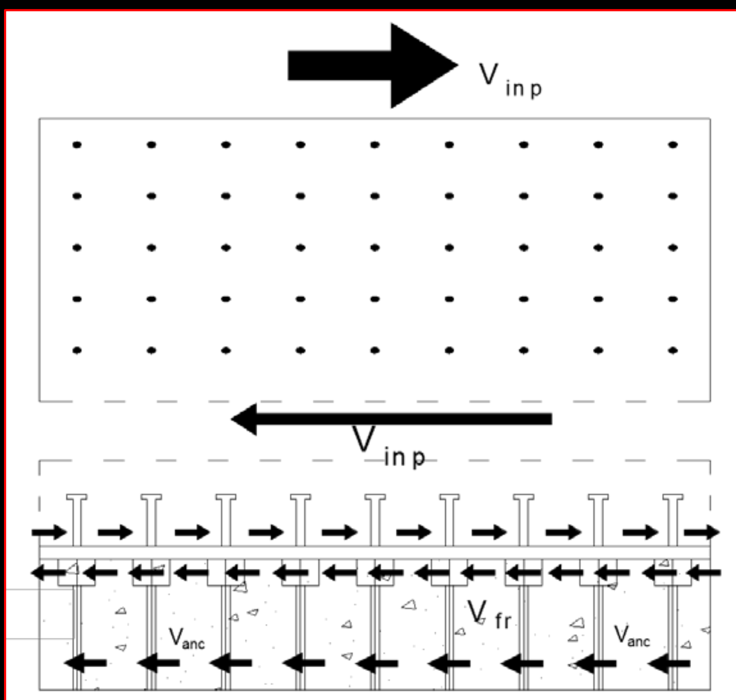
Split-baseplate SC Wall-to-Basemat Connection

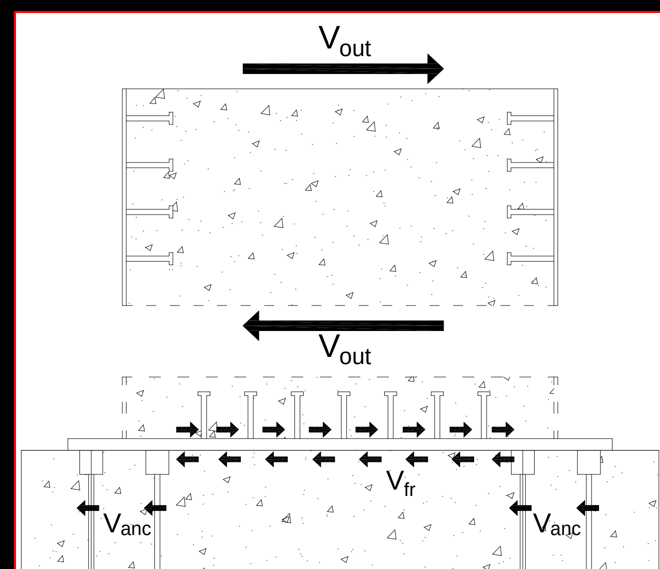
Force Transfer Mechanisms











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.

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DIRECT SHEAR STRENGTH OF REBAR-COUPLER ANCHOR SYSTEMS FOR STEEL-PLATE COMPOSITE (SC) WALLS

Efe G. Kurt[1], Amit H. Varma[2], and Young M. Sohn[3]

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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[2] Professor, Lyles School of Civil Engineering, Purdue University, ahvarma@gmail.com
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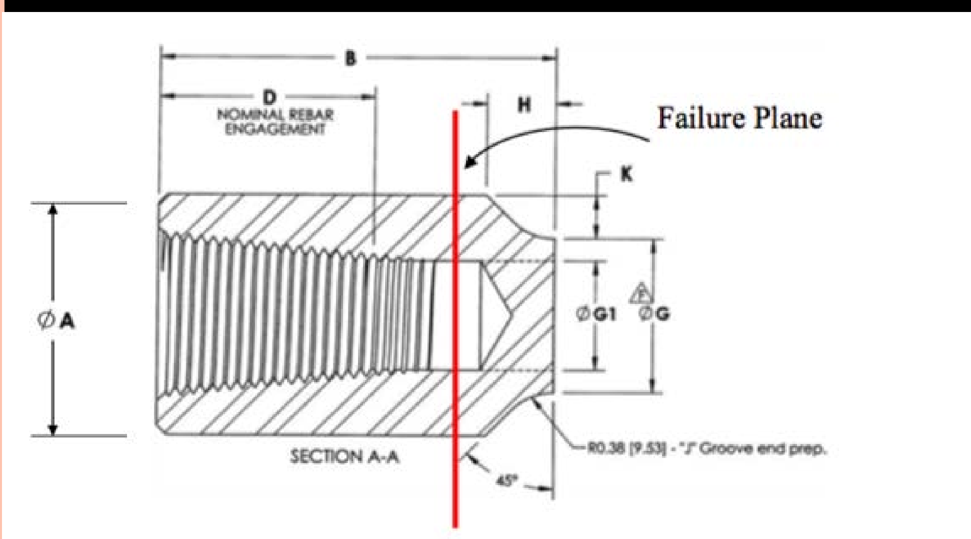
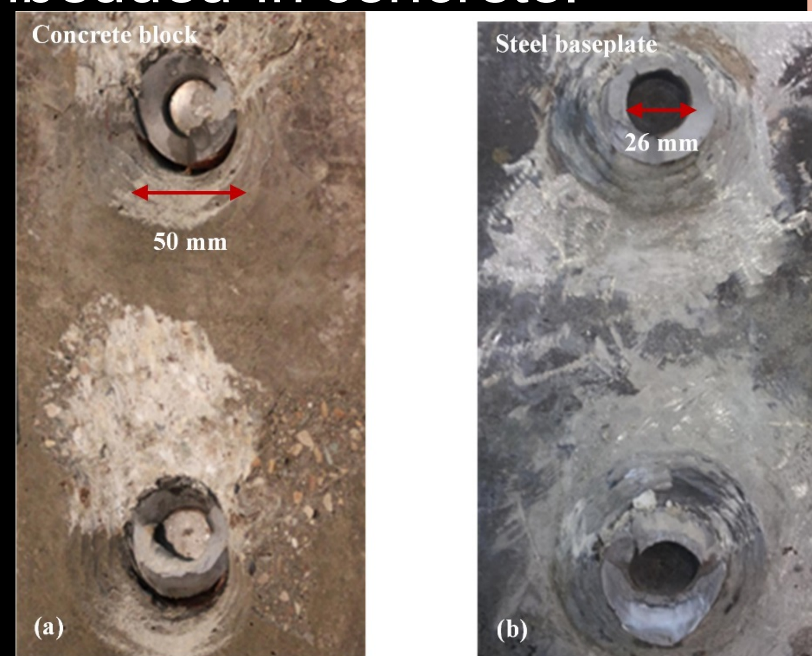
MAJOR RESEARCH PRODUCTS - 1

- 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.





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In-Plane Behavior and Design of Rectangular SC Wall Piers without Boundary Elements

Efe G. Kurt, S.M.ASCE[1]; Amit H. Varma, M.ASCE[2]; Peter Booth[3]; and Andrew S. Whittaker, M.ASCE[4]

Abstract: This paper focuses on the in-plane behavior, analysis, and design of steel-plate composite (SC) wall piers without boundary elements. A series of SC wall pier specimens with aspect ratios (wall height-to-length ratios, h/l_w) ranging from 0.6 to 1.0 were tested under cyclic loading until failure. The results include the lateral load-displacement (V-Δ) responses of the specimens along with observations of steel plate local buckling and concrete crushing. Detailed 3D finite element models of the SC wall specimens were developed and benchmarked using the experimental results. The models explicitly accounted for the effects of geometric nonlinearity and material inelasticity including steel local buckling, concrete crushing, and tension fracture. The benchmarked models were used to conduct parametric studies. The parameters included were the wall aspect ratio (h/l_w), reinforcement ratio (ρ), and wall thickness (T). The experimental results and parametric studies indicated that the lateral load capacity of SC wall piers with aspect ratios greater than or equal to 0.6 is governed by the flexural yielding of the steel faceplates in tension, and by local buckling of the steel faceplates and crushing of the concrete infill in compression. The experimental and analytical results were used to propose preliminary design equations for predicting the lateral load capacity of SC wall piers without boundary elements. DOI: 10.1061/(ASCE)ST.1943-541X.0001481. © *2016 American Society of Civil Engineers.*

Author keywords: Composite; Wall pier; Steel-plate composite; Steel-concrete; In-plane shear; Metal and composite structures.

Introduction

Steel-plate composite (SC) walls are being used in the third generation (Gen. III) of safety-related nuclear facilities and they are also being considered for small modular reactors (SMRs) of the future. SC walls consist of a plain concrete infill sandwiched between two steel faceplates. The steel faceplates are connected to each other using tie bars that are embedded in the concrete infill. The steel faceplates are also anchored to the concrete infill using steel headed stud anchors (also referred to as shear studs). These steel faceplates serve as the primary reinforcement for the concrete infill, and also serve as stay-in-place formwork during construction. The concrete infill prevents the steel faceplates from buckling inward thus improving their stability (Zhang et al. 2014). SC walls are being used for safety-related nuclear facilities because of their structural efficiency (Varma et al. 2014), construction schedule and economy (DOE 2006), and resistance to impactive and impulsive loading (Bruhl et al. 2015). The AISC N690s1 (AISC 2015) specification includes provisions for the design of SC walls in safety-related nuclear facilities, and has been developed based on prior research in the United States, Japan, South Korea, and China (Sener and Varma 2014; Sener et al. 2015a, b).

There is growing interest in the use of SC walls for commercial building applications in seismic regions. This interest stems from the perceived structural efficiency and construction (or schedule) economy of modular composite construction. Recent research (Selvarajah 2013; Bruneau et al. 2013) has focused on the use of SC walls with boundary elements in commercial building applications. The ASCE 7-10 (ASCE 2010) and AISC 341-10 (AISC 2010) seismic provisions permit the use of composite steel plate shear wall (C-PSW) systems in seismic regions, but do not include adequate provisions for the design and detailing of SC walls particularly those without boundary elements or flanges. SC wall piers without boundary elements are comparable to reinforced concrete (RC) wall piers without boundary elements, which (RC walls) can be designed using ACI 318-14 (ACI 2014) requirements.

Several researchers including Hidalgo et al. (2002), Rocks et al. (2011), and Srithamn et al. (2014) have discussed the seismic behavior of squat rectangular RC walls without boundary elements or flanges. For example, Rocks et al. (2011) tested several rectangular RC wall piers with wall aspect (height-to-length) ratios from 0.33 to 0.94, and reinforcement ratios from 0.33 to 1.0%. The peak strengths of these specimens were lower than those calculated using ACI 318-14 (ACI 2014) code provisions in Chapter 21, and the story drift ratios at peak strength were approximately 1%. Sritharan et al. (2014) performed an extensive review of tests conducted on squat rectangular RC wall piers and confirmed that their deformation capacity reduces as the wall aspect ratio decreases. Hidalgo et al. (2002) tested 26 squat RC wall piers with aspect ratios ranging from 0.35 to 1.00. The story drift ratios at initial concrete cracking were about 0.1%, and the drift ratios at maximum strength varied from 0.2 to 0.8%. The story drift ratio at ultimate strength varied from 0.3 to 1.3%, and depended on the reinforcement distribution within the walls. Adorno-Bonilla and Vidot-Vega (2015) have recently discussed various models for estimating the ultimate displacement (drift) capacity of squat RC shear walls subjected to cyclic loading.

SC wall piers can be viable candidates for replacing equivalent RC wall piers when rebar congestion issues or schedule economy issues are present. The reinforcement distribution in SC walls is uniform because of the use of steel faceplates, and the reinforcement ratio is defined as the ratio of the total faceplate thickness-to-the wall thickness ($\rho = 2t_p/T$). In safety-related nuclear facilities,

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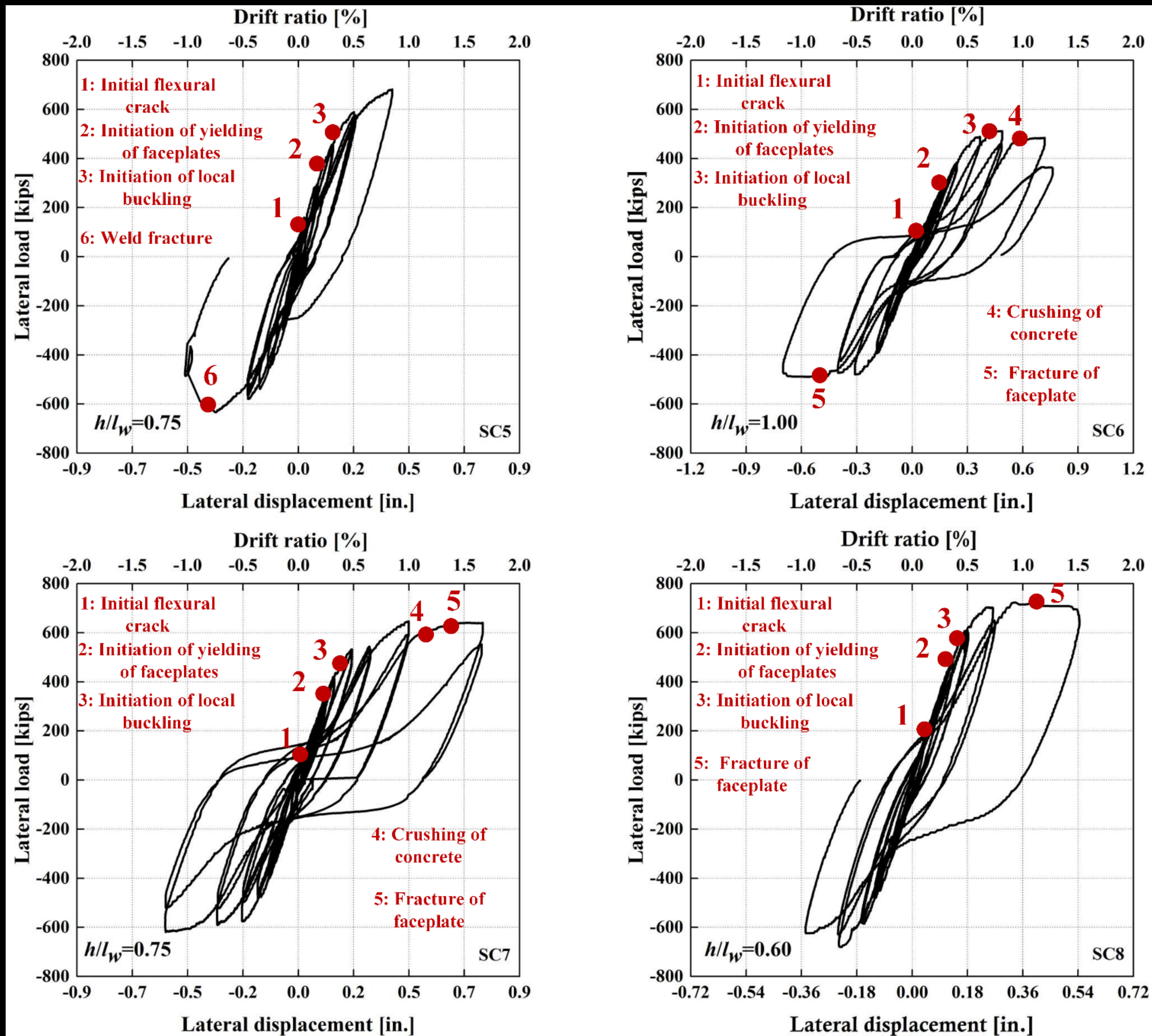
Major Research Products - 2



Sp.	F_y (MPa)
SC1	262
SC2	262
SC3	262
SC4	262
SC5	393
SC6	393
SC7	393
SC8	393

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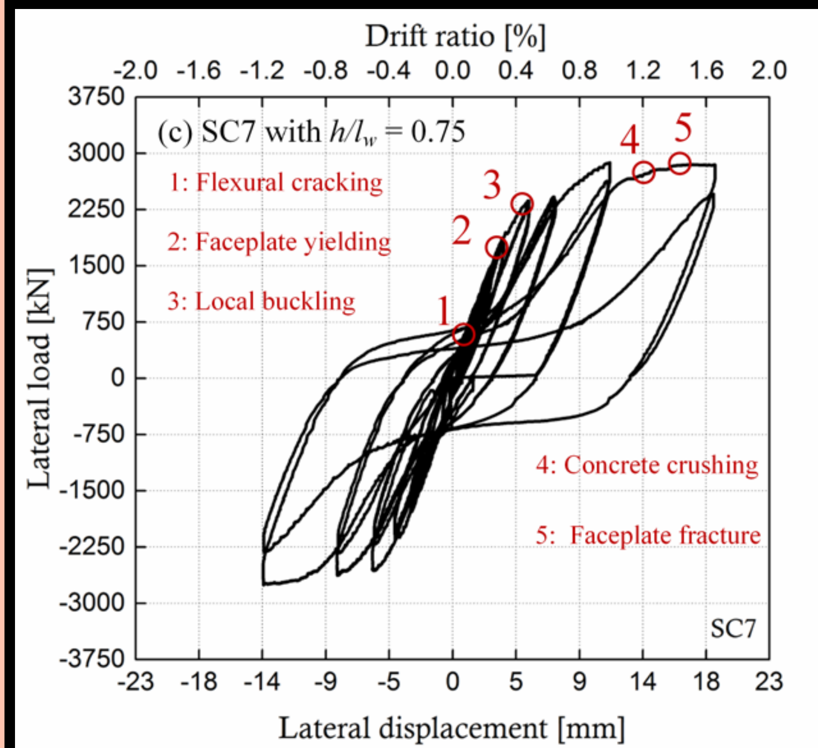

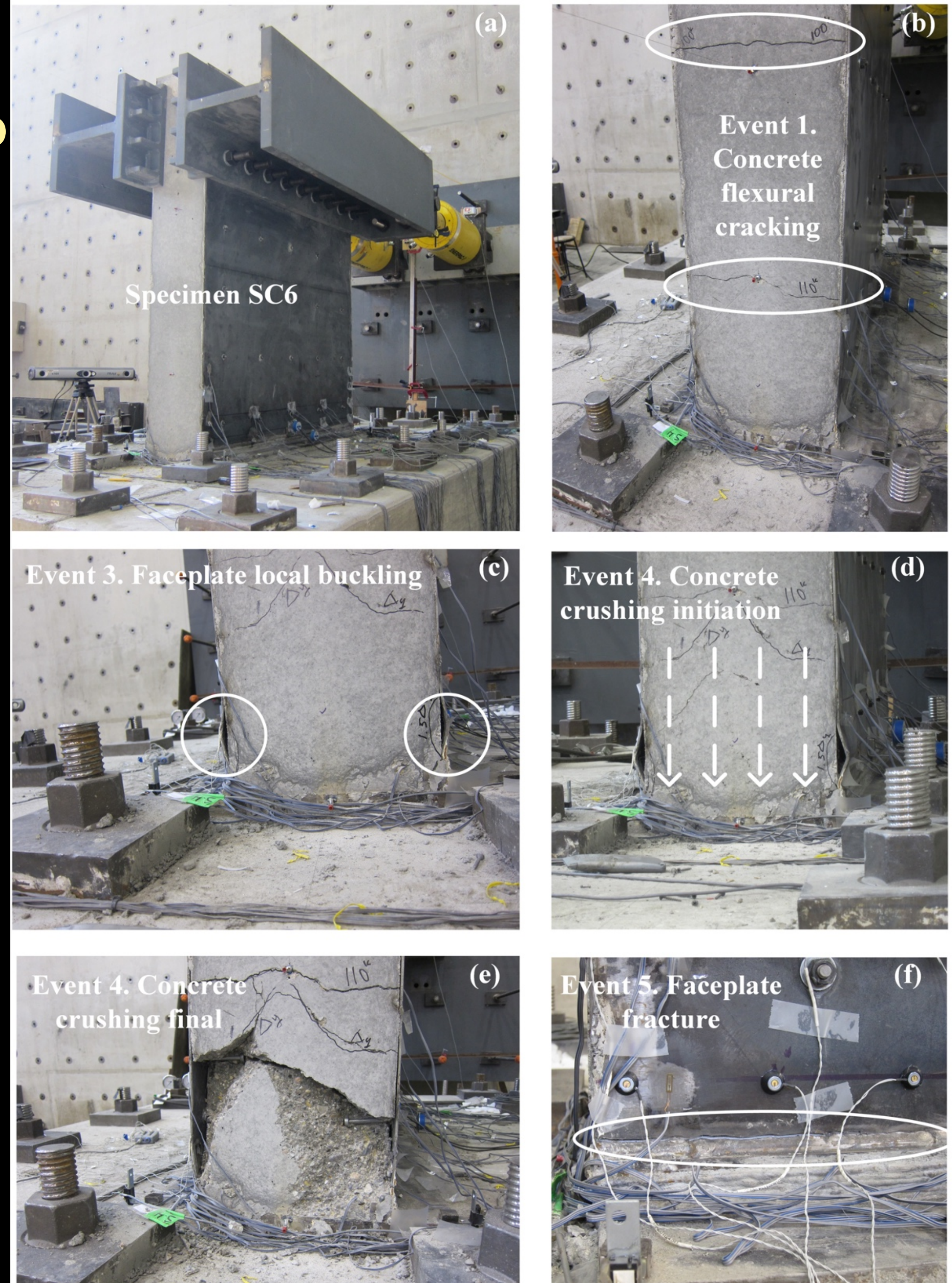

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In-Plane Seismic Behavior of Rectangular Steel-Plate Composite Wall Piers

Siamak Epackachi, A.M.ASCE[1]; Nam H. Nguyen[2]; Efe G. Kurt[3]; Andrew S. Whittaker, M.ASCE[4]; and Amit H. Varma, M.ASCE[5]

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 basemat with a pretensioned bolted 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 pretest analyses, global force-displacement responses, contributions of the steel faceplates and infill concrete to the lateral resistance, load transfer between the faceplates and infill concrete, and damage to the face plates and infill, are 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 faceplates, and fracture of the steel faceplates. The walls achieved the peak shearing strengths estimated using simplified procedures and ABAQUS. Pinching of the force-displacement response was observed at displacements greater than those associated with peak load. The distance between the baseplate and the first row of connectors affected the postpeak shear strength behavior and the fracture of the faceplates. 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.

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 faceplates, infill concrete, headed steel studs anchoring the faceplates to the infill, and tie rods connecting the two faceplates 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 in part 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 containment internal structures and shield buildings in nuclear power plants has begun in the United States and China (e.g., Varma et al. 2014; Zhang et al. 2014).

The use of ice-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; Matsuishi and Iwata 1987; O'Flynn and MacGregor 1987; Smith and McLeish 1987; Link and Elwi 1995). Double skin composite construction was proposed in 1987 for submerged tunnels. Pilot tests were performed and design guidelines were drafted by Wright and his coworkers (e.g., Oduyemi and Wright 1989; Wright et al. 1991a, b).

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 a body of 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. 1989; Sasaki et al. 1995; Takeda et al. 1995; Takeuchi et al. 1998; Usami et al. 1995; Akita et al. 2001; Kazuaki et al. 2001; Ozaki et al. 2001, 2004). The Japanese data were used to develop the Japanese code on SC wall construction: JEAG 4618 (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 Korean 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 N690s1 (2014). This draft standard under public review is based on recent tests performed in the United States (e.g., Booth et al. 2007; Sener and Varma 2014; Varma et al. 2011, 2012, 2013, 2014), available Korean and Japanese data,

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Journal of Constructional Steel Research 119 (2016) 202–215

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ELSEVIER

Steel-plate composite (SC) walls: In-plane shear behavior, database, and design

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A R T I C L E I N F O

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Steel-plate composite walls
Nuclear facilities
In-plane shear
Experimental database

A B S T R A C T

The in-plane shear strength of steel-plate composite (SC) walls is governed by the onset of Von Mises yielding in the steel faceplates. This paper uses a mechanics based model (MBM) to present the fundamental in-plane shear force–shear strain (V–γ) response of SC walls. The MBM accounts for concrete cracking due to principal tensile stresses, and the post-cracking orthotropic composite behavior of SC walls subjected to pure in-plane shear forces. This fundamental behavior of SC walls is illustrated using the results from a large-scale in-plane shear test of an SC wall specimen (with flange walls), and compared to the predictions from the MBM. The paper also includes a comprehensive experimental database of all in-plane shear tests conducted in Japan, S. Korea, and US. The database consists of 26 SC wall tests with a wide range of parameters for the wall thickness, reinforcement ratio, aspect ratio, and the presence (or absence) of axial stress. The experimental results are used to identify the key parameter influencing the in-plane shear strength of SC walls, which is shown to be the steel faceplate reinforcement ratio. The design code equations used in engineering practice around the world are used to predict the in-plane shear strength of all 26 SC wall specimens in the database. The conservatism and accuracy of the code predictions of strength are evaluated by comparing them with experimental results, and reliability analysis are performed to estimate the associated strength reduction (ϕ) factors.

1. Introduction

Steel plate composite (SC) walls have been used for safety-related facilities in the third generation of nuclear power plants and they are also being considered for future small modular reactor (SMR) plants. SC walls consist of structural steel modules that are filled with plain concrete to develop composite systems. As shown in Fig. 1, the steel modules consist of: (i) two steel faceplates that form the surfaces of the SC wall, (ii) uniformly distributed steel headed stud anchors (or shear studs) on the inside surfaces of the steel faceplates, and (iii) tie bars or rods connecting the two faceplates together. The concrete filled into the steel modules is either conventional normal weight concrete or self-consolidating concrete (SCC). The stud anchors provide composite action between the steel faceplates and the concrete infill (after it sets), and the tie bars provide connectivity between the steel faceplates and structural integrity (resistance to splitting or lamellar fracture) to the composite SC wall.

The interest in SC walls is motivated by their suitability and efficiency for modular construction techniques, which enable considerably faster erection and construction compared to traditional reinforced concrete (RC) construction. The steel modules are fabricated in shops with quality control and automation where possible, and shipped to the site for assembly and construction. The modules serve as stay-in-place formwork for casting concrete, which may not require vibration for consolidation if it is self-consolidating concrete. Thus, SC walls can improve the construction efficiency and economy of safety-related nuclear facilities over conventional reinforced concrete (RC) construction [1].

SC walls are being used in safety-related nuclear facilities as part of containment internal structures, for example, steam generator compartments, pressurizer, refueling cavity walls etc. in US-APWR® [2]. SC walls are also being used for containment external structures such as the shield building in AP1000® [3]. These nuclear power plant structures are labyrinthine in plan with several SC walls intersecting and providing cross walls to each other. Sener et al. [4] have discussed the seismic (lateral load) behavior and design of such safety-related nuclear facilities consisting of SC walls. Experimental and analytical investigations indicate that the seismic behavior and design of these structures is governed by the in-plane shear behavior of the SC walls, which serve as the primary lateral load resisting system. It is imperative to evaluate the in-plane shear behavior and strength of SC walls to assess the global response and strength of the overall structure.

Experimental studies have been conducted in Japan, S. Korea, and the US to investigate the in-plane shear behavior of SC walls. These studies have focused on: (i) the pure in-plane shear behavior of SC wall panels [5,6], or (ii) the lateral load capacity of SC walls with flanges (or cross walls), which is governed by the in-plane shear strength of the

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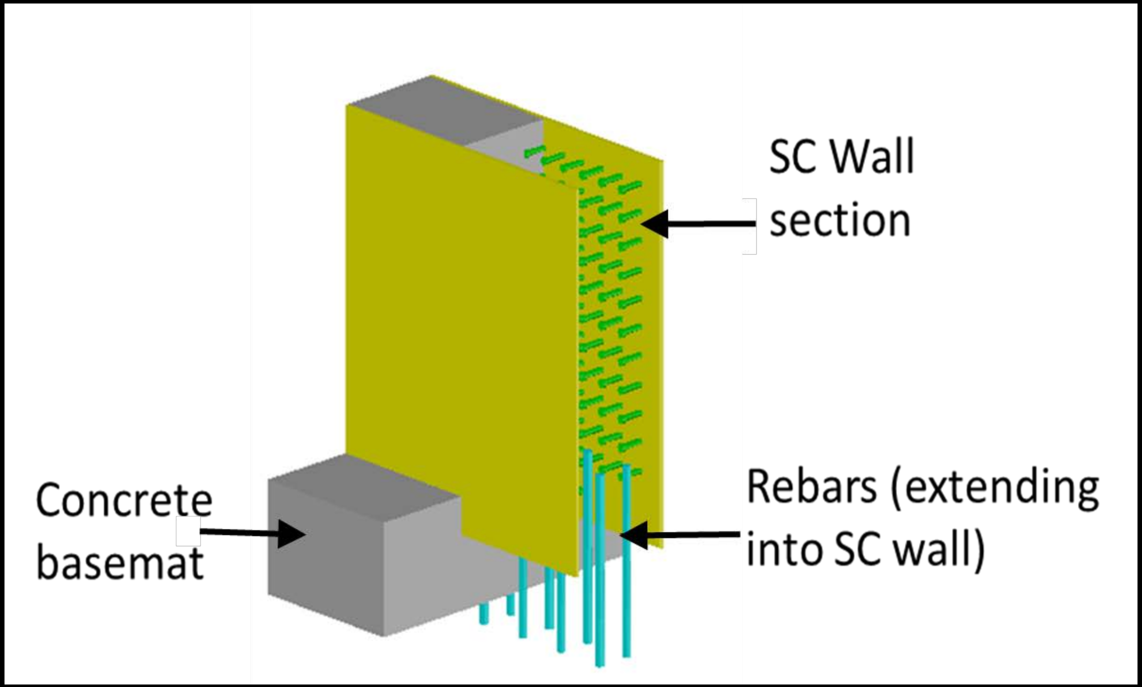
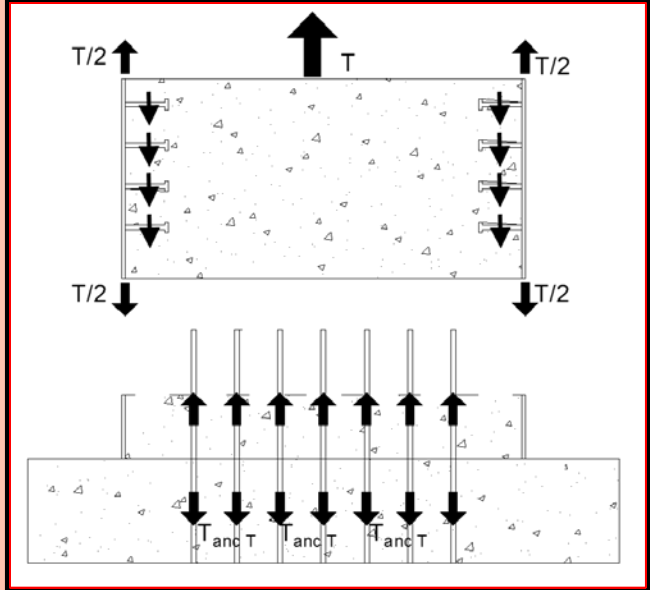
SC Wall-to-Basemat Anchorage Connection

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

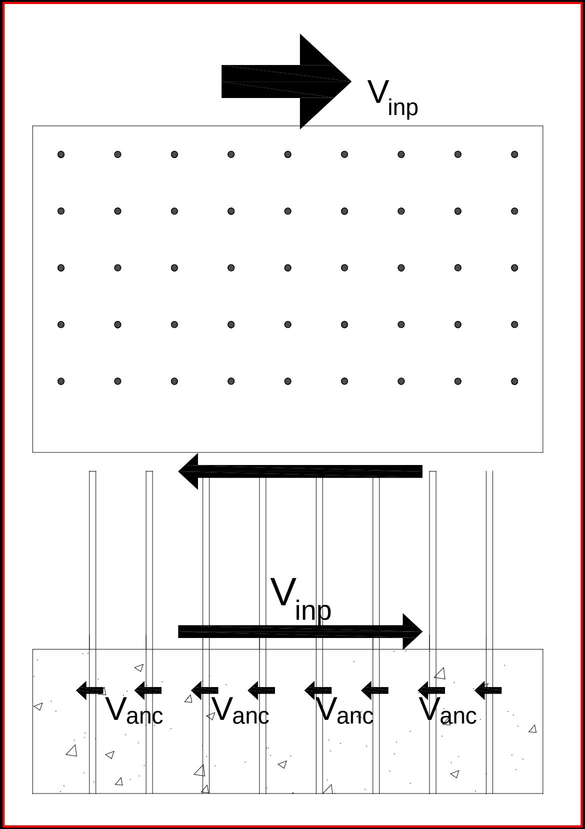


SC Wall-to-Basemat Anchorage using
non-contact spliced rebars

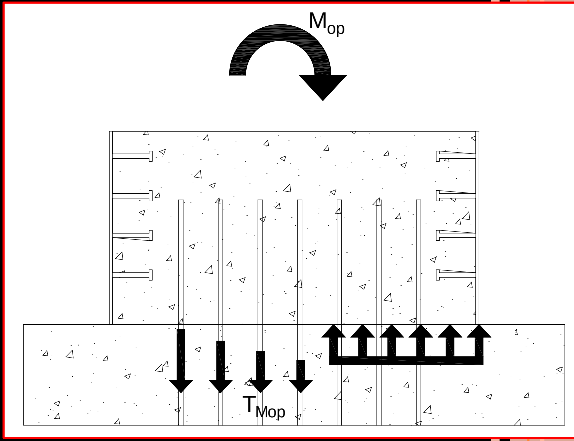
Force Transfer Mechanisms



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.

MAJO

- Seo, J., a … and Design of … (SC-to-RC) Lap … eering, ASCE, Ac…
- This pape… numerica… SC-to-RC lap-sp… s included t… stance between … gth, and tie ba…

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

Jungil Seo[1] and Amit H. Varma[2]

[1] Research Engineer, School of Civil Engineering, Purdue University, 1040 South River Road, West Lafayette, IN, USA 47907 (corresponding author). saojunga@gmail.com
[2] Professor, School of Civil Engineering, Purdue University, West Lafayette, IN, USA. ahvarma@purdue.edu

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 (L_d) in the RC portion and embedded (L_{emb}) 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 (L_{emb}), 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_t). 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 L_{emb}, n, α, and ρ_t. 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.

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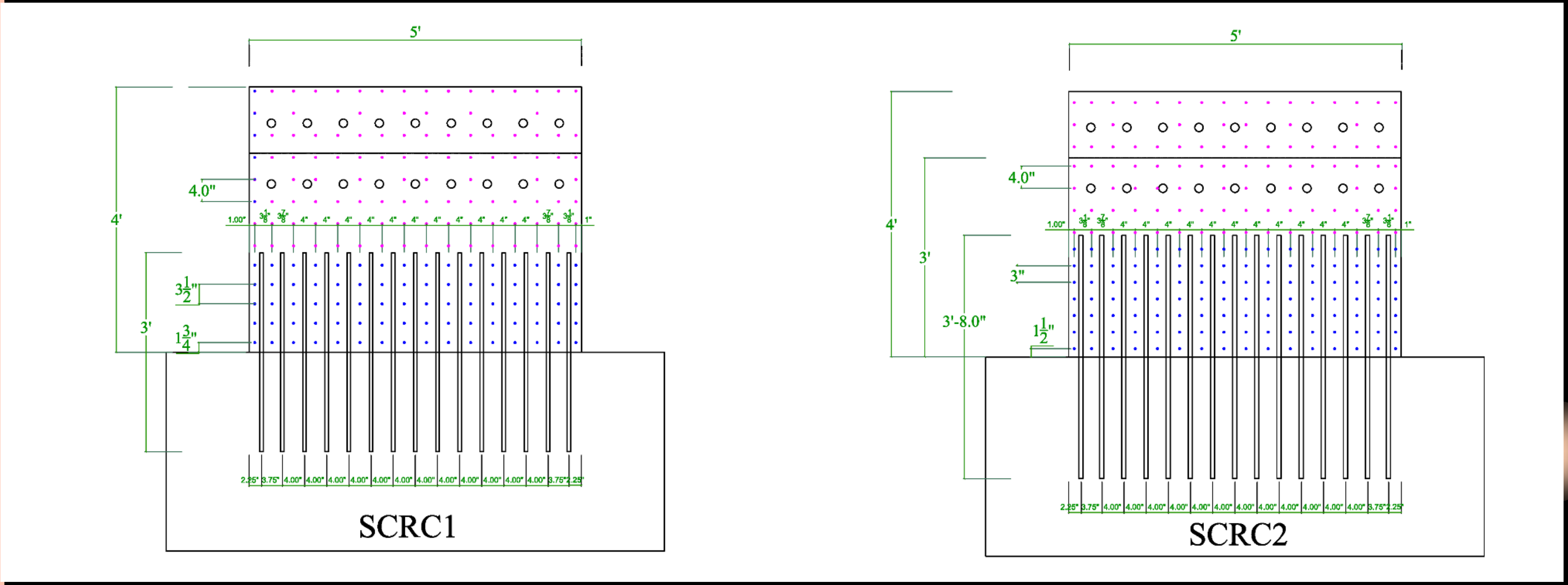
MAJOR RESEARCH PRODUCTS - 4

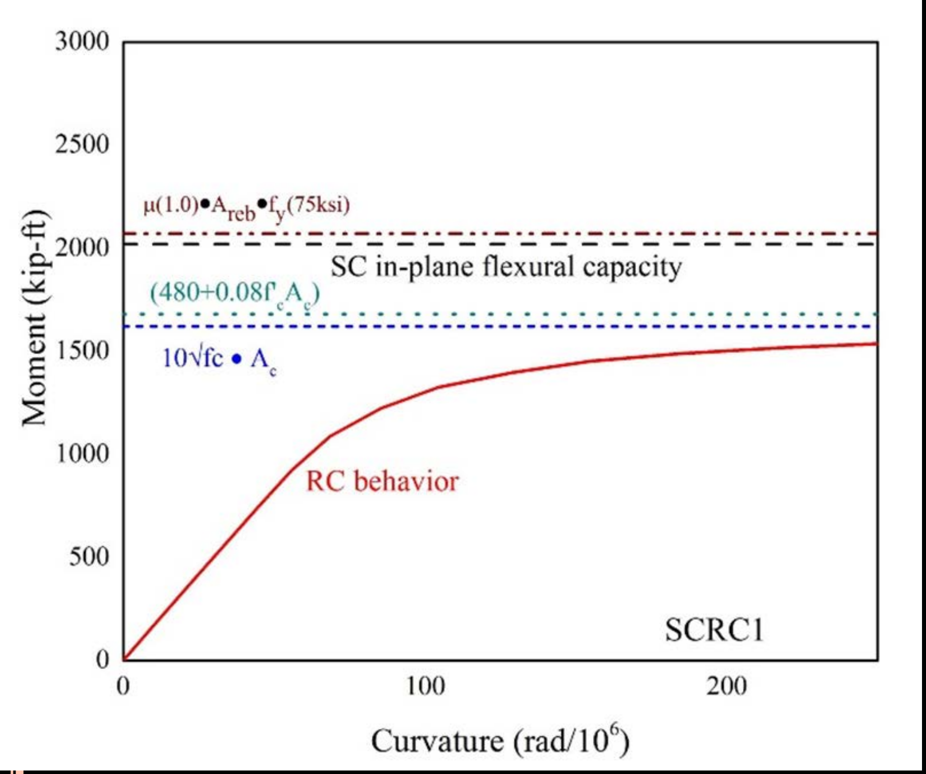
- PRIMARY FINDINGS
- Force transfer from the steel faceplates (of the SC portion) to the steel dowels (of the RC portion) can be accomplished using stud anchors.
- The number (*n*) and strength (Q_n) of these stud anchors and ties should be designed and detailed to develop the expected strength (N_r) 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 (ρ_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.

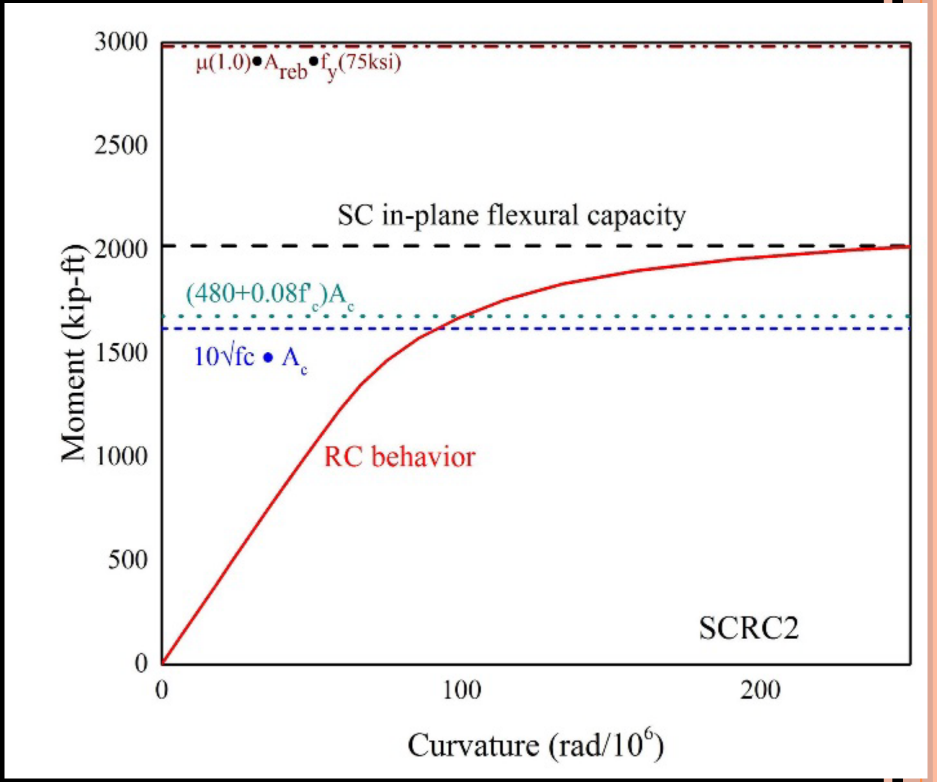
Major Research Products - 5

- 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

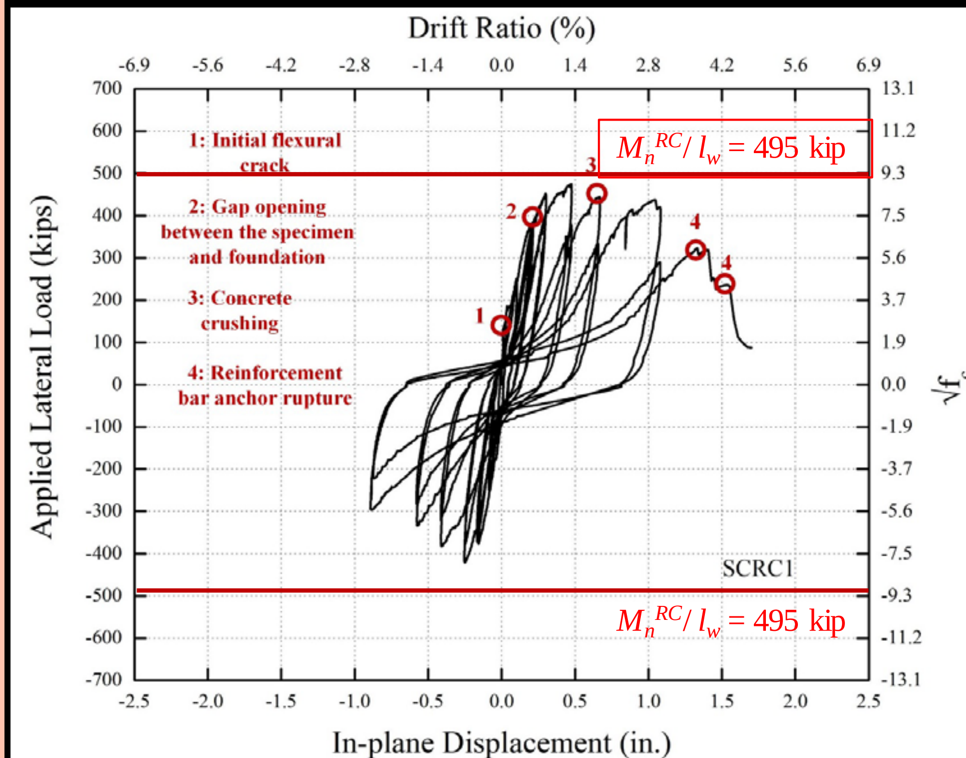


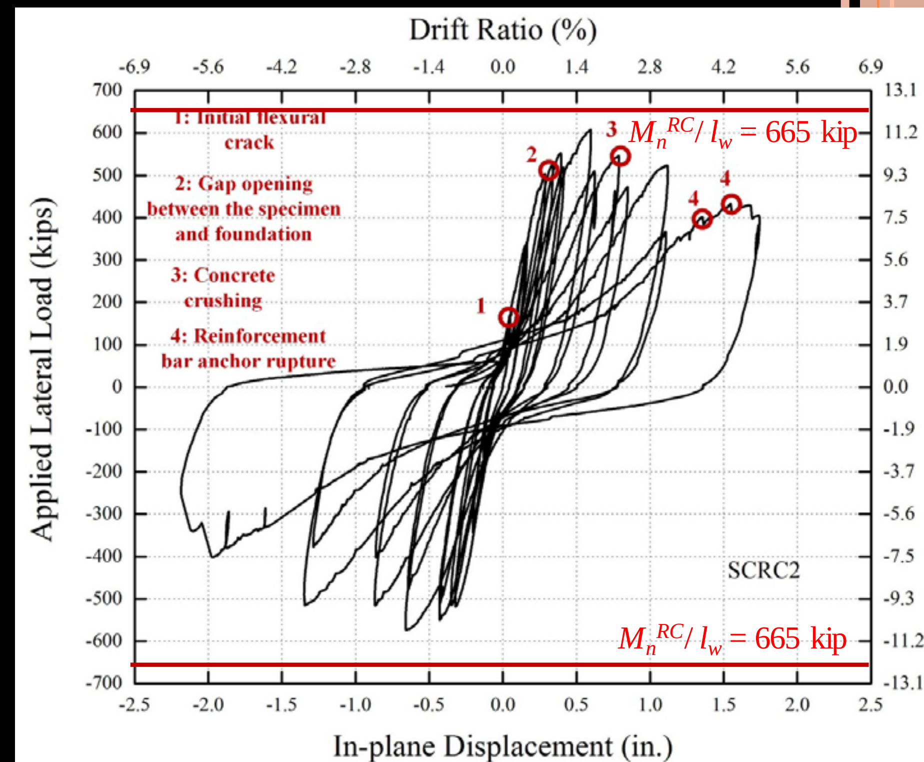


SCRC1 designed to be governed by flexural capacity of RC portion at base

SCRC2 designed to be governed by shear strength of RC portion at base

MAJOR RESEARCH PRODUCTS - 5



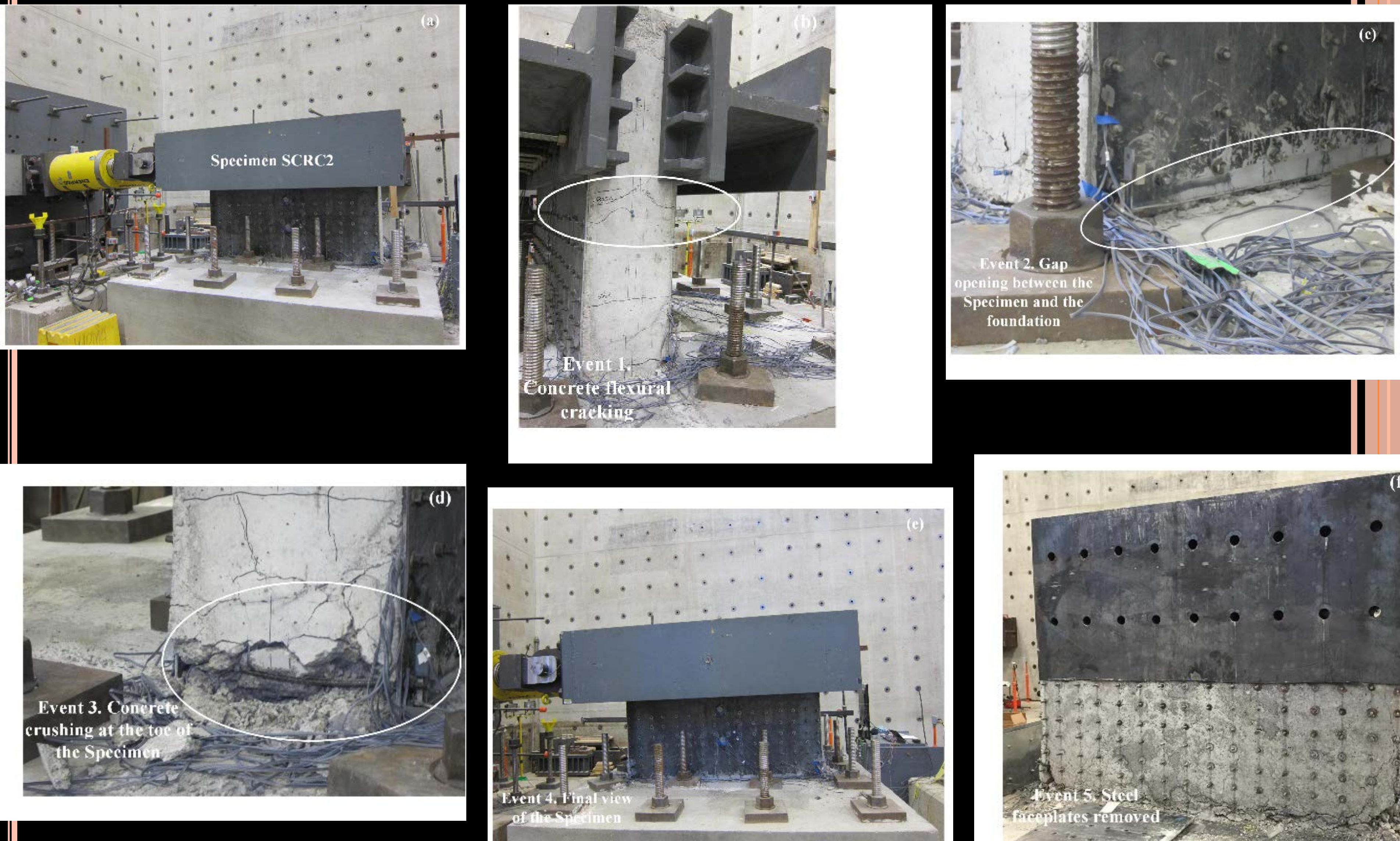


Cyclic behavior of SCRC1 governed by flexural yielding of the RC portion at the base. Does not develop SC wall strength Overstrength connection demonstrated

Cyclic behavior of SCRC2 also governed b flexural yielding of the RC portion at the base. Does not develop SC wall strength Overstrength connection demonstrated

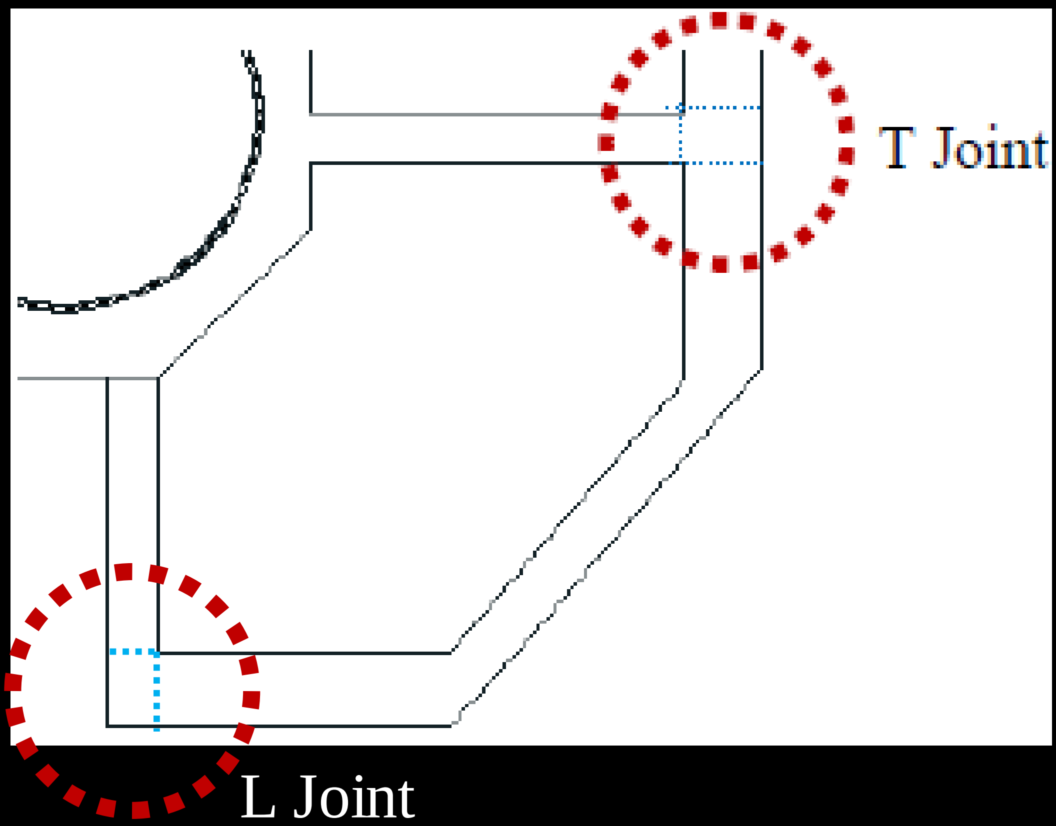
Major Research Products - 5

Published in Ph.D. Dissertation of Efe Kurt. The corresponding journal article is still being prepared



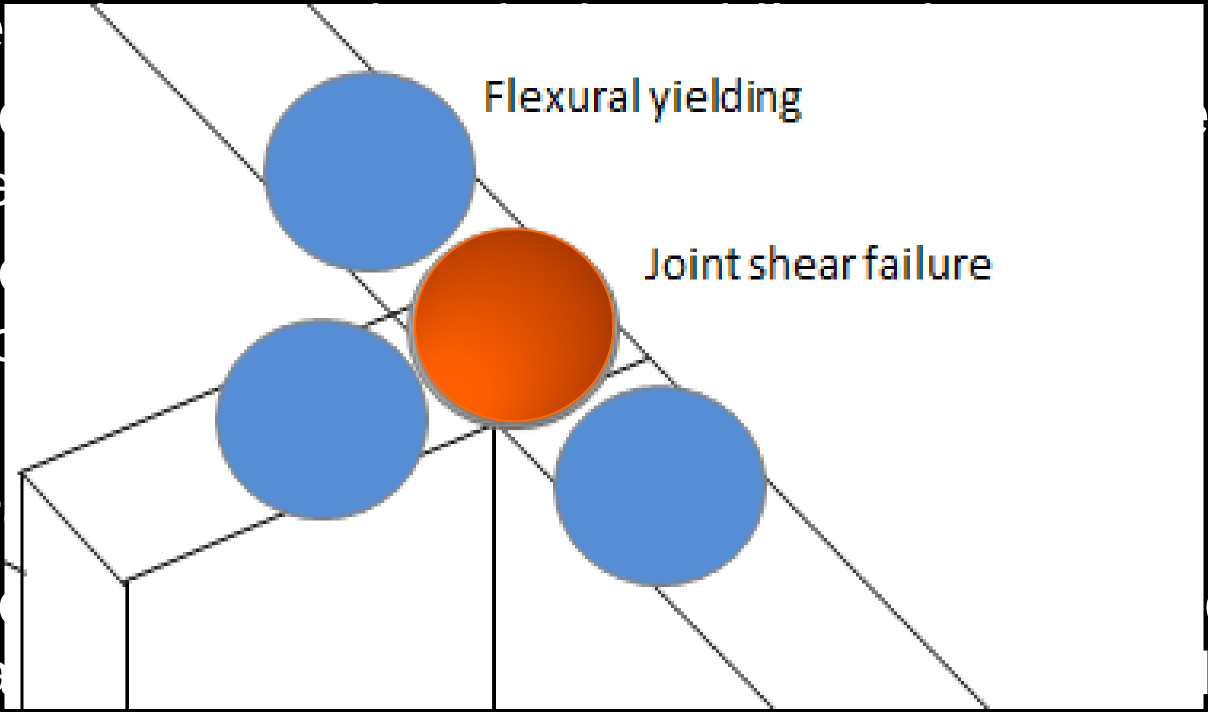
SC WALL-TO-WALL CONNECTIONS

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



SC WALL-TO-WALL JOINTS

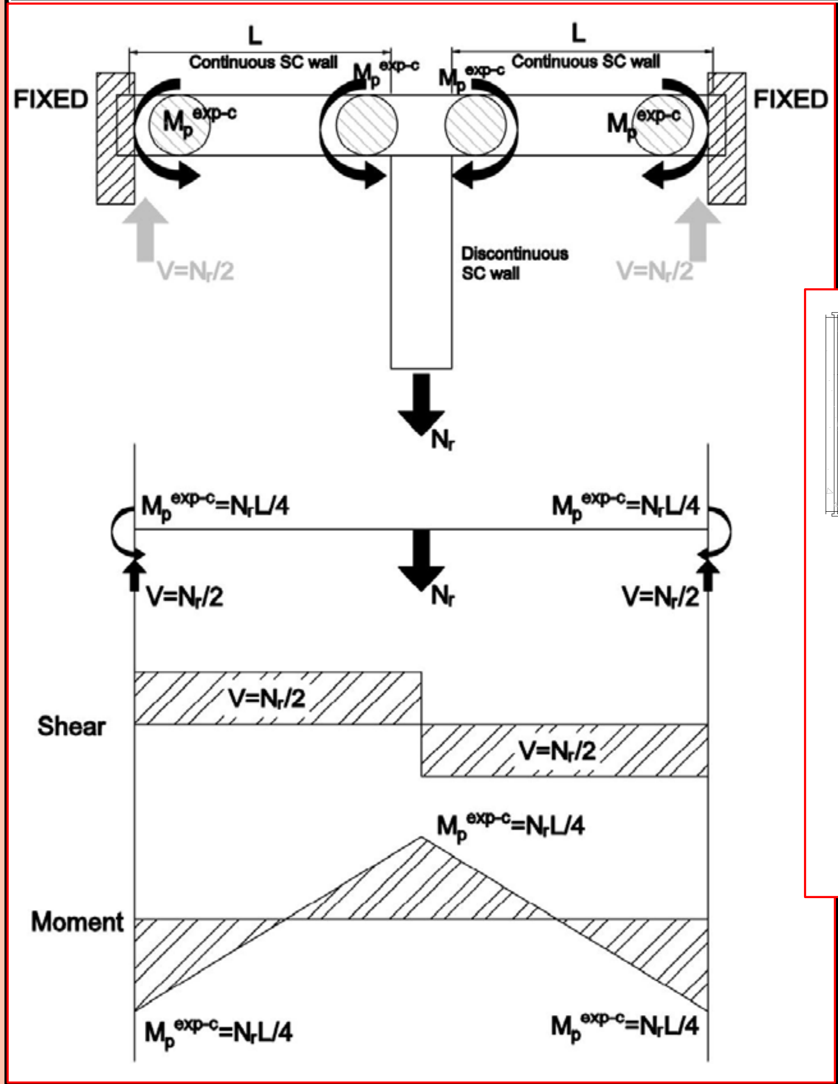
- Full-stre
  - Devel e two conne
  - Failur n of plastic
- Over-str
  - Devel er than the ca load)



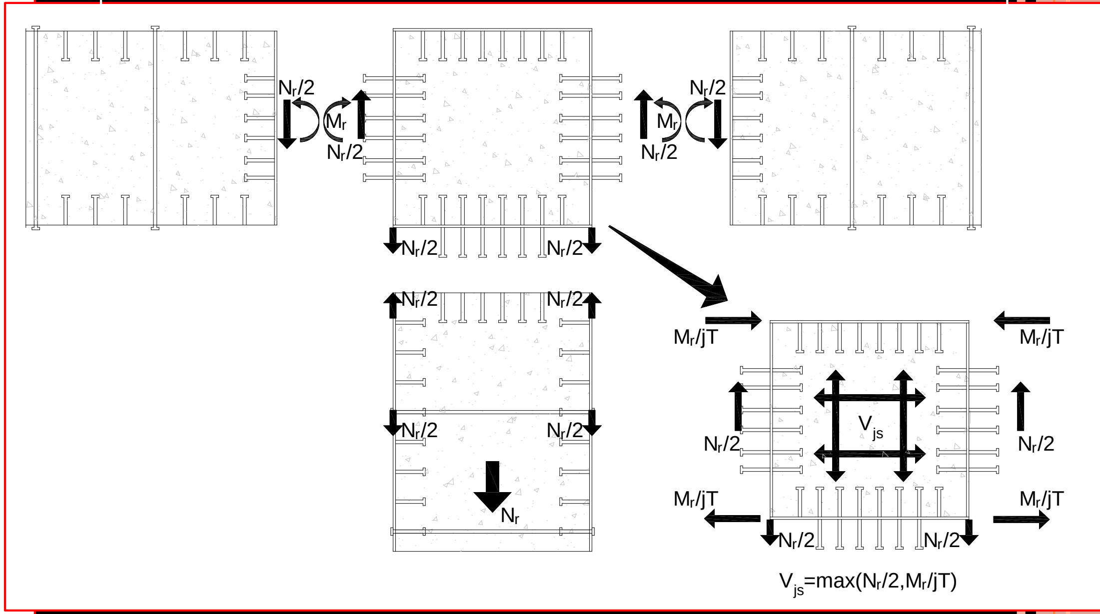
- *In order to implement either philosophy, need to calculate JOINT SHEAR STRENGTH to either prevent it (for full-strength) or have over strength with respect to it.*

Force Transfer Mechanisms

Axial Tension in Discontinuous Wall

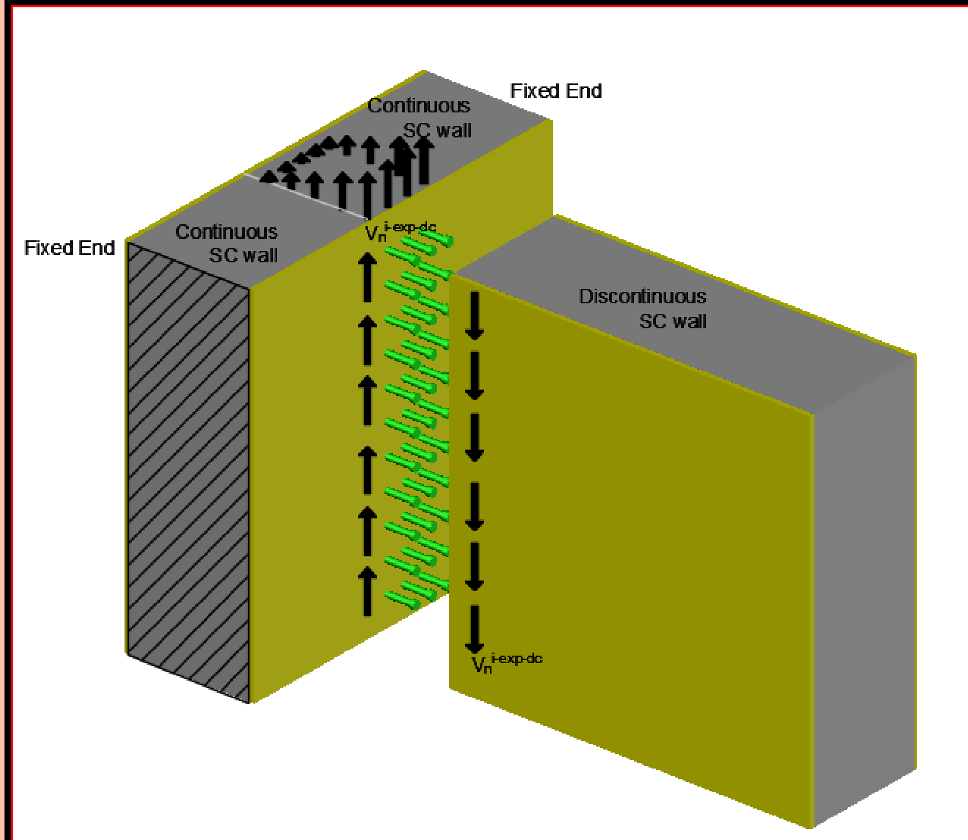


Resulting Joint Shear Force to Achieve Flexural Yielding in Cont. Walls

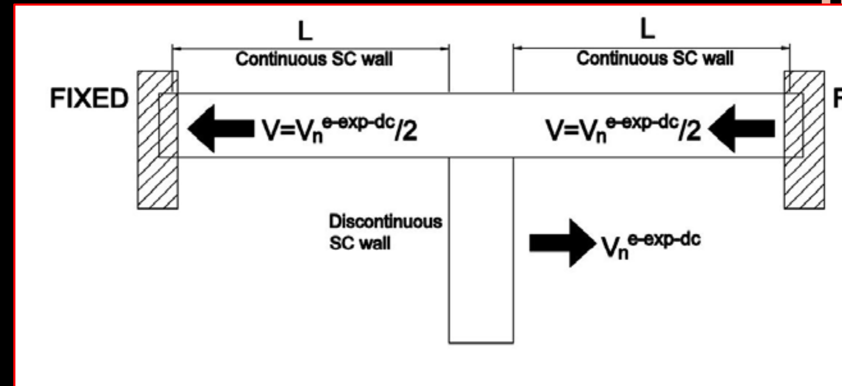


Force Transfer Mechanisms

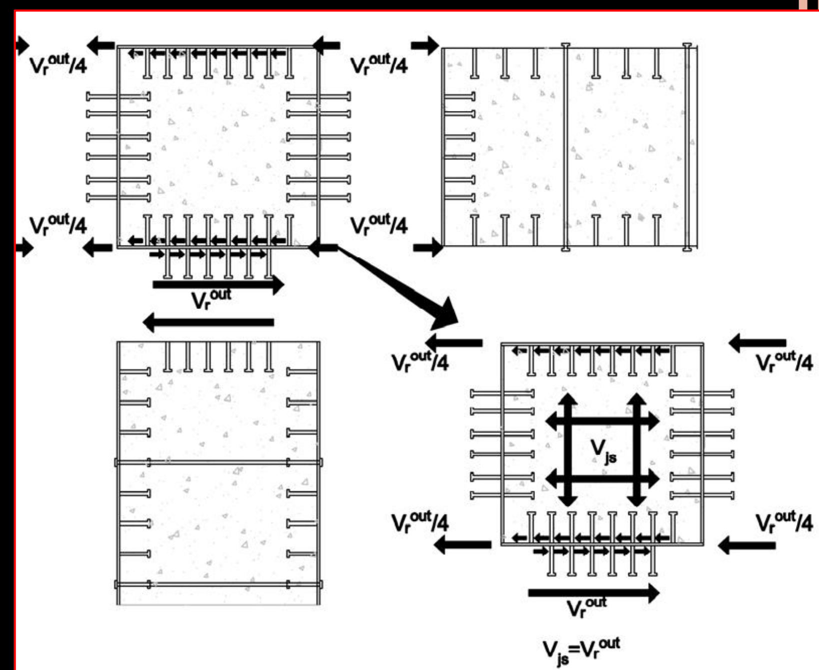
For In-Plane Shear Demand



For Out-of-Plane Shear Demand



Resulting Joint Shear Force



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

Seo, J., and Varma, A.H. (2016). “Behavior and Design of Corner or L-Joints in SC Walls.” Structures, Elsevier Science, Submitted May 2016.

Major Research Products - 6

- Seo, J. and Varma, AH (2016). “Joint Shear Strength of SC Wall-to-Wall T-Joints.” *Journal of Structural Engineering*, ASCE, Submitted for review and publication.

- Seo, J. and Varma, AH. (2016). “Behavior and Design or Corner or L-Joints in SC Walls.” *Structures,* Elsevier Science, Submitted for review and publication

- Ph.D. Dissertation of Jungil Seo, Purdue Univ.

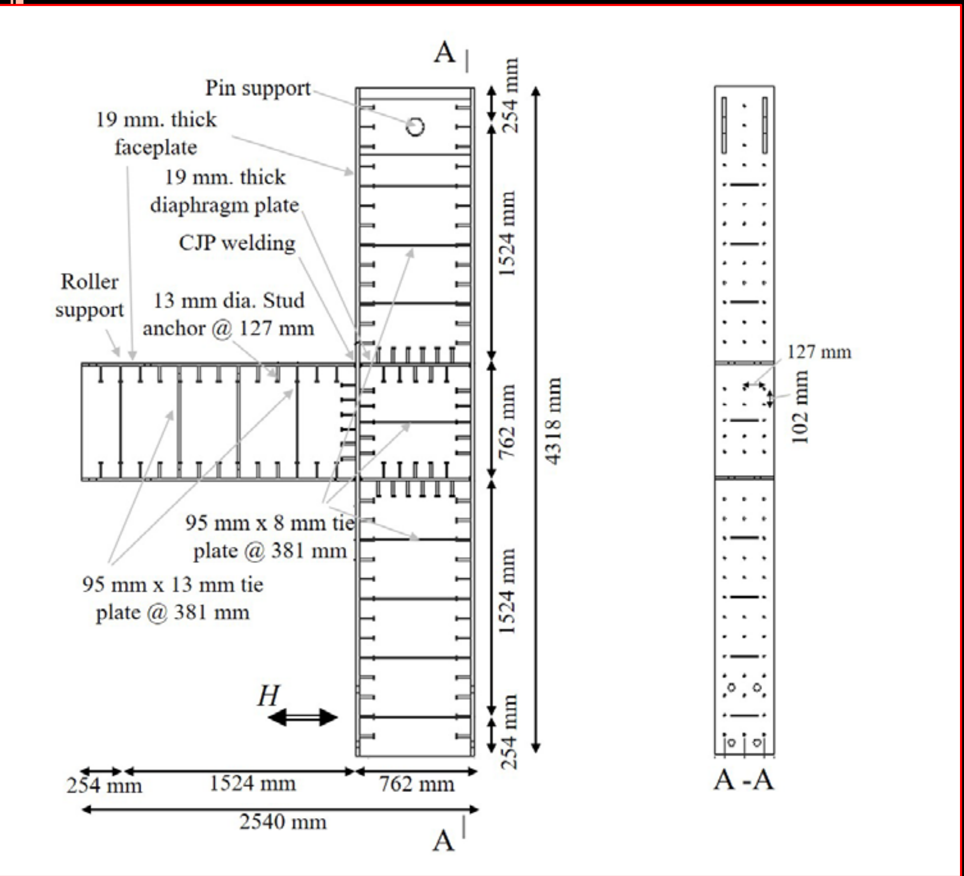
Major Research Products - 6

- 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

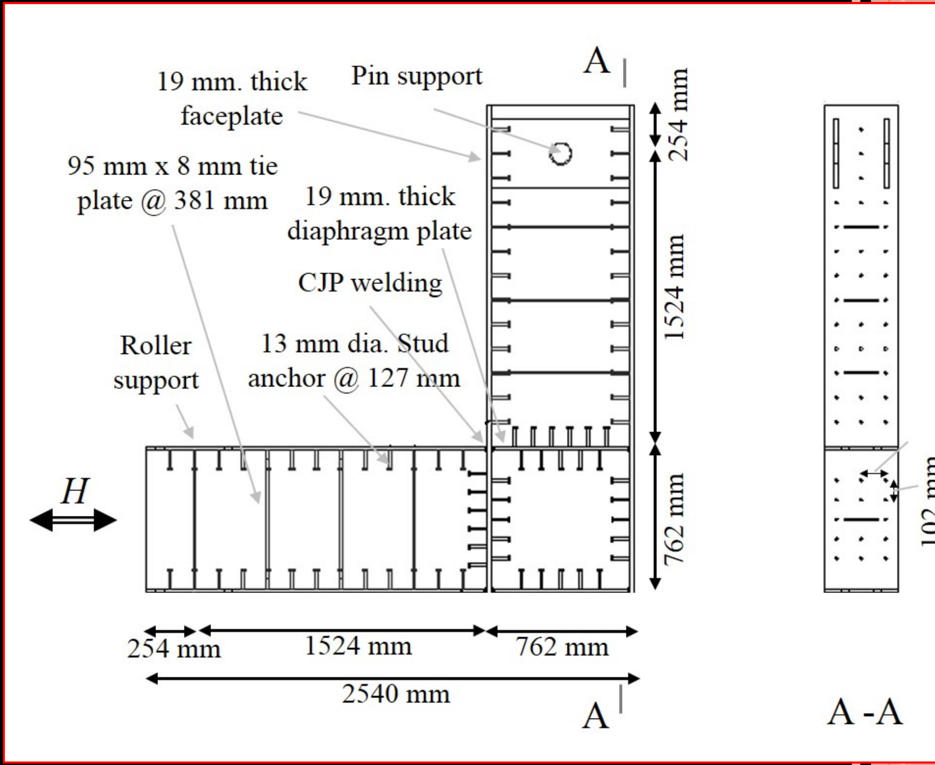
$$V_n = \gamma \sqrt{f'_c} A_j$$

- $\gamma = 12$ 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

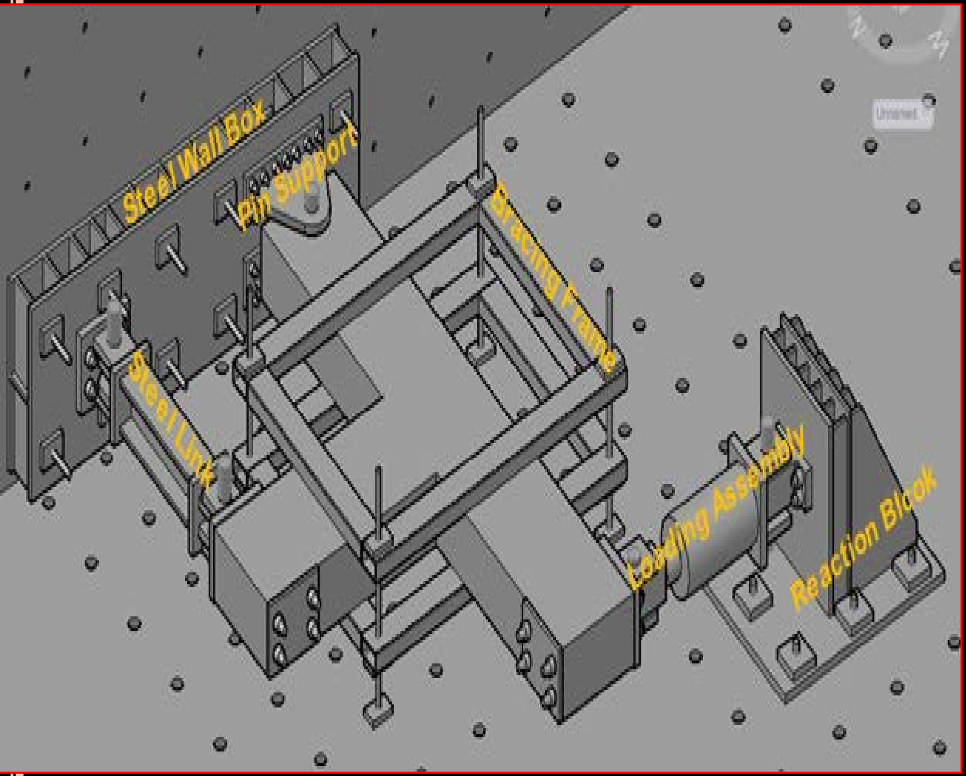


Details of T-Joint Specimens

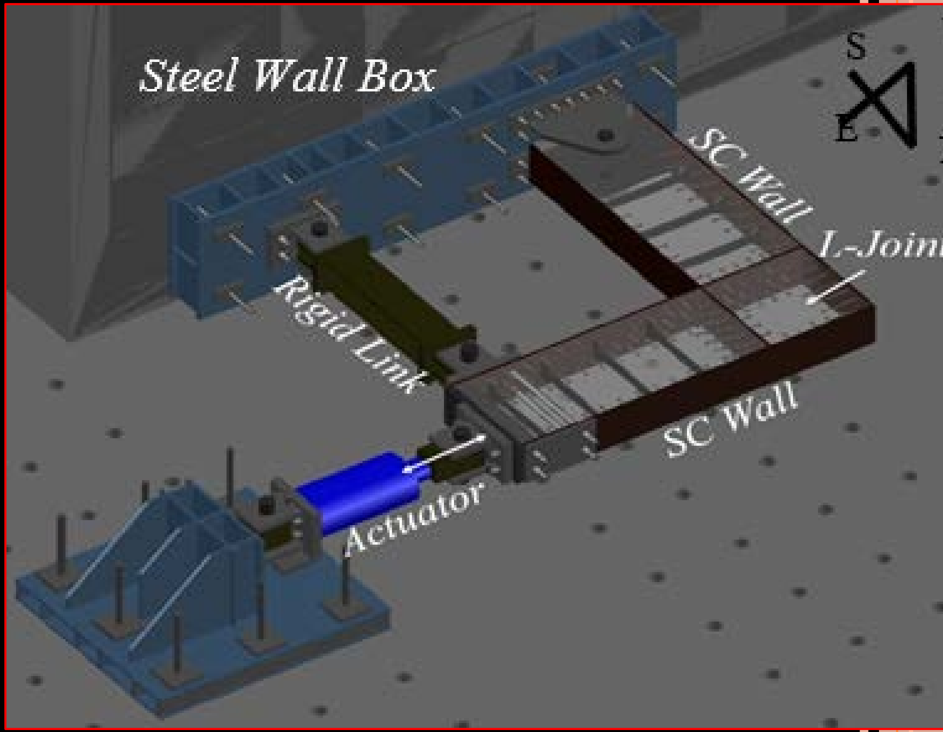


Details of L-Joint Specimen

Major Research Products - 6



Test-Setup for T-Joint Specimens



Test-Setup for L-Joint Specimens

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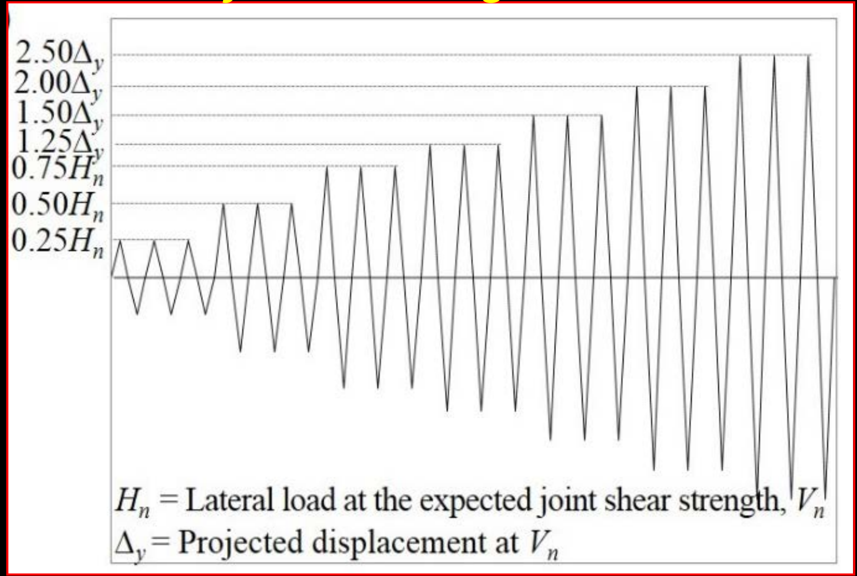
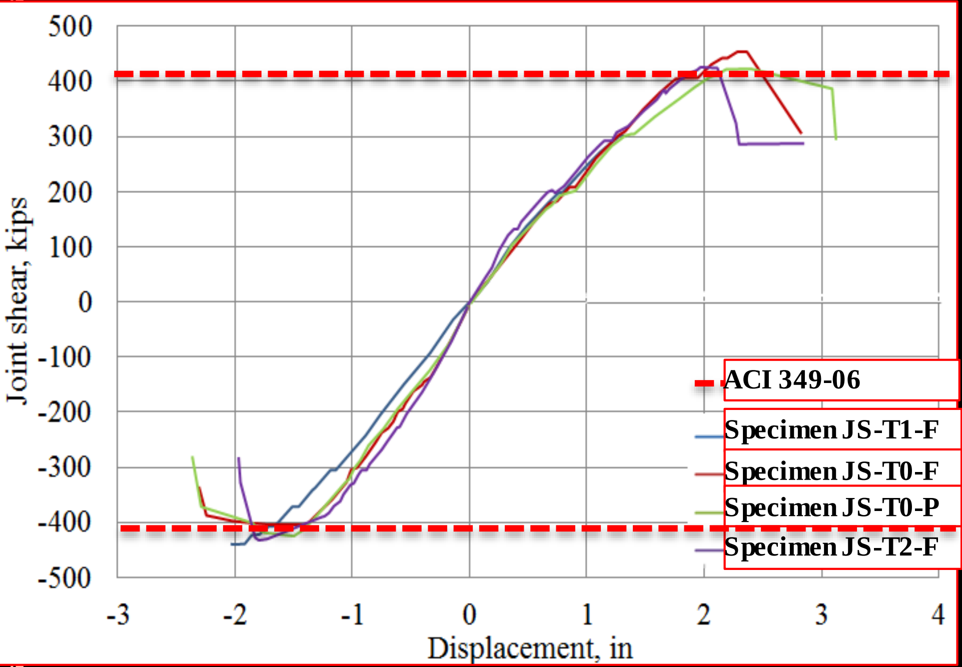
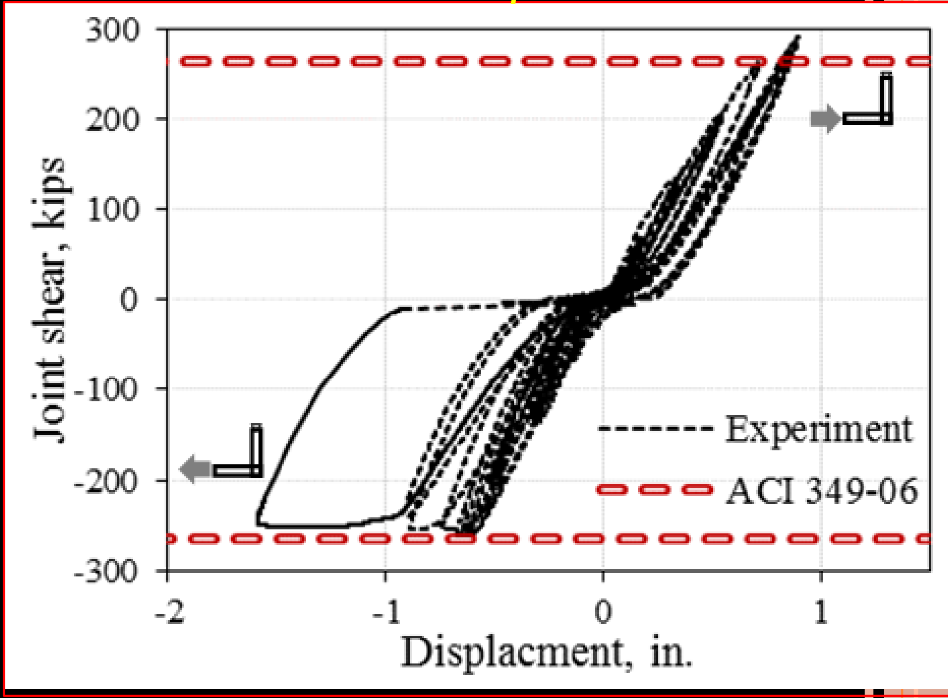
Cyclic Loading Protocol



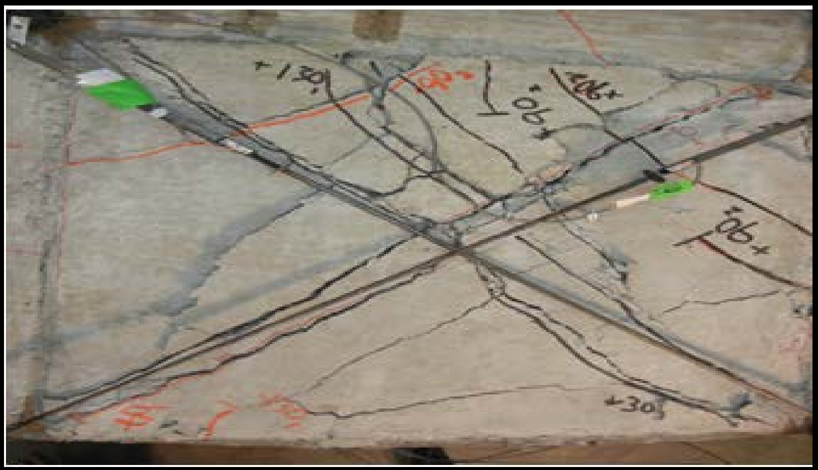
Shear Force-Displacement Behavior of T-Joint Specimens



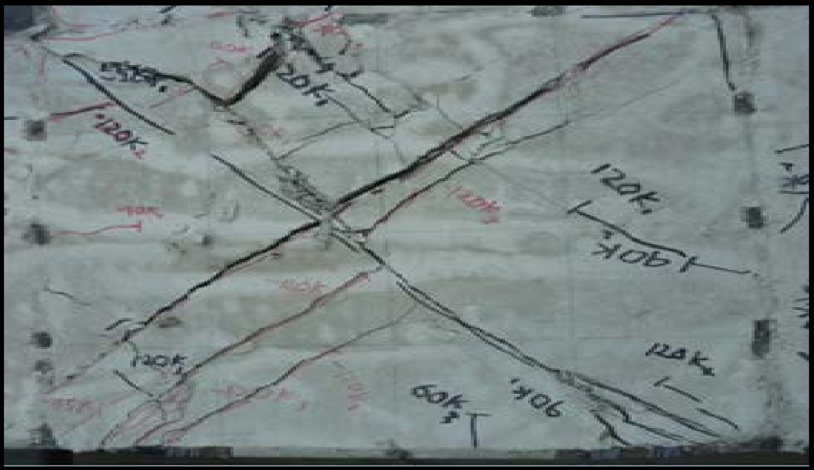
Shear Force-Displacement Behavior of L-Joint Specimen



- Crack pattern at the ultimate joint shear : all specimens



JS-T1-F

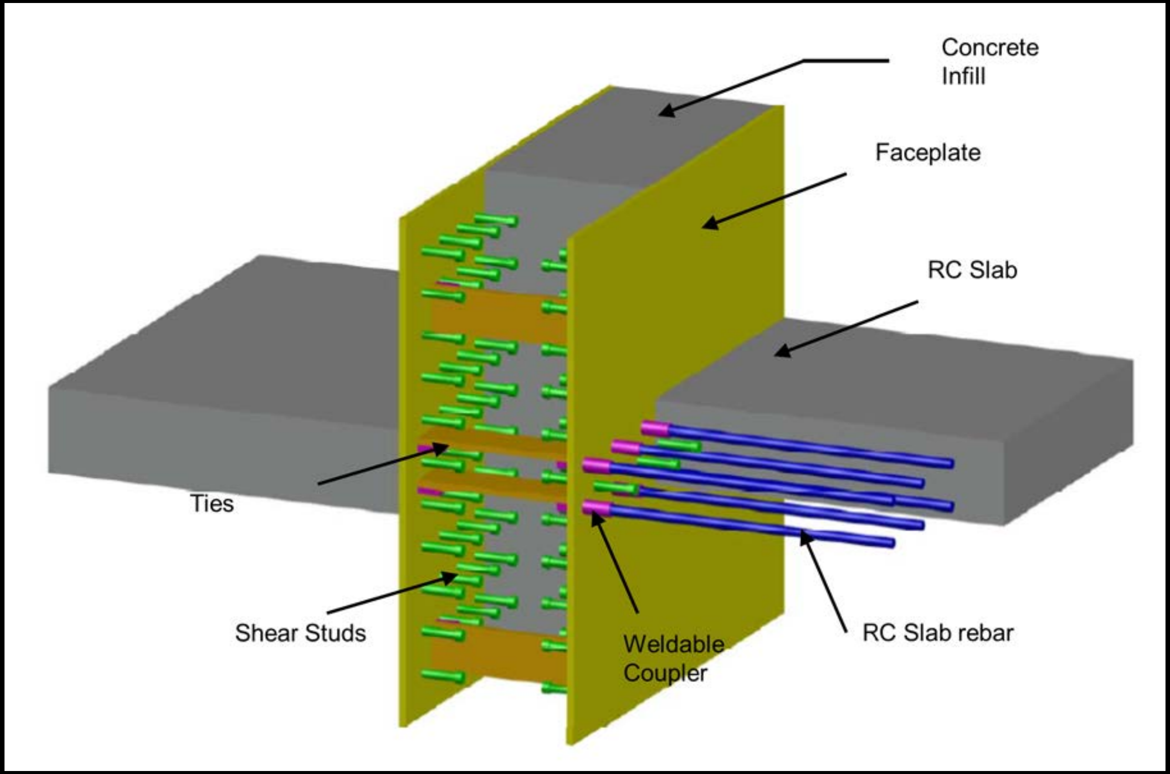


JS-T0-F

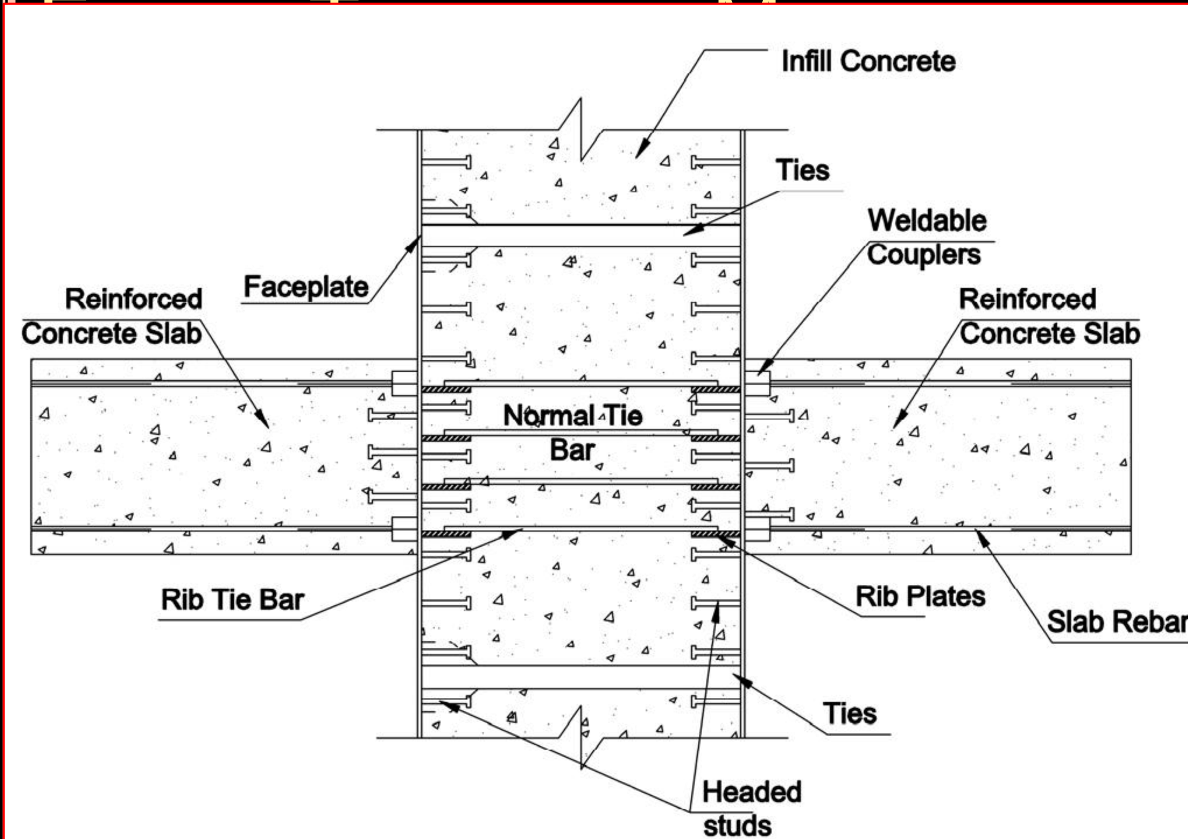
JS-T0-P

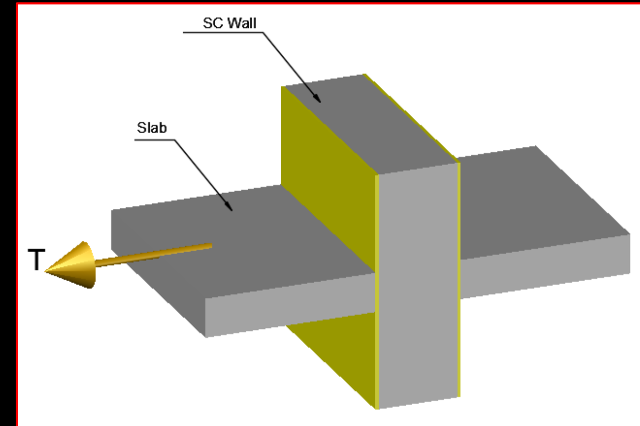
JS-T2-F

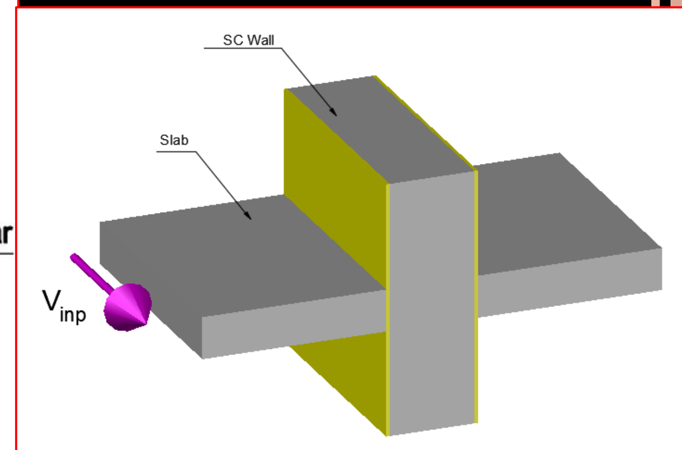
SC Wall-to-Slab Connections

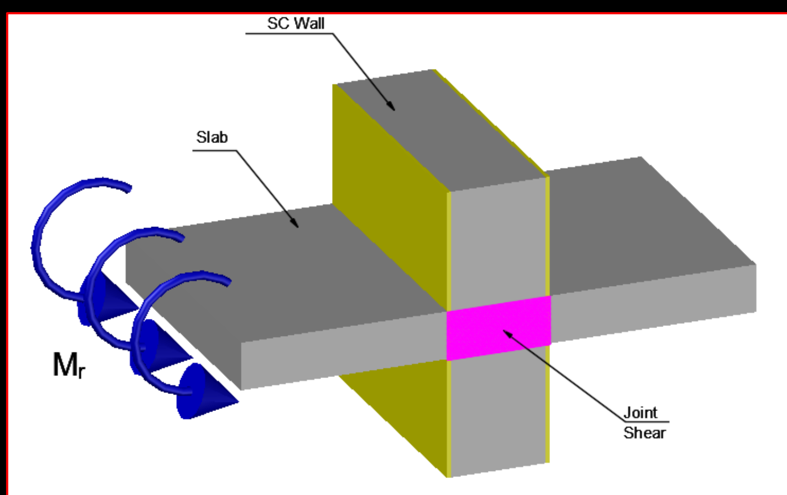


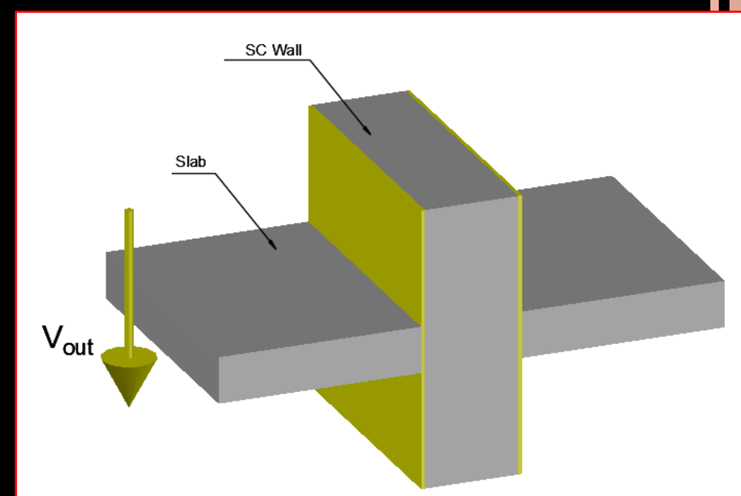
Typical SC Wall-to-RC Slab Connection


Infill Concrete
Ties
Weldable
Couplers
Faceplate
Reinforced
Concrete Slab
Reinforced
Concrete Slab
Normal Tie
Bar
Rib Tie Bar
Rib Plates
Slab Rebar
Ties
Headed
studs


SC Wall
Slab
T


SC Wall
Slab
V_{inp}


SC Wall
Slab
M_r
Joint
Shear


SC Wall
Slab
V_{out}

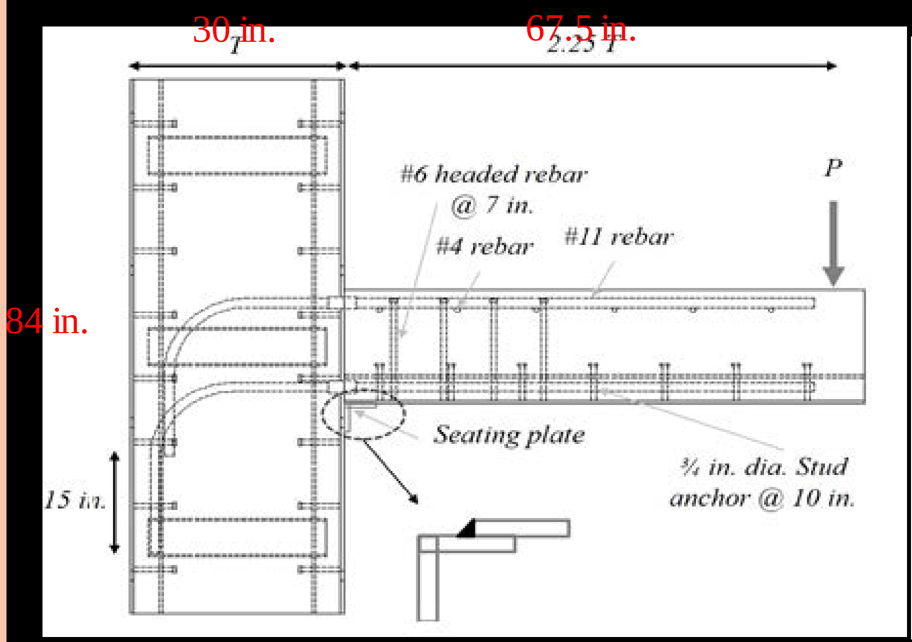
Research Needed to Complete Design

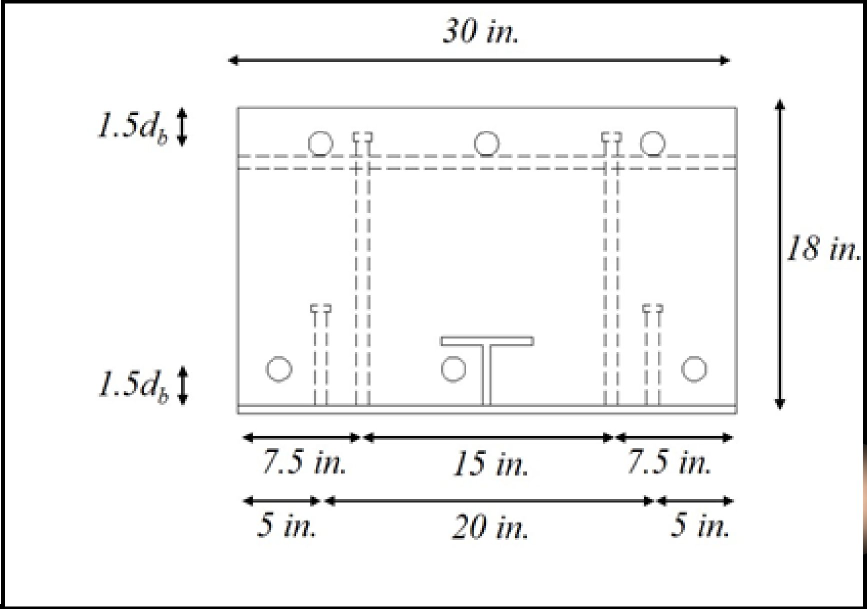
- Out-of-plane shear and moment transfer mechanism need experimental validation. There are no codes / standards for estimating the out-of-plane shear strength of the wall-to-slab joint region.

- Experimental verification of the wall-to-slab out-of-plane shear strength is needed.

Major Research Product - 7

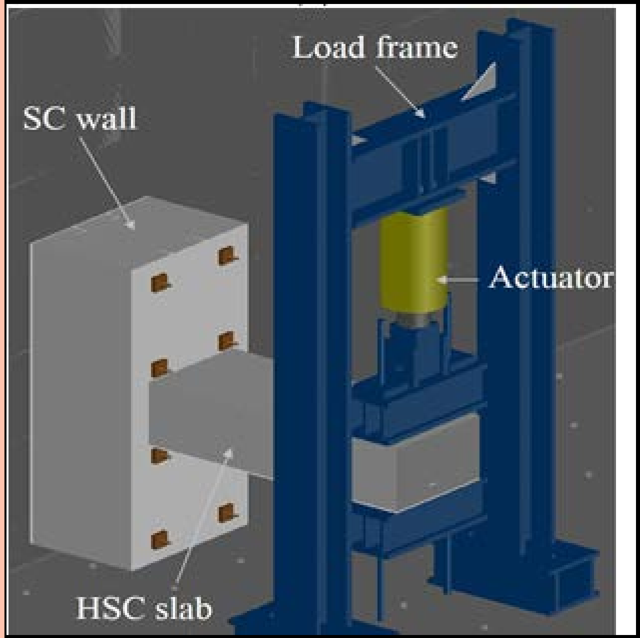
- Two large-scale SC wall-to-RC slab specimens were tested to evaluate the out-of-plane moment transfer mechanism, and out-of-plane shear strength
- Specimens were designed to develop the flexural capacity of the RC slab (using rebars).



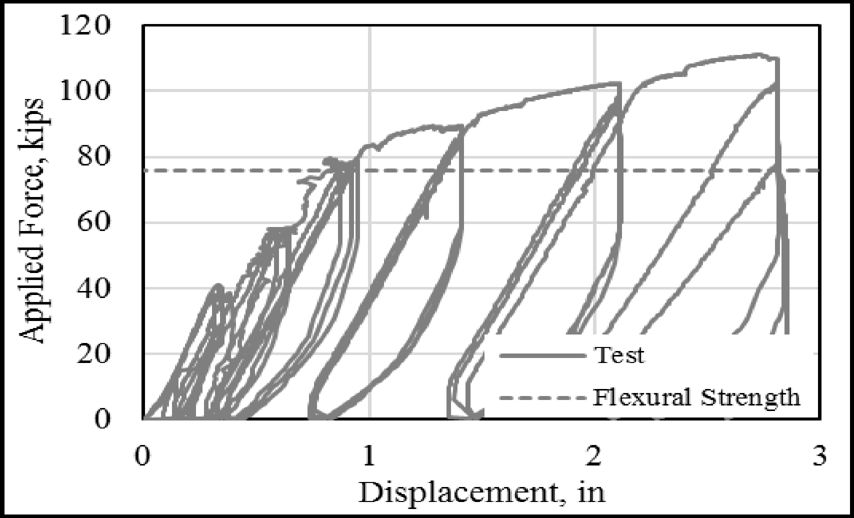


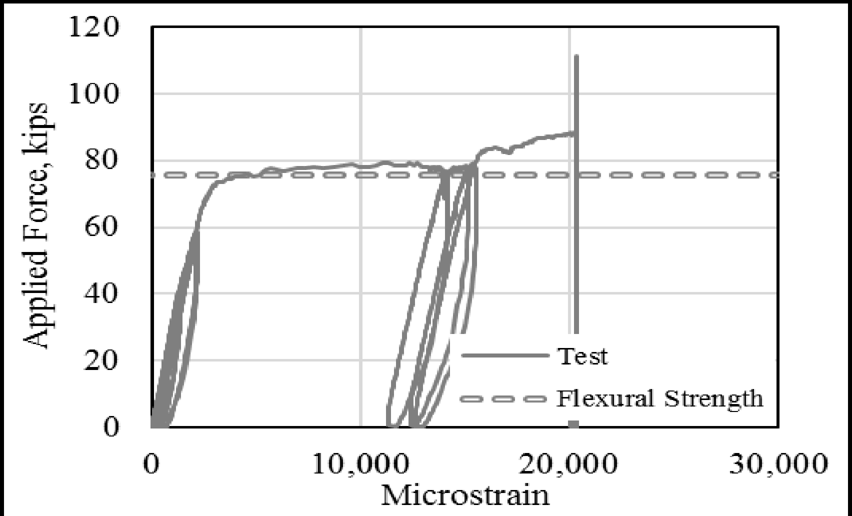
Major Research Product - 7

Test Setup



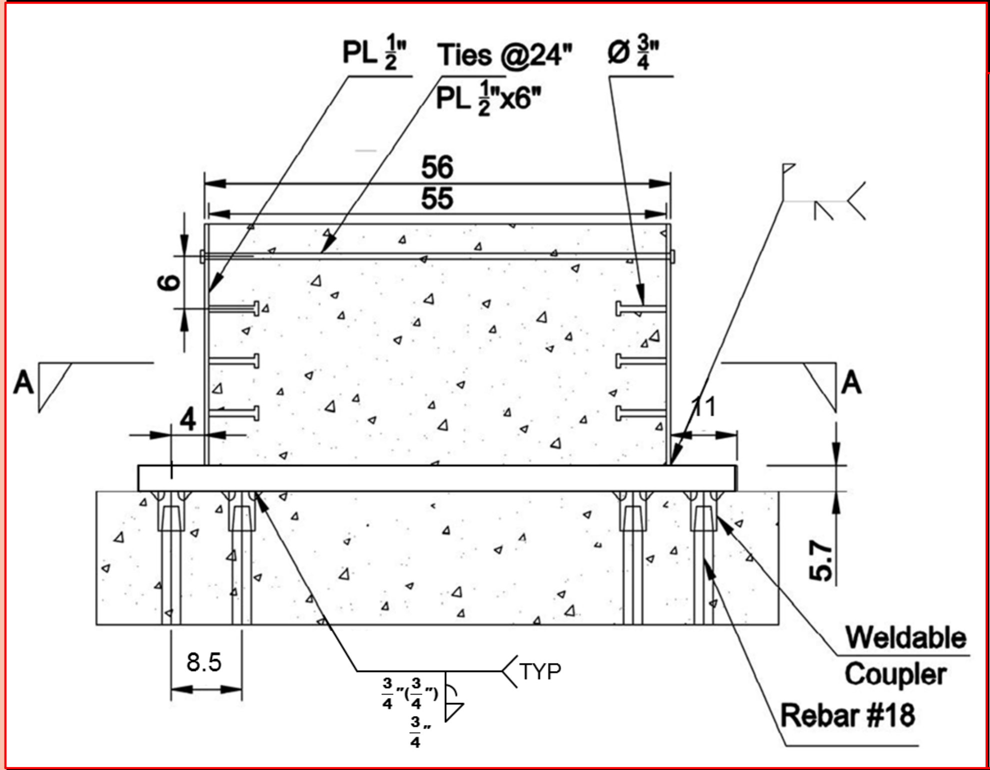
Force-Displacement

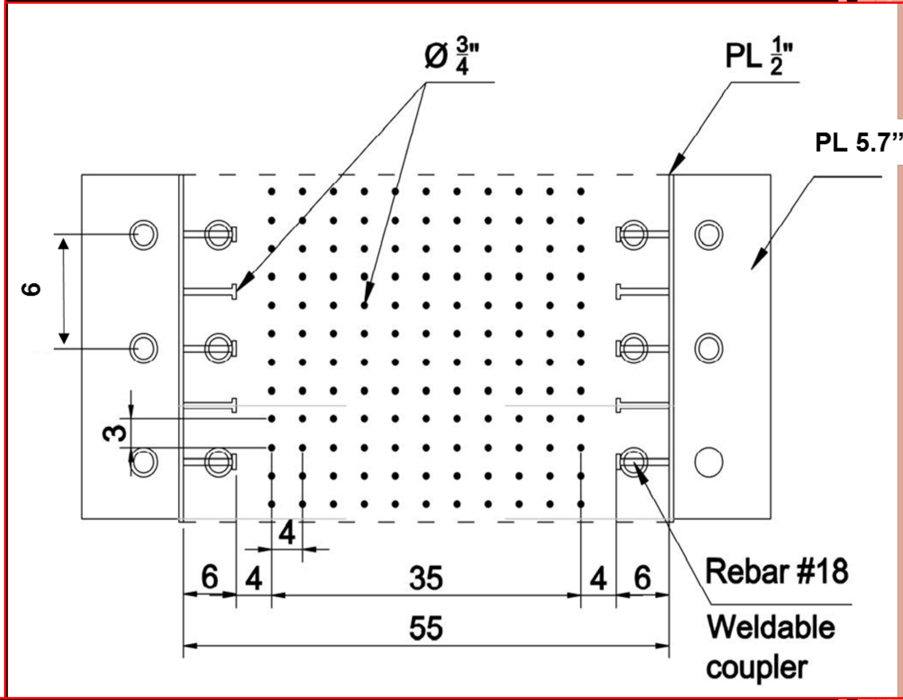




Complete Design Example

- 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

ACKNOWLEDGMENTS

- Westinghouse Electric Company
- Tod Baker, Keith Coogler, Kai Zhang, Bernd Laskewitz, Jurie Van Wyk, Michael Corletti
- Hirschfeld Industries, LLC for fabricating specimens
- DOE- NEUP Program