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SMR-300 Concrete Strengthened Steel Structures Design and Analysis Methodology Licensing Topical Report

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Export Control restrictions do not apply to this record.

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Revision Log

Revision	Description of Changes
0	Initial Issue.

Executive Summary

SMR, LLC plans to construct certain SMR-300 structures using Concrete-Strengthened Steel Modules (CSSMs), a novel class of a steel-concrete composite design developed for safety-related nuclear applications. CSSMs combine steel faceplates, stiffeners and cast-in-place concrete infill within a modular framework that enables accelerated construction and delivers robust structural performance.

CSSMs are interconnected to form various building structural members such as structural walls, slabs, basemats, beams, columns and beam-columns. Current industry codes and standards do not directly address the design or analysis of such structural elements; therefore, this Licensing Topical Report (LTR) establishes the design basis, analysis methodology, and acceptance criteria for CSS structural elements.

The LTR consolidates and adapts applicable provisions from existing industry design codes and standards, to provide a comprehensive methodology commensurate with regulatory requirements for safety related and containment pressure retaining nuclear structures.

Additionally, this LTR includes provisions and design principles appropriate for quality assurance and control during fabrication and construction, as well as for lifecycle in service inspection activities, ensuring continued structural reliability and safety throughout the plant's operational life.

Acronym List

ACI:	American Concrete Institute
AISC:	American Institute of Steel Construction
AR:	Annular Reservoir
ASME:	American Society of Mechanical Engineers
BPVC:	Boiler & Pressure Vessel Code
BSW:	Bio Shield Wall
CFT:	Concrete Filled Steel Tube
CIS:	Containment Internal Structure
CJP:	Complete Joint Penetration
CPSW-CF:	Composite Plate Shear Wall - Concrete Filled
CS:	Containment Structure
CSS:	Concrete-Strengthened Steel
CSSM:	Concrete-Strengthened Steel Module
CVN:	Charpy V-Notch
FE:	Finite Element
FEA:	Finite Element Analysis
FP:	Faceplate
GDC:	General Design Criteria
IB:	Intermediate Building
LEFE:	Linear Elastic Finite Element
LOCA:	Loss of Coolant Accident
LRFD:	Load and Resistance Factor Design
LTR:	Licensing Topical Report
METCON™:	Metal-Concrete™
NDE:	Nondestructive Examination
NI:	Nuclear Island
NIFE:	Non-linear Inelastic Finite Element
PARI:	Purdue Applied Research Institute
PS:	Primary Stiffeners
QA:	Quality Assurance
QC:	Quality Control

RAB:	Reactor Auxiliary Building
RB:	Reactor Building
RC:	Reinforced Concrete
RG:	Regulatory Guide
SCCV:	Steel Concrete Containment Vessel
SC:	Steel-Plate Composite
SC-I:	Seismic Category-I
SCV:	Steel Containment Vessel
SS:	Secondary Stiffeners
TG:	Transfer Girder
TI:	Turbine Island
NRC:	Nuclear Regulatory Commission
WPS:	Welding Procedure Specification

Table of Contents

List of Figures

List of Tables

1.0 INTRODUCTION

1.1 Purpose

This LTR describes a design approach and analysis methodology for use of concrete-strengthened steel modules (CSSMs) in safety-related, Seismic Category-I (SC-I) structures, including containment boundary structures. In addition, the LTR establishes requirements for the fabrication, construction, and inspection of CSSMs and the concrete-strengthened steel (CSS) structures constructed from CSSMs. The design approach, analysis methodology and associated requirements are technically acceptable and consistent with current regulations. Applicable regulations and guidance are described in Section 2.0 of this LTR.

SMR, LLC requests that the Nuclear Regulatory Commission (NRC) review and approve the design approach, analysis methodology, and associated requirements as a reasonable and adequate means to meet the safety and performance objectives of regulatory requirements for safety-related, SC-I structures, including containment boundary structures. Specifically, SMR, LLC requests the NRC to:

- Review and approve the design approach and analysis methodology established in Sections 3.0 through 10.0 and Section 12.0 of this LTR.
- Review and approve the requirements for the material, fabrication, construction, inspection, examination, and testing of CSSMs and CSS structures, established in Sections 3.2 and 11.0 of this LTR.

1.2 Scope

1.2.1 Applicability

This LTR is applicable to CSSMs that meet the general requirements established in Section 3.0; and to CSS structures that are constructed from CSSMs. It is applicable to safety-related SC-I structures and containment boundary applications.

1.2.2 Content and Organization of the LTR

The LTR presents the overall approach and supporting technical bases for demonstrating compliance with applicable regulatory requirements by utilizing and adapting, to the extent practicable, relevant existing codes and standards. These codes and standards are further supplemented and modified with design rules specific to the CSS structures.

The LTR includes the following:

- Section 1.3 presents a general description of the SMR-300 structures constructed from CSSMs. Section 1.4 presents a description of the novel CSSMs. These descriptions are intended to familiarize the staff with typical CSSMs and applications to facilitate review of the LTR.
- Section 2.0 presents a discussion of applicable NRC regulations, aspects of NUREG-0800 “Standard Review Plan for the Review of Safety Analysis Reports for

Nuclear Power Plants: LWR Edition," (the Standard Review Plan, or SRP) and regulatory guides (RGs).

- Section 3.0 presents the general design process and establishes the general design requirements that define the CSSMs within the scope of this LTR. This section also presents the required material properties and section detailing criteria that address potential failure modes such as faceplate local buckling, interfacial shear failure and empty module buckling.
- Section 4.0 presents design loads and load combinations used for design of CSS structures.
- Section 5.0 presents modeling approaches and structural analysis methodologies. The effective stiffness equations for the CSS structural elements are developed to conduct linear elastic finite element (LEFE) analyses that determine the design demands for the CSS structural elements.
- Section 6.0 presents design capacity and interaction equations for evaluation against design demands. For CSSMs used in containment boundary structures, additional stress-based acceptance criteria are also provided.
- Section 7.0 presents the design philosophy and performance requirements for connections of CSSMs.
- Section 8.0 presents specifications for design and analysis of openings in CSSMs and CSS structures.
- Section 9.0 presents the approach for impactive and impulsive loads applied to CSSMs and CSS structures.
- Section 10.0 presents the design considerations for performance related to fire.
- Section 11.0 presents quality assurance and quality control requirements for CSSMs and CSS structures, including fabrication and tolerance specifications, welding inspection and examination requirements, erection, construction and concrete fill parameters.
- Section 12.0 presents corrosion protection requirements to address life-cycle considerations.
- Section 13.0 presents planned scaled physical testing. The testing is not considered necessary to justify the technical adequacy of the methodology described in this LTR. However, the results will provide additional insight into CSSM behavior, will support benchmarking of nonlinear inelastic finite element (NIFE) models, and will support evaluations of any nonstandard designs, including connections. The intent of this description is to inform the NRC of current and future development efforts, not to justify the technical adequacy of the LTR or to obtain NRC approval of the specific test plan.
- Appendix A and Appendix B present design example calculations that demonstrate the application of the design methodology developed in this LTR. The structural designs and corresponding design demands are included to illustrate the methodology and facilitate NRC understanding. The intent of these examples is to demonstrate the application of

the design approach, not to obtain NRC approval of the specific design configurations presented.

1.3 Overview of SMR-300 Structures

A general description is provided of the SMR-300 structures to assist the NRC staff in their review of this LTR. While the names, arrangement, dimensions and configuration of these structures may evolve as the design matures, such changes will not affect the applicability or validity of the design and analysis methodologies presented.

The SMR-300 is a passively safe, advanced pressurized water reactor. The design features a dual unit configuration. The Nuclear Island (NI) consists of two Reactor Buildings (RBs), a single Reactor Auxiliary Building (RAB) shared by both units, and two Intermediate Buildings (IBs). The IBs primarily house the Main Steam System and Main Feed System piping, which interface between the NI and the Turbine Island (TI). A pictorial view of the NI structures is presented in Figure 1-1.

1.3.1 Reactor Building

The SC-I Reactor Building (RB) functions as an integrated containment and enclosure structure. It is composed of several substructures, each serving distinct safety and functional purposes. The RB consists of the following major structures:

- **Containment Enclosure Structure (CES):** The CES is an above-grade enclosure constructed primarily of CSSMs that shields the containment and reactor from external hazards. It also provides a leak-tight boundary for the Annular Reservoir (AR).
- **Containment Structure (CS):** The CS is further divided into above-grade and below-grade portions:
    - The above-grade portion of the CS is called the Steel Containment Vessel (SCV), a steel containment that provides the primary pressure boundary. It is surrounded by the Annular Reservoir (AR) and is connected to and rests on the Transfer Girder (TG).
    - The below-grade portion of the CS is constructed using CSSMs and consists of three main structural components:
        - **Transfer Girder (TG): [[** [redacted] **]]**
        - **Steel Concrete Containment Vessel (SCCV):** A composite shell structure that constitutes the below-grade containment wall. It resists both external soil pressures and internal containment loads.
        - **RB Basemat:** A foundation slab that supports the entire RB structure, forms part of the containment boundary, and transfers loads to the subgrade.

- **Containment Internal Structure (CIS): [[** [redacted] **]]**

Figure 1-2 shows the exterior shell of the building. The internal structures (except for the BSW) are removed for clarity.

1.3.2 Reactor Auxiliary Building

The SMR-300 features a common RAB for the two RBs. The RAB is a multi-story, partially embedded structure constructed primarily of CSSMs. The south portion of the RAB shares the same basemat and elevation as the RB. The north portion is founded on a separate basemat. The RAB structural elements are designed using CSSMs.

A pictorial view of the RAB is presented in Figure 1-3.

1.3.3 Intermediate Building

The SMR-300 design includes two IBs, one for each RB, which serve to house the steam and feedwater lines and to connect the Turbine Island to the Nuclear Island. Each SC-I portion of the IB is connected to the RB. The IB basemats, walls and roof slabs are constructed using CSSMs. A pictorial view of one of the two IBs is presented in Figure 1-4.

1.4 Introduction to CSSM Design

As described in the brief overview of Section 1.3, the SMR-300 SC-I NI structures, consisting of various structural elements (e.g., basemats, walls, floor and roof slabs) are to be primarily constructed using CSSMs for both containment and non-containment boundary applications. These CSSMs may be designed in a range of configurations, shapes and sizes, including horizontal arrangements for slabs and basemats, vertical configurations for walls, and both straight and curved geometries.

The design for CSSMs draws its inspiration from the HI-STORM overpack, a METCON™ structure [1]. A typical CSSM consists of two parallel steel faceplates interconnected by primary and secondary stiffeners to form the empty steel module. The modules are typically fabricated in a controlled shop environment. After fabrication, the empty modules are transported to the construction site, where they are assembled into their final configuration and connected. After assembly, the modules are filled with plain concrete to form the composite structural element. CSSMs are typically joined together to form robust monolithic structural members.

1.4.1 CSSM Configuration

The structural load-resisting system of a CSSM is formed by four primary components: faceplates, primary stiffeners, secondary stiffeners, and plain concrete infill. Each of these components is described below.

- **Faceplates: [[** [redacted] **]]**
- **Primary Stiffeners**: **[[** [redacted] **]]**
- **Secondary Stiffeners**: **[[** [redacted] **]]**
- **Concrete**: The module interior is filled with concrete, providing stiffness, strength, mass, damping, and fire resistance. Once cured, the concrete works in composite action with the faceplates and stiffeners to complete the structural load-bearing system.

A typical CSSM configuration is depicted in Figure 1-5. The concrete infill is omitted so that the internal stiffener arrangement is visible.

Additional components may be included in CSSMs to support fabrication and construction activities (e.g., lifting lugs, temporary bracing, erection aids). These are not part of the structural load-resisting system and may vary depending on the application.

1.4.2 Coordinate System

To ensure clarity, consistency, and improved organization of this LTR, a standardized local Cartesian coordinate system is defined for a typical CSSM, independent of its application in the actual structural configuration. In this system, the *x*-axis is oriented parallel to or along the longitudinal direction of the primary and secondary stiffeners, the *y*-axis is perpendicular or transverse to the stiffeners, and the *z*-axis corresponds to the thickness of the section. This coordinate system is illustrated in Figure 1-6. All equations presented in this LTR are expressed in terms of this local coordinate system. For structural design applications, the equations will be transformed into the structural coordinate system of the component under consideration.

Design parameters of the CSSM configurations are as follows:

t_{sc} = CSSM section thickness, in (mm)

t_p = Thickness of CSSM faceplates[1], in (mm)

t_c = Thickness of the concrete infill, in (mm)

t_{ss} = Thickness of the secondary stiffeners, in (mm)

t_{ps} = Thickness of the primary stiffeners, in (mm)

s = Spacing between secondary and primary stiffeners[2], in (mm)

s_{ps} = Spacing of primary stiffeners, in (mm)

F_y = Specified minimum yield stress of the faceplates, primary and secondary stiffeners[1], ksi (MPa)

F_u = Specified minimum tensile stress of the faceplates, primary and secondary stiffeners[1], ksi (MPa)

f_c' = Specified compressive strength of the concrete, ksi (MPa)

E_s = Modulus of elasticity of steel for faceplates, primary and secondary stiffeners, ksi (MPa)

E_c = Modulus of elasticity of the concrete, ksi (MPa)

1.4.3 Use of CSSMs in SMR-300 NI Structures

While the core concept of CSSMs remains consistent, their configurations vary depending on the functional requirements of different individual structural members. These variations are primarily governed by the orientation of the primary and secondary stiffeners, section thickness, faceplate and stiffener thicknesses, and the spacing of stiffeners. Although the modules differ in configuration, each satisfies the minimum requirements defined in Section 3.0.

Table 1-1 summarizes representative CSSM configurations employed in the SMR-300 NI structures and identifies the key parameters that characterize each configuration. The table is provided to support the NRC staff with understanding the different module types used in the design. The dimensions provided in the table are representative values and are subject to change. The table is not intended to provide an exhaustive list of all configurations that may be used for the SMR-300 NI structures. The methodology described in this LTR is applicable to other CSSM configurations that meet the minimum requirements established in Section 3.0.

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1 [[[redacted].]]

2 [[[redacted].]]

1.4.4 Comparison to SC Walls, CFTs and SpeedCore Systems

As a structural system, CSSMs are similar to other concrete-filled steel structural systems such as steel-plate composite (SC walls) from American Institute of Steel Construction, *Specification for Safety-Related Steel Structures for Nuclear Facilities ANSI/AISC N690-24* (AISC N690) [2], concrete-filled steel tubes (CFTs) from American Institute of Steel Construction, *Specification for Structural Steel Buildings ANSI/AISC 360*-22 (AISC 360) [3], composite plate shear walls and concrete filled from American Institute of Steel Construction, *Seismic Provisions for Structural Steel Buildings ANSI/AISC* 341 (AISC 341) [4] (C-PSW/CF, also known as SpeedCore). Some of these structural systems have been used extensively in commercial and nuclear safety-related construction.

A comparison of the CSSMs and other filled-composite systems is presented in Table 1-2. The comparisons are not intended to be exhaustive but does provide an understanding of CSSMs compared to established composite structural systems.

1.4.5 Introduction to Design Philosophy

The design philosophy for CSS structural elements follows principles consistent with conventional reinforced concrete (RC) and steel-plate composite (SC) systems. The design and analysis methodology developed for CSS structural elements is based primarily on the provisions and guidance from AISC N690, AISC 360, AISC Design Guide-32 [5] (Design Guide-32), ACI 349-23 [6] (ACI 349), ACI 318-25 [7] (ACI 318) and RG 1.243 [8]. Provisions specific to containment applications, in addition to those referenced above, are primarily derived from ASME Section III, Division 2 [9] (ASME CC).

CSSMs exhibit structural behavior similar to existing composite systems depending on the direction of loading. **[[** [redacted] **]]** Accordingly, the design philosophy for CSSMs has been developed from the provisions of AISC N690 Appendix N9 for SC walls and AISC 360 Chapter I for filled composite members.

[[

[redacted]

]]

Figure 1-1: SMR-300 NI Structures

[[

[redacted]

]]

Figure 1-2: Cross-Section View of Reactor Building with CIS Hidden for Clarity

[[

[redacted]

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Figure 1-3: Pictorial View of SMR-300 Reactor Auxiliary Building

[[

[redacted]

]]

Figure 1-4: Pictorial View of SMR-300 Intermediate Building

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[redacted]

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Figure 1-5: Typical CSSM Configuration

[[

[redacted] **]]**

Figure 1-6: Typical CSSM with Local Coordinate System

Table 1-1: Representative CSSM Configurations Used in SMR-300 NI Structures

[[

[redacted]

]]

Table 1-2: Comparison of CSSMs with Other Composite Systems

Parameter	SC Walls	SpeedCore	CFT	CSSM
Configuration	Comprises steel faceplates with plain concrete infill	Comprises steel faceplates with plain concrete infill; required to have boundary elements such as steel flange plates	Comprises hollow steel shape (square, rectangular, or circular) with plain concrete infill	[[[redacted]]]
Ties	Discrete steel elements (bars or plates) which are uniformly spaced (orthogonal spacings may be the same or different) serve as ties, out-of-plane shear reinforcement, interfacial shear connectors. Also needed for empty module stability	Typically comprise discrete bars that are bolted/welded to the steel faceplates, uniformly spaced. Serve as interfacial shear connectors, out-of-plane shear reinforcement (as needed). Also needed for empty module stability	Since hollow closed steel shapes form the steel reinforcement, the webs of the steel shapes act as out-of-plane shear reinforcement	[[[redacted]]]
Shear Connectors	Typically steel anchors (steel headed shear studs), in combination with ties, are used as interfacial shear connectors.	Typically ties also serve as interfacial shear connectors. Steel headed shear studs may not be used.	CFTs typically do not have interfacial shear connectors. Interfacial bond at steel-concrete interface is achieved by existent friction at the interface.	[[[redacted]]]

2.0 REGULATORY REQUIREMENTS AND GUIDANCE

The design philosophy and methodology rules detailed in this report can be used to demonstrate compliance with the following regulatory requirements and applicable aspects of the referenced guidance documents.

2.1 Code of Federal Regulations

2.1.1 10 CFR 50.44

Containment structures constructed of CSSMs are required to maintain their integrity in response to loads associated with combustible gas generation and burning.

2.1.2 10 CFR 50.55a(g)

CSSMs used in containment applications (e.g., modules that form the SCCV and TG) are subject to the applicable requirements for pre-service and inservice inspection of Class CC concrete containments and metallic shell and penetration liners of concrete containments in accordance with the ASME BPVC, Section XI, Division 1, “Rules for Inspection and Testing of Components of Light-Water-Cooled Plants,” Subsections IWE and IWL [10].

2.1.3 10 CFR 50.65

CSSMs used in safety-related applications or non-safety-related applications within the scope of § 50.65 are subject to monitoring to provide reasonable assurance that the CSS structures are capable of fulfilling their intended functions.

2.1.4 10 CFR 50.150

CSSMs may be used in CSS structures that are designed to provide protection against aircraft impact to ensure that (i) the reactor core remains cooled, or the containment remains intact, and (ii) spent fuel cooling or spent fuel pool integrity is maintained.

2.1.5 10 CFR 50 Appendix A

Containment boundary structures constructed from CSSMs shall comply with the following General Design Criteria (GDC):

2.1.5.1 GDC 1 Quality Standards and Records

CSSMs and CSS structures are subject to design, manufacturing, and operating quality assurance requirements commensurate with their safety functions.

2.1.5.2 GDC 2 Design Bases for Protection against Natural Phenomena

SC-1 CSSMs and CSS structures used in safety-related applications are subject to design requirements to withstand the effects from the most severe natural phenomena such as earthquakes, tornadoes, hurricanes, floods, seiches, and tsunami without loss of capability to perform their safety functions. Loads and load combinations are discussed in Section 4.0 of this report.

2.1.5.3 GDC 3 Fire Protection

CSSMs and CSS structures are subject to design requirements to withstand the effect of fires and explosions.

2.1.5.4 GDC 4 Environmental and Dynamic Effects Design Bases

CSS structures are subject to design requirements to accommodate the effects of and to be compatible with the environmental and dynamic conditions associated with normal operation, maintenance, testing, and postulated accidents, including loss of coolant accidents (LOCAs). CSS structures are to be appropriately designed against dynamic effects. Loads and load combinations are discussed in Section 4.0 of this report.

2.1.5.5 GDC 16 Containment Design

The CSS structures that form containment are subject to design requirements to provide an essentially leak-tight barrier against the uncontrolled release of radioactivity to the environment and to ensure design conditions important to safety are not exceeded for as long as postulated accident conditions require.

2.1.5.6 GDC 50 Containment Design Basis

The CSS structures, including access openings and penetrations, are subject to design requirements to provide sufficient margin to accommodate the pressure and temperature conditions caused by a LOCA without exceeding the design leakage rate.

2.1.5.7 GDC 51 Fracture Prevention of Containment Pressure Boundary

The CSS structures forming the containment pressure boundary including their associated properties (e.g., ductility, deformation, material selection, stresses and flaw size) are subject to pressure and temperature considerations and design requirements to provide sufficient margin to assure that their ferritic materials behave in a nonbrittle manner, and that the probability of rapidly propagating fracture is minimized under operating, maintenance, testing, and postulated accident conditions.

2.1.5.8 GDC 52 Capability for Containment Leakage Rate Testing

The CSS structures forming the containment and other equipment, which may be subjected to containment test conditions, are subject to design requirements for periodic integrated leakage rate testing conducted at containment design pressure.

2.1.5.9 GDC 53 Provisions for Containment Testing and Inspection

The CSS structures forming the containment are designed to permit: (1) appropriate periodic inspection of all important areas, such as penetrations; (2) an appropriate surveillance program; and (3) periodic testing at containment design pressure of the leak tightness of penetrations which have resilient seals and expansion bellows.

2.1.6 10 CFR 50 Appendix B - Quality Assurance Criteria for Nuclear Power Plants and Fuel Reprocessing Plants

The scope of this LTR is subject to the requirements of 10 CFR 50 Appendix B.

2.1.7 10 CFR 50 Appendix J - Primary Reactor Containment Leakage Testing for Water-cooled Power Reactors

The CSS structures forming the containment are subject to design requirements to meet containment leakage test requirements. These test requirements provide for pre-operational and periodic verification by tests of the leak-tight integrity of the primary reactor containment and systems and components which penetrate containment and establish the acceptance criteria for these tests.

2.1.8 10 CFR Part 50, Appendix S - Earthquake Engineering Criteria for Nuclear Power Plants

Safety-related CSS structures are subject to the requirement of this appendix for Safe Shutdown Earthquake ground motions, so that SSCs will remain functional and within applicable stress, strain, and deformation limits. The required safety functions of SSCs must be assured during and after vibratory ground motion through design, testing, or qualification methods.

2.2 U.S. NRC Regulatory Guides

The design of SC-I CSS structures and CSSMs are subject to the guidance of the following NRC regulatory guides (RGs):

- RG 1.7, “Control of Combustible Gas Concentrations in Containment Following a Loss of Coolant Accident” [11]
- RG 1.26, “Quality Group Classifications and Standards for Water, Steam, and Radioactive Waste Containing Components of Nuclear Power Plants” [12]
- RG 1.28, “Quality Assurance Program Criteria (Design and Construction” [13]
- RG 1.54, “Service Level I, II, III and In-Scope License Renewal Protective Coatings Applied to Nuclear Power Plants” [14]
- RG 1.57, “Design Limits and Loading Combinations for Metal Primary Reactor Containment System Components” [15]
- RG 1.61, “Damping Values for Seismic Design of Nuclear Power Plants” [16]
- RG 1.160, “Monitoring the Effectiveness of Maintenance at Nuclear Power Plants” [17]
- RG 1.199, “Anchoring Components and Structural Supports in Concrete” [18]
- RG 1.216, “Containment Structural Integrity Evaluation for Internal Pressure Loadings Above Design-Basis Pressure” [19]
- RG 1.217, “Guidance for the Assessment of Beyond-Design-Basis Aircraft Impacts” [20]

- RG 1.243, “Safety-Related Steel Structures and Steel-Plate Composite (SC) Walls for other than Reactor Vessels and Containments” [8]

2.3 NUREG-0800 SRP Guidance

CSS structures and CSSMs may be subject to review guidance of the SRP sections listed below.

2.3.1 NUREG-0800, SRP 3.5.3

SRP 3.5.3, “Barrier Design Procedures,” [21] provides review guidance of the procedures utilized during the design of SC-I structures that must withstand the effects of missile impact in order to ensure conformance with 10 CFR 50, GDC 2 and 4. Impactive and impulsive loading is discussed in Section 9.0 of this LTR.

2.3.2 NUREG-0800, SRP 3.8.1

SRP 3.8.1, “Concrete Containment,” [22] provides review guidance for structural analysis reviews of concrete containments. Although the SRP section is focused on RC construction, the guidance is considered for applicability to CSSMs used in containment applications.

2.3.3 NUREG-0800, SRP 3.8.3

SRP 3.8.3, “Concrete and Steel Internal Structures of Steel or Concrete Containments,” [23] provides review guidance for structural analysis reviews of SC-I containment internal structures that are constructed from CSSMs. The design, analysis, fabrication, construction, inspection and testing of CSS containment internal structures are subject to the applicable safety and performance objectives of SRP Section 3.8.3.

2.3.4 NUREG-0800, SRP 3.8.4

SRP 3.8.4, “Other Seismic Category I Structures,” [24] provides review guidance for structural analysis reviews of SC-I structures (other than containment). The design, analysis, fabrication, construction, inspection and testing of SC-I CSS structures (other than containment) are subject to the applicable safety and performance objectives of SRP Section 3.8.4.

2.3.5 NUREG-0800, SRP 3.8.5

SRP 3.8.5, “Foundations,” [25] provides review guidance for structural analysis reviews of the design, analysis, and construction of foundations to ensure they can support loads from structures and withstand seismic and soil-related effects while maintaining their safety functions. The design, analysis, fabrication, construction, inspection and testing of CSSMs used in foundations supporting SC-I structures are subject to the applicable safety and performance objectives of the regulatory guidance of SRP Section 3.8.5.

2.3.6 NUREG-0800, SRP 19.0

SRP 19.0, “Probabilistic Risk Assessment and Severe Accident Evaluation for Reactors,” [26] provides review guidance for probabilistic risk assessment of the plant and also deterministic evaluation of design features for the prevention or mitigation of severe accidents. The structural performance of the containment under severe accident loads encompasses:

1) assessment of the Level C (or factored load) pressure capability of the containment in accordance with 10 CFR 50.44(c)(5),
2) demonstration of the containment capability to withstand the pressure and temperature loads induced by the more likely severe accident scenarios as stipulated in SECY 93-087, “Policy, Technical, and Licensing Issues Pertaining to Evolutionary and Advanced Light-Water Reactor Designs,” Section I.J. [27],
3) containment structural fragility assessment for over-pressurization, and
4) assessment of the seismic capacity of the containment structure in meeting the expectation documented in SECY 93-087, Section II.N.

CSSMs that are used in containment applications shall comply with the applicable safety and performance objectives of SRP Section 19.0.

2.3.7 NUREG-0800, SRP 19.5

SRP 19.5, “Adequacy of Design Features and Functional Capabilities Identified and Described for Withstanding Aircraft Impacts,” [28] provides review guidance for assessment of the effects on the facility of the impact of a large commercial aircraft. CSS structures that are intended to resist aircraft impact are subject to the applicable safety and performance objectives of SRP Section 19.5.

3.0 GENERAL REQUIREMENTS

The general requirements for the design and detailing of CSS structural elements are based on industry best practices, accepted codes and standards, and supporting test data. The methodologies being established in this topical report are applicable to CSS structural elements that meet these general requirements. Therefore, CSS structural elements that do not meet these generic requirements of this report require appropriate engineering justification that shall include one or more of the following:

- conservative mechanics-based calculations or explanations, or
- detailed analytical evaluations, including NIFE analyses with models benchmarked to relevant experimental data.

3.1 General Provisions

The following provisions apply to CSS structural elements:

(a) For exterior CSS structural elements, the minimum section thickness, t_{sc}, shall be 15 in. (380 mm). For interior CSS structural elements, the minimum t_{sc} shall be 10 in. (250 mm). This provision is based on Section N9.1.1(a) of AISC N690 and associated commentary.

(b) Faceplates shall have a thickness, t_p, not less than 0.25 in. (6 mm) nor more than 1.5 in. (38 mm). This provision is based on Section N9.1.1(b) of AISC N690 and associated commentary.

[[

[redacted]

[redacted]

[redacted]

[redacted]]]

(d) Some CSSM connections use bolted connections or splices, which require holes in the faceplates. In such cases, the nominal rupture strength of the faceplate per unit width, $F_u A_{sn}$, shall be greater than 1.10 times the nominal yield strength per unit width, $F_y A_s$,

where,

A_s = gross area of the faceplates per unit width, in^2/ft (mm^2/m)

A_{sn} = net area of the faceplates per unit width, in^2/ft (mm^2/m)

Splices at the seams between adjoining faceplates shall be designed to develop the nominal yield strength of the weaker of two connected faceplates.

3.2 Material Properties

The mechanical properties and applicable codes and standards for the materials used for construction of CSSMs are defined for both non-containment and containment applications.

The specified minimum yield stress of the CSSM faceplates, F_y, shall not be less than 50 ksi (345 MPa). **[[** [redacted] **]]** The minimum elongation shall be at least 15%, and the minimum tensile-to-yield ratio, F_u/F_y, shall be 1.20.

The specified compressive strength of the concrete, f_c', shall not be less than the greater of 4 ksi (28 MPa) or [$0.04 + 0.80\rho$] times F_y, nor more than 10 ksi (70 MPa).

3.2.1 Non-Containment Applications

3.2.1.1 Concrete Infill

Material requirements for concrete infill in CSSMs are per the applicable guidance in **[[** [redacted] **]]**

High-density concrete may be utilized in areas requiring radiation shielding. For high-density concrete, the aggregates shall conform to applicable requirements in ASTM C-637 [29].

[[[redacted] **]]**

Concrete material and mechanical properties used for design at elevated temperatures shall be as per Appendix N4.2.3 of AISC N690.

3.2.1.2 Structural Steel

The steel materials used in CSSMs shall conform to the applicable requirements of AISC N690 Section NA3. **[[** [redacted] **]]**

Steel material and mechanical properties used for design at elevated temperatures shall be as per Commentary NB3.1 of AISC N690.

3.2.2 Containment Applications

For CSSMs used in containment boundary (pressure-retaining and load-bearing) applications, the concrete and steel material properties shall be as per this section.

3.2.2.1 Concrete Infill

[[[redacted] **]]**

3.2.2.2 Structural Steel

[[[redacted]]]

3.3 Design for Stability

Second-order analyses of structures with vertical CSS structural elements need not be performed if the conditions of ACI 318, Section 6.2.5.1, are satisfied. For cases where conditions of ACI 318 are not satisfied, second order effects are considered as described in Section 3.3.1 or Section 3.3.2.

3.3.1 Considering Second Order Effects in Finite Element (FE) Models

As explained in Section 5.0, 3D LEFE models of the CSS structures are developed to calculate the design demands for various load combinations. The finite elements, material properties, and geometric parameters of the models implicitly account for the effects of concrete cracking reflecting the representative state of the structure for the applicable load combination, as discussed in Section 5.2.

[[[redacted]]]

3.3.2 Using Alternative Methods in AISC 360

CSS structures not meeting the requirements of ACI 318 Section 6.2.5.1 will typically meet the limitations of AISC 360 Appendix 7, Section 7.3 permitting a first-order analysis with notional loads. [[[redacted]]]

3.4 Faceplate Slenderness

The faceplates of CSSMs are anchored to the concrete infill by the primary and secondary stiffeners. The spacing of these stiffeners determines the effective unsupported span of the faceplate. When subjected to compressive stresses, the faceplates may undergo local buckling depending on their normalized slenderness ratio (λ), which is defined using Equation (3-2).

[[[redacted]]](3-2)

where,

s = Maximum faceplate clear span, spacing between secondary and primary stiffeners, in (mm)

t_p = Thickness of CSSM faceplates, in (mm)

F_y = Specified minimum yield stress of the faceplates, ksi (MPa)

E_s = Modulus of elasticity of steel for faceplates, ksi (MPa)

[[[redacted]

- [redacted]
- [redacted]
- [redacted]]]

The normalized slenderness ratio (λ) that the faceplates must satisfy to be non-slender depend on the geometric aspect ratio of the faceplate, the boundary conditions along four edges, and the loaded edge, as shown in Table 3-1.

[[[redacted]]]

In addition to the configurations summarized in Table 3-1, steel plates that are fully embedded in concrete are not susceptible to local buckling. This includes the primary stiffeners embedded within the concrete core as well as faceplates that are embedded on both sides, such as the bottom faceplate of the RB basemat, which is confined by the concrete mud mat below and the concrete infill above.

CSS structural elements need not meet these slenderness limits before concrete placement and hardening. **[[** [redacted] **]]**

3.5 Interfacial Shear

The steel faceplates and concrete infill of CSSMs act together as a composite section through the transfer of interfacial shear stresses (also referred to as bond stresses) between the two materials. Interfacial shear transfer in CSSMs occurs in two principal directions via the following mechanisms:

- **[[** [redacted] **]]**

The primary requirement for detailing the primary and secondary stiffeners is to achieve adequate interfacial shear strength to prevent interfacial shear (bond) failure before out-of-plane shear or flexure failure of CSSMs subjected to out-of-plane loading with shear span-to-depth ratio greater than or equal to 2.5. This is the same criteria as that in shear connector spacing requirement in Section N9.1.4b(b) of AISC N690.

3.5.1 Classification of Shear Connectors

As per Section N9.1.4a of AISC N690, both the primary and secondary stiffeners function as yielding shear connectors with interfacial slip capacity exceeding 0.2 in. (5 mm). The interfacial shear strength of the stiffeners is equal to their direct shear yield strength.

3.5.2 Spacing of Shear Connectors

3.5.2.1 Development Length

AISC N690 includes a requirement for steel faceplate development length of less than or equal to three times the thickness (t_{sc}). This is considered a secondary requirement, and not enforced in the CSSM design, as it does not govern over the primary requirement.

[[[redacted] **]]**(3-3)

where,

L_d = development length, in (mm)

$\leq 3t_{sc}$

3.5.2.2 Interfacial Shear Failure

Section N9.1.4b-(b) of AISC N690 provides formulations for SC walls to ensure that interfacial shear failure does not occur prior to out-of-plane shear failure. These formulations were developed for systems with discrete shear connectors and therefore do not directly apply to CSSMs, which utilize continuous stiffeners. Accordingly, the formulations have been modified to account for the continuous primary and secondary stiffeners used in CSSMs. This modification is provided in the following equation below in conjunction with. Figure 3-1. **[[** [redacted] **]]**

Substituting these expressions results in:

[[[redacted] **]]**(3-4)

where,

Q_{cv}^{avg} = Weighted average of the available interfacial shear strength of primary and secondary stiffeners per unit width, kip/ft (N/m)

M_n = nominal flexural strength per unit width of CSSM structural element, as defined in Section 6.1.3, kip-in./ft (N-mm/m)

Further, Q_{cv}^{avg} can be calculated as follows:

[[[redacted] **]]**(3-5)

where,

n_{eps} = effective number of primary stiffeners contributing to a unit cell

n_{ess} = effective number of secondary stiffeners contributing to a unit cell

[[[redacted]

[redacted]

[redacted]

[redacted]]]

An example calculation of Q_{cv}^{avg} is shown in Figure 3-2.

[[[redacted]]]

3.6 Primary Stiffener Spacing

The primary stiffeners of CSSMs serve multiple functions. [[[redacted]]] The spacing required to prevent shear buckling of empty steel modules before concrete placement is presented in this section.

3.6.1 Empty Module Buckling

One of the requirements influencing primary stiffener spacing (s_{ps}) is the structural flexibility and strength of the empty steel modules of CSSMs before concrete casting Varma et al. [34]. Typically, empty steel modules of conventional SC structures (i.e., SC sections with tie rods and stud anchors) are extremely shear flexible. The behavior is dominated by their shear deformation and effective shear stiffness (GA_{eff}), which also governs their resistance to overall (global) buckling.

The empty modules of CSSMs can be characterized by two orientations of the primary stiffeners. In one orientation, the faceplates are continuously braced with primary stiffeners, effectively preventing global buckling. In the other orientation, although CSSMs perform better than SC structures due to the continuous nature of the primary stiffeners, they remain shear flexible, and thus, an assessment of their stability is still warranted.

Varma et al. evaluated that for an empty steel module, buckling will occur when the critical buckling load (P_{cr}) is equal to the effective shear stiffness (GA_{eff}). The critical buckling stress (σ_{cr}) can be calculated as P_{cr} divided by steel cross-section area over unit width. Equation (3-6) presents the simplified expression for the critical buckling stress of an empty steel module of the CSSM, which is a modified version of the equation proposed by Varma et al. [[[redacted]

[redacted]

[redacted] **]]**(3-6)

[[[redacted] **]]**(3-7)

Varma et al. state that the requirement for the CSSM empty configuration is to have critical buckling stress greater than or equal to 1000 psi. Hence, the spacing requirement can be simplified to Equation]](3-8)**.** Primary stiffeners meeting this requirement would provide adequate restraint for global buckling during the erection stage (before concrete placement).

[[[redacted] **]]**(3-8)

3.7 Effects of Curvature

AISC N690 Appendix N9.1.1 Commentary states that the Appendix was developed for straight SC structural elements, and that curvature effects should be evaluated when radius-to-thickness ratio is below 20. Similarly, ACI 349 states that shell instability be investigated and that nonlinear variations in circumferential and meridional stresses across the thickness be considered.

The effects of curvature on the behavior, analysis, design, and detailing of CSS structural elements are considered explicitly. **[[** [redacted]

[redacted]

[redacted]

[redacted]]]

[[

[redacted]

]]

Figure 3-1: Interfacial Shear Failure Diagram

[[

[redacted]

]]

Figure 3-2: Average Interfacial Shear Strength Example Calculation

Table 3-1: Faceplate Normalized Slenderness Ratio for Different CSSM Configurations

[[

[redacted]

]]

4.0 LOADS AND LOAD COMBINATIONS

The safety-related nuclear structures in SMR-300 that are constructed using CSS structural elements are designed for loads and load combinations as follows.

- CSS structures that form part of the pressure-retaining containment boundary structures shall be designed for loads and load combinations specified in ASME Section III, Division 2, Subsection CC-3230 and Table CC-2330-1 [9].
- All other nuclear safety-related CSS structures shall be designed for loads and load combinations (Load and Resistance Factor Design (LRFD)) specified in AISC N690, Section NB2.5, as modified by Table 1 of RG 1.243 [8].

5.0 MODELING APPROACH

LEFE analyses are performed to analyze CSS structures for the design basis load combinations identified in Section 4.0. The LEFE models that are used in these analyses need to capture the representative member section stiffnesses for the expected level of concrete cracking and expected behavior of the structure under these loads and load combinations. The considerations for the finite element type and size are discussed in Section 5.1. The calculation of effective stiffness properties of the CSSMs are discussed in Section 5.2. The calculation of modeling parameters for the LEFE analysis to represent the relevant stiffnesses is discussed in Section 5.4. The determination of required strengths from the LEFE analyses is discussed in Section 5.5.

Modeling requirements for openings, including the refined mesh around openings, are discussed in Section 8.0.

Section 5.6 discusses an alternative approach using advanced NIFE analysis for CSS structures.

5.1 General Methodology

The CSS structural elements are analyzed using elastic, three-dimensional, thick-shell or solid finite elements. The finite element size shall be limited to $2t_{sc}$ or 5 ft (1.5 m), whichever is less. These element sizes are based on the capacity equations which are deemed appropriate up to $2t_{sc} \times 2t_{sc}$ region of the CSS structural member. This is consistent with recommendations from AISC N690, Appendix N9.

Second-order effects are considered as discussed in Section 3.3.

The methodology for finite element analyses involving accident thermal conditions follows the provisions of Section N9.2.4 of AISC N690.

5.2 Effective Stiffness for Analysis

This section presents the methods to calculate effective stiffness values for CSS structural elements used in the analysis. **[[** [redacted] **]]**

Alternatively, mechanics-based equivalent stiffness calculations may be used where appropriate and justified on a case-by-case basis.

5.2.1 Effective Flexural Stiffness

The methods to calculate effective flexural stiffness for the two orthogonal directions are provided in this section.

5.2.1.1 Flexural Stiffness About the Plane Perpendicular to the Stiffeners

The method to calculate effective flexural stiffness of the CSSM member about the plane perpendicular to the stiffeners, as depicted in Figure 5-1, is provided below.

[[[redacted]

[redacted]]](5-1)

where,

E_s = modulus of elasticity of steel

= 29,000 ksi (200,000 MPa) for carbon steel and duplex stainless steel

= 28,000 ksi (193,000 MPa) for austenitic stainless steel

$I_{s,x}$ = moment of inertia of steel about the plane perpendicular to the stiffeners per unit width, in^4/ft (mm^4/m)

[[[redacted]]](5-2)

t_p = thickness of faceplate, in (mm)

t_{sc} = thickness of the CSSM section, in (mm)

t_{ps} = thickness of primary stiffener, in (mm)

t_c = thickness of concrete infill, in (mm)

= $t_{sc} - 2t_p$

s_{ps} = spacing of primary stiffeners, in (mm)

l = 12in/ft (1000 mm/m)

[[[redacted]

]]

A_g = $t_{sc} l$

E_c = modulus of elasticity of concrete

$$= w_c^{1.5}\sqrt{f_c'}, \text{ ksi } (0.043 w_c^{1.5}\sqrt{f_c'}, \text{ MPa}) \quad (5\text{-}5)$$

f_c' = specified compressive strength of concrete, ksi (MPa)

w_c = weight of concrete per unit volume, lb/ft^3 (kg/m^3)

I_c = moment of inertia of concrete infill per unit width, in^4/ft (mm^4/m)

$= l\left(\frac{t_c^3}{12}\right)$

$\Delta T_{s,avg}$ = average of the maximum surface temperature increases for the faceplates due to accident thermal conditions, °F (°C)

[[[redacted]]]

5.2.1.2 Flexural Stiffness About the Plane Parallel to Stiffeners

The method to calculate effective flexural stiffness of the CSS structural members about the plane parallel to the stiffeners, as depicted in Figure 5-2, is provided below. [[[redacted]

[redacted]]](5-6)

where,

$I_{s,y}$ = moment of inertia of steel (faceplates) per unit width, in^4/ft (mm^4/m)

[[[redacted] (5-7)

[redacted]]](5-8)

ρ' = stiffness-adjusted reinforcement ratio

$= \rho n$

n = modular ratio of steel and concrete

$= E_s/E_c$

ρ $= \frac{2t_p}{t_{sc}}$

5.2.2 Effective In-Plane Shear Stiffness

The effective in-plane shear stiffness per unit width, $(GA)_{eff}$, for all load combinations that do not involve accident thermal loading is based on the required in-plane shear strength per unit width, S_{rxy}, in the CSS structural elements.

1) When $S_{rxy} \leq S_{cr}$

[[[redacted]]](5-9)

2) When $S_{cr} < S_{rxy} \leq 2S_{cr}$

[[[redacted]]](5-10)

3) When $S_{rxy} > 2S_{cr}$

[[[redacted]]](5-11)

where,

$(GA)_{uncr}$ = in-plane shear stiffness per unit width of uncracked composite CSS structural elements, kip/ft (N/m)

[[[redacted]]](5-12)

G_s = shear modulus of elasticity of steel

= 11,200 ksi (77 200 MPa) for carbon steel and duplex stainless steel

= 10,800 ksi (74 500 MPa) for austenitic stainless steel

$A_{s,y}$ = cross-sectional area of steel in the plane parallel to the stiffeners, in^2/ft (mm^2/m)

= $2t_pl$

G_c = shear modulus of concrete

= $772\sqrt{f_c'}$, ksi ($2000\sqrt{f_c'}$, MPa) (5-13)

A_c = area of concrete infill per unit width, in^4/ft (mm^4/m)

= lt_c

S_{cr} = in-plane shear force per unit width at concrete cracking threshold, kip/ft (N/m)

[[[redacted] (5-14)

[redacted] **]]** (5-14M)

S_{rxy} = required membrane in-plane shear strength per unit width in the structural element, kip/ft (N/m)

[[([redacted] **]]** (5-15)

$\overline{\rho}$ = strength-adjusted reinforcement ratio

[[[redacted] (5-16)

]] (5-16M)

The effective in-plane shear stiffness per unit width, $(GA)_{eff}$, for all load combinations involving accident thermal conditions, accounts for the effects of concrete cracking by setting $(GA)_{eff}$ equal to $(GA)_{cr}$.

5.2.3 Effective Axial Stiffness

The effective axial stiffness of the CSS structural elements in compression is calculated using Equation I1-2 of AISC 360 for a composite plate shear wall.

[[[redacted] (5-17)

]] (5-18)

For CSS structural elements in tension, the axial stiffness is offered by bare steel, and all concrete is considered cracked.

5.3 Damping

Damping values specified for SC walls in Tables 1 and 2 of NRC RG 1.61 are used to account for the dissipation of energy in the CSS structural elements. These values are 5% of critical damping for Safe Shutdown Earthquake (SSE) and 2%-3% of critical damping for Operating Basis Earthquake (OBE).

5.4 Modeling Parameters

Consistent with AISC N690 provisions, geometric and material properties of the CSS structural elements are modeled in the LEFE analyses as follows:

1) The as-modeled Poisson's ratio, ν_m[3], thermal expansion coefficient, α_m, and thermal conductivity, k_m, used in the LEFE analysis of CSSM panel sections are assumed to be those of the concrete.
2) The as-modeled thickness of a CSSM panel section, t_m, and the material elastic modulus used in LEFE analysis of CSSM panel sections, E_m, are established through calibration to match the effective stiffness values for analysis. **[[** [redacted]

[redacted]

- [redacted]
- [redacted] **]]**

The following equations are used to calculate these modeling parameters:

[[[redacted] (5-19)

(5-20)

]](5-21)

4) The as-modeled material density used in LEFE analysis of the CSSM panel sections, γ_m, is established through calibration to match the mass of the model to the mass of the CSSM section. This calibration uses the previously obtained model thickness, t_m.

The as-modeled specific heat used in LEFE analysis of CSSM panel sections, c_m, is established through calibration after establishing density such that the model specific heat equals the specific heat of the concrete infill.

5.5 Determination of Required Strengths

The required strengths for the eight different demand types are obtained from the LEFE analysis consistent with AISC N690.

The required strength for each load effect is calculated by averaging the load effect over panel sections that are no larger than twice the section thickness or 5 ft (1.5 m) in length and width. The required strength is calculated by averaging the load effect over panel sections no larger than the section thickness in length and width in the vicinity of openings and penetrations and in connection regions.

[3] The Poisson's ratio may be adjusted within generally accepted limits to improve correlation of the modeling parameters with the target effective stiffness values.

The required strengths for the panel sections of CSS structural elements for each load effect are denoted as follows:

M_{rx} = required out-of-plane flexural strength per unit width in direction x, kip-in./ft (N-mm/m)

M_{rxy} = required twisting moment strength per unit width, kip-in./ft (N-mm/m)

M_{ry} = required out-of-plane flexural strength per unit width in direction y, kip-in./ft (N-mm/m)

S_{rx} = required membrane axial strength per unit width in direction x, kip/ft (N/m)

S_{rxy} = required membrane in-plane shear strength per unit width, kip/ft (N/m)

S_{ry} = required membrane axial strength per unit width in direction y, kip/ft (N/m)

V_{rx} = required out-of-plane shear strength per unit width along edge parallel to direction x, kip/ft (N/m)

V_{ry} = required out-of-plane shear strength per unit width along edge parallel to direction y, kip/ft (N/m)

x, y = subscript relating symbol to local coordinate axes in the plane of the panel section associated with the finite element model

These required strengths are illustrated in Figure 5-3.

5.6 Design by Advanced Analysis

[[[redacted]

[redacted]

[redacted]]]

[[[redacted]]]

Figure 5-1: Flexural Stiffness About the Plane Perpendicular to the Stiffeners

[[[redacted]]]

Figure 5-2: Flexural Stiffness About the Plane Parallel to the Stiffeners

[[

[redacted]

]]

Figure 5-3: Force and Moment Demand Types in a Typical CSSM

6.0 DESIGN CAPACITIES

The individual design demands determined by the methodology of Section 5.0 are compared against their individual section capacities. Tension and compression are differentiated in capacities but correspond to S_{rx} and S_{ry}. Section 6.1 provides the methodology by which these individual section design capacities or strengths of the CSS structural elements are determined. Section 6.2 describes and provides interaction equations for verifying the adequacy of CSS structural elements subjected to combinations of demand types. For the CSS structural elements that are part of the containment boundary, additional stress-based checks are performed as described in Section 6.3.

Note that the tensile strength contribution of concrete infill to the available strengths of CSS structural elements is neglected.

6.1 Individual Capacities

The methods for determining the eight individual section design capacities for CSS structural elements, consistent with the eight demand types described in Section 5.5, are provided in this section. Due to the presence and orientation of primary stiffeners, several of these capacities are direction dependent. The corresponding capacities for each direction are detailed in the following subsections.

6.1.1 Uniaxial Tensile Strength

The available uniaxial tensile strength per unit width of CSS structural element panel sections is determined in accordance with AISC 360 Chapter D.

Where holes are present in faceplates, the available rupture strength shall be greater than the available yield strength as specified in AISC N690 Appendix N9.3.1.

6.1.1.1 Uniaxial Tensile Strength Parallel to the Stiffeners

For uniaxial tension applied parallel to the stiffener direction, the primary stiffeners contribute to the overall tensile capacity in addition to the steel faceplates.

The design tensile strength per unit width, $\phi_t P_{n,x}$, of CSS structural elements in this direction is determined for the limit state of steel yielding as follows:

$$\phi_t = 0.9$$

$$P_{n,x} = F_y A_{s,x} \tag{6-1}$$

6.1.1.2 Uniaxial Tensile Strength Perpendicular to the Stiffeners

For tension applied perpendicular to the stiffener direction, only the steel faceplates contribute to its strength.

The design tensile strength per unit width, $\phi_t P_{n,y}$, of CSS structural elements in this direction is determined for the limit state of steel yielding as follows:

$$\phi_t = 0.9$$

$$P_{n,y} = F_y A_{s,y} \quad (6\text{-}2)$$

6.1.2 Uniaxial Compressive Strength

The uniaxial compressive strength of CSS structural elements in the two directions is provided in this section. **[[** [redacted] **]]** For the direction perpendicular to the stiffeners, the formulations are based on provisions of SC Walls from Appendix N9 of AISC N690.

6.1.2.1 Uniaxial Compressive Strength Parallel to the Stiffeners

The compressive strength of CSS structural elements along the stiffener direction, as shown in Figure 6-1, is provided in this section. The strength is comparable to that of filled HSS composite members in Section I2.2b of AISC 360. The corresponding formulations have been adapted to a per unit width basis, which is appropriate for CSS structural elements.

The design compressive strength per unit width, $\phi_c P_{n,x}$, of CSS structural elements is determined for the limit state of flexural buckling based on member slenderness as follows:

$$\phi_c = 0.75$$

(a) When $\frac{P_{no,x}}{P_{e,x}} \leq 2.25$

$$P_{n,x} = P_{no,x}\left(0.658^{\frac{P_{no,x}}{P_{e,x}}}\right) \quad (6\text{-}3)$$

(b) When $\frac{P_{no,x}}{P_{e,x}} > 2.25$

$$P_{n,x} = 0.877 P_{e,x} \quad (6\text{-}4)$$

where,

$P_{e.x}$ = elastic critical buckling load per unit width, kip/ft (N/m)

$= \pi^2 (EI)_{eff,x} / L_{c,x}^2 \quad (6\text{-}5)$

[[[redacted] **]]**

$L_{c,x}$ = effective length of member in x-direction, in. (mm)

$P_{no,x}$ = nominal compressive strength in x-direction per unit width depending on the section slenderness, kip/ft (N/m)

[[[redacted]

[redacted]

[redacted] (6-9)]]

6.1.2.2 Uniaxial Compressive Strength Perpendicular to the Stiffeners

The compressive strength in the direction perpendicular to the stiffeners, as shown in Figure 6-2, is determined as shown in this section. The capacity is provided by faceplates and concrete infill and is determined in accordance with Section N9.3.2 of AISC N690.

The equations from Section 6.1.2.1 are applicable with the following additions or modifications:

$P_{no,y}$ = nominal compressive strength per unit width, kip/ft (N/m)

[[[redacted] (6-10)

]](6-11)

6.1.3 Out-of-Plane Flexure

The out-of-plane flexural strength of CSS structural elements in the two directions is provided in this section. [[[redacted]

[redacted] **]]** For the direction perpendicular to the stiffeners, the formulations are based on provisions of SC Walls from Appendix N9 of AISC N690.

6.1.3.1 Out-of-Plane Flexure Parallel to the Stiffeners

The available flexural strength of CSSMs in the direction parallel to the stiffeners, as shown in Figure 6-3, is determined and shown in this section. **[[** [redacted] **]]** The corresponding formulations have been adapted to a per unit width basis, which is appropriate for CSS structural elements.

The design flexural strength per unit width, $\phi_b M_{n,x}$, of CSS structural elements is determined as follows:

$$\phi_b = 0.90$$

[[[redacted] **]]**

6.1.3.2 Out-of-Plane Flexure Perpendicular to the Stiffeners

The available flexural strength of CSS structural elements in the direction perpendicular to the stiffeners, as shown in Figure 6-4, is determined and shown in this section.

[[[redacted] **]]** The design flexural strength per unit width, $\phi_b M_{n,y}$, of CSS structural elements is calculated in accordance with Section N9.3.3 of AISC N690.

$$\phi_b = 0.9$$

[[[redacted] **]]**(6-13)

where,

A_s^F = gross area of faceplate in tension due to flexure per unit width, in²/ft, (mm²/m)

6.1.4 In-Plane Shear

The in-plane shear strength of CSSM sections, as shown in Figure 6-5, shall be determined as per AISC N690, Section N9.3.4, based on the limit state of yielding of the faceplates. **[[** [redacted] **]]**

The design in-plane shear strength per unit width, $\phi_{vi} V_{ni}$, shall be determined as follows:

$$\phi_{vi} = 0.9$$

[[[redacted] **]]**(6-14)

where,

[[[redacted] (6-15)

[redacted] **]]**(6-16)

6.1.5 Out-of-Plane Shear

The out-of-plane shear strength of CSS structural elements consists of contributions from both the concrete infill and the steel shear reinforcement (i.e., the primary stiffeners). In the direction perpendicular to the stiffeners, these contributions are combined as follows:

[[

[redacted]

[redacted] **]]**

6.1.5.1 Out-of-Plane Shear Parallel to the Stiffeners

The design out-of-plane shear strength per unit width, $\phi_{vo}V_{no,x}$, of CSS structural elements in the parallel direction, as shown in Figure 6-6, is determined as follows:

$$\phi_{vo} = 0.90$$

[[[redacted] **]]**(6-17)

where, **[[**

[redacted] **]]**(6-18)

6.1.5.2 Out-of-Plane Shear Perpendicular to the Stiffeners

The design out-of-plane shear strength per unit width, $\phi_{vo}V_{no,y}$, of CSS structural elements in the perpendicular direction, as shown in Figure 6-7, is determined as follows:

[[

[redacted]

[redacted]

[redacted]]]

6.2 Interaction of Design Strengths

This section provides interaction equations for verifying the adequacy of CSS structural elements subjected to combination of demand types due to individual load cases and specified load combinations. The interaction equations are valid for load combinations involving both operating thermal and accident thermal load cases.

The interaction equations distinguish between: (a) primary stiffeners, and (b) faceplates of CSSMs. The primary stiffeners resist the in-plane membrane force (S_{rx}) parallel to their longitudinal direction, and out-of-plane shear forces (V_{rx}, V_{ry}). The interaction equation for primary stiffeners accounts for the simultaneous effects of these demands. The faceplates resist the in-plane membrane forces (S_{rx}, S_{ry}, S_{rxy}) and out-of-plane moments (M_{rx}, M_{ry}, and M_{rxy}). The interaction equation for faceplates accounts for the simultaneous effects of these demands.

6.2.1 Interaction of Design Demands on Primary Stiffeners

[[[redacted]

[redacted]

[redacted] (6-29)**]]**

Q_{cv}^{avg} = weighted average of the available interfacial shear strength per unit width of primary and secondary stiffeners, kip/ft (N/m)

V_c = available out-of-plane shear strengths per unit width of CSSM panel section in local x (V_{cx}) and y (V_{cy}) directions, kip/ft (N/m)

$V_{c.conc}$ = available out-of-plane shear strength contributed by concrete per unit width of CSSM panel section, kip/ft (N/m)

V_r = required out-of-plane shear strength per unit width of CSSM panel section in local x (V_{rx}) and y (V_{ry}) directions, kip/ft (N/m)

s = spacing of shear connectors, or spacing between secondary and primary stiffeners in. (mm)

6.2.2 In-Plane Membrane Forces and Out-of-Plane Moments

Similar to SC Walls, the design adequacy of the CSS structural elements subjected to the three in-plane required membrane strengths (S_{rx}, S_{ry}, S_{rxy}) and three out-of-plane required flexural or twisting strengths (M_{rx}, M_{ry}, M_{rxy}) are evaluated for each notional half of the CSSM section that consists of one faceplate, half the primary stiffener and half the concrete thickness.

[[[redacted]]]

For each notional half, the interaction shall be limited by Equations (6-30) to (6-32). These equations are used with the maximum and minimum required principal in-plane strengths per unit width for the notional half of the CSS structural element, $S_{r,max}$ and $S_{r,min}$, calculated using Equations (6-33) to (6-37). These equations are consistent with interaction equations in AISC N690, N9.3.6b.

[[

[redacted]

[redacted]

[redacted] **]]**

j_y = parameter for distributing required flexural strength, M_{ry}, into the corresponding membrane force couples acting on each notional half of CSS structural element

= 0.9 if $S_{ry} > -0.6P_{no,y}$

= 0.67 if $S_{ry} \leq -0.6P_{no,y}$

j_{xy} = parameter for distributing required flexural strength, M_{rxy}, into the corresponding membrane force couples acting on each notional half of CSS structural element

= 0.67

$P_{no,x}$ = nominal compressive strength per unit width parallel to the stiffeners, calculated using Section 6.1.2.1, kip/ft (N/m)

$P_{no,y}$ = nominal compressive strength per unit width perpendicular to the stiffeners, calculated using Section 6.1.2.2, kip/ft (N/m)

---

4 **[[** [redacted] **]]**

[[

[redacted] **]]**(6-38)

α $= V_{ci}/T_{ci}$

$= V_{ci}/P_{ci}$

[[redacted]

[redacted]

[redacted] **]]**

V_{ci} = available in-plane shear strength per unit width for each notional half of CSS structural element, kip/ft (N/m)

$= \phi_{vs}V_{ni}/2$

ϕ_{ci} = 0.80

ϕ_{ti} = 1.00

ϕ_{vs} = 0.95

6.3 Stress Limits for Containment

For the CSS structural elements that are used to form the containment, the individual design demands from the LEFE analysis models also need to be compared against their capacities as described in Section 6.1. The interaction of design demands on primary stiffeners also need to be performed as described in Section 6.2.1, but additionally, instead of a strength based interaction check as per Section 6.2.2, principal stresses in faceplates and concrete infill are calculated as presented in Section 6.3.1. For steel faceplates of containment CSSMs, the principal stresses are used to calculate von Mises stresses and compared against allowable limits in Section 6.3.2. For concrete infill of containment CSSMs, the principal compressive stresses are compared against allowable limits in Section 6.3.2.

The steel faceplates primarily resist membrane forces (S_{rx}, S_{ry}, S_{rxy}) and out-of-plane moments (M_{rx}, M_{ry}, M_{rxy}), and the stress states are calculated using these demands. The concrete infill primarily resists compressive principal stresses (if any) induced by membrane forces and moments.

6.3.1 Calculation of Stress Demands

Section forces and moments induced by factored load combinations are calculated for the CSS containment structure elements. At each evaluation location, a CSSM panel section with unit widths in the hoop (circumferential) and meridional directions shall be considered. The CSSM panel section is divided into two notional halves (inside half and outside half). The section principal forces (maximum principal force S_{p1} and minimum principal force S_{p2}) for each notional half are calculated as follows:

[[[redacted] (6-39)

[redacted] **]]**

S_x = factored membrane force per unit width in direction *x*

S_y = factored membrane force per unit width in direction *y*

S_{xy} = factored membrane in-plane shear force per unit width

M_{xx} = factored bending moment per unit width about direction *x*

M_{yy} = factored bending moment per unit width about direction *y*

M_{xy} = factored twisting moment per unit width

S'_x = factored membrane force per unit width in direction *x* for each notional half

S'_y = factored membrane force per unit width in direction *y* for each notional half

6.3.1.1 Steel Faceplates

For each notional half, the section principal forces described in Section 6.3.1 are used to calculate principal stresses in the corresponding steel faceplates ($\sigma_{p1,2}$). The principal stresses in each steel faceplate ($\sigma_{p1,2}$) are then used to calculate the von Mises stress (σ_{VM}). The calculated von Mises stress (σ_{VM}) for each steel faceplate under factored load combinations are not to exceed the allowable stresses as summarized in Table 6.1.

(a) S_{p1} > 0 and S_{p2} > 0

When both S_{p1} and S_{p2} are greater than 0, concrete tensile strength is not relied upon to resist the section forces. The principal stresses and von Mises stress in the steel faceplate (of the corresponding notional half) are calculated as follows:

[[[redacted] (6-40)

[redacted] (6-41)

]](6-42)

(b) S_{p1} > 0 and S_{p2} < 0

When one of the section principal forces is less than 0, concrete compressive strength is relied upon to resist the corresponding section principal forces and the von Mises stress in the steel faceplate (of the corresponding notional half) is calculated as follows.

[[[redacted]

[redacted] (6-43)

(6-44)

]](6-45)

(c) S_{p1} < 0 and S_{p2} < 0

When both section principal forces are less than 0, concrete compressive strength is relied upon to resist both forces. The principal stresses and von Mises stress in the steel faceplate (of the corresponding notional half) are calculated as follows:

[[[redacted] (6-46)

(6-47)

]](6-48)

6.3.1.2 Concrete Infill

For each notional half, the section principal forces described in Section 6.3.1 are used to calculate principal stresses in the corresponding concrete infill ($\sigma_{p1,2}$). The calculated principal stresses ($\sigma_{p1,2}$) are not to exceed the allowable stresses for concrete for factored load combinations summarized in Table 6.1.

(a) S_{p1} > 0 and S_{p2} > 0

When both S_{p1} and S_{p2} are greater than 0, concrete tensile strength is not relied upon to resist the section forces. The principal stresses in the concrete infill (of the corresponding notional half) shall be 0.

[[[redacted] (6-49)

]](6-50)

(b) S_{p1} > 0 and S_{p2} < 0

When one of the section principal forces is less than 0, concrete compressive strength is relied upon to resist the section principal forces and the principal stresses in the concrete infill (of the corresponding notional half) are calculated as follows:

[[[redacted] (6-51)

]](6-52)

(c) S_{p1} < 0 and S_{p2} < 0

When both sectional principal forces are less than 0, concrete compressive strength is relied upon to resist the section principal forces and the principal stresses in the concrete infill (of the corresponding notional half) are calculated as follows:

[[[redacted] (6-53)

]](6-54)

6.3.2 Allowable Stresses

The allowable stresses and strains specified in this section are used to essentially keep the containment elastic under service load conditions and below the range of general yield under factored loads. The allowable stresses provided in Table 6.1 and Table 6.2 are not to be exceeded when the containment is subjected to the loads provided in Section 4.0. The allowable stresses presented in this section are adapted from the allowable stress limits for concrete and steel rebars in ASME CC.

[[[redacted] **]]**

Figure 6-1: Uniaxial Compression Parallel to the Stiffeners

[[[redacted] **]]**

Figure 6-2: Uniaxial Compression Perpendicular to the Stiffeners

[[[redacted]]]

Figure 6-3: Out-of-Plane Flexure Parallel to the Stiffeners

[[[redacted]]]

Figure 6-4: Out-of-Plane Flexure Perpendicular to the Stiffeners

[[

[redacted]]]

Figure 6-5: In-Plane Shear

[[

[redacted]]]

Figure 6-6: Out-of-Plane Shear Parallel to the Stiffeners

[[

[redacted]]]

Figure 6-7: Out-of-Plane Shear Perpendicular to the Stiffeners

Table 6.1: Allowable Stresses for Factored Loads

Material	Force Classification	Type of Force Action [(1)]	Criteria for Factored Loads	
			Stress Limit	Strain Limit, if any
Concrete	Primary	Membrane	$0.60f_c'$	-
		Membrane + Bending	$0.75f_c'$	-
	Primary + Secondary	Membrane	$0.75f_c'$	-
		Membrane + Bending	$0.85f_c'$	0.002
[[[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
	[redacted]	[redacted]	[redacted]	[redacted]]]

Notes:

(1) Type of force action is for the entire CSSM section.

(2) [[[redacted]]]

(3) This strain limit is applied on mechanical (net) membrane strain in the faceplates. It is calculated by subtracting strain induced by secondary force from the total strain. This limit is derived from Subparagraph CC-3422.1(e) ASME CC.

Table 6.2: Allowable Stresses for Service Loads

Material	Force Classification	Type of Force Action (1)	Criteria for Service Loads	
			Stress Limit	Strain Limit
Concrete	Primary	Membrane	$0.30f_c'$	-
		Membrane + Bending	$0.45f_c'$	-
	Primary + Secondary	Membrane	$0.45f_c'$	-
		Membrane + Bending	$0.60f_c'$	-
[[[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
	[redacted]	[redacted]	[redacted]	[redacted]]]

Notes:

(1) Type of force action is for the entire CSSM section.

(2) [[[redacted]]]

(3) The stress limit may be increased by 50% when the temporary pressure loads during the test condition are combined with other loads in the load combination. This is in accordance with Subparagraph CC-3432.1(c) ASME CC.

7.0 CONNECTION DESIGN

CSS structural elements are connected to other structural members using a variety of connection types. These include CSSM-to-CSSM connections, CSSM-to-RC connections and CSSM-to-steel connections. Typical configurations include:

- Co-planar splices between CSSM members.
- Co-planar splices between CSSM and RC, or CSSM and steel members.
- Intersection connections between CSSM members.
- Intersection connections between CSSM and RC, or CSSM and steel members.

7.1 Connection Design Philosophy and Required Strength

Consistent with AISC N690, ACI 349, and explanations in AISC Design Guide-32 [5], the design of CSSM connections follows the capacity design philosophy. Two general approaches are used:

1) Full Strength Connection – The connection is designed to remain stronger than the weaker of the two connected members, ensuring that inelastic deformations occur in the member rather than the connection.
2) Overstrength Connection – The connection is designed to provide direct overstrength in the connection design with respect to the calculated force and moment demands.

These two design philosophies are further discussed in the following subsections.

7.1.1 Full Strength Connection Design

The full-strength connection is designed to be stronger than the expected strengths of the weaker of the connected parts. Therefore, for beyond design basis loads and load combinations, inelastic deformations and energy dissipation will primarily occur in the weaker of the connected parts.

For full-strength connection design, the required strength of the connection shall be greater than or equal to the expected strength of the weaker of the two connected parts. **[[** [redacted] **]]**

7.1.2 Overstrength Connection Design

Connections designed for the required strength according to overstrength connection design develop overstrength with respect to the connection design demands.

The required strength for the connections shall be determined as 200% of the required strength due to seismic loads plus 100% of the required strength due to non-seismic loads, including thermal loads. This is consistent with the provisions of Section N9.4.1a of AISC N690.

7.2 Types of Connector and Force Transfer Mechanisms

CSSM connections primarily utilize a variety of steel connectors to achieve the required force transfer, including welded plates, splice plates, doubler plates, baseplates, shear lugs, embedded steel shapes, welds, bolts, and direct bearing in compression.

For each connection, the force transfer mechanisms are clearly identified and assessed for adequacy under all applicable load combinations. If the connection can develop more than one force transfer mechanism, the one that provides the greatest strength is assumed to be governing.

7.3 Types of Connections

7.3.1 Splices

[[[redacted]

[redacted]

[redacted]]]

7.3.2 Connections

Depending on the function of the connection, the CSSM connections are designed to be rigid or pinned, and consistent analysis models are used. In certain cases, connections may be designed and detailed to accommodate specific translations or rotations to permit thermal elongation or contraction of CSSMs as well as differential settlements. For each connection, the connection type is clearly defined, the applicable connectors and force transfer mechanisms are identified, and the selected connectors are qualified to meet the demands of either full strength or overstrength design.

[[[redacted]]]

8.0 ANALYSIS, DESIGN, AND DETAILING FOR OPENINGS

As mentioned in Section N9.1.7 of AISC N690, the term “openings” is used to describe penetrations through the entire thickness of a CSS structural element. Holes in faceplates that are meant for stiffeners, ties, connection bolts, or other hardware are not considered to meet this definition of openings.

For both pressure-retaining containment boundary structures as well as other SC-I structures, the analysis and detailing for openings in CSSMs follows the provisions of AISC N690 Section N9.1.7, as applicable. The commentary for Section N9.1.7 includes several helpful illustrations related to the detailing requirements around openings. The analysis model consists of finite element sizes of less than or equal to t_{sc} in the immediate vicinity of openings, a region specified in AISC N690.

The following subsections provide a general discussion as well as some of the specific requirements regarding the attributes of openings in CSSMs.

8.1 Types of Openings

Consistent with Section N9.1.7 of AISC N690, openings are categorized into three types:

- **“Very Small” openings**: openings with their largest dimension up to the smaller of one-fourth of the CSS structural element thickness or 6 in
- **“Small” openings**: openings with their largest dimension up to one-half the CSS structural element thickness
- **“Large” openings**: openings with their largest dimension exceeding one-half of the CSS structural element thickness

A group of closely spaced openings (i.e., a “bank of openings” per AISC N690) for linear commodities may occur in some situations. Based on the provisions of Section N9.1.7c of AISC N690, a bank of openings may need to be designed and detailed as an equivalent “large” opening. The additional detailing provisions of Section N9.1.7c may be applicable, depending on the sizes and spacing(s) of the individual openings as well as the largest opening dimension of the group. Applicability is as defined in Section N9.1.7c.

8.2 Analysis Requirements and the Associated Design and Detailing Requirements

The following analysis and the associated design and detailing requirements are used based on the opening size:

- **“Very Small” openings:** These openings need not be modeled and no reduction in the affected CSS structural element capacities need be considered as long as the detailing requirements (1), (2), and (3) in AISC N690 Section N9.1.7a(b) are satisfied.
- **“Small” openings with free edge at their perimeter**: While this option is permitted in AISC N690, it will not be exercised for structures constructed using CSSMs.
- **“Small” openings with fully developed edge around their perimeter:** This situation applies when the detailing around the small opening meets all requirements in Section

N9.1.7a(b). In this case, the analysis will be performed without modeling the actual opening, and no reduction in available strengths needs to be considered for any of the affected elements.

- **“Large” openings with free edge at their perimeter**: Similar to the case of “Small” Openings with Free Edge at their perimeter, this option, while it is permitted in AISC N690, will not be exercised for structures constructed using CSSMs.
- **“Large” openings with fully developed edge around their perimeter**: For this case, the detailing requirements shall be in accordance with Section N9.1.7a(b), which is the same as those for the corresponding case of “small” openings. Analysis shall be performed by considering the actual opening and the design evaluation shall consider unreduced capacities in the immediate vicinity of the opening.
- **“Bank of Openings” openings that together constitute a “small” opening**: The design, analysis, and detailing requirements for this case shall be the same as those for a small opening with a fully developed edge around its perimeter.
- **“Bank of Openings” openings that together constitute a “large” opening**: The design, analysis, and detailing requirements for this case shall the same as that for large openings with fully developed edge around its perimeter.

9.0 IMPACTIVE AND IMPULSIVE LOADINGS

Analysis and detailing requirements for CSS structural elements subjected to design basis impulsive and impactive loads are specified in Section N10.3 of AISC N690. As discussed in Sections 9.1 and 9.2, these requirements along with the applicable modifications specified in the RG 1.243 are used for design basis impulsive and impactive loads for both containment and non-containment CSSM applications [8]. **[[** [redacted] **]]**

Evaluation of beyond-design-basis impulsive and impactive loads is discussed in Section 9.3.

Impulsive loads can arise from events such as compartment pressurization, jet impingement, and external blasts. The load may cause elastic response in the CSSM target or inelastic deformation in a localized region. Impulsive loads do not pose a penetration and perforation risk for the target structure. Accordingly, both local and, where significant structural response is expected, global dynamic evaluations are applicable for impulsive loads.

Impactive loads can arise due to internal or external sources such as a whipping pipe, a tornado-borne missile, or an aircraft impact. Depending on the missile's properties, especially its velocity and nose profile, the resulting impactive loads can cause local perforation or local inelastic response. Similar to impulsive loads, the response due to impactive loads can be elastic or inelastic.

9.1 Local Perforation Check for Design Basis Missiles

CSSMs provide increased missile perforation resistance compared to the SC embodiments covered in AISC N690 (i.e., those involving discrete ties) because of the presence of primary stiffeners that span the entire member thickness. Additionally, passive confinement of the concrete within the impacted CSSM provides increased resistance to perforation, because higher missile energy will be needed to eject the associated concrete plug and frustum. The extent of this benefit depends on the spacing of primary stiffeners relative to the member thickness.

Despite these benefits, the perforation resistance of CSSMs for design-basis missiles (e.g., those due to tornados) is conservatively considered to be the same as the SC wall embodiments covered in Appendix N10 of AISC N690. The conservative empirical evaluation method in Section N10.3.2 of AISC N690 is used for evaluating the local perforation of a missile.

9.2 Analysis Requirements and Acceptance Criteria for Local Response due to Design-Basis Impulsive and Impactive Loads

Section N10.3.4 of AISC N690 is used to perform design-basis impulsive and impactive loads applicable to CSS structures. Section N10.3.4 permits the use of both simplified and refined models for local response evaluation. The associated acceptance criteria are based on ductility limits for the simplified method and strain limits for the refined method. In general, the simplified method is appropriate for internal and tornado or hurricane missiles, while the refined method is appropriate for the remainder of the missile loads and for impulsive loads. However, either method is acceptable.

The detailing requirements for CSS structural elements subjected to impulsive or impactive loads are those provided in Section N10.3.3 of AISC N690. Additionally, the ductility factors permitted in RG 1.243 may be used for non-containment applications of CSSMs.

9.3 Evaluation for Beyond-Design-Basis Loads

9.3.1 Evaluation for Beyond-Design-Basis Impulsive Loads

For beyond design basis loads, Subsection 9.2 above applies, except that higher strain limits are used. Refined models may be used to evaluate the performance of CSS structures under beyond-design-basis impulsive loads. **[[** [redacted] **]]**

9.3.2 Evaluation for Beyond-Design-Basis Impactive Loads

The general guidance and acceptance criteria from NEI 07-13 are used to the extent that they are applicable to CSS structures. Detailed NIFE analyses are performed to verify that the following criteria are met:

[[

[redacted] **]]**

10.0 PERFORMANCE UNDER FIRE

The design of CSS structural elements under fire loading follows the design recommendations and methodology for generic SC walls under fire loading as provided in AISC 360 Appendix 4 [3] and AISC Design Guide 38 [37] based on the research of Anvari et al. (2020) [38].

Anvari et al. (2020) conducted scaled experimental investigations, detailed numerical analyses, and numerical parametric studies to evaluate the fire resistance and rating of generic SC walls. These studies led to the development of a closed-form equation that can be used to calculate the fire resistance rating of a generic SC wall under a standard fire. This equation has been adopted in AISC 360 and is presented in Appendix 4.3.2g.

$$R = \left[-18.5\left(\frac{P_u}{P_n}\right)^{0.24-\frac{\frac{L_v}{t_{sc}}}{230}} + 15\right]\left(\frac{1.9t_{sc}}{8} - 1\right) \tag{10-1}$$

where,

R = fire rating, hours

P_u = required axial load, kips

P_n = ambient-temperature compressive strength per AISC 360 Chapter I, kips

L_v = unbraced length, in

t_{sc} = wall thickness, in

[[[redacted]]]

Although test results indicate that SC structures with comparable configurations demonstrate strong fire performance, variations in structural geometry, material properties, and loading conditions of applicable CSS structures warrant additional evaluation. To comply with the fire resistance requirement, the following three-step approach is implemented for CSS structures:

[[

- [redacted]
- [redacted]
- [redacted]]]

10.1 Vent Holes

At elevated temperatures, the evaporation of free and bonded water within the concrete can lead to vapor pressure buildup at the interface between the faceplate and the concrete. The effects of this internal vapor pressure on the fire resistance rating and structural behavior of

CSSM walls and slabs are assessed numerically using the evaluation methods developed by Anvari et al. If the results of these assessments indicate a need for pressure relief, vent holes will be provided where practical, following the recommendations of Anvari et al.

Table 10-1: Calculated Fire Ratings for SC Walls

[[[redacted]]]

11.0 QUALITY ASSURANCE & QUALITY CONTROL REQUIREMENTS

As required by GDC 1, CSSMs and structures constructed with CSSMs must be designed, fabricated, erected, and tested to quality standards commensurate with the importance of their safety function. This section describes quality assurance (QA) and quality control (QC) requirements applicable to fabrication of CSSMs and the installation of CSSMs to form structures. QA refers to proactive measures that are implemented prior to executing design, fabrication, and construction tasks. QC refers to in-process checks that are performed to verify the acceptability of design, procurement, and construction tasks after they have been completed.

This section does not define all requirements that are applicable to design, fabrication, and construction activities, but it establishes minimum requirements specific to CSSMs. For containment applications, the requirements are based on ASME CC, ASME Section III, Division 1, Subsection NE [41], and ASME Section IX [42], and are supplemented by the applicable provisions of AISC N690, AISC 360, ACI 349, and ACI 318. For non-containment applications, the requirements are based on AISC N690, AISC 360, ACI 349, and ACI 318. For both containment and non-containment applications, appropriate modifications have been made to reflect the unique characteristics of CSSMs within the scope of this topical report. Implementation of these requirements must be performed in accordance with a QA program that meets the requirements of 10 CFR 50, Appendix B.

11.1 Applicable Sources of Nuclear Quality Requirements

Chapters NM and NN of AISC N690 contain multiple fabrication and erection-related inspection requirements for SC modules consisting of faceplates with discrete ties and steel-headed stud anchors. Additionally, Section NN6 of AISC N690 contains post-erection inspection requirements for SC structural elements both prior to and after concrete placement. CSS structural elements differ slightly from the SC module embodiments covered in AISC N690 in that CSSMs contain primary stiffeners that span between the opposite faceplates.

The welding and bolting-related inspection and module erection-related requirements in AISC N690 are the same as those for regular structural steel construction (Section NN5), except as augmented by Section NN6. The applicable AISC N690 inspection requirements are also applicable for CSSMs.

AISC N690 specifies two types of field inspection activities, field QA activities and field QC activities. For both sets of activities, the required inspections can be of two types:

- “Observe,” which means that the inspector is required to observe these items on a random basis. Operations need not be delayed pending these inspections.
- “Perform,” which means that the inspector is required to perform the specified inspection task(s) before construction can progress.

[[[redacted]

[redacted] **]]**

11.2 Design Tolerance Limits

This section defines dimensional tolerances for CSSMs to ensure that the modules are fit for assembly without adversely impacting the strength or functional requirements of the associated connection or structure. Tolerances are to be applied consistent with AISC N690 Section NM2, except as modified in this section.

11.2.1 Fabrication Tolerances

CSSM inspections verify a variety of aspects of the modules. Two key parameters require particular attention: **[[**

[redacted] **]]**

Any deviation outside these limits shall be justified by engineering evaluation on a case-by-case basis.

CSSM section thickness tolerances are specified in Table 11-1. These tolerances are adapted from Table C-NM2.1 of AISC N690, modified to reflect the use of continuous primary stiffeners in CSSMs. Continuous stiffeners provide improved structural performance compared to the discrete tie bars used in AISC N690.

The spacing of primary and secondary stiffeners shall be within **[[** [redacted] **.]]** of the nominal design spacing.

The module planar dimensional tolerances (i.e., the overall dimensions of the module) will be defined in applicable fabrication drawings. Tolerances will be established to ensure acceptable stiffener spacing and to address fit-up requirements established in Section 11.2.2.

11.2.2 Tolerance Limits for On-Site Fit-Up

Tolerance limits for on-site assembly of CSSMs will be established by the qualified weld procedure used to fabricate the joint. Standard welding procedure specifications defined in ASME Section IX and AWS D1.1 may be used.

11.2.3 As-Built Tolerances

After concrete curing, the faceplate waviness shall conform to the following limit, which is consistent with Equation NM2-1 of AISC N690, with variables redefined for CSSMs:

[[[redacted] **]]** (11-1)

where,

s = spacing between secondary and primary stiffeners, in (mm)

s_{ps} = spacing between primary stiffeners, in (mm)

t_p = thickness of faceplate, in (mm)

For cases where only primary stiffeners are used, s_{ps}/s shall be taken as 1.0.

11.3 Weld Inspections & Examinations

11.3.1 CSSM Weld Inspections

Requirements for CSSM weld inspection activities are adapted from Chapter NN of AISC N690 and Chapter N of AISC 360, with modifications as provided in this section. Observation of welding operations and visual inspection of in-process and completed welds is the primary method to confirm that the materials, procedures, and workmanship conform with requirements.

Inspections are differentiated based on whether the weld is classified as demand-critical.

[[[redacted]

- [redacted]
- [redacted]

[redacted] **]]**

11.3.1.1 Weld Inspection Tasks for Demand-Critical Welds

Inspection tasks for demand-critical welds are conducted in accordance with Table 11-2, Table 11-3 and Table 11-4. In these tables, the inspection tasks are as follows:

Observe (O) - The inspector shall observe these items on a random basis.

Perform (P) - These tasks shall be performed for each welded joint or member.

11.3.1.2 Weld Inspection Tasks for All Other Welds

Welds not classified as demand-critical shall be inspected in accordance with the provisions of AISC 360, Section N5.4. Visual inspection remains the primary verification method.

11.3.2 Weld Examination

Nondestructive examination (NDE) requirements for CSSM welds are summarized in Table 11-5. These requirements ensure that containment or leak barrier welds receive comprehensive inspection coverage.

The requirement for faceplates which form the containment leak barrier is consistent with the weld examination of liners per Subsection CC-5500 of ASME CC and with weld examination of metal containments per NE-5200 of ASME BPVC Section III, Division 1, Subsection NE [41].

The requirement for faceplates which form a water leak barrier are based on ASME BPVC Section VIII, Div 2 [43] for Category A and B welds in pressure retaining components, supplemented by a surface examination.

The requirements for all other welds are in accordance with Chapter NN5 of AISC N690.

11.4 Bolting Inspections

Similar to welded connections, bolted connections in CSSMs are classified as demand-critical or not based on their role in structural performance.

A demand-critical bolted connection is one that satisfies both the following conditions:

[[

[redacted]]]

Inspections of demand-critical bolted connections follow AISC N690, Section NN5.6, which include verification of bolt type, installation method, pre-tensioning and final torque.

Inspections for all other bolted connections follow AISC 360, Section N5.6.

11.5 Concrete Placement

[[[redacted]

[redacted]

[redacted]]]

Table 11-1: Section Thickness Tolerances for Fabricated CSSMs and Sub-Modules

[[

[redacted]

]]

Table 11-2: Inspection Tasks Prior to Welding

[[

[redacted]

]]

Table 11-3: Inspection Tasks During Welding

[[

[redacted]

]]

Table 11-4: Inspection Tasks After Welding

[[

[redacted]

]]

Table 11-5: Weld Examination Requirements

[[

[redacted]

]]

12.0 CORROSION PROTECTION/MITIGATION REQUIREMENTS

CSS structural elements must be designed to accommodate environmental degradation that may occur during the life of the structure. **[[** [redacted] **]]** Typically, a combination of these methods can be employed.

Acceptable methods to protect against corrosion and mitigate its consequences will be application-dependent, considering factors like site location, site meteorology, site geology, and the immediate environment of the CSS structural element. The corrosion protection or mitigation method will be application-dependent, considering factors like site location, site meteorology, site geology, and the immediate environment of the CSS structural element. Specific requirements are to be defined and justified in design, fabrication, or construction documents.

12.1 Non-Embedded Applications

In applications where the CSS structural elements are not embedded, typical corrosion mitigation methods like routine coating are appropriate to maintain the CSS structure.

Acceptable methods for protection of steel faceplates that are exposed to non-soil external or internal environmental conditions are:

[[

[redacted] **]]**

A combination of the above measures may be used. The specific measures will be selected based on the application. For exterior applications, site-specific environmental conditions are to be considered. For interior applications, such as walls or tanks, application-specific internal environmental conditions are to be considered.

12.2 Embedded Applications

CSS structural elements may be used in embedded applications where the modules are exposed to soil and groundwater. In such applications, access to the exterior of the buried CSSMs may be restricted, making routine coating maintenance and inspection impractical.

The corrosion rate is dependent on a variety of factors. **[[** [redacted]

[redacted].]]

Acceptable methods for protection of steel faceplates that are exposed to soil are:

[[

[redacted] **]]**

A combination of the above measures may be used. The specific measures are to be selected based on the application, considering site-specific soil and water conditions.

13.0 EXPERIMENTAL EVALUATIONS

The methodology presented in this LTR is justified based on the technical rationale included in this report, supported by analytical evaluations, comparisons with accepted industry codes, the foundational studies underpinning those codes, and additional research published in the literature.

Separately, large-scale experimental evaluations of CSSMs are being conducted. These experimental evaluations are not necessary to validate the methodology described in this report. However, they provide:

[[

- [redacted]
- [redacted]
- [redacted] **]]**

The fabrication and construction of large-scale specimens **[[** [redacted] **]]** also allow the constructability and modularity of the CSSM design to be evaluated. The experiments will evaluate the behavior of individual CSSMs and critical connections between CSSMs for individual and combined demand types.

For CSSMs, experiments will include studies to confirm behavior under:

[[

- [redacted]
- [redacted]
- [redacted]
- [redacted]
- [redacted] **]]**

For CSSM connections, the experimental program will include studies to confirm the behavior and design of non-standard connections. Examples may include:

[[

- [redacted]
- [redacted]
- [redacted] **]]**

13.1 CSSM Component Behavior

Component behavior experiments will focus on CSS structural elements under individual demand types and combination of demands. Experiments can quantify additional margin in the designs and support resolution of challenges during fabrication, construction, or operation. This section describes the potential experiments for various CSSMs. The experiments and test matrices for CSSM configurations in different structural elements will be established as the design development and experimental program progresses.

13.1.1.1 In-Plane Shear Behavior

The design approach for in-plane shear behavior is described in Sections 5.0 and 6.0. Testing will be performed to confirm the analytical predictions and to further study the actual structural response.

[[[redacted]

[redacted]]]

13.1.1.2 Out-of-Plane Behavior

The design approach for out-of-plane behavior and capacities of CSSMs is described in Sections 5.0 and 6.0. [[[redacted]

[redacted]]]

13.1.1.3 Axial Behavior

The design approach for axial behavior and capacities of CSSMs is described in Sections 5.0 and 6.0. [[[redacted]

[redacted]]]

13.1.1.4 Interfacial Shear Behavior

The composite behavior of CSSMs depends on interfacial shear transfer between steel plates and concrete infill through the primary and secondary stiffeners acting as shear connectors.

[[[redacted] **]]**

13.2 CSSM Connection Behavior

Connection design philosophies are described in Section 7.0. **[[** [redacted] **]]**

13.2.1 Steel Faceplate Weld Splice Connections

Empty CSSMs are spliced together to form CSS structures. **[[** [redacted]

[redacted] **]]**

13.2.2 Connection Between Different CSS Structural Elements

The performance of non-standard connections between CSS structural elements will be evaluated. **[[** [redacted]

- [redacted]
- [redacted]
- [redacted]

[redacted]

[redacted]. **]]**

13.2.2.1 CSSM Wall-to-Basemat and Slab Connections

[[[redacted]

[redacted]]]

13.2.3 Additional Connection Tests

13.2.3.1 Splice Plate Connections

[[[redacted]

[redacted]]]

13.2.3.2 Tests to Confirm Permissible Tolerances for Splice Connections

Constructability for CSSM-based structures is influenced by the tolerances for module splices. The connection splice designs will be evaluated to quantify their imperfection-tolerance.

13.3 Sample Experimental Results

Experimental studies are ongoing to evaluate the CSSM behavior under compressive loading, and interfacial shear behavior of CSSMs. A summary of experimental results for one experiment for each of the two series is presented in the following sections.

13.3.1 Pushout Tests

The composite behavior of CSSMs depends on interfacial shear transfer between steel plates and concrete infill through shear connectors (primary and secondary stiffeners). Pushout tests are included in the test plan, as described in Subsection 13.1.1.4.

[[[redacted]

[redacted]

[redacted]]]

13.3.2 Axial Compression Tests

The axial compression behavior of CSSMs depends on the faceplate slenderness, the direction of loading, and the material strengths. **[[** [redacted]

[redacted]

[redacted]]]

[[

[redacted]

]]

Figure 13-1: In-Plane Shear Test Setup

[[

[redacted]

]]

Figure 13-2: Out-of-Plane Test Setup

[[

[redacted] **]]**

Figure 13-3: Schematic for Axial Loading Test Setup

[[

[redacted] **]]**

Figure 13-4: Pushout Test Setup

[[

[redacted]

]]

Figure 13-5: Schematic for Faceplate Splice Testing under Biaxial Tension and Accident Thermal Loading

[[

[redacted]

]]

Figure 13-6: Illustrative Test Setup for Transfer Girder Connections (Side Elevation)

[[

[redacted]]]

Figure 13-7: Potential Detail for CSSM Wall-to-Basemat Connection

[[

[redacted]

]]

Figure 13-8: Summary of an Interfacial Shear Experiment for CSSMs

[[

[redacted]

]]

Figure 13-9: Summary of an Axial Compression Experiment for CSSMs

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15.0 LIST OF APPENDICES

15.1 Appendix A: Design Example for Application of CSSMs to SMR 300 SCCV

(50 Pages)

15.2 Appendix B: Design Example for Application of CSSMs to SMR-300 RAB Walls

(23 Pages)