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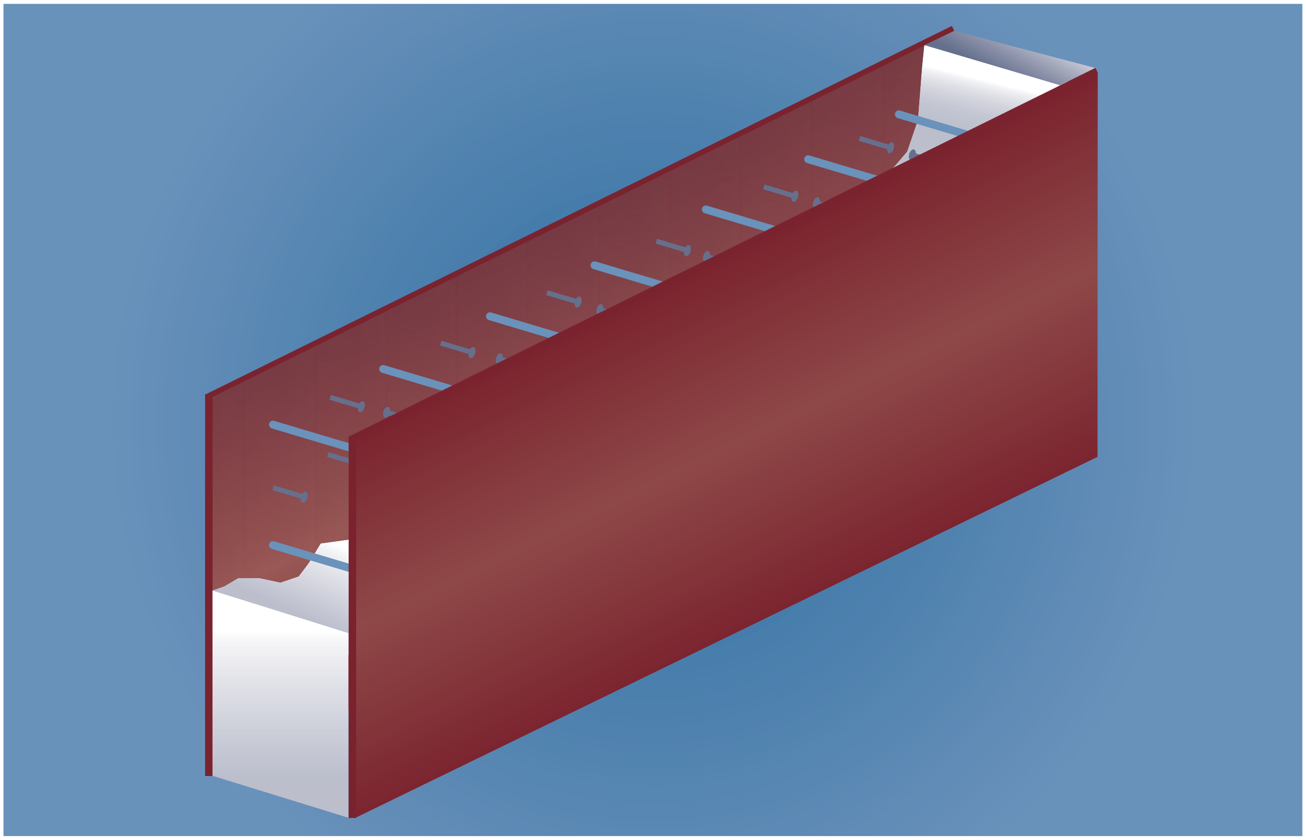
Steel Design Guide

Design of Modular Steel-Plate Composite Walls for Safety-Related Nuclear Facilities



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Design of Modular Steel-Plate Composite Walls for Safety-Related Nuclear Facilities

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Preface

This Guide is intended to facilitate the design of steel-plate composite (SC) walls for safety-related nuclear facilities and is to be used in conjunction with ANSI/AISC N690. The Guide discusses the behavior and design of SC walls subjected to various demands, including both individual and combined force demands. The detailing, analysis and design of SC walls and connections are based on the provisions in Appendix N9 of ANSI/AISC N690. The design of SC walls and connections is illustrated in a design example in Appendix A.

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Chapter 1
Introduction

Nuclear structures involve heavy concrete construction to provide adequate radiation shielding and resistance to severe and extreme loads. This results in longer construction durations and large field labor requirements. Generic modular construction, especially modular steel-plate composite (SC) construction, can minimize schedule and labor requirements. In SC construction, concrete walls are reinforced with two steel faceplates attached to concrete using steel anchors, such as steel headed stud anchors, and connected to each other using steel tie bars. Figure 1-1 illustrates a typical SC wall section. Steel anchors ensure composite behavior of faceplates and concrete. Ties provide structural integrity, prevent delamination of the plain concrete core, and serve as shear reinforcement. The SC walls may have sleeves for penetrations and embed plates for commodity attachments.

The behavior of SC walls under axial tension and compression (Zhang et al., 2014), out-of-plane flexure (Sener et al., 2015b), and out-of-plane shear (Sener and Varma, 2014; Sener et al., 2016) is similar to that of reinforced concrete (RC) walls. However, behavior of SC walls under in-plane shear (Seo et al., 2016; Varma et al., 2011e; Ozaki et al., 2004), combined in-plane forces, and out-of-plane moments (Varma et al., 2014) can be significantly different from that of RC walls. Additionally, specific limit states such as faceplate local buckling (Zhang et al., 2014), interfacial shear failure (Sener and Varma, 2014; Sener et al., 2016) between the faceplates and concrete infill, and section delamination through the concrete infill (Bhardwaj et al., 2017) need to be adequately considered in the design of SC walls. These limit states are discussed in Chapters 3 through 6, along with section detailing provisions to prevent them from limiting the design.

1.1 BACKGROUND

The initial application of SC walls was in non-nuclear commercial projects to resist extreme events in large concrete structures. SC walls were expected to provide better resistance to extreme blast and earthquake events. Other non-nuclear applications of SC walls included submerged tube tunnels (Narayanan et al., 1987), offshore oil rigs (Adams and Zimmerman, 1987), and ship building (Dai and Liew, 2006). The need for construction schedule reduction and better constructability and performance aspects of SC walls in comparison to RC walls led to the consideration of their use in safety-related nuclear facilities (Schlaseman and Russell, 2004).

Some of the early studies on nuclear power plant type structures composed of SC walls were conducted in Japan. For example, the seismic behavior of a containment internal structure (CIS) composed entirely of SC walls was evaluated experimentally by testing a 1/10-scale model of the entire structure by Akiyama et al. (1989). The structure was subjected to a cyclic loading history with load control cycles in the elastic range and displacement control cycles in the inelastic range. The cyclic response of the structure included events such as concrete cracking, steel yielding, local buckling, shear buckling, and eventual fracture failure of the steel plates. The cyclic lateral load displacement responses and hysteresis loops indicated that the structure had excellent stiffness, strength and ductility. The equivalent viscous damping factor, obtained from the hysteresis loops, was about 5% before steel yielding, and increased significantly thereafter due to yielding and inelasticity. Sener et al. (2015a) recently developed and verified a 3D nonlinear inelastic finite element model of the 1/10-scale test structure. They used the model to predict, further evaluate and gain insight into the seismic response of the SC structure. Both the experimental and numerical results confirmed that the seismic response including the stiffness, strength and drift capacity were governed by the in-plane shear behavior and corresponding concrete cracking and yielding of the steel plates of the SC walls. The lateral load ultimate strength was governed by the in-plane shear strength and failure of the SC walls parallel to the lateral loading direction. The final fracture occurred in regions where transverse shear reinforcement—web plates—in the SC walls were discontinued abruptly. The overturning moment at the base also contributed to inelastic deformations with extensive concrete cracking and yielding in the SC walls at the exterior outer regions of the CIS.

Akiyama et al. (1989) compared the cyclic response of the SC structure with that of an equivalent RC structure that had been tested earlier using a similar size model by Kato et al. (1987). Akiyama et al. concluded: (1) The ultimate strength of the SC structure was much higher than the corresponding RC structure due to the significant contribution of the steel plates; (2) cyclic loading causes some stiffness degradation in the elastic range due to concrete cracking, and this degradation was about 30% for the SC structure as compared to about 65% for the RC structure; and (3) the SC structure was more ductile as the corresponding RC structure lost capacity rapidly after peak load due to shear failure. It is important to note that these conclusions were limited to specific SC and RC structures that were tested by Akiyama et al. and Kato et al., and the corresponding design, reinforcing and connection details. These conclusions cannot be generalized, but they motivated extensive research and studies in

Japan, China, South Korea, the United States and Europe to establish rational design provisions, codes and standards for SC structures.

Significant research on the behavior of SC walls for various loading conditions, both in-plane and out-of-plane, has been performed in Japan (Takeuchi et al., 1998; Takeuchi et al., 1999; Ozaki et al., 2000; Ozaki et al., 2001; Ozaki et al., 2004; Mizuno et al., 2005), China (Song et al., 2014; Leng et al., 2015a; Leng et al., 2015b), and South Korea (Moon et al., 2007; Moon et al., 2008; Kim and Kim, 2008; Lee et al., 2008; Lee et al., 2009; Hong et al., 2009). The research in Japan and South Korea has been the basis for design standards for SC construction in Japan (JEAG, 2005) and South Korea (KSSC, 2010), respectively.

In the United States, extensive research has been conducted over the past decade to evaluate the behavior of SC walls and connections and to develop consensus design standards, such as the AISC *Specification for Safety-Related Steel Structures for Nuclear Facilities* including Supplement No. 1 (AISC, 2015), hereafter referred to as ANSI/AISC N690. For example,

- The behavior of SC walls subjected to accident thermal and mechanical loading was evaluated by Booth et al. (2007), Varma et al. (2009), Varma et al. (2013), and Booth et al. (2015a).
- The out-of-plane shear behavior and design of SC walls was evaluated by Varma et al. (2011c), Sener and Varma (2014), and Sener et al. (2016). The out-of-plane flexure behavior of SC walls was analyzed by Sener et al. (2015a).
- The in-plane behavior and design of SC walls was evaluated by Varma et al. (2011e), Seo et al. (2016), and Kurt et al. (2016a).
- The local buckling behavior of steel faceplates in SC walls and the composite action between steel plates and concrete infill was evaluated by Varma et al. (2013), Zhang (2014), Zhang et al. (2014), Zhang (2014), and Bhardwaj and Varma (2016).
- The behavior and design of SC walls subjected to combined in-plane forces and out-of-plane flexure was presented by Varma et al. (2011b; 2014).
- The missile impact behavior and design of SC walls was evaluated by Bruhl et al. (2015a; 2015b). The effects of impulsive loading on the design of SC walls was also evaluated by Bruhl and Varma (2015; 2016).

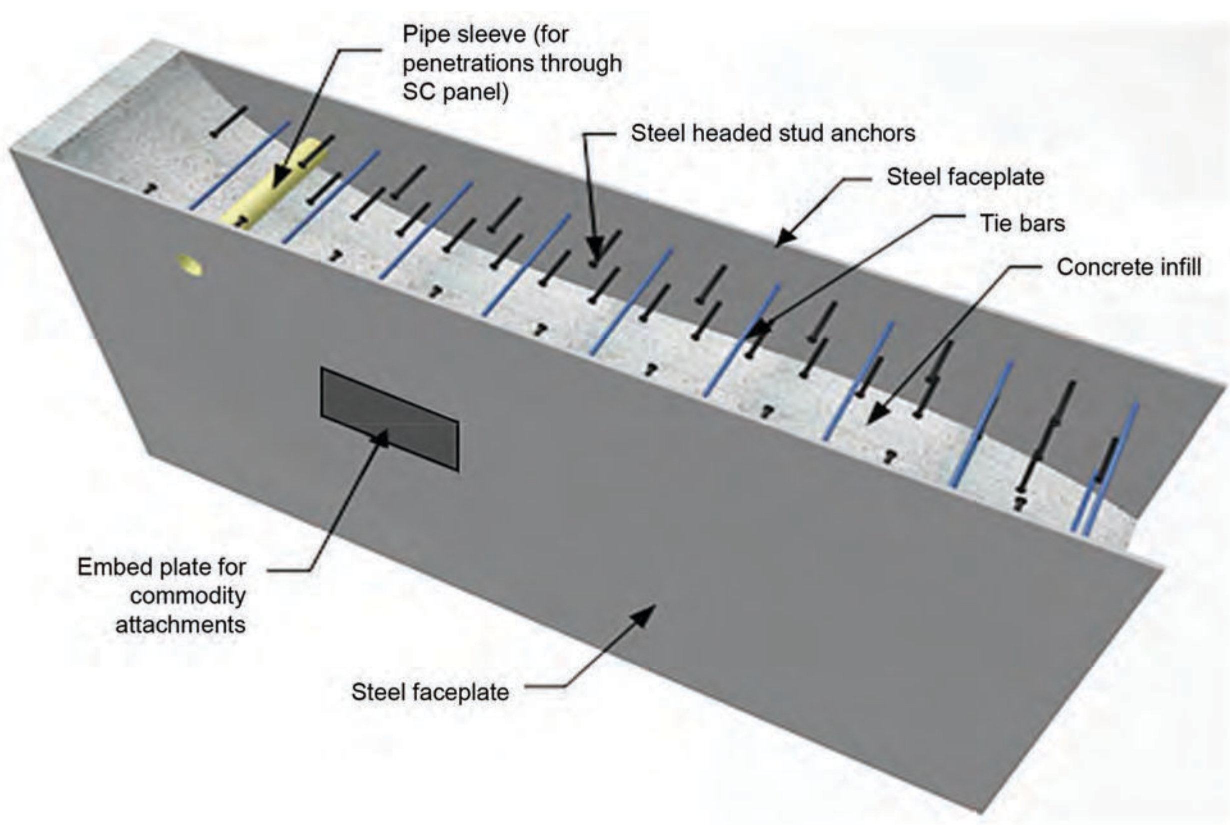

Fig. 1-1. Typical SC wall configuration (AISC, 2015).