Transactions, **SMiRT-26**
Berlin/Potsdam, Germany, July 10-15, 2022
Division X

Challenges Implementing Detailing Requirements of AISC/N690 Code for Openings in Steel-Composite (SC) Walls for Nuclear Power Plants

Rim Nayal[1], Amber Berger[2], Michael Marohl[3], Lisa Cleveland[4]

[1] Civil/Structural Engineer, NuScale Power, Corvallis, OR (RNayal@nuscalepower.com)
[2] Supervisor Civil/Structural Design, NuScale Power, Corvallis, OR
[3] Senior Manager, Nuclear Power Group Structural Engineering, Sargent & Lundy, Chicago, IL
[4] Project Associate, Nuclear Power Group Structural Engineering, Sargent & Lundy, Chicago, IL

ABSTRACT

Steel-Composite (SC) walls have been developed and used for a variety of applications in commercial structures as well as in nuclear power plants. Use of SC walls in nuclear power plants is a viable modularization option due to the associated economic advantages, short construction duration, shop fabrication and added efficiency. Design and detailing rules of SC walls shall take into consideration the unique nuclear building layouts and specific needs and come up with innovative solutions to benefit from the merits of SC walls while not compromising safety.

Appendix N9 of ANSI/AISC N690-18 (2018) addresses the requirements for design and detailing of SC walls in safety related structures for nuclear facilities. While in general the appendix addresses design approaches and requirements for SC walls, the provisions could be improved to more easily facilitate the use of SC walls in nuclear power plants taking into account their unique configuration. This paper specifically sheds light on the requirements of design and detailing around openings in SC walls per Appendix N9 of ANSI/AISC N690-18 (2018) and demonstrates challenges associated with the application of these requirements in nuclear power plants.

Section N9.1.7 of ANSI/AISC N690-18 (2018), specifies the requirements for design and detailing around openings. ANSI/AISC N690-18 (2018) -frequently referred to hereafter as the "code"- categorizes openings into small and large. An opening with its largest dimension not exceeding half of the SC wall thickness qualifies as a small opening; otherwise, the opening is categorized as a large opening. Furthermore, ANSI/AISC N690-18 (2018) categorizes openings into free edge and fully developed edge openings with different detailing requirements for each category.

Design and detailing requirements for free edge openings vary by opening category. Small openings are addressed by applying a reduction factor on available strength of the wall section. Furthermore, small openings need not be included in the finite element analysis (FEA) model. Large free edge openings require modelling of openings significantly larger than their physical size in the FEA model. In addition, free edge openings are not permitted in connection regions of the wall. Openings in connection regions shall be detailed using the fully developed edge detailing option. In addition, the code requirements for a bank of openings can result in extensive detailing requirements for groups of openings typically found in SC walls of safety related buildings. Based on the aforementioned requirements, utilizing the option of fully developed edge for openings, both small and large, is essential in the design of nuclear power plants.

Sections N9.1.7(a) and (b) of ANSI/AISC N690-18 (2018) provide the design and detailing requirements for a fully developed edge opening. The code specifies welded flanges around the opening at the connection of the sleeve and faceplate. The flanges must have a material nominal strength equal or

greater than that of the faceplates. The flanges are to be at least the thickness of the faceplate, and extend a distance of at least the wall thickness beyond the perimeter of the opening in all directions. In certain cases, the code also specifies a requirement for joining the flange to the faceplate using a CJP weld. With the required size of the flanges, the CJP weld becomes challenging due to the length of the weld and the typical thickness of the faceplate. The flanges required for fully developed edge openings present challenges to the SC wall panel configuration, layout and constructability due to their significant size and welding requirements.

While the detailing requirements for fully developed edge openings can be satisfied in commercial and residential buildings, it becomes challenging to satisfy in nuclear power plants due to the amount and size of openings in walls as well as the proximity of these openings to one another. Thus, it becomes imminent to provide an alternative standard detailing which satisfies load redistribution around openings yet be feasible to implement in nuclear power plants.

This paper reviews the detailing requirements for openings in SC walls and demonstrates, with examples, challenges to satisfy the fully developed edge detailing requirements common in nuclear power plants. This paper highlights the advantages associated with developing additional detailing methodology around openings for use in nuclear power plants.

INTRODUCTION

Utilizing steel-plate composite walls (SC walls) in design and construction of nuclear power plants offers many well-documented advantages. In addition to SC wall's structural performance providing high capacity, earthquake resistance and ductility, the modular construction of SC walls provides efficiency in construction by minimizing schedule and labor requirements as well as improved quality due to the controlled environment of the fabrication shop.

Appendix N9 of ANSI/AISC N690-18 (2018) has sufficiently covered sizing, detailing, and strength design aspects of SC walls. However, many areas of design and detailing do not yet have prescriptive rules, or have room for refinement due to the relatively new pedigree of the available testing and bases such that implementation of code requirements can substantially increase cost and challenge in fabrication and erection.

ANSI/AISC N690-18 (2018), Section N9.1.1(a) defines a minimum allowable wall thickness of 12″ for interior walls and 18″ for exterior walls. However, due to fabrication and construction logistics associated with SC walls, walls below 2ft are less common in nuclear power plants. Thus, the case study is demonstrated using 2ft thick walls and 5 ft thick walls which represent lower and upper bound for wall thickness taking into account constructability and code limits.

CODE CATEGORIZATION OF OPENINGS

Similar to other structural members, SC wall design shall account for a reduction in strength due to openings. SC wall design shall incorporate sufficient detailing requirements to ensure redistribution of loads around openings. Stress concentration effects around openings are highly dependent on factors like the size and the shape of the opening as well as the presence of sharp re-entrant corners.

Rules of Appendix N9, Section N9.1.7, of ANSI/AISC N690-18 (2018) provide options to account for the presence of openings in SC walls by means ranging from applying reduction to SC wall capacity for small openings not included in the FEA model to providing detailing requirements to reduce stress concentration and achieve sufficient load redistribution. The detailing requirements are also different based on the opening size categorization and detailing as a free edge or fully developed edge. Some of the detailing requirements in ANSI/AISC N690-18 (2018) are found to be impractical for many walls as discussed later in this paper.

Section N9.1.7 of the commentary of ANSI/AISC N690-18 (2018) defines an opening having its largest dimension less than or equal to ($t_{sc}/2$), where t_{sc} is the thickness of the SC wall, as a small opening. An opening with any dimension larger than ($t_{sc}/2$) is categorized as a large opening. Based on this categorization, the detailing requirements for a 1″ round opening (hole for reinforcing bar at interfacing slab) in a 5 ft SC wall is similar to that for an opening of 30″ by 30″ in that same wall. Similarly, the same large opening requirement for an opening with one of the dimensions barely exceeding 30" in a 5 ft SC wall are the same required for a large double door opening. With the rigorous ANSI/AISC N690-18 (2018) detailing requirements discussed later in this paper, this coarse categorization of openings results in challenges that make the design and construction of opening reinforcement impractical, if not impossible. Providing design requirements for a more stratified system of opening by size is recommended to improve SC wall fabrication and constructability.

While code requirements provide the choice for detailing of openings as a free edge or as a fully developed edge opening, free edge openings are not allowed in connection regions. Section N9.1.2 of ANSI/AISC N690-18 (2018) and Figure C-A-N9.1.4 of its commentary define the extent of connection regions in SC walls. Thus, at least all openings located within a wall thickness distance from intersecting walls or slabs has to be detailed using the fully developed edge option. This requirement is challenging to implement using the current detailing requirements as demonstrated in the following case study.

In addition, for small openings closely spaced, the bank of openings is treated as one large enveloping opening. As defined in Section N9.1.7c of ANSI/AISC N690-18 (2018), fully developed small openings with a clear distance less than the SC wall thickness are treated as one large opening. Further, free edge small openings with a clear distance less than twice the thickness of the SC wall are treated as a single large opening. For example, a 5 ft thick wall with two fully developed small openings, each having a 1″ diameter and spaced less than 5 ft apart are treated as one large opening. The opening size considered in the SC wall FEA then encompasses these two openings and the space between them. The current code requirement is a challenge to implement as large sections of wall are removed from the global structural analysis despite the minimal size of physical openings in the wall.

Detailing Requirements for openings in AISC N690

This section summarizes the detailing requirements for free edge large opening as described in Section N9.1.7b(a) of ANSI/AISC N690-18 (2018) as well as the fully developed edge detailing requirements for small and large openings as illustrated in Section N9.1.7a(b) and Section N9.1.7b(b) of ANSI/AISC N690-18 (2018). Detailing requirements for fully developed edge small or large openings are similar, these requirements are summarized as follows: 1) Re-entrant corners for noncircular openings have to satisfy corner radii not less than 4 times the faceplate thickness; 2) Steel sleeve spanning the openings to the opposite faceplate, sleeve shall have nominal yield strength and thickness equals or exceeds that of the faceplate; 3) The steel sleeve has to be anchored into the concrete with a specific requirement; 4) Provide a welded flange fitted at each end of the sleeve extending a distance equals to the thickness of the wall in all direction beyond the perimeter of the opening, the flange yield strength and thickness shall be equal or exceed that of the faceplate; 5) Connection between the flange and the sleeve is full complete joint penetration (CJP) groove weld; 6) Connection between the flange and faceplates is based on the flange thickness. For flange with thickness less than 25% thicker than the faceplate, the outer edges of the flange shall be connected to the faceplate using the maximum size fillet weld. In cases where the flange is greater than or equal to 25% thicker than the faceplate, the faceplate shall be joined with the flange only along the outer perimeter with a CJP groove weld. The fully developed edge requirements result in considerable amount of welding between the flange and the faceplate taking into account the perimeter of the flange. This can potentially present constructability challenge in terms of the number of these welds in a typical SC wall and the amount of welding associated with this connection in addition to the local effect on the faceplates of the wall resulting from welding.

The requirements for free edge large openings stipulate modelling the opening larger than the actual physical size in the FEA. The size of the opening in the FEA model shall be larger than the actual size by at least one wall thickness in each direction of the opening per Section CN.1.7b(a) of ANSI/AISC N90-18 (2018) Commentary. Given the amount of large openings in walls of nuclear power plants (i.e. doors, ducting, stacked cable trays), implementation of this requirement removes significant sections of wall from the global FEA model, and presents significant challenges to qualifying the building structure for design basis and beyond design basis structural demand.

CASE STUDY

A case study is presented in this paper to highlight the challenges in implementing the ANSI/AISC N690-18 (2018) code detailing requirements for small and large openings. The case study provides examples for a typical opening layout in an interior SC wall in a nuclear power plant.

The wall layout is shown in Figure 1. The SC wall between gridline 1 and gridline 2 is 2ft thick, and the wall between gridlines 2 and 3 is 5ft thick. These wall thicknesses are representative of those found in a typical nuclear plant building design. The 5 ft wall thickness represents the maximum permitted SC wall thickness per N9.1.1(a) of ANSI/AISC N690-18 (2018).

Table 1 shows the properties of the SC walls and includes wall thickness, faceplate thickness and the resulting reinforcement ratio of the walls calculated per Section N9.1.1(c) of ANSI/AISC N690-18 (2018). Faceplate thickness is within the allowable limits N9.1.1(c) of ANSI/AISC N690-18 (2018). As shown in Table 1, the reinforcement ratio of the walls is within the allowable limit of 1.5% and 5% from section N9.1.1c of ANSI/AISC N690-18 (2018).

Table 1: Steel-plate composite wall properties

Wall Location	Wall thickness (ft)	Faceplate thickness (in)	Reinforcement ratio	Maximum dimension for small openings
Between GL-1 and GL-2	2	0.5	0.042	<=12″
Between GL-2 and GL-3	5	1	0.033	<=30″

As noted previously, only fully developed edge openings are permitted in the connection regions. The connection region width is at least the SC wall thickness per ANSI/AISC N690-18 (2018), Commentary section CN9.3.2 and Figure C-A-N9.2.9. Size limit for small openings for the two wall segments is shown in Table 1.

The rules of N9.1.7c which applies to bank of small openings are taken into account where free edge small openings with clear distance $<=2t_{sc}$ and fully developed edge openings with clear distance $<t_{sc}$ are treated as one large opening.

Table 2 shows the dimensions of the openings in the two segments of the SC wall. Figure 1 shows the layout of the walls and openings.

Table 2: Opening dimensions

Opening Number	Opening Size (*)	Opening Number	Opening Size (*)	Opening Number	Opening Size (*)	Opening Number	Opening Size (*)
# 1	3″	# 7	2″	# 13	4″	# 19	10″
# 2	3″	# 8	3″	# 14	7’ ½″× 6’ ½″	# 20	7’ ½″× 6’ ½″
# 3	3″	# 9	10″	# 15	14″	# 21	14″×14″
# 4	4″	# 10	2″	# 16	2’ 8″ × 10″	# 22	3″
# 5	3″	# 11	2″	# 17	12″×12″	# 23	2″
# 6	2″	# 12	4.5″	# 18	5″	# 24	2″

(*) Opening size for circular openings is the diameter of the opening

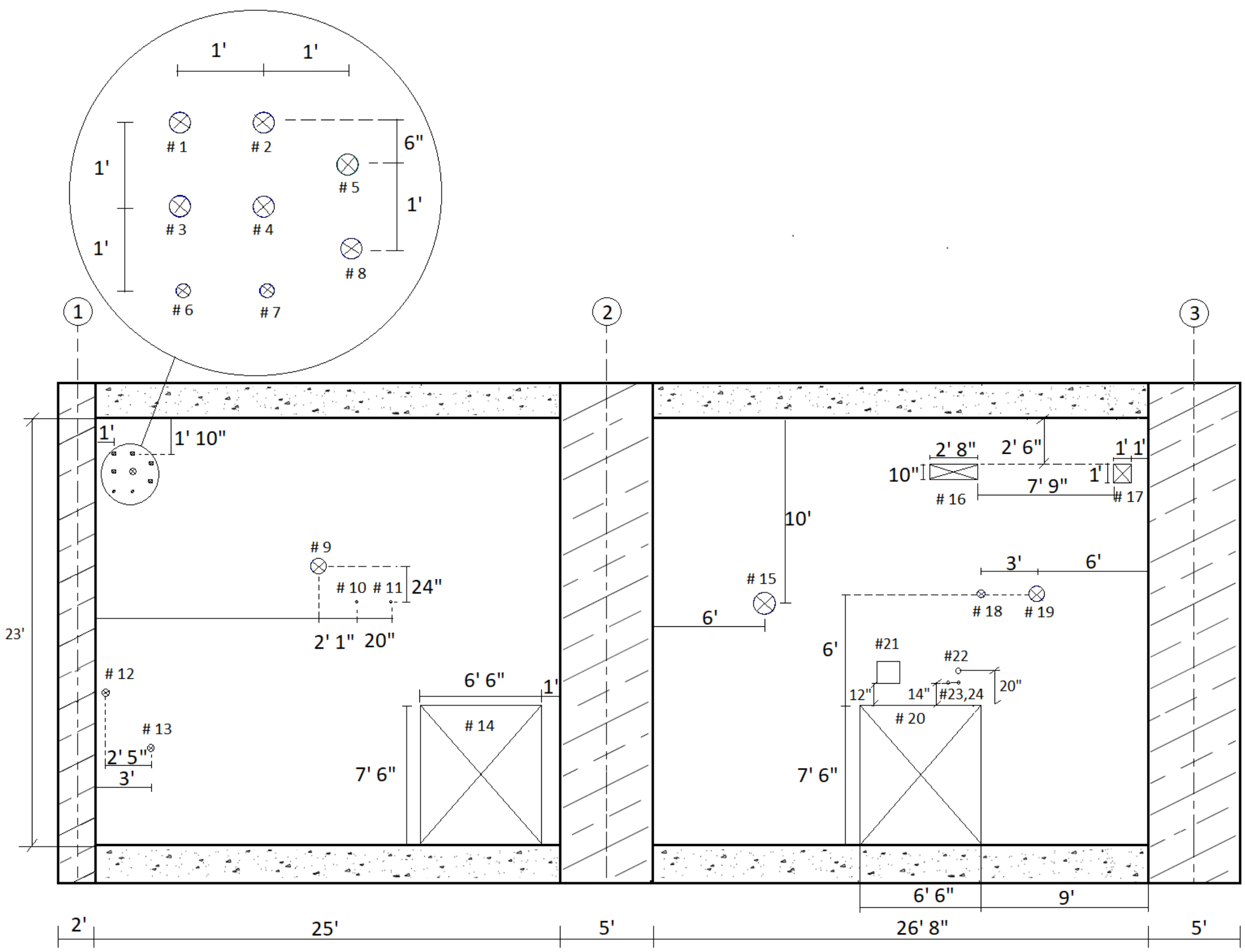

Figure 1. Layout of interior SC walls and openings

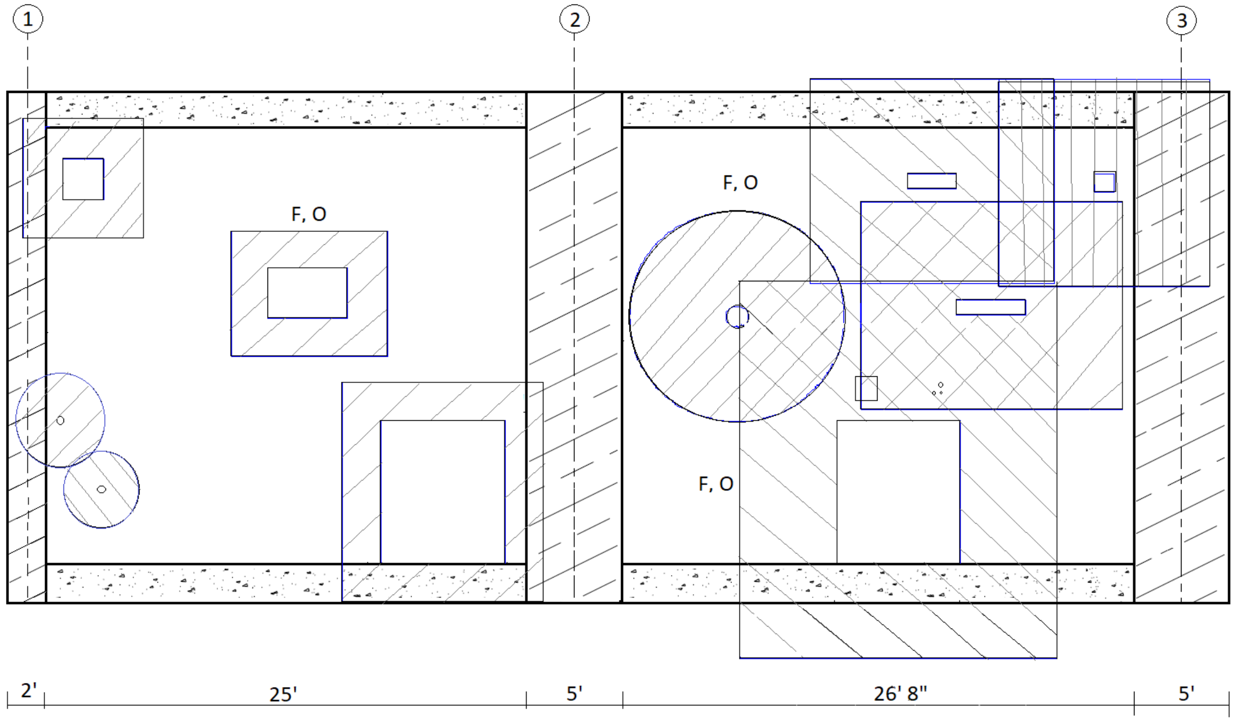

Figure 2. Flange or Oversizing requirements for openings in SC walls per ANSI/AISC N690-18 (2018)

Based on the discussion above, ANSI/AISC N690-18 (2018) detailing requirements are examined for openings shown in Table 2 and Figure 1. The requirements for grouping openings, oversizing of free edge opening or utilizing a flange around the opening for fully developed edge are discussed. Figure 2 provides a visualization of the detailing based on the current requirements for ANSI/AISC N690-18 (2018).

- Openings #1, #3 and #6 are within the connection region of the wall. In addition, the group of openings #1, #2, #3, #4, #5, #6, #7 & #8 have a clear distances less than 24″ between them. This requires treating openings #1 through #8 as a bank of small openings according to N9.1.7c of ANSI/AISC N690-18 (2018). In this case, these openings are considered as one large opening. Since some of these openings are in the connection region, the resulting large opening must satisfy the requirements for a fully developed opening. The size of the resulting opening is 2′ 3″ by 2′ 2.5″. According to the requirements of N9.1.7b for fully developed openings, the flange shall extend at least the thickness of the wall section in each direction. Thus, a flange at least 0.5″ thick, 6′ 3″ tall and 6′ 2.5″ wide shall be provided around the penetration sleeve. Referencing Figure 2, the size of this flange does not fit within the confines of the surrounding structure and is not constructible as it interferes with the perpendicular wall at gridline 1, and poses challenges with the slab interface.

- Also, for openings #9, #10 and #11, the clear distance between the openings is sufficiently small that these three openings are evaluated as one large opening. The size of this large opening is 4′ 3″ by 2′ 6″. Since this opening is not located in the connection region, it can be detailed as free edged without a flange or as a fully developed opening with a flange plate. Detailing the equivalent large opening as free edged requires oversizing the opening in the FEA model, the size of the opening has to be increased at least the wall thickness in each direction. Detailing this group of openings as a single free edged opening requires modelling it as 8′ 3″ by 6′ 6″ in the FEA model. This can present design challenges for the wall to provide enough strength to resist demand in the modelled wall segments. For a fully developed opening a flange plate that extends the thickness of the wall in each direction beyond the opening perimeter is required. Since this opening is in a 2 ft thick wall, the flange must extend 2 ft beyond the opening perimeter in each direction. Thus, the required 0.5″ thick flange plate is 8′ 3″ by 6′ 6″. This required flange is significant compared to the actual opening size and can result in construction challenges when one flange interferes with other wall attachments or adjacent flanges.

- Opening #12 is located in the connection region, thus, opening details shall follow the fully developed edge requirements with a flange extending the section thickness beyond the opening perimeter. As shown in Figure 2, a flange sized based on the ANSI/AISC N690-18 (2018) requirements for fully developed small opening shall have an inner diameter equals to the opening diameter, 4.5″, and an outer diameter of 52.5″. The required flange interferes with the perpendicular wall on gridline 1. Thus, this detailing requirement is not constructible.

- The clear distance between opening #12 and opening #13 is larger than the wall thickness, thus openings #12 and #13 can be detailed separately provided openings #12 and # 13 are detailed as a fully developed openings.

  Opening #13 fully developed edge option results in a flange size requirement with 4″ inner diameter and a 4′ 4″ outer diameter, this flange also interferes with the flange around opening # 12 and results in a non-constructible scenario.

- Opening #14 represents a typical door opening in the wall. The door is located in the connection region of the wall, thus the opening must be fully developed with a 24″ flange extending the thickness of the wall in all directions. This results in a required flange size of 10′ 6″ by 11′ 6″. The flange extends to the floor below and interferes with the connection of the slab to the SC wall. The flange also interferes with the perpendicular intersecting wall on gridline 2 which makes the detail non-constructible.

- Opening #15 has a 14″ diameter. Since the opening is away from the connection region and away from other openings, the opening can be detailed as a free edge opening or as a fully developed opening. The opening is located in a 5ft wall section. For the fully developed detailing option, the code requires a flange with outer diameter of 11′ 2″. The flange size is significant compared to the opening size and causes construction challenges and interferences with adjacent flanges in this case study. For the free edge option, modelling the original 14″ diameter opening as 11′ 2″ challenges the ability of the wall segment to meet the structural demand.

- For opening #16, detailing of a fully developed edge opening is required. A flange, at least 1″ thick, with dimensions of 12′ 8″ by 10′ 10″ is required around the opening. The required flange size results in interference with flanges of adjacent openings. Further, the flange interferes with the slab connection and potentially interferes with other attachments and supports. This detail is non-constructible.

- Opening #17, is located in the connection region, thus, fully developed edge detailing is required. Based on the parameters in Table 2, a flange at least 1″ thick, 11′wide and 11′ tall is required. As shown in Figure 2, the flange interferes with the perpendicular wall at gridline 3 as well as the connection between the upper slab and the wall. The flange also interferes with the flanges of other openings. This makes the fully developed opening non-constructible.

- Openings #18 and #19 are 5″ and 10″ diameter respectively, which qualifies them as small openings. However, due to the proximity of these openings to each other, both are treated as one large opening. The size of the equivalent large opening is 3′ 7″ by 10″. This equivalent large opening can be detailed as free edge opening where the opening is modelled as 13′ 7″ by 10′ 10″ which drastically reduces the capacity of the wall and is an impractical design. Alternately, the opening may be detailed as the fully developed edge, which requires a 1″ thick flange 13′ 10″ wide by 10′ 10″ tall. Similar to other openings, a flange of this size interferes with other flanges, attachments or commodity supports on the same wall.

- Opening #20 represents a typical door opening with openings # 21, 22, and 23 located close enough where the bank of opening rules become applicable. This is a common situation in nuclear plant buildings. Two options for the opening detailing exist. For the free edge opening option, the opening shall be modelled as 16′ 6″ in the horizontal direction and 19′ 8″ in the vertical direction in the FEA model. This option does not only affect the capacity of the wall, it also affects modelling the connection of the slab to the wall. The fully developed option requires a flange at least 1″ thick with dimensions 16′ 6″ by 19′ 8″. This option also causes interference between the flange and other flanges as well as other attachments and commodities supports.

CONCLUSION

The paper reviews the detailing requirements from ANSI/AISC N690-18 (2018) for openings. A case study of a typical 2-segment interior wall in a nuclear power plant with openings is provided. The wall segments are 2 ft and 5ft thick and represent a practical lower bound due to fabrication limitations and a codified upper bound.

Due to the uniqueness of nuclear power plant layouts, the layout of openings in walls, opening sizes, and spacing between openings, the detailing requirements from ANSI/AISC N690-18 (2018) become a challenge to implement. The case study highlights these challenges and demonstrates the most impactful requirements on SC wall design, fabrication and construction. It also emphasizes the advantages associated with implementing a more robust methodology for detailing around openings that accounts for uniqueness of a nuclear power plants design and layout.

REFERENCES

American National Standards Institute/American Institute of Steel Construction N690-18. (2018). *Specification for Safety-Related Steel Structures for Nuclear Facilities.* Chicago, IL.