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RIGOROUS MECHANICS-BASED STRESS ACCEPTANCE CRITERIA FOR SC CONTAINMENT STRUCTURE

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ABSTRACT

Steel-plate composite (SC) walls are well-suited for containment structure application because they enable design/construction of a passive concrete structure (i.e., without the prestressing tendons) while avoiding the need for a shield building structure (i.e., as in the case of steel containment structure). Being a pressure vessel, containment structures need to be designed using stress-based acceptance criteria (e.g., criteria similar to those in ASME Section III Division 2). It is therefore necessary to develop SC-specific stress-based acceptance criteria for SC wall application to nuclear containment structures. A formulation that accounts for presence of linear reinforcing elements (e.g., ribs or bands) is also desirable because such features are useful for addressing rigging/construction loads while also enabling the designer to vary their size/spacing to suit the calculated force demands (e.g., explore reinforcement pattern to address large difference in hoop tension and meridional tension demands). This paper presents an allowable stress-based acceptance criteria for SC containment structures reinforced with linear steel elements. A mechanics-based formulation is developed to evaluate stress demands in the concrete sandwich and steel plates and reinforcing elements. For accident load combinations including the accident pressure case (the governing load case for containment design), the mechanics-based formulation is simplified (since the concrete is fully cracked), which leads to closed form expressions for stresses in the steel plates and linear reinforcing elements. The formulation will be verified using results from detailed finite element analyses and experimental results.

INTRODUCTION

SC walls are well-suited for containment structure application because of the following advantages over steel, reinforced concrete (RC) and prestressed concrete (PC) containment structures:

- SC containment is a passive structure; i.e., there is no need for lifelong inspections and surveillance to ensure that the prestressing force remains adequate, and it avoids the need for a shield building structure (as in the case of steel containment structures).
- A passive reinforced concrete (RC) containment structure is generally about 1.5-meters thick, with eight layers of #18 rebar (which is difficult from construction standpoint), whereas an SC containment structure is expected to be less than 1-meter thick without the need for any rebar layers.
- Faceplates and linear structural steel reinforcing elements (if used) enable use of prefabricated modules that eliminate formwork and rebar erection, which results in reduced field labor force and shorter construction schedule.
- The presence of faceplates helps resist tornado missiles and aircraft impact (especially the latter) such that it is possible to have a containment wall that is only about 1m thick (as opposed to about twice that thickness for RC containment structures).

- For SC containment structure, it is possible to develop and specify relatively straightforward stress-based acceptance criteria that can be applied for sizing of the steel elements.

Being a pressure vessel, containment structures need to be designed using stress-based acceptance criteria [e.g., the criteria in ASME Section III Division 2 (ASME, 2011)]. It is therefore necessary to develop SC-specific stress-based acceptance criteria for SC wall application to nuclear containment structures. AISC N690s1 (AISC, 2015), Supplement No. 1 to AISC N690-12 (AISC, 2012), incorporates force-based acceptance criteria for SC walls. These criteria are applicable to non-pressure retaining applications of SC walls without linear reinforcing elements (e.g., embedded ribs, bands on the exterior, web plates, or embedded linear shapes or trusses). The AISC N690s1 force-based acceptance criteria are based on either Load and Resistance Factor Design (LRFD) or Allowable Strength Design (ASD) approach in AISC 360 (AISC, 2010), whereby the available strength for both approaches is based on the same nominal strength as the starting point.

The basic manifestation of SC wall (as shown in Figure 1) does not involve linear reinforcing elements (i.e., they use faceplates as a sole means for concrete reinforcing), which makes it easier to perform their analysis and design. The typical SC wall configuration can be upgraded to include linear reinforcing elements (with desired spacing and cross-sectional area) in one direction or two orthogonal directions. These elements can be intermittently welded (using fillet welds) or bolted on the inner surface (in contact with concrete infill) or the outer surface of the faceplates. Another alternative is to have these elements welded or bolted to a centrally embedded steel plate within the concrete sandwich, in which case the thickness of faceplates can be reduced.

The use of linear reinforcing elements provides the following advantages:

- Increased stiffness and strength during rigging, transportation, and construction (e.g., for resisting load due to concrete placement)
- Ability to vary the reinforcement to suit the calculated demands (i.e., similar to RC construction, the size and spacing of the linear reinforcing elements can be varied according to the demands)
- The faceplate thickness can be optimized to that required for minimum necessary strength and stiffness for rigging/construction and a threshold datum strength for calculated demands (i.e., the additional stiffness and strength can be brought to bear, as needed, to suit special rigging/construction needs and excess strength demands beyond the threshold datum)
- Connection designs can be simplified since the faceplate is not thick everywhere. Bhardwaj & Varma (2017) show that designing the connections to transfer the nominal strength of the wall (full-strength connection design philosophy per AISC N690s1) can result in impractical connection details. Since the size of faceplates is reduced by use of linear reinforcing elements, the required strengths for yielding limit states for connection design will be reduced.

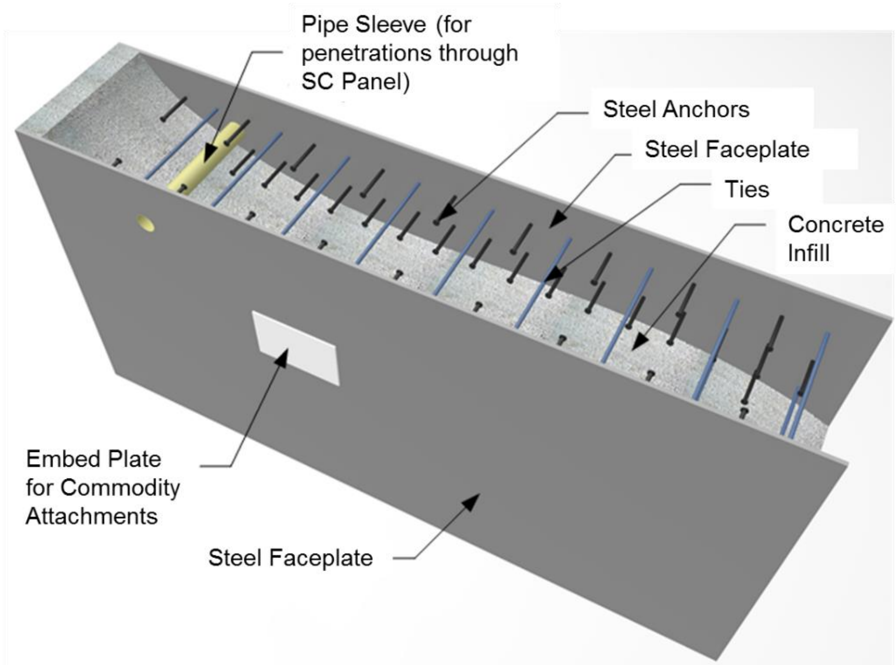

Figure 1. Basic SC Wall without Linear Reinforcing Elements (from AISC, 2015)

This paper briefly discusses the basis of acceptance-criteria presented in AISC N690s1 (AISC, 2015). A summary of existing literature discussing the contribution of linear reinforcement elements to SC wall strength and stiffness is presented. The paper then discusses the development of a stress-based acceptance criteria for SC containment structures that are reinforced with linear steel elements. A mechanics based model is developed to evaluate the response of containment SC structures to combination of in-plane demands. The model includes the stiffness and strength contributions of concrete, steel faceplates, and linear reinforcing elements; however, the formulation recognizes that the concrete contribution is negligible for the governing load cases/combinations. Based on this recognition, the mechanics-based formulation provides closed form expressions for stresses in the steel plates (whether faceplates or embedded plate) and linear reinforcing elements.

BACKGROUND

AISC N690s1 (AISC, 2015) presents the force-based acceptance criterion for non-pressure retaining applications of SC walls without reinforcing elements. The criterion defines a failure surface for interaction of in-plane force and out-of-plane moment demands, and is based on the mechanics-based model (MBM) developed by Varma et al. (2014). The development of interaction surface is discussed in Bhardwaj et al. (2017). Application of the AISC N690s1 provisions to a typical SC wall (by using a design example) is illustrated by Bhardwaj and Varma (2017). The MBM (Varma et al., 2014) uses proportionally incremental loading to determine the principal directions, and crack orientation for concrete. The orthotropic stress-strain relationship of cracked concrete, and the isotropic stress-strain relationship of steel faceplates are then used to determine the force distribution in faceplates and concrete infill.

Ozaki et al. (2004) experimentally observed the in-plane response of SC walls. Two of the nine SC panels tested had vertical partition walls (their contribution will be analogous to, although much higher than, simpler vertical reinforcing steel elements such as ribs or bands). The authors employed truss analogy to analytically determine the force distribution in concrete infill and steel elements. It was experimentally observed that partition web increased post-cracking stiffness, and higher shear strains were observed post-yield behavior (in comparison to specimen with no partition web). Hong et al. (2011) also evaluated the contribution of vertical steel rib stiffeners to the in-plane response of the SC walls. Sener et al. (2015) evaluated the contribution of steel ribs to the out-of-plane flexure response of SC walls. The authors observed that the compression contribution of linear stiffening elements was negligible and can be ignored. However, the tension contribution of the ribs needs to be considered.

The Korean specification, KEPIC-SNG (KSSC, 2010), considers certain contributions of ribs to SC walls (referred to as stiffened SC walls). The contribution is considered for axial compression and tension strength, and out-of-plane flexure and shear strengths, depending on the rib orientation relative to the demand type. The contribution of ribs to in-plane shear strength is not considered.

A formulation that accounts for presence of simple linear reinforcing elements (i.e., ribs or bands) is desirable because these elements are useful for handling rigging/construction related stresses while also enabling such reinforcement to be adjusted to suit the force demands (e.g., hoop tension due to accident loading combination could be be twice as large as the corresponding meridional tension). An SC containment wall element will be primarily subjected to membrane forces; however, significant out-of-plane shear forces and bending moments will be present at locations of discontinuities in the meridional direction (e.g., at basemat connection). Also, thermally induced bending moments will be present in the circumferential direction. Introduction of linear reinforcing elements will provide more flexibility in addressing the differing magnitudes of various types of demand (in comparison to conventional SC configuration, where the faceplate behavior is isotropic).

MECHANICS-BASED STIFFNESS MATRIX FOR SC ELEMENTS

Stress-based acceptance criteria for containment SC structures can be developed by upgrading the MBM devised by Varma et al. (2014) to include the contribution of linear reinforcing elements. As discussed previously, the model evaluates the distribution of demands in concrete infill and steel faceplates depending on the stiffness contribution of cracked concrete and steel faceplate. The stiffness matrix of the SC wall (K_{sc}) comprises of orthotropic cracked concrete stiffness (K_c) and faceplate stiffness (K_p). Based on Varma et al. (2014), Equation 1 presents the relation between the in-plane force demands (S_x, S_y, and S_{xy}) and strains for an SC wall panel, where t_p is the faceplate thickness, and t_c is the thickness of concrete infill.

$$\begin{Bmatrix} S_x \\ S_y \\ S_{xy} \end{Bmatrix} = \left[K\right]_{sc} \begin{Bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{Bmatrix}$$

$$\begin{Bmatrix} S_x \\ S_y \\ S_{xy} \end{Bmatrix} = \left[2t_p\left[K\right]_p + t_c\left[K\right]_c\right] \begin{Bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{Bmatrix} \tag{1}$$

The stiffness matrix of the composite SC wall panel (K_{sc}) can be updated to include the stiffness contribution of linear reinforcing elements (K_r), where K_r will be orthotropic owing to the potentially different areas and/or spacing of the linear reinforcing elements in two orthogonal directions. Since the linear reinforcing elements are intermittently welded (or bolted) to the faceplates, strain compatibility between the faceplates and the linear elements is achieved. The grid of these orthogonally oriented reinforcing elements (acting in tandem with steel faceplates or an interior embedded plate) can be considered to behave as a two-dimensional plane stress orthotropic material (similar treatment may not be possible for orthogonal rebar grids embedded in concrete, as Poisson's effect of rebar grids cannot be ensured). General stress-strain relationship for a material exhibiting two-dimensional plane stress orthotropic behavior is presented in Equation 2, where K_{ortho} is the stiffness matrix (presented in Equation 3), and E and ν are the moduli of elasticity and Poisson's ratios in the corresponding directions.

$$\begin{Bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{Bmatrix} = \left[K_{ortho}\right] \begin{Bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{Bmatrix} \tag{2}$$

$$K_{ortho} = \begin{pmatrix} \dfrac{E_x}{1-\nu_{xy}\nu_{yx}} & \dfrac{\nu_{yx}E_x}{1-\nu_{xy}\nu_{yx}} & 0 \\ \dfrac{\nu_{xy}E_y}{1-\nu_{xy}\nu_{yx}} & \dfrac{E_y}{1-\nu_{xy}\nu_{yx}} & 0 \\ 0 & 0 & \dfrac{E_{xy}}{2(1+\nu_{xy})} \end{pmatrix} \tag{3}$$

For linear steel reinforcing elements, the modulus of elasticity for the orthogonal elements can be considered to be the same (E_s). The Poisson's effect of these linear elements can be conservatively ignored. Additionally, the intermittently welded linear elements (behaving analogous to truss elements) are not expected to have any direct shear stiffness contribution (i.e., the K_{33} term will be zero). The orthotropic behaviour of the grid of the linear reinforcing elements results from the difference in the net contribution of these elements per unit width of the section. The difference in the net contribution of the orthogonal reinforcing elements arises from them having different cross-section areas or spacing. For example, Figure 2 shows an elevation view of an SC wall with linear reinforcing elements. For the arrangement considered in the figure, elements have the same spacing (s_{rl} and s_{rt}), but the cross-sectional areas of the longitudinal and transverse reinforcing elements are different. The effective thickness of the reinforcing element per unit width is obtained by dividing its cross-sectional area by the spacing of the elements (s_{rl} or s_{rt}). The effective (smeared) thickness of the reinforcing elements in the orthogonal directions can be expressed as αt_p and βt_p, where α and β are thickness multipliers for x and y directions, and t_p is the faceplate thickness.

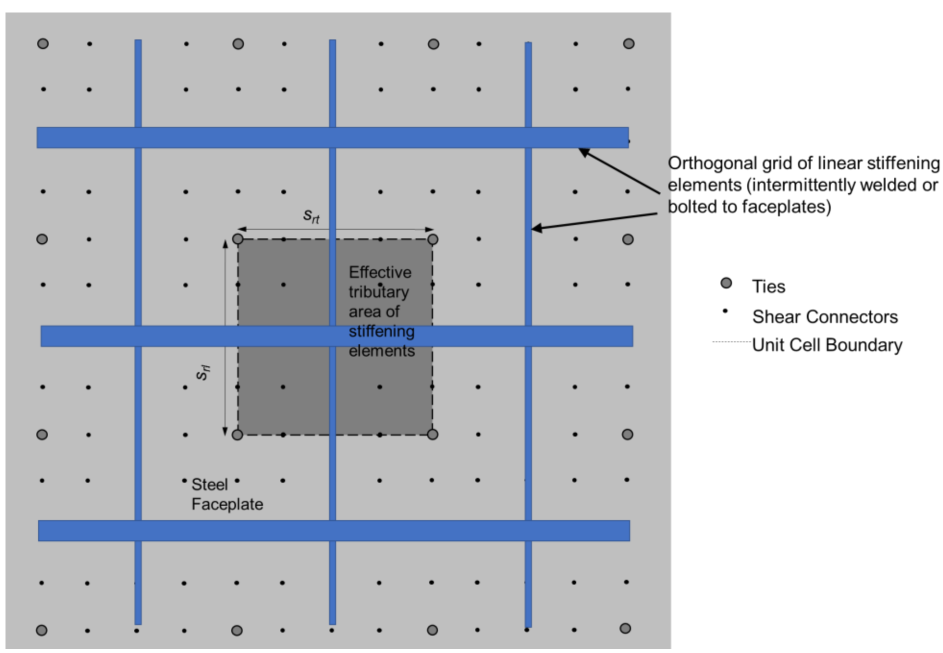

Figure 2. Elevation view of a typical SC wall with linear reinforcing elements (faceplate not shown for clarity)

Substituting these parameters into Equation 3, and multiplying with corresponding areas gives the relationship between force demands in the linear reinforcing elements and the section strains (as presented in Equation 4). In Equation 4, $S_{x.r}$, $S_{y.r}$, and $S_{xy.r}$ are contributions of the linear reinforcing elements to the total in-plane axial and shear demands (per unit width) acting on the section.

$$\begin{Bmatrix} S_{x.r} \\ S_{y.r} \\ S_{xy.r} \end{Bmatrix} = \frac{E_s 2t_p}{1-\nu_s^2} \begin{pmatrix} \alpha & 0 & 0 \\ 0 & \beta & 0 \\ 0 & 0 & 0 \end{pmatrix} \begin{Bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{Bmatrix} \tag{4}$$

Based on the above, the stiffness matrix for the linear reinforcing elements can then be presented using matrix K_r, as in Equation 5. Accordingly, the stiffness matrix of the SC wall element can be updated to include K_r (for contribution of an orthogonal grid of reinforcing elements), as shown in Equation 6. Equation 6 considers two faceplates (i.e., no embedded plate), and an orthogonal grid of linear reinforcing elements welded (or bolted) to each faceplate. In case an embedded plate is provided in addition to the faceplates, the stiffness contribution of the embedded plate can be added to K_p. Preliminary numerical analyses were conducted using Layered Composite Shell (LCS) elements (linear reinforcing elements modeled as embedded rebars) in ABAQUS (Dassault, 2016) for pure shear loading. The results from the numerical analysis are consistent with those obtained from the updated MBM (using the stiffness matrix presented in Equation 6).

$$K_r = \frac{E_s}{1-\nu_s^2} \begin{pmatrix} \alpha & 0 & 0 \\ 0 & \beta & 0 \\ 0 & 0 & 0 \end{pmatrix} \tag{5}$$

$$\begin{Bmatrix} S_x \\ S_y \\ S_{xy} \end{Bmatrix} = \left[2t_p \left[K\right]_p + 2t_p \left[K\right]_r + t_c \left[K\right]_c \right] \begin{Bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{Bmatrix} \tag{6}$$

The updated stiffness matrix (for SC wall with linear stiffening elements) can be employed to determine the principal directions, and the crack orientation, using the proportionally increasing loading approach in Varma et al. (2014) (for in-plane forces and out-of-plane moment demands). Based on the crack orientation, the stress distribution in concrete infill, steel faceplates, and linear reinforcing elements can be determined for the combination of demands.

SC CONTAINMENT DESIGN

SC containment design is typically governed by accident load combinations, especially when they include the accident pressure load case. Such accident load combinations subject the containment to membrane tension demands in both orthogonal directions, rendering the concrete to become fully cracked. The cracked concrete will not contribute to the strength and stiffness of the containment, and the design will therefore be governed by steel elements. Accordingly, the K_c term in equations 1 and 6 can be ignored. The resulting stiffness matrix (with just the steel plate and linear reinforcing elements contributions) for the SC section can be employed to obtain closed-form expressions for determining the stresses in the steel faceplate (and linear reinforcing elements) directly from the combination of demands.

For containment SC structures without linear reinforcing elements, Equation 1 can be re-written as Equation 7 (considering concrete fully cracked for accident load combinations).

$$\begin{Bmatrix} S_x \\ S_y \\ S_{xy} \end{Bmatrix} = \left[2t_p \left[K \right]_p \right] \begin{Bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{Bmatrix} \tag{7}$$

The steel faceplate stress check can then be implemented in terms of force demands as presented in Equation 8, where F_{yp} is the yield stress of the faceplate, and Ω_p is the safety factor for allowable stress design (which will depend on the type of load combination).

$$\frac{\sqrt{S_x^2 + S_y^2 + 3S_{xy}^2 - S_x S_y}}{2t_p} \leq \frac{F_{yp}}{\Omega_p} \tag{8}$$

For containment SC structures with linear reinforcing elements, Equation 6 can be re-written as Equation 9 (considering concrete fully cracked for accident load combinations). The steel faceplate stresses (${}_p\sigma_x$, ${}_p\sigma_y$, and ${}_p\tau$), and the linear reinforcing element stresses (${}_r\sigma_x$ and ${}_r\sigma_y$) can then be determined from the force demands as presented in Equations 10 to 14 (for brevity, the derivation of these expressions is not presented here).

$$\begin{Bmatrix} S_x \\ S_y \\ S_{xy} \end{Bmatrix} = \left[2t_p \left[K \right]_p + 2t_p \left[K \right]_r \right] \begin{Bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{Bmatrix} \tag{9}$$

$${}_p\sigma_x = \frac{1}{2t_p \gamma} \left[\left(\delta + \beta \right) S_x + \left(\alpha \nu \right) S_y \right] \tag{10}$$

$${}_p\sigma_y = \frac{1}{2t_p \gamma} \left[\left(\delta + \alpha \right) S_y + \left(\beta \nu \right) S_x \right] \tag{11}$$

$${}_p\tau = \frac{S_{xy}}{2t_p} \tag{12}$$

$${}_r\sigma_x = \frac{1}{2t_p \gamma} \left[\left(1 + \beta \right) S_x - \nu S_y \right] \tag{13}$$

$${}_r\sigma_y = \frac{1}{2t_p \gamma} \left[\left(1 + \alpha \right) S_y - \nu S_x \right] \tag{14}$$

where,

$$\delta = 1 - \nu^2$$

$$\gamma = \alpha + \beta + \alpha\beta + \delta$$

The faceplate stress values can then be used to check the Von Mises yield criteria as shown in Equation 15. The stresses in the reinforcing elements can be checked against the allowable stresses as shown in Equations 16 and 17.

$$\sqrt{{}_p\sigma_x^2 + {}_p\sigma_y^2 + 3\,{}_p\tau^2 - {}_p\sigma_x\,{}_p\sigma_y} \le \frac{F_{yp}}{\Omega_p} \tag{15}$$

$$_r\sigma_x \le \frac{F_{yr}}{\Omega_r} \tag{16}$$

$$_r\sigma_y \le \frac{F_{yr}}{\Omega_r} \tag{17}$$

Being that the SC containment structure will be designed using allowable stress formulation, the stresses in steel faceplate and linear reinforcing elements will be compared with the allowable stresses. For example, for the steel plates, the Von Mises stress may be limited to $0.67F_y$ (Ω_p=1.5) for membrane loads and $0.8F_y$ (Ω_p=1.25) for membrane plus out-of-plane bending loads due to accident load combinations [the allowable Von Mises stress could be increased to $0.9F_y$ (Ω_p=1.1) if accident thermal load case is included]. Similar values of safety factors may be considered for linear reinforcing elements. When concrete contribution is considered for accident load combinations that do not include accident pressure, the concrete compressive stress is typically limited to $0.7f'_c$ for membrane loads and $0.85f'_c$ for membrane plus out-of-plane bending loads. These allowable stresses are proposed for accident loads; lower stress limits will be appropriate for normal load combinations.

In future, the updated MBM (i.e., including contribution of simple linear reinforcing elements) discussed here will be verified (and revisited, if needed) using rigorous finite element models and applicable experimental results available in literature. The parametric finite element studies will include variation in orientation, area, and spacing of stiffening elements. The reinforcing elements will be explicitly modeled, and the force distribution in concrete infill, steel faceplates, and stiffening elements will be compared with that obtained from the updated MBM. The data obtained from rigorous finite element studies and experimental studies will be plotted on the interaction surface obtained from the updated MBM to evaluate the suitability and conservatism of the MBM.

SUMMARY

The current AISC N690s1 provisions for conventional SC walls provide force based acceptance criteria for SC walls. This paper provides a framework for developing a stress based acceptance criteria for SC containment structures with linear reinforcing elements. SC walls are being considered for containment structure application because of the numerous advantages over reinforced concrete (RC), prestressed concrete (PC), and steel containment structures. Also, conventional SC walls (i.e., without any linear reinforcing steel elements), preclude flexibility in terms of varying the reinforcement ratio along the expanse of the wall. The proposed SC containment wall addresses this concern by using linear reinforcing elements. A mechanics based model has been developed to consider the stiffness contributions of concrete infill, steel faceplates, and reinforcing elements. Since accident pressure, which is generally the controlling load case that is also accompanied by accident thermal load, causes the section to become fully cracked (i.e., no concrete strength and stiffness contribution), the model has been simplified to recognize that the design is controlled by stiffness and strength contributions of steel plates and reinforcing elements. The simplified and realistic model is employed to obtain closed form expressions for stresses in faceplates and linear reinforcing elements. In future, the stress-based interaction surface for SC wall developed using the mechanics based model will be verified using rigorous finite element simulations and experimental results.

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