STEEL PLATE COMPOSITE (SC) WALLS FOR SAFETY RELATED NUCLEAR FACILITIES: DESIGN FOR IN-PLANE AND OUT-OF-PLANE DEMANDS

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INTRODUCTION

- There is significant interest in the behavior, analysis, and design of steel-plate composite (SC) wall for third generation safety-related nuclear facilities.

- These SC walls are being used as secondary shield walls for containment internal structures of nuclear facilities, and in some cases even the exterior shield building.

- Feasibility to used as containment structure.

BACKGROUND

- The design of conventional reinforced concrete (RC) walls for nuclear facilities is governed by the American Concrete Institute (ACI) code 349 [1].

- However, there is no such code for design of SC walls for safety-related nuclear facilities in the US.

- The American Institute of Steel Construction (AISC) has formed a sub-committee to develop an appendix to AISC N690 [2] focusing on SC walls.

- This appendix is currently in development, and this presentation includes some of the design specifications and associated commentary for SC walls.

OBJECTIVES

- Propose a simple mechanics based model (MBM) to investigate the in-plane behavior of SC wall panels.

- Verify the model using existing experimental results, and also detailed nonlinear finite element models.

- Develop an interaction surface in principle force space for design.

- Further develop the MBM to account for the effects for out-of-plane moments combined with the in-plane forces.

- Develop a simple design approach that is based on the interaction surface in principal force space and can be implemented easily for SC wall sections.
Experimental Values (kips)

- The mechanics based model was also used to predict the behavior of SC wall panels subjected to combined axial compression and in-plane shear by Ozaki et al. [4].
- The concrete behavior was assumed to be linear elastic (albeit with reduced stiffness and orthotropic behavior as shown before).
- Therefore, the concrete minimum principal stress should be checked to ensure that it is still within the elastic range.
- For example, \( \min \{ \sigma_{x}, \sigma_{y} \} \geq -0.7 f'_{c} \), where 0.7\( f'_{c} \) is assumed to represent the limit of linear elastic behavior from the concrete.

**MECHANICS BASED MODEL**
- The section averaged strains (\( \varepsilon_{x}, \varepsilon_{y} \), and \( \gamma_{xy} \)) can then be used to compute the stresses (\( \sigma_{x}, \sigma_{y} \), and \( \tau_{xy} \)) in the concrete infill and the steel faceplates (\( \sigma_{x}, \sigma_{y} \), and \( \tau_{xy} \)).
- The stress transformation matrix \([T]\) can then be used to compute the principal stresses (\( \sigma_{c} \) and \( \sigma_{0} \)) in the concrete infill and the steel faceplates (\( \sigma_{c} \) and \( \sigma_{0} \)).
- The steel plate (SC) composite section was modeled using layered composite shell (LCS) finite elements in ABAQUS.
- As shown, the section averaged strains can be estimated using the applied forces, and the steel and cracked concrete stiffness matrices \([K]\) along with their respective areas.

**NONLINEAR INELASTIC FINITE ELEMENT MODEL**
- Address some of the limitations of MBM.
- The concrete material model was based on multiaxial plasticity with Von Mises yield surface, associated flow, and kinematic hardening.
- The concrete material model was based on multiaxial plasticity in compression with Drucker-Prager compression yield surface, non-associated flow, and hardening followed by softening.
NONLINEAR INELASTIC FINITE ELEMENT MODEL

An example of the results from the finite element analysis of an SC composite wall panel subjected to pure in-plane shear.

**SC WALL BEHAVIOR FOR IN-PLANE FORCE**

- The nonlinear finite element modeling approach was further verified by using it to predict the behavior of all specimens tested by Ozaki et al. [4].
- The verified model was used to predict the complete in-plane behavior of SC wall panels subjected to combinations of in-plane membrane forces (Sx, Sy, and Sxy). The focus was on the entire gamut of behavior, i.e., both axial tension + in-plane shear, and axial compression + in-plane shear.
- These membrane forces were used to compute the principal forces (Sp1 and Sp2), which were plotted to develop the interaction surface, as shown below.

**SC WALL BEHAVIOR FOR IN-PLANE FORCES + OUT-OF-PLANE MOMENTS**

- The nonlinear finite element modeling approach was used to evaluate the behavior of SC wall panels subjected to combinations of in-plane forces and out-of-plane bending moments (Mx, My, and Mxy).
- The mechanics based model was also modified to include several layers through the composite section, and three more deformations at the central layer ($\varepsilon_x$, $\varepsilon_y$, and $\gamma_{xy}$) corresponding to the moments (Mx, My, and Mxy).
- A computer program was developed to solve the force and moment equilibrium equations iteratively, i.e., to determine the strains ($\varepsilon_x$, $\varepsilon_y$, $\gamma_{xy}$, $\phi_x$, $\phi_y$, and $\phi_{xy}$) associated with the applied forces (Sx, Sy, Sxy, Mx, My, and Mxy).

**DESIGN FOR COMBINED FORCES AND MOMENTS**

- The results from the finite element analyses and the mechanics based models were used to develop a simple design approach for evaluating SC wall sections subjected to combined in-plane forces (Sx, Sy, Sxy) and out-of-plane moments (Mx, My, Mxy).
- The design approach considers the SC composite section in two notional halves (top and bottom) that are subjected primarily to membrane forces (Sx, Sy, and Sxy) that can be calculated using the in-plane forces and out-of-plane moment demands using an assumed arm length (for example, 0.90 T).
These membrane forces \( S_{x1}', S_{y1}', \text{ and } S_{xy1}' \) can be used to compute principal membrane forces \( S_{p1} \text{ and } S_{p2} \) for each of the two notional halves. These principal forces \( S_{p1} \text{ and } S_{p2} \) must lie within the interaction surface shown below for both notional halves.

### Region Definition and Behavior

<table>
<thead>
<tr>
<th>Region</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>( S_{p1} \geq 0, S_{p2} \geq 0 ) Tension</td>
</tr>
<tr>
<td>II</td>
<td>( S_{p2} + S_{p1} \geq 0 ), ( S_{p1} &lt; 0 ), or ( S_{p2} &lt; 0 ) Tension + Shear</td>
</tr>
<tr>
<td>III</td>
<td>( S_{p1} + S_{p2} \leq 0 ), ( S_{p1} &gt; 0 ), or ( S_{p2} &gt; 0 ) Compression + Shear</td>
</tr>
<tr>
<td>IV</td>
<td>( S_{p1} \leq 0, S_{p2} \leq 0 ) Biaxial Compression</td>
</tr>
</tbody>
</table>

### Principal Force

- \( T_{ci} = 0.5 \times \text{Design Tension Strength (kip/ft)} \)
- \( V_{ci} = 0.5 \times \text{Design In-Plane Shear Strength (kip/ft)} \)
- \( P_{ci} = 0.5 \times \text{Design Compression Strength (kip/ft)} \)

### Summary and Conclusions

- This presentation gives a simple design approach for SC walls subjected to combined in-plane forces and out-of-plane moment demands.
- The approach is applicable to SC walls that are detailed to prevent SC specific failure modes like local buckling, interfacial shear failure, etc.
- The design approach has been developed using the results of mechanics based models verified using experimental results and detailed nonlinear finite element analyses.
- The design approach consists of developing an interaction surface in principal force space \( (S_{p1}, S_{p2}) \), and using it to check each notional half of the SC wall section subjected to combined in-plane forces and out-of-plane demands.

### References

1. ACI 349 (2006), "Code Requirements for Nuclear Safety-Related Concrete Structures and Commentary," American Concrete Institute, Farmington Hills, MI.