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Composite and Modular Structures, Part 2

ACI Spring 2012 Convention
March 18 – 21, Dallas, TX

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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

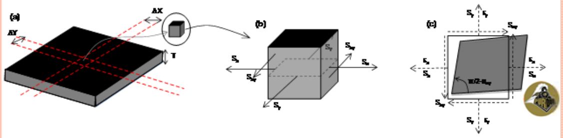
- The design of conventional reinforced concrete (RC) walls for nuclear facilities is governed by the American Concrete Institute (ACI) code 349 [1].
- However, there is no such code for design of SC walls for safety-related nuclear facilities in the US.
- The American Institute of Steel Construction (AISC) has formed a sum-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.

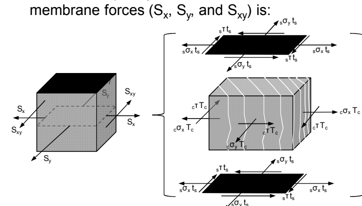
Mechanics based model

- Assumptions:
  1. The SC wall panels are assumed to have plan dimensions at least equal to the section thickness (T);
  2. The SC wall panels are subjected to uniform membrane forces (S_x, S_y, and S_{xy}) per unit (a, b);
  3. Membrane forces cause deformations and membrane averaged strains (ε_x, ε_y, and Υ_{xy});
  4. The steel plates and concrete infill are assumed to have compatible strains as an engineering approximation (over the plan dimensions of at least T x T). This is typically achieved by using shear connectors that have adequate size, length and spacing.



Mechanics based model

- The free body diagram of the SC composite section subjected to membrane forces (S_x, S_y, and S_{xy}) is:



$$\begin{Bmatrix} S_x \\ S_y \\ S_{xy} \end{Bmatrix} = 2t_s \times \begin{Bmatrix} {}_s\sigma_x \\ {}_s\sigma_y \\ \tau_s \end{Bmatrix} + T_c \times \begin{Bmatrix} {}_c\sigma_x \\ {}_c\sigma_y \\ \tau_c \end{Bmatrix}$$

$$\therefore \begin{Bmatrix} S_x \\ S_y \\ S_{xy} \end{Bmatrix} = \left[2t_s[K]_s + T_c[K]_c\right] \begin{Bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{Bmatrix}$$

$$\therefore \begin{Bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{Bmatrix} = \left[2t_s[K]_s + T_c[K]_c\right]^{-1} \begin{Bmatrix} S_x \\ S_y \\ S_{xy} \end{Bmatrix}$$

- As shown, the section averaged strains can be estimated using the applied forces, and the steel and cracked concrete stiffness matrices $[K]_s$ and $[K]_c$ along with their respective areas.

Mechanics based model

- The section averaged strains (ε_x, ε_y, and γ_{xy}) can then be used to compute the stresses (${}_c\sigma_x$, ${}_c\sigma_y$, and τ_c) in the concrete infill and the steel faceplates (${}_s\sigma_x$, ${}_s\sigma_y$, and τ_s).
- The stress transformation matrix $[T]_\sigma$ can then be used to compute the principal stresses (${}_c\sigma_{p1}$ and ${}_c\sigma_{p2}$) in the concrete infill and the steel faceplates (${}_s\sigma_{p1}$ and ${}_s\sigma_{p2}$).
- The steel faceplate principal stresses can be used to determine the occurrence of Von Mises yielding using the following equation, where σ_{VM} is the Von Mises stress and yielding occurs when it becomes equal to the steel plate yield stress F_y.

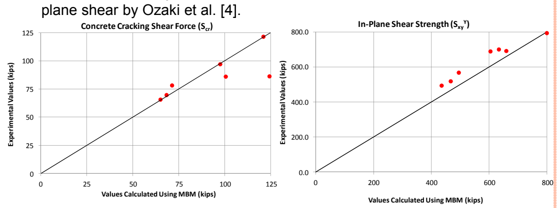
$$\sigma_{VM} = \sqrt{\sigma_{p1}^2 + \sigma_{p2}^2 - \sigma_{p1}\sigma_{p2}} \le F_y$$

Mechanics based model

- 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{${}_c\sigma_{p1}$, ${}_c\sigma_{p2}$} ≥ $-0.7 f'_c$, where $0.7f'_c$ is assumed to represent the limit of linear elastic behavior from the concrete.

Verifications using experiment data

- The mechanics based model was used to predict the pure in-plane shear behavior of SC composite walls tested by Ozaki et al. [4] and Varma et al. [3].
- 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].

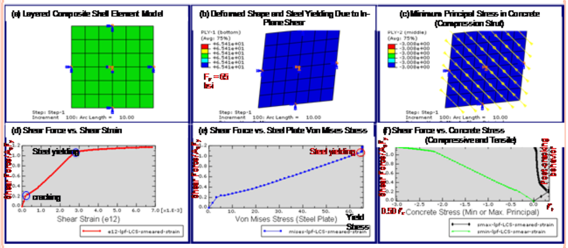


Nonlinear inelastic finite element model

- Address some of the limitations of MBM.
- The steel-plate (SC) composite section was modeled using layered composite shell (LCS) finite elements in ABAQUS.
- The steel 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

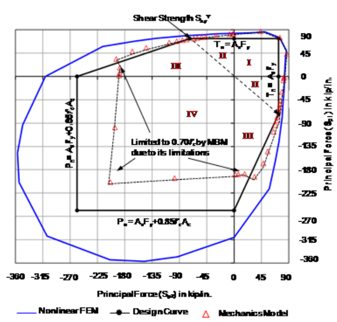
- An example of the results from the finite element analysis of an SC composite wall panel subjected to pure in-plane shear.



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 (S_x, S_y, and S_{xy}). 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 (S_{p1} and S_{p2}), which were plotted to develop the interaction surface, as shown below:

SC wall behavior for in-plane force



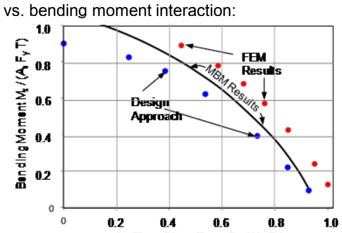
Region Definition and Behavior			
I	$S_{p2}\geq 0$	$S_{p1}\geq 0$	Biaxial Tension
II	$S_{p1}+S_{p2}\geq 0$	$S_{p1}<0$, or $S_{p2}<0$	Tension + Shear
III	$S_{p2}+S_{p1}\leq 0$	$S_{p1}>0$, or $S_{p2}>0$	Compression + Shear
IV	$S_{p1}\leq 0$	$S_{p2}\leq 0$	Biaxial Compression

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 (M_x, M_y, and M_{xy}).
- The mechanics based model was also modified to include several layers through the composite section, and three more deformations at the central layer (ε_x, ε_y, and γ_{xy}) corresponding to the moments (M_x, M_y, and M_{xy}).
- A computer program was developed to solve the force and moment equilibrium equations iteratively, i.e., to determine the strains (ε_x, ε_y, γ_{xy}, ϕ_x, ϕ_y, and ϕ_{xy}) associated with the applied forces (S_x, S_y, S_{xy}, M_x, M_y, and M_{xy}).

SC wall behavior for in-plane forces + out of plane moments

- The results from the nonlinear finite element analyses and the computer program compared reasonably with each other, particularly when the failure limit state was governed by Von Mises yielding of the steel plates. For example, the in-plane shear vs. bending moment interaction:

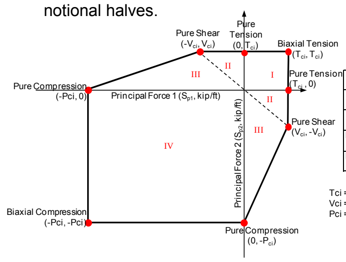


Design for combined forces and moments

- 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 (S_x, S_y, S_{xy}) and out-of-plane moments (M_x, M_y, M_{xy}).
- The design approach considers the SC composite section in two notional halves (top and bottom) that are subjected primarily to membrane forces (S_x', S_y', and S_{xy}') 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).

DESIGN FOR COMBINED FORCES AND MOMENTS

- These membrane forces (S_x', S_y', and S_{xy}') can be used to compute principal membrane forces (S_{p1} and S_{p2}) for each of the two notional halves. These principal forces (S_{p1} and S_{p2}) must lie within the interaction surface shown below for both notional halves.



Region Definition and Behavior			
I	$S_{p1} \geq 0$	$S_{p2} \geq 0$	Biaxial Tension
II	$S_{p2}+S_{p1} \geq 0$	$S_{p1}<0$, or $S_{p2}<0$	Tension + Shear
III	$S_{p1}+S_{p2} \leq 0$	$S_{p1}>0$, or $S_{p2}>0$	Compression + Shear
IV	$Sp1 \leq 0$	$S_{p2} \leq 0$	Biaxial Compression

Tci = 0.5 x Design Tension Strength (kip/ft)
Vci = 0.5 x Design In-Plane Shear Strength (kip/ft)
Pci = 0.5 x 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} and 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.
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- [4] Ozaki, M., Akita, S., Oosuga, H., Nakayama, T., Adachi, N. (2004). "Study on Steel Plate Reinforced Concrete Panels Subjected to Cyclic In-Plane Shear." *Nuclear Engineering and Design*, Vol. 228, pp. 225-244.