Modular Composite Walls Subjected to Combined Thermal and Mechanical Loads

Sanj Malushte, PhD, PE, SE
Bechtel Fellow & Sr. Principal Engineer
Bechtel Power Corporation

Amit H. Varma, PhD
Associate Professor
Purdue University

Members, AISC Subcommittee for Modular Composite Construction

Introduction

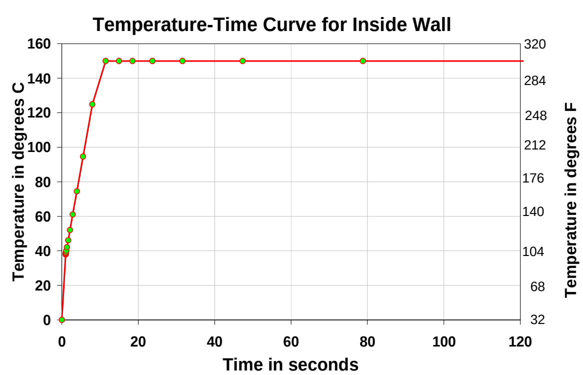
- Bechtel has investigated a modular wall system through two technical grants
- Preliminary design has been conducted in-house in Bechtel and further analytical/experimental investigations have been conducted at Purdue University
- The Bechtel Modular Wall concept has now been further refined and extended to modular flooring
- This presentation focuses on the effects of combined thermal and mechanical loading on MC walls
- Ongoing work focuses on:
  - Development of b/t limits, fire behavior, axial load capacity
  - Development of interaction equation for multi-axial forces
  - Participation in the development of AISC design specification

Behavior Combined Thermal and Mechanical Load

- Steam generator compartment walls are exposed to simultaneous internal pressure and elevated temperature under postulated pipe break accident scenarios
- Bechtel and Purdue have addressed the problem both analytically and experimentally
- Both Bechtel Modular Wall and Westinghouse's modular wall specimens were tested for this type of loading at Purdue
- The experimental results showed that both specimens have tremendous reserve margin beyond the design load; the specimens were capable of resisting much higher pressure load without inelastic deformation
- The analytical results were used to develop simple design rules for calculating the combined effects of thermal and mechanical loading

Introduction and Motivation

- Wall modules must effectively resist a postulated high energy line break accident with the following properties:
  - (1) Internal pressure = 10 psi (69 kN/m^2). The pressure is uniform along the height of the compartment.
  - (2) Thermal loading specified as surface temperature-time curve for the inside wall of the structure.



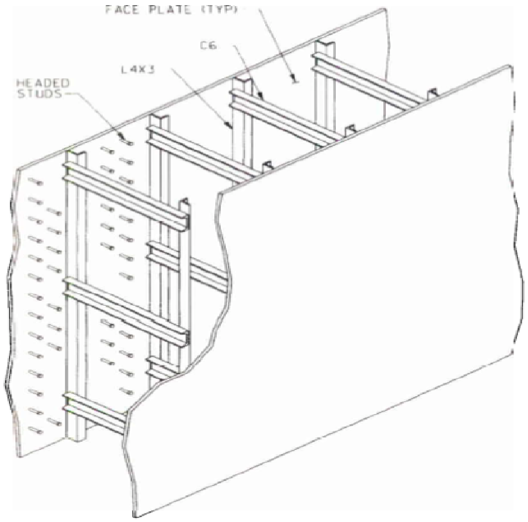
Impetus for Experimental Investigations

- Preliminary analytical investigations of an SG compartment indicated the general behavior of SC walls under combined thermal and mechanical loading
- *Experimental investigation and verification of the analytical results was deemed ESSENTIAL to determine:*
  - Yielding and/or bucking (if any) of the steel faceplates occurs in compression or tension
  - The effectiveness of composite action from shear connectors under combined thermal and mechanical loading (deleterious effects, if any, of concrete cracking on the behavior of shear connectors)
  - The extent of concrete cracking under thermal loading and its influence on section properties and deflections

EXPERIMENTAL INVESTIGATIONS

- Objectives: The experimental investigations were conducted to address the inherent limitations of the analytical modeling, to verify the performance of this structure, and to evaluate the combined effects of thermal and mechanical loading.
- Limitations: Full-scale experimental investigations of the complete SG compartment with SC walls is impractical. Large-scale investigation of even one SC wall was impractical.
- Hence, the experiments were conducted on a representative strip of the SC wall. This strip well captured the predominant one-way bending behavior of the SC wall.
- The specimens were “full-scale” in that they employed the same concrete and steel plate thicknesses and comparable bending span as the actual wall of an SG compartment

EXPERIMENTAL INVESTIGATIONS



Westinghouse SC Wall from DCD for AP1000

EXPERIMENTAL INVESTIGATIONS

- SPECIMEN DETAILS

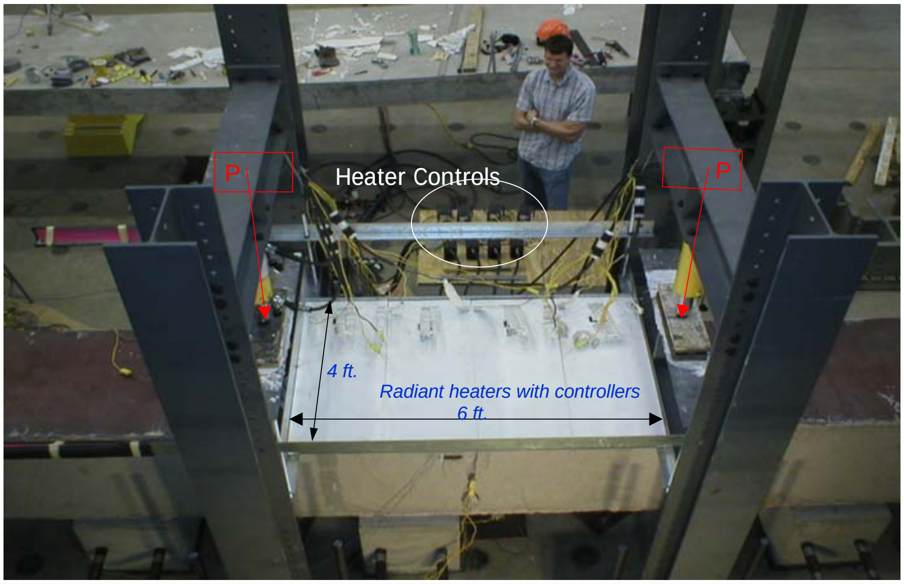
EXPERIMENTAL INVESTIGATIONS

- SPECIMEN CASTING DETAIL

EXPERIMENTAL INVESTIGATIONS

PLAN VIEW OF STRUCTURAL SETUP

EXPERIMENTAL INVESTIGATIONS

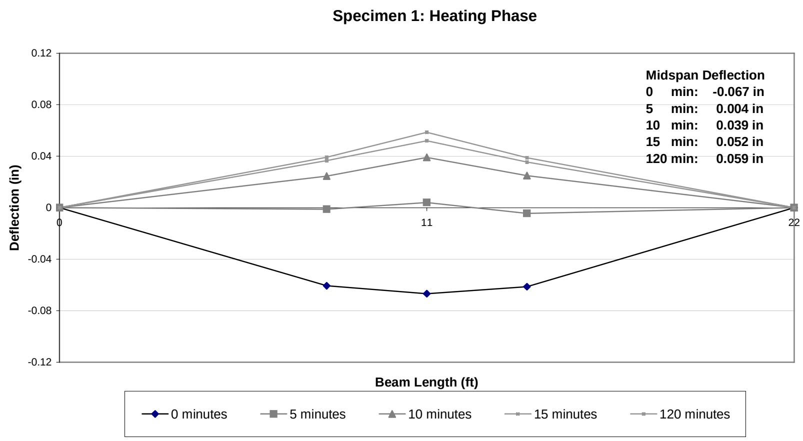


EXPERIMENTAL INVESTIGATIONS

- Testing Procedure: Each specimen was subjected to the following loading sequence:
  - Apply two 25 kip point loads at the third points to simulate the effects (moment) of a 10 psi uniform pressure.
  - Rapidly apply heating by subjecting the inner steel plate (subjected to the uniform pressure) to a temperature increase of about 300 F.
  - Maintain the elevated temperature of the inner steel plate at 300 F for a duration of two hours.
  - After heating for two hours, increase the point loads at the third points up to 90 kips (capacity of loading frame) or failure, whichever occurs first.

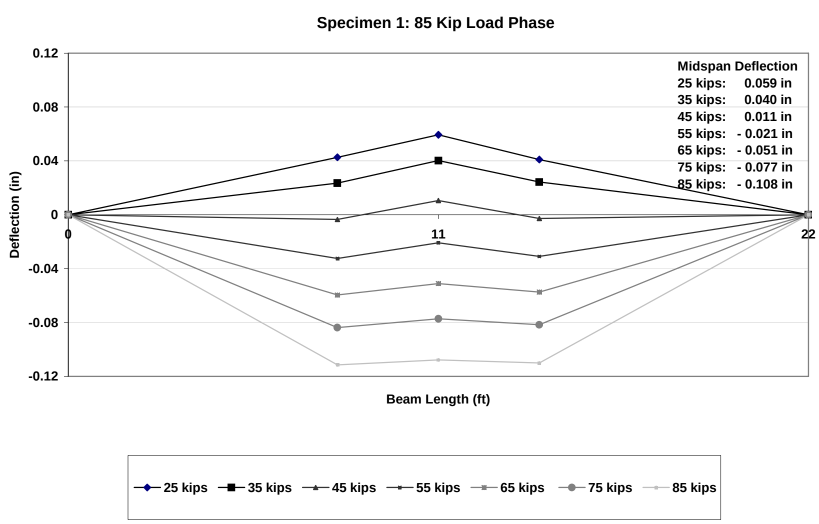
Experimental Results for WEC Wall Specimens

Behavior of Specimen 1 during the
second loading phase - heating for two hours



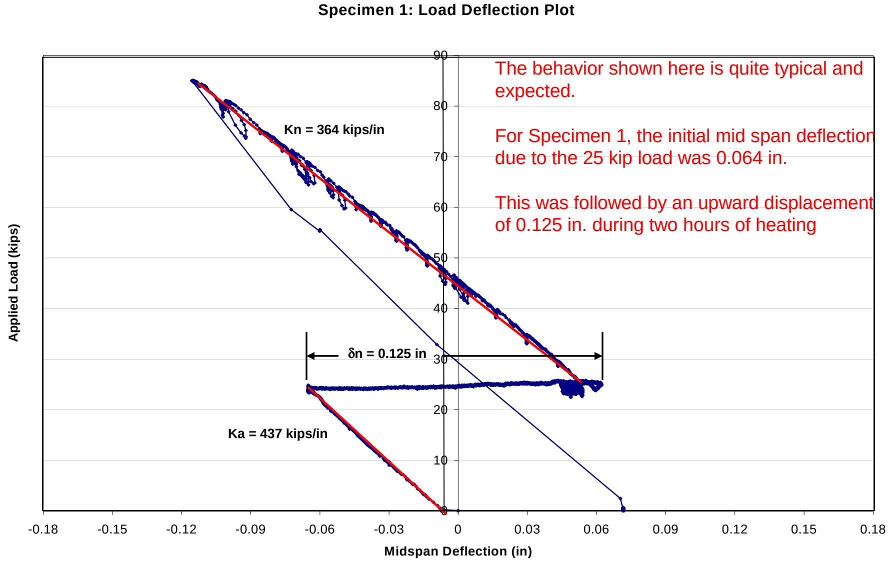
Experimental Results for WEC Wall Specimens

Behavior of Specimen 1 during the
third loading phase after two hours of heating
Increase applied loads at each load point



Experimental Results for WEC Wall Specimens

Midspan Load-Displacement Behavior of Specimen 1

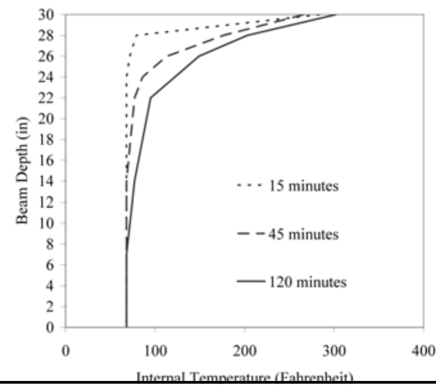


Summary Findings of Experimental Investigations

- All specimens had similar behavior for the 10 psi design pressure. The flexural stiffnesses and midspan deflections of the two specimens for each system type, i.e., Westinghouse and Bechtel, were comparable.
- The thermal loading caused both specimens to bend (convex) upwards similarly. The upward deflection was largest at the center of the heated region.
- All specimens sustained 2 hours of heating without damage or distress.
  - Additional concrete cracking (hairline) was observed in the heated region.
  - The cracking occurred close to the top (heated) surface but extended down about 15 in. (half depth) in the specimens.
  - Some water oozed out of these microcracks as the specimens were heated further.
- The applied loading was increased to 90 kips, which is more than 3.0 times the postulated accident pressure of 10 psi (or 25 kips) with no additional damage or distress.

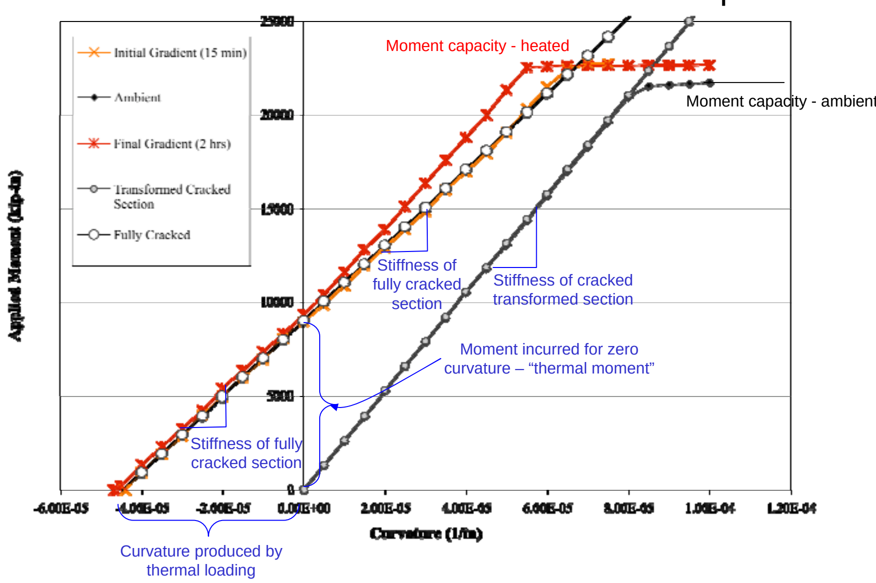
Summary Findings of Experimental Investigations

- The strains in the bottom steel plate were well within the elastic range.
- The strains in the top steel plate were also within the elastic range.
- There was no major slip between the steel plate and the concrete.
- The flexural stiffness of the specimens after heating was slightly lower than the ambient stiffness due to fully cracked behavior.
- The thermal gradient through the section depth was highly nonlinear.



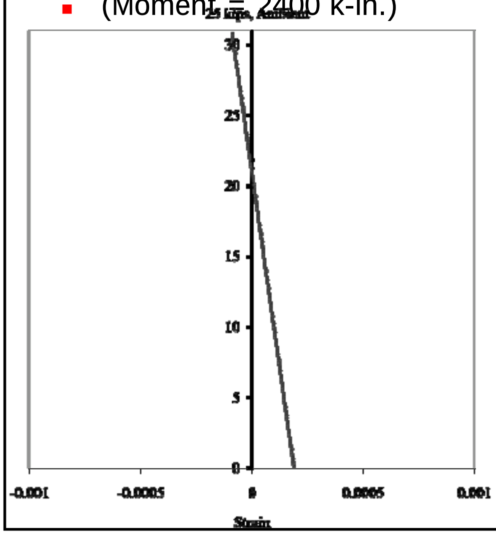
Results from Fiber Model

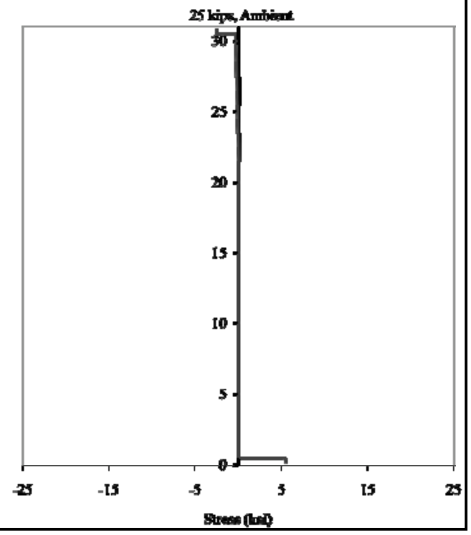
Predicted Moment-Curvature Behavior of Specimens



Results from Fiber Model

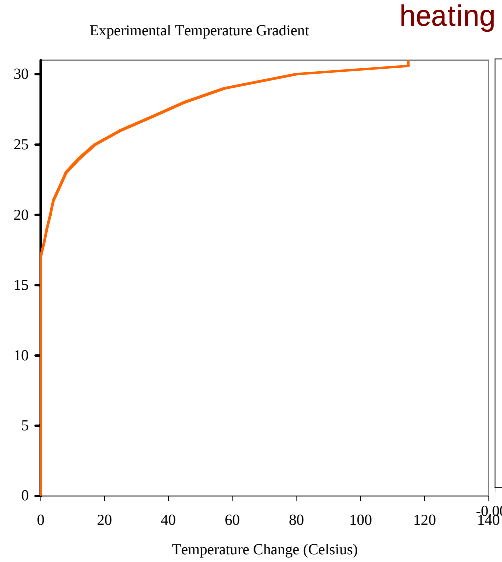
- Strains and stresses for 25 kip loading - ambient conditions - phase 1
  - (Moment = 2400 k-in.)

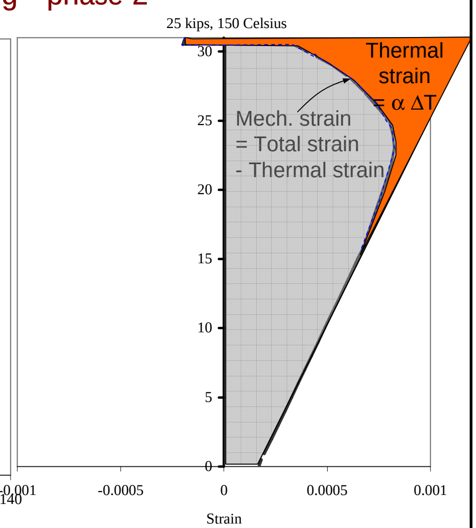




Results from Fiber Model

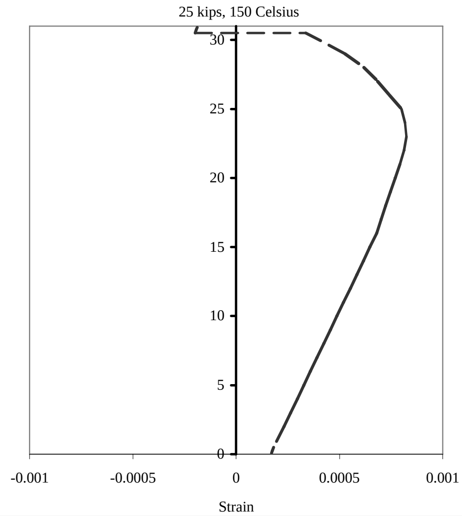
- Thermal gradient and mechanical strains after two hours of heating - phase 2

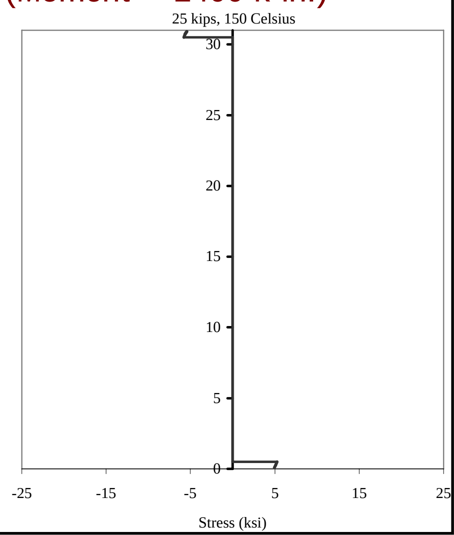




Results from Fiber Model

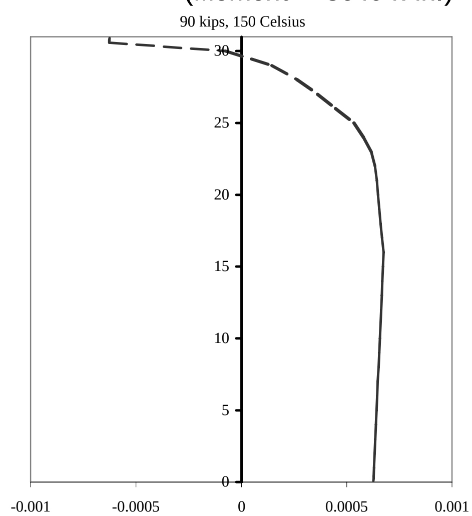
- Stresses corresponding to mechanical strains after two hours of heating - phase 2 - (Moment = 2400 k-in.)

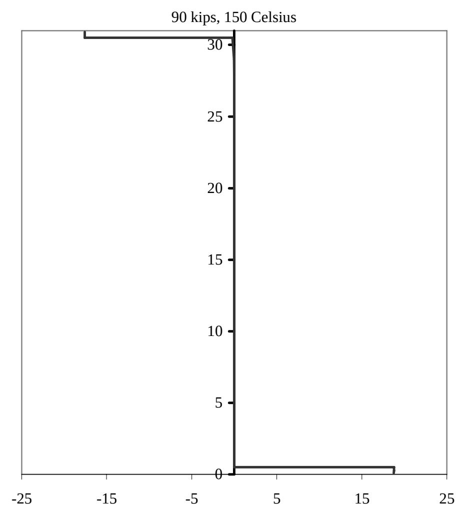




Results from Fiber Model

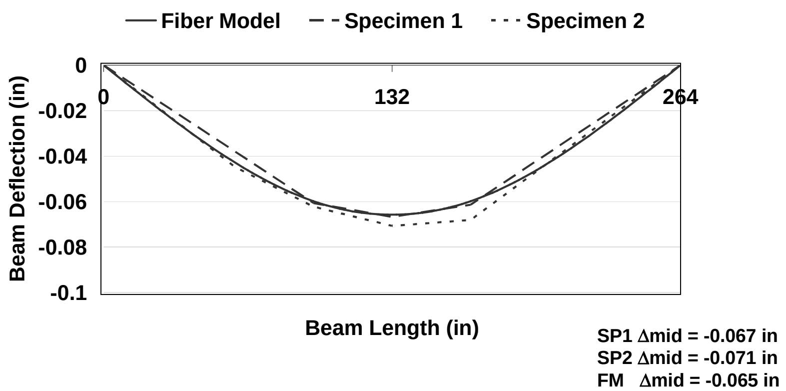
- Mechanical strains and stresses for heated specimens
  - Two hours of heating and 90 kip loads - phase 3 - (Moment = 8640 k-in.)





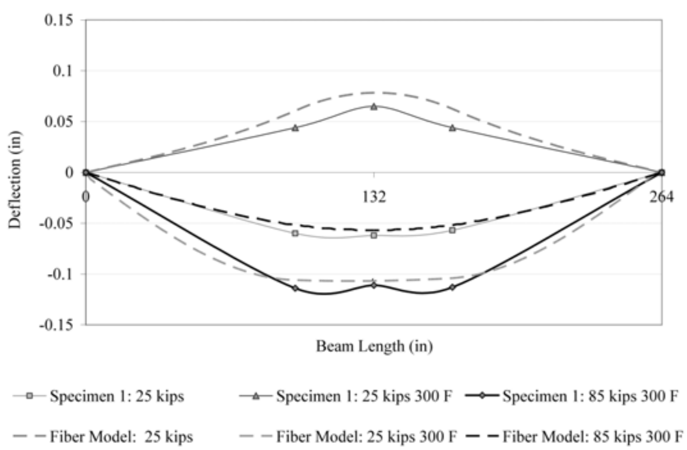
Predicting Beam Behavior

- Moment-area method to integrate the section moment-curvature relationships along the length to predict member behavior.
- Alternately, use conjugate beam method or numerical integration analysis method.



Predicting Beam Specimen Behavior

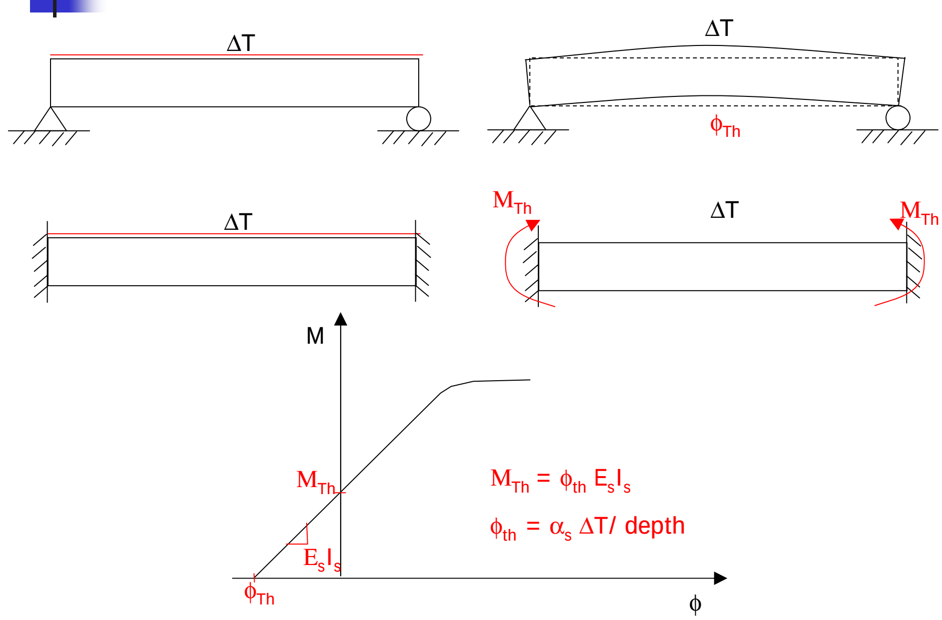
- Good comparisons between experimental and predicted behavior.



Effect of Wall End Conditions

- The experimental investigations focused on simply supported boundary conditions. However, there will be some fixity and membrane tension at the ends of compartment walls due to interactions between them.
- How does end fixity affect the wall behavior? This is addressed in the next few slides.

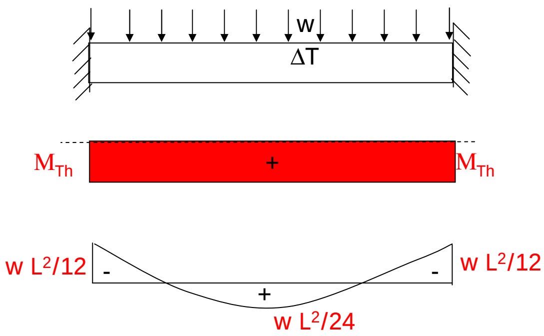
Effects of Thermal Gradient



$M_{Th} = \phi_{th} E_s I_s$

$\phi_{th} = \alpha_s \Delta T/\text{ depth}$

Effects of Fixed Boundary and Thermal Gradient



$$M_{max} = wL^2/24 + M_{th}$$

$$\sigma_{max} = (wL^2/24 + M_{th}) \times (d/2) / I_s$$

When membrane tension is also present:

$$\sigma_{max} = T/A_s + (wL^2/24 + M_{th}) \times (d/2) / I_s$$

Discussion of findings

- Ambient stiffness of the composite walls can be predicted using cracked transformed section properties.
- The stiffness of the composite wall subjected to heating (to 300 F) can be predicted using fully cracked (steel only) section properties. This is similar to the behavior of RC sections.
- The specimens resisted moments and shears for pressures well in excess of three times the expected design pressure of 10-psi.
  - No visible distress/abrupt stiffness reduction, shear connector failure, local buckling of steel plate, loss in through-thickness shear strength, etc was noticed at these loads, thus indicating further reserve margins.
- The fiber model approach predicts the experimental results with reasonable accuracy.
- A simple equation was developed (based on the analytical results) to predicts the effects of combined thermal and mechanical loading.
  - This equation is valid for all types of SC systems

Acknowledgments

- Bechtel Corporation
- Purdue University Bowen Laboratory