ABSTRACT

Title: Behavior and Design of Composite Plate Shear Walls/Concrete Filled Under Fire Loading
Author: Ataollah Taghipour Anvari
Advisor: Dr. Amit H. Varma
Institution: Purdue University

Composite Plate Shear Walls - Concrete Filled (C-PSW/CF), also known as SpeedCore, are increasingly used in commercial buildings. C-PSW/CF offer the advantages of modularization and expedited construction time. The performance of C-PSW/CF under wind and seismic loading has been extensively studied. As such, building codes permit the use of these walls in non-seismic and seismic regions. In addition to these lateral loads, C-PSW/CF may be exposed to fire loading during their service life. Elevated temperatures resulting from the fire loading subject structural components to a set of forces and deformations. These elevated temperatures result in the significant degradation of the material properties. Thus, fire loading may lead to the failure of structural components during fire incidents within the buildings.

This dissertation describes (i) experimental, numerical, and analytical studies conducted to evaluate the performance of C-PSW/CF and (ii) the development of design guidelines for C-PSW/CF subjected to fire and gravity loading. The results from prior experimental investigations were compiled, and five additional fire tests were conducted to address gaps in the experimental data. The fire tests were conducted on laboratory-scale specimens subjected to axial compressive loading and simulated standard fire loading (heating). The parameters considered in the tests were axial compressive loading (21% – 30% of section compressive strength, $A_g\ f'_c$), steel plate slenderness (24 – 48, tie spacing/steel plate thickness), and uniformity of heating (all-sided versus three-sided heating).

Numerical and analytical studies were conducted using two independent methods namely Finite Element (FE) and fiber-based analyses. The models were benchmarked to test data, and the benchmarked models were used to conduct parametric studies to expand the database. The thermal and structural material properties recommended by Eurocode standards were applied in these models. The parameters considered were the wall thickness (200 mm – 600 mm), wall slenderness (story height-to-concrete thickness ratio, H/t_c= 5 – 25), axial loading ($P_u \leq$ 30% section concrete

strength, $A_c f'_c$), heating uniformity (all-sided versus three-sided heating), boundary conditions (pinned versus fixed), steel plate reinforcement ratio (A_s/A_g =1.3% – 5.3%), steel plate slenderness ratio (s_{tie}/t_p = 20 – 75), tie bar spacing-to-wall concrete thickness ratio (s_{tie}/t_c = 0.5 – 1.0), and concrete strength (f'_c = 40 MPa– 55 MPa).

Symmetric nonlinear thermal gradients were developed through wall thickness for the walls exposed to uniform fire loading. Due to the high thermal conductivity of concrete, the temperature decreased nonlinearly through the wall thickness towards the mid-thickness of the walls. For the non-uniform fire exposure, temperatures through the wall thickness decreased nonlinearly towards the unexposed surface of the walls. A consistent trend was observed in the axial displacements of C-PSW/CF at elevated temperatures. The observed trend consists of several steps including (i) thermal expansion, (ii) gradual axial shortening, (iii) fast axial shortening, and (iv) failure.

Local buckling of steel plates between tie bars was observed on all walls. However, this phenomenon did not cause significant degradation in structural performance or failure of the walls. The results from parametric studies indicated that wall slenderness ratio (story height-to-wall thickness), wall thickness, applied load ratio, and end conditions have a significant influence on the fire resistance of C-PSW/CF. Higher wall slenderness ratios and load ratios have a detrimental effect on the fire resistance of walls. The walls with higher wall slenderness ratios failed due to global buckling. In thicker walls, the lower temperatures in the middle regions of the concrete core helped to maintain the axial compressive capacity of walls under fire loading. Limiting the plate slenderness ratio can slightly improve the fire resistance of unprotected walls by reducing the extent of local buckling between tie bars.

The results from the parametric studies have been used to develop an approach for designing C-PSW/CF subjected to fire and gravity loading. The total (linear) length of the wall was discretized into unit width columns, where each unit width column corresponded to a width equal to the tie bar spacing (s_{tie}). Thus, each unit is like a column with steel plates on two opposite surfaces, concrete infill, and tie bars distributed uniformly along the height. The axial load capacity of C-PSW/CF can be estimated as the axial load capacity of the unit width column, calculated using the developed approach, multiplied by the linear length of the wall divided by the unit width (tie bar spacing). For this approach, the wall slenderness ratio (H/t_w), has a limiting value of 20.

Walls with wall slenderness ratios greater than 20 should be fire protected. The expansion of the material on the exposed surface of walls generated moments through the wall cross-section in non-uniform fire scenarios. This phenomenon caused the early failure of walls (~40 minutes) with wall slenderness ratios greater than 20. An approach was developed to conservatively estimate the fire-resistance rating (in hours) of unprotected C-PSW/CF walls exposed to the standard fire time-temperature curve. The fire-resistance rating of C-PSW/CF depends directly on the applied axial load ratio, wall slenderness, and wall thickness.

The temperature profile through the wall thickness can be calculated by discretizing the section into fibers (or elements). Since the temperature of the elements is uniform along the height and width of walls, 1D thermal analysis (through wall thickness) can be performed using heat transfer equations or the fiber-based program developed in the study.

Vent holes are recommended to relieve the buildup of steam or water vapor pressure as the moisture from the concrete evaporates at temperatures exceeding the boiling point of water. A rational method was developed to design the vent holes as a function of the maximum temperature and thermal gradient through the wall thickness, heating duration, moisture content, and the acceptable level of pressure buildup on the steel plates. However, in typical cases, unprotected C-PSW/CF walls can be provided with 25 mm diameter vent holes spaced at a distance equal to story height or 3.6 m (maximum) in the horizontal and vertical directions to relieve the buildup of steam or water vapor pressure.

This research study also led to the development and validation of a computer program that can be used instead of the design equations to more accurately model and calculate the thermal and structural performance of composite C-PSW/CF walls. This program is based on a fiber-based section and member analysis method that can be used to evaluate the performance and axial (gravity) load capacity of unprotected and protected C-PSW/CF subjected to uniform or non-uniform heating. The analysis can be conducted by implementing standard (ISO 834 or ASTM E119), Eurocode parametric, or user input gas (or surface) time-temperature curves.

The proposed equations and the recommendations in this study can be used to develop design guidelines and specifications for fire design of C-PSW/CF under fire loading. A code change proposal will be proposed to AISC *Specification* - Appendix 4 (Structural Design for Fire Condition).