Improvement of Design Codes to Account for Accident Thermal Effects on Seismic Performance

Final Report

Amit H. Varma

Purdue University

Table of Contents

1. SUMMARY

This report summarizes the results of experimental and numerical studies conducted to evaluate the effect of accident thermal loads on the seismic response of steel-plate composite (SC) walls and reinforced concrete (RC) walls and beams. The research was sponsored by U.S. Department of Energy through the Nuclear Energy University Program (NUEP), Award Number DE-NE-0008256. Summary and conclusions of the research conducted are presented in this report. Based on the observations, analysis and design recommendations for SC and RC structures are also summarized.

1.1. SC Wall and Wall Piers

Experimental and numerical studies were conducted to evaluate the response of SC wall and wall piers to combined seismic and accident thermal loading. The test matrix was designed to evaluate the effect of different magnitudes and durations of accident temperatures on the in-plane response of SC walls. One SC wall pier (without flange elements) and one SC wall (with flange elements) specimen were tested for combined in-plane and thermal loading. Wall pier specimen was designed to have a flexure-controlled response (aspect ratio of 0.6). The wall specimen was designed to undergo in-plane shear failure. Two temperature magnitudes (300˚F and 450˚F) and two heating durations (1-hour and 3 hours) were selected. The specimens were subjected to heating and loading cycles. SC wall pier specimen was subjected to heating on the faceplates. SC wall specimen was subjected to heating on the faceplates (webplate) and flangeplates. The test setup was designed based on the expected in-plane capacity of the specimens. Clevis with press-fit spherical plain bearings was designed and fabricated to enable orthogonal deformations of the specimens without resulting in stresses in the loading rams.

Accident thermal loading resulted in non-linear thermal gradients through the thickness of the specimens. The non-linearity of thermal gradients was higher for higher surface temperatures. The gradient reduced as the duration of heating increased. The measured in-plane strength of heated wall pier specimen was 1.25 times the in-plane force corresponding to compression yield moment capacity (initiation of compression yielding in the faceplates). Similarly, the measured in-plane strength of heated wall specimen was 1.29 times the nominal in-plane shear strength (using measured properties) per AISC N690s1. Therefore, typical accident thermal temperatures do not significantly reduce the strength of SC walls. The strength can be calculated using current strength equations (per US codes) for ambient temperatures.

However, non-linear thermal gradients lead to concrete cracking due to external and self-restraint. The concrete cracking results in significant reduction in the stiffness of SC walls. The extent of reduction in stiffness depends on the temperature magnitude and duration of the thermal accident. The heated secant (and shear) stiffness for the SC wall reduces by about 25% for 300˚F and 40% for 450˚F, in comparison to ambient secant (and shear) stiffness for the SC wall. For SC wall piers, the reduction is about 20% for 300˚F and 40% for 450˚F. The in-plane shear and flexural stiffnesses of SC walls can be considered to linearly reduce from cracked stiffness to steel only (fully cracked) stiffness for temperature increments (ΔT) of 150˚C. The recommended stiffnesses compare reasonably with experimentally observed stiffness for heated cycles. Since the recommendations provide a lower bound stiffness, they eliminate the need for considering temperature-dependent properties for typical accident temperatures.

Finite element (FE) analyses for SC wall pier and wall specimens subjected to combined in-plane and accident thermal loading were conducted. The analysis results agreed reasonably with experiments. The ambient stiffness of SC wall FE models compares well with experimentally observed stiffness. Ambient SC wall pier FE models marginally overestimate the stiffness in comparison to experimentally observed stiffness. SC wall pier FE models subjected to accident thermal loadings reached a peak strength marginally greater than the force corresponding to plastic moment capacity (V_{Mp}). SC wall models reached a peak strength of 1.30 times the nominal in-plane shear strength of the wall (V_n^{AISC}). Peak strengths for ambient and heated FE models were similar. Accident thermal loads resulted in significant reduction in the stiffness. Reduced stiffness leads to heated SC FE models reaching peak strengths at drift ratio significantly larger than that for ambient FE models. The magnitude of reduction in stiffness observed in FE models was consistent with that observed in the experiments. Reduction in stiffness is primarily due to cracking of concrete caused by non-linear thermal gradient through the cross-section of the wall. Concrete cracking results in reduced contribution of concrete to lateral strength, which increases the stress in steel at similar force levels. This leads to hastening of steel yielding in the specimen.

The research on SC walls and wall piers has been presented at international conferences, and journal articles describing the research and the results are currently being prepared. These articles have been mentioned below.

1. Bhardwaj, S.R., Sener, K.C., Varma, A.H. (2018). "Numerical Evaluation of SC wall structures subjected to combined seismic and accident thermal loading," to be submitted to *Journal of Structural Engineering*, ASCE, in September 2018
2. Bhardwaj, S.R., Sener, K.C., Varma, A.H. (2018). "Multi-hazard Investigation and Testing of Composite (SC) Wall Piers: Seismic and Thermal Loads," to be submitted to *Journal of Structural Engineering*, ASCE, in July 2018.
3. Bhardwaj, S.R., Sener, K.C., Varma, A.H. (2018). "Multi-hazard Investigation and Testing of Composite (SC) Walls: Seismic and Thermal Loads," to be submitted to *Journal of Structural Engineering*, ASCE in June 2018.
4. Bhardwaj, S.R. (2018). "Multi-hazard In-plane Response of Steel-plate Composite (SC) Walls: Out-of-plane and Accident Thermal Loadings," *Ph.D. Dissertation*, Purdue University, May 2018.
5. Bhardwaj, S.R., Sener, K.C., Varma, A.H. (2018). "Experimental Evaluation of Structural Walls for Seismic and Thermal Forces," *Accepted for Eleventh U.S. National Conference on Earthquake Engineering*. Los Angeles, CA, U.S.A, 11 pp.

6. Bhardwaj, S.R., Sener, K.C., Varma, A.H. (2017). "Investigation of Accident Thermal Effects on Seismic Performance of Structural Walls," *Transactions of Structural Mechanics in Reactor Technology, SMiRT-24*, Busan, South Korea, 10 pp.
7. Sener, K.C., Varma, A.H., and Bhardwaj, S.R. (2015). "Accident Thermal Loading Effects on Seismic Behaviour of Safety-Related Nuclear Structures." *Transactions of SMiRT 23*, Manchester, UK, Paper ID 701, IASMIRT, North Carolina State University, Raleigh, NC, pp. 1-10,http://smirt23.uk/attachments/SMiRT-23_Paper_701.pdf
8. Bhardwaj, S.R., Sener, K.C., and Varma, A.H. (2015). "Investigation of Accident Thermal Effects on Seismic Performance". *Proceedings of the American Nuclear Society Winter Meeting*, 2015, Washington DC, 4 pp.

1.2.RC Walls

Experimental and numerical studies were conducted to evaluate the response of RC walls to combined seismic and accident thermal loading. Four planar RC shear walls, with an aspect ratio of 0.62, were tested at temperatures ranging between ambient and 450°F. Wall 1 and Wall 4 had vertical and horizontal web reinforcement ratios of 0.93%. Wall 2 and Wall 3 had vertical and horizontal web reinforcement ratios of 2.0%. Flexural strength was expected to control the maximum lateral load in Wall 1 and Wall 4. Shear strength was expected to control the maximum lateral load in Wall 2 and Wall 3. Most of the loading of Wall 1 was performed at a surface temperature of 300°F. Because little effect of temperature was observed from the testing of Wall 1, the elevated surface temperature for the remaining three walls was increased to 450°F.

Prior experiments (e.g., Luna et al. 2015, 2018) on low aspect ratio shear walls have shown a wide range in initial lateral stiffness, with large percentage reductions from uncracked values at ambient temperature due to restrained shrinkage near locations of stiffness discontinuity and cracking at construction joints. Mechanical loading to a significant fraction of peak strength leads to additional cracking (i.e., mechanical damage) where demands are high with respect to yield values and leads to further reductions in lateral flexural and shear stiffness. Increasing the temperature of a shear wall leads to cracking and a reduction in lateral stiffness over the heated region, with the percentage reduction being a function of the ratio of the lateral loading to the peak lateral strength (normalized loading).

Experimental results indicate that typical accident temperatures (up to 450ºF) do not result in a significant reduction in the peak strength of RC specimens. The measured strengths for the RC specimens were within 5% of the nominal strength per ACI 349 (using measured properties), regardless of whether flexure or shear controlled the failure. The response of walls with 1% reinforcement was flexure dominated, and was shear controlled for walls with 2% reinforcement. The reduction in stiffness in RC walls is due to concrete cracking. The cracking may be caused by mechanical loads (flexural or shear cracking) or thermal loads. Once cracked (due to thermal or mechanical loads), additional reduction is stiffness at same force/displacement level due to thermal or mechanical loads is not significant. For lateral loads less than the shear strength contribution of concrete (per ACI 349), accident thermal loads resulted in a stiffness reduction of up to 30% in comparison to ambient stiffness. However, for higher magnitudes of lateral loads, specimens developed significant shear and flexural cracking, and accident thermal loads did not result in significant additional reduction in stiffness.

The research on RC walls has been presented at international conferences, and journal articles describing the research and the results are currently being prepared. These articles have been mentioned below.

1. Anwar, H.S., Bhardwaj, S.R., Sener, K.C., Varma, A.H. (2018). "Numerical Evaluation of RC walls subjected to combined seismic and accident thermal loading," to be submitted to *Materials and Structures Journal*, ACI, in October 2018.
2. Bhardwaj, S.R., Varma, A.H., Sener, K.C., Deshpande, A., Whittaker, A. (2018). "Multi-hazard Investigation and Testing of Squat Reinforced Concrete (RC) Walls: Seismic and Thermal Loads," to be submitted to *Journal of Structural Engineering*, ASCE, in August 2018.
3. Anwar, H.S. (2018). "Investigation of Reinforced Concrete (RC) Wall Behavior for Combined Seismic and Accident Thermal loading," *Master's Thesis*, Purdue University, July 2018.
4. Bhardwaj, S.R., Sener, K.C., Varma, A.H. (2018). "Experimental Evaluation of Structural Walls for Seismic and Thermal Forces," *Accepted for Eleventh U.S. National Conference on Earthquake Engineering*. Los Angeles, CA, U.S.A, 11 pp.

5. Sener, K.C., Varma, A.H., and Bhardwaj, S.R. (2015). "Accident Thermal Loading Effects on Seismic Behaviour of Safety-Related Nuclear Structures." *Transactions of SMiRT 23*, Manchester, UK, Paper ID 701, IASMIRT, North Carolina State University, Raleigh, NC, pp. 1-10,http://smirt23.uk/attachments/SMiRT-23_Paper_701.pdf
6. Bhardwaj, S.R., Varma, A.H., and Sener, K.C. (2015). "On the Calculation of Design Demands for Accident Thermal Loading Combination." *Transactions of SMiRT 23*, Manchester, UK, Paper ID 850, IASMIRT, North Carolina State University, Raleigh, NC, pp. 1-10, http://smirt23.uk/attachments/SMiRT-23_Paper_850.pdf

1.3. RC Beams

Six reinforced concrete beam specimens were subjected to different combinations of accident thermal heating and shear loading. The test matrix included one control specimen at ambient condition, four specimens with heating on one of the shear spans, and one specimen with heating in the constant-moment region. The parameters included in the experimental investigations were the; (i) maximum accident temperature, (ii) concrete clear cover, (iii) one or two-sided heating, (iv) constant-moment region or shear span heating.

The experimental results indicate that the accident thermal conditions reduced both the out-of-plane shear strength and stiffness of the tested RC beams. The reduction in shear strength was greater for specimens with reduced concrete clear cover, higher surface temperature, higher longitudinal rebar temperature, and two-sided heating. Wider concrete crack widths and greater shear reinforcement strains were observed for the heated specimens compared to the ambient specimen, at similar shear force levels. It was also confirmed that the section shear stiffness was reduced due to the thermal loading. However, thermal loading did not significantly reduce the section flexural stiffness, which remained at the cracked transformed stiffness level. The shear strengths calculated using measured material properties per ACI code were either greater or marginally (3-5%) smaller than the experimental shear strength of the tested RC specimens. The calculated values were marginally (3-5%) less than the specimens with higher (250-300°F) longitudinal rebar temperature due to higher surface temperature (450°F [232.2°C]) or reduced concrete cover.

The research on RC beams has been presented at international conferences, and journal articles describing the research and the results are currently being prepared. These articles have been mentioned below.

1. Sener, K.C., Wang, S., Bhardwaj, S.R., Varma, A.H. (2018). "Numerical Evaluation of RC beams subjected to combined shear and accident thermal loading," to be submitted to *Materials and Structures Journal*, ACI, in November 2018.
2. Sener, K.C., Bhardwaj, S.R., Varma, A.H. (2017). "Experimental Investigations of Accident Thermal Effects on Reinforcement Concrete Members for Nuclear Facilities," Revised version submitted. *Structures and Materials Journal*, American Concrete Institute.
3. Varma, A.H., Sener, K.C., Bhardwaj, S.R. (2017). "Investigation of Accident Thermal Effects on Reinforced Concrete Beams," *Transactions of Structural Mechanics in Reactor Technology*, *SMiRT-24*, Busan, South Korea, 10 pp.
4. Bhardwaj, S.R., Varma, A.H., and Sener, K.C. (2015). "On the Calculation of Design Demands for Accident Thermal Loading Combination." *Transactions of SMiRT 23*, Manchester, UK, Paper ID 850, IASMIRT, North Carolina State University, Raleigh, NC, pp. 1-10, http://smirt23.uk/attachments/SMiRT-23_Paper_850.pdf
5. Bhardwaj, S.R., Sener, K.C., and Varma, A.H. (2015). "Investigation of Accident Thermal Effects on Seismic Performance". *Proceedings of the American Nuclear Society Winter Meeting*, 2015, Washington DC, 4 pp.

2. RECOMMENDATIONS FOR ANALYSIS

Wall structures can be analyzed for estimating the strength and stiffness using detailed non-linear finite element analyses. However, non-linear analyses are complex and need to be benchmarked with experiments. The analyses may also need to be peer-reviewed. Considering the complexities of conducting non-linear finite element analysis, design demands for wall structures are typically obtained from elastic finite element analysis (wall structures are modeled using elastic material properties). Model thickness and elastic modulus of the model are calibrated to match the model stiffnesses with the cracked wall stiffnesses. For SC wall pier (with no boundary elements), the ambient in-plane wall stiffness can be calculated considering the wall to be cracked in flexure and shear. For SC walls, the ambient in-plane wall stiffness can be calculated considering the wall to be cracked in flexure [AISC N690s1 does provide recommendations for in-plane flexural stiffness for SC walls]. AISC N690s1 recommends the in-plane shear stiffness of SC walls to be considered as cracked or uncracked depending on the magnitude of lateral loading. For lateral loads less than cracking threshold (S_{cr}), the in-plane shear stiffness is uncracked. For lateral loads greater than $2S_{cr}$, the in-plane shear stiffness is cracked. The stiffness can be linearly interpolated for loads between S_{cr} and $2S_{cr}$. Uncracked shear stiffness was not observed experimentally, and will typically not manifest in SC walls with flange plates as boundary elements. The SC wall flexural stiffness for accident thermal loading combinations can be considered to linearly reduce from cracked stiffness to steel-only (fully cracked) stiffness for ΔT of 150˚C. For lateral loads less than S_{cr}, the SC wall shear stiffness for accident thermal loading combinations can be considered to be cracked. For lateral loads greater than S_{cr}, the SC wall shear stiffness for accident thermal loading combinations can be considered to linearly reduce from cracked stiffness to steel-only (fully cracked) stiffness for ΔT of 150˚C. The elastic model can be subjected to a temperature increase (ΔT_{avg}) that is equal to the average of peak ΔT for the faceplates (obtained from thermal-hydraulic analysis for the accident) in combination with seismic loads, to obtain design demands. The out-of-plane moment due to thermal gradient can be calculated based on AISC N690s1 and added to the demands obtained from elastic analysis.

For RC walls, the ambient cracked stiffness, and the reduction in stiffness due to accident thermal loading depends on the magnitude of lateral force. For lateral force magnitude less than the concrete contribution to in-plane shear strength (V_c) per ACI 349, the ambient stiffness can be calculated considering the wall to be cracked in flexure and un-cracked in shear. For accident thermal loading, when lateral force is less than the concrete contribution to in-plane shear strength, the stiffness can be calculated considering the wall to be cracked in flexure and shear. For lateral force magnitude greater than V_c, the ambient stiffness can be calculated considering the wall to be cracked in flexure and shear. For accident thermal loading, when lateral force is greater than the concrete contribution to in-plane shear strength, the flexural stiffness can be considered to linearly reduce from cracked stiffness to steel-only (fully cracked) stiffness as the accident temperature increases from 120˚F to 450˚F. The shear stiffness can be considered to be cracked. The elastic model can be subjected to a temperature increase ($\Delta T_{r\text{-}avg}$) that is the average of peak ΔT for at the centroid of outermost layer of rebars (obtained from thermal-hydraulic analysis, and 1-D heat transfer analysis for the accident), in combination with seismic loads, to obtain design demands.

In case non-linear finite element analyses are performed, components of the wall structure (e.g., concrete infill, rebar, steel plates, studs, ties) need to be explicitly modeled, and their interfaces defined. Concrete infill can be modeled using solid elements, steel plates using shell elements, and studs and ties (or rebars) can be modeled using beam elements. Connector elements may be employed to simulate the force-slip behavior of studs and ties. 'Piecewise linear plasticity' or 'plasticity with damage' models can be used to define the constitutive stress strain relationship for steel (to include the strain hardening behavior of steel). Concrete stress-strain behavior in compression can be considered as without damage (or post-peak softening) or post-peak damage can be incorporated. The concrete model needs to account for tension softening and shear retention. Analyses for thermal and seismic loading can be fully coupled (both analysis performed simultaneously) or sequentially coupled (thermal analysis performed followed by seismic analysis). For simplification, evolution of through thickness temperature gradients may be obtained by performing a 2-D heat transfer analysis, where the steel (steel plates or rebars) is not considered. The detailed non-linear finite element analyses will be discussed in the final report.

For RC beams, three different modeling approaches for analyzing the behavior of reinforced concrete beams at ambient and elevated condition were investigated. These modeling approaches included developing; (i) layered shell element (LCS) models, (ii) linear elastic conventional shell element (LEFE) models, and (iii) nonlinear solid finite element (3D-solid) models. The applicability of the developed models was tested by comparing against the structural behavior and response of the experimentally tested specimens. The benchmarking studies leading up to the final models included investigating the: (i) effective out-of-plane shear stiffness to be used in the shell (both LCS and LEFE) models for ambient and elevated temperature conditions, (ii) applicability of equivalent section properties calibrated based on cracked stiffness properties for the LEFE models, (iii) influence of using different surface contact properties (tie vs. cohesive bond models) for the concrete-reinforcement contact interactions.

The studies on beam models concluded that the nonlinear solid (3D-solid) models provided the most accurate estimates for the force-displacement response of the tested beams among the different modeling approaches. These models had the most geometrical and material complexities, and therefore can capture concrete cracking, crushing and steel yielding properties. The addition of interface bond properties between concrete and steel rebars improved the analysis predictions against the experimental results. Despite the accurate results, these models are computationally expensive and not practical.

Using the nonlinear layered shell (LCS) models with non-linear concrete models for modeling the tested beams have provided acceptable predictions for response if appropriate modeling parameters are used. LCS models should be used with caution as this modeling approach is incapable of capturing out-of-plane shear failure modes, therefore the out-of-plane force capacity for LCS models is governed by flexural strength. Additionally, the out-of-plane shear stiffness of shell element models needs to be modified as the default stiffness is formulated to account for uncracked out-of-plane shear stiffness. The parametric studies conducted on recommending effective out-of-plane shear stiffness factors for the shell models concluded that; (i) 50% of the uncracked concrete section stiffness to be used for ambient conditions, and (ii) a further reduction of 50% (25% of the uncracked concrete stiffness) from the effective cracked stiffness to be used for the heated cases.

Lastly, the usage of linear elastic shell (LEFE) models for modeling the tested beams demonstrated that the response stiffness can be conservatively estimated if implemented with appropriate modeling considerations. These include the calculation of equivalent section properties for the shell elements based on cracked concrete section properties. The linear elastic shell elements calibrated for this study was based on the equivalent section properties recommended in ASCE 41, which recommends the usage of 50% of the uncracked concrete stiffness. The effective out-of-plane shear stiffnesses recommended for the LCS models are applicable to these shell models to resolve the inaccuracy in the default formulation.

3. RECOMMENDATIONS FOR DESIGN

Experimental and numerical studies indicate that typical accident temperatures do not result in significant reduction in the strength of the specimens. The design strength of the structural walls can be calculated using the existing strength equations for ambient conditions (per US codes).

For SC walls, the in-plane shear strength can be calculated corresponding to Von-Mises yielding of the faceplates [per Equation A-N9-19 of AISC N690s1]. The in-plane flexural strength of SC walls depends on the boundary elements, and can be calculated as the moment corresponding to the compression yielding of the boundary elements. The in-plane response of SC wall piers with aspect ratios greater than or equal to 0.6 is governed by the flexural strength, and the in-plane flexural strength can be calculated corresponding to the initiation of compression yielding of faceplates.

The in-plane strength of RC walls can be calculated using ACI 349 provisions. The flexural strength will correspond to plastic moment capacity of the wall, and the in-plane shear strength will be the sum of concrete and steel contributions (depending on shear reinforcement spacing, limited by $10\sqrt{f'_c}A_c$).

The calculated shear strengths of the tested beams per ACI code were either greater or marginally (3-5%) smaller than the experimental shear strength. Therefore, the out-of-plane shear strength of RC walls subjected to out-of-plane shear and accident thermal loading can be calculated using the existing ACI provisions without any modification.