Investigation of Steel-plate Composite (SC) Wall Behavior for Beyond Design Basis Fire Events

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ABSTRACT

Steel-plate composite (SC) walls have been used in third generation nuclear power plants and are also being considered for Small Modular Reactors (SMRs). The SC walls in safety-related nuclear facilities may be subjected to beyond design basis fire scenarios (e.g., due to jet fuel combustion from an aircraft impact). Existence of steel plates (analogous to reinforcing bars in traditional reinforced concrete construction) on the surface of the shear walls means that the steel plates will be directly exposed to fire temperatures. Fire loading will result in elevated steel and concrete temperatures and non-linear thermal gradients through the cross-section of the walls. Elevated temperatures result in degradation of mechanical properties of steel and concrete. This can result in local buckling of steel plates or global instability of the walls, and may lead to collapse of the walls at gravity load magnitudes significantly lower than the ambient compression strength of the walls. Experimental and numerical research is being conducted to investigate the stability behaviour of SC walls subjected to standard fire curves. Existing database of standard fire tests conducted on scaled SC wall specimens in S. Korea and China is discussed in the paper. The experimental database has been used to benchmark finite element models for thermal and structural response of the system. The results of numerical studies indicate that the thickness of wall and the slenderness ratio play a vital role in enhancing the fire rating of the SC wall. The slenderness ratio, in particular, must be kept below a certain value to avoid a substantial loss in the fire rating. It is also observed that buckling of steel plate is the most common mode of failure. The benchmarked analyses have been employed to develop full-scale models of SC walls. Parametric studies will be conducted to study the effect of variation in section thickness, steel reinforcement ratio, steel plate slenderness on the local and global stability behaviour of SC walls subjected to standard fire curves. Results of these studies will be used to provide recommendations for fire scenarios for SC walls. These recommendations will enable the engineers to consider beyond design basis fire events for the design of SC walls in safety-related nuclear facilities.

1. Introduction

Increasing concerns related to energy security and global warming have led to a need for innovative solutions to tackle these impending issues. Traditionally, safety-related nuclear facilities have comprised of reinforced concrete (RC) walls. RC walls or pre-stressed concrete walls have been used for construction of different compartments of a nuclear reactor. The compartment walls are designed to resist seismic as well as accidental thermal and pressure loads. At the same time, these walls provide insulation from dangerous nuclear radiations. Therefore, to maintain structural integrity, even during the most extreme events, these walls are extremely thick and are heavily reinforced. However, beyond-design basis events like the Chernobyl disaster and Fukushima disaster have raised concerns about the stability of these walls.
In Chernobyl, the steam explosion dismantled the core of the reactor, subjecting the structure to colossal pressures (USNRC 1987) and temperatures rising up to 2500 °C (U.N. 2008). A significant portion of the reactor cover was destroyed, exposing the outside world to the perilous gamma radiations emerging from the core of the reactor (Kinly 2005). Similar events took place in Fukushima, but the implications were less threatening. Both these disasters have underscored the importance of the stability of the containment structure for beyond-design events. Therefore, it is necessary to employ structural systems that are sustainable, sturdy as well as affordable.

Steel-plate composite (SC) walls have been used in the third generation nuclear power plants due to the advantages of modularity and schedule construction. Rib-stiffened SC wall system is also being considered for containment applications (Malushte et al. 2017). The SC system comprises of steel plates sandwiching concrete infill. Steel plates are connected to each other through ties. Ties ensure structural integrity of the system (Seo et al. 2017) and serve as out-of-plane shear reinforcement (Bhardwaj et al. 2017). Composite action between steel plates and concrete infill is provided by shear studs and / or ties. There has been significant research regarding the behavior and design of steel-plate composite walls for application in safety-related nuclear facilities. The research and design provisions have been discussed in detail by Bhardwaj and Varma (2017a).

An important aspect of applicability evaluation of SC walls for nuclear industry is the stability behavior of these walls under beyond design basis fire events. This evaluation becomes especially important for containment applications of SC walls. Steel plates (analogous to reinforcing bars in traditional reinforced concrete construction) form the exterior of SC walls. The steel will be directly exposed to fire temperatures (in absence of fire protection). Fire loading will result in elevated steel and concrete temperatures and non-linear thermal gradients through the cross-section of the walls. Elevated temperatures will result in degradation of mechanical properties of steel and concrete and may cause instability (local or global) and failure of walls at axial loads significantly lower than the ambient strength of the walls. There is a need to experimentally and numerically evaluate the stability response of SC walls under fire loading.

The authors have initiated a research project focusing of behavior of SC walls subjected to axial compressive and fire loading. The stability behavior of SC walls under fire loading is being evaluated experimentally. Benchmarked numerical models have been developed to conduct parametric studies. The experimental and numerical results will be employed to develop recommendations for prescriptive design of SC walls under fire loading. Numerical tools will be developed that enable the engineers to perform performance-based design of SC walls subjected to fire loading. This paper summarizes the existing experimental studies for SC walls subjected to fire loading. The paper focuses on the development and benchmarking of 2-D and 3-D finite element models for investigating the response of SC walls. The paper presents a summary of the proposed experimental and parametric study cases.

2. Background study

Varma et al. (2013) examined the local buckling behaviour of SC Composite walls at ambient and elevated temperatures (up to 350°C). Benchmarked finite element models were used to assess the performance of the walls subjected to a combination of thermal and gravitational loads. The researchers observed that the design provisions, for SC walls at elevated temperatures, in the existing codes are unconservative. Booth et al. (2007) conducted experiments to examine the out of the plane structural response of SC walls subjected to thermal and mechanical loads. Two full-scale specimens were tested with the temperatures rising up to 300 °F. Finite element models were also developed to obtain the results analytically.

The events at Chernobyl and Fukushima, and aircraft impact analyses have indicated that the temperatures in safety-related nuclear facilities in case of a fire can rise above 1000 °C. Therefore, it becomes necessary to examine the behaviour of these walls in fire conditions. There is a dearth of experimental work on the response of SC walls exposed to fire temperatures. However, some researchers in the recent past have started to investigate the behaviour of these walls in the event of a fire. Researchers in South Korea have conducted experimental studies for stiffened steel plate concrete walls (with ribs as
stiffeners) subjected to fire loading (Moon et al. 2009). Moon et al. subjected 3000 ×3000×300 mm wall specimens to ISO 834 fire curve (ISO 1975). The specimens were subjected to single sided fire. The specimens experienced a lateral displacement towards the exposed surface during the initial stages of fire; however; at later stages, the lateral displacement towards the unexposed side began. The specimens failed due to local bulging of surface steel plates, spalling of concrete and stud / tie weld rupture. Kim et al. (2009) evaluated the response of half SC slabs subjected to one-sided fire loading.

Recently, Wei et al. (2017) have carried out experiments to examine the fire resistance of 12 concrete-filled steel plate composite wall specimens. The tests were conducted in a gas furnace with the air temperature controlled to match the ISO 834 fire curve. The specimens were subjected to a combination of gravity and thermal loads. Specimens 1 to 8 were subjected to uniform fire and specimens 9 to 12 were subjected to one-sided fire. The specimens had a width of 1000 mm. The parameters varied included (a) height: 850, 1000, 1350 and 1850 mm, (b) thickness: 150 and 200 mm, (c) steel plate thickness: 2 to 5 mm, and (d) fire loading: uniform and one-sided fires. The axial load ratio was maintained at around 30% of the ambient capacity. Specimens subjected to uniform fires failed due to local buckling or weld cracking. The fire resistance times were higher than 2 hours for all the specimens. Specimens subjected to single-sided fires underwent thermal insulation failure, with the earliest failure time being 166 minutes. No specimen failure was observed for one-sided fires. The specimen with a thickness of 200 mm did not undergo insulation failure until the test was stopped (207 minutes). Experimental studies by Wei et al. (2017) present significant data for the development of benchmarked models for parametric numerical studies.

3. Numerical Models

The Finite Element Method (FEM) is employed to numerically investigate the behaviour of SC walls under combined fire and gravity loads. The FEM models are developed and benchmarked to the experimental studies conducted by Wei et al. (2017). The two-dimensional modeling was employed to evaluate the fundamental thermal behaviour of the SC walls when subjected to fire. Three-dimensional models were developed to evaluate the stability response of SC walls under gravity and fire loading. The finite element models of the specimens tested by Wei et al. (2017) were developed in a commercially available software, ABAQUS (Simulia 2016). The numerical results have been used to comprehend the response of SC walls under combined gravity and thermal loading. In addition, the effect of various parameters on the behaviour of SC walls has been studied.

3.1 2-D Models

Two-dimensional finite element models of walls were developed to obtain evolution of through thickness temperatures in the wall. The wall assembly comprises of a concrete mid- and side-blocks, which are enclosed by steel plates (consistent with specimens tested by Wei et al. 2017). The thermal properties of steel and concrete are defined as per the Eurocode (2005).

3.2 3-D Models

Three-dimensional models are developed to evaluate the behaviour of CFSWs when subjected to fire and gravity loads. The details of the specimens tested by Wei et al. (2017) were modeled, including the studs and tie bars. Fig. 1 shows the 3-D model of SC walls. The concrete block is modeled using 3-D solid elements whereas the steel flange, web and inner plates are modeled as shell elements (use of shell elements makes the sequentially coupled analysis computationally efficient). Beam elements are used for modeling the shear studs and ties.
Figure 1. 3-Dimensional model of the SC walls (as tested by Wei et al. 2017)

The thermal properties of steel and concrete for both two-dimensional and three-dimensional models are defined as per the Eurocode (2005). The concrete moisture content is considered to be 3%. The upper limit values of thermal conductivity specified by the Eurocode are used for concrete. Concrete material behaviour was modeled using ‘Concrete damaged plasticity’ model in ABAQUS. The steel material was modeled as ‘elastic-plastic’. Further details about the models and properties used can be found in Bhardwaj et al. (2019).

3.4 Sequentially coupled analysis

Sequentially coupled thermal-stress analysis technique was employed for the numerical studies. In this technique, the heat-transfer analysis is conducted first. After that, the stress analysis is conducted using the nodal temperatures from heat-transfer analysis as inputs.

The heat transfer model consisted of concrete blocks and the steel assembly. The concrete is modeled using an 8-node linear heat transfer brick element, and the steel plates are modeled using shell element. The heat transfer between steel and concrete is allowed by tying the steel plates to the outer surface of the concrete block. The inner plates are also tied to the concrete block. This approach is conservative as it does not consider the energy loss at steel-concrete interface. The specimens are subjected to ISO-834 standard fire curve for 4 hours. A ‘FILM’ subroutine in ABAQUS is used to model heat flow between the burning gases and the steel surface. For brevity, the details of this subroutine are not discussed here and are reported by Cedeno et al. (2009). The ambient temperature was assumed to be 20 °C.

The stress model includes the shear studs and tie bars, in addition to the heat transfer model. The concrete is modeled using an 8-node linear brick element with reduced integration. The steel plates are modeled using a 4-node general-purpose linear shell element. The shear studs and the tie bars are modeled using a 2-node linear beam element. Cartesian type connector elements were employed to simulate the temperature dependent force-slip behaviour of studs and ties. The SC wall is fixed at the bottom. Gravity loading is applied on the top surface. The tie bars and shear studs are embedded in the concrete block. The stress analysis consists for two steps. The first step involves the application of an incremental axial compressive load. In the second step, the axial load is maintained constant, and nodal temperatures based on the heat transfer analysis are applied. A hard and frictionless contact is defined between different components of the assembly. The numerical analysis is explained in detail in Bhardwaj et al. (2019).

4. Validation of Numerical Results

The numerical results are validated by comparing them with the experimental results. For brevity, thermal and stress analysis for only two specimens [1 uniform fire specimens (SCW8) and 1 one-sided fire
specimen (SCW9) are discussed in detail. However, the details and the summary of the results for all the specimens are presented in Table 1.

4.1 Thermal analysis
Heat transfer analyses were conducted for specimens following the procedure discussed previously in Section 3. The typical through thickness temperature distributions at four hrs (in °C) for uniform fire and one-sided fire conditions are shown in Fig. 2(a) and Fig. 2(b) respectively. The presence of thermal gradient is visible for both the specimens.

![Figure 2](image)

Figure 2. Temperature Distribution for (a) Uniform fire and (b) One-sided fire conditions (at 4 hours after the start of fire)

The comparison of temperature profiles obtained numerically with those observed experimentally (for SCW 8 and 9) is shown in Fig. 3. The numerically observed mid-thickness temperature for uniform fire specimens (SCW 8) and unexposed-side temperature for single-sided fire specimen (SCW 9) compare well with experimental results. However, the outer surface temperature or exposed-side temperature values obtained from FE models are higher than the experimental values in some regions of the curve.

The experimentally observed surface temperatures indicate a plateau in the first 30 minutes of the heating. Wei et al. (2017) attribute this to the latent heat associated with the loss of moisture content from the concrete infill. To investigate this, concrete specific heat values corresponding to different moisture content were used in the FE models. However, no significant difference in the surface temperature evolutions was observed. The change in moisture content affected the evolution of temperature at mid-thickness of the cross-section. The plateau observed in experimental measurements could be due to some heat loss or inconsistencies in the measurements. The experimental surface temperatures are reported at 2 mm from the concrete surface. The steel surface temperatures are not reported. The plateau observed after 30 minutes may be due to an air gap between steel and concrete as the plate buckling initiates. Additionally, the FE models incorporate thermal ties (no heat loss at interface) at steel concrete interface. This may conservatively result in higher surface temperatures in the FE models. The higher surface temperatures in FE models will result in higher heat flux input for FE models (in comparison to experiments) and may reduce the time to failure of the specimens.
4.2 Stress analysis

The fire loading of SC walls resulted in failure of the specimens due to local buckling of the steel plates, weld cracking, and concrete crushing (Wei et al. 2017). The state at failure for uniform fire specimen is shown in Fig 4a. FE model exhibited buckling of the steel plates (both web and flange) at failure (Fig. 4b). Fig. 5 and 6 present the axial deformation with time for the specimens. The axial deformation curves for experiments have been corrected for inconsistencies in the measurements. In the initial stages (up to 30 minutes), the uniform-fire specimens (Fig. 5) underwent a thermal expansion. This was followed by a stage of axial compression, which lasted for next 60 minutes. As the steel and concrete temperatures increase, resulting in degradation of material strengths, the axial compressive deformation overcomes thermal expansion. The axial compression increased gradually, and finally the specimen failed undergoing rapid axial shortening. Similar behaviour was observed on the exposed side of the one-sided fire specimen (Fig. 6a). However, the unexposed side kept on expanding throughout the fire, before specimen failure (Fig. 6b).

Figure 3. Comparison of predicted temperatures from the Finite Element (FE) analysis with the Experimental values at different sections

Figure 4. Specimen state at failure (uniform fire loading)
Axial deformation vs time response obtained from FE models compares reasonably with that observed experimentally (Fig. 5 and 6). However, the FE failure time is lower than experimental failure times. This may be because of higher surface temperatures for FE models (as discussed previously) or some variability in the recorded experimental measurements. To investigate this further, the axial displacements of the specimens were plotted against the surface temperature (Fig. 7 and 8). The FE model surface temperature at failure agrees well with experimentally observed surface temperature at failure. Therefore, surface temperature may be a better indicator of specimen failure for FE models. The failure time can then be calculated using heat transfer equations and surface temperatures.

Figure 5. Comparison of axial displacement for SCW 8 obtained from the Finite Element (FE) analysis with the Experimental Values

Figure 6. Comparison of axial displacement for SCW 9 obtained from the Finite Element (FE) analysis with the Experimental Values at (a) Unexposed Side (b) Exposed Side
A summarized comparison of experimental and finite element results for all the specimens barring one is presented in Table 1. The table presents the parameters varied in the specimens. The experimental and numerical failure times as well as surface temperatures at failure are also given. For some of the specimens (SCW1, SCW2, SCW3 and SCW5), the experimental failure temperatures are left blank because the experimental temperatures have not been reported for these specimen.

Figure 7. Comparison of axial displacement v/s outer surface temperatures for SCW 8 obtained from the Finite Element (FE) analysis with the Experimental Values

Figure 8. Comparison of axial displacement v/s outer surface temperatures for SCW 9 obtained from the Finite Element (FE) analysis with the experimental (Exp.) data at (a) Unexposed Side (b) Exposed Side
Table 1. Summary of Finite Element and Experimental Results (specimens tested by Wei et al. 2017)

<table>
<thead>
<tr>
<th>Fire Scenario</th>
<th>Specimens</th>
<th>Height (H)</th>
<th>Wall thickness (T)</th>
<th>Steel plate thickness (t)</th>
<th>Shear studs</th>
<th>Tie bars</th>
<th>Load Ratio (d)</th>
<th>Exp. Failure Time (min)</th>
<th>FE Failure Time (min)</th>
<th>Exp. Failure Surface Temp. (C)</th>
<th>FE Failure Surface Temp. (C)</th>
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<tbody>
<tr>
<td>Uniform Fire</td>
<td>SCW1</td>
<td>850</td>
<td>150</td>
<td>3</td>
<td>Ø 2@40</td>
<td>Ø 10@160</td>
<td>0.34</td>
<td>161</td>
<td>127</td>
<td>-</td>
<td>960</td>
</tr>
<tr>
<td></td>
<td>SCW2</td>
<td>850</td>
<td>150</td>
<td>3</td>
<td>Ø 2@60</td>
<td>Ø 10@160</td>
<td>0.34</td>
<td>178</td>
<td>108</td>
<td>-</td>
<td>910</td>
</tr>
<tr>
<td></td>
<td>SCW3</td>
<td>850</td>
<td>150</td>
<td>3</td>
<td>Ø 2@80</td>
<td>Ø 10@160</td>
<td>0.34</td>
<td>174</td>
<td>120</td>
<td>-</td>
<td>950</td>
</tr>
<tr>
<td></td>
<td>SCW4</td>
<td>1350</td>
<td>150</td>
<td>3</td>
<td>Ø 2@40</td>
<td>Ø 10@160</td>
<td>0.34</td>
<td>156</td>
<td>65</td>
<td>972</td>
<td>800</td>
</tr>
<tr>
<td></td>
<td>SCW5</td>
<td>1850</td>
<td>150</td>
<td>3</td>
<td>Ø 2@40</td>
<td>Ø 10@160</td>
<td>0.34</td>
<td>133</td>
<td>60</td>
<td>-</td>
<td>770</td>
</tr>
<tr>
<td></td>
<td>SCW6</td>
<td>850</td>
<td>200</td>
<td>4</td>
<td>Ø 2@40</td>
<td>Ø 10@160</td>
<td>0.34</td>
<td>212</td>
<td>150</td>
<td>870</td>
<td>1000</td>
</tr>
<tr>
<td></td>
<td>SCW7</td>
<td>850</td>
<td>150</td>
<td>2</td>
<td>Ø 2@40</td>
<td>Ø 10@160</td>
<td>0.4</td>
<td>178</td>
<td>120</td>
<td>930</td>
<td>950</td>
</tr>
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<td></td>
<td>SCW8</td>
<td>850</td>
<td>150</td>
<td>5</td>
<td>Ø 2@40</td>
<td>Ø 10@160</td>
<td>0.26</td>
<td>166</td>
<td>138</td>
<td>980</td>
<td>980</td>
</tr>
<tr>
<td>One-sided Fire</td>
<td>SCW9</td>
<td>1000</td>
<td>150</td>
<td>3</td>
<td>Ø 2@40</td>
<td>Ø 10@160</td>
<td>0.34</td>
<td>191</td>
<td>187</td>
<td>960</td>
<td>1000</td>
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<tr>
<td></td>
<td>SCW11</td>
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<td>Ø 2@40</td>
<td>Ø 10@160</td>
<td>0.26</td>
<td>185</td>
<td>205</td>
<td>900</td>
<td>1030</td>
</tr>
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<td></td>
<td>SCW12</td>
<td>1000</td>
<td>150</td>
<td>3</td>
<td>Ø 2@40</td>
<td>No tie bars</td>
<td>0.34</td>
<td>166</td>
<td>196</td>
<td>950</td>
<td>1015</td>
</tr>
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</table>

4. Discussion

The failure times and temperatures obtained from Table 1 highlight the effect of various parameters on the behaviour of SC walls under fire condition. The failure times reported by FE analyses are conservative with respect to experimental failure times. Table 1 indicates that the experimentally observed surface temperature at failure is in better agreement with the numerical results (in comparison to failure times). Therefore, the surface temperature at failure is recommended to be used to determine the fire resistance of SC walls. The FE models are expected to be conservative in comparison to experimental results due to inherent limitations of the material stress-strain curves at extreme temperatures. It must also be noted that the failure times for one-sided fire specimens are much higher than the uniform fire specimen. Also, single-sided fire specimens are able to endure higher temperatures for longer times.

An important deduction from the results in Table 1 is that the slenderness of the wall has a major effect on the failure time. This is because slender walls are more vulnerable to buckling. Increasing the slenderness from 6 (for SCW1) to 9 (for SCW4) caused a 50 percent reduction in the fire resistance time. However, after a certain slenderness ratio, the change in fire resistance time is small. In addition, increase in the thickness of the steel plate makes the specimen more resistant to local buckling and leads to an increase in the failure time. The thickness of the wall also plays an important role in its fire resistance. It is observed that thicker specimens have a higher fire resistance. It can be seen that increasing the wall thickness by 30 % (see SCW1 and SCW6 in Table 1) leads to around 20 % increase in the fire resistance. The stud spacing does not seem to have a major effect on the fire resistance of the specimen. Increasing the spacing makes the steel plates susceptible to local buckling. Therefore, increasing the spacing between...
studs should lead to a reduction in the fire resistance. However, this is not observed in both the experiments and numerical results.

The numerical models developed in this study have been able to predict the experimental behaviour reasonably. The heat transfer results, particularly, were on the conservative side. The numerical results have shown that the outer temperatures for a uniform fire specimen can rise above 1000 °C. Such high temperatures can deteriorate the load carrying capacity of the member significantly. It was also observed that the majority of specimens failed due to complete collapse of the specimen, resulting from buckling of steel plate and excessive bulging of concrete block. Local buckling of steel plates between the shear studs was also observed. The single-sided fire specimen failed due to excessive bending toward the exposed side. Local buckling was also observed in the specimen, only on the exposed side. The results show that buckling is the cause of failure for most specimens.

5. Future work

The authors are currently conducting experimental studies to examine the stability response of SC walls with different configurations. SC walls specimens will be subjected to a combination of gravity and fire loading. Fire loading will be applied using radiant ceramic fiber heaters. The parameters considered in the experiments will be tie diameter and spacing, magnitude of axial load, uniform and one-sided heating, steel reinforcement ratio, and specimen height. The results from these experiments will be evaluated and additional specimens may be tested to consider the effect of a wider range of parameters. Benchmarked numerical models of the specimens tested by authors will also be developed to gain deeper insight into the behaviour of SC walls for fire loading. Additional numerical studies are being conducted to evaluate the effect of variation in parameters such as (a) Height (b) Length (c) Thickness (d) Tie Diameter (e) Tie Spacing and (f) Load Ratio. The results from experimental and numerical studies will be employed to develop design recommendations for fire loading. Additionally, numerical tools will be developed for performance-based design of SC walls.

6. Summary and conclusions

SC walls are being used in the third generation of nuclear plants and also being considered for containment applications in safety-related nuclear facilities. The stability response of these walls under fire loading needs to be investigated. This paper presents the development of detailed finite element models to numerically investigate the behaviour of SC walls under gravity and fire loading. The numerical models have been benchmarked with existing experimental data. The finite element models conservatively estimate the response of experiments. The fire resistance time of SC walls increases with increase in section thickness. However, the fire resistance time decreases with increase in specimen height. Due to potential variability associated with experimental data, the conservative failure time and surface temperature estimates from the finite element models are the preferred option to determine the fire resistance of SC walls. The surface temperature at failure of finite element models matches closely with the surface temperatures of specimens at failure (in comparison to time to failure). Therefore, it is recommended to use the surface temperature at failure as a metric to determine the fire resistance of SC walls. The time to failure can then be calculated using the section properties and heat transfer equations.

The paper also presents a discussion on the experiments that are being conducted by the authors. The benchmarked numerical models will be employed to conduct parametric studies for SC walls. The results from experimental and numerical studies will form the basis for detailing and design recommendations for SC walls subjected to fire loading. The results will also be used to benchmark and validate numerical tools for performance-based design of SC walls.
7. References


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