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THERMAL-MECHANICAL ANALYSIS OF A STEEL CONCRETE STRUCTURE SUBJECT TO SOLAR GAIN

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ABSTRACT

Steel concrete (SC) construction is a form of modular construction that is becoming increasingly popular as the nuclear industry moves towards embracing design for manufacture and assembly (DfMA). SC provides an attractive construction form for Small Modular Reactor (SMR) developers across the globe due to the benefits of utilising off-site manufacturing and potentially achieving reduced on-site construction schedules.

The aim of this paper is to present the study of a thermal-mechanical analysis of a generic, simplified SC curved section and complete a comparison with a reinforced concrete equivalent structure. The analysis has been undertaken using ANSYS. The analysis considers convective heat transfer between air and internal/external steel plates, solar radiation on the external steel plate during peak summertime clear sky conditions, convective losses from the wall, and minimum/maximum internal and external temperatures. The temperature variation over a 24-hour period has been considered in the analysis.

INTRODUCTION

Steel concrete (SC) construction is a form of modular construction that is becoming increasingly popular as the nuclear industry moves towards embracing design for manufacture and assembly (DfMA). SC provides an attractive construction form for Small Modular Reactor (SMR) developers across the globe due to the benefits of utilising off-site manufacturing and potentially achieving reduced on-site construction schedules. The use of SC in place of reinforced concrete (RC) structures may result in different design challenges. One such potential difference is the thermal response of the structure. Due to the exposed nature of the steel plates, there is the potential for internal and external temperatures to have a different effect on the structural behaviour when compared to traditional RC construction.

Solar gain is the increase in thermal energy of a structure as it absorbs incident solar radiation. The specific heat capacity of steel is significantly lower than RC, meaning that less energy is required to heat up steel and in turn cause increased heat-induced stresses.

Mott MacDonald have self-funded a non-project specific research programme to develop a greater understanding of SC construction. This research includes aircraft impact analysis, missile impact analysis and thermal-mechanical analysis. The aim of this paper is to present a thermal-mechanical analysis of a SC curved section and compare the results to those of a similar analysis of an equivalent RC wall.

STEEL CONCRETE CONSTRUCTION

SC construction is a form of modular construction comprising two steel faceplates internally connected by tie bars or diaphragm plates, serving as shear reinforcement, to create a sandwich panel filled with concrete, see Figure 1. Faceplates provide permanent shuttering during concrete infill pouring and flexural strength once the concrete has cured. Composite action between the faceplates and concrete is facilitated by shear studs welded to the internal side of the steel plates, whilst composite action between the two faceplates is facilitated by the tie bars/diaphragm plates welded to the internal face of each plate.

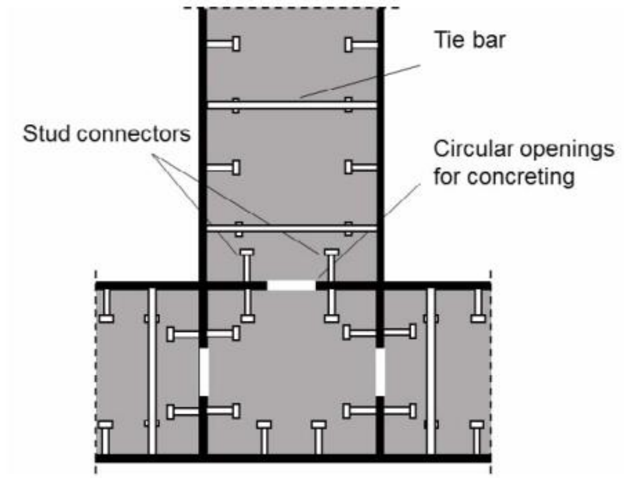

Figure 1: Steel concrete construction sectional view

Due to the modular construction of SC, there are multiple potential benefits over traditional reinforced concrete and other modular/pre-cast panel type structures. These include reduction in on-site programme, improved quality control and structural performance. It should be noted there are potential disadvantages to SC construction such as increased material costs and in-service inspection and maintenance challenges.

Generally nuclear related SC structures are designed in accordance with Appendix N9 of AISC N690 (ANSI/AISC, 2018). This standard provides guidance on the assessment of SC for thermal effects but does not specifically provide design guidance on solar gain effects.

ANALYSIS

The thermal-mechanical analysis was undertaken using ANSYS, a finite element analysis software used to perform structural analysis using advanced solver options including linear dynamics, thermal analysis, materials, composites etc. A curved wall section, representing a typical nuclear related structure, was used to undertake a comparison of the thermal mechanical effects of a daily temperature variation on a SC structure and an equivalent RC structure. For simplicity, this study has assumed linear elasticity.

Geometry

To ensure consistency, the SC and RC models were developed with the same geometry. A cylindrical form was used to represent a typical nuclear power plant containment structure. The geometry was modelled in LS-PrePost and transferred to ANSYS for the analysis runs. The key dimensions of the model are outlined in Table 1, while Figure 2 show images of the FE models. The brown elements of the SC model represent the steel plates, while green elements are the concrete elements.

Table 1: Curved wall section dimensions

Variable	**Dimension**
Internal concrete arc length	3973mm
Radius	1700mm
Height	5000mm
Curvature	33.7°

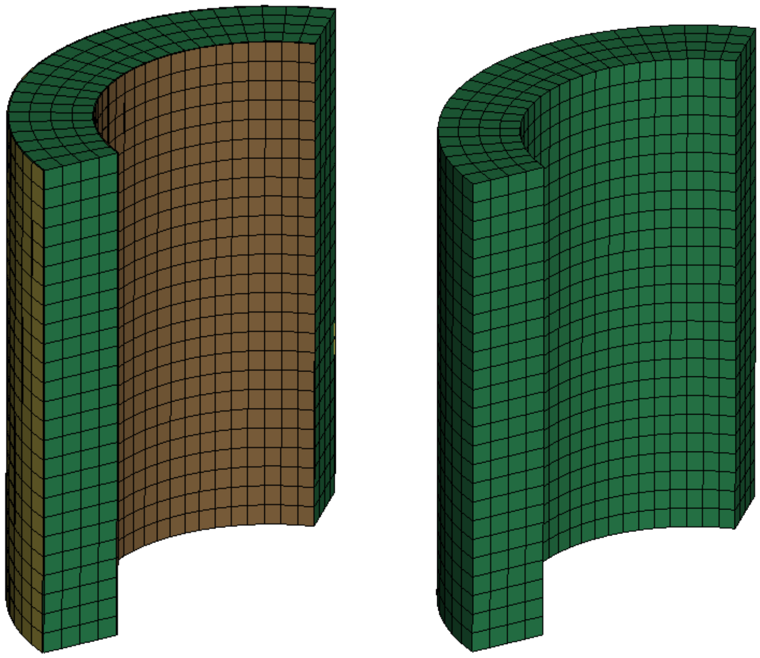

Figure 2: SC (left) and RC (right) Wall FE Models

The RC and SC walls have the same overall thickness of 850mm. The SC comprises 800mm concrete between 25mm thick steel faceplates. All concrete elements are modelled as solid elements, whereas steel plates are modelled as shell elements. A mesh size ranging from 200 to 250mm was used to provide an accurate representation of the stresses. This results in 4 elements across the thickness and 25 along the height. The model for the SC contains approximately 1,250 shell elements and 2,500 solid elements. The layer of concrete solid closest to the steel plates share common nodes with the steel plate shells. The steel plates shells are modelled with a 12.5mm offset from the concrete face to provide an accurate representation of stiffness. Through the shared nodes, a bonded contact was created between the steel plates and respective concrete faces. No shear studs are modelled in the SC model. It is understood that the continuous bond between steel and concrete elements through each node point at the interface is a significant simplification which could result in under estimation of the local stresses at the locations of steel tie bars or diaphragm plates. However, the purpose of this preliminary research study is to provide broad conclusions on the generic performance of SC vs RC. Further analysis specific to the design of a SC structural component would be necessary to assess the impacts of these local stresses.

No reinforcement bars were included in RC model. This is judged to be acceptable as the steel bars, studs and studs occupy a small percentage of the overall volume compared to the concrete volume and therefore are ignored in this preliminary study.

System boundary conditions were applied in the x and z direction along the top edge of the arc, shown at the yellow marker in Figure 3, while both exposed side faces of the arc, shown in green in Figure 3, are restricted in the y direction.

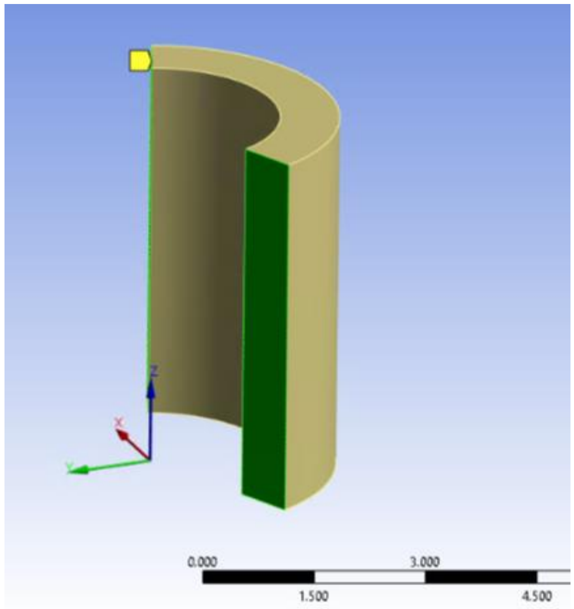

Figure 3: Boundary Conditions

Materials

The thermal and structural material properties used are shown below in Table 2. All materials are assumed to behave as linear elastic and isotropic. For the steel elements of the model, the linear elastic assumption is supported by the analysis results as the stresses in plate are less than the yield strength.

Table 2: Material properties

Property	**Concrete**	**Steel**
Elastic Modulus	35 GPa	200 GPa
Coefficient of thermal expansion	$1x10^{-5}$	$1.2x10^{-5}$
Characteristic compressive strength	40 MPa	N/A
Tensile ultimate strength	N/A	$460N/mm^2$
Poisson’s ratio	0.2	0.3
Thermal conductivity	3.6 W/m°C	60.5 W/m°C
Specific Heat	936.3 J/kg°C	434 J/kg°C

Solar Radiation Input

The solar radiation was calculated for a period of a full year using the Bird Clear Sky Radiation Model developed by the US Department of Energy (Bird & Hulstrom, 1981). This calculates the solar radiation throughout a year based on some assumptions related to the location. For this study, the location of

Coningsby, Lincolnshire was chosen because it presented the highest temperature recorded in UK in the recent years (Met Office, 2022). The solar radiation time-history of the day with the peak values for the entire year was considered. The resultant solar radiation history is presented in Figure 4. Conservatively, it is assumed that the solar radiation is uniform across the surface.

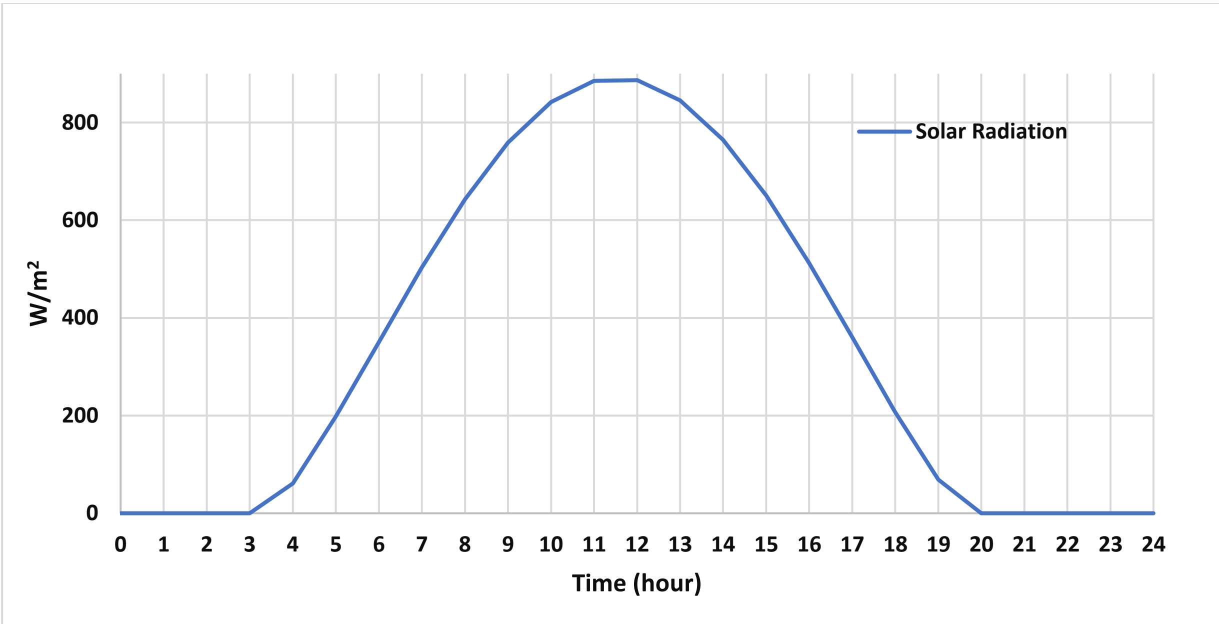

Figure 4: Solar radiation time history

Analysis

The analysis considers convective heat transfer between air and the internal/external faces of the SC and RC structures with solar radiation during peak summertime clear sky conditions applied to the external face of the structures. The temperature variation over 24 hours has been considered in the analysis as outlined above.

A transient heat transfer analysis was carried out assuming that the internal temperature (internal face of RC and SC structures) remains controlled at 21.1°C. The heat transfer analysis takes into account convection losses which are due to the surrounding fluid (air) flow passing along the external and internal face of the structures. A convection coefficient of $5W/m^2.°C$ was applied to both the internal and external faces. This value is at the lower end of the range for natural convection and is therefore a conservative estimate for the external face as wind would result in higher heat losses. The temperatures predicted by the transient analysis are used as input for a mechanical analysis, in order to predict the heat-induced stresses in the wall.

Results

The transient thermal analysis predicted a maximum external temperature of 60.7°C on the external steel plate for the SC wall. The maximum temperature of the external face of the RC structure was 65.0°C. Although the steel plates have a significantly higher thermal conductivity and are therefore more likely to heat at a more rapid rate, this also results in a higher rate of losses and transfer to the external air and to the concrete within the SC wall. Figure 5 shows the gradient of temperatures through the SC wall, while Figure 6 shows the temperature change throughout the external (maximum) and internal (minimum) faces of both the SC and RC walls.

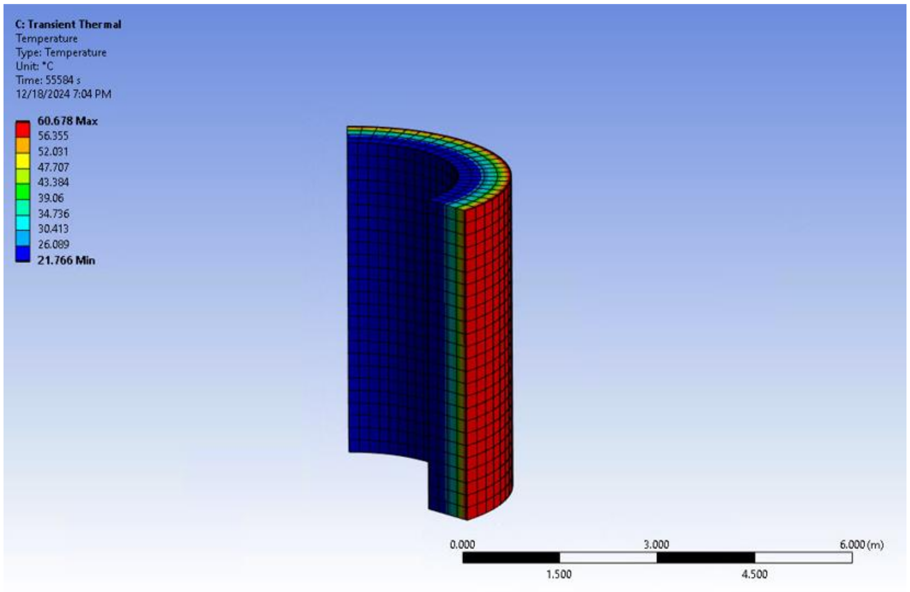

Figure 5: Temperature Gradient Through SC Wall

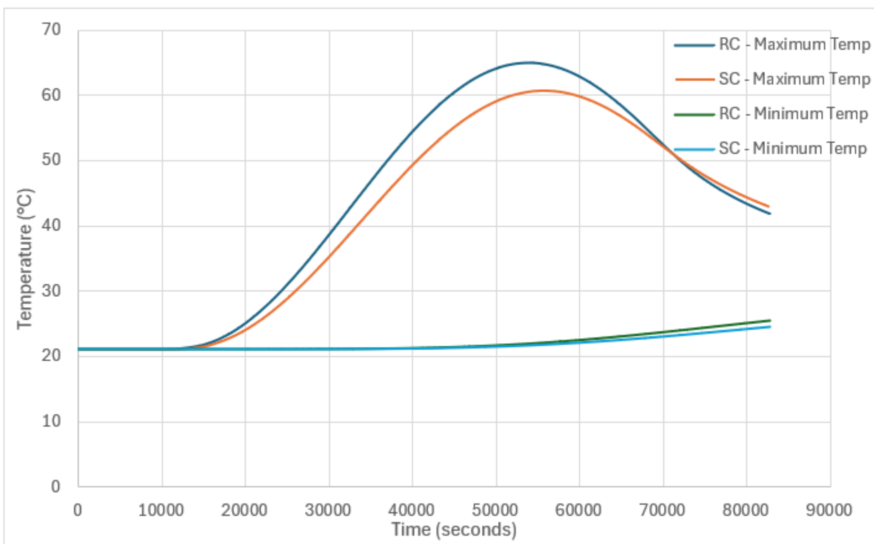

Figure 6: Temperature Gradient on External (maximum) and Internal (minimum) Faces

The peak temperature distribution was used as input for linear elastic mechanical analysis. The maximum and minimum principal stress distributions resulting from this mechanical analysis are shown in the below figures. As expected, the stresses in each face of the SC structure are significantly greater than those in the RC equivalent. The figures demonstrate that the solar radiation induces compression in the external (exposed) side of the wall and tension in the temperature controlled, internal face of the wall.

Figure 7 and Figure 8 show that the maximum compressive (minimum principal) stresses are relatively low. The compressive stresses in the external plate of the SC increase at a significantly greater rate than that of the RC wall, as shown in Figure 11. The solar radiation generates a maximum circumferential compressive stress of 105MPa in the external steel plate at 15 hours, compared to 24MPa for the RC wall.

The tensile (maximum principal) stresses in the internal plate of the SC increase at a more rapid rate than the internal face of the RC wall and peaks at 16 hours with a maximum stress of 67MPa, compared to 11.4MPa in the RC, as shown in Figure 9, Figure 10 and Figure 12. The internal face compressive forces remain almost constant throughout the SC wall, whereas the external face of the RC wall experiences a significant change in compressive stresses throughout the duration. This shows that the steel plates are restraining the concrete, whereas without the plates, the concrete can expand more resulting in compressive and tensile stresses. It should be noted that the average stress remains relatively constant throughout, see blue line.

The tensile stress in both the SC and RC walls exceed the tensile strength of concrete, therefore cracking is anticipated. To determine the extent of cracking in the concrete core and how this affects the performance of both structures, a nonlinear mechanical analysis would be required with the same temperature distribution calculated by the transient thermal analysis. This has not been completed herein and is identified for future works.

A comparison of the stresses for the RC and SC walls are provided in Figure 11 and Figure 12. A summary of the von mises stress in each face is provided in Table 3.

Table 3: Von Mises stress in both face of the structural elements

	SC	**RC**
External face (compression)	105MPa	24MPa
Internal face (tension)	67MPa	11.4MPa

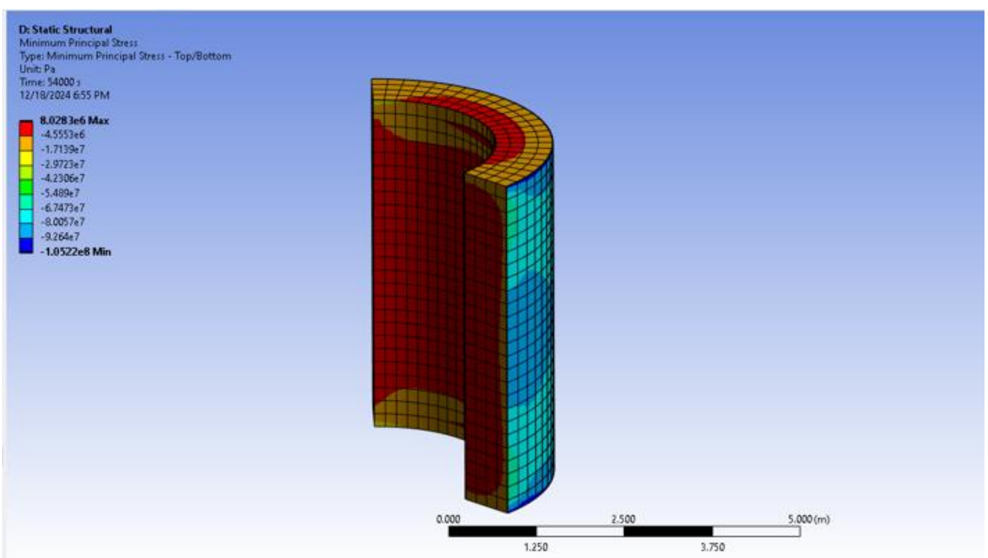

Figure 7: Minimum Principal (compressive) Stress at 15 hours (SC)

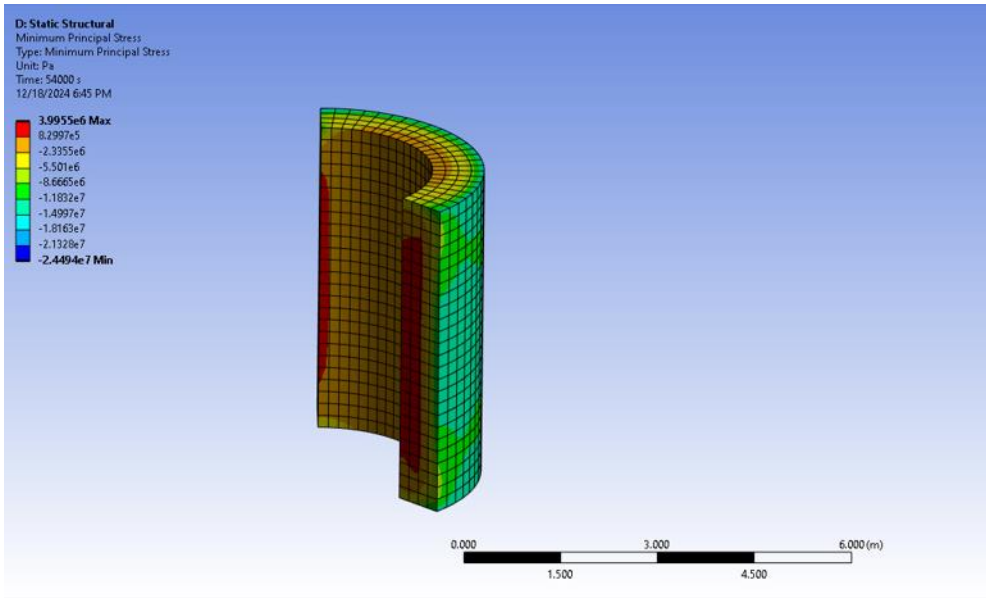

Figure 8: Minimum Principal (compressive) Stress at 15 hours (RC)

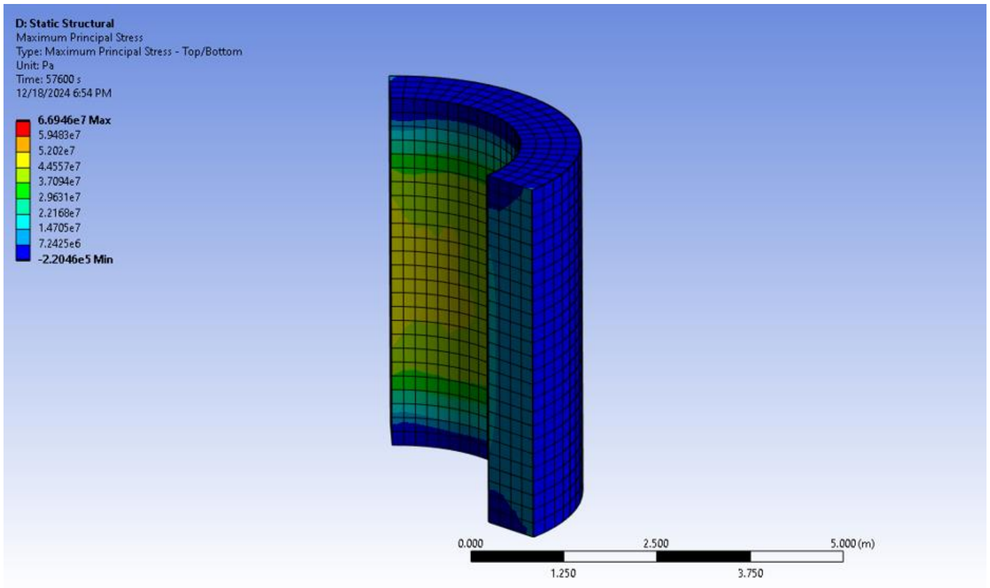

Figure 9: Maximum Principal (tensile) Stress at 16 hours (SC)

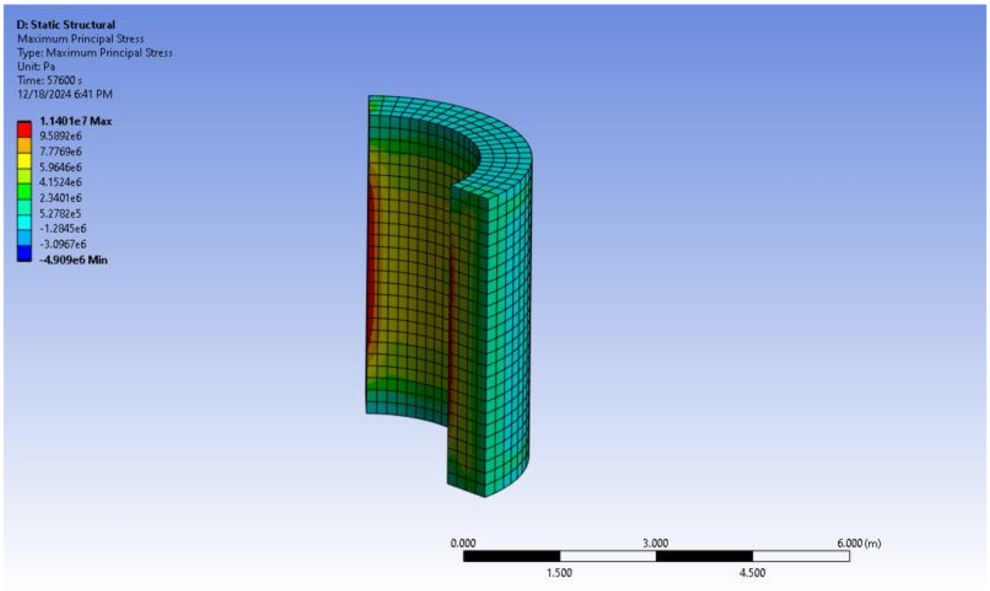

Figure 10: Maximum Principal (tensile) Stress at 16 hours (RC)

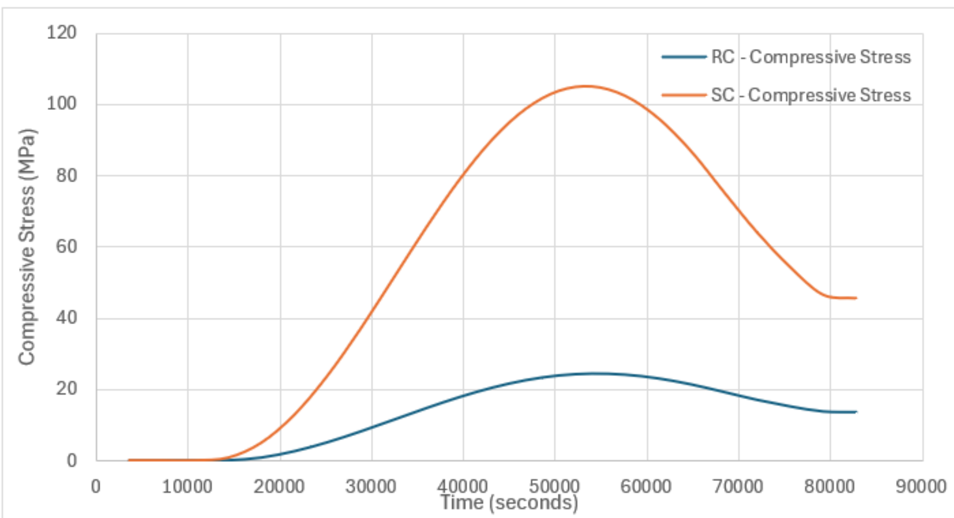

Figure 11: Comparison of peak compressive stresses in external face of the RC and SC walls

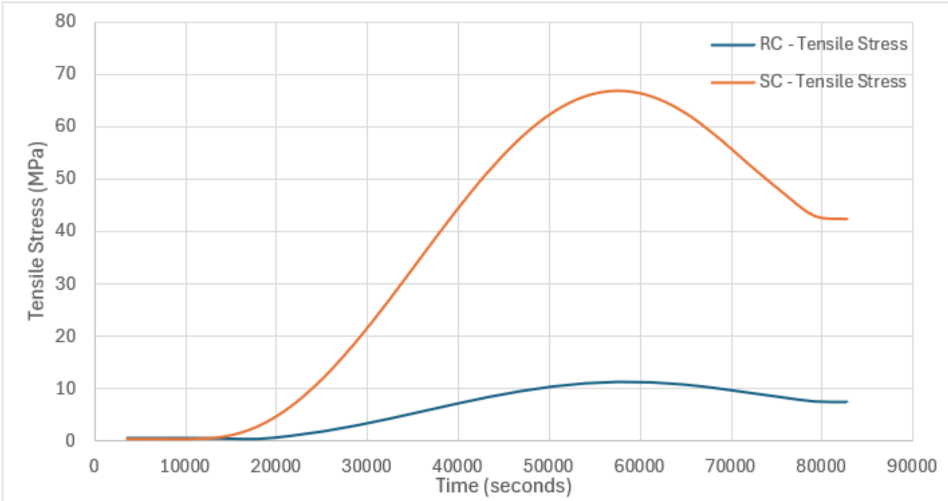

Figure 12: Comparison of peak tensile stresses in inner face of the RC and SC walls

CONCLUSION

This paper has presented a thermal-mechanical analysis of two structures: a steel concrete and a reinforced concrete curved section. A transient heat transfer analysis was carried out assuming that the internal temperature (internal face of RC and SC structures) remains controlled, and a solar radiation time-history was applied to the external face of both structures. The solar radiation time history for the hottest day ever recorded in the UK was used as the input time history.

The peak temperature distribution from the heat transfer analysis was used as input for linear elastic mechanical analysis of the structures. The maximum and minimum principal stress distributions have been presented herein. The results demonstrate that the solar radiation induces compression in the external (exposed) side of the wall and tension in the temperature controlled, internal face of the wall. As expected, the stresses in each face of the SC structure are significantly greater than those in the RC equivalent. The compressive stresses remain within acceptable limits, although the SC stresses are approximately 400% greater than those in the RC. Similarly, the tensile stress in SC is approximately 600% greater than the RC structure. In addition, the tensile stress in both the SC and RC walls exceed the tensile strength of concrete, therefore cracking is anticipated. A nonlinear mechanical analysis would be required to analyse the extent of cracking. This has not been completed herein and is identified for future works.

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