TIME-DEPENDENT BEHAVIOUR OF WELDS IN STEEL CONNECTION AS SUBJECTED TO FIRE TEMPERATURES

This article summarises an integral part (Chapter III) of the authors' PhD study that emphasises the importance of time or loading rate effects on the behaviour of welds and welded connection when exposed to fire.

THE CHANGE TOWARDS PERFORMANCE-BASED DESIGN APPROACH

The current building fire safety regulations and codes mainly follow the *prescriptive* approach whereby engineers or architects rely on codes to determine the fire-resistance rating to meet the required fire protection on the structural components of the building. This fire design approach is performed either through standard fire tests on the individual building components or empirical approaches [1]. This approach cannot predict accurately the structural performance of the entire structure when subjected to fire. Following the *World Trade Center collapse in 2001*, the prescriptive approach has been further studied by many professionals, calling for a change to performance-based fire-resistance design and for the fire and structural engineers to take over the responsibility of the fire-resistance design of the structure by conducting fire analysis [1,2]. However, many reports [3, 4, 5, 6] have indicated that performance-based fire design codes for steel structures require several key elements that are not fully developed or understood. These key elements mainly include a better understanding of the performance of base materials, welds, and bolts in the event of a fire, and a development of advanced engineering tools as an alternative to fire protection design. The performance of steel, bolts, and welds in a fire is not only dependent on the exposed temperatures and loads, but also on the time-dependent fire scenarios, fire time durations, and heating-cooling regimes. As a result, a fundamental understanding of the thermal and time-dependent behaviour of structural steel, welds, and bolts at elevated temperatures is an integral part of the performance-based fire design for steel structures.

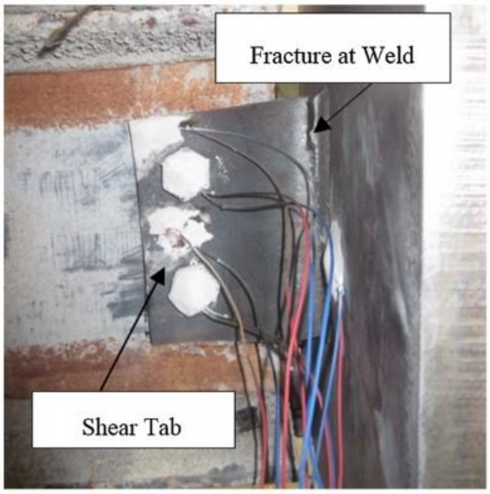
Hence, the performance-based fire design is an alternative approach that permits engineers to design accurately for the structural and thermal responses of steel structures when exposed to a wide range of fire temperatures.

WELDED CONNECTIONS IN FIRE

Welds are commonly used in steel structures and play a crucial role in transferring the loads between connected components. The large deformation and force demands due to the applied gravity loads and the thermal expansion and contraction of structural members, combined with material strength degradation, can potentially result in the failure of welded connections during the heating or cooling stages of a fire (Figure 1) [7,8,9]. Failure of welded connections during a fire event depends not only on the applied load and temperature but also on the rate and time duration at which loads are applied. Although the applied gravity loads may remain relatively constant during a fire, the load developed by thermally induced deformations can vary significantly with time. Therefore, accurate knowledge of the time-dependent mechanical properties of weld materials is an important part of predicting the real response of welded steel connections in a fire.

(a)

(b)



(c)

Figure 1. *Weld failures from previous studies: (a) Daryan and Yahyai [7], (b) Hosseini et al [8], (c) Selden et al. [9]*

THE THEORETICAL PHENOMENON OF TIME-DEPENDENT CREEP BEHAVIOUR OF STEEL

Steel materials and structures, when exposed to fire temperatures, experience increasing permanent deformation with time, even when the applied load level is below the yield stress. The time-dependent inelastic deformation under constant stress and temperature is referred to as isothermal creep phenomenon. Creep of steel occurs when the steel material is subjected to a constant load at a temperature slightly above one-third of the material melting temperature. Creep of steel is a thermally activated process that is highly dependent on the type of base materials, bolts, and welds used.

Modelling the thermal creep of steel in structural-fire engineering analysis can be classified into two approaches: implicit and explicit thermal creep. An implicit creep model is considered when the steel material is subjected to either variable stress or temperature conditions or both parameters together. In this case, the creep strains are included indirectly into the stress-strain curves of the material and cannot be explicitly computed [10].

An explicit creep model is when the steel material is subjected to constant load and temperature conditions, and the only variable is time. In this case, the creep strains are added directly into the strain profile of the cross-section of the steel material [10]. The explicit creep strain for a steel material can be computed explicitly through a one-dimensional tensile test to produce a displacement-time plot, known as a creep curve, as presented in Figure 2. This creep curve shows three distinct stages known as primary, secondary and tertiary creep stages. More details regarding the implicit and explicit creep behaviour of steel can be found in [11, 12, 13].

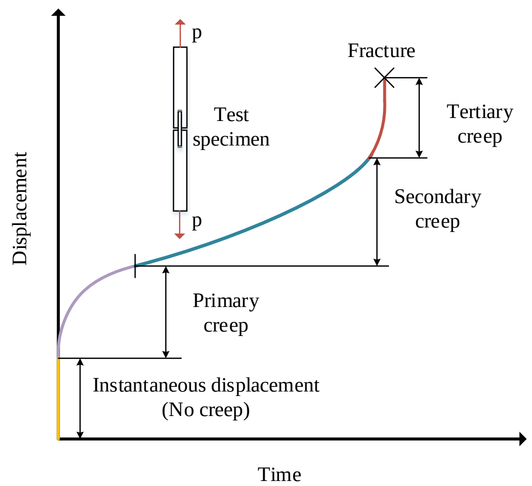


Figure 2. *Classical creep curve*

EXPERIMENTAL INVESTIGATION INTO THE TIME-DEPENDENT BEHAVIOUR OF WELDS IN WELDED CONNECTION WHEN SUBJECTED TO FIRE TEMPERATURES

Limited studies have been conducted to examine the time-dependent or creep behaviour of welds and welded connections when subjected to elevated temperatures. To address this issue, two experimental programs were conducted to examine the implicit and explicit time-dependent thermal creep behaviour of weld material in transverse welded lap joints (Figure 3).

Test specimen

Details of the transverse welded lap joint specimens are shown in Figure 3. The specimens consisted of two large plates (222.3 mm × 50.8 mm × 12.7 mm) connected through two smaller plates (76.2mm × 12.7 mm × 12.7 mm) with equal-leg fillet welds with leg sizes of 4.8 mm. The fillet welds were designed such that failure will occur in the fillet welds at both ambient and elevated temperatures. All plate material was made of ASTM[1] A529 Gr.50 (S275).

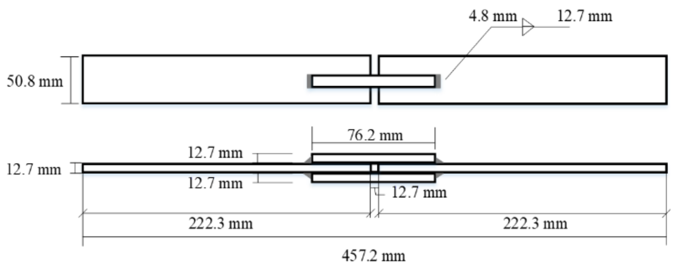


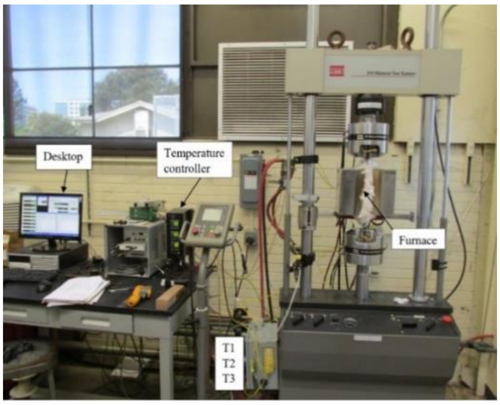
Figure 3. *Transverse welded lap joints configuration*

Test procedure

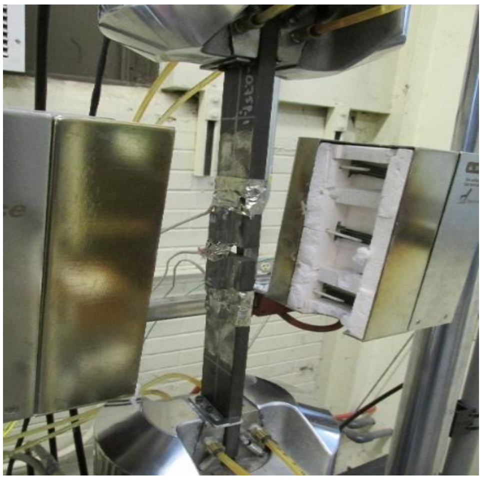
A 98-kN capacity MTS-810 test frame with water-cooled grips was used to perform

[1] American Society for Testing and materials

the direct tension tests for the transverse welded lap joints at ambient and elevated temperatures as shown in Figure 4 (a). An MTS Model-653 furnace with a temperature control system was used as the heating device for the elevated temperature tests. To control the uniform temperature distribution, three thermocouples (Type K) were used to measure the surface temperature of the specimen at different locations throughout the length of the specimen as shown in Figure 4b. The specimens were wrapped by stainless steel foils (SSF) to protect the thermocouples from direct exposure to thermal radiation from the heating coils of the furnace. Note that before loading was applied, the temperature was held constant for 30 minutes.



(a)



(b)

Figure 4. *Setup and instrumentation: (a) Experimental test equipment, (b) Thermo-couple implementation*

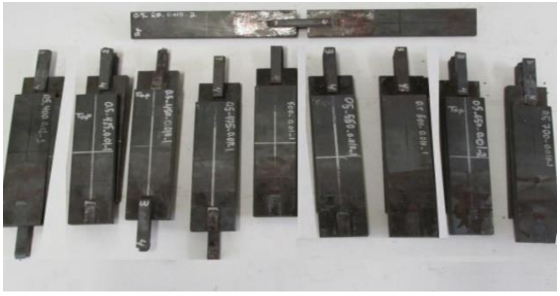
THE IMPLICIT CREEP BEHAVIOUR OF TRANSVERSE WELDED LAP JOINT

Loading protocol

To investigate the implicit creep behaviour of transverse welded lap joint specimens, steady-state thermal testing was used; the transverse welded lap joint specimens were first heated up to a target temperature with no load, and then the temperature was held constant as load was applied to the specimen, and increased until fracture occurred. Two cross-head displacement loading rates of 0.254 mm/min (fast) and 0.0254 mm/min (slow) were used.

Experimental results

All specimens failed due to fracture of the weld under fast and slow loading rates as shown in Figure 5. It can be seen that the effect of loading rates on the weld fracture mode is not significant. More specifically, Figure 6 shows samples of the failure modes for the welded specimens at ambient and different elevated temperatures. As the test specimens were exposed to different elevated temperatures, the steel surfaces exhibited changes in colour and texture. For tests conducted at elevated temperatures up to 500°C, the fracture surfaces are smooth, whereas for temperatures beyond 500°C, the fracture surfaces become rough and large deformations and necking are observed in the weld region. These observations suggest that for temperatures greater than 500°C, the weld exhibits increasing ductility before complete failure.



(a)

(b)

Figure 5. *Failure at the throat of the weld for all test specimens: (a) Fast tests, (b) Slow tests*

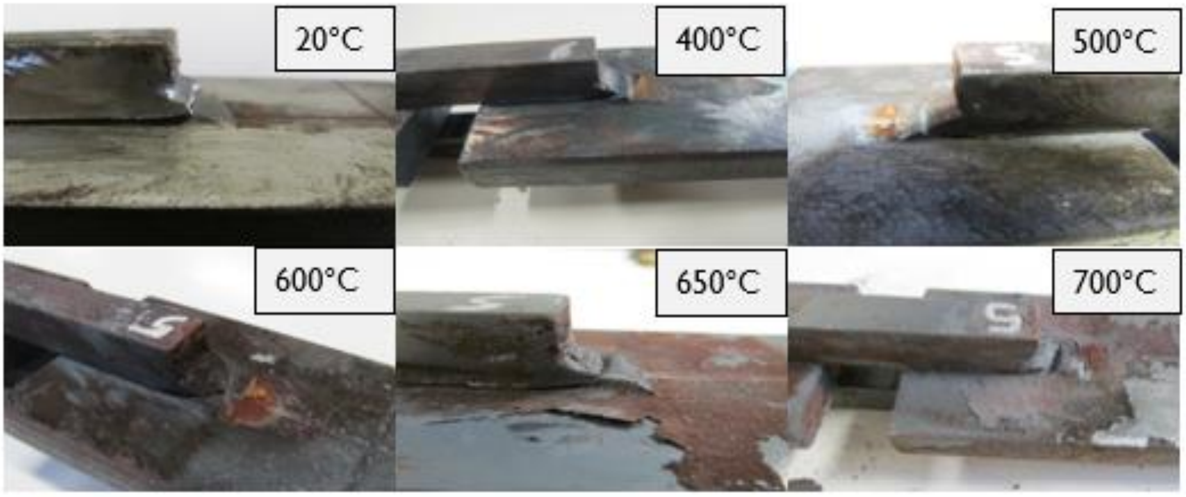


Figure 6. *Failure modes for welded specimens subjected to ambient and different elevated temperatures*

All illustrative plots of axial load-displacement at temperatures from 450°C to 700°C under both fast and slow loading rate scenarios are shown in Figure 7. Figure 7 (a) shows little difference in stiffness, strength, and ductility between the tests performed at 450°C under both fast and slow loading rates. This indicates that, as expected, for temperatures below or equal to one-third of the steel melting temperature, creep is not significant.

However, the effect of loading rates becomes noticeable on the behaviour of transverse welded lap joints as the temperature reaches 475°C and becomes more significant as it reaches 700°C. More specifically, the slow loading rate results in an 11% to 29% decrease in strength capacity compared with the fast loading rate, as temperature increases from 475°C to 700°C. More details and data for tests conducted at 20°C, 425°C, 550°C, 600°C, and 650°C under both fast and slow loading rates can be found in [11,12].

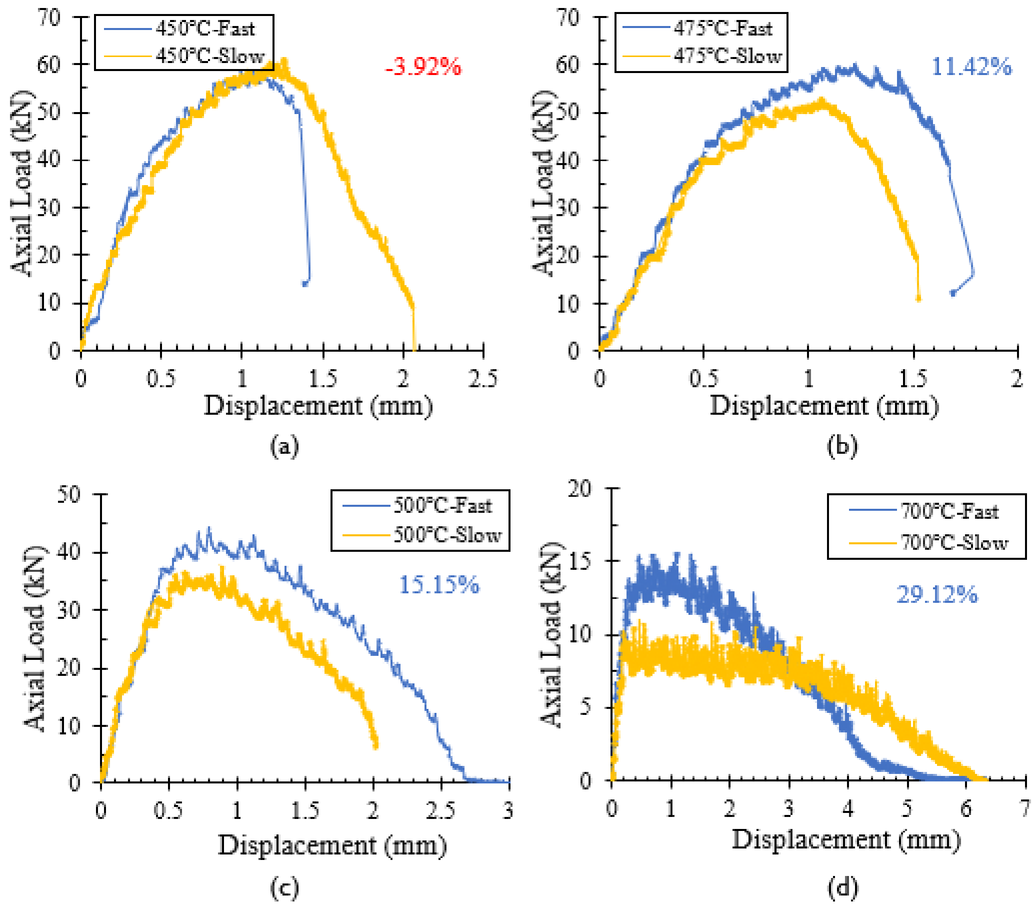


Figure 7. *Effect of loading rate on the behaviour of transverse welded lap joints at: (a) 450°C, (b) 475°C, (c) 500°C, (d) 700°C*

The effect of loading rates on weld behaviour and design against fire can be seen in Figure 8. This shows the axial load-displacement characteristics of test specimens at different elevated temperatures (500°C and 600°C) under different loading rates (0.254 mm/min and 0.0254 mm/min). When the welded specimen is heated up to 600°C and subjected to a fast loading rate (0.254 mm/min), it gives approximately the same capacity as when it is subjected to 500°C with a slow loading rate (0.0254 mm/min). This indicates that failure of welded connections due to fire temperatures depends not only on the applied load and temperature but also on the rate at which the load is applied.

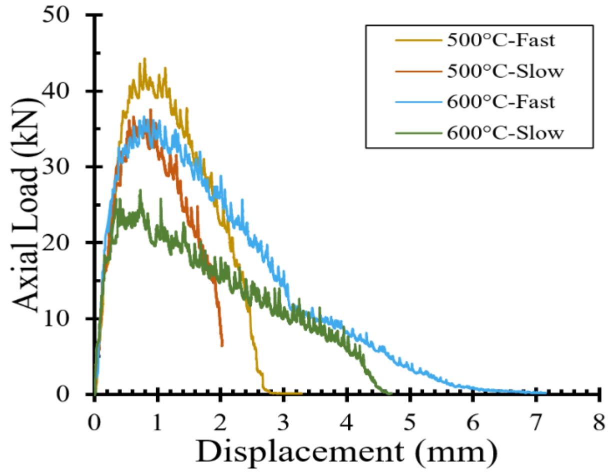


Figure 8. *Results from tests performed at 500°C and 600°C under fast and slow loading rates*

THE EXPLICIT CREEP BEHAVIOUR OF TRANSVERSE WELDED LAP JOINT

Loading protocol

This approach requires conducting two series of experimental test analyses: fast temperature tests and creep tests. The fast temperature tests are part of the implicit creep test program that was conducted under the fast loading rate to estimate the peak load ***P*** at each temperature. In this series, the peak loads are assumed to be the maximum time-independent loads that the specimen can resist excluding the effect of time on the strength and stiffness of the tested specimens. In the creep tests, and after the specimen was heated up to a specified temperature, a force-controlled load equal to a fraction of the peak load ***P*** predicted in the first series of analysis was applied in a very fast manner (within 1 second) and kept constant throughout the test. In this case, the only variable is time as temperature and loading conditions are kept constant. Note that, the creep tests were conducted for a time duration of 120 minutes or until the test specimen failed. More details about the fast-loading tests, peak loads, and ways of selecting the creep test matrix can be found in [11,13].

Experimental results

The time-dependent deformation and failure for the transverse welded lap joints when subjected to various constant load and temperature conditions are presented in Figure 9. No failures occurred in the specimens for temperatures equal to or below 450°C although 90% of the peak loads were applied. However, for the 475°C creep test with 90% peak load, the specimen failed in the weld region. For the test conducted at 500°C, a fracture occurred at the throat of the weld when subjected to 80% peak. However, for those conducted at higher temperatures, 600°C and 700°C, fracture occurred at greater or equal to 60% peak.

Figure 10 presents the fracture mode that occurred at the throat of the welds for tests conducted at 475°C, 500°C and 700°C with 90% peak load application.

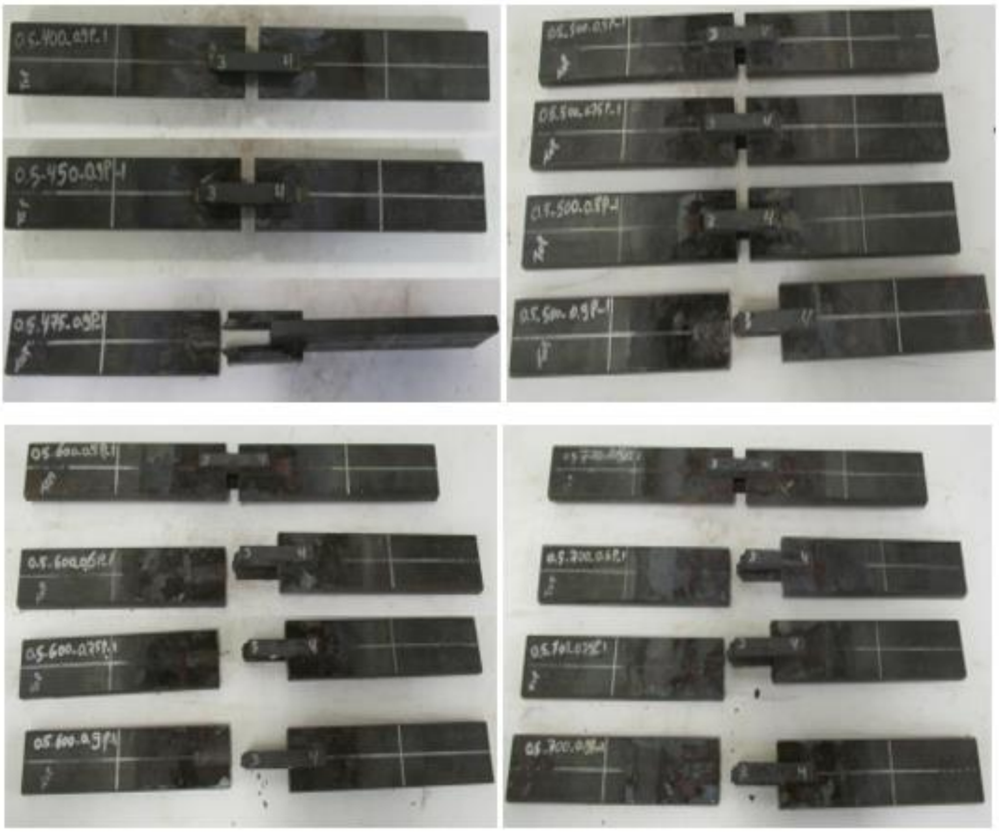
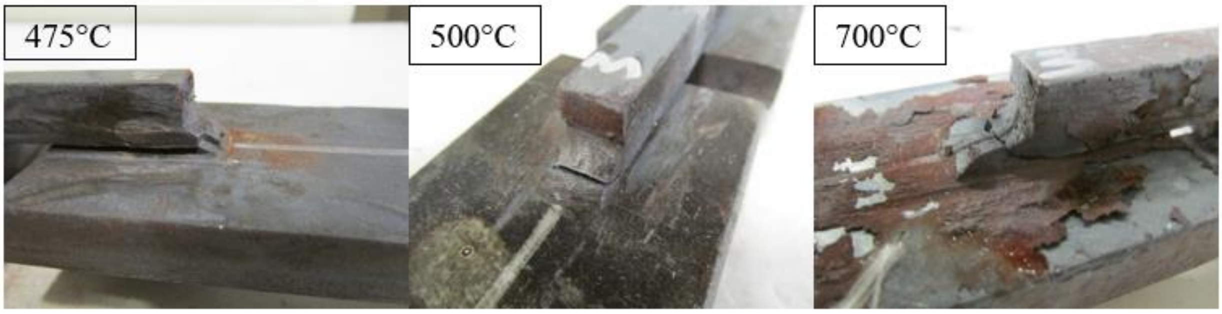


Figure 9. *Failure mode for transverse welded lap joints for different temperature and load levels*

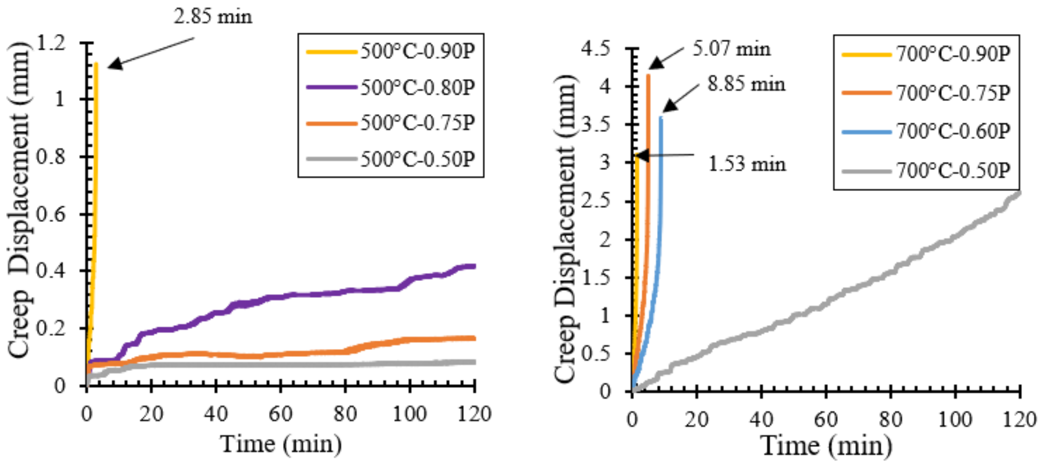
It can be seen from Figure 10 that the sign of necking starts to be noticeable at 500°C and become more significant at 700°C. This is because the damage starts with the formation of cavities or voids in the microstructure of the weld material resulting in the reduction of the material cross-section and consequently fracture.



(a) (b) (c)

Figure 10. *Creep fracture at the throat of the weld for transverse welded lap joints subjected to 0.90P at: (a) 475°C, (b) 500°C, (c) 700°C*

Figure 11 shows selected thermal creep curves for transverse welded lap joints subjected to different peak load ratios at different temperatures. Figure 11(a) shows that the welded specimen can sustain loads up to 80% of the peak load predicted in the fast temperature test at 500°C for a 120 min time duration. However, for 90% of the peak load, the welded specimen rapidly failed after *2 min and 51 sec*. This indicates that for temperatures at which creep is significant (500°C), load or stress level dominates the thermal creep behaviour of transverse welded connections in fire. For creep tests conducted at 700°C, the results show that the welded specimen cannot resist loads greater than 50% peak for a 120 min time duration as shown in Figure 11(b). However, the specimen cannot resist 60% peak for a duration of more than *8 min and 51 sec*. Further, as the load increases up to 90% of peak, the welded lap joints rapidly failed at *1 min and 32 sec*. Figure 11(b) also shows that there is a large gap between the tests conducted at 700°C with peak loads of 50% and 60%. This indicates that at higher elevated temperatures, the temperature significantly dominates the thermal creep behaviour of the welded connection more than the peak load ratio.



(a) (b)

Figure 11. *Effect of peak load ratio on thermal creep response of transverse welded lap joints at: (a) 500°C, (b) 700°C*

A selection of representative results of creep curves are illustrated in Figures 12(a) and 12(b). These present the thermal creep behaviour of transverse welded lap joints subjected to 90% peak for all temperatures above and below 475°C, respectively. Recall that, although the curves in Figure 12 correspond to 90% peak at each temperature, the actual applied load is different from one temperature to another. It can be seen that for tests conducted at 475°C and above (Figure 12(a)), the transverse welded lap joint failed in welds at early stages where a maximum time recorded to resist the 90% peak was *5 min and 6 sec* at 475°C. However, for those conducted below 475°C, the welded specimen resisted 90% peak for 120 mins. Note that both the creep tests conducted at 450°C and 475°C were subjected to approximately the same constant load (~59 kN). This indicates that the thermal creep of weld material becomes significant for temperatures slightly greater than 450°C and becomes more prominent for higher temperatures.

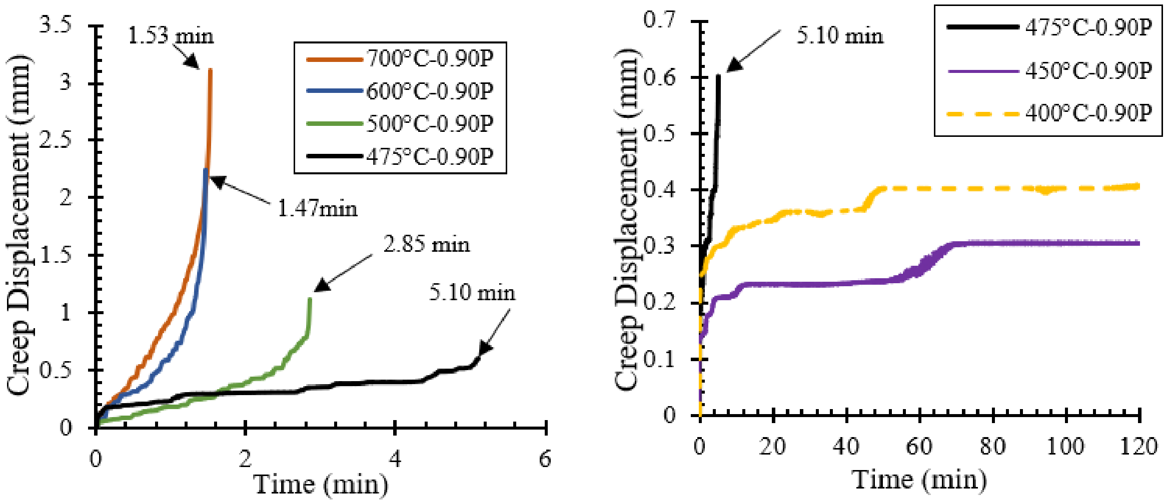


***Figure 12.** Effect of temperature on thermal creep response of transverse welded lap joints*

GENERAL CONCLUSION

The experimental results showed that the creep of weld material under implicit and explicit modelling approaches has a large impact on the welded connections for temperatures greater than 450°C and becomes more prominent for larger elevated temperatures. Also, the behaviour of welds and welded connections in fire events is not only dependent on the applied loads and temperature, but also it is highly dependent on the time durations and rates at which these loads are applied. More data regarding the time-dependent retention factors for welds, the effect of load angles on weld creep behaviour, and the weld creep modelling can be found in [11].

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