

Steel Beam-To-Column Connection Fire Design



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Abstract With architectural styles changing and the knowledge of fire behaviour constantly evolving, it is important to continue advancing the field of fire safety engineering to ensure that the existing and expanding infrastructure is safe and resilient. Within the National Building Code of Canada and subsequent provincial and material design standards, there exists flexibility for designers to consider more advanced computational practices that can optimize the fire protection design. These clauses permit alternative design solutions to be used when they can be proven to be equivalent or superior to the prescriptive design. This, however, can be hard to implement regarding structural fire designs as the Authorities Having Jurisdiction (AHJs) typically do not have the fire education and resources to evaluate and compare a design. Alternative solutions, especially for structural fire design, allow for economic and material savings. A performance-based solution is able to check for all possible scenarios and optimize the fire protection, reducing the environmental impact of the design by reducing the need for excess fire protection, which can be toxic and have negative life cycle analysis impacts. The connections are known as the most vulnerable part of a steel-framed building construction. A preliminary series of fire tests were undertaken at York University's Fire Resiliency Lab, with different methanol pool fire durations, to understand the deformation behaviour of a simple steel post-and-beam frame and how the forces and heat are dissipated into the connections. With an accurate understanding of the thermal forces created by a localized fire, the design of connections would be able to dissipate the large forces that occur through ductile connections. The tests demonstrated how connections and the remaining structure behave intrinsically when exposed to thermal forces, such as displacements and rotations.

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1 Introduction

The current design methods for structures in fire in Canada are purely prescriptive, which results in designs often being either underdesigned or overdesigned. The current predominant method of fire design in Canada uses the CAN/ULC-S101-14 standard fire [30] in its prescriptive approach. This temperature–time curve assumes uniform burning and homogeneous temperature conditions throughout the compartment regardless of the compartment size, as well as other assumptions that are no longer valid as the standard was first codified in 1917 and is unrepresentative of contemporary fire dynamic theory [10]. Using such a curve can result in the building response not being entirely representative of reality, resulting in potentially unconservative or even overly conservative and wasteful designs. Within the National Building Code of Canada [4] and subsequent provincial and material design standards, there exists flexibility for a designer to consider more advanced computational practices that can optimize the fire protection design. These clauses permit alternative design solutions to be used when they can be proven to be equivalent or superior to the prescriptive design. Alternative solutions in structural fire design can provide greater architectural freedom due to alternative protection and design solutions which can result in economic and material savings. Using performance-based design can also help reduce the environmental impact of the design by optimizing the fire protection and reducing the need for excess fire protection, which can be toxic and have high cradle-to-grave impact. They also have the ability to demonstrate to a practitioner the life safety, economy and robustness benefits available with various fire solutions, as multiple different fire scenarios would be considered. This ensures that the designed structures are resilient. However, structural fire designs can be computationally intensive, and training regarding fire design in Canada is limited.

Steel structures are very common, and the behaviour of their beams and columns during fire events has been extensively studied. The behaviour of steel beam-to-column connections within these structures under thermal loading, however, is not well understood. When exposed to a fire, the members within steel structures expand during heating and contract in cooling, inducing large forces upon the connections. To ensure resiliency, steel connections, such as beam-to-column connections, must be able to withstand the loading that would be induced due to fire. The behaviour of beam-to-column connections under thermal loading is currently not well understood, limiting the current design to being overly conservative rather than using a performance-based solution [9].

There has been limited experimental studies into the behaviour of beam-to-column connections under fire exposure, mainly due to the high cost of fire tests. The majority of the research is focused on modelling, using the limited experiments as forms of validation [18, 22, 24]. A large portion of the previous fire tests, dating early 2000s and earlier, were focused on understanding moment-rotation characteristics of end-plate

connections [1, 2, 15, 16, 27, 28, 32, 34]. The largest, in compartment size, experimental study utilized the Cardington steel structure to perform a large-scale test. This experiment, reported by Wald et al. [31], examined the temperatures selected structural elements, including the connections, would reach using a fuel load of 40 kg/m² of wooden cribs evenly distributed across the compartment. The structure did not experience collapse; however, some local buckling and fractures occurred, some during the cooling stage. Details about the connection forces or specific behaviours were not discussed. An experimental programme examining semi-rigid steel moment connections was undertaken by Mao et al. [17], leading to modelling. The National Institute of Standards and Technology (NIST) in the United States conducted a series of four experiments on long-span steel–concrete composite floor beam to measure the axial loads created by the thermal exposures [5]. Two major experimental research programmes were also undertaken at the University of Sheffield and the University of Manchester examining connection behaviour, summarized in [33]. The first programme comprised of isolated connection tests at high temperatures [14, 35–37], while the second programme undertook fire tests on structural subassemblies [8, 33]. The full research undertaken by this team until 2012 was summarized by Burgess et al. [3].

Due to the limited knowledge regarding beam-to-column connections, an experimental programme based on a case study building located in London, UK, known as the Scalpel, was conducted. This building is a 38-storey skyscraper with a unique layout causing many angled facades, shown in Fig. 1, designed in accordance with the Eurocode (UK) building standards. This building was ideal for examining the forces that are generated within connections since the uncommon geometry resulted in the buildings having inclined columns. The Scalpel has become recognized for its fire design, performed by ARUP UK, which has created a precedent in the UK for using the travelling fire methodology. The case study provided a baseline of a real, built structure and allowed for the investigation of similar physical responses that could be expected within a similar building. The experiments planned as part of this research project begin to address the need for large-scale experiments to validate complex and detailed modelling of structures under thermal exposure.

2 Methodology

2.1 *Experimental Setup*

Through a collaboration with ARUP UK, a beam-to-column setup within the Scalpel was identified to be used for a case study analysis. The original setup, however, had dimensions much larger than could be tested and therefore needed to be scaled down while ensuring that the scaled version would behave the same as the original configuration. The sections were therefore scaled to a quarter scale while keeping

Fig. 1 The Scalpel in London, UK, with its angled facades (photograph captured by author)



the relative rotational stiffness constant. The relative rotational stiffness was defined as the ratio of the stiffness of the beam to the stiffness of the column.

A series of three preliminary fire experiments of various thermal exposure durations were undertaken within York University's Fire Resiliency Lab to produce a conceptual framework. The focus within these experiments was on identifying the thermal distribution into the connections when a steel beam was subjected to a localized fire at its centre, as well as the deformations observed due to thermal expansion within the beam and connections. Based upon the scaling to keep the same behaviour, the experimental setup used a $W410 \times 85$ beam and two $HSS406 \times 406 \times 16$ columns, conserving a representative connection stiffness. This setup is shown in Fig. 2.

The connections between the beam and columns were designed by Benson Steel Ltd, a steel manufacturer located near Toronto, ensuring that the connections would be designed as is currently done in Canada. Due to their brittle behaviour, shear tab connections were selected for this experimental series. Additional connections will be examined in further studies. Since the beam-to-column setup was scaled using relative stiffness, the connection forces could not be taken from the design of the Scalpel. The scaling ratio from the relative stiffness was also not applicable to the forces directly. Instead, the connection forces were assumed to be 95% of the capacity of the beam member (the lesser of shear and moment capacities). The connection forces were calculated using ambient conditions, unlike the connections in the Scalpel, which would have considered the increased capacities induced by a fire event. This was done since it is representative of design performed in Canada, where a prescriptive design is used, and the connection fire capacities are not considered.

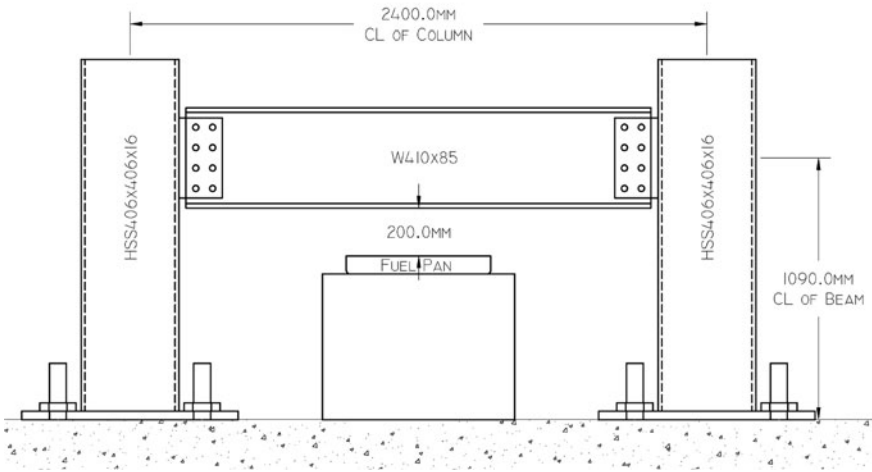
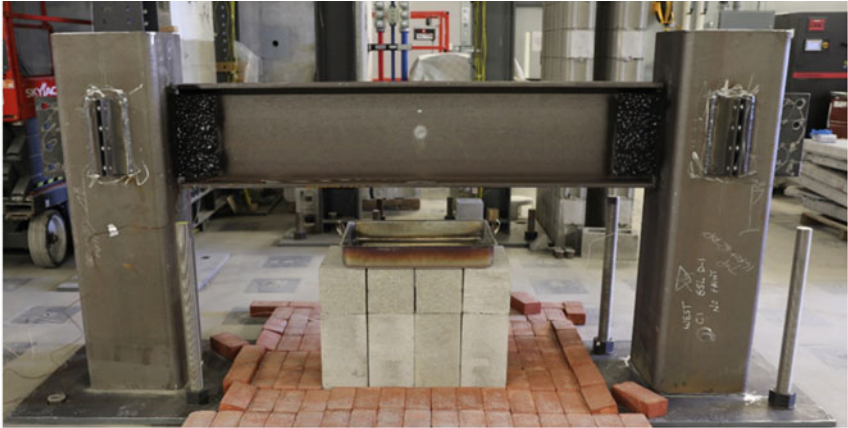


Fig. 2 Beam-to-column connection experimental setup

2.2 Instrumentation

The deformations were recorded using digital image correlation, and narrow spectral illumination was used on the images captured at the centre span to filter out the flames from the photographs. This method is described in [13, 25] and allows visual observation of strains and deflections within the flame area, such as the lower flange at the centre of the span. Narrow-spectrum illumination is a technology developed by NIST and refined at York University where high-intensity blue LEDs illuminate a target and selective colour filters are used to filter light bands above blue. This then allows see through fire measurement [13]. Three Canon EOS 5Ds (Mark IV) 30.4 MPx cameras were used to capture the movements within the experimental setup. The connections which were far enough from the pool fire were painted black with

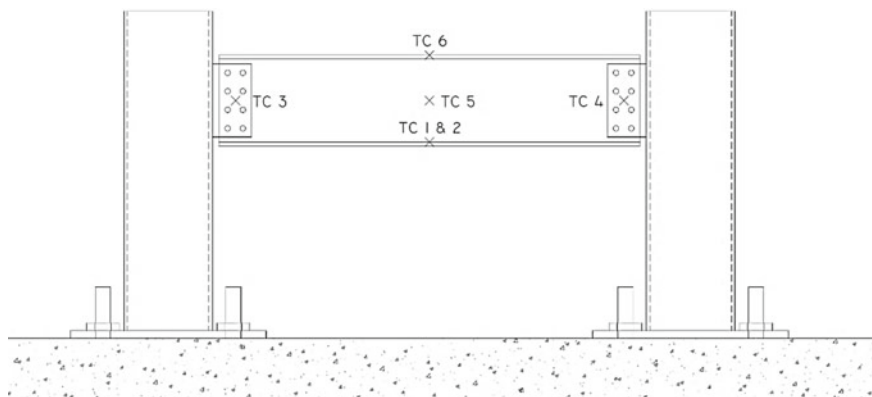


Fig. 3 Thermocouple location on experimental setup

white speckles to provide a high-contrast pattern to facilitate DIC analysis. The DIC analysis for multiple locations along the experimental setup was performed using the GeoPIV RG software [29]. The procedure for measuring strains and deformations is achieved through post-processing where pre-recorded imagery is compared and contrasted using the software to discern minute changes that can then be calculated manually as strain or deflections. Following best practices as defined by Gales et al. [11], error is minimized. This DIC technique has been shown to be accurate for monitoring displacements in [7, 20].

Six K-type thermocouples were used to record the steel temperatures at set points within the experimental setup. Each thermocouple was attached to the steel using ceramic fibre wool and aluminium tape padding, following the methodology described in [12]. This is to shield the thermocouple from the influences of surrounding heat and allow it to record the actual temperature of the steel. The location of each of the thermocouples is illustrated in Fig. 3. These locations allowed for the understanding of the thermal gradients that would occur throughout the depth and span of the beam during thermal exposures.

2.3 Thermal Exposures

To ensure that the experiment was realistic, a form of localized heating was needed. A pool fire resembles as close as possible a pool fire where the connectors may not be exposed to fire. It also inflicts both radiative and convective heating, which is more similar to a real fire compared to other thermal exposures. The beam would also be heated upon multiple faces, creating a realistic heat distribution within the steel beam. It should be acknowledged that a pool fire is not a realistic exposure; however, it does allow for a controlled observational study of the structural system under

an exposure that can be repeated. This type of exposure, combined with narrow-spectrum illumination, was previously used by Nicoletta et al. [21] and Chorlton et al. [7]. These studies used similar setups consisting of methanol pool fires and narrow-spectrum illumination to monitor material deformations and behaviours, and this technique has allowed for repeatable results in creating a representative fire exposure of near 700 °C.

Three different thermal exposures were used to identify the behaviour within the experimental setup. These included a short, a medium and a long methanol pool fire, which created temperatures in excess of 700 °C. Each exposure was then allowed to cool, naturally, until all steel temperatures were measured to be below 100°C. Due to the soot production of other fuels such as acetone or kerosene, it was decided to use methanol, which produces the least soot. The research by Chorlton et al. [7] describes the process used to determine the most suitable fuel type and volume used in these experiments.

For each fire exposure, the specified amount of fuel was placed in a 0.48 m × 0.6 m pan, located 200 mm below the centre of the beam, to create the desired fire exposure. This created an incident heat of the order of 700–800 °C, as characterized in [19]. For the short, medium and long experiments, 4, 8 and 16 L were used, respectively. This resulted in overall exposure times of 12 min, 20 mi and 38 min, respectively. As each experiment reached different steel temperatures, they required different cooling periods, which were recorded as 39 min, 47 min and 106 min, respectively.

3 Results

3.1 Temperature Distribution

As shown in Fig. 3, the thermocouples were placed along the beam and connections to obtain an understanding of the thermal distribution that would occur due to a localized fire. Figure 4 plots the temperatures recorded with the thermocouples. Some experimental errors occurred during testing, including a thermocouple detaching (TC5 in the long experiment after 80 min). The detached thermocouple recorded the air temperature for approximately 30 min before it was noticed, after which it was reattached to the web of the beam. The air temperature segment of the data was omitted from the graph; however, it is assumed that the web would have cooled in a similar fashion to the previous experiments, following the decrease in temperature observed throughout the beam.

From Fig. 4, it can be observed that the temperature distribution within the beam behaves as expected. The pool fire would have reached temperatures of around 700 °C, as demonstrated by previous pool fire studies using the same configuration [7, 20]. This temperature is illustrated as the upper bounds of the figures and indicates the degree of heat transfer observed. The bottom flange and web above the pool fire saw rapid increases in temperatures as the pool fire reached steady state;

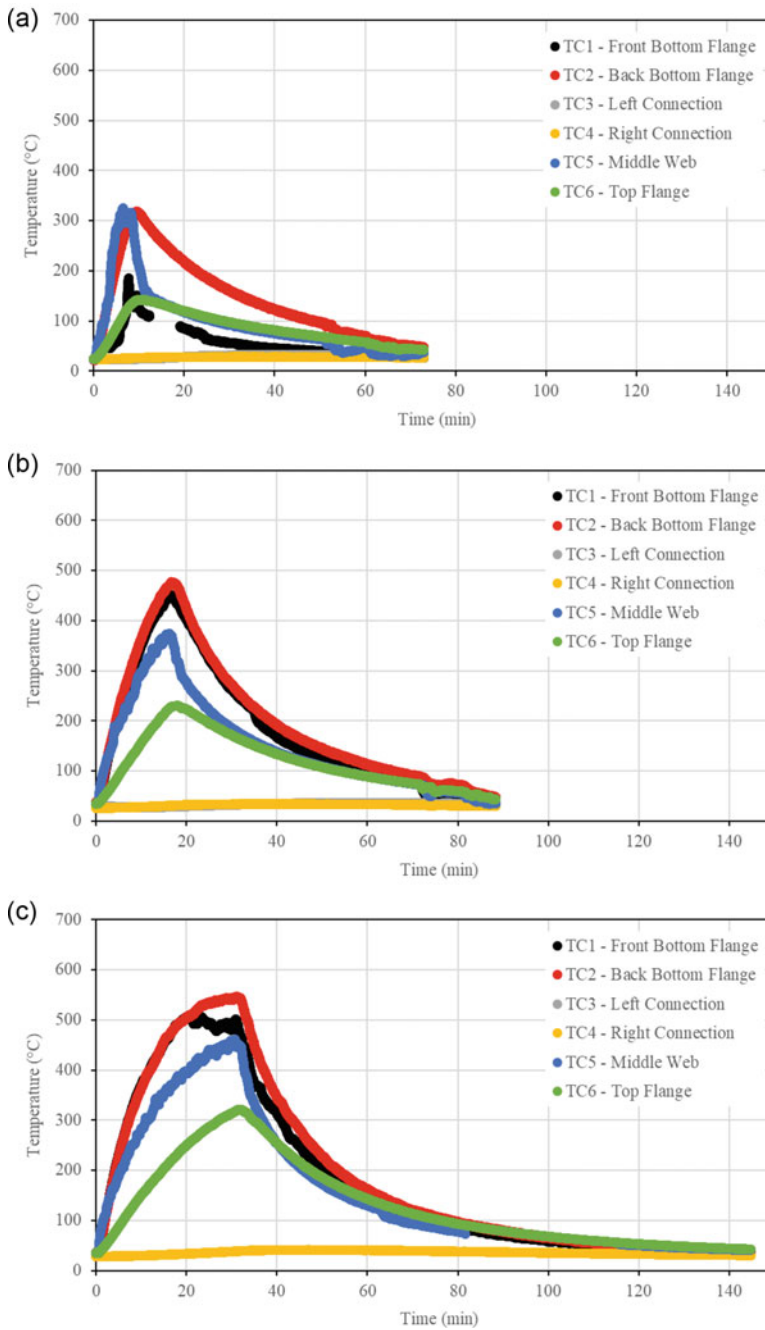


Fig. 4 Temperature distribution through the experimental setup for **a** short, **b** medium and **c** long thermal exposures

however, the beam never reached the fire temperature, although this might have been possible with a longer exposure. The top flange heats up at a slower rate, as it was outside the reach of the flames, relying on heat transfer through the web and the hot air convection to heat up.

The connections, located approximately 950 mm away from the centre of the pool fire, experienced minimal temperature increases. The maximum connection temperatures recorded were 33 °C, 37 °C and 43 °C for the short, medium and long experiments, respectively. The peaks in the connection temperatures occurred after the fire was already extinguished, illustrating the delay in the heating of the connections due to heat transfer through the beam. The low connection temperatures are related to the experimental setup and should not be utilized as proof of low connection temperatures within real fire scenarios. The experimental setup applied a short thermal exposure to the centre of the beam, which does not capture all possible scenarios a structure may experience.

Rapid cooling is observed immediately after the thermal exposure, with the hot steel rapidly losing heat to the surrounding cool air. The cooling rate reduces as the temperature difference decreases. Within the short and medium graphs, some abnormal temperature rates are observed which can be attributed to the water misting applied to aid in cooling. The misting was not applied on the long test to prevent any temperature disruption. The temperatures measured are what would be expected from heating from one side and indicate that the connectors themselves are not fire exposed taking only thermal loading from the beam itself as is intended in this experimental procedure.

3.2 Centre Span Deflection

The deflections at the centre span of the beam were recorded using digital image correlation (DIC) with narrowband illumination technologies. Using the GeoPIV RG software [29], points were selected at the upper edge of the top flange and lower edge of the bottom flange located along the centreline of the beam. No paint was applied within this area due to the uncertainty of the behaviour of the paint at such high temperatures—potentially releasing toxic fumes that may not be fully extracted by the exhaust system without harming researchers. In future tests, different paint configurations designed for high-temperature testing may be considered. Traditional deflection measurements were not used as there was still a degree of substantial heat above the beam which could have influenced the connecting cords. This would cause the deflection metres themselves to thermally expand and give false measurements. Errors occurred within the DIC tracking at the centre span due to the heat radiation distorting the image. This haze induced some data static, resulting in the need to splice the data. This was done using the methodology described and validated in [19].

The recorded deflections are shown in Fig. 5 for all the three tests. It should be noted that the time, shown on the x-axis, is different for the graphs of each test.

The deflection, y-axis, however, was kept the same to allow comparison between experiments. The deflections of both the top and bottom flanges of the beam were recorded to capture the thermal bowing that would occur, as well as the thermal expansion that would occur predominantly within the bottom flange. This can be seen to occur within all the three tests, with a difference of approximately 1.5 mm occurring.

The maximum deflections were seen to occur around the peak temperatures experienced within the beam. These were recorded in Table 1, for each test. As Fig. 5 illustrates, there was some noise in the data, which can be explained by the haze distorting the image. The values included in Table 1 are therefore calculated using a rolling average, with a period of 5, to remove overestimations of the deflection. Figure 5 also illustrates that an upward camber is created within the beam as it cools down. This upward is minimal, remaining below 2 mm at the centre of the span for all tests. This type of behaviour occurs within the experiments as the beam was unloaded. The maximum upward camber for each test is also included in Table 1.

4 Discussion

The experiments described herein were the first experiments to assume realistic rigidity or restraint within the experimental setup. The majority of the limited experiments in literature examined other behaviours experienced within connections without considering the restraint of a real structure. The experiments described herein were based upon a real structure and, while they were scaled down, this was done in a manner to ensure that the rigidity and restraint that would be demonstrated within the case study structure would remain between the frame elements.

The recorded thermocouple data demonstrate the repeatability of a methanol pool fire. From Fig. 4, it can be seen that the steel within the flaming region (on the lower web) consistently followed the same increase between all the three tests. This demonstrates the consistent thermal exposure generated by a methanol pool fire, even when different volumes of fuel are used. The recorded temperatures were also compared to a hand-calculation model, described within the Eurocodes for steel temperatures during uniform thermal exposures. The comparison illustrated that the hand calculations are conservative compared to the experimental results; however, this may be due to the localized heating used.

The deflection measurements demonstrated that unloaded beams exposed to temperatures below 700 °C for short durations experience no permanent thermal degradation. Instead, a slight upward camber is observed due to the uneven cooling that occurs within the assembly. This type of upward camber would not be expected within a structure after a fire. Had the beam been loaded, which would be more likely within a structure, there would have been creep (plastic) deformations that would have occurred in addition to this upward camber, resulting in the camber not being observable. It is therefore not possible for a typical structure to have a final upward deflection after fire, and this camber is a result of the experimental setup.

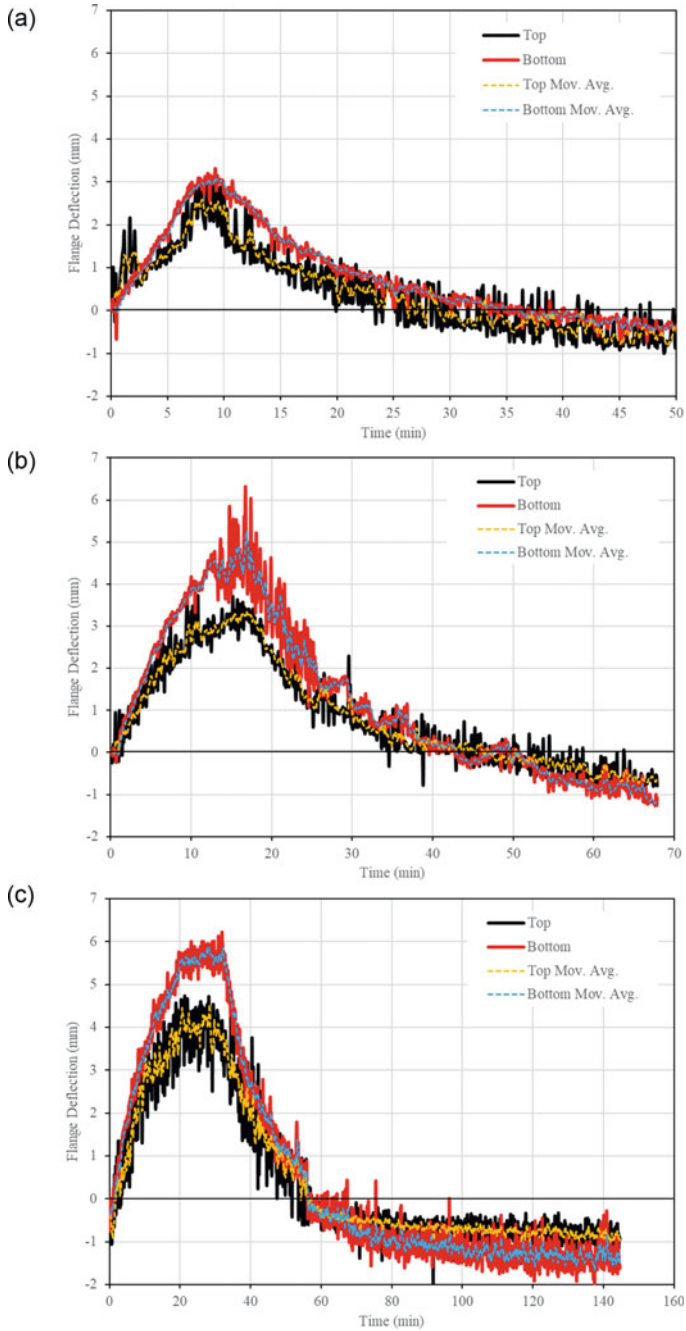


Fig. 5 Deflections at the centre span of the experimental setup for a short, b medium and c long thermal exposures

Table 1 Averaged maximum deflection and upward cambers for each thermal exposure and flange

Thermal exposure	Flange	Maximum deflection (mm)	Maximum upward camber (mm)
Short	Top	2.6	0.8
	Bottom	3.1	0.5
Medium	Top	3.3	0.7
	Bottom	5.3	1.2
Long	Top	4.5	1.0
	Bottom	5.9	1.7

The outward deflections of the columns, as well as other movement within the connections, were also recorded using DIC. These data were not discussed within this paper as it is under development. The outward deflection of the columns will be used to determine the restraining forces being generated within these experiments. There has been limited experimental studies to date that validated the large connection forces experienced due to thermal exposure [5, 6, 23]. To date, the scale of the forces being generated into connections has largely relied on theoretical knowledge. Typically, forces within the range of 1 MN are used for a steel frame building exposed to standard, parametric and travelling fires [26]. The experimental results will be a preliminary step to validate the forces currently used within design, identifying representative forces that could possibly be generated within a steel frame structure.

Additional studies are needed to examine various different configurations of this experimental setup, which would allow for the validation of computational modelling and the forces currently used within fire connection design. This would include experiments with different pool fire locations, different thermal exposures and different connection types. Additional experiments using the current setup are currently underway to ensure the repeatability of the results observed. Future works should include the validation of a finite element analysis model using the experimental series, which would then allow for the undertaking of a parametric study.

5 Conclusion

Practitioners are in need of tools which facilitate the improvement of connection design in order to create resilient infrastructure that can resist thermal loading. When a realistic experimental design is used, it allows for accurate forces and behaviours to be generated. This generates greater understanding of this area which requires additional research. In a fire scenario, the thermal expansion and contraction of beams inflict large restraining forces horizontally on the connections. An experimental programme of three pool fire experiments of various thermal exposures was undertaken to produce preliminary validations of structural fire modelling. The realistic rigidity and stiffness of the experimental setup allowed for accurate forces and behaviours to be generated,

expanding the understanding of the forces and deformations that occur in steel beam-to-column connections. The thermal distribution, centre span deflections and column rotations were recorded during the experiments, using thermocouples and digital image correlation combined with narrow-spectrum illumination. The experimental program outlined above is a preliminary and conceptual research program, which is needed to generate a framework for further testing which will lead to analytical tools and guidance regarding steel connections in fire being developed.

The movement towards alternative solutions and performance-based design in Canada requires more robust codes that include innovations and research progress illustrative of Canadian and international design. The research herein has demonstrated the need to further study the behaviour of steel beam-to-column connections, to ensure safe and resilient infrastructure if exposed to fire.

Statement of Authorship All persons who have met authorship in this manuscript are listed as authors. These authors certify that they have participated sufficiently in the work to take public responsibility for this manuscript's content, including the participation in the concept, design, analysis, writing and revision of this manuscript. Those that do not meet these criteria are listed in the acknowledgements.

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