Structural Steel Columns Subjected To Localised Fires

Conference Paper · June 2017

Felix Wiesner
The University of Queensland

Luke A. Bisby
The University of Edinburgh

IFireSS 2017 – 2nd International Fire Safety Symposium
Naples, Italy, June 7-9, 2017

STRUCTURAL STEEL COLUMNS SUBJECTED TO LOCALISED FIRES




Felix Wiesner[1] Grant Peters[2] Luke Bisby[3] Rory Hadden[4]

ABSTRACT

In large open spaces within modern buildings, the application of standard compartment fire curves based on small compartments may be inappropriate for assessing the potential thermal actions imposed on structural members in fires. Instead, a localised fire approach should be considered for determining the fire protection requirements for steel structural elements in these situations. A series of experiments using real waste bin fires or controlled gas burners placed next to I-section steel columns is described. The goal of the research was to test the validity of the widely applied lumped thermal mass assumption, and potentially to propose alternative approaches. The experimental results show that steep temperature gradients developed both along the column length and over its cross-section, confirming that conventional thermal and mechanical analysis may be inappropriate for design. For the waste bin fires the maximum steel temperatures were controlled primarily by the burning duration.

1 INTRODUCTION

In large compartments, such as in transport terminals or stadia, fires may reasonably be considered as unlikely to reach flashover, particularly if the fuel load is localised into smaller, discrete and separated fuel packages. This also reduces the likelihood of fire spread in many cases. In such cases, the thermal and structural response of a structural element located adjacent to a localised fire source must still be considered to ensure adequate levels of life safety and property protection. However, currently available design methods widely used in structural fire engineering fail to properly account for the effects of localised fires on structural steel columns, likely because much of the available research and guidance is based on the behaviour of structural elements subjected to post-flashover compartment fires – the majority of which assume that the member is isothermal and that gas temperatures are uniform throughout the compartment – or on horizontal structural elements located *above* isolated fires.

The application of fire protection measures derived from standard fires may therefore be unsuitable or unnecessary for localised fire exposures. Meade [1] estimates that, in the USA in the 1990s, structural fire protection measures were the second highest cost associated with fires in buildings at a cost of more than USD$20 billion. It is therefore likely that considerable cost savings might be

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[1] PhD Student. School of Eng., Univ. of Edinburgh. SCOTLAND. e-mail: F.Wiesner@ed.ac.uk. **Corresponding Author**

[2] Structural Engineer. David Narro Associates, SCOTLAND. e-mail: gpeters@davidnarro.co.uk

[3] Arup Professor of Fire and Structures. School of Eng., Univ. of Edinburgh. SCOTLAND. e-mail: luke.bisby@ed.ac.uk

[4] Rushbrook Lecturer in Fire Investigation. School of Eng., Univ. of Edinburgh. SCOTLAND. e-mail: r.hadden@ed.ac.uk

achieved by accurate specification of the required fire protection measures designed by applying realistic fire exposures during design.

1.1 Localised Fires

All fires begin as localised fires and, with limited fuel confined to a small area within a large compartment, many fires are likely to remain localised [2]. Although not explicitly using the term ‘localised fire’, Butcher & Cooke [3] have described how steel columns in buildings can remain unprotected in cases where the fire compartment is sufficiently large and the fuel density is limited, thus limiting fire spread and avoiding a fully developed post-flashover compartment fire.

To assess the structural performance of a steel structural element in fire, a limiting temperature that depends on (1) the applied loads (i.e. utilisation) and (2) its boundary conditions (i.e. restraint and continuity), is often adopted during design. Limiting temperatures for structural steel columns are typically in the range of 538°C [4] to 550°C [5], depending on their utilisation during fire. This limiting temperature is based on the (reasonable) assumption that steel loses approximately half of its yield strength at these temperatures [6].

One application in which localised fires are considered to be likely is in the concourse areas of sports stadia, where fuel loads are sparse and localised. As an example, waste bin fires in stadia concourse areas are likely candidates for localised fires, and are specifically investigated in the current paper. A prior experimental study by NIST [7] found that (1) the heat release rates (HRRs) for waste bin fires ranged between 150 and 300 kW, (2) the peak heat flux at 80 cm height and 80 cm distance from the bin boundary was 5 kW/m^2 (measured using Gardon type heat flux meter) and importantly (3) that the burning behaviour was greatly influenced by the stability of the bin (i.e. whether the bin remained upright, melted, or otherwise collapsed). An extensive test series on wastebasket fires was also performed by Gross and Fang [8] to assess the influence of such fires on wall linings and unprotected structural steel columns. For metal bins it was found that the available ventilation for the fuel is a limiting factor controlling the fire size. Gas temperatures and heat fluxes in the bin fire plumes and immediately adjacent to the waste baskets for these localised fires exceeded those of a standard fire curve in the early fire stages (~ 5 minutes from ignition); however, localised fires had comparatively short burning durations as compared with standard fire curves and structural fire resistance ratings. The maximum heat flux directly above the rim of the waste basket fires [8] was measured as 49.7 kW/m^2 using thin skin calorimeters (TSCs) [9] .

1.2 Previous Experiments

Steel has a comparatively high thermal conductivity, and this, coupled with the assumption of uniform temperatures in fire compartments, has led to widespread use of a lumped thermal capacitance approach for the analysis of locally-heated structural steel members in fire [6]. However, a range of experiments has shown that, particularly for localised fire exposures, steel members actually heat in a significantly non-uniform manner [10-16]. Higginson [10] has reported results from fire tests on a structural steel I-beam located directly above a 200 kW pool fire, and showed that the heating was highly localised and that large temperature variations existed between the bottom flange and the web (up to 1600 K/m vertically), as well as along the length of the beam (up to 746 K/m between exposed and unexposed beam section) .

A series of tests on box section columns exposed to a variety of configurations of gas burner heating are described by Kamikawa et al. [13]. Measurements of heat fluxes and steel temperatures confirmed that the front flange heated more rapidly than the webs or the rear flange, but that for a localised fire surrounding the column the heating was essentially uniform over the column’s cross section but not over its length. Kamikawa et al. [13] also suggest that internal heat transfer due to re-radiation from the front to back flange ought to be considered to make good temperature predictions.

A series of pool fire experiments on hollow circular steel columns, with constant heat release rates (HRR) of 0.59 and 1.68 MW, were performed by Ferraz et al. [11] and showed that asymmetrical heating occurred over the height and cross sections of the columns, and that the thermal actions depended significantly on the tilt of the flames; this was influenced by the ventilation conditions inside a compartment [12].

Localised fire tests have also been performed by Sjöström et al. [14] for circular hollow steel columns suspended above a pool fire. Due to tilting of the flames the temperature increases in the column were highly asymmetrical over its cross section and along its length, causing visibly observable thermal bowing of the column. Such behaviour highlights the importance of heat transfer, flame shape, and position for predicting the thermal and structural impacts of localised fires on both protected and unprotected structural steel columns in large, open compartments with discrete fuel loads.

1.3 Available design guidance

The preceding sections suggest a practical need and interest from researchers in exploring the issue of localised heating of steel columns, however the available guidance for designers on calculation methods and thermal boundary conditions is rather limited. The Structural Eurocodes [17] propose a semi-empirical method to calculate the heat flux to structural elements from localised fires; however, this was derived for horizontally oriented members, and is thus not directly applicable to columns.

The SFPE's "Engineering Standard on Calculating Fire Exposures to Structures" [4] suggests an alternative method to deal with localised fires from which incident heat fluxes and exposure durations for structural members exposed to localised fires can be approximated for design. However this method is also focused on fluxes to horizontally oriented elements (i.e. beams and slabs, rather than columns). Essentially, the heat flux is coarsely prescribed as being either 20 kW/m^2, or 120 kW/m^2, depending on the relationship between the 'flame' height and the 'target' height. While theoretically this approach could be used for beams as well as columns, proposing a 100 kW/m^2 step change in heat flux based on the flame height suggests that it is intended only to be applicable to beams, since a beam is likely to be either immersed in the flame (120 kW/m^2) or not (20 kW/m^2).

Improved methods are needed so that structural fire engineering designers can rationally determine the protection requirements for structural steel columns in scenarios where a fire in their vicinity is likely to remain localised. The aim of the research presented in this paper is to produce data that can be developed beyond simple pass or fail rules, to link up increasing knowledge in research and design on the effects of non-standard fires.

2 EXPERIMENTS ON LOCALLY HEATED COLUMNS

To test conventional models for localised fires, and obtain experimental temperature data on the temperature increase in a realistic localised fire scenario, six waste bin fire tests were undertaken. The waste bins varied in volume from 50 litres to 110 litres, all of which were made from black polypropylene, and for each of which two orientations were tested with respect to the proximity to a structural steel column: (1) flange facing the bin or (2) web facing the bin. The testing matrix for the bin fires considered is shown in *Table 1.*

A steel column (actually a standard beam section) of size UKB 203 × 133 × 25 was fitted with steel stands to prevent it from toppling over, and then instrumented with Inconel clad K-type thermocouples along its height and over its cross section, as shown in *Fig. 1 a).* Positions near the centre of the column and the potential fuel sources were instrumented with a greater sensor density to account for non-uniform heating more accurately. The thermocouples were fed through holes in the column parts and bent into smaller partial depth holes, which reached halfway into the steel plates. This was done to secure the thermocouples in position and did not slip out, to ensure that steel temperatures (rather than gas temperatures) were measured during testing.

A thermocouple tree consisting of eight evenly spaced thermocouples was positioned along the central vertical axis above the fire source, allowing the centreline gas temperatures to be sampled at various heights above the fuel. The tests were performed underneath a 1.0 MW furniture calorimeter, and the analysis of the combustion gases enabled calculation the HRR by oxygen consumption and carbon dioxide generation calorimetry.

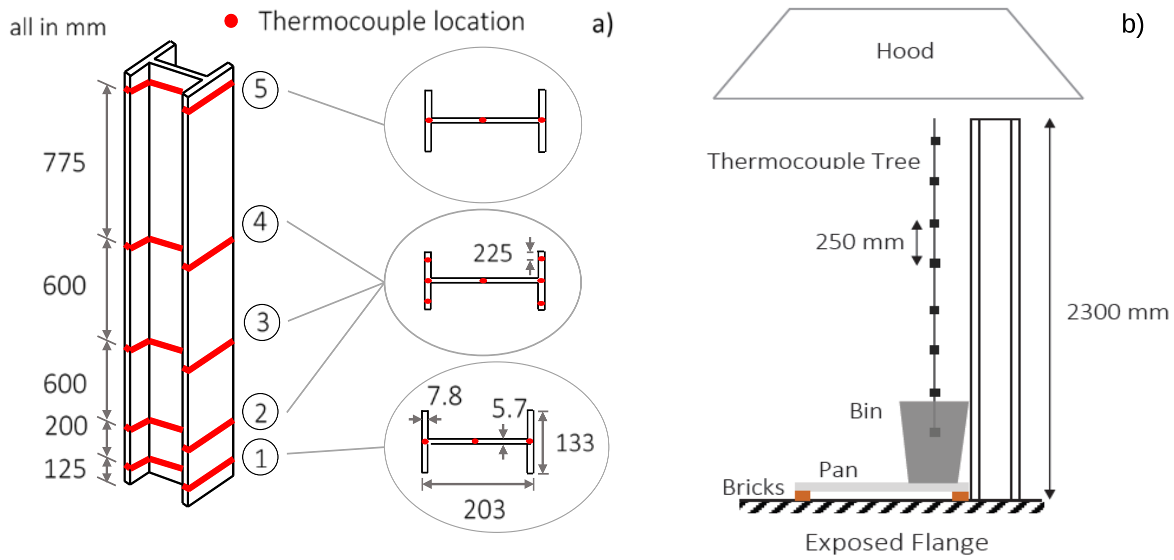

Fig. 1. a) Thermocouple placements along the column length and over its cross-section; b) Waste bin fire test set up schematic for the exposed flange testing configuration

A refuse mixture, which was chosen to be representative of that expected in a large sports venue in Scotland, was used as bin content. Five bags of refuse were collected from Murrayfield Ice Rink, Edinburgh, following an ice hockey match. The mass composition of the refuse was determined and recreated in the laboratory. This particular stadium has a capacity of 3,500 people and sells food and refreshments typical of a sports venue. By replicating the fuel source from a sports event, a better understanding of the burning behaviour of a localised fire in such a venue can be attained. A large proportion of the refuse mass was made up of water and sludge, this was omitted from the replicated refuse mix, so as to create a conservative fuel mix that would burn without accounting for the effects of liquids in the mix. The final make-up of the recreated fuel mix is shown (by mass composition) in *Fig. 2 a).*

The refuse in the centre of the waste bin was ignited with a propane torch. After ignition the fire was observed to propagate downwards through the refuse, with only a small HRR, but generating a considerable amount of smoke, until the base of the bin was reached. After a period of subsequent slow burning, a hole eventually formed in the side of the bin, resulting in increased ventilation to the fire. Subsequently the HRR rapidly increased and reached its peak value as the polymer from which the bin was made melted into and became involved in the fire; this eventually caused collapse of the bin, which then melted entirely and burned essentially as a pool fire (*Fig. 3).*

3 RESULTS

The HRR developed similarly for all the tests, as shown in *Fig. 2 b).* There was an incipient phase, in during which the refuse mix burning towards the bin base, followed by a rapid growth period, due to the sudden increased ventilation and the collapse of the bin. This was then followed by a pool fire period, which remained relatively stable, followed by slow burn out as several isolated pockets of fuel as the fuel was consumed.

An overview of the waste bin fire test results is given in *Table 1.* The burning duration is taken as the absolute burning time, from ignition to flameout; however, as seen in *Fig. 2 b),* only a small part of the burning duration encompassed the critical heat release values. During the incipient phase the HRR was low due to limitations in ventilation, and during the burnout period the HRR was distributed over several small spots of flaming and was not critical.

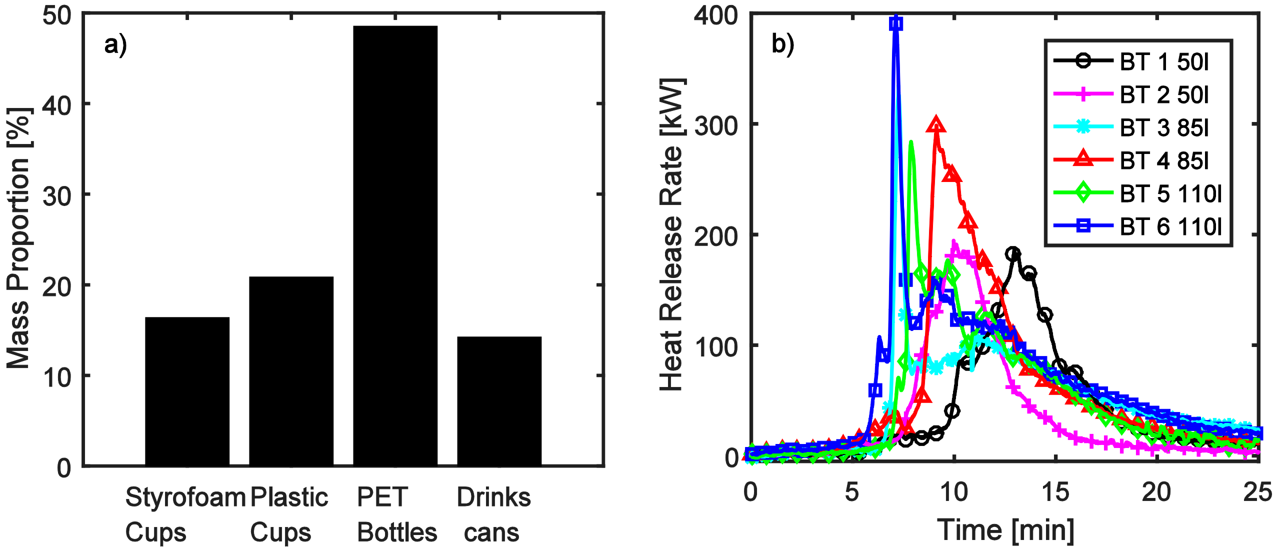

Fig. 2. a) Sampled refuse mix composition, excluding 'sludge'; b)HRR development for bin tests plotted from ignition

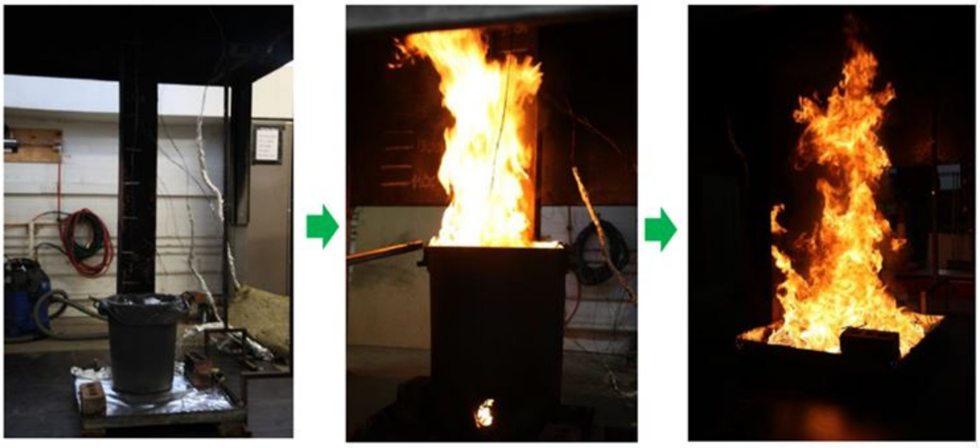
a) b) c)

Fig. 3. Development stages of a localised waste bin fire in a polymer waste container; (a) pre-ignition, (b) fire growth and loss of containment, and (c) transition to a polymer pool fire.

In addition to the bin tests, a series of tests with gas burners were also undertaken to investigate heating parameters in a more controlled heating scenario with a constant HRR. The gas burner was used to generate six different steady state HRRs in each of the two test orientations. Additionally, tests were performed in which the distance between the burner and the column was varied.

Table 1. Overview of waste bin fire test setups and results

Name	Volume [l]	Bin Mass [kg]	Diameter [cm]	Orientation	Max HRR [kW]	Burning Duration [min]	Energy Released [MJ]	Max. Steel Temperature [°C]
BT 1	50	1.3	41	Flange	187	39	66	-[1]
BT 2	50	1.3	41	Web	195	38	54	366
BT 3	85	2.65	46	Flange	335	60	89	289
BT 4	85	2.65	46	Web	299	39	89	384
BT 5	110	4.09	52	Flange	284	86	96	454
BT 6	110	4.09	52	Web	398	74	117	444

[1] Thermocouples moved out of their holes and were measuring gas instead of steel temperatures. The highest steel temperature could therefore not be reliably determined and is omitted.

3.1 Steel Temperatures

For columns exposed to the constant HRR gas burner fire a well-defined rise in temperature was observed, as shown in *Fig. 4 a)*. The heating of the three individual plates of the column is clearly distinguishable. For a fire facing the front flange, a temperature increase is observed up to a quasi-steady state, until the burner is switched off. The maximum steel temperature in this case did not exceed 449 °C.

For the waste bin tests, a similar steel temperature development was observed in *Fig. 4 b)*; however, the temperature across the front flange was not as uniform in this case. This was due to the observed collapse of the bins in these cases, which created asymmetrical fire exposure conditions, engulfing the tips of the flange in flames. During the incipient phase of the bin fires, when only the refuse was involved in the fire, the steel did not heat up significantly. Once the bin became involved in the fire the steel temperatures rose relatively rapidly, and it is clear that a longer burning duration could have caused the maximum steel temperature to exceed the 454 °C maximum temperature that was measured for this test. There was a time delay between the temperature peaks for different parts of the columns. This was caused by the variation in HRR throughout the burning duration, and due to the influences of conduction within the steel section.

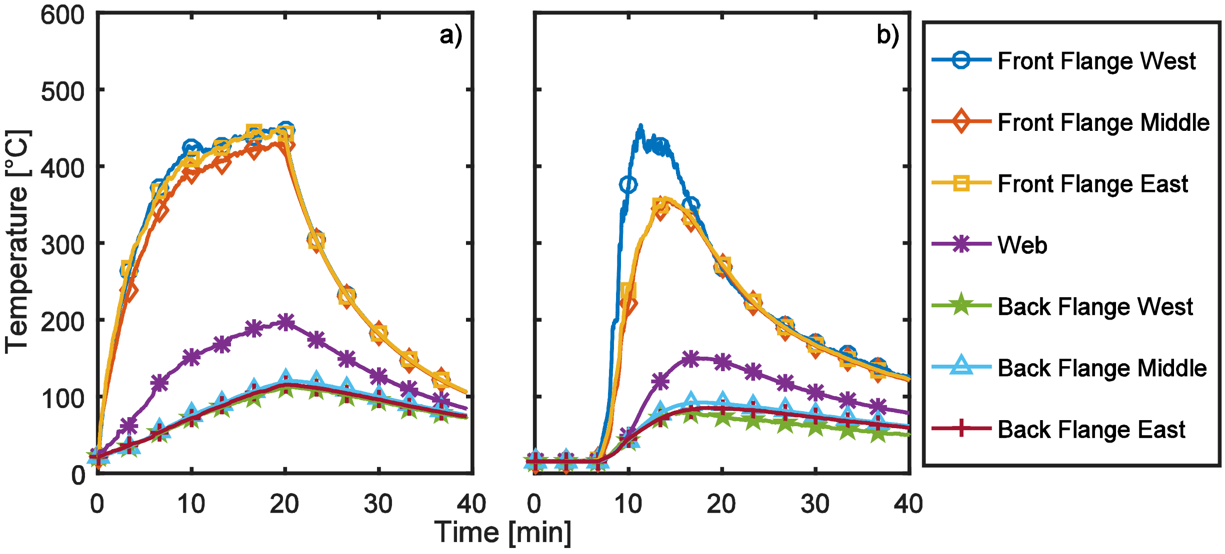

Fig. 4. Steel temperature development in a column cross section exposed to: a) a steady state 82 kW gas burner flame at the hottest height (925 mm); and b) to 110 l bin fire, at the hottest height (325 mm), with exposure to the front flange in both cases. Both curves plotted from the moment of ignition

4 DISCUSSION

For all waste bin tests (refer to *Fig. 2 b)*) a relatively long incipient phase can be observed in which the fuel mix burns with a low HRR. Following the incipient phase, a sudden increase in the HRR is clear. As already noted, this is because the bottom of the bin melted and provided additional ventilation to the fire, which is critical for the bin fire to grow to a critical size and for the majority of fuel to then be provided by the polypropylene of the bin itself. It can be assumed that without the loss of integrity due to melting, the HRR would have remained small, and the columns most likely would not have heated up to temperatures anywhere close to critical. In practice, this result can be easily achieved by specifying the strict use of metal waste bins in all relevant occupancies, since they reduce the available fuel *and* prevent the creation of additional ventilation paths to the fuel; they will also provide physical protection from radiation of burning refuse within the bin itself.

Comparing *Fig. 4 a)* and *b)*, it is evident that the gas burner tests resulted in higher column temperatures when compared against the largest waste bin fire test, despite the fact that the peak HRR of the bin fires exceeded the maximum HRR for the gas burner. However, the gas burners have a constant HRR over a longer period, and the peak HRR for the bins have only short durations on the order of seconds to a minute. Therefore the total duration of the exposure to heating was longer for the gas burner tests.

The temperature distribution over the cross section was highly non-uniform for all of the tested fire scenarios. For the waste bin fires (see *Fig. 4 b)*) the steel temperatures were non-uniform within the different plates of the I-section column. Due to the collapse of the bin during the fire, the flames of the fire heated the column asymmetrically, causing clearly non-uniform heating to be observed. This highlights the critical importance of radiation from the flame to the steel, and the significant influence of flame tilt on heating of steel elements subjected to localised fires, as has been observed in similar studies by others [11-13]. The commonly applied assumption of a lumped thermal capacitance for the steel could not be defended technically, similar to results and conclusions from previous studies [2, 10-13, 15, 16]. Furthermore, it is noteworthy that using a lumped thermal capacitance approach could potentially lead to unsafe designs, since local buckling of steel plates making up a structural section could occur due to non-uniform heating and the resulting steep thermal gradients and differential thermal expansion. Additional research into the effects on the load bearing capacity of non-uniform heating of steel columns is needed.

A limiting steel temperature of ~550°C, as is commonly used in practice to assess fire protection requirements for structural steelwork, was not exceeded in any of the tests. However, an assessment of the structural capacity in case of fire would need to be undertaken by consulting engineers on a case-by-case basis, and should ideally incorporate an evaluation of the load levels expected and the structural behaviour of the individual column plates. More experimental work to investigate different local buckling modes and post buckling behaviours of locally heated columns is required to develop guidance that can be used to defensibly assess the load bearing capacity in both the temperature and time domains.

5 CONCLUSION & RECOMMENDATIONS

The following conclusions can be drawn on the basis of the preliminary research presented herein:

- A lumped thermal capacitance assumption is not applicable to the thermal analysis of structural steel members in case of asymmetrical, localised fire exposure.
- Temperatures in different parts of structural steel columns exposed to localised fires will vary, resulting in thermal gradients, differential thermal stresses, thermal bowing, and possibly local buckling of the individual steel plates making up a structural section.
- The duration of burning was, in the case of the tests described herein, a critical parameter for considerations of thermal exposure of structural steel columns from localised waste bin fires.

Given the above, the effects of non-uniform temperature distributions on the buckling resistance and load bearing capacity of steel columns should be investigated further; such work is currently underway at the University of Edinburgh.

ACKNOWLEDGMENTS

The authors gratefully acknowledge advice from Dr Susan Deeny and Dr Graeme Flint at Ove Arup and Partners Ltd. on various aspects of the research presented herein. We would like to acknowledge the financial support of Ove Arup and Partners Ltd. Special thanks are due to Michal Krajcovic at the University of Edinburgh for his advice on the various experimental procedures.

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