DEVELOPMENT AND TESTING OF A COMBINED HEAT, AXIAL LOAD AND LOW IMPACT TESTING RIG

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ABSTRACT
The effect of combined static, impact and thermal loads on structures is a relatively little-known area of research with large potential applicability to sectors including defence and energy. In order to study the effect of these combined loads on structural elements, it is important to conduct controlled laboratory testing in order to validate computational analyses. There are currently few or no testing apparatus which are able to repetitively test structural elements to combined heat, axial and impact loads at a low cost. This paper details the development of a bespoke combined low-impact testing rig capable of testing 500 mm long, 100 mm wide structural elements. The rig can apply combined load sets including a thermal load (up to 400°C) an axial load (up to 150 kN) and an impact load from a 7.5 kg drop weight. For the developmental testing 500 mm long, square and rectangular concrete sections were tested as part of a wider study into the performance of concrete containing hybrid polypropylene (PPE) and steel fibres at high temperatures. Recorded results from the study include external and internal concrete temperatures via thermo-couples, longitudinal strains and vertical deflections. Conclusions regarding the suitability of the bespoke testing rig to impart the combined load sets on structural columns are presented along with discussions on the effects of the hybrid fibres in concrete columns. The study found that the rig is able to impart the combined load sets effectively and accurately enabling multiple repeated testing on elements at a low cost. The presence of PPE fibres allowed the concrete to reach higher temperatures without spalling and improved its overall resistance.
Keywords: impact, thermal, axial load, concrete, polypropylene fibres.

1 INTRODUCTION

A bespoke experimental rig was designed and developed for the testing of combined thermal, axial and low velocity impact loads on concrete structural elements. Sixty trials were undertaken on a range of concrete column types under different heating regimes. The tested concrete columns were 500 mm in length, containing a mix of high strength steel fibres (SF), standard reinforcing bars, Polypropylene (PPE) fibres and plain concrete. Tests were conducted to observe the effect of the addition of PPE fibres on the resistance of concrete columns subject to combined thermal, compression and low velocity impact loads. Conclusions regarding the suitability of the developed rig are made along with the effect of the inclusion of PPE fibres within the concrete mixes. Further development of the rig is proposed including the testing of different structural elements, improved thermal load application, static loading configurations and impactor head types.

2 POLYPROPELENE FIBRES IN CONCRETE

High strength steel fibres (SF) are used in concrete applications to increase load bearing capacity and durability. Research into SF use for exceptional, non-standard service loads, e.g. blast and impact loads [1] has shown an increased tensile resistance and ductility. SF can also be used in thin structural slabs and walls which would require low standard covers to normal reinforcement. If plain or standard reinforced concrete (RC) is subject to high temperatures in a rapid heating regime there is a high probability that explosive spalling will occur. This spalling is due to trapped and expanding water vapour pressures within the concrete matrix [2]. After spalling, the concrete compressive capacity is compromised and

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the reinforcing bars are exposed enabling quicker heat transfer to the rebar and subsequent degradation of yield strength and Young's modulus. The addition of PPE fibres in concrete has been previously researched to show an improved resistance to explosive spalling at high temperatures [3], [4]. The PPE fibres do not add any additional tensile or compressive capacity to the concrete. At high temperatures the PPE fibres melt at 160°C to170°C, leaving a network of fine channels through the concrete matrix. These channels act as routes for trapped water vapour to escape thus lowering the probability of explosive spalling at high temperatures. With no explosive spalling the concrete retains its structural integrity and the reinforcement remains unexposed from direct thermal radiation. The use of PPE fibres in combination with normally reinforced or SF reinforced concrete increases structural resistance to heat loads from fire and other thermal loads, this consequently maintains the structural resistance to any subsequent impact or blast loads. Prior to the combined thermal, compression and impact testing on the concrete columns documented in this paper, a series of material characterisation trials were undertaken to determine the optimum PPE fibre dosage [5]. The optimum dosage determined was 2.5%, this was subsequently adopted within the concrete columns for the combined load testing.

3 RIG DEVELOPMENT

A bespoke rig was developed at the University of Portsmouth (UoP) Civil Engineering laboratories to impart a combination of thermal, compression and impact load on to structural concrete columns. The rig is a low-cost alternative to full scale field testing, with the ability to test consecutive multiple samples with varying characteristics in controlled conditions. The following describes the rig development detailing the separate load application methods.

3.1 Compressive load

A critical goal of the column testing was to recreate in-service conditions as closely as practical in a controlled laboratory. Therefore, the structural columns should be subject to stresses akin to a standard building axial load. Options were investigated included the use of an in-house hydraulic rig, but it was deemed impractical due to the high risk of damage to the rig instrumentation from the thermal load. A manually operated floor standing hydraulic press, capable of applying 200 kN (Fig. 1(a)), was adopted. The press was adjusted and laid flat, enabling test samples to be positioned horizontally, which allowed a drop rig to be positioned vertically above the centre of any test sample. A 500 kN capacity load cell (Fig. 1(b)) was positioned between the end of the concrete column and the press plate to record the applied compression, ensuring all tests were subject to the same initial load (150 kN).

(a) (b)

Figure 1: (a) Hydraulic press [6]; and (b) Load cell.

3.2 Heat load

A main research requirement was that the heat load applied to the structural columns should be akin to a fire load and that it should cause a significant, observable thermo-mechanical response in the concrete columns. From prior research, the PPE fibres would melt at 160°C to 170°C, therefore this was set as the minimum required temperature with a maximum achievable temperature of 400°C. This maximum temperature was set due to the health and safety requirements within the laboratory and the capacity of the heating system. The use of an in-house rapid heating chamber furnace (1200°C maximum) was not appropriate for the trials there was no ability to apply the compression and impact loads to the column samples within the chamber. The option of heating the samples within the furnace, then subsequently removing and testing them with applied compression and impact loads in a separate rig was deemed unpractical and unsafe. Therefore, ceramic heating elements were used to heat the sides of the columns to the required temperatures. Two 1000 W full quartz ceramic heating elements [7] were fixed inside aluminium boxes with protective wire meshes. These boxes were placed within a thermally insulated aluminium channel positioned to face the columns in the centre, with a 20 mm gap between the sides of the columns and the heating boxes (Fig. 2). The central 250 mm of each column were heated via the ceramic heaters. The ceramic heaters are able to reach surface temperature of 770°C, however, due to the air gap and safety considerations the maximum achievable concrete surface temperature was set at 400°C.

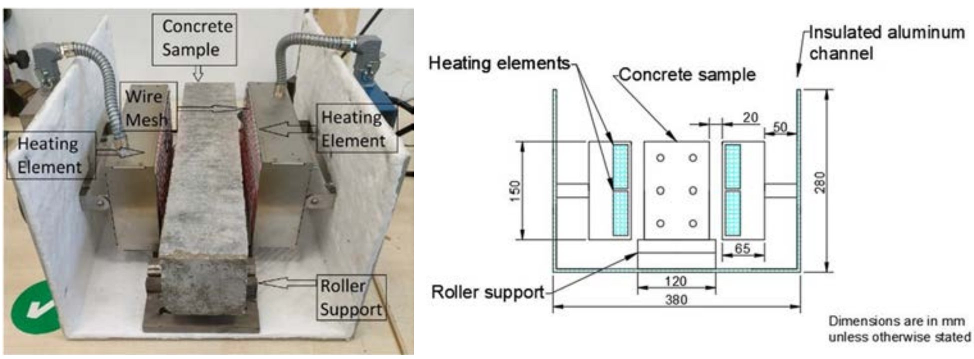

Figure 2: Thermal load application.

3.3 Impact load and combined rig

The main requirements for the impact load included a lateral application over the central section of the columns, the practical lifting of the impactor, the imparting an intense load over a very short duration and no sustained damage to the impactor during tests. A 720 mm long, 41 mm diameter, high-strength steel rod was manufactured for this purpose. Galvanised steel tubes positioned above the columns guided the 7.5 kg steel rod to impact the concrete columns at their midpoint. The columns were supported by roller supports at 450 mm centres, thus the vertical impact load imparted three-point bending on to the columns. The steel tubes were machined with guide holes and pins to allow the rod to be dropped from up to 2 m height (imparting 147 J), for these trials a consistent height of 1 m (73.5 J) was selected. The rod was manually lifted between tests via a pulley system using strong wire connected to the top (Fig. 3(a)).

(a) (b)

Figure 3: (a) Impactor rod; and (b) Combined rig.

The three separate loading mechanisms were configured to work together in a combined rig (Fig. 3(b)). The rig was fixed via brackets to the strong floor of the laboratory. A lightweight aluminium frame held the impactor guide tube and rod in place over the columns.

4 EXPERIMENTAL METHODOLOGY

After the development and calibration of the rig, the trials were undertaken. Sixty concrete columns were tested with a variety of fibre/reinforcement configurations under a range of thermal loads. The applied compressive load and impact load were constant across the tests. The following section details the concrete column mix design and experimental procedure.

4.1 Concrete column preparation and mix designs

Table 1 details the concrete column sections tested; six square, and six rectangular column types were tested with a mix of 10 mm reinforcement bars, plain concrete, PPE fibres, steel fibres and two hybrid mixes: PPE + rebar and PPE + steel fibre. Five tests were conducted per mix and the mean values subsequently calculated and presented. The concrete columns were cast based on a high strength concrete (HSC) mix design as shown in Table 2. This mix design had been previously determined from a material characterisation study [5], to find the optimum dosage of PPE fibres using compressive tests on 100 mm × 100 mm concrete cubes. The concrete columns were cast in 600 mm length moulds (with 50 mm sacrificial polystyrene at each end). The concrete was placed in two layers to allow compaction and placing of thermocouples at centre of columns. Bespoke steel bar holders which also acted as shear links were specially manufactured for the RC columns (Fig. 4). These bar holders ensured the bars were placed at consistent 50 mm centres with 20 mm concrete cover. Columns were set for 24 h under a damp hessian sheets then water cured for 28 days in accordance with BS EN 12390-2:2019 [8].

Table 1: Concrete column samples.

Column sizes	Naming convention	PPE fibre content (kg/m^3)	SF content (%)	No. rebar	No. specimens
100×100×500	SQ_CTRL	0	0	0	5
100×100×500	SQ_CTRL_PP	2.5	0	0	5
100×100×500	SQ_RC	0	0	4	5
100×100×500	SQ_RC_PP	2.5	0	4	5
100×100×500	SQ_SF	0	2	0	5
100×100×500	SQ_SF_PP	2.5	2	0	5
150×100×500	RECT_CTRL	0	0	0	5
150×100×500	RECT_CTRL_PP	2.5	0	0	5
150×100×500	RECT_RC	0	0	6	5
150×100×500	REC_RC_PP	2.5	0	6	5
150×100×500	REC_SF	0	2	0	5
150×100×500	REC_SF_PP	2.5	2	0	5

Table 2: Concrete mix designs.

Constituent material	Plain HSC	HSC and PPE	HSC, PPE and SF
Cement (kg/m^3)	415	415	415
Water (kg/m^3)	139	139	139
Superplasticiser	13.75	13.75	13.75
Steel fibre (kg/m^3)	–	–	157
Silica fumes (kg/m^3)	45	45	45
Polypropylene (%)	–	2.5	2.5
Silica sand (kg/m^3)	432	432	432
Sharp sand (kg/m^3)	439	439	439
Fine aggregate 10 mm (kg/m^3)	488	488	488
Coarse aggregate 20 mm (kg/m^3)	561	561	561

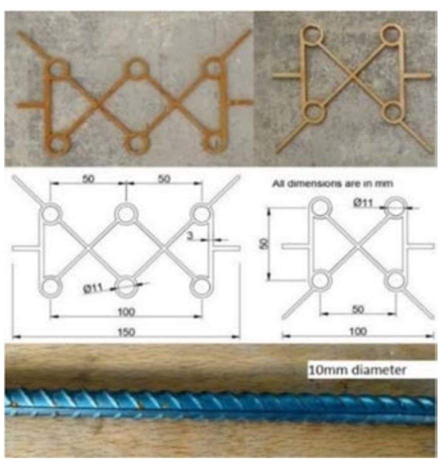

Figure 4: Shear links / reinforcement bar holders.

4.2 Instrumentation

The instrumentation used for the concrete column tests is detailed below:

- Thermocouples: K-type, max. four per test: 1× each side facing heaters, one top, one cast in concrete.
- Strain gauges: 150/120 LY41, 150 mm length HBK strain gauges, fixed with heat resistant adhesive to top face of column (longitudinally).
- Vertical displacement gauge: Novatech DC2.5 type linear variable differential transducer (LVDT), fitted with long rod to reach top face of concrete column.
- Load cell: 500 kN capacity.
- Temperature control: Proportional integral derivative (PID) controller connected to external thermocouples.
- Data acquisition system: DT80 dataTaker acquisition system, connected to laptop via USB.

4.3 Testing procedure

The following flow chart (Fig. 5) details the testing procedure for each concrete column.

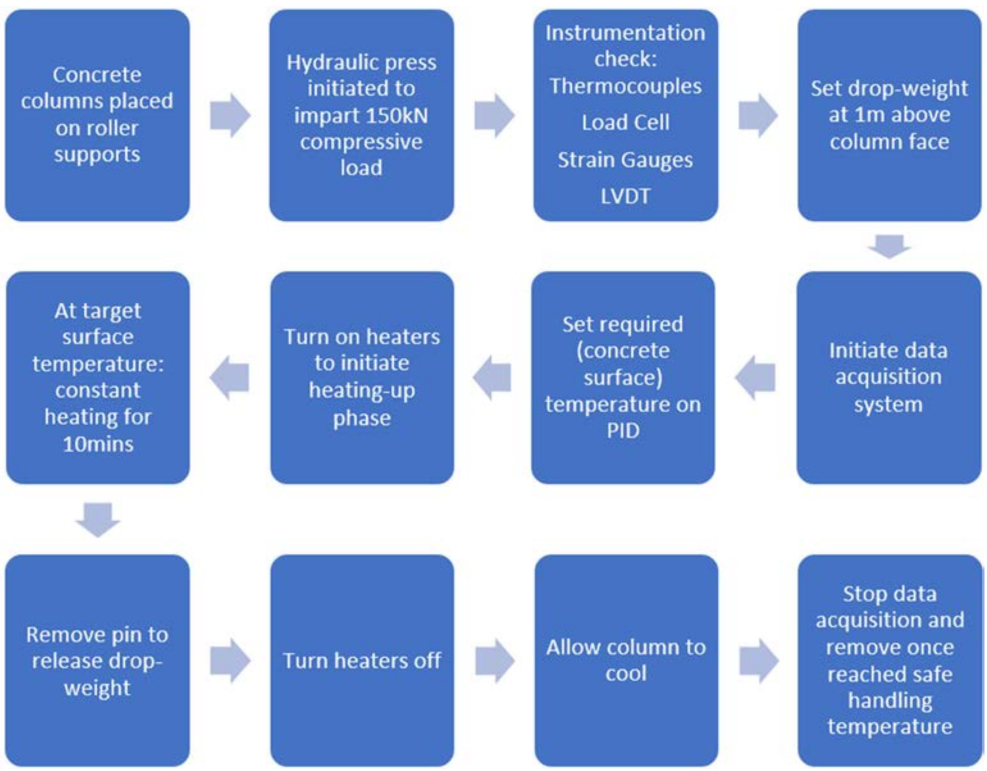

Figure 5: Experimental testing procedure.

5 EXPERIMENTAL RESULTS

For each test the columns were heated at a rate of 27°C/min (due to lab conditions), until the target temperatures were reached. All tests were set to reach 400°C maximum on the concrete surface; once the target was achieved, the temperature was maintained for 10 min to allow further heat soak into the concrete, increasing the internal temperature further. The following details results from the trials. The majority of columns were tested to full temperature and subsequent impact, however several columns failed prior to reaching the target temperature due to the explosive spalling under the thermal and compressive loads alone.

5.1 Thermal results

Fig. 6 shows the surface temperature vs. time for the rectangular columns with different concrete mixes; RECT_CTRL_PP, RECT_RC_PP and RECT_SF_PP. The different column samples had an identical heating rate, constant temperature phase and end time. This pattern was repeated on all column tests. Internal temperatures were recorded for the rectangular concrete columns via thermocouples set in the centre of the section during pouring of the wet concrete. Fig. 7 shows the recorded internal temperatures for the three rectangular sections. There is an initial delay, followed by a temperature increase rate of approximately 11°C/min. At approximately 14 min (400°C external temperature), the applied heat is constant. Fig. 7 shows that the internal temperature continues to rise after 14 min and also rises further after the heaters stop at approximately 24 min. A slight deviation is observed at 14 min which correlates to the application of the impact loads. The CTRL_PP shows a slightly higher rate and maximum internal temperature (228°C compared to 215°C), this could be due to a combination of early crack development and slight thermocouple misalignment.

Fig. 8 shows the temperature differential calculated from the surface and internal temperatures for the square columns. At the end of the heating phase the average temperature differential was 178°C, equating to 3.56°C/mm across the sections. The temperature differentials increased rapidly during the first 5 to 10 min, reaching a peak then followed by a slower drop. The columns with the lowest temperature differential increase (therefore

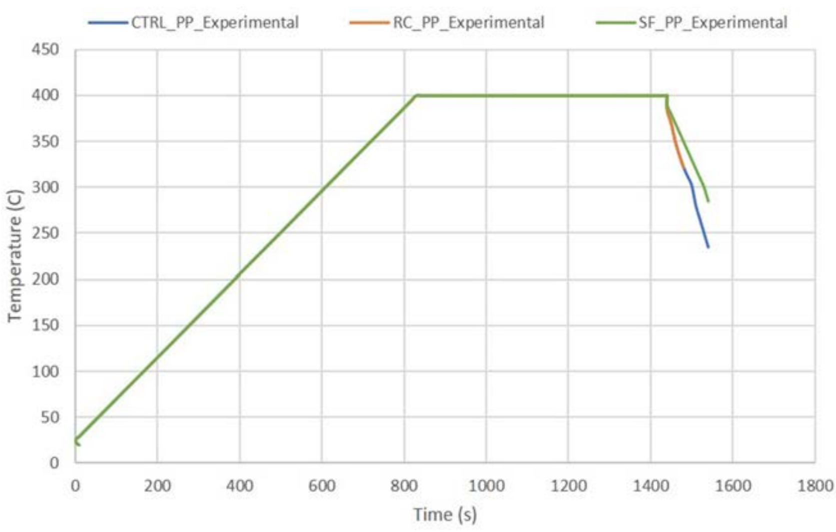

Figure 6: Surface temperature of rectangular columns.

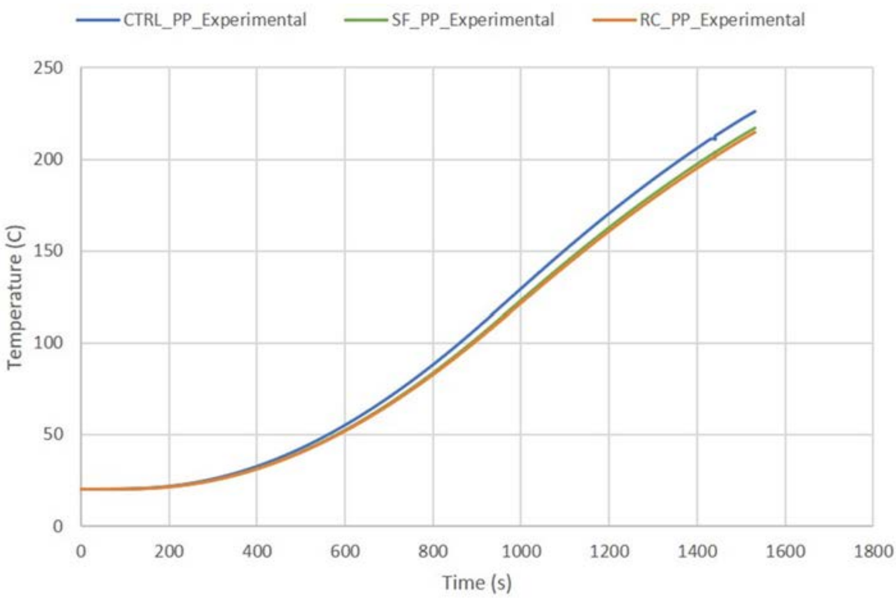

Figure 7: Internal temperature of rectangular columns.

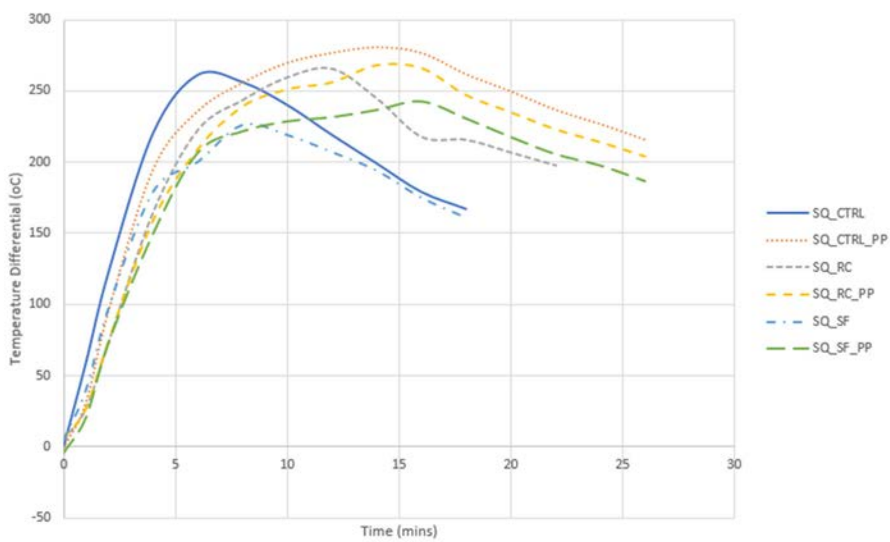

Figure 8: Surface to internal temperature differential.

higher internal temperatures) contained either steel fibre, or reinforcement bars. Some notable phenomena include the sudden drop in differential at approximately 175°C to 225°C; this could be due to surface cracks, PPE fibres melting and the change of state of any embedded water.

5.2 Concrete cracks and visual observations

During heating a network of fine cracks were observed at approximately 300°C on the thermally exposed column faces, with evidence of moisture migration to surface. At 350°C several control samples with no PPE exhibited explosive spalling on the thermally exposed faces. For safety and equipment damage reasons the tests were subsequently stopped (heaters turned off and no impact load applied) if explosive spalling occurred prior to reaching 400°C. No explosive spalling was observed in the concrete samples containing PPE fibres. At 400°C a reddish colour was observed on the surface of the concrete columns. Fig. 9 shows the CTRL column heated to 350°C (post-test) with no impact load; the explosively spalled region is clearly noted. After testing, deep cracks were also observed on samples heated to 400°C.

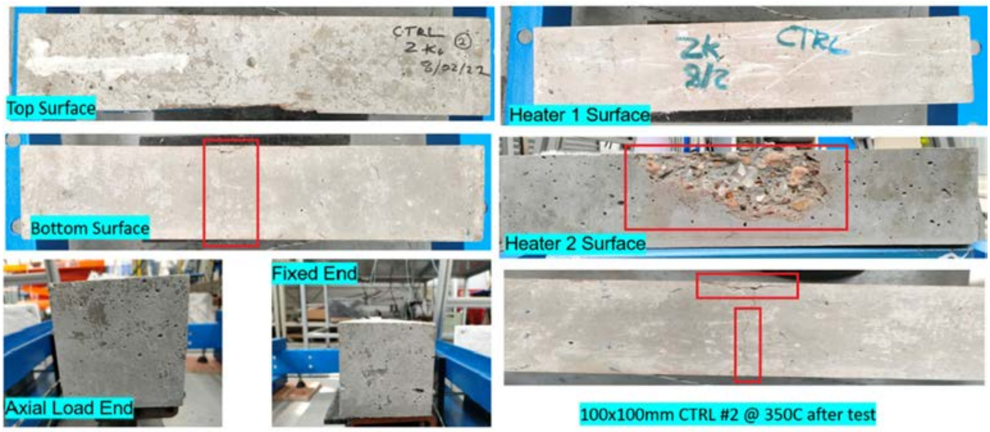

Figure 9: CTRL square column post-test.

5.3 Vertical deflections

The deflections during the trials were measured with an LVDT, placed adjacent to the midspan of the beam (avoiding the central impact area). Table 3 shows the recorded peak deflections for the different column sections heated from 250°C to 400°C. Most columns exhibited an increase in vertical deflection under impact from 250°C to 400°C, with some exceptions. For the square sections the columns with reinforcement bars and steel fibres exhibited lower deflections compared to the plain columns; CTRL = 13.9 mm, RC = 9.7 mm and SF = 11.1 mm. There was also a small decrease in the vertical deflection between the columns without and with PPE; 13.9 mm to 13.2 mm (CTRL), 9.7 mm to 9.3 mm (RC), 11.1 mm to 10.8 mm (SF). Similar correlations between columns without and with PPE are noted with the rectangular columns. The recorded vertical displacement during three tests are shown in Fig. 10 and Fig. 11. Fig. 10 shows the vertical deflections of three different square columns (control + PP, RC + PP and SF + PP) during the heat loading phase. Up to 900 s, the deflections of the three different samples are relatively linear and consistent. After which the control column deflection increases more rapidly than the RC and PP columns. Fig. 11 shows the deflections of the same samples, during the subsequent impact load phase (at

Table 3: Column peak deflections.

Column naming convention	Peak deflection (mm)			
	250°C	300°C	350°C	400°C
SQ_CTRL	–	13.5	–	13.9
SQ_CTRL_PP	–	–	–	13.2
SQ_RC	10.6	–	–	9.7
SQ_RC_PP	–	9.9	–	9.3
SQ_SF	–	9.45	–	11.1
SQ_SF_PP	–	8.25	–	10.8
RECT_CTRL	–	9.2	–	10.04
RECT_CTRL_PP	9.5	–	–	9.95
RECT_RC	–	–	–	9.37
RECT_RC_PP	9.39	–	9.27	8.8
RECT_SF_PP	9.04	9.10 and 7.59	–	9.17

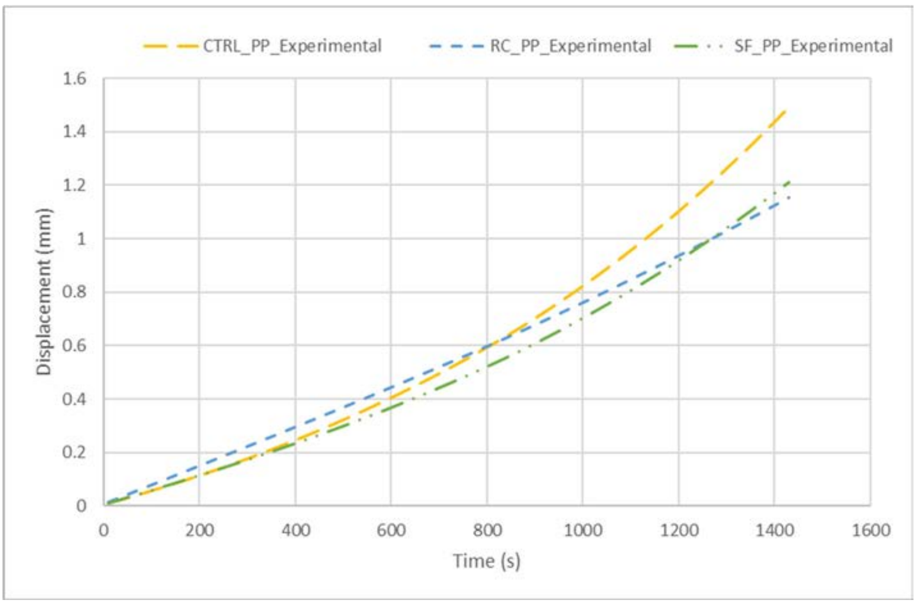

Figure 10: Vertical deflections during thermal load.

1,440 m/s). All samples exhibit a sudden increase in deflection with peak deflections of 13.2 mm (control + PP), 9.3 mm (RC+PP) and 10.8 mm (SF + PP). The inclusion of RC and SF improves resistance to the impact load, with the standard RC exhibiting higher resistance than SF. The post-impact residual deflections are all approximately 4 mm.

6 FURTHER RIG DEVELOPMENTS AND APPLICATIONS

For these experiments the compression rig was configured to apply a compressive axial load to the column sections. Modifications to the positioning of the columns or the compression

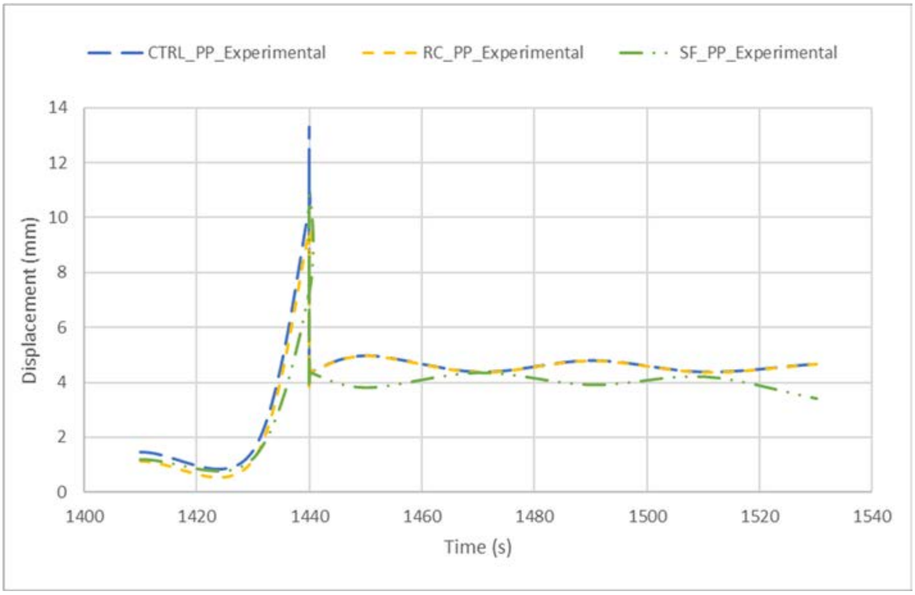

Figure 11: Vertical deflections under impact load.

rig will enable the application of a non-concentric axial load to the columns. This eccentric axial load will develop bending stresses within the structural element, allowing the combination of bending stresses, thermal and impact load to be researched. This combination of load sets would be more akin to beams and structural frames. Initial experimental testing has begun on rectangular, square and circular hollow steel sections. Further investigation could also look into the response of thin gauge steel sections, different materials and section types used for secondary structural applications including cladding and curtain wall systems, such as aluminium channels. This work will be validated with detailed computational studies using non-linear finite element analysis. Alterations to the impact rig include dropping the impact rod from a higher height to achieve a higher imparted kinetic energy. The use of interchangeable impact heads types such as conical, pointed and triangular could be adopted. In order to increase the applied temperature to the columns, the rig could be developed with wrap around insulated panels to maintain high temperatures and reduced the heat loss via radiation and convection. Further ceramic tiles along the full length (500 mm) of the column could be adopted.

7 CONCLUSIONS

This paper documents the development of a combined impact, thermal and compression rig for testing short structural columns. A series of concrete columns were tested in the rig with PPE, SF, RC and plain concrete. All columns with PPE were able to reach the maximum set temperature of 400°C without explosive spalling, whereas several column sections without PPE exhibited explosive spalling before reaching 400°C. The vertical deflection of all column types (CTRL, RC and SF) containing additional PPE were lower than the non-PPE equivalents, demonstrating that the use of PPE in the concrete mix improves the resistance at higher temperatures and enables stability against explosive spalling. The columns subject to higher temperatures also exhibited the higher deflections from the subsequent impact.

The testing rig was successful in producing high thermal loads in combination with compressive axial loads (akin to a column in service), and impact loads. The results from the concrete column trials have demonstrated that the rig can replicate extreme loading events on short structural elements, repeated at a low cost with a reasonable level of accuracy. The current limitations including limited maximum temperature (400°C), low impact energy and applied compressive stresses will be overcome with further rig developments.

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