Journal of Physics:
Conference Series

PAPER • OPEN ACCESS

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To cite this article: Florian Put *et al* 2024 *J. Phys.: Conf. Ser.* **2885** 012105

Journal of Physics: Conference Series **2885** (2024) 012105 doi:10.1088/1742-6596/2885/1/012105

High-Intensity Fast-Response Electric radiant Panel (HIFREP) for increased accuracy on thermal boundary conditions during fire testing

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Abstract. Fire resistance tests rely on the use of standardized furnaces to apply specific thermal boundary conditions to assess the performance of construction materials and systems in fire conditions. However, these tests are very expensive and encounter challenges related to repeatability and uncertainties in establishing thermal boundary conditions. Moreover, their incapacitance to tailor experiments hinders advancements in understanding structural behaviour during fire exposure. In this work, a novel type of radiant panel, that operates on electricity, is introduced: the High-Intensity Fast-Response Electric radiant Panel (HIFREP). This innovation offers enhanced sustainability performance while ensuring more precise control over thermal boundary conditions. By eliminating the need for gas combustion, the panel can be used in a traditional structural testing lab to investigate non-combustible materials (e.g. concrete), without requiring extraction hoods and other provisions. The presented electric radiant panel system represents a significant step forward from fire resistance furnace testing.

1. Introduction

Fire testing generally refers to the evaluation of different properties of building materials and building components. Commonly assessed properties include flammability, burning characteristics, mechanical behaviour at elevated temperatures, integrity and fire resistance [1]. In structural fire engineering, the main property of interest is the fire resistance, R, which indicates the time a system can maintain load-bearing capacity when exposed to a prescribed standard heating regime, e.g., ISO 834 [2] or ASTM E119 [3]. These tests are commonly performed in standardized furnaces. It is a conventional approach that allows for comparison, but it has not been designed specifically to provide insight into structural fire performance during natural fire exposure.

Although standardized furnace tests aim at the harmonisation of fire tests by introducing a systematic approach, it is well known that they face challenges regarding repeatability and uncertainties in thermal boundary conditions [4]. Crucially, natural fires can differ significantly from standard heating regimes, which do not consider fuel and ventilation characteristics and ignore the existence of a fire decay and cooling phase. The real fire performance can differ significantly from what might be expected from the fire resistance rating. Hence, a system that easily allows for different exposures in the function of the application is desirable. In addition, standardized furnace tests lack the possibility to tailor experiments to allow for an improved understanding of structural behaviour during fire exposure.

In recent years, bench-scale testing has become increasingly popular to overcome the challenges of standardized furnace tests. Precise control of thermal boundary conditions is generally achieved by isolating the radiative heat transfer, reducing the uncertainties inherent to convective heat transfer. Gas-fired radiant panels, such as the Heat-Transfer Rate Inducing Systems (H-TRIS), have had worldwide success as they are capable of imposing high (above 100 kW/m²) and stable heat fluxes on specimens [5]. Because of its reliance on combustion, such panels cannot be readily used in a traditional structural testing lab such as the Magnel-Vandepitte laboratory at Ghent University.

This paper discusses the High-Intensity Fast-Response Electric radiant Panel (HIFREP) which has recently been developed in the Structural Fire Engineering research group at Ghent University. The panel was custom-made and is powered by electricity. Therefore, it avoids the direct combustion of gas to impose the desired thermal boundary conditions and results in a broader applicability in traditional structural testing laboratories.

2. Panel configuration

The main mode of heat transfer in the radiant panel is radiation, allowing for a precise control of the thermal boundary conditions of exposed specimens. The entire setup consists of 4 main parts, being the radiant panel itself, the power supply, the cooling system, and the control system. Each of the four components and their respective role in the overall setup is discussed below.

2.1. Radiant panel

The radiant panel itself consists of densely spaced infrared emitters. Each emitter consists of a thin filament in tungsten material, 50cm long, separately surrounded by a quartz glass tube as protection. The backside of this tube is covered in a reflective quartz coating, which reflects the radiation to the front of the panel, increasing the heat flux at the front of the panel. An illustration of the radiant panel and emitters can be found in Figure 1. A close-up of the emitters can be found in Figure 2.

Figure 1: Infrared emitters operating at 10% intensity.

Figure 2: Close-up of emitters operating at 10% intensity.

The radiative heat flux is created by running a current through the tungsten filaments. The filaments heat up and radiate heat in function of their temperature (wavelengths ranging from 300 nm to 5000 nm with a peak around 1100 nm). The radiative heat flux can thus be controlled by modifying the current through the filaments and they will respond quasi-instantaneously. To protect the radiant panel from unwanted events during testing, such as concrete spalling or unexpected failures during mechanical testing, the setup is protected with an additional quartz glass plate, positioned between the tested specimens and the emitters. The presence of this glass pane causes a reduction in heat flux of 13%.

2.2. Power supply

The power supply is provided through an electric cabinet which converts a three-phase current from the general electricity grid into a DC current for the panel. The power of the entire system at full capacity is 91 kW. The power supply has two safety levels that will shut down the radiant panel when the temperature inside the box, behind the infrared emitters, becomes too high. The first level is an alarm at 50°C, warning the operator. The second level is the complete shutdown of the panel at 80°C.

2.3. Cooling system
Although the radiant panel is used to mimic fire exposure, the panel itself should keep a relatively normal operating temperature in order to avoid damage to its components. Sufficient cooling of the panel is ensured by an air cooling system, which takes in ambient air and blows it through the panel, cooling the emitters and the radiant panel frame (see Figure 3). The air stream is evenly distributed over the emitters by a perforated steel plate, located behind the emitters. After cooling the emitters, the air stream is deflected by the protective quartz glass pane at the front of the panel, limiting its influence on the convective flows at exposed specimens.

An important factor to consider in the cooling system is the positioning of the intake fans. They should be sufficiently far from the panel itself to avoid the intake of air at elevated temperature (i.e., air heated by the panel), since this would hamper proper cooling. As can be observed in Figure 3, both the panel and the fans are mounted on a frame, which can be viewed in more detail in Figure 4, to ensure sufficient distance and allow for easily changing the positioning of the panel from horizontal to vertical. Nevertheless, when used in the horizontal position as demonstrated in Figure 3, an additional external fan is used to provide ambient air for the intake fans.

Figure 3: Fan positioning with respect to the radiant panel to ensure adequate cooling.

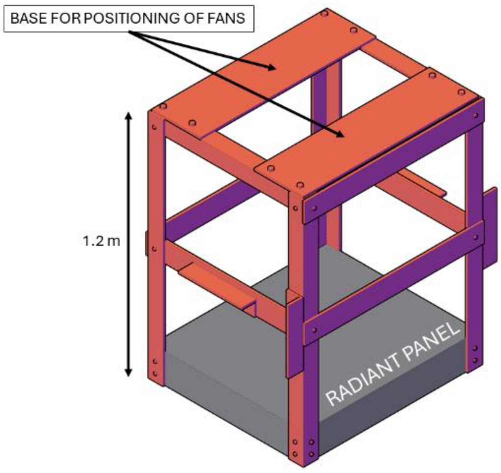

Figure 4: Sketch of the metal frame carrying the panel and cooling system.

2.4. Control system
The radiant panel setup is controlled by an in-house developed Python-based graphical user interface, in which the intensity can be controlled, ranging from 0 to 100%. This intensity is communicated to the cabinet through a voltage signal (range 0-10V) which the panel then translates into a current passing through the emitters. Due to this mode of operation and the emitters' low thermal inertia, the imposed thermal boundary conditions can be adjusted very quickly and accurately. A change in input intensity is quasi-instantaneously translated into a change in radiative intensity, allowing for a precise control of the incident radiation.

The control system also directly monitors a heat flux gauge, which can be freely positioned, although an obvious choice for the position would be in the same plane as the exposed surface to record the imposed heat fluxes during the test. Although the radiant panel exposes the surface to a purely radiative heat flux, a boundary layer flow is created between the exposed surface and the panel as a result of natural convection, resulting in an increased total heat flux (radiation + convection).

3. Panel Calibration

Within this study, the radiant panel has been installed and calibrated in a horizontal position, with the emitters facing towards the floor. Nevertheless, the same concept can be applied to any configuration. The radiant panel can thus also be used in vertical position, although it is noteworthy that this will alter the convective heat transfer, both on the surface of the panel and on the exposed surface of the specimen. Heat flux measurements have been performed for a quarter of the panel in a grid of 6 x 4 points with a 10 cm spacing at four distances (5, 10, 15, and 20 cm) and for two panel intensities (i.e. 50 and 100%). Assuming pure symmetry, the results for one quarter of the panel can be extrapolated to the other quadrants. The results of these heat flux measurements at 100% intensity are demonstrated in Figure 5 for distances of 10 and 20 cm respectively (starting from the protective glass). In these pictures, the red line indicates the radiating area of the panel, the blue line represents the uniform zone according to design specifications, and the green dots represent the measurement positions. The results show that in the centre of the panel, a heat flux of over 100 kW/m² can be reached when operating at 100% intensity, and that the heat flux remains high in the zone of uniform heat flux. Outside this zone, the heat flux decreases quickly, according to the reduction of the view factor. In addition, it was confirmed that the rate of change is quasi-instantaneous with the panel going from 0 to 100% intensity in around 1s.

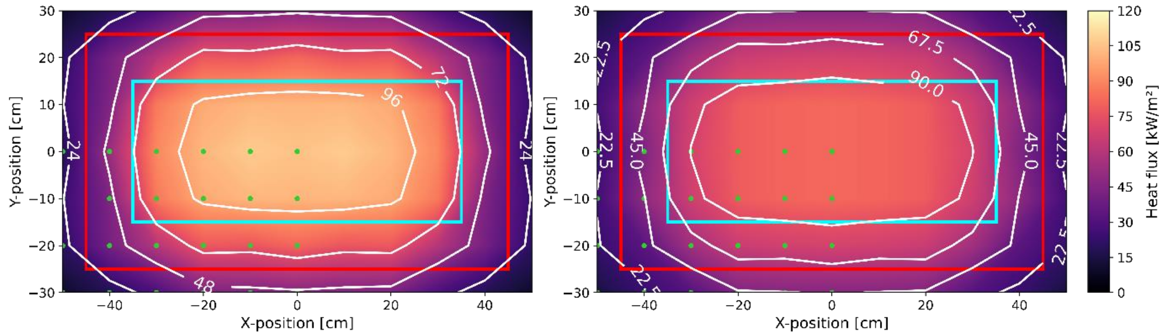

Figure 5: Heat flux map for 100% intensity at a distance of 10 cm (left) and 20 cm (right)

Additional measurements have been performed in the three other quadrants to verify the assumption of symmetry of the heat flux imposed by the panel. A total of 9 measurement positions were chosen over these three quadrants. For each of these positions, measurements were performed at 50 and 100% intensity. The results, visualized in Figure 6, demonstrate that the measurements in quadrants 2, 3, and 4 (respectively top left, top right, and bottom right quadrants in Figure 5) resemble the measurements in the first quadrant very well, especially given the uncertainty inherent to the heat flux gauge measurement.

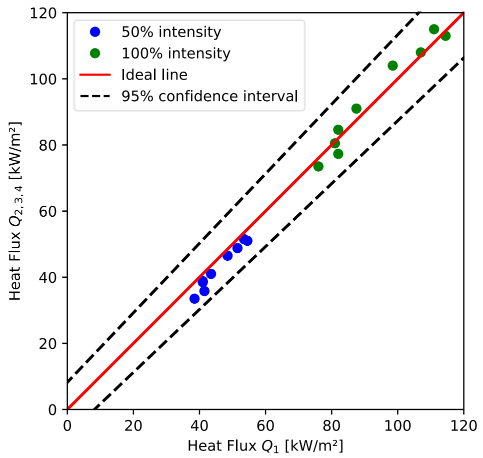

Figure 6: Comparison of measured heat fluxes in quadrant 1 with a selection of locations in the other quadrants.

4. Application case

To demonstrate the effectiveness of HIFREP for structural fire testing applications, measured temperatures inside a fire-exposed specimen are compared to calculations, performed using the finite element software SAFIR [6]. The default settings for the parameter values were used for the concrete moisture content, thermal conductivity etc.

The experiment considered a reinforced concrete beam subjected to a reversed 4-point bending test (supports in the middle of the beam and loaded on the sides). The middle 70 cm of the beam was exposed to a parametric fire curve, mimicked by the radiant panel through a time history of the incident heat flux. An illustration of the setup is shown in Figure 7, which shows a picture of the setup taken during fire exposure. Figure 8 depicts a schematic overview of the test setup. The hydraulic jacks can be observed on the left and right of the picture, hidden from the radiation by protective calcium silicate boards. In the middle of the beam, the radiant panel imposes fire exposure. The heating zone is confined to a zone with a length of 70 cm (size of the zone of uniform heat flux) by a protective mask of calcium silicate boards, which aims at reproducing a one-dimensional heat transfer. The temperatures are recorded using K-type thermocouples that were casted inside of the beam.

The heat exposure was stopped after 110 min as a steep increase in deformations was measured, indicating eminent total failure of the beam. The temperatures were still recorded after this point, as demonstrated in Figure 9.

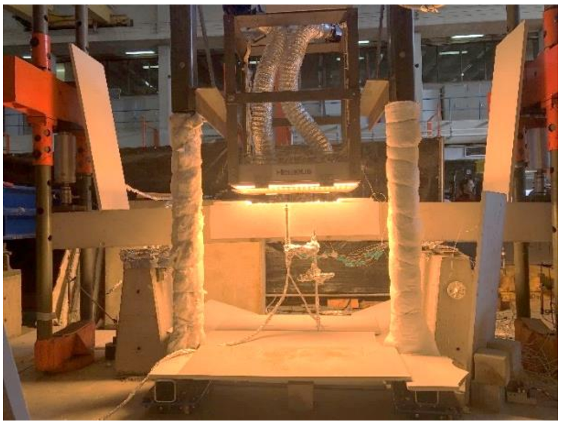

Figure 7: Reinforced concrete beam in reversed 4-point bending setup with the middle part exposed to fire using the electric radiant panel.

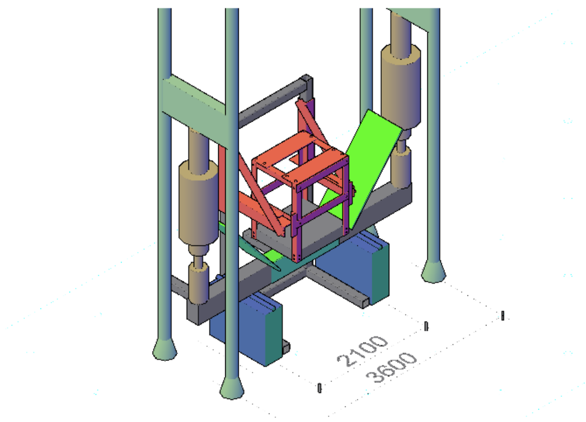

Figure 8: Schematic view of reversed 4-point bending setup with the middle part of the beam heated with the radiant panel.

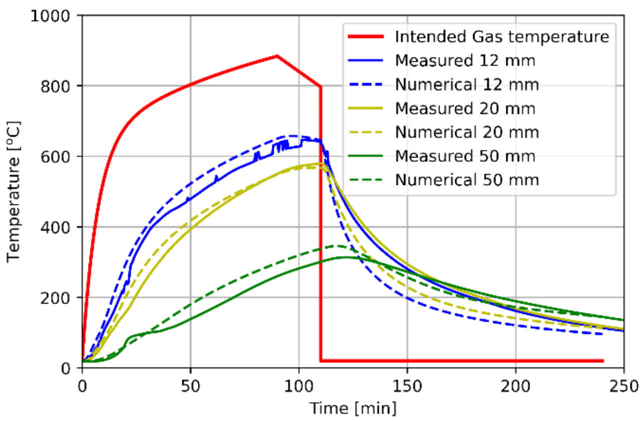

Figure 9: Temperatures at different depths from the exposed surface as simulated (dashed lines) and recorded during the fire experiment (full lines).

The temperature profiles recorded during the fire experiment are presented alongside finite element calculations for three distinct depths (i.e., 12, 20, and 50 mm from the exposed surface). The comparison between measured and calculated temperatures reveals extremely good agreement over the entire beam, with a special emphasis on the central region of the beam, indicating an accurate definition of the thermal boundary conditions. However, slight deviations become apparent near the exposed surface. This phenomenon may be attributed to the significant temperature gradient near the surface, where minor discrepancies in the thermocouple positioning can result in notable variations in temperature readings. Also near the bottom of the beam, slight deviations can be observed. These are mainly related to an underestimation of the water content in this region, resulting from the moisture wave induced by the fire exposure.

5. Conclusions

The High-Intensity Fast-Response Electric radiant Panel (HIFREP) has been developed by Ghent University's Structural Fire Engineering research team. The panel offers a sustainable alternative to standardized fire tests due to the bespoke nature of the experiments, allowing for an improved understanding of the behaviour, high repeatability and better control of key variables. The panel consists of infrared emitters that are voltage-controlled, allowing for a precise and easily adjustable heat flux, and a high degree of repeatability.

Calibration of the panel confirmed the design specifications of a zone with a uniform heat flux of 70 cm by 30 cm. Using a showcase experiment involving a reinforced concrete beam exposed to a natural fire curve, it was demonstrated that the panel has the ability to accurately replicate thermal boundary conditions and can be used for structural fire testing considering non-standard fire scenarios. Measured temperatures closely matched those of finite element calculations.

Acknowledgements

The first author is funded by Research Foundation of Flanders (FWO) within the scope of the research project (Grant number 1137123N) "Characterization of the thermal exposure and material properties of concrete during the fire decay phase for performance-based structural fire engineering". Balša Jovanović is funded by Research Foundation of Flanders (FWO) within the scope of the research project (Grant number 3G010220) "Vibration-based post-fire assessment of concrete structures using Bayesian updating techniques". Andrea Lucherini would like to gratefully acknowledge the financial support for the FRISSBE project within the European Union's Horizon 2020 research and innovation program (GA 952395).

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