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A Method for Controlled Heating of Reinforced Bars to Simulate Thermal Conditions in WAAM-Fabricated Steel

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Working Group 2: Concrete Technology

1 Introduction

Pull-out tests, as specified by RILEM RC6, are used to evaluate the bond strength between a reinforcement bar and the surrounding concrete matrix. In these tests, a reinforcement bar is centrally embedded in a cubic mold (side length of 200 mm) which is afterwards casted with concrete. The bar is divided into an embedment section where bond takes place, typically five times the bar diameter (5 × d_s), and an isolated section, where bond is prevented. This is often realized with a sleeve around the reinforcement bar to prevent concrete adhesion.

Within the framework of the DFG-funded TRR 277 project (Subproject A02), we aim to combine the Selective Paste Intrusion (SPI) method as an additive manufacturing technique for concrete elements, with the Wire Arc Additive Manufacturing (WAAM) method to simultaneously produce steel reinforcement within the particle bed. This combination aims to enable the production of steel-reinforced concrete components with enhanced geometric freedom. A key challenge in integrating WAAM with SPI are the high temperatures generated during the WAAM process, which may affect the properties of the surrounding SPI-made concrete. Elevated steel temperatures could potentially compromise the bond strength between WAAM-produced steel and SPI concrete. Therefore, this study aims to develop a method to heat steel reinforcement to a defined temperature in a RILEM TC6 pull-out test setup and to maintain that temperature for a specified duration. The overall goal is of course to quantify the bond strength between WAAM-made reinforcement within the SPI-made concrete as a function of reinforcement temperature and thus the WAAM process parameters.

2 Methods

To achieve steel temperatures exceeding 200 °C, five heating methods were evaluated:

- **Gas Torch:** Direct heating via radiation.
- **Hot Air Gun:** Heating through convection.
- **Oven Preheating:** Preheating steel bars in a hot air oven.
- **Induction Coil:** Electromagnetic induction for controlled heating.
- **Heating Cartridge:** A cartridge inserted into a drilled core in the steel bar.

For the gas torch and hot air gun tests, a WAAM reinforcement bar was placed in a pull-out formwork and heated directly.

Oven tests involved preheating WAAM bars before their placement in the mold. Induction coil tests aimed to regulate the steel temperature precisely, including post-concreting, without direct steel access. Similarly, heating cartridge tests involved inserting a cartridge into a drilled core in the WAAM steel bar to enable precise temperature control through direct contact.

3 Results and Discussion

<u>Gas Torch</u>

The gas torch achieved temperatures above 200 °C. However, precise temperature control or maintenance was not feasible, limiting its suitability for reproducible tests.

<u>Hot Air Gun</u>

The hot air gun was tested to achieve more controlled heating compared to the gas torch, as it delivers lower thermal energy. However, similar to the gas torch, precise temperature regulation was challenging, rendering this method unsuitable for consistent results.

Oven Preheating

Oven preheating allowed better temperature control than direct heating methods. However, non-uniform temperature distribution along the bar was observed, likely due to variations in steel microstructure or oven temperature zones, see Fig. 1. Additionally, rapid cooling at ambient conditions after removal from the oven prevented consistent temperature application to the concrete. This high cooling rate also complicates reproducibility across test series.

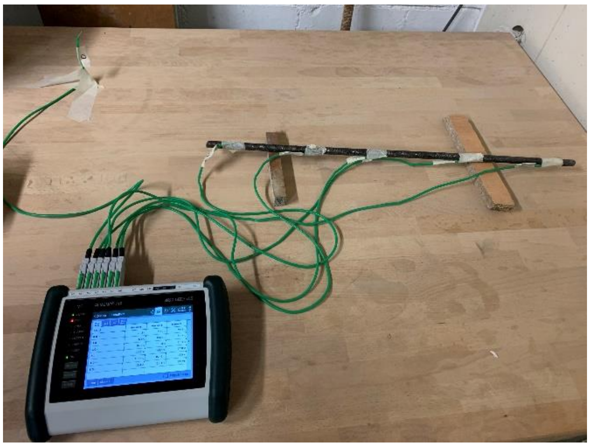

Figure 1: Measuring cooling rates at different locations on the rebar

Induction Coil

An induction coil prototype was developed to achieve and maintain target temperatures at ambient conditions, enhancing reproducibility, see Fig. 2. Despite varying current and voltage settings, the coil failed to generate a sufficient induction field to heat an embedded bar to 200 °C. Further tests were discontinued due to safety concerns.

Figure 2: Induction coil to heat steel reinforcement.

Heating Cartridge

A heating cartridge was inserted into a longitudinally drilled core in the WAAM steel bar, sie Fig. 3 and Fig. 4. The cartridge was controlled by a PID controller (Shinko GCS) to achieve and maintain defined temperatures in the steel core and on the bar surface in direct contact with the concrete.

The controller was set to a target temperature 5°C below the desired value, operating in an on/off mode without integral or derivative components. Upon reaching the setpoint (target temperature minus 5°C), brief heating pulses were applied, causing the cartridge temperature to overshoot momentarily to the target temperature plus 7°C to 10°C. Consequently, the cartridge temperature fluctuated between the target minus 5°C and plus 10°C. This approach ensured a relatively stable surface temperature on the steel, with fluctuations limited to the target temperature minus 2°C to plus 4°C. This method enabled precise and reproducible temperature regulation, even after concreting, without requiring direct access to the steel surface.

Figure 3: Heating cartridge being inserted into a pre-drilled rebar embedded in the pull-out test setup

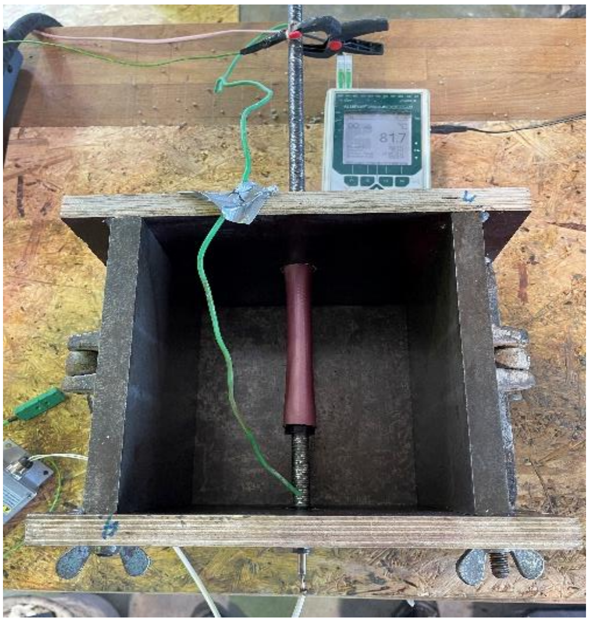

Figure 4: Measuring the Temperature on the rebar surface while heating with heat cartridge.

4 Conclusion

The heating cartridge method demonstrated the highest potential for controlled and reproducible heating of WAAM steel reinforcement in pull-out tests. It allows precise temperature regulation and maintenance, addressing the challenges posed by WAAM process temperatures in SPI concrete production. Future work will focus on optimizing this method and conducting pull-out tests at various steel temperatures to quantify their impact on bond strength.

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