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INDUCTION HEATING SYSTEM FOR TENSILE COUPON TESTS

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Abstract: *The paper focuses on the impact of fire-induced dynamic actions on structures, particularly material behavior at high temperatures and strain rates. The goal is to calibrate an induction heating system for tensile coupon tests to obtain material properties under dynamic loading. Previous studies on creep effects and strain rates in steel were reviewed. The research uses steady-state testing to assess the mechanical properties of steel under heating and loading conditions, ensuring a uniform temperature distribution within the specimen. Experimental results are combined with numerical simulations to predict temperature distribution and analyse the effects of different heating and loading rates on creep.*

Keywords: induction heating, tensile test, creep, steel, numerical model

1. Introduction

In addition to thermal effects, the structure in a fire can be exposed to other extreme actions, such as impact or explosion. The former may occur during progressive collapse, when failure of one element, or part of the structure, results in an impact on the others. To analyze the effect of such a type of loading on a structure, it is important to know the sensitivity to the strain rate of the structural material considered (Jankowiak, 2016). In these cases, the material exhibits thermoelastic-viscoplastic behavior (Glema et al., 2009). The aim of the ongoing research titled “Material and structural response to dynamic actions in fire” in cooperation between Poznan University of Technology and Czech Technical University in Prague is therefore to investigate the influence of fire-induced dynamic actions on structures. Achieving this goal requires acquiring knowledge about the behavior of materials at simultaneous high temperatures and high strain rates. The results of planned experiments on material behavior will further enable the calibration of mathematical material models. This paper deals with a part of this research focusing on calibration of induction heating system for quasi-static tensile coupon tests.

In the recent past the properties of structural steel at high strain rates and high temperatures have been studied by Kajberg and Sundin (2013) and Forni et al. (2016), who provided properties of structural carbon steel at strain rates up to 850 s^{-1} and temperatures up to 1200 °C. The group of researchers Forni et al. (2016) published a series of articles dealing with material behaviour at high strain rates and high temperatures, including very-high strength structural steels such as S960QL (Cadoni and Forni, 2019). The research mentioned on material behaviour at high temperatures and high strain rates, also provides information on the testing methodology. In all the referred papers, different methods of heating were used for

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testing – an induction coil (Kajberg and Sundin, 2013), induction heating system (Cadoni and Forni, 2019), and circular electric ovens (Quinn et al., 2020).

2. Thermal creep

The importance of creep strains in modeling the stress-strain relationship was first pointed out by Anderberg in the 1970s (Anderberg, 1976). Except Anderberg´s model, there are other models that describe the behavior of steel at elevated temperatures, for example (Rubert and Schaumann, 1985), and Poh (2001). The Eurocode 3 steel material model (EC, 2005) is widely used for design and research purposes. The model itself was created on the basis of test results from (Anderberg, 1976, 1983) conducted with a heating rate of about 10 °C/min. Therefore, the model may logically be considered as conservative for heating rates which are over 10 °C/min. However, this does not apply for heating rates below 10 °C/min (expected for protected and unprotected steel members, depending on the heating rate of the fire), in which case more substantial creep is expected to occur (Anderberg, 1988).

The influence of the magnitude and rate of development of stress and high temperature on creep strain in steel structures was described in (Rubert and Schaumann, 1986), or in the recent past (Kodur and Dwaikat, 2010; Torić and Burgess, 2021). The results of the studies show that slower heating leads to greater creep. According to Torić and Burgess (2021), high temperature in a fire can be divided into three heating-rate categories: high heating rates (> 20 °C/min), intermediate heating rates (10–20 °C/min) and low heating rates (< 10 °C/min). Kodur and Dwaikat (2010) reported fast heating rates (20–50 °C/min) and slow heating rates (3–7 °C/min). Results of the study also state that the effect of thermal creep can be neglected when exposed to heating rate higher than 15 °C/min. Generally, high heating rates occur when the fire is close to a structural element. A good example of this is fire testing using the ISO 834 standard fire curve, which results in very high heating rates for the tested elements during the first 5 minutes of exposure. Lower heating rates are observed in elements that are either protected by fire-resistant measures or located further away from the fire source. The heating of a natural or traveling fire can be represented by a heating rate of 20 °C/min. Numerical study in (Kodur and Dwaikat, 2010) discusses also an exposure to natural fire scenarios with a cooling phase, summarizing the findings that high-temperature creep should be incorporated in the fire resistance analysis since creep influences response under cooling phase. In (Torić and Burgess, 2021) three categories of strain rates have been introduced: high (>0.1/min), medium (0.02–0.1/min) and low (<0.02/min). Low strain-rates are present in cases when creep is initially activated and in normal service load conditions. High strain rates are present at the onset of a structure's collapse mechanism.

3. Material testing

Elevated-temperature material properties can be assessed through either using steady or transient state test. In steady-state testing, a specimen is heated up to a target temperature, then gradually loaded until fracture while maintaining a constant temperature. In contrast, during transient-state test, a specimen is first loaded to a predefined stress level and is then exposed to uniformly increasing temperatures. While transient-state testing more accurately replicates real-building fire scenario, it results to slightly lower strength and stiffness due to the extended testing duration, especially at temperatures above 400°C at which the creep effect of steel is more significant. Steady-state tests are more effective for determining elevated-temperature material properties because they are less affected by creep and provide direct stress-strain data. To resolve the influence of fire-induced dynamic actions on structures experimental study is focused on different ways of heating (slow, medium, fast rates, natural fire) and high strain rates representing an effect of dynamic action. Steady-state method is adopted for testing as it represents the case of a failure of one element, or part of the structure due to an ongoing fire.

4. Induction heating system and its calibration

The authors propose to perform steady-state tensile coupon tests in order to find out the material's mechanical sensitivity to high temperature under loading with purpose to obtain realistic mathematical models of materials for numerical simulations. For these tests uniform and well-defined temperature inside the specimen is very important. The sample were heated locally using an induction coil heater. The internal diameter of the coil is approx. 27 mm and the length of the directly heated zone inside the coil was approx. 20 mm.

The heating was regulated through a programmable PID digital controller unit and followed a desired temperature gradient up to the target temperature. The controller unit monitored temperature directly in the heated zone using a selected K-type thermocouple.

Circular specimens of diameter 10 mm and length of 180 mm of steel grade S355J2 were used for calibration tests. They were equipped with K-type thermocouples of 0.5 mm diameter with ceramic fiber coating in eight positions to control the uniform distribution of temperature along the specimen (Fig.1 left). As the target temperature is reached in the centre of the specimen (monitored by an average of four thermocouples located below the induction coil), it is loaded until failure (Fig.1 right). To calibrate the method and to gain knowledge about effect of creep in different thermal and mechanical loading conditions, following parameters are studied: 1. rate of heating up to maximal temperature, 2. the maximal temperature (450 °C and 600 °C in this study), 3. duration of the maximal temperature before mechanical loading, 4. rate of mechanical loading (from 10 mm/min up to 200 mm/min in this study). Fig. 2 shows results of one of the pilot tensile tests. The specimen was heated with induction system up to 600 °C in 20 seconds. After next 20 seconds a loading with speed 100 mm/min was applied.

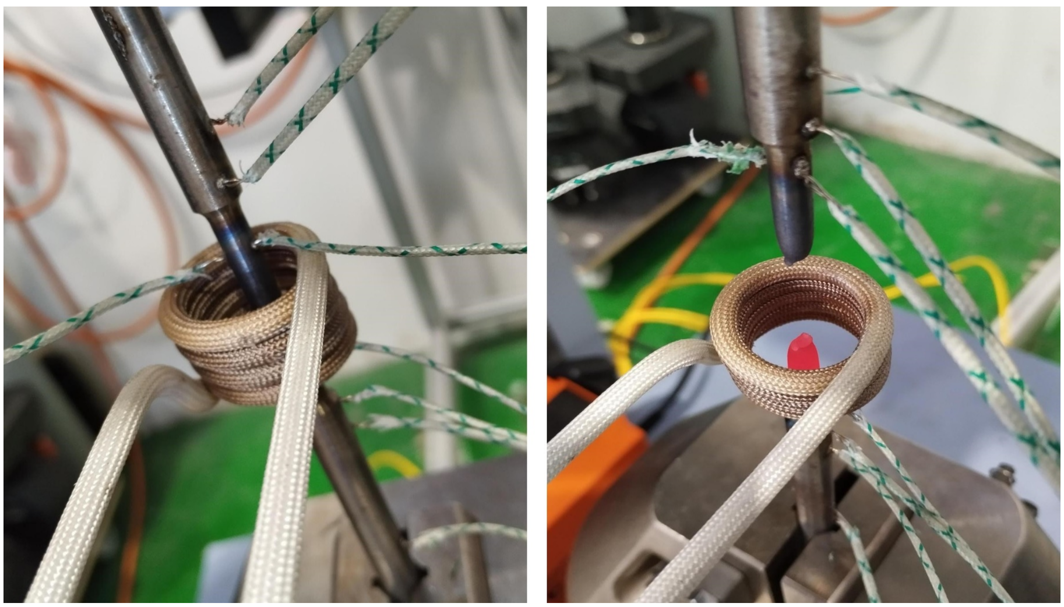

Fig. 1: Before heating with induction coil fitted with thermocouples (left); After failure (right).

The calibration of the heating system is based on coupling of the numerical simulation in Ansys software, and experimental results. Transient thermal heat transfer analysis is used to predict the distribution of temperature in the volume of the specimen. The thermal properties of steel are taken as temperature dependent according to Eurocode 1993-1-2 (EC, 2005). Thermal load following the measured temperature-time development on the central four thermocouples is applied to the central ring of the specimen. Sensitivity of temperature distribution inside the specimen to parameters studied due to possible effect on creep strain (magnitude and rate of development of high temperature) is studied in the numerical models.

5. Conclusions

This study emphasizes the impact of dynamic actions induced by fire on the behavior of materials in structures, particularly at high temperatures and strain rates. Creep effects become significant at temperatures above 300–400 °C and are influenced by heating and loading rates. Steady-state testing is effective in determining material properties as it minimizes creep effects and provides direct stress-strain data. The induction heating system ensures fast and controlled heating of specimens, which is ideal for fire conditions testing. Combining experimental results with numerical simulations allows accurate predictions of the temperature distribution and the effects of various heating rates on creep. These findings improve the calibration of material models, improving the accuracy of the fire resistance analysis for steel structures.

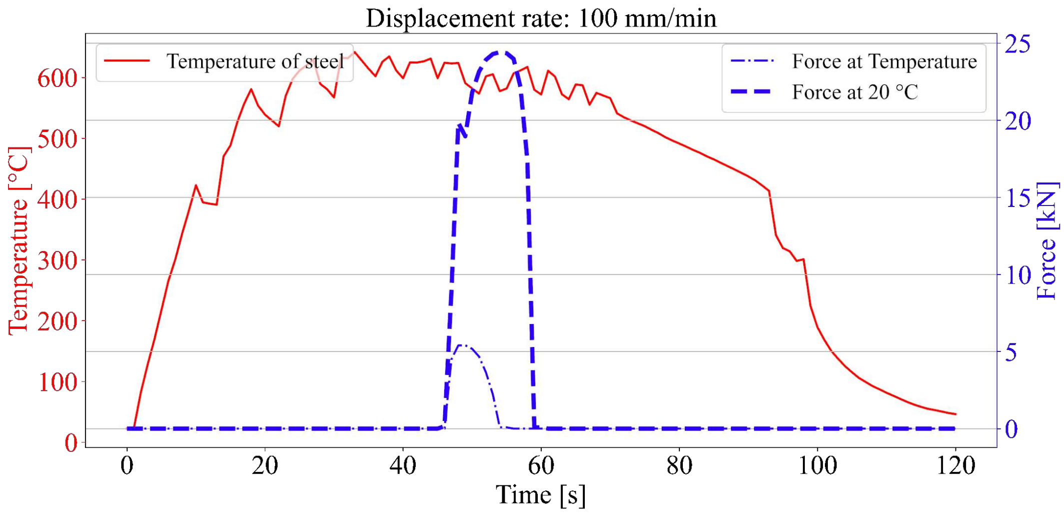

Fig. 2: Results of one of the pilot tensile test.

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