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Development and experimental validation of a simplified Finite Element methodology to simulate the response of steel beams subjected to flame straightening

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HIGHLIGHTS

- A FE model was developed to characterize (Rykalin approach) the propane flame used.
- A FE model of flame-heated plates was developed and experimentally validated.
- A method to obtain the deformation of flame-treated beams was validated.
- With three FE simplistic simulations, the shape of a heated beam can be obtained.

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ABSTRACT

The most important factor in achieving a successful result in the application of the flame straightening procedure on structural steel parts is, as of today, the operator's skill and experience. In many cases, it is necessary to undertake a trial and error process until the desired final geometry is obtained. A simplified methodology, based on the Finite Element technique, is proposed in this paper, allowing the final geometry and the residual stress state in components subjected to flame straightening to be determined. The behavior of three structural profiles -HEA 300, HEM 340 and IPE 450- manufactured in three widely used steel grades -S235 JR, S355 J2 and S460 ML- has been investigated. The research can be broken down into the following stages. First, the thermal properties have been obtained from the scientific literature and the mechanical behavior of the materials has been experimentally determined by means of tensile tests carried out in the range 20–1000 °C. Second, a thermal Finite Element model was developed to characterize the properties of the propane flame employed in this research. This thermal numerical model was validated by comparing its predictions with the records provided by a set of thermocouples attached to a plate subjected to flame straightening. Next, a thermo-mechanical numerical model was prepared and experimentally validated subjecting a second instrumented steel plate to flame heating. Finally, a simplified approach has been developed and contrasted experimentally to allow the response of a large beam subjected to flame heating to be simulated by means of conventional computational resources. The method proposed is based on breaking down the original beam into a set of short beams, one for each of the heated regions in the original beam. Under very general conditions, one thermal simulation and two mechanical simulations suffice to estimate the whole deformation of a beam, resulting in a great simplification of the problem.

1. Introduction and scope

The flame straightening (or flame bending) process is a very common practice in steel-made structural elements. It consists in applying local heat to the component by means of a torch (the most common used fuel gases are oxy-acetylene, natural gas or propane) following predefined patterns to control geometric distortions or tolerance deviations (typically caused during fabrication or welding). The restrictions imposed to the material free thermal expansion create a distribution of residual stresses leading —if the process is correctly applied— to the desired permanent deformation of the component after cooling down. These restrictions may be internal (due to the non-uniform temperature distribution in the material) or external (as a consequence of the loads

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or boundary constraints deliberately applied to the part). As typical examples, this process is commonly used to form the compound curvature of ship hull plates or to bend structural beams (this practice being commonly applied in construction sites).

It is a matter of fact that many aspects of the process remain as uncertainties: for example, what are the optimum heating sequences and patterns, how should constraints be utilized or how to evaluate the residual stresses after heating and cooling. As Professor Avent has emphasized [1–5], "the process remains more of an art than a science". Indeed, the technical background in the workshops of steel constructors is usually mostly based on empirical grounds. This situation often leads to expensive and unsafe trial-and-error processes. In a previous contribution by the same authors [6], the influence of the flame bending procedure on the material properties of three very different structural steels (S235 JR, S460 ML and S690 QL, respectively), widely used for the construction of metallic structures for buildings or bridges, was studied in depth. In that work, the microstructural and metallurgical changes induced by the flame heating were correlated with the mechanical and fracture properties of these three steels.

The scope of the present paper deals with several of the open issues mentioned above. Even though there are analytical solutions available [7–11] to determine the final shape and stress state in flame straightened components, their scope and reliability is limited by the stringent simplifying assumptions imposed. It does not seem possible to develop an analytical method capable of covering all the complexities associated with a real flame straightening process. For example, the characteristics of the torch (which determines the distribution of heat input), the specific heating patterns followed by the torch, the highly nonlinear thermal and mechanical responses of the material, the arbitrary geometry of the component or the effect arising from the restrictions imposed, represent difficulties virtually impossible to be modelled by means of an analytical procedure. For these reasons, in this research the Finite Element (FE) method was employed to determine the final state (geometry and stress distribution) of structural beams subjected to flame straightening. Needless to say, the difficulties mentioned above can be numerically modelled provided high quality experimental information is available. There is an additional problem in this case, which is the large size of the components to be modelled (6 meters long structural beams). In general, simulating the response of parts of this nature would usually require non-conventional computational resources (such as workstations and parallel computation) to deal with this CPU and memory intensive problem. For this reason, this paper offers a simplified approach, experimentally validated, to foresee the final configuration of structural beams that allows a personal computer with non-exceptional capabilities to be used.

This research involves three main stages. First, the (nonlinear) mechanical and thermal properties of the available materials were determined as a function of temperature. Second, the amount and characteristics of the heat input supplied by the propane torch employed was obtained. Following the method proposed by previous researchers [12–17], Rykalin in particular, the input heat flux of the flame was modelled as a normal Gaussian distribution. The free parameters of the Gaussian distribution were determined combining the experimental data, obtained by heating a plate, with the information provided by a thermal FE model. The last stage of the research consisted in the practical application of the above results to develop a series of thermo-mechanical FE models to predict the final geometry after flame straightening of different types of components. Thus, the experimental results obtained on a plate subjected to flame straightening were employed to validate the FE model; then, similar models were used to foresee the response of a series of large-size structural beams. As mentioned above, in the latter case, a simplified numerical method was implemented to make it possible to deal with such simulations in a reliable and affordable way.

2. Materials

The three following structural steel grades [18,19] were studied in this research: S235 JR, S355 J2 and S460 ML. The three materials selected for the research are representative, from the point of view of their microstructure and their chemistry, of a wide range of structural steels. Moreover, their mechanical and fracture behaviors are also noticeably different. S235 JR grade [18] is a non-alloyed structural steel with a minimum yield strength of 235 MPa and a minimum required longitudinal Charpy V-notch impact energy at 20 °C of 27 J; the typical tensile strength in this material is between 360 and 510 MPa. S355 J2 steel [18] is also a non-alloyed structural steel with a minimum yield strength of 355 MPa and a minimum required longitudinal Charpy V-notch impact energy at −20 °C of 27 J; the typical tensile strength of this material is between 470 and 630 MPa. S460 ML [19] represents a thermomechanically rolled weldable fine grain structural steel with a minimum yield strength of 460 MPa and a minimum required longitudinal Charpy V-notch impact energy at −50 °C of 27 J T_{27J} = −50 °C. The tensile strength is usually in the range of 550–720 MPa.

A number of S235 JR, S355 J2 and S460 ML steel plates, with dimensions $570 \times 470 \times 20$ mm^3 and $570 \times 470 \times 50$ mm^3, were available for the research. The tensile specimens used to characterize the mechanical response of the materials as a function of temperature were obtained from these plates. The S355 J2 plates were tested to determine the properties of the propane flame and for the validation of the thermal-mechanical FE model developed. In addition to this, three structural beams (6 meters long) were delivered to be heat-straightened. Specifically, one HEA 300 (fabricated in S355 J2), one HEM 340 (S460 ML) and one IPE 450 (S235 JR) were available for the research.

3. Experimental results

3.1. Mechanical behavior of the materials as a function of the temperature

The mechanical properties of the materials is one of the inputs needed for the FE models; moreover, the dependency between the mechanical response and the applied temperature must be obtained for a reliable simulation of the flame straightening process. For this reason, a series of tensile tests were carried out to determine the stress-strain curves of the materials in the range of temperatures between 20 °C and 1000 °C following the procedure established by the ASTM E21 Standard. The geometry of the specimens in shown in Fig. 1. These specimens were machined from the available plates, previously described. The tests were performed by means of a Universal Instron 8501 testing machine,

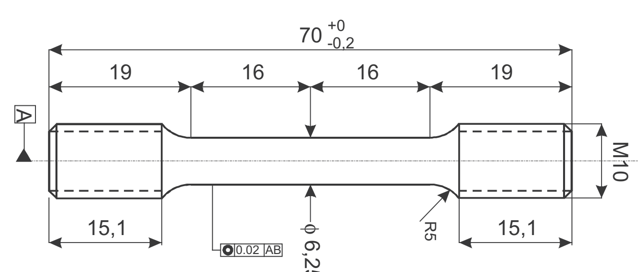

Fig. 1. Schematic description of the tensile specimens employed to determine the mechanical response of the materials as a function of the temperature.