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Fire behavior of steel wire ropes: Experimental investigation and numerical analysis

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ABSTRACT

This paper describes the mechanical behavior of wire ropes under fire conditions with the aim of developing a method for determining the fire resistance of steel wire ropes for civil and ropeway applications. The behavior of ropes subjected to severe thermal transients representative of fire scenarios has been investigated through numerical and experimental analyses. Since no standards are available for studying the fire behavior of these structural elements, the ISO 834 standard curve was considered as fire model owing to its severity. For this purpose, parametric finite element models, capable of simulating the thermo-mechanical response of both full locked and Warrington Seale ropes have been developed. The obtained information in terms of load redistribution during the test as well as evolution of damage and failure mechanisms was used to set up the experimental investigation. The good agreement between experimental and numerical results indicates the proposed approach as an effective methodology for the analysis of the fire behavior of wire ropes, once the material properties and loading conditions have been established.

1. Introduction

Structural fire safety is one of the main concerns in the design and maintenance of civil infrastructures. The ever-increasing diffusion of ropes in tall buildings, bridges, cable car, as well as in industrial applications, gives the reason for investigating rope's fire behavior. After the serious accidents occurred at the beginning of the last decade (Kaprun funicular in Austria 2000, Zugspitze ropeway in Germany 2001), Oplatka [1] investigated the most important fire events involving ropeways and recorded 35 cases, 10 of which led to the rope's failure. In two cases, failure occurred in less than 15 min. This report gave a serious warning for any ropes application. The rope exposure to high temperatures is particularly critical, since it produces a rapid deterioration of the wires' mechanical properties ending in the eventual collapse of the rope. The high carbon content and the wire drawing process produce fine pearlitic microstructures and high level of work hardening, thus combining a significant increase in tensile strength with a worsening of material ductility (Wistreich [2], Fontanari et al. [3], Ray et al. [4], Phelippeau et al. [5]). The wire exposition to temperatures above 300 °C activates the dislocation movements responsible for the annealing, thus producing an irreversible loss of the beneficial effect of work-hardening on the mechanical properties. A further increase of the temperature up to 600 °C activates the recrystallization process, responsible for the nucleation and growth of a new crystalline structure. The resulting detrimental effects on the strength characteristics are well known in the literature (Dieter [6]), moreover, for long exposure to high temperatures, viscous flow (creep) can be activated. During a fire event, however, the rope generally collapses in a very short time, hence suggesting an almost negligible contribution of both recrystallization and creep phenomena.

Despite this somewhat alarming situation in view of the widespread use of ropes in civil construction and mechanical applications, the current approaches to assess their fire safety are pretty limited. No systematic studies yet sporadic contribution can be found in the technical literature. Fontanari et al. [7] proposed recently an approach to test the fire behavior of full locked ropes, whereas Ridge and Hobbs [8] published an experimental investigation on rope sockets behavior at elevated temperatures focusing both on cast metal and polymeric socketing. Kim et al. [9] studied the fire behavior of high strength concrete columns laterally confined by wire ropes. Fontenot et al. [10] and by Horn et al.

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[11]. Presented some interesting results about the fire behavior of textile ropes. The high costs of the experiments and the difficulties in setting up the experimental devices still represent a major obstacle to the acquisition of an experimental database including different classes of ropes and to the development of a specific design code. For this reason, in facing the problem of the fire characterization of ropes, it may be useful to look at what has been already published in the literature about civil infrastructures. Although some criticisms regarding its effectiveness have been recently raised by Almand [12], one way to investigate the fire resistance of a structural element is to perform a standard fire resistance test, in order to simulate the temperature profile experienced by the structural part during a real fire event. Different time–temperature histories are suggested by the standards: one of the most used is the ISO 834 standard, which is aimed at reproducing the time–temperature evolution during a fire accident in a closed environment surrounding the structure (Hasofer [13], Drysdale [14], Rasbash et al. [15]). The component, stressed by the 'in service' structural loads and undergoing the aforementioned time–temperature history, is monitored until the final collapse or the loss of its functionality (i.e. excess of deformation, not compatible with its structural integrity). The standard temperature curves represent an overestimate of the fire heaviness: the thermal load at flashover is considered, thus neglecting the initiation of the combustion and its expansion phase, during which the temperature increases more slowly.

Transferring the outcomes of these tests into the design of ropes is not an easy task since the thermal history of each single wire is hardly predictable during the fire transient. In the scientific literature, a great effort has been devoted to understand the mechanical behavior of wire ropes under different loading conditions. The very complex load distribution among wires has been explained by means of analytical models and more recently by finite element simulations. The books of Costello [16] and Feyrer [17] summarize the theoretical foundations and also report a comprehensive database of experimental results. The analytical models are based on some simplifying assumptions and can correctly evaluate the rope's performance in the elastic regime (Velinsky [18], Velinsky [19]), Raoof and Kraincanic [20], Wang and McKewan [21], Elata et al. [22]). These approaches can reasonably describe some of the phenomena, such as contact, friction, large displacements (the full-slip regime vs. the no-slip regime), simultaneously affecting the rope's mechanical response and have been therefore adopted in the design of ropes. Finite element analysis can contribute to the comprehension of such complex phenomena. Significant contributions have been published by Nawrocki and Labrosse [23], Jiang et al. [24] Stanova et al. [25], Moradi et al. [26], Kmet et al. [27]. All of these papers are primarily focused on the rope response in the elastic regime, very little can be found dealing with the mechanical behavior of ropes in the elastoplastic regime and even less during severe thermal transients.

In the present work, the structural response of wire ropes in the presence of very severe thermal transients simulating a fire scenario is addressed both experimentally and numerically. The principal aim is to define a design tool for predicting the ropes fire resistance. For this purpose, the method proposed by the authors in [7] has been developed and extended to cover a broader class of ropes. Parametric FE models have been developed both for full locked and for stranded ropes, able to simulate the rope's thermo-mechanical response during the fire transient following the ISO 834 standard, representing a fully developed fire in a compartment. The ISO 834 time–temperature curve was adopted considering that some very severe fire accidents occurred in compartments, such as for example in the engine room of cableways. The results of this analysis are essential to define the experimental setup for safely performing the tests on the ropes. The models were set up and calibrated on the basis of experimental data measured on the rope and on single wires: i.e. tensile tests at room temperature, thermal histories of different wire layers during the ISO 834 thermal transient. Moreover, in order to correctly simulate the mechanisms of load redistribution among wires during the thermal transient, an extensive campaign was carried out on single wires to build up a database of σ–ε curves at different temperatures. These curves were then incorporated into the model for the simulation of the thermo-mechanical response of the rope. The information gained from the numerical model, in terms of load redistribution, time and mechanism of collapse made it possible to set up the experimental configuration. The results of experimental tests in terms of rope's time to failure were compared with the results of numerical modeling both for full locked and Warrington Seale ropes.

2. Geometry of the full locked and Warrington Seale strand ropes

The analysis is focused on two rope configurations: full locked and strand rope with polymeric core. In this last case the Warrington Seale strand configuration was considered in view of its widespread application. Different nominal diameters were investigated, but for the definition and the development of the finite element model, two specific geometric configurations were considered, corresponding to a full locked rope having a nominal diameter of 60 mm composed of 124 wires and a stranded Warrington-Seale 6×31 rope composed of 186 wires, respectively. These representative geometries are briefly described in the following.

2.1. The full locked rope

The sectional view shown in Fig. 1 depicts the constructive characteristics of the rope having a nominal diameter equal to 60 mm, consisting of a central straight wire, three layers of round wires and three external mantles of Z shaped wires, all with cross winding configuration. The rope labeling indicates the number of wires of each layer, starting from the core wire. The metal section of the rope is equal to 2486 mm^2, which corresponds to a filling ratio (ratio of metal to nominal cross section) of about 88%. This rope is usually adopted in buildings and bridges as tie rods.

2.2. The Warrington Seale rope

The Warrington-Seale strand configuration and the corresponding standard wire's layers definition are illustrated in Fig. 2a. This solution consists of three concentric wire layers helically wound about the core wire, comprising a total of 31 wires having different cross sections, aligned in a parallel configuration. The rope configuration made up of 6 strands wound around a polymeric core is shown in Fig. 2b. The standard sequence labeling of the strand $12 + 6/6 + 6 + 1$ indicates the number of wires from the external layer to the inner core, whereas the rope labeling includes information on the number of strands (6) and on the polymeric core (PPC polypropylene core). The metal section area of the rope is equal to 721 mm^2, which corresponds to a filling ratio (ratio of metal to nominal cross section including core) of about 64%. This geometry is typically adopted for producing ropes used for cableways and similar applications.

3. Properties of the wires at room temperature

The wires were produced by cold drawing high carbon steel C80 bars characterised by a pearlitic microstructure typical of nearly eutectoid steels. The nominal chemical composition of the wires is given in Table 1.