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Behaviour of a two-pinned steel arch at elevated temperatures

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ABSTRACT

Because of their geometrical shape, two-pinned steel arches (TPSAs) have special internal force distributions and deformations compared with conventional straight beams. However, the present studies on TPSAs exposed to fire are still quite limited with regard to their fire-induced deflection modes or deflection limits and ultimate temperatures. This paper employs several numerical models to analyse the high-temperature performance of TPSAs at elevated temperatures in terms of the effects of the load ratios, horizontal restraints, rise-to-span ratios, fire fields and geometrical sizes of the cross-section. The results show that TPSAs exposed to high temperatures are more sensitive to the load ratios than the horizontal restraint stiffness and geometrical size of the cross-section. The TPSAs could not develop catenary actions such as those of straight beams in fire; previous investigations have not predicted the behaviour of TPSAs in fire. The in-plane buckling and excessive mid-span sagging of TPSAs are the final failure modes regardless of the location of the fire actions. To date, the acceptable rise-to-span ratio is approximately 0.25–0.35 for TPSAs in fire. Finally, this paper presents a prediction formula for the limit state of TPSAs at elevated temperatures by using trigonometric functions and logarithmic regression.

1. Introduction

Two-pinned steel arches (TPSAs) are extensively used in large-span steel frames as the primary structural members [1–3]. In contrast to ordinary straight steel beams (OSSBs), TPSAs must bear a pair of push forces at the supported ends.

Although arches have been used over the last few decades, the investigations still focus on their mechanical responses at ambient temperature in terms of the geometrical shape and the lateral stability [4,5]. The studies on TPSAs exposed to a fire are still quite limited.

For the high-temperature performance of OSSBs, research has achieved many results such as the development of fire-induced forces and the modes of catenary actions [6,7]. These results are usually considered as indices for estimating the safety of OSSBs at elevated temperatures. However, there is still a need for deep discussion regarding whether these indices could be employed in the investigation or be used as an assessment criterion for the fire safety of TPSAs.

TPSAs have curved geometrical shapes compared with OSSBs. Pi et al. [8] presented that a steel arch with a small rise height was similar to a column with a small initial geometric imperfection under axial loading at a given temperature. Subsequently, Bradford et al. [9] noted that the flat arch did not develop buckling at elevated temperatures when the uniform thermal strain or a strain gradient through the cross-section interacted, and the first yield was unlikely to occur at elevated temperatures. At the same time, Bradford [10], using a nonlinear formulation of the strain–displacement relationship, found that the stiffness of the elastic spring supports is important to the temperature-dependent first yielding of a pinned steel arch.

By using geometrical nonlinear analysis, Young et al. [11] stated that long-span structural arch roofing elements were stressed at a low level. Thus, the roofing systems could not influence the arch in terms of developing its inelastic deformations during a typical fire. The stiffness between the arch-ends and the supported columns would become the dominative factor on the fire response of the steel arch.

Similarly, Heidarpour et al. [12] found that the temperature gradient exerted significant effects on the magnitude of the radial deflection and the end reactions of the steel arch at elevated temperatures. Unlike at ambient temperature at which the sustained loads caused a downward deflection, the thermal load induced the deflection of a steel arch upward at elevated temperatures.

For these, Cai et al. [13] concluded that the thermal loads would significantly affect the critical loads for both the symmetric snap-through and anti-symmetric bifurcation modes and the post-buckling behaviour. Moreover, the critical loads increased almost linearly with increasing temperature. The influence of thermal

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loads increased with increasing ratio of the span to the radius of gyration of the cross section of shallow arches. The critical loads increased with increasing initial stiffness at the supported ends.

The above studies all illustrated some important factors on the high-temperature performance of TPSAs, such as the rise-to-span ratios, the load ratios and the restraint stiffness at the arch-ends. Regrettably, these researchers did not to present the extents of these influences or develop prediction methods for the failure or the limit state of steel arches.

This paper conducts several investigations on the behaviour of unprotected TPSAs at elevated temperatures and focuses on the effect of load ratios, the stiffness of horizontal restraints at the supported ends, rise-to-span ratios, fire fields and geometrical sizes of the cross-section. Based on the failure modes and the mid-span deflections, the paper presents a logarithmic regression formula for the design deflection limits and the ultimate temperature.

2. Numerical models

This study applied ABAQUS [14] for the numerical simulation.

2.1. Numerical models of TPSAs

The TPSA models were taken from a single-floor building with a large span, as shown in Fig. 1a. The steel arch, with a span of 12 m, was supported between two columns with a height of 3.6 m. The rise, *f*, was changed within the analysis of the effects of the rise-to-span ratios where the radii, *R*, and the angle, θ.

The numerical models employed the shell elements of S4R. Multi-Point Constraints/beam (MPC/beam) was defined at the two supported ends of the steel arches so that it could be modelled as the pinned supports at the MPC master node. The type of MPC/beam provides a rigid beam effect between the master node and the cross-section to restrain the displacement and rotation at the master node to the displacement and rotation at the cross-section.

The horizontal restraints produced by the columns at the arch-ends were modelled by the 1D linear spring element (Spring1) of ABAQUS, which replaced the actions of the columns at the arch-ends. Their stiffness was defined as the lateral stiffness of the cantilever column in this study, as seen in Fig. 1b. Actually, this paper focuses on the in-plane high-temperature performance of the TPSAs at elevated temperatures; therefore, the out-of-plane restraints were employed at the top flange of the steel arch.

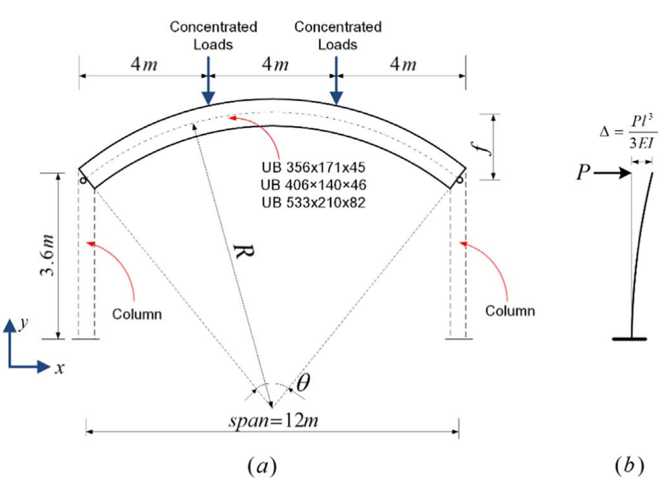

Fig. 1. Numerical models of TPSAs.

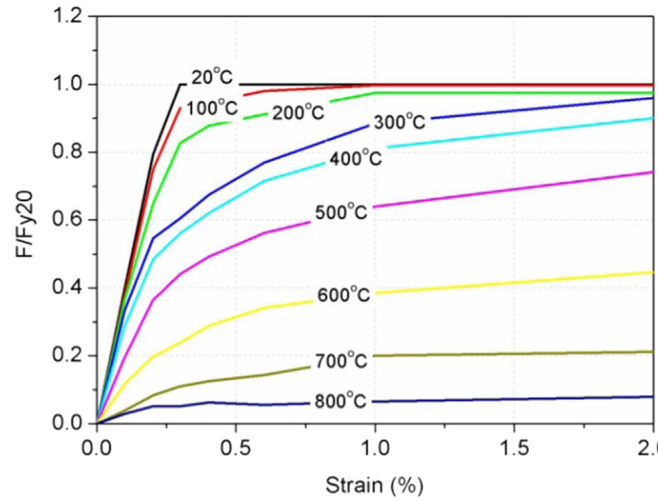

Fig. 2. Stress–strain curves of structural steel at elevated temperatures.

2.2. Material properties

The material of model was S355 steel, with a yield strength of 355 N/mm^2 and a Young's modulus of 2.00×10^5 N/mm^2 at ambient temperature [15]. At elevated temperatures, the steel high-temperature properties were degraded according to EC 3: part 1–2 [15] as shown in Figs. 2 and 3. The thermal expansion secant coefficient was 1.4×10^{-5} m/°C. The specific heat and thermal conductivity of the steel beam are both temperature dependent and determined from EC 3: part 1–2 [16].

This energy fraction was chosen by trial and error to be small enough to have almost no effect on the behaviour of the beam. An amplitude of $h/400$ of the first mode was assigned to the nodal displacements that served as the initial geometric imperfection of the arch models [17], in which *h* was the height of the cross-sections of the TPSAs.

2.3. Validation of numerical approach

Given the lack of experimental data on steel arches exposed to a fire, the numerical validation was conducted following a static test on the two-pinned steel arches at ambient temperature. In the experiment executed by Poutré et al. [18], the specimen was fabricated by rolling the HE 100A, as shown in Fig. 4. The steel grade was S235, and the elastic modulus was 2.0×10^5 N/mm^2. In this

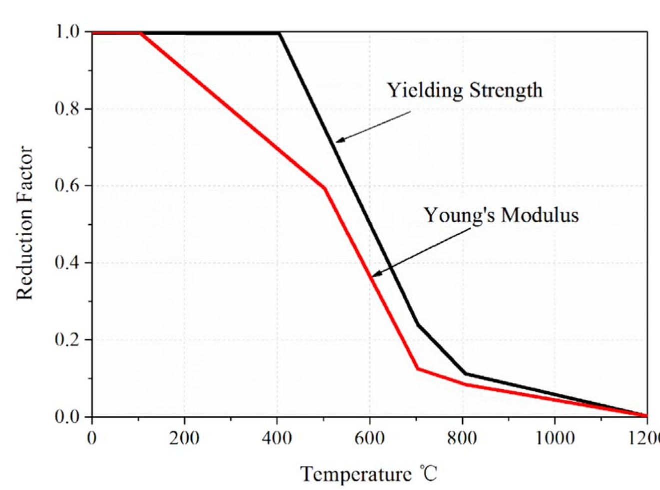

Fig. 3. Reduction factors for Young's modulus and yield stress of steel at different temperatures.