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Axially restrained steel beams with web openings at elevated temperatures, part 1: Behaviour and numerical simulation results

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ABSTRACT

Steel beams with web openings are frequently used as floor and roof beams in building construction to achieve attractive, flexible and optimised design solutions for passage of services. In practical construction, such beams may be axially restrained by the surrounding structure. The presence of axial restraint can drastically change the behaviour of such beams in fire, but the behaviour of axially restrained steel beams with web opening has received little attention. This paper investigates the effects of openings on axially restrained steel beams at elevated temperatures through extensive numerical simulations. The examined parameters include opening shape, opening size and opening position, load ratio, level of axial restraint and cross-section temperature distribution profile. The results of this numerical investigation identify the key stages and quantities that should be evaluated in fire resistance design of axially restrained perforated steel beams.

The simulation results show that axially restrained steel beam with web opening may enter catenary action at a much lower temperature than the commonly accepted critical temperature of the beam calculated assuming no axial restraint. This happens when the opening is slender (long and deep) and when it is placed at high bending moment regions of the beam. The effect is more severe as the level of end axial restraints increases. An important implication of this finding is that additional tensile forces may exist in such beams at the critical temperatures calculated without considering axial restraint.

The results of this paper also indicate that when the maximum axial tension in the beam is reached, the top tee-section has almost zero axial force. At the same temperature, the bottom tee-section (in tension) has reached its maximum tensile capacity. Hence the maximum axial force in the beam is the same as the tensile capacity of the bottom tee-section. This finding can be used to determine the maximum tensile force against which the connections. The companion paper presents an analytical solution.

1. Introduction

With many advantages such as attractive architectural appearance and flexibility in accommodating building services, steel beams with web openings are increasingly being used in floors and roofs of building construction. Such steel members may be in composite action with concrete slab on top as in typical multi-storey construction, or may be used without composite action, such as roof beams (Fig. 1a), floor beams supporting pre-cast slabs (Fig. 1b) or non-composite beams supporting composite beams (Fig. 1c).

The presence of openings usually leads to substantial reduction in the load carrying capacity of beams with web openings and different failure modes may occur at the locations of openings and in the narrow regions of web posts between the openings. Over many years, there have been many research studies on the behaviour of steel beams at ambient temperature [2–11], leading to development of design methods [1,12–18].

These research studies have revealed that the main failure modes at the locations of openings are bending failure, shear failure, Vierendeel mechanism (Fig. 2 (a)) and tee-section buckling (Fig. 2 (b)). Vierendeel mechanism is the most critical failure mode of the openings. In this mechanism, the transfer of a shear force across the opening generates secondary bending moments which leads to the formation of plastic hinges in the tee-sections near the opening corners [9,16,19,20]. Furthermore, the interaction of forces at the narrow web regions in beams with multiple close openings may experience web post buckling (Fig. 2 (c)). Web post buckling is not addressed in this paper because it is only a failure mode not affected by axial restraint.

The current fire limit state design of steel beams with or without openings [22,23] is based on the behaviour and limit temperature of the simply supported beam with no axial restraint. The limiting (critical) temperature is the value at which the applied load exceeds the reduced bending capacity of the steel beam (due to degraded material properties) at elevated temperatures, and the bending capacity is evaluated based on the ambient temperature failure mode. Therefore, for a beam with web opening, the limiting temperature is reached when the material properties are degraded enough such that the beam's

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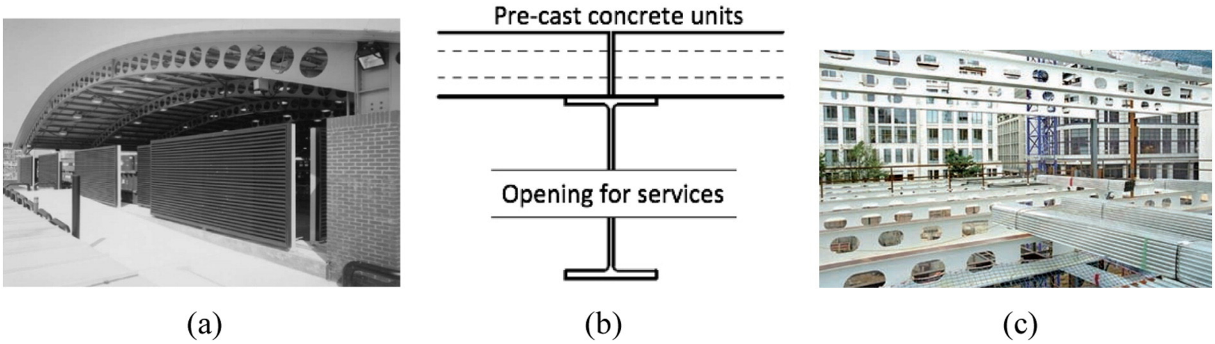
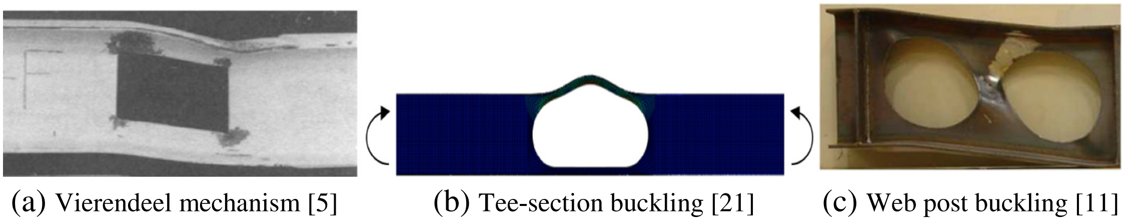


Fig. 1. Steel beams with openings [1].



(a) Vierendeel mechanism [5] (b) Tee-section buckling [21] (c) Web post buckling [11]

Fig. 2. Failure modes of perforated steel beams.

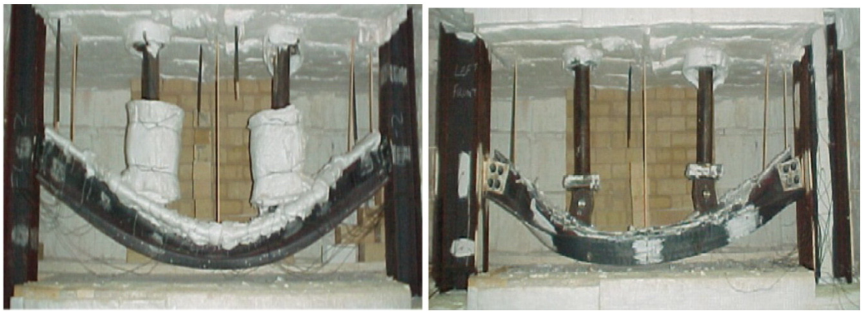


Fig. 3. Large deflection behaviour of beams in fire [33].

capacity in bending or Vierendeel mechanism falls below the applied moment and shear in fire [22].

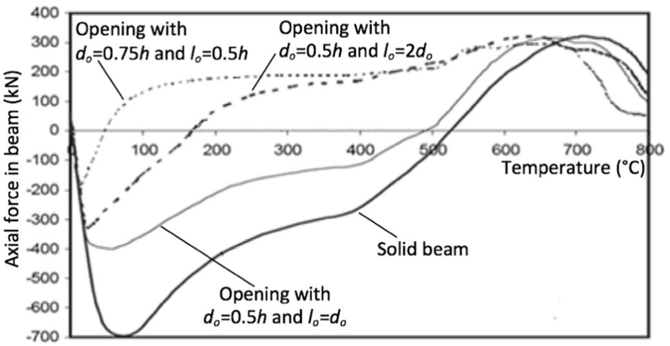


Fig. 4. Comparison of behaviour of beams with and without single opening at mid-span, full axial restraint, uniform temperature distribution [35].

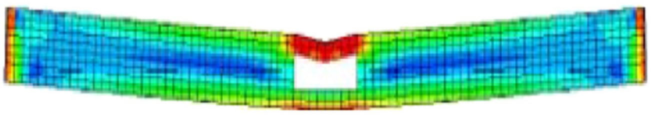


Fig. 5. Buckling of the top tee-section in the simulated axially restrained beam of [35].

However, in realistic structures, there will be axial restraints to the beam, provided by the surrounding structure. The behaviour and fire limit state condition of an axially restrained steel beam are different from that of the beam without axial restraint. Research investigations [24–34] on axial restraint effects on solid steel beams in fire have revealed complexity of the behaviour of restrained steel beams in fire.

Table 1
Description of validations studies.

Source	Type of beam/test or modelling	Structural phenomenon under investigation
Numerical simulations of Gillie [27] and Elsawaf et al. [37]	Axially restrained solid beams without catenary action/modelling	Effect of restrained thermal elongation
Yin [26]	Axially restrained solid beams with complete development of catenary action/modelling	Complete range (restrained thermal expansion, full development of catenary action) of axially restrained solid steel beam
Nadjai et al. [38]	Axially unrestrained perforated beams/fire tests	Effects of fire on perforated steel beams under bending
Yin and Wang [35]	Axially restrained perforated beams with catenary action/modelling	Complete range (restrained thermal expansion, full development of catenary action) of axially restrained steel beam with web opening