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An analytical and numerical prediction for ductility demand on steel beam-to-column connections in fire

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ABSTRACT

In this paper a simplified analytical method to assess the ductility demand on connections according to fire resistance requirements is developed on the basis of fundamental structural mechanics principles. An objective is to enable the development of a viable method to allow engineers to take the ductility of connections into account in design practice. Numerical finite element simulations of the single beam model were also performed to validate the simplified analytical model and reveal the important parameters that can influence the ductility demand within the connections. Using both analytical and numerical methods, the principal factors which influence the ductility demand of a connection, such as the span of the connected beam and the required connection strength, are also assessed. It is shown that:

1. The compressive ductility of connections is helpful in reducing the push-out of perimeter columns and the possibility of local buckling of beams.
2. Provision of high tensile deformation capacity allows large deflection in the beam, substantially reduces catenary forces on the connections, and consequently reduces the risk of structural collapse in fire.
3. The ductility demand of the connection is closely related to its stiffness and strength, as well as to the slenderness and load ratio of the connected beam.

1. Introduction

After the events of 11 September 2001, the focus of research in structural fire engineering has gradually moved towards the robustness of structures in fire. The capacity of a structure to prevent fire-induced progressive collapse is now recognized as one of the more important criteria in performance-based structural fire engineering design. Structural integrity in fire is a rather complex issue, involving the strength and expansion performance of different materials under elevated temperatures, the behaviour of individual members and their interactions. Amongst the structural components that contribute to the robustness of a frame, beam-to-column connections have vital importance, since they bridge the horizontal and vertical members and provide the load paths from slabs and beams to columns. Restrained by surrounding structure, steel/composite beams can develop significant forces in the connections, which are not considered in the ambient-temperature design of the connections, when exposed to fire. In this sense, connections can be both the most vulnerable and the least adequately designed parts of a frame, having the potential to trigger progressive collapse in exceptional fire events. The failure of connections can also lead to loss of fire compartmentation, and consequently cause the spread of fire between compartments, which can trigger a catastrophic escalation of failures within the structure.

The current trend of fire engineering design has been to move away from prescriptive methods to performance-based methods, in which the behaviour of structural members and their interactions are embedded into the assessment of overall structural fire resistance. In advanced fire engineering design, large deformations are allowed, provided that structural integrity (robustness) is maintained [1]. Tests and numerical studies have revealed that catenary action in beams, which occurs at high deflection, can increase the structural resistance to avoid progressive collapse. Li et al. [2] conducted high-temperature experiments on axially restrained steel beams, in which significant axial forces were measured. Liu et al. [3] investigated the effect of restraint on steel beams, leading to the catenary action which might be able to prevent deflections from running away at very high temperatures,

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Nomenclature

A	area of the beam's cross-section
$D_{cu,T}$	compressive deformation limit
$D_{tu,T}$	normal tensile deformation capacity, or ductility
$f_{y,T}$	yield strength of steel at temperature T
$K_{B,T}$	axial stiffness of the beam at temperature T
$K_{c,20}$	axial compressive stiffness of the connection at ambient temperature
$K_{c,T}$	initial stiffness in tension of a connection at temperature T
k_c	axial stiffness of each connection
$k_{E,T}$	degradation of elastic modulus due to temperature rise
$K_{JR,T}$	rotational stiffness of the connections
$K_{R,T}$	the rotational stiffness of the steel beam
$K_{t,T}$	initial stiffness in tension of a connection at temperature T
$k_{y,T}$	reduction factor for the yield strength of steel at temperature T
E_T	elastic modulus of steel at temperature T
I	second moment of area of beam section
M_E	externally applied free bending moment at mid-span
M_I	bending moment at the mid-span of the beam
M_m	mid-span bending moment for a pin-ended beam of span l without restraint
$M_{P,T}$	moment capacity of the beam's cross-section at temperature T
$M_{Rd,20}$	moment capacity of beam section at ambient temperature
$M_{Rd,T}$	moment capacity of beam section at temperature T
M_R	moment at the left-hand connection
$M_{t,T}$	moment at the beam ends
$N_{C,T}$	axial force in the connection at temperature T
$N_{Cmax,T}$	maximum axial compression force
$N_{CRd,T}$	axial compression capacity of the connection at temperature T
$N_{Rd,20}$	axial capacity of beam section at ambient temperature
$N_{Rd,T}$	axial capacity of beam section at temperature T
N_T	axial force of a beam
$N_{TRd,T}$	tensile capacity of a connection at temperature T
N_V	shear force at each beam-end connection
T	temperature in fire
T_1	temperature at which the connection contacts with the column flange
T_B	temperature at point B in Fig. 2
T_C	temperature at point C in Fig. 2
T_D	temperature at point D in Fig. 2
α	thermal expansion coefficient
θ	temperature change
δ_c	compressive deformation in the connection at temperature T
δ_S	accumulated mechanical strain of the beam
$\overline{\delta_{c,m}}$	normalized ductility of the connection up to its contact with the connected column
$\overline{\delta_{m,T}}$	normalized ductility of the connection at temperature T
ρ_T	the ductility factor at temperature T
δ_m	design ductility at ambient temperature
μ	load ratio of the beam, normalized with respect to its plastic moment capacity
ϕ	tensile capacity of the connection, normalized with respect to the plastic moment capacity of the beam
λ	slenderness ratio of the beam
r_s	radius of gyration
Δ	maximum (mid-span) deflection of the beam
β_c	axial restraint ratio of each connection
$\delta_{t,m}$	designed-in tensile ductility of the connection at ambient temperature
$\overline{\delta_{t,m}}$	normalized designed-in tensile ductility of the connection at ambient temperature
$\delta_{c,m}$	designed-in compressive ductility of the connection at ambient temperature
$\overline{\delta_{c,m}}$	normalized designed-in compressive ductility of the connection at ambient temperature

also experimentally. Catenary action was observed in these tests, and it was clear that horizontal restraint and catenary action are both important to the behaviour of beams in fire conditions.

In order to utilize the catenary action in beams exposed to fire, one of the key issues is to retain the robustness of the connection under the complex set of internal forces caused by heating. Sufficient strength and ductility within the connections is clearly necessary to sustain these forces along with large deflections. Nevertheless, recent experimental studies [4,5] have indicated that the conventional connections (endplates, fin plates and web cleats) exhibit relatively limited ductility under fire conditions. Thus, taking into account the ductility demand on connections at the design stage of a building is imperative in order to ensure their robustness when it is necessary to utilize beam catenary action in the event of a fire. Achieving sufficient ductility in connections to prevent the collapse of beams in fire will require: (1) a design method to quantify the ductility demand on the connection; (2) innovative design of the connection details such as bolts, endplates and their overall geometry.

Simplified methods to predict the behaviour of steel beams have been proposed by many researchers. Wang and Yin [6] used the finite element and simplified methods to predict the behaviour in fire of restrained steel beams. Their simplified method iteratively predicts the deflections and internal forces of beams on the basis of both equilibrium and a moment–axial force interaction. Tan and Huang [7] studied the fire-induced restraint forces in steel beams considering the effects of slenderness ratio, load utilization factor and thermal gradient across the steel section. Dwaikat and Kodur [8,9] proposed a simplified approach to predict the fire-induced forces and deflections of restrained steel beams. This method applies equilibrium equations to obtain critical fire-induced forces, and then utilizes compatibility principles to obtain the temperature-deflection history of the beam. It is validated by comparing its predictions with results obtained from detailed finite element analysis. Although these proposed approaches might be applicable in practical design to assess a beam's behaviour in fire, none of them have taken the ductility within connections into account.

The intention of this study is to propose a simplified method to estimate approximately the ductility demand on a steel beam-to-column connection in fire. Such an estimate could potentially serve as a baseline for subsequent detailed connection design calculations for the fire limit state. Numerical finite element modelling of steel beams with connection at both ends have been performed, firstly to validate the simplified analytical model and secondly to reveal the important factors which can influence the ductility demand within the connections. Using both analytical and numerical approaches, a series of parametric studies on the ductility