Thin-Walled Structures 98 (2016) 48–57

Contents lists available at ScienceDirect

Thin-Walled Structures

journal homepage: www.elsevier.com/locate/tws

Factors governing onset of local instabilities in fire exposed steel beams

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ARTICLE INFO

Article history:
Received 28 January 2015
Received in revised form
31 March 2015
Accepted 7 April 2015
Available online 2 May 2015

Keywords:
Local buckling
Fire resistance
Steel beam
Shear
Composite action
Finite element analysis

ABSTRACT

This paper presents critical factors that influence the onset of local buckling in steel beams when exposed to fire conditions. A three-dimensional nonlinear finite element model, capable of accounting for critical factors that influence local instability in fire exposed steel beams is developed. This model is applied to investigate the effect of beam-slab interaction, strength properties (Grade) of steel, and presence of fire insulation on the onset of local instability, and resulting capacity degradation in fire exposed steel beams. Results from numerical simulations are utilized to evaluate failure of beams under different limit states including flexure, shear, sectional instability and deflection. These results infer that web instability can occur at early stages of fire loading, leading to faster degradation of shear capacity and premature failure of steel beams before attaining flexural capacity. Also, results from the analysis indicate that the contribution of concrete slab to shear capacity can counterbalance the adverse effect of web local instability to a certain degree. Overall, neglecting the effect of fire-induced web local instability can lead to unconservative design in steel beams or girder subjected to high shear loading and/or local instabilities.

1. Introduction

In current practice, steel beams are to be designed to satisfy flexural, shear and serviceability limit states [1]. In ambient design, one of the key factors that need to be satisfied in achieving required moment and shear capacity is local buckling limitations. However, in current fire design provisions, only moment capacity at a given fire exposure time is utilized to evaluate failure of steel beams under fire loading without giving any due consideration to shear and sectional instability. Although deriving failure of beams based on flexural limit state is valid in most application and loading scenarios, this assumption may not be representative in certain situations where shear and instability (i.e., web local buckling) effects can be dominant in a fire exposed member [1].

Shear effects can be dominant under certain loading scenarios such as beams with concentrated loads acting at interior or end supports, as in the case of beams connecting offset columns in a building and transfer beams. In addition, temperature-induced buckling of web can be a governing factor in steel structural members with certain geometrical features i.e., beams with coped ends, deep beams and plate girders (with slender webs) [2–6]. Since webs are typically much more slender than flanges, larger surface area of web gets exposed to fire, leading to rapid rise of temperature in webs [1]. The faster rise in web temperatures leads to rapid degradation in strength and stiffness properties. This can initiate local buckling in web at lower steel temperatures and accelerate failure of beams.

Temperature-induced sectional instability in fire exposed steel beams results from the built-up of internal compressive stresses due to applied loading, and also due to rapid degradation in strength and modulus properties of steel with temperatures. When these built-up stresses reach the plastic limit, sectional instability is said to occur. Occurrence of such instability reduces effective area, which in turn decreases available flexural and shear capacity under fire conditions. In fire exposed beams subjected to high shear forces, a combination of temperature-induced strength degradation (in web) and earlier onset of local instability due to temperature-induced web local buckling can cause failure of beams in "Shear" before attaining flexural capacity.

The effect of local buckling on the response of fire exposed steel members was studied by some researchers [7–9]. For instance, Uy and Bradford [7] studied local buckling of cold-formed steel structural members at elevated temperatures using the finite strip method. The authors reported that the degradation in properties of steel at elevated temperatures can influence local buckling in steel–concrete composite construction. Zhao and Kruppa [8] performed fire tests on fire exposed steel composite beams and reported that steel beam sections classified as compact (at room temperature) can undergo local buckling under high temperature exposure.

In a recent study, Kodur and Naser developed a three dimensional finite element model to study the shear response of fire

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http://dx.doi.org/10.1016/j.tws.2015.04.005
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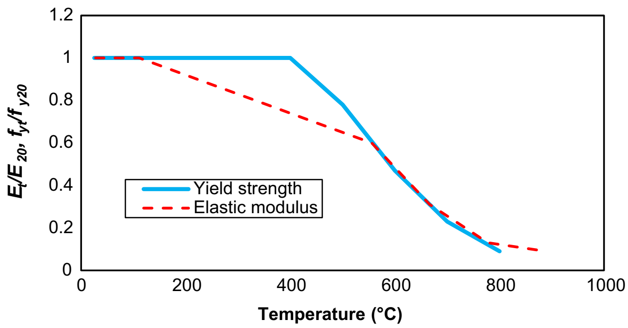

Fig. 1. Degradation of strength and stiffness properties of steel at elevated temperatures.

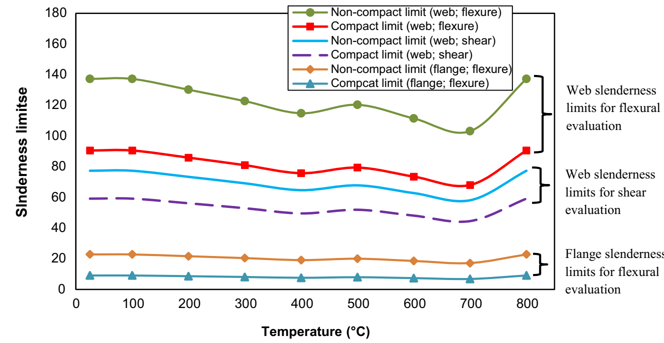

Fig. 2. Variation of slenderness limits adopted in flexural and shear design at elevated temperatures.

exposed steel beams [1]. The authors investigated the effect of different loading patterns, web slenderness and presence of fire insulation on steel beams subjected to high shear loading and exposed to fire conditions. Based on results from numerical studies, Kodur and Naser reported that shear capacity can degrade at a much higher pace than flexural capacity, thus leading to premature failure under shear limit state. This shear failure is initiated prematurely due to local buckling in the web which can occur at early stages of fire loading. The authors showed that this failure may occur under certain loading conditions, such as in beams loaded with high shear forces near end or interior supports.

The beneficial effect of composite action is generally accounted for in evaluating flexural capacity at room temperature. Yet, in current provisions (AISC) of composite beam-slab assemblies, shear capacity is evaluated based on contribution of web only, without any consideration to contribution from concrete slab of composite beam-slab assemblies [10]. Similarly, Eurocode 4 provisions state that resistance to vertical shear should be taken as the resistance of the structural steel section alone (web) "unless the value for a contribution from the reinforced concrete part of the beam has been established" [11]. Hence, any contribution of reinforced concrete (RC) slab through composite action is neglected in evaluating shear capacity.

Although current design provisions neglect the positive contribution of concrete slab, experimental evidence suggests otherwise [12–14]. For instance, Johnson and Willmington studied the shear capacity of composite beams in the negative moment regions and reported that the concrete slab contributes 20–40% of the total shear capacity [12]. Shear capacity of composite steel beams was also studied by Nie et al. [13] through tests on 16 composite beams and two individual steel beams at ambient conditions. The authors reported that steel–concrete composite beams designed with full shear transfer between steel beam and concrete slab can develop much higher shear capacity as compared to plain steel beams. Also, it was found that the contribution of the concrete slab can enhance shear resistance by 33–56%. The above studies clearly show that current code provisions underestimate the shear capacity of composite beams by neglecting the positive contribution of concrete slab.

Unfortunately, the effects of local instability and composite action on fire response of steel beams were not considered in earlier studies. In order to bridge this knowledge gap, a numerical study is carried out using a three-dimensional nonlinear finite element model. The developed model can trace fire response of steel beams subjected to significant bending moment and shear loading. The model is applied to examine the effect of beam-slab interactions, strength properties (Grade) of steel and fire insulation on the onset of local instability in steel beams exposed to fire.

2. Effect of local buckling on flexural and shear capacity

Adverse effect of local buckling on the response of steel beams is taken into account in evaluating flexural and shear capacity at room temperature [10,11]. For instance, the AISC design manual classifies cross-sectional shapes as compact, non-compact and slender based on sectional slenderness (width-to-thickness ratio λ) of flange and web. This sectional slenderness ratio is usually compared against two upper limits to classify the shape of the section: compact (λ_p) and non-compact (λ_r). These upper limits are a function of strength and stiffness properties ($\sqrt{E/f_y}$) of steel.

Under fire conditions, local buckling can occur once strength and stiffness properties start to degrade with rise in steel temperature. Onset of local buckling can induce further degradation in flexural and shear capacity of beams under fire conditions. Strength and stiffness properties of steel start to degrade at different rates after about 400 and 150 °C, respectively (see Fig. 1). Hence, local buckling can occur at earlier stages of fire, even before strength properties starts to degrade. Therefore, capacity degradation in steel beams can arise from temperature-induced web local buckling (at 150 °C) followed by degradation of strength properties (at 400 °C) [1].

Fig. 2 illustrates how the width-to-thickness classification limits of Grade 50 steel (345 MPa) change with elevated temperatures. Slenderness limits generally decrease as a function of temperature. However, flange slenderness limit, used in flexural evaluation, tends to be stable and experience slight fluctuation at elevated temperature (see Fig. 2). It can also be seen in the figure that web slenderness limits (for shear evaluation) vary over a smaller range ($59 \le \lambda \le 77$) than the flange slenderness limits used in shear calculation ($90 \le \lambda \le 137$). Thus, fire exposed steel beams are more sensitive to local buckling in web than that in flange.

Sectional slenderness (width-to-thickness ratio λ) depends only on the geometrical features (dimensions) of a section. Thus, flange and web slenderness ratios (λ_{flange} and λ_{web}) of a given shape remain invariant even under fire exposure. Since width-to-thickness classification limits decrease at high temperature, the constant value of flange and web slenderness ratios (λ_{flange} and λ_{web}) can exceed that of the degraded width-to-thickness classification limits. Once flange and/or web slenderness ratios exceed corresponding classification limits, temperature-induced local buckling is said to occur. Therefore, classification of a fire exposed steel section can change from that at room temperature.

To illustrate this, a W16 × 31 beam section made of Grade 50 (345 MPa) steel with web slenderness (λ_{web}) of 57.8 is selected. When comparing this web slenderness with the web slenderness limit (λ_{wp}) of Grade 50 (345 MPa) steel at room temperature ($\lambda_{wp} = 1.10\sqrt{k_v E/f_y} = 59.24$), this beam falls under "compact" section