Engineering Structures 116 (2016) 95–106

Contents lists available at ScienceDirect

Engineering Structures

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

Effects of non-uniform temperature distribution on critical member temperature of steel tubular truss

E. Ozyurt [a], Y.C. Wang [b,*]

[a] Department of Civil Engineering, Gumushane University, Gumushane, Turkey [1]
[b] School of Mechanical, Aerospace and Civil Engineering, University of Manchester, UK

ARTICLE INFO

Article history:
Received 27 October 2015
Revised 19 February 2016
Accepted 24 February 2016
Available online 9 March 2016

Keywords:
Circular Hollow Section (CHS)
Failure temperature
Localised fire
Multiple heated members
Non-uniform heating
Axially restrained compression member

ABSTRACT

This paper examines the effects of thermal restraint, caused by non-uniform temperature distribution in different members, on the failure temperatures of critical members of steel tubular trusses. Non-uniform temperature distribution develops in trusses exposed to localised fire attack. The truss member nearest to the fire source experiences the highest temperature, with reduced temperatures in the nearby members. The number of the nearby truss members being heated and their temperatures will affect the failure temperature of the critical truss member which has the highest temperature. The aim of this paper is to develop a simplified method to account for the effects of different numbers of members being simultaneously heated to different temperatures on the development of compression force and failure temperature of the critical member.

Finite Element (FE) simulations were carried out for Circular Hollow Section (CHS) trusses using the commercial Finite Element software ABAQUS v6.10-1 which has previously been validated by the authors. The simulation trusses were subjected to constant mechanical loads and then increasing temperatures until failure. The elevated temperature stress-strain curves were based on EN-1993-1-2 [1]. Initial geometrical imperfections were included, based on the lowest buckling mode from eigenvalue analysis.

The numerical study examined the effects of truss type, critical member slenderness, applied load ratio and axial restraint stiffness ratio on the failure temperatures of the critical truss members. The numerical simulation results were used to check the accuracy of a proposed simplified calculation method, combining linear elastic static truss analysis at ambient temperature and analytical equations to calculated the failure temperatures of thermally restrained truss members based on the regression equations of Wang et al. [2]. The calculation method was shown to be sufficiently accurate for fire resistant design purpose.

1. Introduction

Welded steel tubular trusses are frequently used to cover very large spaces, such as airports, exhibition halls, shopping malls and sport halls. For the fire resistant design of these large structures, the fire exposure is often assumed to be localised because of the small size of the fire compared to the large dimensions of the truss. Under localised fire, the different members of a truss will experience different temperatures. In welded trusses, because of restraint, non-uniform temperature distribution in different truss members will generate additional forces in the most heated member due to restrained thermal expansion.

Assessing the fire resistance of a steel truss exposed to localised fire involves quantifying the fire size, calculating the truss member temperatures and checking whether the critical member (the one with the highest temperature) has sufficient load carrying capacity. Quantification of localised fire can follow the method in EN-1991-1-2 [3], which calculates the size of the localised fire, including the height and temperature of the flame, as functions of the rate of heat release and distance to the fire source. Heat transfer analysis can then be used to obtain temperature distributions in the different members of the truss. Relevant research studies include Chen et al. [4,5] who tested and numerically modelled a steel roof truss without fire-proof coating under localised pool fire condition to obtain the truss temperature distributions and displacements. The members directly above the fire experienced the highest temperature, while the members away from the fire source experienced reduced temperatures. Whilst the quantification of localised fire behaviour and heat transfer analysis are important

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* Corresponding author.

E-mail address: yong.wang@manchester.ac.uk (Y.C. Wang).

[1] Formally School of Mechanical, Aerospace and Civil Engineering, University of Manchester, UK.

http://dx.doi.org/10.1016/j.engstruct.2016.02.044
0141-0296/

Nomenclature

The following symbols are used in this paper

A	cross section area of truss member
E	elastic (Young's) modulus
$F_{\beta l}$	function for the axial restraint stiffness
F_{ρ}	function for the initial axial load level
F_{λ}	function for the column slenderness
$F_{\mathrm{cric},i}$	increase in tension force of the critical member when the ith adjacent member is heated
$F_{i,i}$	additional force in member "i"
$F_{\mathrm{unit},i}$	change in internal force in the critical member when there is unit compressive force in member "i"
k_1	axial restraint stiffness at end 1
k_2	axial restrained stiffness at end 2
k_b	axial stiffness of member
$k_{c.0}$	axial stiffness of member at ambient temperature
k_f	modification factor for axial restraint ratio
k_i	axial restraint stiffness of member "i"
k_l	stiffness of the axial restraint
k_{total}	total axial restraint stiffness of the surrounding structure
l_b	length of member
n	total number of heated adjacent members
$P_{20\,^{\circ}\mathrm{C}}$	member force at ambient temperature
$P_{\max}$	member force at buckling temperature from truss analysis
T_0	limiting temperature of the unrestrained member
$T_{20\,^{\circ}\mathrm{C}}$	failure temperature from individual member analysis without axial restraint
T_f	failure temperature of member
$T_{\max}$	the highest temperature in the critical truss member
T_{θ}	failure temperature from individual member analysis with axial restraint
ρ_N	load ratio
λ	slenderness
β_l	axial restraint ratio
ε	engineering strain
ε_T	true strain
σ	engineering stress
σ_T	true stress
α_{th}	coefficient of thermal elongation of steel
ΔT_f	reduction in member failure temperature due to restrained thermal expansion
$\Delta T_{\mathrm{ABAQUS}}$	reduction in member failure temperature due to restrained thermal expansion, from ABAQUS simulation
$\Delta T_{\mathrm{Wang\ et\ al.}}$	reduction in member failure temperature based on the regression equations of Wang et al. [2]
$\Delta T_{\max}$	temperature increase in the critical member
$\Delta F_{\mathrm{single\ member}}$	increase in compression force of the critical member when one member is heated
$\Delta F_{\mathrm{multiple\ members}}$	increase in compression force of the critical member when the adjacent members are heated

parts of fire resistant design, this paper will only focus on the mechanical behaviour of welded trusses with non-uniform temperature distributions in different members.

Due to complexity, the assessment of mechanical behaviour of non-uniformly heated truss is often resorted to using numerical modelling. For example, Lin et al. [6] carried out numerical simulations to investigate the effects of loading ratio, temperature distribution, fire location and size on the fire resistance of a steel roof truss under local fire exposure. Non-uniform temperature distribution along the truss was calculated by using the equations of Du and Li [7]. Yu et al. [8] simulated the behaviour of steel space structures under localised travelling fires. The same maximum temperature was assumed in the fire zone and the temperatures in the other zones decreased depending on the distance from the fire zone. Ho et al. [9] modelled an unprotected long span steel truss to examine both the temperature distribution along the steel truss and the effect of restrained thermal expansion under a moderate fire. They observed that large compressive forces were generated due to restrained thermal expansion under even small fires. Kotsovinos [10] attempted to recreate the failure mechanisms of the WTC towers and reached similar conclusions as others (e.g. Usmani et al. [11], FEMA report [12] and NIST report [13]). This study noted that additional forces were generated in the truss members as a result of restrained thermal expansion. This type of numerical modelling requires time and specialist expertise which many structural engineers do not possess. It is necessary to develop thorough understanding of the effects of non-uniform heating to develop a simplified calculation method that is easy to use by structural engineers without specialist training in detailed modelling of structural behaviour at elevated temperatures. This is the aim of the paper.

The key issue is calculating the changing force in the critical member of truss due to the effects of restrained thermal expansion. The effects of restrained thermal expansion on the behaviour and failure temperature of single steel member have been investigated by a number of researchers. For example, Wang and Moore [14,15] developed a general equation to calculate the additional compression force in steel column due to restrained thermal expansion. Ali et al. [16] tested 37 axially restrained steel columns in fire to investigate the influences of column slenderness ratio, axial restraint ratio and column load ratio on the failure temperatures of thermally restrained columns. Franssen [17] used SAFIR to numerically investigate the behaviour and failure temperatures of axially restrained columns at elevated temperatures. Wang [18] examined the post-buckling behaviour of axially restrained columns. An analytical method was derived to trace the entire column load-temperature relationship, including increasing axial compression due to restrained thermal expansion, initial buckling and post-buckling behaviour. Tan and Yuan [19] developed an analytical method to calculate fire resistances of non-uniformly heated columns. However, that method did not consider high slenderness and plasticity. Li et al. and Wang et al. [20,21] completed both experimental and numerical analyses on the response of restrained steel columns at elevated temperatures. Their findings are consistent with other research studies which have found that the failure temperatures of steel columns with high restraint ratio or high slenderness or small load ratio are higher than the buckling temperatures. Correia et al. [22] performed a parametric study on HEA, HEB and HEM steel columns with restrained thermal expansion. They provided a series of simplified equations to calculate the fire resistances and critical temperatures of restrained steel columns. In contrast to earlier findings, they noted that axial restraint had no effect on the fire resistance of steel columns. Wang et al. [2] carried out a regression analysis of their extensive numerical simulations and derived a set of analytical equations to calculate the restrained column buckling and failure temperatures. These analytical equations were derived based on numerical simulations of I-sections. These studies on axially restrained single members form important basis of knowledge for steel truss column under localised fire attack. However, there is a key difference: in steel trusses