Engineering Structures 139 (2017) 15–30

Contents lists available at ScienceDirect

Engineering Structures

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

The behaviour and effects of beam-end buckling in fire using a component-based method

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ARTICLE INFO

Article history:
Received 13 September 2016
Revised 25 January 2017
Accepted 29 January 2017

Keywords:
Post-buckling behaviour
Steel beam
Component-based model
Connection
Fire

ABSTRACT

A combination of beam-web shear buckling and flange buckling at the ends of steel beams is very commonly observed during full-scale fire tests. This can affect the behaviour of the steel beams, as well as on their adjacent connections, under fire conditions. This phenomenon has not previously been sufficiently investigated and cannot be simulated in high-temperature global frame analysis, which could potentially lead to unrealistic results being used in structural fire engineering design. In this research, a component-based beam-end buckling element has for the first time been created for Class 1 and 2 beams. The beam-end buckling element is composed of nonlinear springs, respectively representing the buckling of beam flange and web, also considering the interaction between these two buckling phenomena. Each spring is able to deal with loading-unloading-reloading force-deformation paths. A significant challenge is to enable the flange buckling spring to deal with post-buckling deformation reversal. The buckling element has been implemented into the structural fire engineering frame analysis software Vulcan, to be used adjacent to existing connection elements in frame modelling.

The buckling element has been verified against ABAQUS finite element modelling on isolated beams. It is shown that the newly created component-based buckling element is able to simulate the effects of beam-end shear buckling in the web and local buckling of the bottom-flange, with satisfactory accuracy. The influence of the buckling element on the bolt-row force distribution within the adjacent connection element has been investigated. Analyses using isolated beams indicate that the implementation of the buckling element considerably improves the prediction of connection force resultants. A general observation from numerical studies with and without the buckling element is that beam-end buckling seems to reduce the connection component forces generated at elevated temperatures.

1. Introduction

Significant developments [1,2] have been made in investigating the behaviour of steel structures under fire conditions in the last two decades. The Cardington full-scale fire tests [3,4] demonstrated that the behaviour of a continuous composite structure can be completely different from the behaviour of isolated members seen in conventional standard fire testing. Structural behaviour in fire can be highly nonlinear and complex, and perhaps the most important goal of fire design is to prevent progressive collapse of the whole building. Therefore, designers are becoming increasingly aware of the importance of performance-based design, which treats the structure integrally, and attempts to sufficiently consider the interactions between different parts of a structure in analyses which contribute to the design process. Due to the high cost of full-scale fire testing and the complexity of the interactions involved, it has become essential to develop full-structure computational simulation tools in order to enable performance-based design. Detailed finite element modelling using software such as ABAQUS [5] and ANSYS [6] can provide sufficient accuracy, but the creation of structural models is time-consuming and the analysis can be computationally demanding; this approach is therefore undesirable for practical full-structure analysis, especially when detailed semi-rigid connection models have to be generated.

The software Vulcan [7] was developed by the Fire Engineering Research Group at the University of Sheffield. Vulcan allows engineers to conduct three-dimensional frame analysis and structural robustness assessments under fire conditions. A variety of element types (beam-column, slab, shear connector and connections) has already been implemented. The development of connection elements [8–10] in Vulcan has been based on a "component-based" representation instead of modelling the details of the connection

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http://dx.doi.org/10.1016/j.engstruct.2017.01.076
0141-0296/

Nomenclature

Notation

b	flange width
c	half flange width
d	beam web depth
D_B	spring deformation of Node B
D_{CREF}	spring deformation of the Reference Point
D_{CREF1}	spring deformation of the Reference Point at temperature T_1
D_{INTER}	spring deformation of the Intersection Point
D_{INTER1}	spring deformation of the Intersection Point at temperature T_1
D_{INTER2}	spring deformation of the Intersection Point at temperature T_2
D_n	spring deformation of Node P_n
D_{n-1}	spring deformation of Node P_{n-1}
D_x	real spring deformation in an arbitrary iteration
F_x	internal horizontal force of the buckling element
F_B	bottom spring force
F_{INTER1}	spring force of the Intersection Point at temperature T_1
F_{INTER2}	spring force of the Intersection Point at temperature T_2
F_R	spring yield strength
F_S	shear spring force
F_T	top spring force
F_{UB}	internal force of the unbuckled spring
F_y	internal vertical force of the buckling element
k_E	reduction factor for young's modulus at elevated temperatures
KIC	initial elastic stiffness of the compression spring
$KT1$	initial elastic stiffness of the compression spring at temperature T_1
$KT2$	initial elastic stiffness of the compression spring at temperature T_2
k_y	reduction factor for yield stress at elevated temperatures
K_1	slope of the line segment between Point B and Point P_{n-1}
K_2	slope of the line segment between Point P_{n-1} and Point P_{n-2}
l	beam length
L_p	flange-buckling wavelength length
M	applied bending moment
M_n	moment resistance of Point P_n
M_{n-1}	moment resistance of Point P_{n-1}
M_P	plastic moment resistance of the buckling element
M_x	moment resistance in an arbitrary iteration
M_{xy}	in-plane elemental moment
t_f	thickness of the flange
t_w	thickness of the beam web
α_T	thermal elongation coefficient
Δ_T	top spring deformation
Δ_B	bottom spring/buckling spring deformation
Δ_{2y}	vertical displacement of Nodal 2
Δ_{1x}	horizontal displacement of Nodal 1
Δ_{1y}	vertical displacement of Nodal 1
Δ_{2x}	horizontal displacement of Nodal 2
θ	relative rotation of the two nodes of the buckling element
θ_1	rotation of Nodal 1
θ_2	rotation of Nodal 2
θ_B	relative rotation of the two nodes at the end of the plateau stage
θ_R	relative rotation of the two nodes at the end of the pre-buckling stage
θ_n	relative rotation of the two nodes at Point P_n
θ_{n-1}	relative rotation of the two nodes at Point P_{n-1}
$\sigma_{y,\theta}$	yield strength of steel at elevated temperatures

using solid elements. In the component-based method a connection is considered as an assembly of nonlinear springs, each of which has its individual characteristics. This simplified model is able to represent the key behaviour of certain connection elements to an acceptable accuracy, but adds very few degrees of freedom to the structural model, which makes the computation considerably more efficient [8]. Recently, Khalaf et al. [11] have created a model for predicting the bond-slip between concrete and steel reinforcing bars at elevated temperatures in Vulcan.

It has been observed that both shear buckling of beam webs and beam bottom-flange buckling (Fig. 1), near the ends of steel beams, are very prevalent under fire conditions. These phenomena can affect particularly the internal forces in adjacent connections and the overall deflection of the beam, and may therefore influence the fire resistance of the assembled structure. However, there has not been sufficient research investigating the beam-end local buckling behaviour of Class 1 to 2 beams at high temperatures. On the one hand, there has been no theoretical model which can represent the plastic post-buckling behaviour of stocky (Classes 1 and 2) beams at elevated temperatures. On the other hand, although detailed modelling using commercial FEA packages such as ABAQUS or ANSYS can predict and follow the beam-end buckling phenomena, this is computationally very demanding and becomes unfeasible when global frame analysis is required in the context of practical performance-based structural fire engineering design. It has therefore become essential to develop a simplified model which can be integrated into global analysis, in order to simulate the beam-end buckling phenomena sufficiently accurately within an acceptable time-period, given that this includes both the creation of a model and the actual runtime. In this study, this has been achieved by developing a new buckling element and integrating it into Vulcan.

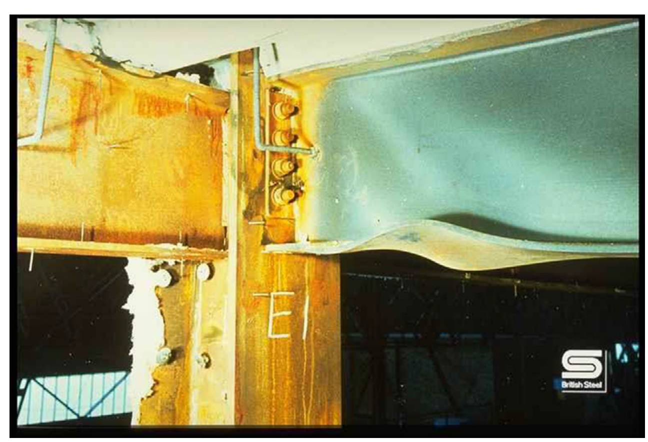

Fig. 1. Flange buckling and beam-web shear buckling in combination [4].

Previous work [12] conducted by the authors has led to the development of an analytical model which can consider the combination and interaction of flange buckling and beam-web shear