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Computational performance of beam-column elements in modelling structural members subjected to localised fire

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ABSTRACT

In the past decades, increasing attention has been directed to understanding the structural response to various scenario fires, which is stimulated by the trend of considering localised burning in large open plan compartments. Beam-column elements as widely used in modelling steel frames have been extended to account for the thermal impact in OpenSees, the development of which is undertaken to formulate the displacement and force-based beam elements. After including the non-uniform thermal expansion along the element length caused by localised heating, the force-based beam-column element has shown greater efficiency compared to the displacement-based element. A detailed discussion regarding the computational performance of both beam-column elements has been presented in this paper, which concludes that force-based beam-column elements can better represent the localised plasticity of fibres caused by non-uniform heating. A generic simply supported steel beam can be modelled even with two force-based elements to reproduce accurate mid-span deflection under localised heating. A steel beam subjected to a localised fire is presented as a case study in this paper, experiencing run-away collapse after 15 min of exposure when the load ratio reaches 50%. Using a 12 element force-based beam-column model and shows equivalent accuracy against 48 element displacement-based beam-column model.

1. Introduction

It has been nearly a century since the concept of standard fire testing was established. It has been extensively applied in design practice to ensure the fire safety of steel framed structures. However, it is only since the Cardington tests in the mid 1990s that proper understanding of the behaviour of steel structures in real fires started to be fundamentally developed. This work has been reported in the form of numerical modelling and experimental studies following the Cardington tests, such as [1–5]. Aiming to capture the global behaviour of steel frame structures in fire, beam-column elements have been widely used in the modelling-based studies to address the material and geometric nonlinearities encountered in the simulation of thermo-mechanical response of structures to fire loading. Most of these studies have been conducted using modelling tools such as VULCAN, SAFIR, ABAQUS and OpenSees recently [6,4,7,8].

One advanced approach to describe the geometrically nonlinear behaviour of frame elements is to use corotational geometric transformation [9], which decomposes the beam displacements as a combination of rigid body motion and strain-inducing local displacements. When modelling structures at ambient temperature, the material nonlinearity along the beam tends to be considered in two different ways: one uses lumped plasticity such as plastic hinges [10] or inelastic zones [11] and the other adopts distributed plasticity [12,13]. It is preferred to employ beam-column elements with distributed plasticity for fire scenarios as the location of plastic hinges is not predictable. The formulation can be displacement-based or force-based which differ in the section interpolation. The displacement-based formulation referring to stiffness method leads to a longitudinally uniform axial deformation and a linearly varying section curvature, while the force-based formulation (flexibility method) assumes the uniform axial section force and linear distribution of section moments. Meanwhile, the cross section of beam-column elements is usually discretised into a number of fibres [14,15], and each fibre is assigned with a material model to represent the unique stress-strain relationship. Jiang [8] has used displacement-based beam-column elements to model steel frames in uniform fire condition, and Jeffers [16] has extended the force-based beam-column element to consider thermal action and concluded that it displays a better performance than the elements using stiffness method. However, these discussions were conducted for uniform fires which only deal with the cross-sectional temperature gradients.

In small compartments of regular (ideally cubic) shapes, uniform

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gas temperature assumption is reckoned to be appropriate after flashover, which is characterised by the stages when simultaneous combustion of nearly all the combustibles begins to occur. In large open plan space, localised burning is found to be more likely and whole compartment flashover may or may not occur. Moreover, such localised burning has the potential to travel or remain confined to the original location, which is dependent on the capability of fire spread and further related to the distribution of fuel around the ignition source. Steel beams and columns subjected to localised fire action have been discussed by Jeffers and Sotelino [17] and Zhang [18,19], where the emphasis was to investigate the structural member behaviour in localised fires but with limited discussion of the element performance.

OpenSees as an open source finite element software framework has implemented a rich collection of beam-column elements for modelling frame structures at ambient temperature and primarily for earthquake loading scenarios. Since 2009, the capability of modelling structural response to fires has been added to OpenSees which comprises fire modelling, heat transfer analysis and thermo-mechanical analysis. The earlier work using displacement-based beam-column element to model steel frames in uniform fires was reported by Jiang [8]. In this paper, the implementation of beam-column elements of displacement-based using force-based formulations is presented, which are developed for non-uniform heating in conjunction with the new thermal loading definitions. Fibre based sections are adopted to describe the section behaviour of frame members, which are associated with structural material models for steel and concrete.

When considering localised heating, the non-uniform thermal expansion along the element length requires modification to the displacement interpolation, so as to overcome the uniform axial deformation in a two-node beam-column element. In OpenSees, this is achieved with a modifier estimating the average thermal elongation at each integration point (section) to the axial deformation. For the force-based beam-column element receiving non-uniform heating, the force interpolation provides the capability of addressing non-uniform thermal elongation. However, necessary modification should be made to the internal element iteration since the element is formulated in a displacement oriented computational environment. The formulation and application of both elements are elaborated in this paper, followed by a summary of the recent beam-column element development in OpenSees with particular emphasis on simulating the response to localised heating. Numerical studies on the computational performance of beam-column elements are presented at low and high temperatures with various longitudinal and sectional temperature gradients. The approach developed is then applied to model a steel beam subjected to a localised fire, which highlights the better performance of the force-based beam-column element. The work in this paper should facilitate the simulation of the thermo-mechanical response of steel frames in complex fire scenarios with a computationally efficient model.

2. Beam-column element formulation considering localised fire action

The hierarchical structure of OpenSees fibre based beam-column elements is illustrated in Fig. 1. The structure state determination refers to the assembling of the global stiffness matrix and residual forces as well as the displacement transformation after the geometric transformation. The element state determination involves the interpolation for the section deformation and the integration to form the element stiffness and residual forces. As the cross-section has been discretised into a number of fibres and each fibre is linked to a material representation, the section state determination is responsible to update the material variables (strain, stress, stiffness) and then form the section resisting force and stiffness. When the fire action is imposed, each beam-column element is assigned with a thermal action to define the temperature profile at each load step. This is later distributed to each section after considering the localised heating effect based on the section location, which determines the temperature in each fibre and varies the material characteristics corresponding to its assigned material model.

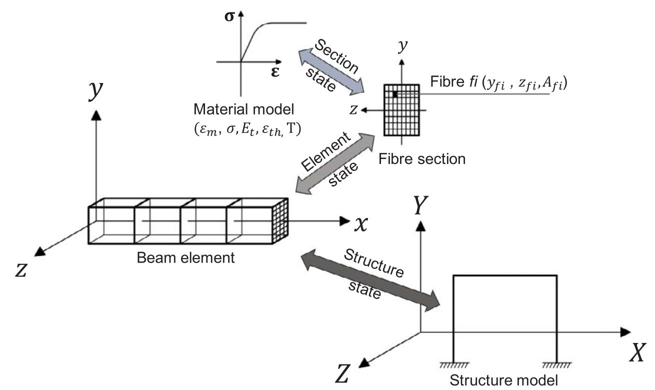

Fig. 1. Thermo-mechanical analysis with displacement-based beam element in OpenSees.

2.1. Element formulation for thermal loading

The first action of updating element state is to determine the trial displacements which are geometrically transformed from the global displacements. Fig. 2 is to illustrate the local force and displacement variables involved in the beam elements, where Q_i, q_i represent the corresponding nodal forces and displacements after removing the rigid body modes, respectively. Note that the axial force Q_5 or displacement q_5 is assumed to be uniform in a conventional two-node beam-column element. At an integration point, the section forces are denoted as N, M_y, and M_z, while the corresponding deformation variables are ζ, ϕ_y, and ϕ_z.

For each new step of thermal action, the element state determination is performed following the workflow shown in Fig. 3. The first iteration is executed to apply the thermally induced force $\mathbf{F}_{th}$ which accounts for the abrupt change of thermal expansion, whereas the following iterations are conducted to eliminate the unbalanced residual forces induced by the material degradation after the temperature rises. As a result of each iteration i, a displacement increment $\Delta\mathbf{q}_i$ is calculated to update the trial displacement $\mathbf{q}_i$.

The key task remaining is to determine the section deformation $\mathbf{d}_{si}$, which can be achieved by the displacement interpolation (displacement-based) or force interpolation (force-based) and element iteration. A displacement-based frame element adopts a linear distribution of the section curvature and uniform axial deformation along the element length. Correspondingly, the force-based formulation interpolates with the local nodal forces, and an internal iterative process is required to estimate the section deformation, which is then integrated for the nodal displacements to conform the convergence check.

The numerical integration scheme uses the Gauss-Lobatto

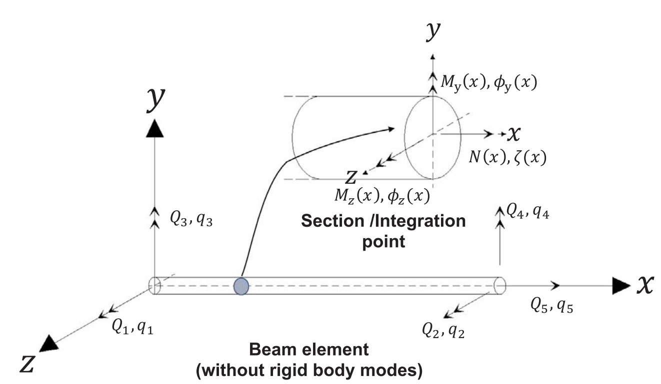

Fig. 2. Generalized forces and deformations at the element and section level (adapted from [20]).