Engineering Structures 33 (2011) 1870–1882

Contents lists available at ScienceDirect

Engineering Structures

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

Consistent virtual work approach for the nonlinear and postbuckling analysis of steel frames under thermal and mechanical loadings

Y.B. Yang [a,*,1], C.T. Chen [b], T.J. Lin [b], C.R. Hung [b]

[a] Department of Construction Engineering, National Yunlin University of Science and Technology, Yunlin, 64002, Taiwan
[b] Department of Civil Engineering, National Taiwan University, Taipei, 10617, Taiwan

ARTICLE INFO

Article history:
Received 31 March 2010
Received in revised form
31 January 2011
Accepted 8 February 2011
Available online 27 March 2011

Keywords:
Nonlinear analysis
Steel frame
Finite element method
High temperature
Postbuckling

ABSTRACT

The aim of this paper is to provide a consistent virtual work formulation for the nonlinear and postbuckling analysis of steel frames at high temperatures. Central to this study is the derivation of the virtual work terms for the *thermal stage*, in addition to those for the *loading stage*, based on the updated Lagrangian formulation. The incremental stiffness equation derived for the beam element, considering both the geometrical and thermal effects, is qualified by the rigid body test. The generalized displacement control (GDC) method is adopted as the path-tracing scheme for postbuckling response. Eurocode-3 reduction factors and transformed section method are both adopted for steel I-sections. Two loading cases are studied. For structures loaded gradually under constant temperature, the critical or ultimate loading strength is obtained from the load-deflection curve. For structures heated gradually under constant loading, the critical or maximum temperature that can be sustained by the structure is computed. Conclusions are drawn for the examples studied in this paper.

1. Introduction

Fire disaster is becoming a noticeable problem in populated metropolitan areas, which is coupled by the increasing use of steel structures. Compared with other structural materials, such as concrete, steel has a high thermal conductivity, which softens rapidly when the temperature reaches some values. Once the critical state is reached, the structure may not collapse immediately, but the overall structural safety may be seriously affected. In this regard, how to simulate the behavior of steel structures under a major fire is crucial to assessment of the remaining strength of a damaged structure for rehabilitation for further use.

Both fire resistance tests and numerical simulations methods, particularly the finite element method, have been employed in evaluating the fire resistance capability of steel structures and components. The fire tests are generally costly and subject to certain physical restraints, such as the furnace environment, member constraints, and so on. In contrast, the finite element method is generally versatile, by which various factors such as non-uniform temperature distribution, geometrical and material nonlinearities, etc., can be easily taken into account [1–6]. The results obtained by a finite element program are often compared with those from the fire tests. But this has been quite limited due to the restraint for preparing the specimens for use inside the furnace and other physical restraints. To ensure the general applicability of a finite element procedure, it is necessary to develop some benchmark problems for which the solutions can be used as the baselines [7].

There exists an abundant literature on the finite element simulation of the behavior of steel frames in fire. Li and Jiang [8] investigated the behavior of steel frames by considering the material and geometrical nonlinearities, and the temperature distribution across member sections. By using the generalized Clough model, the tangent stiffness at high temperature can be obtained and the effect of thermal strain is converted to equivalent thermal loads at structural nodes. However, the geometric and thermal stiffness matrixes were not qualified by the rigid body test described in [9,10]. Iu et al. [11] used the energy method to obtain the incremental force–displacement relationship, and the Newton–Raphson method to study the nonlinear behavior of steel frames with no protection cover. In their analysis, effects such as large deformations, plastic hinges, and strain hardening are included. Yin and Wang [5] used the ABAQUS program to analyze the large deformation behavior of steel frames with different constraints under the heating stage. The parameters considered include the span length, uniform and non-uniform temperature distributions, different loading conditions, rotation constraint, and lateral buckling.

In this paper, a consistent virtual work theory is presented for the nonlinear and postbuckling analysis of steel frames at high temperatures. Central to this study is the derivation of

* Corresponding author. Tel.: +886 2 3366 4245; fax: +886 22362 2975.
E-mail address: ybyang@ntu.edu.tw (Y.B. Yang).
1 On leave from National Taiwan University.

0141-0296/$ – see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.engstruct.2011.02.005