Engineering Structures 105 (2015) 137–151

Contents lists available at ScienceDirect

Engineering Structures

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

A two-scale computational model for thermomechanical analysis of reinforced concrete frames

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ARTICLE INFO

Article history:
Received 10 January 2015
Revised 15 April 2015
Accepted 29 September 2015
Available online 24 October 2015

Keywords:
Damage
Concrete structures
Fire
Elevated temperatures

ABSTRACT

We develop a two-scale numerical model to simulate the response of reinforced concrete (RC) frame structures under thermomechanical loading. In this model, the nonlinear behavior of structural members is captured by a set of nonlinear cohesive elements, which represents the potential damage zones that could form under the given loading. The thermo-dependent constitutive behavior of each cohesive element is determined through finite element (FE) simulations of its corresponding potential damage zone at different elevated temperatures. For the FE simulations, the thermo-dependent material properties are determined based on the existing literature in conjunction with a set of experiments on concrete at elevated temperatures. The proposed two-scale model is used to simulate the behavior of a RC frame subassemblage under thermomechanical loading and the simulation results are compared with the predictions by the standard FE analysis. It is shown that the present model can well capture the thermomechanical behavior of RC frame structures. Finally, the model is applied to analyze the global behavior of a prototype RC frame subjected to compartment fires.

1. Introduction

According to the National Fire Protection Agency, about half a million structural fires occurred in the United States in 2013, which is equivalent to one fire in every 65 s. These fires caused 2855 civilian deaths and direct property losses of 9.5 billion US dollars [29]. During the past several decades, a substantial amount of efforts have been directed toward improving our understanding of the structural behavior of buildings under fires, which has laid the foundation for fire-resistant structural design. There has been a great research interest in steel structures [47,25,54,37,56,18,27], which are known to be highly vulnerable to fires due to high thermal conductivity and significant thermal degradation of material properties. By contrast, concrete is generally regarded to be fire resistant. Nevertheless, reinforced concrete (RC) structures must still be designed against fires since the structural members need to withstand gravity loads with a tolerable amount of damage at evaluated temperatures. For instance, various code committees have proposed guidelines and recommendations for fire resistance design of individual RC structural members [2,19,43,24]. However, there is still a lack of understanding of how the fire resistance of the individual structural member is affected by its surrounding members. As we move toward the paradigm of performance based structural design, it is critical to assess the overall behavior of the entire structure under fire loading.

It is well known that both mechanical and thermal properties of concrete materials are strongly dependent on temperature. For instance, fracture energy, tensile and compressive strengths, elastic modulus, and thermal conductivity of concrete would decrease considerably with an increasing temperature [5,13,48,11,46,52]. Such temperature dependence is believed to be caused by various mechanisms at meso- and micro-scales, which include phase transformation, evolution of pore structure, and thermohygromechanical coupling [55,11]. In order to facilitate numerical analysis of thermomechanical behavior of concrete structures, various constitutive models have been developed for finite element (FE) simulations [42,49,58,38]. Recently, there has also been a considerable interest in applying discrete element models for thermomechanical analysis of concrete materials [57,21]. These existing numerical models were largely applied to individual structural elements. Clearly it is often a challenge to directly use FE or discrete element models to simulate the behavior of large RC buildings under thermomechanical loading due to the excessive demand on computing powers. Therefore, some efficient computational models are needed.

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http://dx.doi.org/10.1016/j.engstruct.2015.09.041
0141-0296/

Over the past two decades, substantial researches have focused on the development of reduced-order computational models for RC buildings [28,22,30,7,39,31]. The essential idea of these models is to employ some types of nonlinear elements to efficiently simulate fracture and damage of RC structural members so that they can be used to handle large RC structural systems under different loading scenarios including quasi-static loading, cyclic loading, and dynamic loading. However, these computational models were developed for pure mechanical loading. So far, only a limited amount of efforts have recently focused on extending these concepts to thermomechanical loading [26].

This paper presents an efficient computational model for simulating the thermomechanical behavior of RC frame structures. Different from the existing models, which largely dealt with thermomechanical behavior of materials [57,58,38,21], the essence of the present model is to link the material behavior with the overall structural response through a set of thermo-dependent cohesive elements. Though the focus of the present study is to demonstrate this new concept by analyzing 2D frame structures, which do not fully represent the behavior of the actual 3D structures, it should be pointed out that the present model can readily be extended to 3D structures.

The paper is planned as follows: Section 2 presents the formulation of the thermo-dependent constitutive relationship of cohesive elements for RC structural members; Section 3 describes the calibration of the cohesive properties through FE simulations and a set of high-temperature experiments on concrete; in Section 4 the present model is used to simulate the behavior of a RC frame subassemblage under thermomechanical loading, which is further compared with the standard FE analysis; and in Section 5 the present model is applied to simulate the behavior of a high-rise RC frame subject to compartment fires.

2. Thermo-dependent cohesive modeling of RC structural members

Pioneered by Barenblatt [8] and Dugdale [16], cohesive models have widely been used for analysis of material fracture. The essential idea behind the cohesive models is that it smears a finite-size damage zone at the crack tip by a zero-thickness nonlinear element whereas the rest part of the structure is considered to behave linear elastically. This provides an efficient means of simulating the nonlinear fracture and damage processes in concrete materials [23,12]. In a recent study [31], the concept of cohesive modeling has been extended to RC buildings, where the nonlinear behavior of each structural member is modeled by a set of cohesive elements representing various potential damage zones (PDZs). The PDZs are identified a priori based on the knowledge of the qualitative behavior of structural members under given loading. Fig. 1a shows the cohesive modeling of a 2D frame subassemblage under gravity loading. As seen, the PDZs are placed at the quarter spans of each beam to capture both single- and double-curvature flexural behaviors; for columns the PDZs are placed at the mid-span and two ends according to the classical Shanley column model [51,9]; and for beam–column joint panels the PDZs are placed along the two diagonals to simulate the diagonal cracking [36,53]. It is clear that the main assumption of the present model is that the failure locations of various structural members are pre-determined and confined. This is reasonable for RC structures due to the damage localization mechanism of concrete materials.

The depth of the cohesive elements is considered to be equal to $0.85D_e$ and $0.75D_e$ for beams and columns, respectively, where D_e – effective depth of beams and columns, which is equal to the distance between the centroid of the tensile reinforcement and the extreme material fiber in compression [36]. It should be pointed out that in this study a single cohesive element consists of multiple Gauss points, which may exhibit different mechanical behaviors due to the arrangement of longitudinal reinforcement. Therefore, the aforementioned effective depths would allow a single cohesive element to simulate the bending behavior of the PDZ. Meanwhile, the cohesive element is also expected to capture shear failure and its interaction with the flexural behavior. This is different from some existing reduced-order modeling of RC structural members, where distinct nonlinear elements were used to simulate different failure modes, e.g. [36].

For the formulation of the constitutive behavior of cohesive elements, the PDZ is separated into two parts (Fig. 1b), (1) effective concrete section, which consists of concrete and transverse reinforcement and (2) longitudinal reinforcement. For each Gauss point, the traction–separation relationship can be written as

$$\sigma_n(w_n, w_s, T) = \sigma_n^c(w_n - \alpha_c \Delta T_c L_p, w_s) + \rho \sigma_n^s(w_n - \alpha_s \Delta T_s L_p, w_s) \quad (1)$$

$$\tau(w_n, w_s, T) = \tau^c(w_n - \alpha_c \Delta T_c L_p, w_s) + \rho \tau^s(w_n - \alpha_s \Delta T_s L_p, w_s) \quad (2)$$

where σ_n, τ – total normal and shear tractions, σ_n^c, τ^c – normal and shear tractions in the effective concrete section, σ_n^s, τ^s – normal and shear tractions in the longitudinal reinforcement, w_n, w_s – normal and shear separations, α_c, α_s – thermal expansion coefficients of concrete and steel, $\Delta T_c = T_c - T_0$, T_c – representative temperature of the effective concrete section, T_0 – room temperature, $\Delta T_s = T_s - T_0$, T_s – temperature of the longitudinal reinforcement, L_p – length of the PDZ (Fig. 1b), and ρ – longitudinal reinforcement ratio. For convenience, we denote $w_{nc} = w_n - \alpha_c \Delta T_c L_p$ and $w_{ns} = w_n - \alpha_s \Delta T_s L_p$.

Following Le and Xue [31], the cohesive behavior of the effective concrete section is formulated based on the concept of

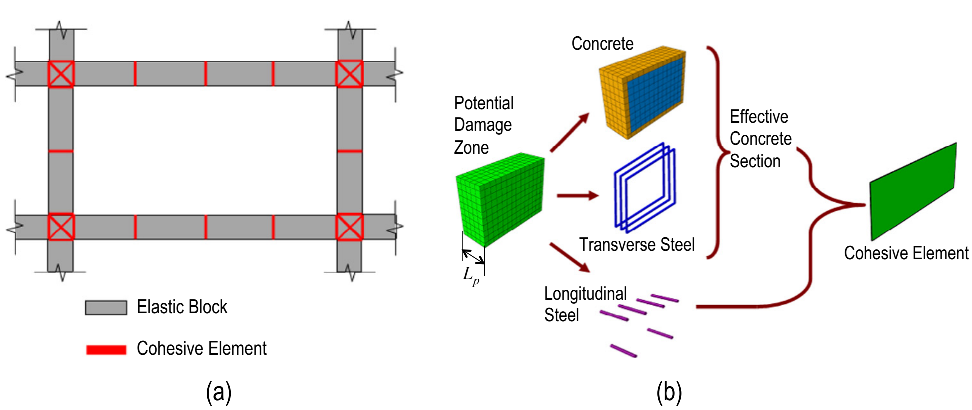

Fig. 1. Cohesive element modeling of RC frames: (a) representation of a frame subassemblage and (b) formulation of cohesive relationship.