Available online at www.sciencedirect.com

SCIENCE DIRECT®

Computers and Structures 83 (2005) 2609–2631

Computers & Structures

www.elsevier.com/locate/compstruc

Damage analysis and numerical simulation for failure process of a reinforced concrete arch structure

X.S. Tang [a,b], J.R. Zhang [a,*], C.X. Li [a], F.H. Xu [a], J. Pan [a]

[a] School of Bridge and Structure Engineering, Changsha University of Science and Technology, Changsha, Hunan 410076, China
[b] School of Mechanical Engineering, East China University of Science and Technology, Shanghai 200237, China

Received 19 April 2004; accepted 25 March 2005
Available online 16 September 2005

Abstract

This work focuses on the implementation of damage mechanics model to explain and understand failure mechanisms of the concrete structures. A tensorial damage theory and an isotropic application to the arch ribs of a real bridge are presented. Two reinforced concrete arch ribs of a 28 year old bridge has been removed from the field to the laboratory. They were loaded up to failure in order to study the remaining strength of the structure. The damage model involves three independent parameters for simulating the damage behaviors of the concrete material. The damage theory—additional load—finite element method is developed to simulate numerically the failure process of the RC structures based on the proposed damage model. The predicted displacements, strains and failure mode of the RC arch are good agreement with the experimental results. The values of the three material parameters that describe the damage characteristics of concrete were obtained. The numerical calculations revealed the interested behaviors of concrete in a damaging process. The proposed damage model can be used effectively to describe the damage and fracture behaviors of concrete.

Keywords: Reinforced concrete structure; Bridge; Arch; Damage theory; Failure process; Numerical simulation; Finite element method

1. Introduction

Evaluation of the residual strength and remaining life of concrete bridges have attracted much attention in recent years as many of the existing structures have aged over the years. Model analysis methods have been developed [1–7] and those involving the numerical simulation of the fracture process of concrete can be found in [8]. Concrete is a typical heterogeneous and quasi-brittle material with a complicated microstructure. Inherent to the concrete are large numbers of microdefects and microcavities that could spread when loads are applied in addition to those that are nucleated in service. The evolution of the failure process is to say the least very complicated. A complete account of the failure process is beyond the state-of-the-art of present analytical capability. Damage theory is therefore used instead by assuming that failure by fracture occurs suddenly near the ultimate load while microcracking prior to failure did not have a significant effect. A different idea was

* Corresponding author. Tel.: +86 731 5219078; fax: +86 731 5219866.
E-mail address: jianrenz@hotmail.com (J.R. Zhang).

0045-7949/$ - see front matter
doi:10.1016/j.compstruc.2005.03.017

proposed in the work [9], in which two- and three-dimensional nonlinear finite element analysis of concrete structures is presented. The concrete material is modeled including the triaxial nonlinear stress–strain behavior, tensile cracking, tension-stiffening, compression crushing and strain-softening.

Kachanov originated the idea of damage theory in 1958 by assuming the reduction of the effective area (or net area) on account of material damage for one-dimensional models. Extension of the concept to three-dimensions was made by replacing the uniaxial load with the effective stress. Proposed also is the strain equivalence principle [10]. It states that the strain constitutive relations for damaged and undamaged material are the same except that the Cauchy stress is replaced by the effective stress. Different versions of the damage theories for concrete can be found in [11–18]. The early works [11–13] were based on the experimental stress–strain curves and the strain equivalence principle. Proposed are the uniaxial and isotropic damage models. The shortcomings of the strain equivalence principle have been pointed out in [19,20]. The anisotropic damage models for the multiaxial damage case of concrete were developed in [14,15]. It is hard to determine too many unknown parameters in the anisotropic damage models. A microplane damage model for concrete and rock was presented in [16]. In addition, the mixture damage model was proposed in [17,18]. The concrete is regarded as a two-phase composite which consists of grout and grain.

It has been argued in [19] that damage theory suffers from both the lack of uniformity in its approach and the lack of rigor in its development. In fact, it has not been yet successful to extend the uniaxial model of Kachanov to three dimensions. It seems to follow that of theory of plasticity. The justification there is based on the tests that the yield points of mild steel specimens are unaffected by hydrostatic pressure at the global scale, i.e., taking the entire specimen into account. This, however, is not the case in the extended version of the damage theory where application is made to the local state of stress. Such a discrepancy could be significant, especially when applying the model to analyze the local damage of material.

In what follows, a modified version of the ordinary damage theory is used; it assumes that the material is elastic even though it can be damaged by cracking. Such a process has been referred to in the literature as ''elastic damage'' which may be interpreted differently. Hence, a thermodynamic approach has been used in [20,21] to provide a more clear physical explanation of the physical damage process. A two dimensional finite element scheme is used to obtain the state of stress and strain in the arch. Good agreement between theory and test results was found. The methodology can thus be used to predict the failure of concrete-like structures.

2. Damage theory based on thermodynamics

The general theory of damage of elastic material can be found in [21]. It will be briefly introduced in this section.

According to the first law of thermodynamics, the internal energy is equal to the Helmholtz free energy for a reversible isothermal process. Hence the second law of thermodynamics for a closed system can be written in terms of time rate as

$$\boldsymbol{\sigma} : \dot{\boldsymbol{\varepsilon}} - \dot{H} = 0 \tag{1}$$

In Eq. (1), $\boldsymbol{\sigma}$ is the Cauchy stress tensor, $\boldsymbol{\varepsilon}$ the infinitesimal strain tensor and H the Helmholtz free energy per unit volume. The dot above the field variables denotes the material derivative and the colon stands for the contraction over two indices. The bolder character indicates a tensor.

A more general interpretation of Eq. (1) has been given by Eq. (2) of [22]. In fact, a more general form of Eq. (1) corresponds to replacing the time rate of Helmholtz function H by the time rate of the dissipation energy density Ψ. In such a case, the equality sign can be replaced by an inequality sign in Eq. (1) and the result can be applied to a dissipation material. In addition, application can be made to an open thermodynamic system. More specifically, if the differential energy density expressed in terms of the sum of the differential available and unavailable energy density are divided by dt, then Eq. (1) would be identical to that presented above. And the left-hand side of Eq. (1) can be identified with the unavailable portion of the energy density. In the language of irreversible thermodynamics, dissipation due to heat flow or the alike such as damage which describes the microscopic discontinuities has been lumped into the energy dissipation density which is not available to do damage at the macroscopic level. This should be distinguished from damage by macrocracking which is also irreversible. In the theory of plasticity, dissipation refers to damage at the microscopic level. Such an effect will not included in the present model of damage. It is pertinent for a damage theory to start with

$$\boldsymbol{\sigma} : \dot{\boldsymbol{\varepsilon}} - \dot{\Psi} \geqslant 0 \tag{2}$$

where Ψ is the energy density per unit volume [22].

The damage state can be characterized by an internal state variable (say damage variable). The scalar damage variable is D for isotropic damage [10], and $\mathbf{D}$ is a symmetric second-order damage tensor for anisotropic damage state [23]. The energy density function Ψ can thus be related to $\boldsymbol{\varepsilon}$ and $\mathbf{D}$ as

$$\Psi = \Psi(\boldsymbol{\varepsilon}, \mathbf{D}) \tag{3}$$