Engineering Failure Analysis 60 (2016) 363–373

Contents lists available at ScienceDirect

Engineering Failure Analysis

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

Failure analysis method of concrete arch dam based on elastic strain energy criterion

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ARTICLE INFO

Article history:
Received 26 June 2015
Received in revised form 11 November 2015
Accepted 16 November 2015
Available online 2 December 2015

Keywords:
Concrete dam
Elastic strain energy
Failure evaluation criterion
Orthotropic damage

ABSTRACT

The arch dam is a type of massive water-retaining structure made of concrete. The overall failure mechanism and corresponding analysis criterion are key issues of concern in the dam engineering field. In this paper, the energy evolution of arch dams in the failure process is studied first, which can be decomposed as energy dissipation accompanied by concrete damage and elastic strain energy absorption and release during elastic deformation. An evaluation criterion for failure analysis of concrete arch dams is then established based on elastic strain energy. An orthotropic damage constitutive model for dam concrete is then proposed along with its numerical simulation method, which is established for structural failure analysis. Numerical simulations show that the elastic strain energy in elements increases with increasing overload safety coefficient and finally converges to the concrete material surface energy, at which time the locally plastic damage area develops rapidly and finally leads to cracking failure of structures. The proposed failure analysis criterion for concrete dams under integrated loads is suitable for analyzing dam instability failure, which has great operability and value in engineering applications in the future.

1. Introduction

The failure mechanism of concrete arch dams under various loads, such as water pressure, sediment pressure, environment temperature and earthquakes, is one of the main focuses of dam safety research [1–3]. In conventional elastic–plastic mechanics methods, the stress–strain relationship is used to describe the mechanical behaviors of a concrete dam, and the strength criteria attempt to identify the failure of a concrete dam [4]. However, affected by discreteness and uncertainty of concrete materials, the local high stresses and high strains make concrete partially damaged—even partially strength depleted—but do not necessarily lead to the destruction of the whole concrete dam. Therefore, these strength theories and failure criteria are difficult to employ in describing the cracking process of a material and identifying the overall failure status of a structure, such as a concrete arch dam [5,6].

The damage and fracture theories are potentially more effective in expounding the cracking status and failure mechanisms of concrete structures. Studies show that, when affected by external loads and alternating environmental factors, small defects or damage such as internal micro cracks and micro holes are easily formed and developed by the stress concentration on the aggregate and mortar interface of concrete. When the external factors increase, these small defects will afflux, break through and fracture to become macro cracks. Failure of the concrete dam may occur if the crack expansion continues [7]. In other words, the

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http://dx.doi.org/10.1016/j.engfailanal.2015.11.045
1350-6307/

failure of an arch dam is a type of complex instability process, starting from material damage to structural fracture and overall failure, owing to the heterogeneous behavior of dam materials [8].

In recent years, with the construction of super-high concrete arch dams, such as the 294.5 m Xiaowan Dam and 305 m Jinping I Hydropower Station, many scholars have studied the whole-dam failure mechanism by numerical simulations and physical model experiments, and the research has made great progress [9–11]. The failure criteria of numerical simulation for arch dams are mainly divided into three categories [12,13]: the convergence criterion, displacement mutation criterion and plastic zone transfixion criterion. The convergence criterion is determined by system instability when numerical calculation iteration does not converge and is caused by a large development of the plastic zone in the structure or a sharp decline of material stiffness. However, calculation divergence does not definitely mean that the structure will approach the critical balance at which the unit morphology of the model and the constitutive relation of material, etc., will affect the convergence of computing. In the mutation criterion, which is also known as the catastrophe criterion, the displacement mutation point was usually determined according to the shape of the load displacement curve. In the plastic zone transfixion criterion, the development shape of the local plastic zone in structures is used as a standard for the overall instability. However, deformation, plasticity, damage and fracture are local quantities of a point, which are not sufficient to judge the overall safety of a structure [14]. Therefore, indicators of the overall status of a structure, especially in terms of the failure criteria, are urgently needed.

The energy value is a comprehensive indicator of a structural system that is suitable for analyzing the failure process under different loads. Large quantities of research indicate that the damage and fracture process of concrete is closely related to the energy value. Susanto [15] calculated the fracture energies of twenty-nine three-point bending beam specimens made of ultrahigh-strength concrete using multiple existing methods. Li [16] developed a simplified coupling damage constitutive model based on the characteristic of damage energy release rate and the uniaxial damage evolution function of concrete material, which is demonstrated to reflect the salient features of concrete under uniaxial and biaxial loading. Wu [17] proposed a plastic-damage constitutive model for concrete, in which the internal variables of the constitutive relation are defined through the elastic Helmholtz free energy and the damage variables are derived corresponding to damage energy release rates. Xu [18] proposed an energy parameter $K = \sqrt{EG}$ to integrate the fracture energy release properties of the double-G fracture model and double-K fracture model, which presents good agreement through experiments and calculations. However, further work is needed to reveal the relations between structural failure and the energy evolution process in concrete cracking.

In this paper, the failure process of concrete dams is described by the energy dissipations during the concrete damage and plasticity evolution process and the elastic strain energy absorption process during structure deformation. Thus, an analysis model and a failure criterion of the entire concrete dam are established based on the elastic strain energy. Moreover, the orthotropic damage model and damage evolution model are constructed according to the orthotropic damage characteristics of concrete materials. Numerical simulations are finally carried out on a concrete arch dam by compiling the structure analysis algorithms.

2. The energy evolution of a concrete dam

For a certain concrete dam in the service period, the time series Q_t is adopted to be the equivalent external loads during the long service period. It is assumed that the concrete dam is a closed system that has no heat exchange with the outside environment during the course of servicing. According to the first law of thermodynamics in a closed system, the total energy input U generated by the external load Q_t is then given as follows:

$$U = U^e + U^d \tag{1}$$

where U^e is the structural elastic strain energy; U^d is the structural energy dissipation; and U is the total energy input.

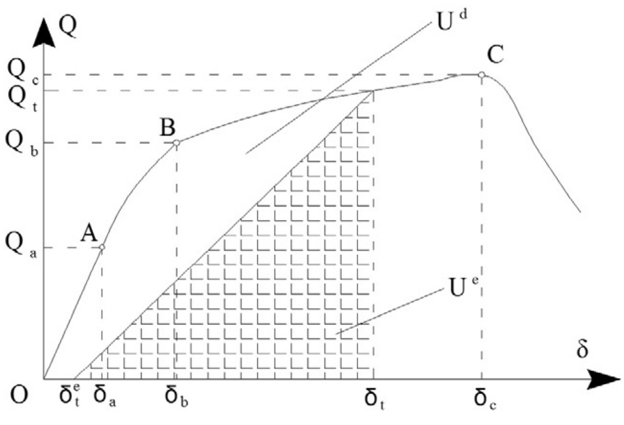

Fig. 1. Energy compositions of concrete dam under generalized load deformation process.