同濟大學
TONGJI UNIVERSITY

博士学位论文

混凝土随机损伤本构模型
与试验研究

（国家自然科学基金委重点基金（90715033）支持）

姓　　名：曾莎洁

学　　号：0810020010

所在院系：建筑工程系

学科门类：工学

学科专业：结构工程

指导教师：李杰 教授

二〇一二年八月

同濟大學

TONGJI UNIVERSITY

A dissertation submitted to

Tongji University in conformity with the requirements for

the degree of Doctor of Philosophy

Dynamic Experimental Research and Stochastic Damage Constitutive Model for Concrete

(Supported by the Natural Science Foundation of China for Major Project
Grant No. 90715033)

Candidate: Shajie Zeng

Student Number: 0810020010

School/Department: Department of Building Engineering

Discipline: Engineering

Major: Structural Engineering

Supervisor: Prof. Jie Li

August, 2012

摘要

作为一种多相复合材料，混凝土材料具有典型的非匀质性和多相多孔性，在外部荷载作用下必然表现出非常复杂的物理力学行为。同时，混凝土材料也是一种率相关性材料，其力学性能还与外部作用的加载速度有关。因此，对于混凝土本构关系的研究，需要从细观物理机制角度考虑非线性、随机性与率相关性的相互耦合作用。本文对混凝土单轴和多轴受力全过程性能进行了系统的试验研究，从物理机理上考察了混凝土力学行为的非线性、随机性与率相关性，进行了混凝土随机损伤本构关系的理论探索。

试验方面，本文进行了强度等级为 C30~C60 的混凝土材料在单轴、多轴（围压分别为 20MPa、40MPa）静力作用（应变速率为 $10^{-5}s^{-1}$）以及动力作用（应变速率范围为 10^{-4}~$10^{-2}s^{-1}$）下的系统试验研究，累积完成静载全曲线试验 132 个、动载全曲线试验 255 个、基本力学性能试验 132 个、其他对比试验 21 个。分别考察了加载速率和侧向约束对于混凝土破坏形态、峰值强度、峰值应变、弹性模量以及受力全曲线等方面的影响规律，其结果与既有结果具有一定的一致性，并且与研究者对混凝土的直观理解相符。同时，发现加载速率和侧向约束对混凝土力学性能的影响存在耦合机制，即约束混凝土的应变率效应存在一个“临界状态”，超过该临界状态，约束混凝土的应变率效应呈现“负增长”。

理论方面，在课题组此前研究的基础上，本文对基于细观随机断裂模型的混凝土弹塑性随机损伤本构模型进行进一步研究。结合概率密度演化方法，将混凝土随机损伤本构关系的二阶统计矩扩展为概率密度的描述，获得了单轴受力状态下任意应变处应力和二维包络的概率密度函数估计。同时，采用细观损伤的随机建模识别算法，利用本文试验数据和相关研究文献，得到细观断裂应变随机场参数和塑性应变参数的系统结果，并结合《混凝土结构设计规范》（GB50010-2010）给出弹塑性随机损伤模型中的基本参数建议值。

动力加载条件下，细观意义上的孔隙自由水是引起混凝土材料表现出率相关性的重要因素。基于自由水的基本物理方程，讨论了低应变率荷载条件下混凝土孔隙中的自由水所产生的黏性机制，发现“应变迟滞”效应是混凝土表现出率相关性的本质原因，Stefan 效应是混凝土动力性能变化的细观物理机理。在此基础上，本文引入“应变迟滞因子”的概念，建立了静力应变与动力应变的联系桥梁，并与前述随机损伤静力模型结合，发展了弹塑性随机损伤动力模型。模型结果与实验结果的对比，验证了模型的合理性和有效性。

在上述研究的基础上，结合《混凝土结构设计规范》（GB50010-2010）中的

本构关系，建议了一类简单实用的工程简化模型，并将其扩展为考虑约束条件的动力模型。通过材料层次和构件层次的数值模拟验证，证实该模型能够较好地模拟混凝土构件在动力荷载作用下的非线性力学特性，且无需任何迭代，适用于对于大型混凝土结构的非线性分析，便于工程实用。

关键词：混凝土，本构关系，率相关性，随机性，动力模型

ABSTRACT

As a multi-phase composite, concrete, which is composed of randomness and heterogeneity, is of rather complicated behaviors under external loadings. Also, concrete material is of rate-dependency, the mechanical behavior of which is observed be sensitive to the strain rate under dynamic loading. Hence, the establishment of sound constitutive model of concrete should describe the coupling behavior of randomness, nonlinearity and rate-dependency base on the micro-scale physical mechanism. The experimental investigation was carried out systematically on the full process properties of concrete under uniaxial and multi-axial loading in the proposed thesis. And based on the physical mechanism of each aspect, the stochastic damage constitutive framework of concrete is proposed.

On the one hand, an experimental research was performed to investigate the dynamic behavior of concrete with static and dynamic loading, the strength grade of which ranged from C30 to C60. By using the MTS servo hydraulic testing system, the strain rate from 10^{-5} s^{-1} to 10^{-2} s^{-1} was achieved. And the hydrostatic pressure up to 20MPa and 40MPa was applied to the specimen with the help of the triaxial loading cell. Based on the analysis of test results of 132 complete stress-strain curves with static strain rate and 255 complete stress-strain curves with high strain rate, the effect of strain rates and hydrostatic pressures on the failure modes, peak strength, peak strain, elastic modules, and the full process properties was studied deeply. In particular, our experimental results suggested a clear coupling effect between the enhancements induced by the strain rate and the confining pressures. The enhancement of the strain rate could be, at least partially, eliminated by the enhancement of the confining pressure.

On the other hand, based on the microscopic stochastic rupture model (MSRM), the stochastic damage model of concrete is studied further. In order to grasp the probability information of the stress strain relationship and the biaxial strength envelope for concrete material, the stochastic harmonic function (SHF) is adopted to simulate the microscopic stochastic field in MSRM. According to the generalized probability density evolution method (PDEM), the probability density function (PDF) of the stress strain relationship, the biaxial strength and their evolution are provided. Furthermore, based on the theory of the stochastic structural system modeling, the identification algorithm for the material parameters (λ,ζ,c) is presented. Lastly, some reference values of the material parameters in MSRM, which are advantageous in engineering application, are suggested according to China Code for Design of Concrete Structures (GB50010-2010).

On the basis of some research findings in recent years, the main factor of rate-dependency of concrete material is micro-scale pore free water. According to the basic physics equation of free water, the viscosity mechanism caused by internal pore free water of concrete under dynamic loading is discussed, and the essential reason of rate-dependency of concrete material, which is the Strain Hysteretic Effect (SHE), are expected to be found out. The physical mechanism of strain rate effect of concrete can be explained by the phenomenon of Stefan effect. With this knowledge, the concept of Strain Hysteretic Effect Factor (SHEF) is introduced to bridge over the static strain and the dynamic strain. Then the dynamic damage evolutions in the forms of mean value and standard derivation are derived based on the stochastic rupture model and a dynamic extension of the stochastic damage model of concrete is proposed. The agreement between the simulated results and experimental data indicates reliability of the present model.

Base on damage mechanics, the discussion is carried out between the basic equations in the China Code for Design of Concrete Structures (GB50010-2010). Simultaneously, considering the damage evolution and the consistency of model, some improvements are performed to the uniaxial stress strain relationship in the code. Then a unified expression for uniaxial constitutive relationship of concrete material is get. And a dynamic extension of the engineering simplified model of concrete material by considering the confining pressures is proposed. Finally, the agreement of the nonlinear mechanical behavior of reinforced concrete members between the simulated results and experimental data indicates the validity of the engineering dynamic model.

Keywords: concrete, constitutive law, rate-dependency, randomness, dynamic model

目录