同濟大學
TONGJI UNIVERSITY

博士学位论文

# 混凝土结构疲劳效应分析与结构非线性荷载效应组合方法研究

（国家自然科学基金重点资助项目 编号：51538010）
（上海市教委科研创新计划重大项目 编号：2017-01-07-00-07-E00006）

姓　　名：高若凡
学　　号：1310227
所在院系：土木工程学院 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
联合指导教师：Prof.A.H-S.Ang

二〇一九年十月

同濟大學
TONGJI UNIVERSITY

A dissertation submitted to

Tongji University in conformity with the requirements for

the degree of Doctor of Philosophy

# Fatigue Effect Analysis of Concrete Structures and Combination Method of Nonlinear Load Effects of Structures

(Funded by the National Natural Science Foundation of China for Key Programs, Grant No. 51538010 and by the Major Project of the Scientific Research Innovation Plan of Shanghai Education Commission, Grant No. 2017-01-07-00-07-E00006)



| | |
|---|---|
| Candidate: | Ruofan Gao |
| Student Number: | 1310227 |
| School/Department: | School of Civil Engineering |
| Discipline: | Civil Engineering |
| Major: | Structural Engineering |
| Supervisor: | Prof. Jie Li |
| Co-Supervisor: | Prof. A.H-S.Ang |



October, 2019

# 摘 要

实际工程中的混凝土结构，在其服役过程中通常需要承受多种性质不同的荷载，且由于荷载的多样化及环境的复杂性，导致服役的工程结构往往呈现出非线性受力的性质。本文以既有混凝土结构作为工程研究背景，首先探究单一疲劳荷载作用下的结构疲劳效应，进而实现疲劳荷载与地震共同作用下的结构非线性荷载效应组合，试图解决疲劳荷载与地震共同作用下的结构可靠度分析问题。

根据工程荷载特点，应用复合泊松过程模型，分别建立了疲劳荷载和地震发生序列的概率模型。创新性地提出了基于随机谐和函数的复合泊松过程模拟方法，实现了离散随机过程的连续随机函数表述。通过与经典的蒙特卡罗模拟方法进行对比分析，表明随机谐和函数方法不仅具有更好的模拟效果，且通过少数的基本随机变量即可很好地反映复合泊松过程的概率特性，从而证明了随机谐和函数方法用于复合泊松过程模拟的正确性和优越性。

从疲劳损伤能量等效的角度，提出了一种等效等幅荷载方法。从混凝土微观尺度的微裂纹扩展过程出发，根据裂纹的扩展速率模型，得到了微观层次的疲劳能量耗散；通过微-宏观尺度的能量转化，获得了宏观尺度的疲劳能量耗散。在此基础上，基于随机疲劳荷载与等效等幅荷载所引起的能量相等的原则，给出了混凝土结构随机疲劳荷载的等效等幅荷载模型。将所提出的等效等幅荷载方法分别应用于材料单元和结构构件层次，并与广泛应用的均方根方法进行了对比。结果表明，所提出的等效等幅荷载方法具有更高的精度，且与相应随机疲劳荷载下的结构响应状态更为接近，从而验证了建议方法的有效性。

基于随机损伤力学，研究了确定性荷载作用下的混凝土结构疲劳响应。研究中采用混凝土疲劳随机损伤本构模型反映疲劳全过程中混凝土材料的性能劣化过程。依据随机疲劳荷载模型及等效疲劳荷载方法，引入循环跳跃式加速算法，并将其与固体力学基本方程相结合，建立了确定性荷载作用下结构疲劳全过程分析的理论框架。将所发展的结构疲劳分析方法应用于实际工程结构，证实了该方法的实用性和有效性。这一方法，实现了结构疲劳全过程分析，可以获得结构全寿命周期内的实时疲劳损伤状态。

基于概率密度演化理论，进行了混凝土结构随机疲劳响应分析。根据概率密度演化理论，建立关于结构响应量的物理方程与概率密度演化方程，发展了结构随机疲劳响应的数值分析方法。据此，可以得到随机疲劳荷载作用下复杂结构响应的概率密度分布。在结构随机疲劳响应分析方法的基础上，提出了两类结构疲

劳可靠度分析方法。其中，基于物理综合法的疲劳可靠度分析方法将随机疲劳系统视为概率耗散系统，建立了系统基本物理量的物理分析方程与概率密度演化方程，并通过引入疲劳失效准则求解系统疲劳可靠度。基于剩余疲劳寿命的分析方法从概率保守系统的角度建立了关于剩余疲劳寿命的概率密度演化方程，据此，得到结构剩余疲劳寿命的概率密度信息，并给出系统疲劳可靠度。将这两种方法分别应用到实际工程结构，说明了两种方法的适用性。通过对比两种方法的计算结果，发现两者高度吻合，从而相互验证了彼此的正确性。

提出了基于概率空间剖分解决荷载遇合问题的基本方法。采用结构随机疲劳分析和随机地震响应分析，实现了疲劳荷载与地震共同作用下的结构非线性荷载效应组合。在研究中，考虑到疲劳荷载和地震作用的特性，提出了双时间尺度的概率密度演化分析，分别建立了疲劳位移和地震位移的概率密度演化方程。综合固体力学物理方程与概率密度演化方程，进行了疲劳荷载和地震共同作用下的结构随机响应分析。进而，通过引入结构疲劳失效准则和地震失效准则，定义了考虑多种失效模式的结构失效准则函数。在此基础上，应用物理综合法，发展了疲劳荷载和地震共同作用下的结构可靠度分析方法。通过工程实例，对单一疲劳荷载作用、单一地震作用与疲劳荷载和地震共同作用下的结构可靠度进行了对比分析。研究表明，既有结构的抗震能力远低于新建结构的抗震能力。通过实例分析，说明了进行结构非线性效应组合及可靠度研究的可行性与必要性。

最后，阐明了本文研究工作中尚存在的问题，并对进一步的研究工作做出了展望。

**关键词：** 随机疲劳荷载，等效等幅荷载，损伤本构模型，概率密度演化理论，疲劳分析，疲劳可靠度，非线性荷载效应组合，结构整体可靠度

# ABSTRACT

In practical engineering, concrete structures are usually subjected to various kinds of loads during their service periods. Due to the variety of loads and the complexity of the service environment, the structures often exhibit nonlinearity. Considering the seismic performance of the existing concrete structures as the engineering research background, the present thesis explores the fatigue effects of structures under single fatigue loads, studies the nonlinear combination of load effects of structures under both fatigue loads and earthquakes, and attempts to solve the problem of structural reliability under various loads.

According to the characteristics of loads, by applying the compound Poisson process model, the probabilistic models of fatigue loads and earthquakes are established, respectively. In order to simulate the compound Poisson process, an innovative simulation method based on stochastic harmonic functions is proposed, which realizes the continuous stochastic function representation of discrete stochastic processes. By comparing with the classical Monte Carlo simulation method, it shows that the stochastic harmonic function method could provide more accurate simulation results, and could well reflect the probability characteristics of the compound Poisson process through much less basic random variables. Hence, the correctness and advantage of the stochastic harmonic function method are verified.

An equivalent constant-amplitude fatigue (ECA) load method is proposed based on the fatigue energy equivalence principle. Starting from the propagation process of micro cracks, the fatigue energy dissipation at the micro-scale is obtained based on the propagation rate of micro cracks and a hierarchy model of cracks. The dissipated energy at the macro-scale is derived by the energy transition from micro to macro scales. According to the principle that the total energy dissipation under random loads equals that under ECA loads, an ECA load model for random fatigue loads of concrete structures is presented. The proposed ECA method is applied to the concrete block and the concrete beam respectively and compared with the widely used root mean square method. The results show that the proposed ECA method gives more precise and satisfactory results, which validates the effectiveness of the proposed method.

The fatigue response of concrete structures under deterministic loads is studied based on the stochastic damage mechanics. In this study, the fatigue stochastic damage constitutive model for concrete is employed to reflect the deterioration process of concrete material in the whole fatigue process. The random fatigue load model is combined with the proposed ECA method to generate the samples of fatigue loads. The cyclic jump acceleration algorithm is introduced and combined with the physical equation of solid mechanics, aiming at improving the efficiency of fatigue analysis. Based on these, the theoretical framework for the fatigue response analysis of structures under deterministic loads is established. The developed fatigue analysis method is applied to a practical engineering structure, which proves the practicability and effectiveness of the developed method. This method realizes the whole fatigue process analysis of structures and obtains the real-time fatigue damage state during the life cycle of structures.

On the basis of the probability density evolution theory, the stochastic fatigue response analysis for concrete structures is conducted. The physical equations and the probability density evolution equation (PDEE) of structural response are established. A numerical analysis method for stochastic fatigue response of structures is developed. On this basis, the probability density function (PDF) of the response of complex structures under random fatigue loads could be obtained. According to the stochastic fatigue analysis method, two new fatigue reliability analysis methods are proposed. The analysis method based on the physical synthesis method regards the stochastic fatigue system as a probability dissipated system. The physical analysis equations and the PDEE of the basic physical variable of the system are properly built. By introducing the fatigue failure criterion, the fatigue reliability of the system is finally obtained. The analysis method based on the remaining fatigue life establishes the PDEE of the remaining fatigue life from the perspective of the probabilistic conservative system. Based on this, the probability density information of the remaining fatigue life is gained, and the fatigue reliability of the system is then calculated. These two methods are applied to the engineering structures to illustrate their applicability. By comparing the calculated results of the two methods, it is found that they agree with each other very well, thus mutually verifying the correctness of each other.

A basic method based on the probability space decomposition is proposed to solve the load coincidence problem. By applying the stochastic fatigue analysis and stochastic seismic response analysis, the nonlinear combination of load effects of structures under both fatigue loads and earthquakes is realized. In the research, considering the characteristics of fatigue loads and earthquakes, a two-time scale probability density evolution analysis is proposed, and thus, the PDEEs for fatigue loads and earthquakes are then established, respectively. Based on the physical equations of solid mechanics and the PDEEs, the stochastic response analysis of structures under both fatigue loads and earthquakes is performed. Furthermore, by introducing the fatigue failure criterion and seismic failure criterion, a structural failure criterion function with multiple failure modes is defined. On this basis, the structural reliability analysis method under both fatigue loads and earthquakes is developed by adopting the physical synthesis method. Through engineering cases, the structural global reliability under both fatigue loads and earthquakes are compared in details with that under single fatigue loads and under single earthquakes. The results show that the seismic ability of existing structures is far lower than that of new structures. The feasibility and necessity of the research on the nonlinear combination of load effects as well as the structural global reliability under various loads are illustrated by the case study.

In the end, some open questions and problems regarding the present research are summarized. Some future research perspectives are clarified as well.

**Key Words:** random fatigue loads, equivalent constant-amplitude loads, damage constitutive models, probability density evolution theory, fatigue analysis, fatigue reliability, nonlinear combination of load effects, structural global reliability

# 目 录