Bauwesen

Jean Mahowald

EVALUATION OF DYNAMIC DAMAGE INDICATORS ON REAL-LIFE CIVIL ENGINEERING STRUCTURES: MEASUREMENT UNCERTAINTY AND ENVIRONMENTAL INFLUENCES CONSIDERED

Shaker Verlag

PhD-FSTC-2013-11
The Faculty of Sciences, Technology and Communication

DISSERTATION

Presented on 08/05/2013 in Luxembourg

to obtain the degree of

DOCTEUR DE L'UNIVERSITÉ DU LUXEMBOURG

EN SCIENCES DE L'INGÉNIEUR

by

Jean MAHOWALD
Born on 24th April 1984 in Luxembourg (Luxembourg)

EVALUATION OF DYNAMIC DAMAGE INDICATORS ON REAL-LIFE CIVIL ENGINEERING STRUCTURES: MEASUREMENT UNCERTAINTY AND ENVIRONMENTAL INFLUENCES CONSIDERED

Dissertation defense committee

Prof. Dr.-Ing. Stefan Maas, dissertation supervisor
Professor, Université du Luxembourg

Ass. Prof. Dr.-Ing. Danièle Waldmann-Diederich, Chairwomen
Assistant-Professor, Université du Luxembourg

Prof. Dr.-Ing. Arno Zürbes, Vice-Chairman
Professor, Fachhoschule Bingen

Prof. Dr. i.r. Guido de Roeck
Professor, Katholieke Universiteit Leuven

Prof. Dr. Jean-Claude Golinval
Professor, Université de Liège

Bibliographic information published by the Deutsche Nationalbibliothek
The Deutsche Nationalbibliothek lists this publication in the Deutsche Nationalbibliografie; detailed bibliographic data are available in the Internet at http://dnb.d-nb.de.

Zugl.: University of Luxembourg, Diss., 2013

Copyright Shaker Verlag 2014
All rights reserved. No part of this publication may be reproduced, stored in a retrieval system, or transmitted, in any form or by any means, electronic, mechanical, photocopying, recording or otherwise, without the prior permission of the publishers.

Printed in Germany.

ISBN 978-3-8440-2673-3
ISSN 0945-067X

Shaker Verlag GmbH • P.O. BOX 101818 • D-52018 Aachen
Phone: 0049/2407/9596-0 • Telefax: 0049/2407/9596-9
Internet: www.shaker.de • e-mail: info@shaker.de

PREFACE

This thesis is the result of my four years' work (June 2009 - May 2013) at the University of Luxembourg in the Faculty of Science, Technology and Communication, in the Research Unit of Engineering Science and under the supervision of Prof. Dr. Stefan Maas. The project *Dynamic Evaluation of Civil Engineering Structures* is financed by the University of Luxembourg in cooperation with the *Administration des Ponts et Chaussées Luxembourg*. The overall aim is to use non-destructive testing methods for condition control of civil engineering structures, and particularly of bridges. During this work, I have learned a lot in the field of vibration analysis, signal processing and conducting different projects. A large part of the work consisted in organising and conducting extensive test programmes for large bridges with artificial damage such as the Champangshiehl bridge which was tested during three weeks and demolished afterwards due to new urban planning. In this instance, one year was spent on the planning and evaluation from the ex ante calculation of the cracks to the organisation of the test series. This project required lot of discussions and organisational meetings as restrictions were imposed for safety and handling reasons. During this major project part, I gained a lot of experience in managing and scientifically approaching a project of this kind, as the opportunity to use an in situ structure for test procedures was unique for such a small country and University of Luxembourg.

Furthermore, as a research worker with a background in physics (specialisation in biophysics), it was initially a challenge to get into the field of engineering science. However, over the years and with the experience in teaching the exercises in mechanics, I acquired the knowledge in the field of engineering science, which was needed to accomplish the project. In addition, it was of high importance during the project to be familiar with using different software for signal processing and finite-element modelling. My background in physics proved to be especially helpful to solve various problems encountered during the research. I can only affirm the common stereotype of physicists being able to handle any kind of problems. Even without a basic in engineering science I have always endeavoured to give my best input in this field of research and hope the gained results can be of interest for future work at the University of Luxembourg and abroad.

First of all, I would like to thank Prof. Dr. Stefan Maas giving me the opportunity to do this type of research at the University of Luxembourg without the usual profile. I remember well when I was sitting in his office for the first interview, and he was already convinced that a physicist, without any knowledge in neither mechanics nor finite-element modelling could handle this project. Secondly, I also want to thank him for several discussions about various problems, which I encountered during my work. In addition, he gave me the possibility to publish at different conferences and journals, which is an asset since nowadays a greater emphasis is given to listed publications and speeches.

I also want to thank my co-workers, especially Frank Scherbaum who was also involved in the project of the Champangshiehl bridge and my predecessors Prof. Dr. Ing Markus Waltering and Dr. Ing. Volker Bungard, from whom I gained my basics in vibration analysis, and who initiated me in the topic. Furthermore, I would like to thank the technical assistants without whom any experimental data, essential for this work, would be missing. Therefore, many thanks are due to Ed Weyer, Marc Seil, Vicente Reis Adonis, Claude Colle, Ken Adam, Cédric Bruyère, Ralph Reiter, Raphael Hinger and Gilbert Klein. I am also very grateful to André Stemper and Lionel Arend for fruitful discussions on signal processing, and Simone Drees for the administrative work. Moreover, another thank you goes to the students, whose Bachelor Theses or Master and Bachelor projects were also a part of this project: Ba Mamadou Aliou, Tom Wagner, Jeff Waldbillig, Pierre Reitz, Mike Scholtes, Philippe Ries, Jeremy Silva Vieira, Andy Tibolt, Thomas Ostrihon, Tom Schmit, Romain Steffen, Nuno Pereira and Patrick Ficerai. I am also thankful to the interims students whose algorithm or evaluation of the results helped a lot on the project: Christian Grosch, Shubham Sirothia and Patrick Lamberty. Further, another thank you goes to Michèle Noblet and Viet Ha Nguyen for the proofreading of the thesis.

Moreover, I would also like to thank the members of the dissertation defence committee: Prof. Dr. Guido De Roeck form the KU Leuven and Prof. Dr. Jean-Claude Golinval from the Université de Liège for fruitful discussions and corrections, and Ass.-Prof. Dr. Danièle

试读结束：需要全本请在线购买： www.ertongbook.com

Waldmann-Diederich from the University of Luxembourg and Prof. Dr. Arno Zürbes from the Fachhoschule Bingen for their input during regular meetings over the four-year period of my research at the University of Luxembourg.

I am also ingratiated to the cooperation partners, without whom the experimental part would have been impossible: Gilles Didier and all his staff of the *division d'ouvrages d'art* and regional divisions of the *Administration des Ponts et Chaussées Luxembourg* for giving me the opportunity to measure the bridges in situ and for the transportation of the force exciters; Joseph Lippis, Dino and David at Construction Baatz for the help and organisation on the Champangshiehl bridge; the *Fonds Kirchberg*, whose donation on the test series on the Champangshiehl bridge was most welcome; Marc Buchler and Max Friob at ArcelorMittal for providing the beam blanks as an experimental mass to load the Champangshiehl bridge and Claude Schmit at Arcoop, project manager at the construction site of the porte de l'europe, for being in charge of the time management at the Champangshiehl bridge.

Last but not least, I am very grateful to my family, Marie-Paule and my friends for their endless patience, interest and support.

ABSTRACT

English

This thesis examines the vibration analysis used for condition control on civil engineering structures. Experimental data of laboratory and in situ structures are presented. Force excitation tests as well as a monitoring system with an automated analysis were conducted to collect the experimental data. The investigated structures were precast, reinforced and prestressed, slab elements under laboratory conditions, as well as a two span composite bridge and a two span prestressed box girder bridge in situ. The precast slab elements and the prestressed box girder bridge were subjected to artificial damage with crack formation until ultimate load. These structures were measured stepwise to have different damage states in order to quantify the possible use on damage assessment using vibration analysis. The dynamic analysis consisted in yielding modal parameters, especially the eigenfrequencies and the mode shapes, in order to show the changes according to the damage states. A particular focus is given to the flexibility matrices which clearly show the changes caused by gaining damage in contrast to the intact state. However, the damage must be over a certain empiric threshold limit, as environmental impacts and measurement uncertainty also leads to changes of modal parameters, shown by repeated force excitation tests on the investigated structures. Moreover the influence of the environmental impacts, especially the temperature, on the damage indicators are investigated by repeated measurements using force excitation tests in winter and summer, as well as on data captured by a monitoring system on the two span composite bridge in Useldange. In terms of the eigenfrequencies, variations up to approximately 5% for the measurement uncertainty and up to 1% per Kelvin for environmental impacts are noticed without any damage, which is relatively high in comparison to effects of damage. Considering the most significant damage indicator, the flexibility matrix, changes of 10% for repeated measurements and approximately 2.5% per Kelvin for environmental influences are recognised. Contrarily, bigger real damage can cause over 10% changes on the eigenfrequencies and even over 20% changes in the flexibility matrices, which are therefore obviously detectable. Another part is the use of model updating techniques in order to show the damage locations on the investigated structures by finite element models. The main conclusion is that care should be taken when measuring and analysing the results as small variations cannot only be assigned to damage, but could also be caused by the above mentioned environmental and practical influences. To this end, recommendations minimising these effects are proposed.

Deutsch

Die vorliegende Arbeit untersucht die Anwendbarkeit von Schwingungsanalysen für die Zustandsbewertung von Ingenieursbauwerken. Die gesammelten experimentellen Daten von Labor- sowie in situ Versuchen werden vorgestellt. Diese wurden in Tests mit erzwungener Kraftanregung, als auch mittels eines Überwachungssystems mit Wind- und Verkehrserregung kombiniert mit automatisierter Auswertung aufgezeichnet. Die untersuchten Strukturen unter Laborbedingungen sind industriell gefertigte Hohldielen aus Spann- und Stahlbeton, wobei letztere speziell für die Universität Luxemburg angefertigt wurden. Desweiteren wurden in situ zwei Brücken untersucht, eine Zweifeldbrücke in Verbundbauweise und eine vorgespannte Zweifeldbrücke mit Betonhohlkasten. Die Fertigteilplatten und die vorgespannte Hohlkastenbrücke wurden schrittweise bis zur Bruchlast künstlich beschädigt. In den verschiedenen Schadenszuständen mit ausgeprägtem Rissbild, wurden dynamische Tests durchgeführt, um die Anwendbarkeit der untersuchten Methoden zur Schadens- und Zustandsbewertung zu überprüfen. Die modalen Parameter, insbesondere die Eigenfrequenzen und die Eigenformen und ihre Änderungen infolge von Strukturschäden wurden analysiert. Ein besonderer Schwerpunkt dabei sind die Nachgiebigkeitsmatrizen, welche aus den modalen Parametern berechnet werden und welche eindeutig Veränderungen bei den verschiedenen Schadenzuständen im Vergleich zum unbeschädigten Zustand aufweisen. Allerdings muss die Veränderung in dieser Matrix über einem bestimmten empirischen Grenzwert sein, da Umwelteinflüsse und Messunsicherheiten einen nicht zu vernachlässigenden Faktor darstellen. Eben diese Umwelteinflüsse und Unsicherheiten werden anhand von Wiederholungstests an den untersuchten Strukturen gezeigt. Der Einfluss insbesondere der Temperatur auf modale Parameter und die vorgestellten Schadensindikatoren werden durch wiederholte Versuche unter erzwungenen Schwingungen an der Zweifeldbrücke in Useldingen im Winter und Sommer analysiert. Ferner werden diese auch mithilfe von Daten des automatischen Monitoring-Systems an derselben Brücke bestätigt. Bei den Eigenfrequenzen können Veränderungen bis zu ca. 5% durch Messunsicherheiten und bis zu 1% pro Kelvin durch Temperaturschwankungen im intakten Zustand festgestellt werden, was im Vergleich zum Schadenseinfluss sehr viel ist. Betrachtet man die genannte Nachgiebigkeitsmatrix, so sind Abweichungen von 10% durch Messwiederholungen und etwa 2.5% pro Kelvin durch Umwelteinwirkungen nachweisbar. Im Gegensatz dazu verursachen größere reale Schäden an der Struktur über 10% Veränderungen in den Eigenfrequenzen und sogar über 20% in den Nachgiebigkeitsmatrizen, so dass diese Schäden dann auch klar erkennbar sind. Ein weiterer Teil der Arbeit befasst sich mit der sogenannten Finiten Elemente *Model-Updating* Methode, welche Strukturschäden durch punktuelle Modelländerungen sogar lokalisieren kann. Zusammenfassend besteht eine wichtige Schlussfolgerungen der Arbeit darin, dass bei der Messung und Analyse der Ergebnisse zur Zustandsbewertung Vorsicht geboten ist, da kleine Veränderungen der untersuchten Indikatoren nicht nur auf Strukturschäden zurückzuführen sind, sondern auch auf Umwelteinflüsse und Messunsicherheiten. Des Weiteren werden auch Vorschläge gemacht, wie eben diese Störeinflüsse reduziert werden können.

Français

La présente thèse examine l'applicabilité des méthodes de vibrations comme contrôle d'état d'ouvrages d'art. Les données expérimentales collectées lors de tests in situ et au laboratoire seront présentées. Les données sont enregistrées lors de tests d'excitations par des forces connues, mais également à l'aide d'un système de surveillance d'excitations provoquées par le vent et la circulation permettant une évaluation automatisée. Les structures étudiées au laboratoire sont des dalles industriellement préfabriquées en béton, dont l'une est précontrainte et l'autre uniquement armée. La dernière est conçue spécifiquement pour des raisons de recherche à l'Université du Luxembourg. Concernant les structures étudiées in situ, des analyses sont faites sur deux différents ponts à deux travées, l'un composé en adhérence béton-acier à Useldange et l'autre précontraint avec un profil de poutre-caisson à Luxembourg-Ville. Les dalles préfabriquées ainsi que le pont précontraint sont graduellement soumis à différents états de dégradation artificielle jusqu'à la charge de rupture afin d'évaluer l'applicabilité des méthodes de vibration présentées dans cette thèse. Pour ces différents états de dégradation, caractérisés par une formation de fissures, des tests dynamiques ont été effectués afin de vérifier l'applicabilité des méthodes d'interprétation de l'état d'endommagement. Une analyse des paramètres modaux, en particulier les fréquences et les modes propres, ainsi que leur évolution en fonction des états d'endommagement a été effectuée. Une attention particulière est portée à la matrice de flexibilité déterminée à l'aide des paramètres modaux qui constitue un bon indicateur permettant de vérifier ces états d'endommagement en comparaison à l'état intact. Cependant, les changements dans cette matrice doivent être au dessus d'un certain seuil défini empiriquement, car les influences environnementales et les incertitudes de mesures représentent un facteur non négligeable. Ces incertitudes de mesures et les influences environnementales sont mises en évidence à l'aide de tests répétitifs effectués sur les structures analysées. De plus, l'influence de l'environnement, en particulier la température, sur les paramètres modaux et les indicateurs d'endommagements sont examinées par des tests répétitifs d'oscillations forcées effectués en hiver et en été sur le pont d'Useldange. En outre, ces influences sont aussi confirmées par des données acquis par un système de contrôle automatique sur le même pont. Pour ce qui est des fréquences propres, on observe une variation jusqu'à environ 5% due à l'incertitude de mesure et jusqu'à 1% par Kelvin due à des changements de température dans l'état intact. Ces variations sont considérablement élevées en comparaison aux effets d'endommagements. La matrice de flexibilité, l'indicateur le plus touché, présente 10% de variation à cause de la répétition des mesures et environ 2.5% par Kelvin due à des influences de l'environnement. Par contre, des grands endommagements réels de la structure causent plus de 10% variation des fréquences naturelles voir plus de 20% dans les matrices de flexibilités, de telle sorte que des endommagements structurels de cette grandeur sont parfaitement identifiables. Une autre partie de la thèse se consacre au *Model-Updating* par la méthode des éléments finis, qui permet grâce à des variations de modèle ponctuelles de localiser les endommagements de la structure. En résumé, une conclusion importante de ce travail est que pendant une analyse évaluant l'état d'une structure avec les méthodes présentées, on doit faire preuve de beaucoup de prudence concernant les petites variations des paramètres étudiés, car ils ne sont pas nécessairement imputables à des endommagements structurels, mais peuvent aussi être affectés par les influences environnementales ou par les incertitudes de mesures mentionnées ci-dessus. A cet effet, des propositions permettant de minimiser ces influences sont présentées.

CONTENTS

试读结束：需要全本请在线购买： www.ertongbook.com

1 INTRODUCTION

Nowadays bridges are indispensable in traffic planning and management. For thousands of years, mankind has needed bridges to link several points of interests. The definition of a bridge is namely as follows: "A structure carrying a road, path, railroad, or canal across a river, ravine, road, railroad, or other obstacle" (Oxford Dictionaries). Therefore, main routes could be built over obstacles of different natures using bridges making the life easier in the past and still now. Structures from then show that their lifetime can be considerable. Improvements on the calculations and the material shows, however that cost reduction to build bridges can be made. This means that the bridges are not oversized anymore, as it is the case for most ancient bridges. Today more and more bridges are built of concrete and steel. In Germany, for example, there are at the moment approximately 120 000 bridges, 88% of which are reinforced or prestressed bridges, 7% are made of steel and 4% are composite bridges. The remaining 1% are made out of stones or wood (Naumann 2004). So in Germany there are 1.5‰ bridges per habitant. In Luxembourg, in contrast, there are approx. 1 100 bridges found, which makes 2.2‰ bridges per habitant. Therefore, the needs for maintaining the existing bridges is obvious as the costs for building new bridges, and demolishing the old ones, are huge.

Nowadays, each country has its own regulations for bridge inspections. For instance, the DIN 1076 for condition control is used in Germany. The Luxembourgish *Administration des Ponts et Chaussées division d'ouvrages d'art* have their own regulations (Didier 2012). Each year all the bridges are inspected visually in brief. Every 5 to 7 years these inspections are more pronounced by looking in detail if any noticeable damage can be discovered. The advantage of these visual inspections is the fact, that once a crack is noticed it can be classified as damage according to specific criteria. In contrast, other methods give only indicators or a probability that a crack could have been formed. Using visual inspections, the bridge can, therefore, be inspected in detail, but only on the outer surface. Problems occur when damage appears inside the bridge, for example under the asphalt layer or inside the concrete where corrosion on reinforced cables or in the worst case on prestressed cables occur. For this kind of damage, there are investigations using sonar or radar equipment. The drawbacks of these methods are the time and sometimes also the costs (Abdel-Qader, Abudayyeh, and Kelly 2003). In addition, there can be some restrictions to the traffic, for instance when inspections need longer or when complete road closure is necessary for safety reasons. Therefore, there is a confirmed need for accurate further and faster non-destructive testing methods to control the condition of a structure in order to reduce cost and time. The problem is that research on new or existing methods does not show reliable results to guarantee ad hoc structural changes. In the end, visual inspections will still be necessary for classification and safety predictions. Nevertheless, if the cadence time could be reduced, it would already help on this topic. Assuming that the presented testing methods hereafter are reliable on the condition of the bridges, the cadence time could be decreased, or when the tested methods show abnormal results, a visual inspection could be performed. Therefore, identifying the condition of a structure using non-destructive testing methods is of great challenge.

This thesis explores the concept of modal analysis. The idea behind it is that modal parameters, here the eigenfrequencies and the mode shapes, also describe a system physically like the equations of motion. Taken the example of a single span beam, the eigenfrequency, one of its modal parameters, can be calculated according the following equation:

$$f = \frac{\frac{\pi^2}{l^2} \cdot \sqrt{\frac{EI}{\mu}}}{2\pi} \tag{1.1}$$

where l represents the length of the beam, EI the bending stiffness and μ the mass per unit length. In this equation, if the bending stiffness changes, the eigenfrequency of the system also changes. This fact is used in this thesis. Further, the evaluation of the mode shapes and known damage indicators using modal parameters are elaborated in the following chapters. However, first the question arises if a changed bending stiffness can be considered as damage, and what the reason for a reduced bending stiffness is. The answer to this is well discussed in literature, but one fact is certain: once a crack occurs, the moment of inertia I of a reinforced concrete structure is reduced, thus also reducing the eigenfrequency. Other damage, like corrosion often leads to cracks. Thus, a crack, whose classification indicates damage, reduces usually the eigenfrequencies. The fact that the elastic modulus is changed is actually not often seen. Only temperature and humidity change the elastic modulus of a material. Therefore, other impacts on the variations on the eigenfrequencies can be caused by environmental influences (Cornwell et al. 1999). The aim is to reduce these influences from the environment on dynamic testing methods and to discover the changes of modal parameters through damage. Once this is manageable, daily tests with automated analysis could make an evaluation of the condition of a structure and then maybe reduce the cadence time for visual bridge inspections.

试读结束：需要全本请在线购买： www.ertongbook.com