An ACI Technical Publication

SYMPOSIUM VOLUME

Sustainable Performance of Concrete Bridges and Elements Subjected to Aggressive Environments: Monitoring, Evaluation, and Rehabilitation

Editors:
Yail J. Kim
Baolin Wan
Isamu Yoshitake

SP-304

American Concrete Institute
Always advancing

Sustainable Performance of Concrete Bridges and Elements Subjected to Aggressive Environments: Monitoring, Evaluation, and Rehabilitation

Editors:
Yail J. Kim
Baolin Wan
Isamu Yoshitake

American Concrete Institute
Always advancing

SP-304

First printing, October 2015

Discussion is welcomed for all materials published in this issue and will appear ten months from this journal's date if the discussion is received within four months of the paper's print publication. Discussion of material received after specified dates will be considered individually for publication or private response. ACI Standards published in ACI Journals for public comment have discussion due dates printed with the Standard.

The Institute is not responsible for the statements or opinions expressed in its publications. Institute publications are not able to, nor intended to, supplant individual training, responsibility, or judgment of the user, or the supplier, of the information presented.

The papers in this volume have been reviewed under Institute publication procedures by individuals expert in the subject areas of the papers.

Printed in the United States of America

Editorial production: Ryan Jay

ISBN-13: 978-1-942727-47-7

Preface

Since the major milestones of sustainability, such as the Hannover Principle in 1991 and the Kyoto Protocol in 1997, the concept of sustainability has been broadly adopted by various disciplines. New construction consumes considerable amounts of energy and materials, and CO_2 emission in 2020 is expected to increase by 100%, compared with that of today. Technical communities are responsible for improving the sustainability of the built-environment by using more durable and highly efficient materials to reduce the need for replacement, maintenance, or repair. When subjected to aggressive environments, the performance of constructed concrete bridges and their elements is of interest from socioeconomic perspectives. Advances in a variety of aspects are required to achieve such a goal, including the durability of concrete members, performance monitoring technologies, evaluation methodologies, damage assessment, and structural rehabilitation. This Special Publication (SP) includes 10 papers selected from the three special sessions held at the ACI Fall convention in Washington, DC, October 2014. Each submitted manuscript has been rigorously reviewed and evaluated by at least two experts. The editors wish to thank all contributing authors and anonymous reviewers for their endeavors.

Yail J. Kim, Baolin Wan, and Isamu Yoshitake
Editors
University of Colorado Denver,
Marquette University, and
Yamaguchi University

TABLE OF CONTENTS

Response Surface Metamodel-based Performance Reliability for Reinforced Concrete Beams Strengthened with FRP sheets

Junwon Seo, Yail J. Kim, and Shadi Zandyavari

Synopsis: This paper presents the performance reliability of reinforced concrete beams strengthened with fiber reinforced polymer (FRP) sheets, including structural fragility. Emphasis is placed on the development of effective strains that can represent FRP-debonding failure. The reliability predicted by a conventional standard log-normal cumulative probability density function and by the proposed response surface metamodel (RSM) combined with Monte-Carlo simulation (MCS) is employed to assess the contribution of physical attributes to debonding failure. The models are constructed based on a large set of experimental database consisting of 230 test beams collected from published literature. Another aspect of the study encompasses the effect of various RSM parameters on the variation of effective strains, such as FRP thickness (t_f), steel reinforcement ratio (ρ), concrete strength (f'_c), beam height (h), beam width (w), span length (L), and shear span (a). The mutual interaction between these parameters indicates that those related to beam geometry (i.e., L, w, h, and a parameters) and the t_f parameter are significant factors influencing the effective strain of FRP-strengthened beams.

Keywords: debonding, effective strain, fiber reinforced polymer (FRP), fragility, performance reliability, response surface metamodel (RSM)

ACI member **Junwon Seo** is an Assistant Professor in the Department of Civil and Environmental Engineering at South Dakota State University, Brookings, SD. He is an associate member of ACI Committees 341 (Earthquake-Resistant Concrete Bridges), 343 (Concrete Bridge Design: Joint ACI-ASCE), and 345 (Concrete Bridge Construction, Maintenance, and Repair). His research interests encompass the structural behavior of irregular bridges and other structures, multi-hazard vulnerability and sustainability assessment, repair, retrofit and rehabilitation, structural reliability and risk analysis, and structural health monitoring. He is a licensed Professional Engineer in Iowa.

ACI member **Yail J. Kim** is an Associate Professor in the Department of Civil Engineering at the University of Colorado Denver, Denver, CO. He is the Chair of ACI Committee 345 (Concrete Bridge Construction, Maintenance, and Repair) and is a member of Committees 342 (Evaluation of Concrete Bridges and Bridge Elements) and 440 (Fiber Reinforced Polymer Reinforcement). He also chairs ACI 440I (FRP-prestressed Concrete). His research interest includes the application of advanced composite materials for structures, structural complexity, structural reliability, and science-based structural engineering, including and statistical and quantum physics. He is a licensed Professional Engineer in the Province of Ontario, Canada.

ACI student member **Shadi Zandyavari** is a Graduate Student in the Department of Civil and Environmental Engineering at South Dakota State University, Brookings, SD.

INTRODUCTION

Structural fragility/reliability has been used for assessing seismic risk in constructed facilities such as highway bridges. Fragility (also known as vulnerability) is defined as a conditional probability that a structure exceeds a prescribed damage state when subjected to various levels of natural or man-made hazards. Reliability is, on the other hand, defined as the extent of achieving the given functionality of a structure exposed to distressful hazards. Previous studies have shown that use of either empirical or analytical vulnerability functions can be regarded as one of the standard approaches for seismic fragility estimation [1-9], while analytical vulnerability functions are dominantly employed because in-situ data are limitedly available in most cases [1-6]. Conventional methodologies for generating analytical vulnerability functions include the statistical extrapolation of a structure's performance along with Monte Carlo simulation (MCS) [2-6]. Seo et al. [5] estimated the structural fragility of steel moment-frame structures using MCS-based response surface metamodels (RSM). The joint RSM-MCS method enables the efficient fragility assessments of a group of steel moment-frame structures when compared to the conventional methodologies. Ghosh et al. [6] utilized metamodels combined with MCS to evaluate existing bridges subjected to seismic load. Although the concept of structural fragility and corresponding reliability are proven to be robust in evaluating the performance of civil structures, it has not fully been integrated into the resiliency appraisal of retrofitted structural members.

Over the past couple of decades, fiber reinforced polymer (FRP) composites have been used for enhancing the behavior of deteriorated reinforced concrete members, including several advantages such as favorable strength-to-weight ratio, non-corrosive characteristics, and reduced long-term maintenance costs [10]. A number of studies on FRP-strengthening were concerned with the performance evaluation of various structural systems in static, fatigue, and seismic loadings [11]. The reliability-oriented assessment of such a strengthening method was, however, rarely reported, particularly structural fragility accounting for critical failure modes such as FRP-debonding. This paper proposes a theoretical framework for examining the debonding vulnerability of reinforced concrete beams strengthened with FRP sheets. Of interest is a relationship between FRP-debonding and performance reliability. An RSM model was built using a large number of laboratory test data compiled from published literature, encompassing geometric and material parameters, in order to predict the effective strain of FRP. It is worth noting that the effective strain controls the response of a strengthened beam in such a way that FRP-debonding failure takes place when the strain of the strengthening system exceeds its effective strain. The experimentally validated RSM model coupled with MCS was implemented to generate the debonding fragility of FRP-strengthened beams, which was compared with a conventional fragility approach, followed by quantifying performance reliability.