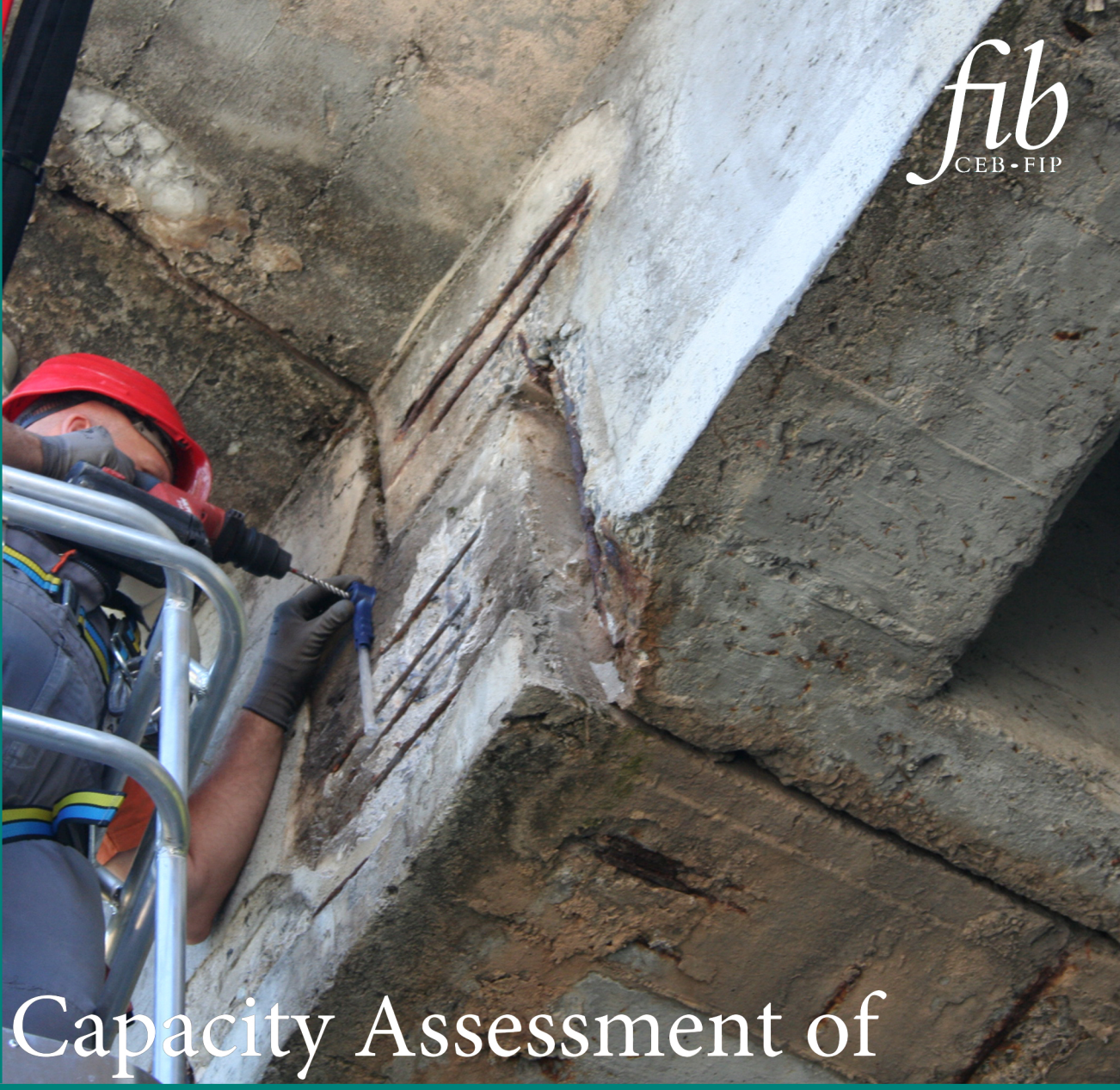

Capacity Assessment of Corroded Reinforced Concrete Structures

Book of Abstracts for the CACRCS DAYS 2020,
on-line event
December 01-04, 2020.

Edited by: Beatrice Belletti, Dario Coronelli

Abstract Proceedings of the CACRCS DAYS 2020 - Capacity Assessment of Corroded Reinforced Concrete Structures
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Editors:
Beatrice Belletti, *University of Parma, Parma, Italy*
Dario Coronelli, *Politecnico of Milan, Milan, Italy*

PREFACE

The capacity assessment of corroding reinforced concrete, fibre reinforced concrete and prestressed structures has become a most relevant engineering task with a significant social and economic impact. The need to develop codes for use in the practice spurs the research community to establish and share methods for the determination of material deterioration and mechanical properties, member resistance and structural capacity.

Special sessions are organised during the workshop. At the beginning of each session, chairpersons prepare two education presentations: the first one illustrates the fundamental, while the second one the research challenges of the topic treated in the session. Therefore, the virtual workshop offers didactic material for engineers, practitioners and a forum for scientists, concrete technologists, researchers, and academics to get a deeper knowledge about the corrosion of reinforced concrete structures.

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Disease inspection and performance evaluation of concrete components in bridges: engineering practices in China

Airong Chen, Zichao Pan

College of Civil Engineering, Tongji University, Shanghai, China

Abstract

Concrete is one of the most widely used construction materials all over the world. Owing to the ingress of harmful agents such as chloride ion and carbon dioxide, physical and chemical reactions, e.g., concrete carbonation, rebar corrosion, alkaline silica reaction (ASR), will occur inside the concrete, which greatly affects the long-term performance of the reinforced concrete (RC) bridge, as well as the principal components in large-scale bridges. To ensure the safety, serviceability and durability performance of RC structures during their service life, it is of importance to periodically inspect them for the possible diseases which are commonly found and to evaluate the current performance of RC structures. Only with an objective and accurate inspection and evaluation, can a proper decision be made for the maintenance strategy and repair/replacement plan where necessary. This paper mainly demonstrates some experiences in China regarding disease inspection and performance evaluation of RC bridges. To begin with, the mechanism of the major diseases of RC bridges such as chloride attack, concrete carbonation and rebar corrosion are briefly reviewed. A statistical result of the diseases that exist in concrete bridges in China is presented as well. Secondly, the inspection practices of surface diseases such as crack by using computer vision and deep learning on the RC pylons of the Jiang-Yin Yangtze River bridge (suspension bridge with a main span of 1385m) is introduced. Thirdly, the specifications used in China for the performance evaluation of RC bridges are introduced. Its general philosophy and framework are explained. The Xia-Men bridge, a sea-crossing bridge, is taken as an example to illustrate how to conduct a quantitative performance evaluation by following the instructions in the specifications. Finally, some perspectives on more advanced and efficient inspection techniques and performance evaluation methods are provided.

KEY-NOTE LECTURE

fib Model Code 2020, life-cycle management of existing concrete structures and the potential benefits of building as little as possible

Stuart Matthews

Convenor fib Task Group 10.1: fib Model Code 2020,
Fédération Internationale du Béton, EPFL, CH-1015 Lausanne, Switzerland

Abstract

The next edition of the *fib* Model Code for Concrete Structures, Model Code 2020 (MC2020), will deal with both the design of new structures and the various activities associated with the life-cycle management of existing concrete structures, including their assessment and undertaking interventions upon them to extend their useful life and/or upgrade their performance. Amongst other matters, MC2020 addresses the safety framework requirements, models for the evaluation of load capacity, structural reliability, serviceability, remaining service life etc taking account of:

- Material degradation, such as corrosion of reinforcement & prestressing.
- Load carrying behaviours not normally considered in design, such as compressive membrane action.
- Circumstances where the materials or details which were used do not comply with contemporary design recommendations.

MC2020 adopts an integrated life-cycle perspective and service life design approach within an overarching sustainability framework which balances environment, social and cost perspectives, plus uses improved models for structural assessment and of the initiation and propagation phases of deterioration, which allows consideration of the associated structural, risk and reliability implications.

[*fib* = Fédération Internationale du Béton, Lausanne, Switzerland]

A1. CORROSION INDUCED DAMAGE IN MATERIALS

KEY-NOTE LECTURE

Experimental evaluation of rebars corrosion in concrete

Fabio Bolzoni[1], Matteo Gastaldi[1]

[1]Dipartimento di Chimica, Materiali e Ingegneria Chimica Giulio Natta, Politecnico di Milano, Milano, Italy

Abstract

The proper evaluation of rebars corrosion rate in concrete can provide reliable data for the evaluation and modeling of the structural behavior. Electrochemical methods, used since the years ’70, are based on the perturbation of the free corrosion conditions by means of DC or AC current (or potential): the experience gained in the last decades shows that the most reliable method is the linear polarization resistance, based on small DC polarisation vs the free corrosion potential. Promising results have also been got by the measurement of concrete resistivity in carbonated concrete. AC methods have been largerly used in laboratory, while their application is limited on site. Accelerated corrosion test have been used to simulate in short time a significant reduction of the cross section: the limitations of these methods are briefly discussed.

KEY-NOTE LECTURE

Advances in the description of corrosion induced cracking

Carmen Andrade[1], Pablo Anaya[2]

[1] *CIMNE: International Center for Numerical Methods in Engineering- UPC-Spain*

[2] *UPM- Politechnical University of Madrid- Spain*

Abstract

The steps in the corrosion development from depassivation of the reinforcement until cracking of the concrete cover, has been studied mainly through computer simulations, although also some very interesting papers have been published on the steel/concrete interface in the preliminary steps of corrosion. In the lecture, based in new tests made by the authors on bond strength of wires, it will be presented some advances on the description of the corrosion processes progressively developed after corrosion initiation and which are the most accessible influencing factors. The parameters that whose calibration is described are: a) the oxide expansion, b) the rust bulk modulus, c) the "porous zone" thickness, d) the generated empty space of the incipient cracks in the diffusion of the oxides.

Effect of environmental exposure conditions on the corrosion rate of carbon steel bars in carbonated concrete

Federica Lollini[1], Elena Redaelli[1]

[1] Department of Chemistry, Materials and Chemical Engineering „Giulio Natta“, Politecnico di Milano, Milan, Italy

Abstract

In urban environments the propagation phase of corrosion can represent a significant part of the entire service life of a reinforced concrete structure. To properly evaluate its duration, the knowledge of the corrosion rate is essential. This paper reports the corrosion rate and corrosion potential of carbon steel bars embedded at different depths (i.e. 10, 25 and 40 mm) in concretes with different binders and water/binder ratio of 0.61, exposed both outdoor in Milan in unsheltered conditions and in laboratory conditions characterized by different temperatures and relative humidity levels. Concrete resistivity at different depths is also reported. Relative humidity strongly influenced the corrosion potential, corrosion rate and resistivity, whilst temperature played an important role only at a high relative humidity level. Correlations between these parameters were analysed and discussed.

Issues in identifying damage progression in corroded post tensioned concrete beams under flexural loads by Acoustic Emission technique

Giuseppe Scionti, Davide Messina, Antonino Recupero, Edoardo Proverbio

Department of Engineering, University of Messina, Messina, Italy

Abstract

Acoustic Emission technique was used to evaluate damage progression during increasing flexural loading tests of six meters long (0.4 x 0.25 m section) twelve years old post-tensioned concrete beams characterized by corrosion damage of the prestressing tendons. Acoustic emission signals have been recorded by sensors placed directly on prestressing strands and on concrete surface. Due to the high sensitivity of the acoustic emission technique a proper data mining procedure has to be adopted to avoid false assignations and erroneous interpretation. By using proper algorithms, it was possible to differentiate acoustic emission hits in different clusters characterized by specific recognition patterns. A tentative assignation to different damage mechanisms (e.g. tensile or shear crack propagation) was carried out.

Durability of reinforced concrete containing biochar

Federica Zanotto[1,3], Alice Sirico[2], Francesca Vecchi[2], Andrea Balbo[3], Patrizia Bernardi[2], Beatrice Belletti[2], Alessio Malcevschi[4], Vincenzo Grassi[3], Sebastiano Merchiori[1], Cecilia Monticelli[3]

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[4] CIDEA & Department of Chemistry, Life Sciences and Environmental Sustainability,
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Abstract

Recently, within the field of new cementitious building materials development, there has been a growing interest in the use of biochar, which represents the solid by-product resulting from biomass pyrolysis or gasification processes. The addition of biochar particles into concrete admixtures can offer an eco-friendly carbon sequestration solution while possibly improving concrete mechanical properties. However, the role of biochar on durability of concrete and steel corrosion is still unexplored. Within this context, this work presents the first results in terms of corrosion potentials (E_{cor}) polarization resistance (R_p) measurements and electrochemical impedance spectroscopy (EIS) recording, of an extensive study on the influence of biochar as a concrete additive during wet and dry (w/d) exposures in saturated $Ca(OH)_2$ solution, containing 0.1 N $CaCl_2$.

Corrosion products resulting from carbonation acting upon chloride-induced corrosion in 22 years old blast furnace slag concrete

Nicoletta Russo[1], Emanuele Rossi[2], Timo G. Nijland[3], Rob Polder[4], Federica Lollini[1]

[1] Department of Chemistry, Materials & Chemical Engineering, Politecnico di Milano, Milan, Italy

[2] Department of Civil Engineering, Delft University of Technology, Delft, The Netherlands

[3] TNO Buildings, Infrastructure & Maritime, Delft, The Netherlands

[4] RPCP, Gouda, The Netherlands

Abstract

The Service life evaluation of reinforced concrete structures is usually limited to initiation of corrosion, whilst in practice corrosion in many structures has already reached the propagation stage. To better understand the processes that lead to the cracking and detachment of concrete cover during this phase, knowledge of corrosion products' development over time is required. This paper investigates corrosion products found in blast furnace slag cement concrete, in which natural carbonation acted upon original chloride-induced corrosion. The sample was cast in 1998, after curing subjected to wet-dry cycles to enhance chloride penetration, and later was exposed to unsheltered outdoor conditions. Corrosion products and textures at the concrete-steel interface and late carbonate veinlets within them have been characterized by a combination of optical microscopy, SEM, Raman spectroscopy and CT scanning.

A2. IN SITU INSPECTIONS IN CASES OF CORROSION

KEY-NOTE LECTURE

Chloride-Induced Corrosion in RC and FRC elements: test procedure and preliminary results

B. Leporace-Guimil[1], A. Conforti[2], R. Zerbino[3] and G.A. Plizzari[4]

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[2] Department of Civil, Environmental, Architectural Engineering and Mathematics, Università degli Studi di Brescia, Brescia, Italy

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[4] Department of Civil, Environmental, Architectural Engineering and Mathematics, Università degli Studi di Brescia, Brescia, Italy

Abstract

Corrosion of rebars is one of the main issues affecting the service life of reinforced concrete (RC) structures since it reduces their lifespan. Nowadays, it is well-known that the use of fibres enhances the mechanical behaviour of RC structures at Serviceability Limit States (SLS) and Ultimate Limit States (ULS). The use of fibres enhances the cracking pattern, leading to narrower and more closely spaced cracks. The crack width is one of the key parameters for controlling the durability of RC structures. However, even though many research studies have been carried out on this topic, the behaviour of RC elements with and without fibres in both cracked stage and aggressive environments is still not well understood. In this context, this article describes a test procedure specifically developed to evaluate the chloride-induced corrosion in RC elements with and without fibres in service condition (cracked stage). Tension ties specimens of 90 x 90 x 830 mm reinforced by a rebar of Ø12 mm were subjected for 280 days both to a constant load and to wet-dry cycles in a water solution containing 50 g/l of NaCl. Preliminary results showed that the adopted test procedure was suitable to speed up and assess the chloride-induced corrosion in RC and FRC elements in cracked stage.

KEY-NOTE LECTURE

Evaluation and Restoration of Severely Damaged Unbonded Post-Tensioned Structures

Pawan R. Gupta

[1] *Principal, Pcubed Associates Inc., Los Angels, CA, USA*

Abstract

The presentation will provide an overview of the assessment techniques used to evaluate severely compromised post-tensioned structures. The discussion will focus on three structures with members that had either failed or are very close to failure. The first case study is a post-tensioned beam that failed at the ends due to loss of concrete section during spall repairs. The other two case studies are of a one-way slab and a two-way slab that were post-tensioned with unbonded post-tensioning tendons. The severe damage was caused by corrosion of post-tensioned tendons caused by water intrusion from deferred maintenance. The presentation will highlight the methods used for the assessment of the structures and approaches that can be used to repair these severely damaged structures

In-situ measurements of corrosion rate: methods and observed values

C. Andrade

CIMNE: International Center for Numerical Methods in Engineering- UPC-Spain

Abstract

Measurement of the corrosion on site has been approached mainly by visual inspection complemented by the determination of the chloride content or the carbonation depth in the concrete. The measurement of the loss in diameter of the bar, which is the crucial parameter for structural assessment has very seldom aroused interest, and even less the question of which are the possible variations in the same structure. In THE present communication will first BE commented the methods for on-site determination of the corrosion penetration and the corrosion rate as indicated in Rilem Recommendation on the Measurement of the Polarization Resistance. Typical levels of corrosion in function of the type of concrete and its level of contamination will be presented. The effect of climatic conditions will be underlined as this is another critical aspect when site assessment is made. Details on how many samples to take and how to interpret the results will be commented together with recommendations on how to generalize measurements on a single visit an.

Upscaling of acoustic emission monitoring from laboratory experiments to on-site application

Charlotte Van Steen, Hussein Nasser, Rutger Vrijdaghs, Els Verstrynge

Department of Civil Engineering, KU Leuven, Leuven, Belgium

Abstract

Dedicated techniques to assess the damage accumulation due to reinforcement corrosion are urgently needed. In the viewpoint of efficient inspection, the acoustic emission (AE) technique is able to detect corrosion from an early stage, however, challenges remain towards on-site application. This research aims to bridge the gap between laboratory experiments and on-site application. Experimental work on two sample scales, RC prims (15x15x25 cm^3) and RC beams (15x20x180 cm^3), was performed to investigate AE curves at different corrosion levels. These findings will be validated on a corroded post-tensioned concrete girder bridge. This paper describes important results of the laboratory experiments as well as a description of the setup and results of the first phase of the on-site monitoring campaign.

The surface crack width: an index to estimate the corrosion level of reinforcement

Armando Benenato[1], Barbara Ferracuti[1], Stefania Imperatore[1], Gian Piero Lignola[2]

[1] Department of Civil Engineering, "Niccolò Cusano" University of Rome, Via Don Carlo Gnocchi, 3, 00166 Rome, Italy

[2] Department of Structures for Engineering and Architecture, University of Naples "Federico II", Via Claudio 21, I-80125 Napoli, Italy

Abstract

Corrosion of reinforced concrete (RC) existing structures occurs in all industrialized countries, causing both safety and economical concerns, hence the degradation assessment of an existing reinforced concrete structure is a very topical issue. Since the earliest expression of corrosion degradation is the cracks formation, a relationship between crack opening and corrosion level can become a very useful tool to predict the degradation level of an existing RC member by means of non-destructive testing. In the present paper, the state of art on the cracking of artificially corroded RC specimen is collected and analyzed, in the aim to relate the crack widths to the corrosion level. Experimental data are finally compared with literature models and some comments are provided.

Evaluation of reinforcement corrosion in reinforced or prestressed concrete bridges: The Province of Brescia case study

Nico Di Stefano[1], Enrico Faccin[2], Stefano Giuseppe Mantelli[3], Fausto Minelli[4]

[1234]Department of Civil, Environmental, Architectural Engineering and Mathematics, University of Brescia, Brescia, Italy

Abstract

Among 340 bridges belonging to the Province of Brescia (in northern Italy) recently inspected, about 80% are in reinforced or prestressed concrete. Many of them experienced corrosion of various types, intensity and distribution. Based on the results of the inspection phase, this paper proposes a model for quantifying the corrosion level of existing bridges. Through simple considerations resulting from visual inspections, corrosion can be quantified through numerical indicators. The application of the method, on a set of 142 bridges, showed how the phenomenon of corrosion is rather widespread, critical and crucial for the structural durability and safety of reinforced concrete bridges.

Monitoring Thermal Resistance of Concrete Slab

Ahmed Abdel-Mohti[1], Shreewan Rupakheti[2]

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[2] *Graduate Student, McNeese State University, Lake Charles, Louisiana, USA*

Abstract

This study aims to investigate the effect of temperature on the performance of concrete samples. It is important to obtain information regarding the ability of the structure to perform its intended function in light of the inevitable aging and degradation resulting from operational environments. Concrete is a highly versatile construction material. It remains in service at a variety of temperatures. The changes in the strength of concrete as a function of temperature are related to, inter alia, concrete composition, the type of aggregate used, the water/cement ratio, etc. In this study, a large number of concrete samples has been prepared and were placed both within A laboratory controlled environment and outside in real conditions so that samples can be subjected to seasonal changes and various environmental conditions. Samples were also continuously loaded with different levels of load.

A3. MECHANICAL PROPERTIES OF CONCRETE AND STEEL, BOND - SLIP RELATION IN THE CASE OF CORROSION

KEY-NOTE LECTURE

What do we know about concrete, steel, and bond-slip relation for corroded bars?

Karin Lundgren, Mattias Blomfors, E Chen

Department of Architecture and Civil Engineering,
Chalmers University of Technology,
SE-412 96 Göteborg, Sweden

Abstract

Reinforcement corrosion influences the deformation and load capacity of steel rebars. Further, it generates splitting stresses that weaken the concrete and strongly affect the bond between reinforcement and concrete. Here, a recently published engineering model to determine the deformation capacity of rebars with pitting corrosion is described. Further, the effect of corrosion on bond is described in a systematic way, with an overview of the effect for various cases depending on reinforcement type, existence of transverse reinforcement, and confinement due to concrete and boundaries. Finally, an engineering model to determine bond-slip relationships for ribbed bars is presented.

KEY-NOTE LECTURE

Research developments on bond between corroded steel and concrete

Francesco Tondolo[1]

[1] *Department of Structural and Geotechnical and Building Engineering, Politecnico di Torino, Torino, Italy*

Abstract

Corrosion of steel in concrete is the most detrimental source for reinforced concrete structures. Among the other effects, corrosion deteriorates the interface between steel and concrete. Bond between steel and concrete is at the base of all the resisting structural mechanism in reinforced concrete structures and it its modification is fundamental in case of anchorages and laps of reinforcing bars on existing structures. Despite a large amount of reseach papers, some critical aspects should be taken into account when considering experimental test on bond in presence of corrosion. An overview of the latest experimental activities is presented and some research challenges related with the reliability of test conditions and significance of the obtained data are discussed.

Experimental tests on bond performance between corroded plain steel bars and concrete

Armando Benenato[1], Barbara Ferracuti[1], Stefania Imperatore[1], Mahdi Kioumarsi[2]

[1] Department of Civil Engineering, "Niccolò Cusano" University, Via Don Carlo Gnocchi, 3, 00166 Rome, Italy
[2] Department of Civil Engineering and Energy Technology, Oslo Metropolitan University, Pilestredet 35, 0166 Oslo, Norway.

Abstract
Among the principal corrosion effects, variation of the steel-to-concrete interface properties could be observed due to the oxides expansion produced by corrosion. Several researches have been carried out on the bond behaviour of corroded ribbed reinforcements, while few studies have been focused on the performance of corroded plain bars typically used for structures built in Italy before the 1970s. In this study, the preliminary results of an experimental campaign devoted to investigate the bond-slip relationship between concrete and artificially corroded plain bars are presented. The present study is a part of an extensive research project, CONSTIN, between Oslo Metropolitan University and Niccolò Cusano University aiming to evaluate the steel-to-concrete interaction in the presence of corrosion and to establish a variation law for the bond strength of the corroded plain bar as a function of the corrosion level.

Bond behaviour of naturally corroded plain bars in reinforced concrete structures.

Samanta Robuschi[1], Ignasi Fernandez[1], Karin Lundgren[1]

[1] Department of Architecture and Civil Engineering, Division of Structural Engineering, Chalmers University of Technology, Sven Hultins gata 8, SE-41296 Göteborg, Sweden.

Abstract

Reinforced Concrete is known to be susceptible to corrosion damage. Corrosion, by reducing strength and ductility of the reinforcing bar and modifying the steel/concrete interface, hinders the overall safety of the structure. This work investigates the bond of naturally corroded, plain reinforcing bars. Specimens were taken from an 80-year-old bridge and tested using pull-out and 3-point bending tests. Additionally, neutron and X-ray tomography is used to observe the distribution of corrosion products. Results highlight the influence of casting position on the bond of plain bars. Specifically, the distribution of corrosion products is influenced by the bleeding zone underneath top-cast bars. Corrosion products are shown to deposit in macro-pores and to adhere to the bar.

Influence of confinement on bond loss of corroded reinforced concrete elements and Model Code 2010

Konstantinos Koulouris, Maria Basdeki, Charis Apostolopoulos

Department of Mechanical Engineering and Aeronautics, Univeristy of Patras, Patras, Greece

Abstract

Corrosion of steel reinforcement degrades significantly the bond mechanism between steel and concrete, which constitutes a basic assumption in design of Reinforced concrete (RC) members. Recent scientific studies focus on the bond behaviour of corroded RC elements, in order to extract appropriate predictive models and introduce them into the technical regulations. In this light, the present experimental study presents the results of pull out tests on corroded RC specimens (in terms of bond loss), after accelerated corrosion (at different levels of damage) investigating the influence of stirrups spacing on bond strength. The outcomes of this experimental study and others in literature are presented and compared with the current recommendations of Model Code 2010, highlighting points that need to be improved. As a main result, the amount of stirrups should be taken into account for the residual bond strength.

Effect of corrosion damage on the tension-stiffening effect: A numerical investigation of the RC tension bar

Hussein Nasser, Rutger Vrijdaghs, Charlotte Van Steen, Lucie Vandewalle, Els Verstrynge

Civil Engineering Department, KU Leuven
Kasteelpark Arenberg 40, 3001 Leuven, Belgium

Abstract

It is important to implement proper damage relations to understand the effect of corrosion on the structural behaviour of reinforced concrete (RC) beams. The paper investigates the calibration of such relations through numerical analysis of an RC tension bar. Firstly, decreasing the bond-slip interface stiff- ness is found to decrease the number of cracks. Secondly, the yield and rupture strength of the rebar as a function of the pitting factor is analysed to obtain damage relations relating the cross-section loss to the material properties of the corroded steel rebar. Finally, the results from the RC tension bar are used in a corroded 2D beam model, which shows a good agreement with the experimental results.

Corroded Tension Chord Model (CTCM) for concrete structures with locally corroded reinforcement

Severin Haefliger, Deniz Yilmaz, Ueli Angst and Walter Kaufmann

Institute of Structural Engineering, Institute for Building Materials,
ETH Zurich, Stefano-Franscini-Platz 3/5, 8093 Zurich, Switzerland

Abstract

Many ageing RC structures suffer from severe localised corrosion of the reinforcing bars, particularly if exposed to chlorides. This damage affects strength and ductility: The cross-section loss of the reinforcing bars reduces the load carrying capacity, and the highly localised damage results in a localisation of deformations, which may severely impair the structure's deformation capacity. A recent study at ETH Zurich investigated these effects on a sound mechanical basis, extending the established Tension Chord Model by corroded crack elements. This paper introduces the modelling concept of the resulting Corroded Tension Chord Model (CTCM) and presents the results of its application to structural elements with several corrosion spots. It reveals a significant decrease of the deformation capacity. Finally, an outlook on ongoing validation experiments is given.

B1. EXPERIMENTAL TESTS ON CORRODED RC AND PC STRUCTURES

KEY-NOTE LECTURE

Failure mechanisms in corroded Reinforced and Prestressed Concrete elements

Zila Rinaldi

Department of Industrial Engineering, Univeristy of Rome Tor Vergata, Rome, Italy

Abstract

One of the major causes of degradation in reinforced and prestressed concrete structures is related to the corrosion of the steel rebars. This phenomenon, as witnessed by recent cases worldwide, can cause severe damages leading to structural unexpected crisis. The failure mechanisms of corroded structures, indeed, can be very different from the ones of new or sound construction (buckling of corroded rebar is a typical example) and they are of paramount importance in the evaluation of the structural safety. For this reason, the main failure mechanisms, due to the steel corrosion, will be showed and discussed, on the basis of experimental test results developed in years of studies on this topic. Both local phenomena, related the steel rebars and bond behaviour, and global structural behaviour of reinforced concrete beams and columns and prestressed beams will be deeply analysed.

KEY-NOTE LECTURE

Some thoughts on the structural performance of corroded concrete structures arising from past experimental results

Jesus Rodriguez[1], Pablo Anaya[2]

[1]Department of Structures and Physic of Buildings, Technical University of Madrid, Madrid, Spain

[2]BAC Consulting Engineering Group, Madrid, Spain

Abstract

This paper summarizes some items when dealing with the experimental work on corroded concrete structures, including the objectives to be considered and the test procedures on corrosion processes, type and size of tested elements, layout of tests with loads, etc. Then, some considerations will be presented on the expected results and their applications in order to obtain either empirical models or to calibrate theoretical and/or numerical models to get simplified engineering expressions to be used for the evaluation of corroded concrete structures. Some applications coming from past tests with reinforced concrete blocks for cracking and bond studies, with reinforced concrete beams and columns and with prestressed concrete beams will be commented.

Cyclic Loading Test on Highly Corroded Reinforced Concrete Columns

Alper Celik[1], Hakan Yalciner[2], Atila Kumbasaroglu[3], Ahmet Ihsan Turan[4]

[1,2,3,4] *Department of Civil Engineering,Erzincan Binali Yıldırım University,Erzincan, Turkey*

Abstract

An experimental study was performed on five reinforced concrete (RC) columns to investigate the structural behavior of highly corroded RC columns. Four of the RC columns were corroded using an accelerated corrosion method for different corrosion levels at longitudinal bars as 15.4, 20.2, 27.3 and 28.3%. RC columns were tested under cyclic load for a constant axial load ratio of 0.40. After the loading test, the actual corrosion levels were obtained by extracting the longitudinal bars and stirrups following the breaking of the RC columns. Load-displacement curves, ductility ratios and energy absorption capacities of tested RC columns were obtained. Test results revealed that the ductility ratios of corroded RC columns should be determined in accordance with energy-based or bilateral failure criteria due to the misleading of increased ductility ratios of corroded RC columns based on the displacement method.

Flexural Tests on Prestressed Beams Exposed to Natural Chloride Action

Francesca Vecchi[1], Beatrice Belletti[1], Lorenzo Franceschini[1], Carmen Andrade[2], Jesus Rodriguez[3], Javier Sánchez Montero[4]

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[2] International Centre for Numerical Methods in Engineering (CIMNE), Universitat Politècnica de Catalunya (UPC), Barcelona, Spain

[3] Department of Structures and Physic of Buildings, University Polytechnic of Madrid (UPM), Madrid, Spain

[4] Institute Eduardo Torroja of Construction Sciences, Serrano Galvache, Madrid, Spain

Abstract

This paper presents an investigation on the flexural capacity of full-scale prestressed concrete (PC) beams, without transversal reinforcement and naturally corroded for 10 years. Before tests, a visual inspection was carried out to detect the damages induced by corrosion. During the three-point bending tests, displacements and strains were measured recording images and post-processing data by using digital image correlation (DIC). After the tests, strands were removed from beams revealing high level of corrosion in correspondence of damage previously detected. Moreover, results show that the flexural capacity of naturally corroded PC beams due to chloride attach is strongly reduced both in terms of resistance and ductility.

Failure behaviour of post-tensioned concrete beams with different corrosion damage in prestressing tendons

Davide Messina, Giuseppe Scionti, Antonino Recupero, Edoardo Proverbio

Department of Engineering, University of Messina, Messina, Italy

Abstract

Diverse six meters long (0.4 x 0.25 m in section) twelve years old post-tensioned concrete beams have been brought to failure during increasing load cycling tests. Distinct corrosion damages were previously induced on prestressing tendon (grouted and ungrouted type). Evolution of failure mode has been monitored by crack mapping, dynamic behaviour analysis and Acoustic Emission monitoring. Significant differences in load displacement response were related to the extent of damage on prestressing tendons. Dynamic analysis and acoustic emission technique allowed to put in evidence the different stage of progressive beam collapse until final failure.

Behaviour of prestressed concrete beams damaged by corrosion

Armando Benenato[1], Barbara Ferracuti[1], Stefania Imperatore[1], Mahdi Kioumarsi[2], Simone Spagnuolo[3]

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Abstract

European industrial and commercial buildings, as well as parking garages, are commonly built in precast concrete. In many instances this kind of structures are exposed to aggressive environments and therefore deteriorated by corrosion. According to previous literature results, corrosion strongly reduces the bearing-capacity of prestressed reinforced concrete (PRC) members, changing the failure mechanism as well. In the framework of the OPTION research project between Niccolò Cusano University and Oslo Metropolitan University, an experimental campaign investigates the behaviour of corroded prestressed beams. The goal is to estimate the corrosion level making a deteriorated PRC beam less ductile keeping the strength unchanged. In the present paper, the first experimental results are presented.

B2. IMPLEMENTATION OF THE EFFECT OF REINFORCEMENT CORROSION IN MODELS FOR THE DETERMINATION THE BEARING CAPACITY

KEY-NOTE LECTURE

Design approaches concerning SLS and ULS in corroded structural elements

Marco di Prisco[1], Matteo Colombo[1], Giulio Zani[1] and Lorenzo Radice[2]

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Abstract

In the paper few examples of real RC and PC structures retrofitted because they presented significant cracking and/or oxidation of reinforcement are discussed. They are instrumental to emphasize the distance between what has been regarded up to now as reasonable approaches to the engineering problem of the intervention on existing structures and what is suggested in advanced design approaches which suggest computing residual bearing capacity on the basis of the geometrical types of corrosion. The emphasis is on the uncertainties problems commonly met by designers to pass from the first to the second approach looking to real cases, and which level of risk should be taken by modern designers in the refurbishment of old structures.

KEY-NOTE LECTURE

Significance of reinforcement corrosion for modelling the behaviour of existing concrete structures

Joost Walraven, Prof. Em.

Delft University of Technology

Abstract

This paper deals with the effect that corrosion has on the properties of reinforcing steel. This does not lead only to a reduction of the effective cross sectional area, and as such to a reduced tensile resistance, but can also result in a reduction of ductility. Moreover, the bond properties and the fatigue resistance suffer from corrosion. In order to assess the influence of those properties on the structural safety, serviceability and service life realistic models are needed to describe the behaviour of corroded concrete structures under various types of loading. The new fib Model Code 2020 is meant to become a recommendation both for the design of new and the assessment of existing structures. Some basic behavioural models are discussed in this paper. For more information reference is made to the fib Bulletin "Modelling Structural performance of existing concrete structures", which will be published soon.

Assessment Procedures for Corroded Structures

Nicolas El-Joukhadar[1], Stavroula Pantazopoulou[2]

[1,2] Lassonde School of Engineering, York University, Canada.

Abstract

Seismic assessment methods of reinforced concrete (RC) structures such as those of Eurocode 8-III (2005), are calculation-intensive, demanding extensive information with regards to reinforcement ratios and detailing. The purpose of such assessment methods is to compare the demands that a credible future seismic hazard will impose on a structure, with a dependable estimate of the deformation capacities of the structural members in order to foresee their seismic performance and expected damage. Assessment guidelines, however, do not take into consideration the condition of reinforcement, which has been proven to affect the member's residual deformation capacity and strength, the hierarchy of likely failure modes and the consequences thereof, on seismic performance. Considering the condition of the reinforcement adds an extra layer of complexity on the rather complex problem of estimating the seismic behavior of poorly detailed RC members. This paper focuses on easy-to-use modifications to existing assessment procedures in order to take the effects of corrosion into consideration. Lateral load capacities of several tested corroded columns from the literature were successfully estimated using these modified analytical assessment procedures. Expressions for residual shear capacity, ultimate drift and stiffness ratio of columns in terms of corrosion damage (mass loss %) were derived based on an assembled database of experimentally tested corroded columns as well as finite element models. The paper also presents a methodology and application example of computational assessment procedures that take corrosion damage into consideration using advanced nonlinear finite element software such as ATENA 3D.

Simulation of the structural effects of corrosion and strengthening of concrete frames using a nonlinear step by step analysis model

Antonio Marí, Jesús Miguel Bairán, Eva Oller, Noemi Duarte

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Abstract

Corrosion reduces the steel area, the mechanical properties of the reinforcement, the bond strength and produces concrete cracking. Thus, reduction of the bearing capacity and stiffness, increments of deflections and redistribution of forces in statically indeterminate structures take place. In addition, the efficiency of strengthening systems of corroded structures depends on their state of stresses, strains and damage previously to strengthening. In this paper, a nonlinear and time dependent step by step analysis model for reinforced and prestressed concrete frames, capable to capture the structural effects of corrosion and the effects of strengthening interventions, necessary to adequately assess corroded and strengthened structures, is presented. Several cases of corroded and strengthened structures are analyzed and the results discussed.

Analytical prediction of flexural response of prestressed concrete beams with corroded strands

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[2] *Department of Engineering, Università degli Studi di Palermo, Palermo, Italy*

Abstract

In the present paper, a simplified model to determine the flexural response of corroded prestressed concrete beams is presented. The model considers elements with a rectangular cross-section, and it takes into account: loss of mass of corroded prestressed strands and bond between strand and concrete; reduction of mechanical properties of strands (yielding and ultimate stress, elastic modulus); cracking of concrete. Analytical expressions utilized to predict the loss of bond and the reduction of mechanical properties of corroded prestressed strands are verified against the experimental data available in the literature.

Effect of corrosion on the fragility assessment of RC buildings under tsunami loads

Marta Del Zoppo, Marco Di Ludovico, Andrea Prota

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Abstract

Most of existing reinforced concrete (RC) structures in Mediterranean coastal areas suffer from ageing problems and degradation due to the aggressive environment. Fragility assessment of existing assets exposed to tsunami hazard may be affected by the reduction of load bearing capacity due to corrosion. This study integrates the corrosion of steel reinforcement in a probabilistic framework for deriving analytical fragility functions of RC frames subjected to tsunami onshore flows. The effect of corrosion on the response of one RC frame is herein investigated at different performance levels up to the structural collapse. Fragility functions with and without corrosion are derived, to point out the effect of corrosion and the error of neglecting such phenomenon in fragility analysis. Both conditions of uniform and pitting corrosion are investigated.

Structural modelling of the Response of Deteriorated RC and PSC members: Levels of Approximation for Model Code 2020

Dario Coronelli [1], Kamyab Zandi [2], Arnaud Castel [3]

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[2] Department of Architecture and Civil Engineering, Chalmers University of Technology, Göteborg, Sweden

[3] School of Civil and Environmental Engineering, University of Technology Sydney, Australia

Abstract

The assessment of reinforced concrete structures affected by deterioration such as reinforcement corrosion involves the use of different models, according to different scientific and technical purposes. The paper presents a framework for structural modelling approaches previously developed by the authors to fit in the concept of Levels of Approximation for Model Code 2020. The concept is here extended to include different accuracy levels in deterioration modelling. The paper moves from simple strut and tie models to analytical models and finite element numerical studies. The possibility of an extension of the framework to modelling the freeze-thaw deterioration is highlighted. The conclusions highlight the available techniques and the needs for research developments.

C1. CASE STUDY OF EXISTING STRUCTURES AND INFRASTRUCTURES

KEY-NOTE LECTURE

What do we need to understand in order to inspect, assess and design interventions in concrete structures affected by corrosion?

Hugo Corres Peiretti[1, 2], Freddy Aríñez Fernandez[2], Javier León González[1, 2]

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[2]Departamento de Obra Civil, FHECOR Ingenieros Consultores, Madrid, Spain

Abstract

Reality has crushed our expectations regarding the durability of concrete structures. For a long time, these elements were assumed to be eternal and, as such, we engineers did not even grasp the notion that they had to be maintained, inspected, diagnosed, repaired and sometimes demolished. Until fairly recently, we did not consider the effect that time has on concrete structures and nowadays, without reservations, we are fully engaged in the management of existing structures.

A quick review of the historical evolution of the facts that surround the deterioration of concrete structures in general, and the damages caused by reinforcement corrosion in particular, shows that the serious study of these phenomena and the continuous conservation of existing structures began a little over 30 years ago.

The preparation of MC2020 has launched the largest intellectual initiative to try to generate a document that would summarize the available knowledge and enable a global approach to concrete structure, from their conception to their dismantlement and reuse of the waste generated, throughout the service life of the structure. In order to accomplish this goal, the new Model Code must consider new and existing structures in a consistent manner.

The draft of MC2020, currently under development, proposes the definition of the Life-Cycle Management that must be defined in the design of new structures, or in the repair and assessment projects of existing structures. It is more than evident that during the design or repair of structures, it is possible to identify general and particular aspects that will impact their conservation.

The conservation of structures has had a different evolution depending on the type of the structure. In many countries the conservation of bridges has been very active for some time. On the other hand, the conservation of buildings, industrial structures and other types still do not have the same level as in bridges.

This work presents different activities related to the conservation process of bridges with comments and explanations, based on real examples, on different matters related to the problems of corrosion of reinforcing and prestressing steel. As well as on aspects related to inspections, different levels of intensity, testing, indicating possibilities and results, assessments, indicating levels, available tools and degrees of approximation, interventions, emphasizing on the importance of the conceptual design stage and the development of ideas strongly constrained by extremely difficult execution conditions.

Finally, we will present some ideas related to the lessons learned fruit of the experience obtained with the inspection and interventions of many bridges affected by reinforcement corrosion processes.

KEY-NOTE LECTURE

A focus on the new Italian guidelines for safety assessment of existing bridges

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Abstract

New Italian guidelines for safety assessment of existing bridges were recently approved. This achievement was reached after the increasing number of casualites which clearly demonstrated the need for an in deep consideration of existing bridges. Actually, most of italian bridges already spent around 50 years of their service life and may require extraordinary repairs to achieve satisfactory safety levels according to latest code provisions.

The guidelines represent an unprecedented document in the international context: they provide with additional analysis cases with different traffic loads and partial safety factors to be adopted in order to establish the bridge safety class at ultimate limit state. After introducing the main scope of the work, a preliminary case-study bridge with relative outcomes is proposed.

Case studies of corroded reinforced concrete bridges in Southern Italy

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[2] Department of Engineering, Università di Messina, Messina, Italy

Abstract

On Italian roads, a lot of reinforced concrete bridges were built in the 1950's and 1960's for short spans, before the advent of prefabricated structures. Many of these bridges, sited on principal or secondary roadways, show the effects of corrosion of reinforcements and high levels of damage, leading to the likelihood of achievement of the Ultimate Limit State, below the required performances of serviceability, especially in the case of Gerber saddles having strongly corroded reinforcements.

Different case studies of bridges sited in Southern Italy (Sicily) are shown, allowing engineers to classify the main effects of damage in corroded structures with the Gerber static scheme (cantilever girder bridges), for a first application of the new Italian Bridge Assessment and Maintenance Guidelines. The case studies are illustrated, and the structural implications are discussed, providing indications for treating the common cases of bridges with Gerber saddles.

Static Safety Assessment of Existing Prestressed Concrete Bridges: Case Studies

Massimiliano Minotto, Tommaso Serrapica, Alessandro Contin, Enrico Viviani, Luigi Casarin, Mauro Cavetti, Andrea Mardegan

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Abstract

The appraisal of existing reinforced concrete bridges in terms of their static safety has been broadly assumed, in years, as of a collateral issue in overall seismic structural behaviour assessment. The Polcevera Bridge collapse (2018) instead solicited a change of paradigm, this triggering new interest in civil infrastructures static safety. Within this emerging framework the knowledge of the degradation gradient of concrete and steel materials plays an essential role. The following paper indeed finds its rationale in examining the major approaches and methodologies for materials degradation and resistance valuation through reference to the Italian Guidelines (2020) by the Ministry of Infrastructures and Transport. To this end, factual track records in bridges and infrastructures retrofitting are hereby brought to attention.

Structural Performance of Corroded Bridge Column and Drilled Shaft Connections with Non-Contact Lap Splices

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Abstract

The connections between non-circular bridge columns and the supporting circular mono-drilled shafts often require non-contact lap splices. It is found from previous laboratory tests that in addition to flexural, shear and split tensile cracks, a major opening occurs at the interface between the bridge column and drilled shaft, resulting in a serious issue of corrosion. Based on the experimental results, a high-fidelity finite element model of a bridge column-drilled shaft connection with non-contact lap splices in Grand Parkway, Texas, is established with consideration of the corrosion effect. Based on existing research, the corrosion density (i_{corr}) of reinforcing bars is around 5 μA/cm^2 for concrete with high humidity content carbonated or containing chlorides and 10 μA/cm^2 for concrete highly contaminated with chlorides. The pit corrosion model is adopted to simulate the strength degradation and area reduction of the dowel bars and column bars. Based on the finite element simulation results, the failure mode and the load-displacement curves are obtained. The influence of key factors, such as the spacing between dowel bars and column longitudinal bars, the corrosion density, and the bridge age, are investigated. The finite element simulation results show that in the current design with a maximum of 8-inch spacing between dowel bars and longitudinal column bars, the lateral capacity of the bridge column will be reduced by 16% and 41% at the corrosion density of 5 μA/cm^2 and 10 μA/cm^2 respectively in 20 years. The lateral displacement at service load increased by 14% and 151% respectively at the corrosion rate of 5 μA/cm^2 and 10 μA/cm^2 respectively in 20 years.

A tale of two bridges: half joint failure and deterioration processes

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[2] Department of Civil Environmental Engineering, Politecnico di Milano, Milan, Italy

Abstract

Load capacity assessment of deteriorating RC structures is a part of the strategy to avoid dramatic failures. Two cases of bridge collapse related to deteriorated half joints are presented. The structures were geographically distant – the *de la Concorde* overpass in Canada and the *Annone* overpass in Italy - but their histories show common features. The paper builds on the information gathered in the forensic investigations to explore the possibilities of load capacity assessment through different levels of data collection and modelling sophistication. Knowledge is gained by the comparison of half joints failure, design and construction errors, visible symptoms of damage, lack of maintenance, interventions carried out without taking care of overall conditions and lack of a bridge management strategy. Both structures were affected by shear design deficiencies. Regarding the deterioration processes, frost damage was the main issue in the North American case, while corrosion was the driving cause of the collapse in the European one. As for specific aspects, the *de la Concorde* overpass was influenced by the presence of a weakness zone resulting from inappropriate shear reinforcement details, further exacerbated by the poor concrete quality and severe exposure conditions. The structure in Annone was characterized by cracking caused by overloading and corrosion of the half joint reinforcement. The possibility to apply models within the assessment framework is discussed, with a focus on simple models for different levels of analysis.

Corrosion assessment and effect on the structural performance of pretensioned bridge girders in coastal climate

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Abstract

A detailed inspection of a pretensioned girder bridge exposed to coastal climate was performed to find areas susceptible to corrosion. Combining the results from visual inspection, half-cell potentials mapping, concrete resistivity, and chloride measurements a higher corrosion probability near the girder support zones than in the mid-span was found, due to increased moisture and chloride content near the support zones. Accordingly, the effect of strand corrosion within the shear span on shear/flexure-shear performance of the pretensioned girders have to be assessed. However, studies dealing with shear performance of corroded pretensioned girders are scarce. Therefore, in this paper Non-Linear Finite Element Analyses (NL-FEA) are performed to study influence of corrosion on the shear capacity of corroded pretensioned girders. The model predicts changes of failure modes and loading capacities for an assumed uniformly distributed 10% corrosion at the most probable location of corrosions of strands.

The Effect of Corrosion and Traffic Loads on Bridge Columns Using Three-Dimensional Non-Linear Finite Element Analysis

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[3] National Research Council Canada, Ottawa, ON, Canada

Abstract

Corrosion of reinforcing steel in reinforced concrete (RC) infrastructure is one of the most detrimental deterioration mechanisms, affecting both safety and serviceability. In the present study, a comprehensive analysis methodology of corrosion damage is adopted, and the detrimental effects of corrosion-induced degradation on the ultimate capacity of an existing aging RC bridge pier are investigated through three-dimensional non-linear finite element analysis (3D-NLFEA) using the commercially available finite element program DIANA. The accuracy of the present methodology is evaluated by simulating corroded columns tests reported in the literature.

C2. PERFORMANCE OF CORRODED REINFORCEMENT CONCRETE STRUCTURES IN SEISMIC SITUATIONS

KEY-NOTE LECTURE

Seismic Performance of Corrosion-Damaged RC Bridges: Current Trends and Future Demands

Dr Mohammad Mehdi Kashani

Associate Professor of Structural Engineering, University of Southampton

Abstract

Ageing structures located in moderate to high seismicity regions are exposed to multiple natural stressors during their lifetime. Large earthquake events coupled with environmental aggressive agents increase the progressive failure probability of these structures. The accumulated damage during the main earthquake event might be exacerbated by its following aftershocks. This might result in catastrophic failure of these structures, and consequently, result in several socio-economic losses. Taking such progressive deterioration mechanism into consideration, the current study presents a framework to assess the vulnerability of ageing Reinforced Concrete (RC) frames subject to real Mainshock-Aftershock (MS-AS) ground motion sequences. Employing an advanced fibre-based finite element modelling technique, the nonlinear static and dynamic behaviour of a case-study RC frame with various ages is simulated under 48 real MS-AS record pairs. Quantifying corrosion-variant damage states, the age-specific fragility curves are developed for the considered structure under both single MS events and MS-AS sequences. It was found that the severely corroded RC frames are most likely to collapse before the second event comes up. Moreover, results show that the PGA ratio of AS to MS plays a critical role in seismic vulnerability assessment of highly corrosion-damaged RC frames.

This presentation will cover some recent studies in modelling nonlinear behaviour of RC bridges and structures under unidirectional and bidirectional multiple earthquake excitations. This presentation will also discuss the challenges and opportunities for the future research in this emerging area.

KEY-NOTE LECTURE

Bridge pier corrosion in seismic areas: forecasting, future behavior and assessment

Camillo Nuti, Angelo Pelle, Giuseppe Quaranta, Alessandro V. Bergami, Bruno Briseghella, Davide Lavorato, Gabriele Fiorentino and Alessandro Rasulo

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Abstract
The detrimental effect of steel corrosion on seismic response is investigated by non-linear analysis. A multiphysics FE model is used to evaluate the time-dependent chloride-induced corrosion. Different steel arrangements are considered. Results show that the greater is the diameter of the reinforcing bar, the lower is the degree of corrosion. Furthermore, numerical investigations of seismic response with IMPAb suggest that pitting corrosion may lead to different bar behavior, producing or avoiding premature bar buckling. Corrosion of transverse reinforcements results to be more severe than for longitudinal ones leading to probable shear failure.

Seismic assessment and retrofit of a concrete building highly damaged by reinforcement corrosion

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[1] *Department of Engineering, Università di Palermo, Palermo, Italy*

[2] *ICARO PROGETTI, Palermo, Italy*

Abstract

In existing concrete structures damaged by corrosion, the limited quantity and poor distribution of reinforcements as well as a lack of seismic details are common to many cases because they are built before the advent of seismic codes. In this paper the seismic assessment and retrofit of a concrete building sited in Sicily is presented in order to show a case-study of a corroded reinforced concrete structure to be transformed with new structural elements for functional reasons linked to Civil Protection. After many decades of complete abandonment, the structure was strengthened with different strategies, allied to the construction of new steel-concrete composite floors: concrete and steel jackets, CFRP wrapping, etc. The role of joints in concrete frames is underlined and the results of the seismic assessment and retrofit intervention are shown for the case-study.

Seismic performance of deteriorated concrete bridges: bonding failure effects

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[3] Politecnico di Torino, Departement of Structural, Geotechnical and Building Engineering, Turin, Italy

Abstract

Nowadays, seismic study of corroded reinforced concrete elements is a matter of increasing concern, in particular for links such as bridges in infrastructural networks.

In a starting step of an ongoing research, a bridge overpass was selected to perform seismic analyses. It allowed to assess the degrading seismic capacity of the bridge pier at different ages because of the reduction of the cross-section of the rebars due to general and pitting corrosion.

An uncontrolled factor of the previous study is that corrosion can also affect bonding, thus increasingly reducing ductility and safety performance. However, in a corroded structure bond strength and confinement capacity can also decrease due to the transverse reinforcement area loss, and concrete cover cracking and spalling.

This new step is focusing on bonding failure effects in bridge corrosion processes and the preliminary results will be presented.

Ultimate chord rotation of corroded reinforced concrete columns subjected to cyclic loading

Francesca Vecchi[1], Beatrice Belletti[1], Luigi Imperia[1]

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Abstract

The seismic response and the failure mode of reinforced concrete structural elements can be significantly affected by the detrimental effects induced by corrosion, as cracking, concrete crushing, size reduction of reinforcement, and degradation of mechanical properties of materials. The aim of this work is to evaluate the influence of corrosion on the structural response of reinforced concrete columns, using finite element analysis. A parametric analysis is conducted in order to investigate the dependency of ultimate chord rotation on the corrosion level of longitudinal reinforcement. Finally, a reductive coefficient, to be applied to the empirical formulation for the calculation of ultimate chord rotation, is proposed.

Some remarks on the seismic assessment of RC frames affected by carbonation-induced corrosion of steel bars

Emrah Erduran, Enzo Martinelli

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Department of Civil Engineering, University of Salerno, Fisciano (SA), Italy

Abstract
In Europe, a significant number of existing buildings have been built in the two decades following WW2 and, hence, they are often affected by degradation phenomena, which result in reducing the resisting sections of structural members. Moreover, in areas currently classified as earthquake-prone, the same buildings were originally designed by either considering only gravitational actions or assuming outdated seismic design criteria. Therefore, the effect of degradation on under designed structure is a subject of concern and needs to be properly addressed with the aim to achieve a realistic assessment of the current safety level of existing RC frames in seismic areas. The present paper presents some numerical results of seismic analyses carried out on structural models including the effect of carbonation-induced corrosion of steel bars in RC members.

A comparison between RC buildings with Dual-Phase and TempCore® bars in reference and corroded conditions

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[1] Department of Civil and Industrial Engineering, University of Pisa, Pisa, Italy

Abstract

In recent years, the need to develop a new typology of steel reinforcement bars provided with enhanced properties in terms of ductility and durability towards aggressive environmental conditions increased progressively: the main reason for this can be found in the decrease of deformation capacity under both monotonic and cyclic loading conditions observed for the most part of actual reinforcing steels (e.g. Tempcore®) in presence of corrosion phenomena. The positively concluded NEWREBAR research project aimed to develop a new reinforcing steel grade with improved durability and ductility performance thanks to its Dual-Phase microstructure and to a specific selection of chemical components – kept within the range of the actual european production. In order to understand the influence of Dual-Phase steel bars on the structural behaviour of RC constructions, case study buildings were designed, modelled and analysed through Incremental Dynamic Analyses, and compared with traditional buildings using Tempcore® rebars. An accurate modelling of plastic hinges was employed to correctly account for the higher deformation capacity of Dual-Phase steel and its undefined yielding stress-strain behaviour: moment/rotation relationships were calibrated based on the results of experimental tests performed on full-scale prototypes.

In the present work, the results of the aforementioned nonlinear dynamic analysis and the evaluation of Expected Annual Loss (EAL) is presented for case-study building using both Dual-Phase and Tempcore® rebars, in reference and corroded conditions, with the aim of comparing their structural performance evaluating the real benefit of adopting the two steel grades.

C3. ROBUSTNESS AND RESILIENCE ISSUES OF CORRODED RC AND PC STRUCTURES. PREDICTIVE ESTIMATION OF THE RESIDUAL LIFE AND THE EFFECTS OF REPAIRING ACTION

KEY-NOTE LECTURE biondini

Life-Cycle Risk, Reliability, Robustness, and Resilience of Corroding RC/PC Bridges and Bridge Network

Fabio Biondini

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Abstract

Concrete bridges are exposed to aging and corrosion. The detrimental effects of these and other deterioration processes can lead over time to unsatisfactory structural performance under service loadings or accidental actions and extreme events, such as natural hazards and man-made disasters [1]. These problems present a major challenge to bridge engineering, since the classical time-invariant structural design criteria and methods need to be revised to account for a proper modeling of the structural system over its life cycle by taking the effects of deterioration processes, time-variant loadings, maintenance actions and repair interventions into account [2]. Risk-based prioritization frameworks are necessary at the infrastructure level to rationally allocate available resources and ensure optimal planning of bridge inspection, monitoring, and maintenance under uncertainty. In this context, decision-making should be based on probabilistic performance indicators aimed at providing a comprehensive description of the life-cycle structural resources, including reliability and robustness [3]. Moreover, resilience is of essence for infrastructure systems exposed to extreme events, such as earthquakes [4]. In this lecture, time variant probabilistic performance indicators are defined and quantitatively evaluated for concrete bridges and transportation road networks with multiple bridges exposed to aging and corrosion processes. The lecture will show the importance of a multi-hazard life-cycle-oriented approach to protect, maintain, restore and improve the long-term performance of aging bridges and infrastructure networks.

KEY-NOTE LECTURE

Time-dependent structural resistance, reliability and robustness assessment of corroded reinforced concrete structures under uncertainty: recent developments and future challenges

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Abstract

Assessment of existing structures is quite different from the design of new structures due to significant differences in the uncertainties related to modelling of existing structures. Some of the influencing effects may be less significant than for new structures (as e.g. deviations from specified dimensions and strengths), some of them may be more significant (as e.g. related to deterioration processes, measurement uncertainties, etc.). In case of deteriorating structures, it is moreover well known that the time-dependent behaviour and the spatial variability of the degradation processes play an important role in the assessment process. However, to realistically account for this still poses many fundamental research challenges. In this contribution, the quantification of structural resistance, reliability and robustness under uncertainty and their time-dependent behaviour is explained and illustrated in relation to corroding reinforced concrete beams and plates. Some recent developments in this field are highlighted and some challenges for future research investigations are formulated.

Statistical considerations of corrosion initiation and propagation

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[2]UPM: Politechnical University of Madrid

Abstract

Active corrosion initiates when the pH on the rebar surface decreases. This decrease is produced either by the arrival of the carbonation front or by the local depassivation due to the chloride attack. The progression of this corrosion would depend on several variables which are function of the variability of the material itself, of its aging with time and of the external climatic conditions. All of them produce an "intrinsic" variability which is necessary to be characterized for the accuracy of the predictions of service life. In the present communication, the statistical analysis made for the characterization of chloride threshold is discussed, as well as the spatial and temporal variability of the corrosion arte in real exposure conditions.

Evaluation of The Residual Life of Corroded Prestressed Concrete Beams

Beatrice Belletti[1], Hugo Corres Peiretti[2], Carmen Andrade[3], Matteo Ghiretti[1], Lorenzo Franceschini[1], Francesca Vecchi[1]

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[3] International Centre for Numerical Methods in Engineering (CIMNE), Universitat Politècnica de Catalunya (UPC), Barcelona, Spain

Abstract

Over time, structures are continuously ageing and rapidly deteriorating during their lifecycle, becoming increasingly vulnerable to catastrophic failures. Nowadays the ability to reliably predict the long-term corrosion performance of reinforced concrete (RC) structures is a challenge. This paper presents a method for assessing the residual life of prestressed concrete (PC) beams without shear reinforcement, considering the failure modes which may affect the ultimate limit state. Two different spatial distributions of the corrosion level of strands have been considered: (i) constant corrosion level along the entire length of the beam and equal to the maximum corrosion level, and (ii) effective corrosion levels, detected measuring the mass loss, and considered constant along strands' pieces 50 mm long.

Effects of corrosion on the structural behaviour of existing structures: Corrosion Risk Scenarios and equivalent parameters

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Abstract

Although corrosion has a strong impact on the behaviour of reinforced concrete elements, its effect is seldom investigated by design professionals for the assessment of existing structures and for the design of retrofit interventions. This is also due to the absence of survey protocols enabling the preliminary evaluation of the risks related to corrosion and its impact on the structural behaviour. For this reason, the development of a simplified protocol aimed at evaluating the residual capacity of existing RC structures in order to identify the best intervention strategy is under investigation. Such protocol guides the user in the identification of a 'Corrosion Risk Scenario' starting from visual inspection and simple on-site tests. Accordingly, equivalent parameters are selected to be adopted for the assessment of the structural behaviour over time. In order to characterize each scenario, the effects of corrosion processes are analysed with tomographic scans and laboratory tests on steel bars extracted from different existing buildings.

New conceptual approach combining the probabilistic nature of localised rebar corrosion and the load-deformation behaviour

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Abstract

There is a need for sound engineering models and concepts taking into account the damage mechanisms of chloride-induced corrosion with respect to the load-bearing behaviour of reinforced concrete structures. In this paper, we present a novel conceptual approach combining the physical-electrochemical processes of chloride-induced corrosion initiation/propagation with the mechanical aspects of load-deformation behaviour. A particular focus lies on the stochastic nature of localised corrosion and the relevance of the location of corrosion for the load-bearing behaviour, which is considered with the Corroded Tension Chord Model (CTCM). We present a numerical implementation of this concept, applied to a case study of a bridge deck cantilever slab.

Efficiently assessing the structural reliability of corroded reinforced concrete bridge girders

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Abstract

The estimation of structural reliability is an important task and different methods have been developed to calculate the reliability index correctly and efficiently. In this paper, a combined methodology is proposed to quickly and accurately determine the failure probability based on response surface sampling and importance sampling. Several key improvements to existing methods are proposed and implemented. The method is validated against 52 benchmark examples, yielding highly accurate results (median error: 0.69 %) with minimal computational cost (>1300× more efficient than Monte-Carlo sampling). Finally, the method is applied to assess the reliability of a corroded concrete bridge girder based on stochastic finite element modelling.

How to schedule seismic retrofitting of RC bridges subjected to environmental deterioration through seismic reliability analyses: Part 1

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Abstract

Bridges may suffer relevant damage in case of a seismic event, and this issue can be magnified due to deterioration phenomena induced by environmental agents, like CO_2 emissions or chlorides. Ensuring adequate seismic reliability levels for existing infrastructure components is therefore a key issue for owners in earthquake-prone countries. The present work illustrates how owners can foresee deterioration of existing reinforced concrete bridge in time and compute loss of seismic reliability during the service life of the structure.

How to schedule seismic retrofitting of RC bridges subjected to environmental deterioration through seismic reliability analyses: Part 2

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Abstract

Bridges may suffer relevant damage in case of a seismic event, and this issue can be magnified due to deterioration phenomena induced by environmental agents, like CO_2 emissions or chlorides. Ensuring adequate seismic reliability levels for existing infrastructure components is therefore a key issue for owners in earthquake-prone countries. The present work illustrates how owners should plan maintenance interventions aimed at improving seismic performance of existing reinforced concrete bridge with the use of a seismic reliability assessment procedure able to quantify time-variant seismic reliability profiles due to aging and gains in terms of structural safety achievable with the implementation of different retrofitting protocols. A closer look on the effectiveness of FRCM retrofitting systems is presented in this study.