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Finite Element Analysis of Thermal Restraint at Early Concrete Ages, Exemplified by a Cooling Tower Shell Structure

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International Conference

Numerical Modeling Strategies for Sustainable Concrete Structures

Chairmen: Pierre Rossi and Jean-Louis Tailhan

(IFSTTAR, former LCPC)

www.sscs2012.com

FINAL PROGRAM AND ABSTRACTS

May 29 - June 1, 2012
Aix-en-Provence, France

Final Program

Invitation from the AFGC President

The French Association of Civil Engineering (AFGC), the International Federation of concrete (fib), the RILEM and the AUGC are pleased to invite you to the international conference on "Numerical Modeling Strategies for Sustainable Concrete Structures" in Aix-en-Provence from, the 29th of May to the 1st of June 2012.

The French Association of Civil Engineering (AFGC) includes all actors in the field of civil engineering, whether they are owners, designers, developers or researchers. The association links the world of materials to the world of structures, the world of education and research to the world of design and construction.

Through close contacts with the IABSE (International Association for Bridges and Structural Engineering), RILEM (International Union of Laboratories and Experts in Construction Materials, Systems and Structures), fib (International Federation for Structural Concrete) and the ACI (American Concrete Institute), the AFGC provides invaluable links between French civil-engineering research and practice and the international scientific community. The Association is a network through which French engineers and researchers working abroad can keep up with French know-how.

The International Conference SSCS'2012 will provide an opportunity for all actors, as designers or constructors, to promote their work and share about the use of computer modeling and present their contribution with respect to sustainable development issues.

On behalf of the four associations and the organising committee, we are looking forward to seeing you in Aix and participating in the dynamic field of Civil Engineering.

Jean-Marc Tanis
President of the AFGC

Invitation from the Organisers

Cement is the more used building material constituent, and will continue to be largely used in the years to come. Its production generates CO_2 emissions.

It is, thus, of primary importance to optimize the use of this cement in the concrete structures, while checking that these structures have lifespan compatible with the stakes of the sustainable development. To take up this challenge, it is essential to use adapted tools of quantification making it possible to justify, in a rigorous and reliable way, the strategic and technical choices adopted.

The numerical methods (finite elements, finite volumes, finite differences...) constitute a relevant response to this challenge. They potentially allow, due to a best taken into account of the rheological, physico-chemical, and mechanical concrete properties, and of thermo-hydro-mechanics and environmental boundary conditions on the structures, to optimize these structures (optimization with respect to time, money, safety, energy, CO_2 emissions, and, more generally, life cycle), in a way more reliable than the codes and analytical approaches currently used.

The control of the concretes placing in the formworks, their durability, their cracking, their shrinkages, and their creeps, with respect to the sustainable development (evaluation of CO_2 emissions, for example) constitute, therefore, the principal topics of this international conference.

The objective is to join together researchers, engineers, architects, urbanists, industrials and owners, to exchange and reflect on the use of these numerical tools and their contribution with respect to the current stakes of sustainable development.

Pierre Rossi and Jean-Louis Tailhan
Chairmen of the Conference

Established in 1981, the AUGC aims developing and promoting the academic teaching (initial formation, continuing formation, PhD studies) and researches in the civil engineering field in the universities and high schools depending on the French Education Ministry.

The association initiates links with other French associations which act in developing civil engineering and its specialities. It supports the international cooperation, identifies graduates job opportunities and encourages contacts between its members.

Every year, the AUGC organizes the academic symposium of civil engineering which includes several events:

- A scientific meeting which themes are open-ended allowing the researchers community to present their work

- The "René HOUPERT" young researchers' price which offers to PhD students the possibility to expose their works to all the researchers and professional communities of civil engineering. By the way, it contributes in the diffusion of a part of their laboratory activities. This price is organized in connection with the Doctoral Network of Civil Engineering.

- Several workshops relating to civil engineering training.

These three events render the AUGC objectives: to collectively contribute to the continuing education of university teachers to increase the quality of our students' training, to participate to the PhD students training and to the dissemination of our research results. The AUGC organizes also scientific events in collaboration with other associations or groups. These events cover more precise topics than that on which focuses the annual general meeting. The AUGC represents the academic community at the different partners of civil engineering field.

The International Federation for Structural Concrete (fib - fédération internationale du béton) is a non-profit organisation created in 1998 from the merger of the Euro-International Concrete Committee (CEB - Comité Euro-International du Béton) and the International Federation for Prestressing (FIP - Fédération Internationale de la Précontrainte). The parent organisations CEB and FIP existed independently since 1952.

The objectives of fib as given in the statutes are to develop at an international level the study of scientific and practical matters capable of advancing the technical, economic, aesthetic and environmental performance of concrete construction. These objectives shall be achieved by the stimulation of research, the synthesis of findings from research and practice, the dissemination of the results by way of publications, guidance documents and the organisation of international congresses and symposia, the production of recommendations for the design and construction of concrete structures, the information of members on the latest developments. The objectives shall be pursued in conjunction with the existing international technical associations and regional standardisation organisations.

RILEM, The International Union of Laboratories and Experts in Construction Materials, Systems and Structures, is a non profit-making, non-governmental scientific association founded in France in 1947, whose vocation is to contribute to progress in the construction sciences, techniques and industries. RILEM members include the leading building research and testing laboratories around the world with interests in industrial research, manufacturing and contracting, as well as a significant number of individual members from universities and industry.

RILEM's focus is on construction materials and their use in building and civil engineering structures, covering all phases of the building process from manufacture to use and recycling of materials. RILEM meets these objectives through the work of its technical committees. Symposia, workshops and seminars are organised to facilitate the exchange of information and dissemination of knowledge.

RILEM publishes the journal Materials and Structures, the flagship of the association, which is a unique international and interdisciplinary forum for new research findings on the performance of construction materials. The journal is dedicated to the publication of high quality reviewed papers examining the fundamental properties of building materials, their characterization and processing techniques, modeling, standardization of test methods, and the application of research results in building and civil engineering.

Many other publications, in the form of reports and proceedings, are produced and published on the website www.rilem.net for free.

Venue of the Conference

The Conference venue is the Congress Centre located 14 boulevard Carnot - 13100 Aix-en-Provence - France

The Conference begins on Tuesday 29 May at 9.00 am with the Opening Session and closes on Friday 1st June at 2.00 pm.

Reception and Registration of participants will start on May 28th, 2012 from 5:00 pm and will be continuing until on may 29th, 2012 morning.

Conference registration fees include: admission to all scientific programs, proceedings, Welcome Reception, coffee breaks, lunches, technical visit and banquet.

Accommodation
Please get in contact with the Hotel Booking Service at your earliest convenience to book your hotel or for any complementary information.

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mail: hotelcongres@aixenprovencetourism.com

Symposium language
English is the official language of the Conference.

Coffee Breaks
Coffee breaks will take place in Picasso and Sainte Victoire rooms.

Lunches
Lunches are offered to participants, on 29, 30, 31 May and 1st June, on presentation of the Lunch tickets (included in the Registration documents) in Picasso and Sainte Victoire rooms.

Welcome Reception
On the first day of the Conference, (May 29th), all participants and accompanying persons will visit Aix-en-Provence from 6:00 pm to 7:30 pm. After this guided tour, a reception in the Gardens of « Pavillon Vendôme » will take place with the presence of the Mayor. Welcome Reception tickets are included in the Registration documents. They will be requested at the reception room entrance.

Abstracts

Invited papers

A multiphase concrete model with application to high temperature, structural repair, leaching and Alkali-Silica reaction
B.A. Schrefler

Multilevel numerical modeling for durability of RC structures
V. Baroghel-Bouny

Cracking of concrete structures: interest and advantages of the probabilistic discrete approaches
P. Rossi, J.L. Tailhan

Implementation of a validation procedure for using numerical models in concrete structure design and assessment
B. Massicotte, M. Ben Ftima, A. Nour, E. Yiliz, D. Conciari

Special Session

A new mock-up for evaluation of the mechanical and leak-tightness behaviour of NPP containment building
E. Galenne, B. Masson

A multiphase concrete model with application to high temperature, structural repair, leaching and Alkali-Silica reaction

[1]B.A. Schrefler, F. Pesavento, G. Sciumè, [2]D. Gawin

[1]Dip. Di Ingegneria Civile, Edile, Ambientale - Università di Padova, Italy
[2]Dept. Of Building Physics and Building Materials – Tech. University of Lodz, Poland

Abstract

We present a general multi-physics model for concrete, with applications to concrete at high temperatures, concrete at early age and structural repair work, leaching in concrete and alkali-aggregate reactions, [1-4]. The model includes most of the processes taking place in the pores of the mix and their interaction with the solid phase in the above mentioned situations. The mathematical model has been developed by writing the relevant balance equations for the constituents at the pore scale and by upscaling these equations to the macroscopic scale, taking into account thermodynamic constraints. The final model after introduction of the constitutive equations, consists of a mass balance equation for dry air, a mass balance equation for the fluid phases (water and vapour), a mass balance equation for the solid phase, an energy balance and a linear momentum balance equation for the mixture fluids plus solid phase and, when needed, a mass balance equation for the calcium ions, [1-4]. The numerical solution of this problem has been greatly enhanced by a new multifrontal parallel solver. The speedups obtained will be shown. Also several other aspects will be addressed as shown in the following.

In the case of concrete at early ages for industrial applications such as structural repair work, not all the aspects included in the reference model are of importance. We present hence also a simplified model with applications to repair of damaged concrete. In general, examples for all mentioned aspects will be shown including a fully integrated analysis for fire in tunnel, [4].

References

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[2] Modelling creep and shrinkage of concrete by means of effective stress, D. Gawin, F. Pesavento, B.A. Schrefler, Materials & Structures, 40, 579-591, 2007.

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Numerical modelling of RC structure durability
- Multi-level concept and various coupled problems -

V. Baroghel-Bouny - M. Thiery - P. Dangla

Paris-Est University - IFSTTAR - Paris - France

Numerical modelling in the field of durability of RC structures is presented through a multi-level concept. The scope is restricted to the problem of chloride- and carbonation-induced reinforcement corrosion (only the initiation phase is considered) and to isothermal conditions. First the needs and purposes in this field are reminded. Then, the various levels of sophistication of the physically-based models developed for the prediction of chloride transport or carbonation of cementitious materials are described. Typical examples of application of the various tools, numerically implemented in the 1-D case, are given in the presentation. The numerical results obtained are compared to experimental data, in order to test the reliability and the efficiency of the models.

The IFSTTAR modelling platform for chloride transport offers currently three levels of sophistication in saturated conditions and one level in non-saturated conditions: *level 1* is a simple chloride diffusion model, *level 2* is a multi-species transport model, *level 3* involves transport-chemistry coupling, whereas *level 4* is a coupled moisture-ion transport model. In the level-2 model, the ionic transport process involves the species Cl^-, OH^-, Na^+ and K^+, which are the main ions present in the pore solution, and is described by the *Nernst-Planck* equation (electro-diffusion of ions). The level-4 model accounts in addition for ionic transport by advection of the liquid phase. In this model, moisture transport includes Fickian water-vapour relative diffusion and Darcian liquid-phase movement. The ion effect on liquid/vapour water equilibrium is taken into account by including the chemical activity of liquid water into the chemical potential formula. The variations of the transport properties *vs.* the degree of saturation are described by integral functions or analytical formulas. A *Freundlich's* type description can be assumed for chloride binding at equilibrium as usually done by researchers, while a kinetic equation is added in order to account for the delayed binding of chlorides when their velocity is high with respect to the rate of the binding process (case of high-rate advective transport).

The selection of the proper level is done in particular according to the purpose of the prediction and to the degree of complexity acceptable (based in particular on the availability of the input data, etc.) and of course of the actual environmental conditions of the structure. Thus, *level 2* can be used for the assessment of some of the required input data, such as *effective* chloride diffusion coefficient and binding-isotherm parameters, by numerical inverse analysis, or for concentration profile and SL prediction of real structures, as illustrated in the presentation. *Level 4* is rather appropriate for understanding and prediction of complex processes, and in particular for the validation of some assumptions/mechanisms. As an illustration, level-4 simulations of wick action tests and of wetting tests by a salt solution after drying in lab are discussed.

With regard to carbonation, *level 1* corresponds to analytical physical-chemical models, while the coupling of such simple models with a numerical moisture transport model is included in *level 2*. *Level 3* corresponds to numerical physical-chemical models (reactive transport). In particular, the level-3 IFSTTAR model includes $CaCO_3$ formation by both $Ca(OH)_2$ and C-S-H, the influence of the kinetics

related to $Ca(OH)_2$ dissolution, an (ideal) solid solution approach for the progressive C-S-H decalcification, and the associated porosity changes. The chemical reactions (which involve the solid compounds $Ca(OH)_2$, C-S-H and $CaCO_3$) are coupled with the transport equations associated with moisture movement (which occur during drying and/or wetting), gaseous CO_2 and ionic diffusion.

Examples of application of probabilistic analytical or semi-analytical carbonation models (levels 1 and 2) are presented for the assessment of the time-dependent reliability index and for SL prediction, as well as for the selection of the appropriate concrete cover for given target SL and reliability index. One of the main advantages of these probabilistic tools is that uncertainties and variability of the parameters (e.g. material properties and boundary conditions) can properly be taken into account. Moreover, the capabilities of the level-3 IFSTTAR model are illustrated in the case of accelerated carbonation though simulations of phase mineral assemblages, as well as of profiles of pH, $Ca(OH)_2$ content and liquid water saturation profiles.

The further developments needed, in order to improve the prediction of long-term durability, are also summarized.

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Cracking of concrete structures: interest and advantages of the probabilistic discrete approaches

P. Rossi, J.-L. Tailhan

Université Paris-Est, IFSTTAR, MAT, F-75732, Paris, France

In the field of numerical modelling of cracking of concrete structures, almost all of the approaches adopted and used nationally and internationally fall into two main families of models:

- Models that address explicitly the propagation of one or several (s) crack (s) within the structure,
- Models that treat cracks as distributed damage and do not take them into account explicitly.

Almost all of these numerical models are deterministic and consider concrete as a homogeneous material. Since 1985 (the first paper in an international journal was published in 1987), LCPC (newly IFSTTAR) develops another philosophy of modelling for concrete cracking: a probabilistic discrete cracking approach.
The numerical modellings developed in this frame are based on three innovations:

- Concrete is considered as heterogeneous through a random spatial distribution of mechanical properties considered as dominant in the cracking process, namely the Young's modulus and the tensile strength;
- Scale effects on concrete cracking (experimentally proved) constitutive modelling are proposed: the mechanical properties of material depend on the size of the mesh elements adopted for the finite element analysis.
- Cracking is treated explicitly, through the creation of random kinematic discontinuities, which provides access to quantitative information on the state of cracking (cracks number, opening and spacing). This knowledge is essential for reliable prediction of the durability of structures and therefore their life span. This is one of the key issues of sustainable development related to this problematic.

In the frame of the modelling strategy developed by Tailhan and Rossi, two scales of analyze of the structure are taken into account: the global scale that means the scale of the whole structure and the local scale for which only a small part of the structure is concerned.
The fact that the developed modellings are related to the discrete cracking implies that they are both able to provide explicit information about cracks, this at the two scales of analysis concerned.
The fact that one calculation corresponds to one random spatial distribution of mechanical properties leads to the necessity of, for a given problem (given geometry of structure and boundary conditions …), realizing a great number of calculations in the frame of a Monte Carlo approach.
In consequence, the modelling strategy does not provide a deterministic result, but an average one associated with a standard deviation which allows a relevant analysis of the structure safety.
One of the main social and technical repercussions of this development of physically based numerical tools concerns the optimization of the concrete quantity used in the structure (and thus to minimize CO_2 related to cement industry) and the operational safety of these structures (cycle of life analysis).
This paper summarizes different applications of the proposed modelling strategy which is related to different scales of problems:

- Macrocrack propagation with explicit information on its process zone,
- Cracking process around an rebar loaded in tension,
- Cracking in a reinforced concrete structure.

Implementation of a validation procedure for using numerical models in concrete structure design and assessment

B. Massicotte, M. Ben Ftima, A. Nour, E. Yildiz, D. Conciatori

École Polytechnique de Montréal, Montréal, Canada

Abstract

For decades engineering processes have used numerical models for developing new industrial products. Increasing computational capabilities and confidence gained through years of experience have allowed remarkable innovations while maintaining or increasing reliability and performance. Such an approach is not common in the field of structural engineering. Several reasons can explain, or even justify, this reality. The uniqueness of many constructions often cannot justify optimising the design using sophisticated models. Moreover design codes limit or even prohibit initiatives toward innovation, justified with the noble principle of protecting public safety. Current practice is generally based on simplified design methods and specifications derived from laboratory tests carried on simple structural elements, often of small scale compared to the actual structure. They are supported by reasonable, though conservative, assumptions, and validated by years of satisfactory performance. Moreover, numerical models and computational capabilities have not been accessible for concrete structures until recently. Nonlinear finite element modelling has been limited to the academic world or for the design of exceptional and rare structures.

Since approximately the Year 2000, the availability of commercial software with sophisticated concrete models has given new opportunities. Nonlinear finite element analysis (NLFEA) is now accessible for determining concrete structures behaviour beyond the linear condition. Although most design and structural assessments will be carried out using traditional approaches, it is most likely that the availability of refined and powerful models, combined with the training acquired by engineers in their graduate degrees, will make more attractive the use of NLFEA. However, there is little if any guidance for using NLFEA in structural calculations. There is also a need for providing procedures aimed at guiding engineers for validating, and correctly using NLFEA software.

The paper presents a validation procedure that can be adopted for the safe use of NLFEA in the context of structural design and strength assessment. The objective of the paper is to propose a philosophy that could be adopted by agencies or large structure owners, and be eventually introduced in design codes. The aspects of quality control and benchmark test selections are discussed. The paper concludes with an invitation to the experts in the field of structural modelling to join their effort in a collaborative project aimed at setting up the scientific background for developing a validation procedure for using numerical models in concrete structure design and assessment.

Keywords: nonlinear analysis, finite element, reinforced concrete, benchmark tests, validation procedures.

A new mock-up for evaluation of the mechanical and leak-tightness behaviour of NPP containment building

E. Galenne, B. Masson

EDF R&D, Clamart, France / EDF SEPTEN, Lyon, France

The passive leak-tightness function of the French 1300-1450 MWe NPP reactors is provided by a reinforced and pre-stress concrete inner wall without steel liner, an outer reinforced wall assuring the protection against external effects. The leak through the internal wall is collected in the annular space being permanently maintained slightly below atmospheric pressure.

The technical objective, in term of leak-tightness, is to maintain the rate of gas escape under a legal criterion. The compliance with the rule is evaluated by measuring the quantity of air leak, obtained during a periodical pressure test at ambient temperature.

Numerical models are up to now not sufficiently mature and accurate to predict the evolution of the leakage rate during these pressure tests, nor during standard design-basis accidents. In the frame of the continuous effort on safety and in the perspective of NPP life extension, the project of building a reduced scale containment mock-up is then studied by EDF. The main ambitions are the following:

- to demonstrate in an indisputable way the good behaviour of inner wall in situation of severe accident (high pressure and high temperature during two weeks);
- to have a better comprehension of the leakage and its evolution with the ageing of the structure. The ageing of the mock-up will be accelerated by the scale effects (reduced thickness, faster drying, faster shrinkage) ;
- to collect experimental data necessary for the development and validation of numerical models.

This project is complementary to other experiments conducted or funded by EDF these last years : cylindral concrete specimens under damaging compression loading [1], cracked wall [2] (3 x 2 x 1 m reinforced concrete wall), MAEVA mock-up [3] (containment cylinder at 1:3 scale), …

At the difference of this last case , we planned to integrate in the new mock-up all complexities of the containment structure : base raft, gusset, penetrations, access hatch, dome, grouted prestressing tendons, … The scale will probably be 1:3.

The conception phase of the mock-up has just began, the construction being planed in 2013. The main conception choices will be presented and discussed during the conference.

References

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Sessions I:

Theoretical and Numerical Models

Session I-1:Flowing and Casting

Experimental and Numerical Techniques to Characterize Structural Properties of Fresh Concrete
Tony Di Carlo
University of Southern California, Daniel J. Epstein Department of Industrial and Systems Engineering

Optimizing the casting of High Performance Concrete structural elements via Computational Fluid Dynamics Modelling of fresh concrete behaviour
Liberato Ferrara, Massimiliano Cremonesi and Alessio Caverzan
Department of Structural Engineering, Politecnico di Milano, Italy

A numerical approach to analyze the particulate flow in concrete pumping circuit
Choi, Myoung Sung *, Kim, Young Jin, Jeon, Se Jin, Kim, Yong Jic
Civil Engineering Research Team, Daewoo Institute of Construction Technology, South Korea

Application of the fluid dynamics model to the field of fibre reinforced self-compacting concrete
O. Svec[1], H. Stang[1], J. F. Olesen[1], L. N. Thrane[2]
[1] Technical University of Denmark, Department of Civil Engineering, [2] Danish Technological Institute

Experimental and Numerical Techniques to characterize Structural Properties of Fresh concrete

Tony Di Carlo, PhD candidate
University of Southern California
Daniel J. Epstein Department of Industrial and Systems Engineering

1. Introduction

This research pertains to the pursuit of structural analysis tools for *Contour Crafting,* an emerging additive fabrication technology that proposes to use computer-controlled layering of cementitious materials to robotically manufacture homes that are more sustainable and affordable.

Contour Crafting works by extruding a special mixture of concrete in successive layers that accrete from the bottom up. This process is accomplished with a robotic arm that is capable of traversing three-dimensional space. The tip of the robotic arm is equipped with a swiveling nozzle which constitutes the point of extrusion. When a layer of material has been successfully deposited (extruded), the nozzle indexes vertically and proceeds to deposit the subsequent layer. Figure 1 depicts prototypical Contour Crafting technology, and its extrudate[1].

Figure 1. Contour Crafting Technology and Research Specimen

By design, Contour Crafting dispenses with the rigid formwork often used to contain poured concrete; therefore, contour-crafted concrete must be load-bearing at a *very* early age. This research proposes to develop structural analysis tools for the in-process fresh concrete subjected to these unprecedented fabrication loads.

2. Objectives

The main objectives of the work are: (a) An analytical structural analysis model, (b) A numerical structural analysis model, and (c) Experimental techniques to characterize the relevant properties of fresh Contour Crafting concrete.

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[1] More can be learned about Contour Crafting at www.contourcrafting.org.

2.1. Analytical Model

The analytical model will couple geometry, density, green strength, and strength-gain relations to relate material stress to material strength, in the fresh extrudate, and thus ascertain the conditions necessary for safe Contour Crafting concreting of simple monolithic structures.

2.2. Numerical Model

The numerical (finite element) model will be developed to evaluate and compare alternative fabrication strategies. This numerical model can be easily implemented with commercially available finite element analysis (FEA) programs, like ABAQUS, using Drucker-Prager (DP) plasticity, which Famiglietti (Famiglietti, et. al. 1994) and others have demonstrated to be adequate in a constitutive model for fresh concrete. This numerical structural analysis model can be useful before construction begins, to evaluate and compare alternative fabrication strategies, and during construction, as a material health monitoring system. As a material health monitoring system the numerical model runs in real time (synchronously) accounting for non-isothermal curing and material strength development (maturity).

2.3. Experimental Techniques

Finally, methods for testing fresh concrete will be implemented, for verification, to develop relations necessary for the analytical model, and to calibrate the finite element analysis (FEA). Figure 1 depicts such testing, and three exemplary 3x4 cylindrical specimens compressed, from left to right, at 19, 37 and 45 minutes after mixing (a time-scale of interest to Contour Crafting). Figure 2 depicts results of a very preliminary FEA intended to duplicate the green strength testing.

Figure 2. Three Green Strength Tests
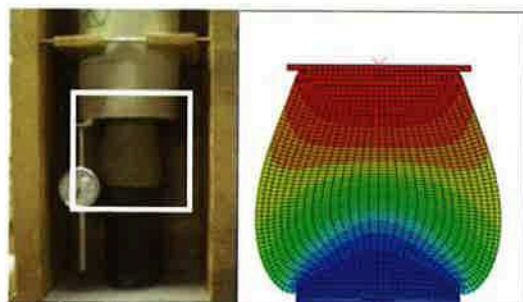
blue = low displacement, red = high displacement

Figure 3. FEA of a Green Strength Test

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Optimizing the casting of High Performance Concrete structural elements via Computational Fluid Dynamics Modelling of fresh concrete behaviour

Liberato Ferrara, Massimiliano Cremonesi and Alessio Caverzan

Department of Structural Engineering, Politecnico di Milano, Italy
Piazza Leonardo da Vinci 21, 20133 Milan
Corresponding author's address: liberato.ferrara@polimi.it

Abstract

The development and the wider and wider spreading applications of concretes characterized by superior performance in the fresh state, such as self consolidating concrete, has promoted in the very last years challenging research on the numerical modelling of the fresh concrete behaviour [1]. Several approaches, ranging from single continuum fluid to suspension modelling to discrete element method, have been developed and successfully applied, e.g. to the modelling of simple fresh state characterization tests, such as slump flow tests, also with the aim of assessing correlation between fundamental rheological properties of fresh cementitious suspensions (such as the Bingham fluid parameters yield stress and plastic viscosity) and parameters garnered from field tests.

A field of cutting edge application of the aforementioned numerical modelling approaches is represented by the simulation of concrete castings which could result instrumental to the optimization not of either the shape of the intended elements and the fresh state performance of the concrete to be employed. In other words either the most suitable shape of the element and its casting process can be sought as a function of the given concrete composition and fresh state performance or the mix-composition and set of fresh state parameters which may result as most conducive to the casting of an element with a given shape and a pre-defined casting process can be assessed.

In this framework a Particle Finite Element based approach, already successfully employed to model the fresh state behaviour of fresh concrete in different field tests [2], is applied in this study to optimize the casting process of a precast ribbed element to be cast with a High Performance (Steel Fiber Reinforced) Cementitious Composite, the cross section of which is shown in the attached Figure 1, upside down with respect to its true position in a structure assembly. A structural peculiarity of the element is represented by its thin slab, which could be cast without any conventional reinforcement if a HPFRCC is used.
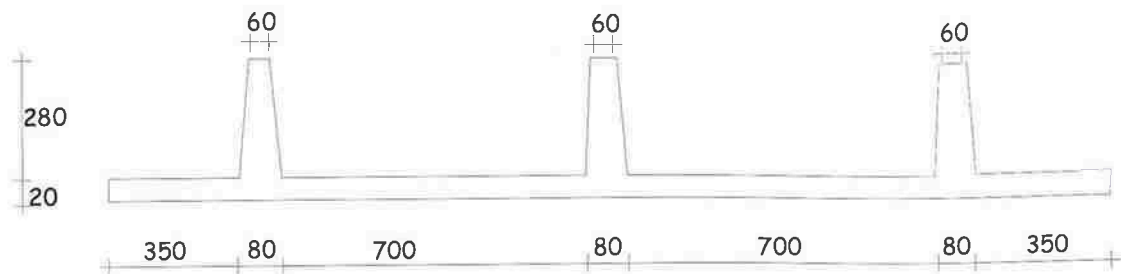
Figure 1

The most effective casting procedure (e.g. from the central rib or from either the outer ones) as well as the "hydraulic height" of concrete in the supplying bucked which is necessary to successfully complete the casting have been studied by means of the aforementioned approach. The most suitable set of rheological properties of the mix, which will be instrumental to the mix-design, has been also study to the aim of successful casting. A final mock-up test with a Plexiglas mould, which would allow also to visualize the casting process will be performed (Figure 2).

Figure 2

The paper represents hence one among the earliest attempts to address to use of Computational Fluid Dynamics as a tool to optimize casting process in the precast industry, also in the sight of promoting the use of High Performance Cementitious Composites for high end structural applications.

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A numerical approach to analyze the particulate flow in concrete pumping circuit

Choi, Myoung Sung*, Kim, Young Jin, Jeon, Se Jin, Kim, Yong Jic

Civil Engineering Research Team, Daewoo Institute of Construction Technology, South Korea

Abstract

Pumping is a commonly used method to cast concrete, especially to build high rise building and high rise pylon structures without the use of any bucket or conveying belt system. To come up with this tendency, a large number of experimental studies about the concrete flow using pumping circuit have been published. But most experimental studies up to date only aimed to evaluate the pumping performance of the finally derived mixing design. So even though it cost a tremendous amount, the test results were only used as a one-time experimental data before really casting to build structures.

So as a part of the establishing the standardized test methods of pumping circuit, a 170 m-long experimental pumping circuit was designed and installed. Before the actual experiments, I simulated various parameters such as the concrete flow characteristics under concrete rheology, aggregate volume fraction and pumping pressure using computational fluid dynamics (CFD) simulation method.

Among them, in this paper we would like to discuss the pumping concrete flow performance regarding the aggregate volume fraction and the resulting characteristics of the formation of lubricating boundary layer. Through the CFD analysis results, depending on the aggregate volume fraction formation of lubricating boundary layer is determined and directly affecting the pumping concrete flow characteristics.

For the validation of analysis results, I also compared with experimental results.

Application of the fluid dynamics model to the field of fibre reinforced self-compacting concrete

O. Svec[1], H. Stang[1], J. F. Olesen[1], L. N. Thrane[2]

1 Technical University of Denmark, Department of Civil Engineering, {olsv, hs, jfo}@byg.dtu.dk
2 Danish Technological Institute, lnth@teknologisk.dk

Abstract

Ability to properly simulate a form filling process of the fibre reinforced self-compacting concrete is a challenging task. Such simulations may clarify an evolution of fibre orientation and distribution which in turn significantly influences final mechanical properties of the casted elements. Such a code has been developed and is shortly introduced in the presented paper. An implicit representation of aggregates is suggested to speed up the computational time. The main focus of the paper is towards validation of the ability of the code to properly mimic the fibre reinforced self-compacting concrete. In order to do that, several experimental parametric studies were carried on. One of them was a parametric study of different slump tests. The resulting "spread versus time" curves were afterwards compared to the curves coming from the simulation, which helped to validate the computational code.

Session I-2:Early age behaviours

Numerical Model for Quantifying Degree of Hydration in Concrete Mixes with Reduced CO_2 Footprint
A. Attari, C. McNally, M. Richardson
School of Architecture, Land scape and Civil Engineering, University College, Dublin, Ireland

Use of original percolation approach in homogenization methods for the prediction of concrete hydro-mechanical behavior at early age
L. Buffo-Lacarrière, A. Sellier, P. Souyris
Université de Toulouse; UPS, INSA; LMDC, Toulouse, France

Monitoring of the creep and the relaxation behavior of concrete since setting time, part 1: compression
Claude Boulay[1], Michela Crespini[1], Stéphanie Staquet[2], Brice Delsaute[2], Jérôme Carette*[2]
[1] IFSTTAR, Paris, France ; [2] Université Libre de Bruxelles, Belgium

Monitoring of the creep and the relaxation behavior of concrete since setting time, part 2: tension
Brice Delsaute[1], Jérôme Carette[1], Stéphanie Staquet[1], Claude Boulay[2], Michela Crespini[2]
[1] Université Libre de Bruxelles, Belgium; [2] IFSTTAR, Paris, France

Using GGBFS to reduce concrete crack control reinforcement under early-age thermal action
Kangkang Tang[1] , Steve Millard[1], and Greg Beattie[2]
[1]Department of Civil Engineering, Xi'an Jiaotong-Liverpool UniversityJiangsu, China, [2]Arup, Liverpool, UK

Load Calculation Model during Construction of Multi-story Concrete Structures
Toshihiko Yamamoto
Professor, Department of Architecture - Daido University, Nagoya, Aichi, Japan

"Time-dependent Deformation" of RC Strut in Retaining Excavation
Yang, Yaoning[1], Yuan, Yong[1], Zhu, Yimin[2]
[1]Department of Geotechnical Engineering, Tongji University, Shanghai, China [2]Shanghai No.1 Construction Co.,Ltd, Shanghai, China

Numerical Model for Quantifying Degree of Hydration in Concrete Mixes with Reduced CO$_2$ Footprint

A. Attari, C. McNally, M. Richardson

*School of Architecture, Land scape and Civil Engineering,
University College Dublin, Ireland*

Abstract

The cement industry is estimated to be responsible for about 7% of the carbon dioxide generated globally. As such, reducing the amount of CO$_2$ emitted during cement production is a key issue if the construction industry is to participate in sustainable development. Under the terms of the Kyoto Protocol Emissions Trading Scheme it is also potentially profitable for cement companies to reduce their CO$_2$ emissions. By using blended cement instead of ordinary Portland cement, it is possible to lower the share of clinker in cement, resulting in reduced CO$_2$ and energy emissions. In Ireland, CEM II now accounts for over 80% of the Irish cement production portfolio.

GGBS is a by-product of steel industry and a common replacement for cement. When compared to Portland cement it has a reduced CO$_2$ footprint and concretes containing GGBS are less prone to deterioration due to aggressive chemical attacks. Its use has the potential to produce more durable concrete with increased service life, lower maintenance costs and a lower carbon footprint, increasing the sustainability of concrete construction.

The widespread application of alternative materials raises the need for more comprehensive investigation of the resulting concrete properties. Early age behaviour is a major factor to be addressed, and tools are required for quantifying the hydration state of concrete members, particularly at early-ages. Numerical models can potentially be used in mass concrete construction to predict and prevent possible thermal crack formation. They also provide an indirect means for characterizing development of the hydration reaction in concrete. The latter can then be utilised in modelling and predicting secondary concrete properties, such as diffusion coefficient.

The aim of the current study is to use this approach to quantify the development of heat of hydration when mixtures of CEM II and GGBS are utilised. Experiments were conducted where the temperature profiles in 4 different mixes of concrete (CEM II with 0%, 30%, 50% and 70% GGBS) are recorded. This was achieved by casting 6 identical concrete samples from each mix, with thermocouples embedded to record the internal temperature of the mix at regular time steps. Temperature changes of the mix are then used to quantify the heat evolved, based on the principles of heat transfer. To account for the combined effect of time and

temperature on hydration development, activation energy of the mix is used, along with the equivalent age maturity method. Total heat of hydration is determined based on the composition and amount of cementitious materials.

It has long been accepted that the liberated heat of hydration, divided by the total available heat of hydration is a good measure of the degree of hydration. The experimental data describing hydration development with equivalent age are then used to calibrate the exponential formulation presenting the S-shaped hydration curve. Values of β, τ, and α_u (the hydration parameters) are obtained for each mix, from the results of multivariate non-linear regression analysis. Comments on the use of this method in quantifying concrete hydration are then made.

Use of original percolation approach in homogenization methods for the prediction of concrete hydro-mechanical behavior at early age

L. Buffo-Lacarrière, A. Sellier, P. Souyris

Université de Toulouse; UPS, INSA; LMDC (Laboratoire Matériaux et Durabilité des Constructions); 135, avenue de Rangueil; 31 077 Toulouse Cedex 04; France

Thanks to recent progress in experimental setups, micromechanical elastic properties of cement components can be estimate by nanoindentation. Moreover, hydration models are able to predict the evolution of volume fractions of different phases during cement hydration. So, the use of homogenisation methods may predict the evolution of properties of cement materials in the early age hydration. As seen in previous works ([1,2]), the use of these methods for concrete is usually divided in three successive steps. First, the paste properties are predicted using a self-consistent scheme which is more adapted to overlapped microstructure of numerous hydrates. Then the Mori-Tanaka is successively used to predict the mortar ones, using the calculated paste properties and experimental sand properties, and so on for concrete.

These methods well reproduce the elastic properties of mature concrete, but at early age, the progressive passage from viscous material to solid (percolation threshold) cannot be reproduced for all concrete compositions and especially for paste with W/C ratio lower than 0.5. Indeed, as self consistent scheme implies a percolation threshold as soon as solid fraction is begins greater than 50% of the REV, it can not correctly represent the material behaviour at the early age. In fact, this method forecasts an excessive stiffness at early age. The main objective of the present work is to solve this problem by proposing a relation giving the fraction of percolated hydrates from the composition of the cement material without using percolation algorithms, and without neglecting the bulk modulus existence for the non percolated part of the material, contrary to the approach proposed in ([3, 4]).In this study, we use a relation based on basic probability considerations to find the percolation fraction of the cement paste. Furthermore, we don't ignore the un-percolated phases but replace it by one with an insignificant shear modulus. This method enables to calculate a realistic bulk modulus at the early age, and this bulk modulus can be then used to estimate the Biot coefficient in the paste, even during the first hours after casting.

The results of the model are compared with experimental data from literature for cement paste and an original experimental campaign. This campaign allows to confront each level of homogenisation with experimental results; On purpose, cement paste, mortar and concrete were casted with a same W/C ratio, the mortar have the same fraction of paste and sand as the concrete fraction without large aggregate. Concerning the hydro-mechanical behaviour of concrete at early age, model predictions are compared with the experimental measures obtained in an autogeneous shrinkage test performed from casting to 1 month.

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Monitoring of the creep and the relaxation behavior of concrete since setting time, part 1: compression.

Claude Boulay[1], Michela Crespini[1], Stéphanie Staquet[2], Brice Delsaute[2],
Jérôme Carette*[2]

1 Institut Français des Sciences et Technologies des Transports, de l'Aménagement et des Réseaux, Département Matériaux, 58 Bd Lefèbvre, 75732, Paris Cedex 15, France, e-mail: Claude.Boulay@ifsttar.fr
2 Université Libre de Bruxelles (ULB), BATir Department, CP194/4, A. Buyl Avenue 87, 1050 Bruxelles, Belgium
e-mail: jecarett@ulb.ac.be, brice.delsaute@ulb.ac.be, sstaquet@ulb.ac.be

Abstract

Early age deformations of concrete are involved in cracking which can lead to service life reduction. In particular, the development of the concrete shrinkage under restrained conditions often leads to durability problems in concrete structures.

This study (part 1& 2) presents an experimental methodology using two different test rigs enabling a monitoring of the stiffness, the creep or the relaxation of a concrete sample at early age. Tension tests realized on the Temperature Stress Testing Machine [1] (TSTM) are presented in a second part while compressive tests, realized on another test rig called BTJASPE [2], are presented in the first one. In each part, models are used for the description of the experimental set of data. Results in compression and in tension are compared in the second part.
Since, in case of restrained conditions, the concrete is mainly submitted to tensions at early age, the purpose of this study is to answer to the question of the equivalence between the early age creep and relaxation behavior of concrete in tension and in compression for a typical reference ordinary concrete.

BTJASPE is a test rig which enable early age compressive test on cylinders. Samples are cast inside a stainless steel mold (sealed conditions) around which a flow of water allows the control of the sample temperature. The Young's modulus, the creep or the relaxation of the sample can be monitored at early age. Cyclic loadings are applied at regular intervals. In each cycle, a loading, controlled in displacement is applied, then the stress or the strain are kept constant during a short period and the sample is unloaded to a zero stress until the next cycle.

Rheological functions are used to model the observations performed in compression. Results are expressed, after the setting time, in function of the maturity. This time is determined both with ultrasonic measurements and the monitoring of the stiffness with the cyclic loading protocol. Parameters of the creep model are used as input for relaxation model whose response is compared to experimental results.

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Monitoring of the creep and the relaxation behavior of concrete since setting time, part 2: tension.

Brice Delsaute[1], Jérôme Carette[1], Stéphanie Staquet[1], Claude Boulay[2],
Michela Crespini[2]

1 *Université Libre de Bruxelles (ULB), BATir Department, CP194/4, A. Buyl Avenue 87, 1050 Bruxelles, Belgium*
e-mail: jecarett@ulb.ac.be, brice.delsaute@ulb.ac.be, sstaquet@ulb.ac.be
2 *Institut Français des Sciences et Technologies des Transports, de l'Aménagement et des Réseaux, Département Matériaux, 58 Bd Lefèbvre, 75732, Paris Cedex 15, France, e-mail: Claude.Boulay@ifsttar.fr*

Abstract

In the first part of this paper (see abstract part 1), the compressive behavior (stiffness and creep or relaxation) of a sample is observed and modeled. In the second part of the paper, an experimental methodology using a test rig (Temperature Stress Testing Machine) specifically designed to measure the evolution of several parameters, such as the elastic deformation, the creep and the relaxation of concrete is presented [1]. In the framework of this study, the TSTM equipment was associated with a mould and a thermal regulation and displacement measurement without contact systems. The TSTM consists of an electromechanical testing setup, where one end of the specimen is restrained by a steel anchorage and the displacement of the other end is controlled by a motor moving the other steel anchorage.

First, the setting time t0 is determined through ultrasonic measurements with P and S waves. Then, automatic loadings or displacements are applied at regular intervals on the studied sample in tension and in compression. The evolution of the elastic modulus is determined. The TSTM device finally allows the very accurate monitoring of the early age deformations and stresses within a concrete sample, in order to determine its creep and relaxation behavior. Traction and compression tests are compared, as well as restrained shrinkage experiments in sealed conditions. This second part of this study presents a comparison of two methods used for modeling basic creep and relaxation coefficient of concrete at very early age (since setting time) in tension and compression. Maxwell Chain (relaxation) or Kelvin-Voigt (creep) are used for this purpose. All results are expressed, as proposed by De Schutter [2], in function of the degree of hydration.

This field of research has already been investigated for the creep, especially in compression and several models have already been proposed [2]. For the behavior of concrete at early age in tension, especially in case of relaxation, it is completely different. The purpose of this study is to answer to the question of the relevance of using the same modeling approach or not for all these phenomena occurring at early age (creep/relaxation in tension and in compression). Indeed, in case of a full restraint shrinkage test, all these phenomena have to be modeled accurately.

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Using GGBFS to reduce concrete crack control reinforcement under early-age thermal action

Kangkang Tang[1, a], Steve Millard[1, b] and Greg Beattie[2, c]

[1]*Department of Civil Engineering, Xi'an Jiaotong-Liverpool University, 111 Ren Ai Road, Dushu Lake Higher Education Town, Suzhou Industrial Park, Suzhou, Jiangsu 215123, China*
[2] *Arup, 12th Floor, the Plaza, 100 Old Hall Street, Liverpool, L3 9QJ UK*
[a]*kangkang.tang@xjtlu.edu.cn,* [b]*stephen.millard@xjtlu.edu.cn,* [c] *greg.beattie@arup.com*

Abstract

Over 160 million tonnes of blast furnace slag is generated in China annually, of which only 55% is recycled. Blast furnace slag, ground to an appropriate fineness, can be used as a cementitious material in concrete. However, most ground granulated blast furnace slag (GGBFS) in China ends up in low-grade applications, including 'Low heat' cementitious material used in low-grade bulk concrete and cementitious material in mortar.

A recently started project at XJTLU aims to contribute to the application of GGBFS in long-span concrete structures in China by avoiding/reducing the use of more expensive crack control reinforcement. This paper reports on the methodology which will be adopted to carry out this project. Special considerations are paid on issues associated with concrete early-age thermal contractions. Modelling of a case study commercial building in Shanghai is used to compare the cost effectiveness of conventional crack control steel reinforcement with the mitigation of thermal crack stresses using GGBFS. This includes the use of finite element modelling to investigate the development of heat during the cement hydration process and the resulting thermal strains produced in the concrete.

Keywords: Thermal cracking, blast furnace slag, cement hydration, crack control steel.

Load calculation model during construction of multi-story concrete Structures

Toshihiko Yamamoto

Professor, Department of Architecture, Daido University, Nagoya, Aichi, Japan

Abstract

Field researches on the construction loads on supporting floors have been performed in recent decades with results indicating that the construction loads may exceed the design loads before reaching their specific concrete strength. Therefore, it is important to prevent the structural damage such as cracking, excessive deflection and yielding of structural members caused by the construction loads. This damage remains after construction and affects the building's lifetime serviceability. To prevent the initial damage of concrete during construction, it is necessary to properly calculate the loads during construction. Most of the conventional load calculation models during construction, because they are linear elastic, cannot handle the nonlinearity of concrete such as creep, shrinkage and temperature effects. This paper presents a nonlinear load calculation model during construction of multi-story concrete structures. In the current formwork for multi-story reinforced concrete buildings, a freshly placed floor is shored by several of the previously cast floors below. The proposed model takes into account the following effects, creep, shrinkage and temperature. The calculated results of the loads during construction indicate that the construction loads are inevitably heavy and the creep deformations are not negligible. The strength and Young's modulus of the concrete and the rigidity of shores affect the load distributions, and temperature changes directly affect the construction loads. Comparison with the measured data, the proposed model is found to express very well the actual situation of construction loads. It is possible to calculate the details of each construction phase of the construction load by this model. Monte Carlo simulations were also conducted to evaluate the coefficient of variation of load and deformation using this model. The coefficients of variation are less than 10% for construction loads and about 20% for creep deflections during construction.

"Time-dependent Deformation" of RC Strut in Retaining Excavation

Yang, Yaoning[1], Yuan, Yong[1], Zhu, Yimin[2]

1.Department of Geotechnical Engineering, Tongji University, Shanghai, China
2.Shanghai No.1 Construction Co.,Ltd, Shanghai, China

Abstract

A conventional task when constructing deep foundation is to constitute retaining system. When excavating in soft ground interior struts are necessary to support diaphragm wall. From local practice reinforced concrete (RC) strut cast-in-place is applied widely for it can provide sound withstand to limit ground deformation. Questions arise when RC strut applied to retain large-scale excavation for its rigidity for the shrinkage of concrete might be of significance. As cast-in-place concrete material properties will develop with its maturity while forces applied on strut varies with excavation. Performance of RC long-strut would vary with ages. To make a clear understanding the time-dependent behavior of RC long-strut, this paper deals with the ways to form RC long-strut and the difference in controlling ground movement. To achieve this purpose, time-dependent behavior of reinforced concrete was investigated with typical experiment and knowledge on the study of early age properties of concrete. Computing models given to several cases to cast RC long-strut. Comparison and analysis between computing and in-site measurement were presented for the reference of decision of the way to construct RC long-strut.

Keywords: concrete long-strut, retaining deep excavation, time-dependent, early age

Session I-3:Drying, Shrinkages and Creeps

Use of FEM to assess shrinkage cracking in restrained concrete structures
L. Leitão*, M. Azenha**, C.F. Sousa*, R. Faria*
*LABEST, Laboratory for the Concrete Technology and Structural Behaviour, University of Porto, Porto, Portugal
**ISISE, Institute for Sustainability and Innovation in Structural Engineering, University of Minho, Guimarães, Portugal

The simulation of time dependent behaviour of cement bound materials with a micro-mechanical model
R. Davies, A.J. Jefferson
Cardiff School of Engineering, Cardiff University, Cardiff, Wales, UK

Hydration Based Model to predict Creep and Shrinkage in Concrete.
D.Harinadha Reddy, Ananth Ramaswamy
Department of Civil Engineering, IISc, Bangalore, India

Analysis of cracking in a massive concrete structure at early age
A. Hilaire[1], F. Benboudjema[1], A. Darquennes[1], Y. Berthaud[2], G. Nahas[3]
[1] LMT, ENS Cachan, France, [2] Université Paris 6, Paris, France, [3] IRSN, Fontenay-aux-Roses, France

Mesh-less diffusion and elastic numerical homogenization of concrete microstructures
F. Lavergne [1,2], J. Sanahuja [2], C. Toulemonde [2]
[1] ENPC, Champs-sur-Marne, France, [2] EDF R&D, MMC Department, Moret sur Loing, France

Approach for Consideration of Viscoelasticity in Time Step Restraint FEM Analyses of Hardening Concrete
Dipl.-Wirtsch.-Ing. Dirk Schlicke and Prof. Dr.-Ing. habil. Nguyen Viet Tue
Graz University of Technology, Institute for Structural Concrete, Austria

Nonlinear basic creep and drying creep modeling
A.Sellier[1], L.Buffo-Lacarriere[1], S. Multon[1], T.Vidal[1], X. Bourbon[2]
[1] Université de Toulouse ; UPS, INSA ; LMDC, Toulouse, France – [2] Andra, Chatenay-Malabry, France

Simulation of the restrained ring test applied to cement-based materials incorporating rubber aggregates and fibre reinforcement
Farouk Tazi
Laboratoire Matériaux et Durabilité des Constructions,Toulouse, France

Use of FEM to assess shrinkage cracking in restrained concrete structures

L. Leitão[*], M. Azenha[**], C.F. Sousa[*], R. Faria[*]

[*]LABEST, Laboratory for the Concrete Technology and Structural Behaviour
University of Porto, Porto, Portugal

[**]ISISE, Institute for Sustainability and Innovation in Structural Engineering
University of Minho, Guimarães, Portugal

Abstract

Consideration of the effects of shrinkage for quantification of the minimum reinforcement for cracking control is usually made through a simplified approach, according to general building codes such as the Eurocode 2 (Part 1). This approach usually consists of considering concrete elements as tensile ties under total restraint to deformation, which is quite conservative in view of the actual restraint to deformation that real structures endure. To overcome this simplification, some regulations devoted to reservoirs (such as the Part 3 of Eurocode 2) are currently taking into account the concept of degree of restraint for a more realistic prediction of actual crack width in concrete structures. However, the number of restraint situations that these regulations can tackle is limited.

The present research has been motivated by this limitation of design codes, and mainly concerns the implementation of numerical simulation strategies with recourse to the finite element method, in order to obtain realistic cracking patterns and crack widths for laminar concrete structures under restrained deformation. As the proposed methodology is intended for practical purposes, it was decided to disregard the non-uniform distribution of shrinkage across the thickness of laminar elements, which would significantly increase the complexity of the problem, requiring the use of hygro-mechanical models. The modelling strategy to be adopted in the paper is devoted to laminar elements modelled in plane stress conditions, with reinforcement being explicitly considered with bar elements, and with consideration of the transient character of the problem, namely in view of concrete creep and shrinkage. Tension stiffening effects associated to cracking are taken into account through the use of appropriate stress-strain relationships for concrete that surrounds the reinforcement.

Validation of the adopted approach is made through comparison of the model predictions with results obtained experimentally in a concrete tie subjected to a direct tension test. The modelling approach is then applied to a set of retaining walls for which crack patterns and openings are available in the literature. Coherence between the in-situ observed behaviour of the retaining walls and the FEM results is thoroughly discussed, together with the description of parametric analyses for assessment of the relative importance of the input variables for the simulation. The paper ends with a critical discussion of the possibility of adopting this kind of numerical approach for computation of minimum reinforcement for concrete structures, with emphasis on the cost-efficiency that can be achieved.

The simulation of time dependent behaviour of cement bound materials with a micro-mechanical model

R. Davies, A.J. Jefferson

Cardiff School of Engineering, Cardiff University, Cardiff, Wales, UK

Abstract

An approach is described for simulating the behaviour of concrete, and other cementitious composites materials, using micro mechanics. The basic mechanical material model is that presented by Mihai and Jefferson[1] which employs micromechanical solutions of a two-phase composite comprising a matrix phase, spherical inclusions, circular microcracks distributed in the matrix and combines these with a rough crack contact component.

The primary focus of the paper is on the enhancement of the model to include time dependent behaviour. This is accomplished by adding visco-elastic rheological units to govern the mechanical behaviour of the cement paste phase of the material. Early age behaviour is dealt with by using an adapted solidification theory[2]. The effects of moisture content and changing moisture content are considered in a model in which groups of rheological units, each comprising three Maxwell elements, are added, to represent the behaviour of the material over different time scales. The recent observations aimed at understanding the fundamental nature of creep by Jennings & Bullard[3] and Vandamme & Ulm et al[4] have been used to guide the development of the functions that govern the relative sizes of the three units and their properties.

Validations are presented using data from a range from drying and creep tests on cementitious materials at different ages.

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Hydration Based Model to predict Creep and Shrinkage in Concrete

D.Harinadha Reddy, Ananth Ramaswamy

Department of Civil Engineering, IISc, Bangalore, India

Abstract

Probably the most uncertain and difficult aspect of the design of reinforced and prestressed concrete structures is the prediction of time-dependent behavior. However, realistic prediction of concrete creep and shrinkage is of crucial importance for durability and long-time serviceability of concrete structures. For some structures, for the long-term performance from the safety view point, prediction of time dependent deformations are critical. Creep and shrinkage cause increases in deflection and curvature, cracking of concrete, loss of prestress, redistribution of stresses and leakages. The present study comprises of an experimental and analytical program to assess the levels of creep and shrinkage in normal, self compacted and heavy density concrete. The experimental program includes tests on creep using standard cylinder specimen, while shrinkage studies have been conducted using prism specimen, both under controlled environmental conditions. The experimental results suggest that creep and shrinkage strains are higher in heavy density concrete than in normal and self compacted concrete. This may be attributed to the relatively smaller pore structure of heavy density concrete that results in larger availability of free water and a relatively slower hydration process in comparison to normal concrete. While there is some scatter in the results, creep strains decrease with age of loading and both creep and shrinkage strains are smaller when the relative humidity is higher. The analytical work is carried out based on the degree of hydraion in the concrete. The mechanical properties of concrete such as Young's modulus, compressive strength, etc. are caliculated with age based on the degree of hydration[4,5]. The Hydration based microprestress solidification theory[1,2,4,6,7] prediction model is able to predict the test results of creep satisfactorily.

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Analysis of cracking in a massive concrete structure at early age

A. Hilaire[1], F. Benboudjema[1], A. Darquennes[1], Y. Berthaud[2], G. Nahas[3]

[1] *LMT, ENS CACHAN, France, {hilaire,benboudjema}@lmt.ens-cachan.fr*
[2] *Université Paris 6, France, {berthaud}@lmt.ens-cachan.fr*
[3] *IRSN, Fontenay-aux-Roses, France, {georges.nahas}@irsn.fr*

Massive structures like concrete containment in nuclear power plants, LNG tanks, dams or tunnels involve making important investments and are designed to have a long lifespan (from several decades to more than one century). At early age, cracks may occur which can reduce the service ability of these structures at long term (improving penetration of aggressive agents like CO_2 which lead to corrosion, reduction of the tightness...).Indeed, during the casting process, the cement hydration reactions release large amounts of heat and large variations of temperature are observed in the core of concrete. A thermal stress state is created due to boundary conditions (i.e. restraint by previous lift after restart of concrete pouring) and temperature gradient. Besides, the hydration reaction occurs also with a reduction of volume, leading to autogeneous shrinkage. For most of the case, compressive stresses are firstly generated during the self-heating phase, followed by tensile stresses during cooling, which may lead to cracks.

In order to predict accurately the risk of cracking, compressive and tensile creep must be taken into account since it induces relaxation of stresses. However, most used numerical simulations are based on data obtained on compressive tests even if some experimental results show a difference between tensile and compressive creep. Besides, to the author's knowledge, no concrete creep model in the literature is able to take into account different creep in tension and compression. In this contribution, a simplified creep model, which integrates the ability to differentiate creep in tension/compression is proposed. It consists in a rheological model with only 4 material parameters and is able to predict also partial recovery of creep strains during unloading, effect of hydration, temperature and long-term aging. Besides, the numerical resolution is carried out using analytical equations, and requires no local iteration (in contrary to model based on generalized Maxwell rheological chains).

An identification process has been carried out thanks to several previous experimental studies, it allows to identify the material parameters and to validate the model (especially ability to distinguish compression and tension). A first study of a 1D embedded concrete element, representative of a massive wall cast on a rigid raft foundation, which is submitted to temperature variation highlights that :

- Tensile creep is beneficial, since it induces relaxation and reduces tensile stresses; • Asymetry of creep in tension/compression is important to consider (see Figure 1(b)), it induces a
- Variation of about 1Mpa on the predicted tensile stresses in some cases.

This model is currently extended to 3D and implemented into Cast3m finite element code, in order to assess risks of cracking in concrete containment of nuclear power plants. However, the scientific explanation of asymetry of creep in tension/compression is still not known. Besides, the effects of temperature on tensile creep at early-age have not been yet studied. These aspects are also currently under investigation.
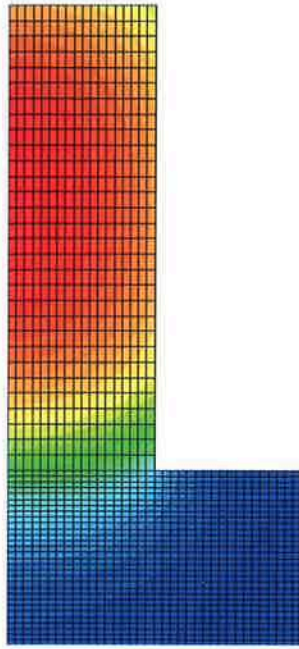
(a) Temperature field 26h after the casting
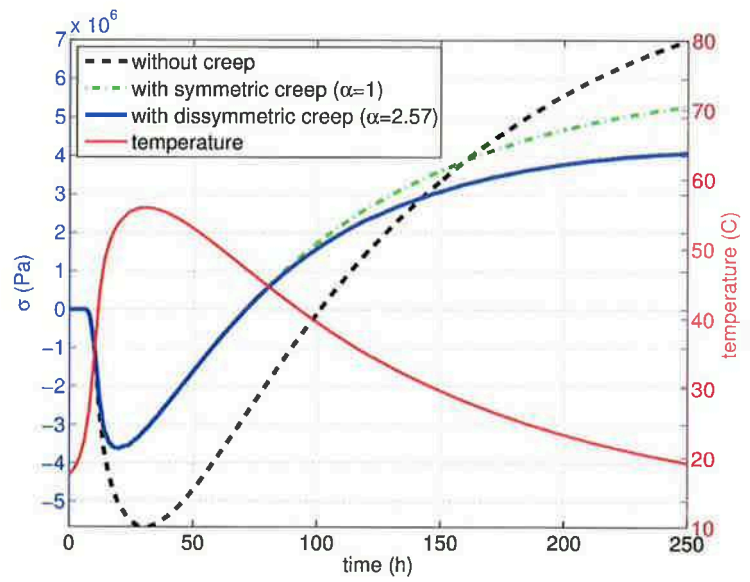
(b) Stress and temperature evolution for a 1D embedded concrete element

Mesh-less diffusion and elastic numerical homogenization of concrete microstructures

Numerical Modeling
Strategies for Sustainable Concrete Structures

Aix-en-Provence, France
May 29-June 1, 2012

F. Lavergne 1,2, J. Sanahuja 2, C. Toulemonde 2

1 ENPC, Champs-sur-Marne, France, francis.lavergne@eleves.enpc.fr
2 EDF R&D, MMC department, Moret sur Loing, France, {julien.sanahuja,charles.toulemonde}@edf.fr

Abstract

EDF operates numerous large facilities and thus, is to warrant their safety and serviceability. Life extension and life-cycle management are key objectives of operators of Nuclear Power Plants (NPP). Continuous safe operation of commercial NPP is economically desirable for operators and necessary to satisfy the needs of the general public. Decade-old industrial plants face aging induced by the environment, the plant operation itself or unexpected pathologies. In addition, in the prospect of building new facilities, the responsibility of the future owner is to prescribe the exposure class and the required properties of a set of concretes depending on their location inside the plant. In both cases, the assessment of the structural integrity requires precise knowledge and anticipation of concrete behaviour.

Concrete is a genuinely complex multi-scale and multi-physics material made up of local materials.

Thus, considering the impossibility to experimentally assess the behaviour of every concrete found in facilities, modelling is the only viable option to properly estimate the long-term behaviour of a large set of concretes, especially regarding creep. The multi-scale nature of the material makes homogenization approaches appealing. The effective behaviour of a given concrete does not only depend on the elementary behaviour of its components (aggregates, air voids, cement paste), but also on its microstructure, that is how these components are spatially arranged. Unfortunately, as far as realistic microstructures of concrete are concerned, the most common numerical homogenization approaches fail. Considering finite elements for example, the mesh creation proves to be an extremely tedious task as, by nature, the aggregates have complex shapes, are densely packed, and follow a very large particle size distribution.

Mesh-less approaches can overcome previously mentioned issues. A revival of finite volumes or differences is proposed here, to allow responsive computations without heavy memory requirements. More precisely, the degrees of freedom are arranged along a cartesian grid, so no mesh is to be stored. The 3D conduction problem is solved by means of finite volumes. Centered finite differences on staggered grids are used to handle 3D elasticity in heterogeneous materials. Algorithmic improvements and careful implementation allow to reach unprecedented performances: an elastic problem with 400 million unknowns can now be routinely solved within one minute on EDF clusters.

Various numerical tests have been performed and are presented so as to ensure the reliability of such methods. The influence of the resolution, of the chosen boundary conditions and of the size of the elementary volume are studied. The local fields are displayed and the macroscopic results are calculated. Most of the computations were performed on a synthetic microstructure made of 2024 polydisperse spherical inclusions. The contrast of the behaviours of the elementary phases is choosen to be very high to challenge the numerical approach and anticipate the needs of viscoelastic computations.

Approach for Consideration of Viscoelasticity in Time Step Restraint FEM Analyses of Hardening Concrete

Dipl.-Wirtsch.-Ing. Dirk Schlicke and Prof. Dr.-Ing. habil. Nguyen Viet Tue

Graz University of Technology, Institute for Structural Concrete, Austria

Abstract

During concrete hardening special regard to the restraint is necessary, especially in case of massive concrete members, but also at the application of new concretes at outstanding constructions. FEM analyses of hydration heat induced temperature development gives sufficient results for the deformation impact. The according restraint stresses can be determined with consideration of the concrete's rising elastic modulus and the restraint degree of the system. But due to duration of the heat flow process height and impact period of the restraint will be affected by viscoelasticity of the concrete.

The viscoelastic effects consist of many components constituted by changing material properties influencing themselves. In practice different simplified approaches are available for considering this in *global step* calculations. Their implementation in time step analyses is not generally admitted and requires expertise. In contrast present research develops material models needing specific input parameters for every use case.

This contribution focuses on a practicable approach considering the superposition of every stress increment's viscoelastic behaviour in time step FEM analysis. The Differentiation between the pure viscoelastic material behaviour (as it is given in the codes for idealistic conditions like creep or relaxation) and the according viscoelastic system response (addicted to the systems variable restraint degree) allows the transfer of this model into practice.
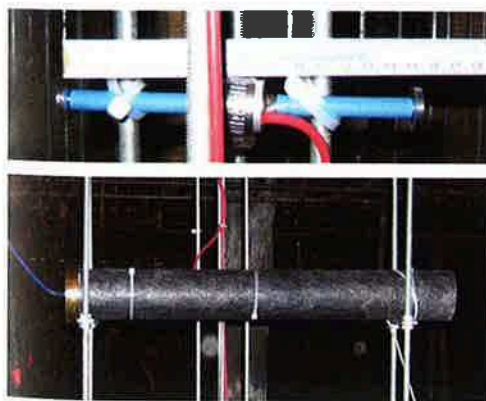
Measurement instruments, above: vibrating wire strain gage, below: stressmeter
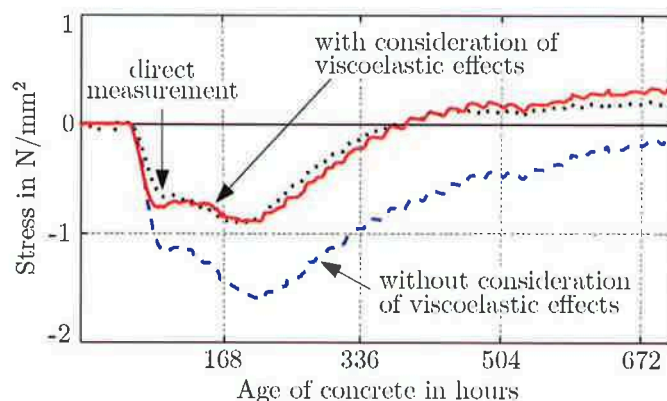
Compatibility of the measurements, stress development during the hardening process determined on strain data

Figure 1. Measuring system for identification of thermal restraint of concrete

The approach is verified by compatibility of measurement data and their FEM based recalculation. Furthermore current experiments of different cured RC beams, built in a deformation disabling frame work, were investigated with this approach.

Nonlinear basic creep and drying creep modelling

A.Sellier(1), L.Buffo-Lacarriere(1), S. Multon(1), T.Vidal (1),X. Bourbon(2)

(1) Université de Toulouse ; UPS, INSA ; LMDC (Laboratoire Matériaux et Durabilité des Constructions) ; 135, avenue de Rangueil ; F-31 077 Toulouse Cedex 04, France,
(2) Andra, Direction Scientifique/Service Colis – Matériaux, Parc de la Croix Blanche, 1-7 rue Jean Monnet, 92298 Chatenay-Malabry

Abstract

The conventional splitting of delayed strain of concrete in autogenous shrinkage, drying shrinkage, basic creep and drying creep assumes a decoupling of underlying phenomena. Even if this splitting is usually used to interpret creep test results, it is not full-compatible with physical phenomena understood by the creep poro-mechanics modelling community. Indeed in the framework of poro-mechanics, drying shrinkage and basic creep can be modelled thanks to a single poro-mechanics scheme in which capillary pressure acts on a concrete skeleton. In this type of model based on the Biot theory, shrinkage is the consequence of capillary pressure acting on the visco-elastic solid. It assumes implicitly a coupling between shrinkage and creep. But, even if this approach is more physic than the traditional ones, it remains unable to explain the additional strain obtained on creep test in drying conditions (Pickett effect), which is usually modelled by an additional module for drying creep. This observation points out a gap in physical phenomena comprehension and consequently in the poro-mechanic formulation.

Moreover, modelling of tertiary creep needs a coupling with the damage theory. Indeed, the increase of basic creep rate observed in this case of loading, can be explained by the stress concentration induced by micro-cracking which takes place at a micro-structural level. If a modelling of this first family of micro cracks is used, the model will be able to simulate non-linear dependency of creep strain toward applied stresses. Nevertheless, it remains unable to explain drying creep.

In the proposed work, a second family of micro-cracks is postulated to explain drying creep. These micro-cracks are due to the paste shrinkage that is restrained by aggregates and anhydrous phases of cement paste. This second family of cracks is modelled thanks to the anisotropic damage theory. The stress field heterogeneity induced by capillary pressure at the microstructure-level is explicitly taken into account in the damage criterion. The damage is then used in the poro-mechanics framework to modify the influence of capillary pressure on solid skeleton (Biot tensor), explaining most of the drying creep strains.

This physical modelling considers explicitly the stress field heterogeneity consequences. It offers a way to link shrinkage effect to Weibull scale effect without using an explicit mesh of elastic heterogeneities as it is often the case in mesoscopic numerical models.

Finally, the proposed modelling allows considering meso-scale random effects through a probabilistic method directly included in the damage criterion. Drying creep and Weibull scale effects, which are interpreted as mesoscopic heterogeneity consequences, can then be considered for the structural level analysis but without resorting to a mesoscopic modelling or an additive module in the poro-mechanic formulation.

Simulation of the restrained ring test applied to cement-based materials incorporating rubber aggregates and fibre reinforcement

F. Tazi[a]

Laboratoire Matériaux et Durabilité des Constructions, 135, av de Rangueil, 31077 Toulouse, Cedex 04, France

Abstract

The assessment of the durability of constructions is a major concern today. Cement-based materials, the most widely used manmade construction materials, suffer from some imperfections and thus highly susceptible to cracking. They particularly suffer from shrinkage cracking, especially when the shrinkage is restrained. Nowadays, Steel bar or fibre reinforcement is an imperfect solution, which does not prevent concrete cracking but restrains the crack opening. However, a better solution to limit brittleness and prevent shrinkage cracking is to design a cimentitious composite exhibiting a high level of deformation before macro/micro cracks appear. For this reason, it was assumed that incorporation of rubber aggregates obtained from shredded non-reusable tyres with low elastic modulus could be a solution. Thus also helping to meet the demand for a clean environment.

Several experimental researchers have recently investigated the influence of material composition on the age of cracking and a significant body of research is being developed to illustrate the influence of mixture composition on the age of cracking. The restrained ring test is becoming widely used as a test method to assess the potential for early-age cracking in the cement composites. Such considerations led us to propose a new numerical approach to reduce the propensity of concrete to crack. In this regard, our investigation aims at developing a numerical model as a direct solution, based on the finite element analysis, to predict the age of cracking for cimentitious composite having a high strain capacity before macro/micro cracking localisation. This paper describes a numerical study of restrained ring specimens tested, using different composite specimen ratios of rubber aggregates and fibre reinforcement, in order to compare with experimental results that have been published recently.

The results for this numerical method estimate the residual stress and strain developing according to time, and consequently quantify the materials potential for cracking. This numerical program is presented to illustrate the favourable correlation that exists between the predicted behaviour of cimentitious composites model and the experimental results.

Keywords: Rubber aggregates, Fibre reinforcement, Drying shrinkage, Shrinkage cracking, restrained ring test, Finite element analysis, Environment.

Session I-4:Cracking behaviours (static, fatigue, dynamic)

Discrete Element Simulation of Concrete Fracture and Crack Evolution
B. Beckman, K. Schicktanz, M. Curbach
Institute of Concrete Structures, TU Dresden, Germany

Crack Elimination in Concrete Floors and Foundations
R. Cajka at al.
VSB – Technical University Ostrava, Czech Republic

Effects of the concrete damage due to corrosion of steel bars on the static and dynamic response of PRC/RC beams
R. Capozucca
Ass. Prof of Struct. Eng., Università Politecnica Marche, Ancona, Italy

Effects of carbonation on the lifetime of concrete structures and updating by Bayesain networks
B. Capra[1], A. Sellier[2], F. Deby[2], P. Rougeau[3]
[1] OXAND S.A.; [2] Université de Toulouse ; UPS, INSA ; LMDC; [3]CERIB

Numerical Modelling of reinforced concrete beam short and long term response to cyclic loading
A. Castel[1], R.I. Gilbert[2], S.J. Foster[2]
[1]Professor, University of Nice, Nice, France - [2]Professor, University of New South Wales, Sydney, NSW, Australia

Modelling of the reinforcing bars and prestressing tendons for containment buildings
M. David[1,2] , E. Lorentz[1], S. Michel-Ponnelle[1], J.-J. Marigo[2]
[1] LaMSID, EDF R&D, Clamart, [2] LMS, Ecole Polytechnique, Palaiseau

Numerical study on load distribution in HC floors
P. Bernardi, R. Cerioni, N. Garutti, E. Michelini
Department of Civil and Environmental Engineering and Architecture,University of Parma, Italy

Determination of the dynamic tensile response and dissipated fracture energy of concrete with a cohesive element model
F. Gatuingt[1], L. Snozzi[2], J.F. Molinari[2]
[1] LMT-Cachan (ENS Cachan/CNRS/Université Paris 6/PRES UniverSud Paris), [2] LSMS, School of Architecture, Civil and Environmental Engineering (ENAC), Ecole Polytechnique Fédérale de Lausanne (EPFL), Switzerland

Three dimensional constitutive law for concrete
R. Hammoud*, A. Yahia**, R. Boukhili*
*École Polytechnique de Montréal, Montréal, Québec - **Université de Sherbrooke, Sherbrooke, Québec

Numerical modeling of the behaviour of UHPFRC
A.P. Lampropoulos and M.N. Soutsos
Department of Civil Engineering, University of Liverpool, Liverpool, UK

Using 3D Microstructural Imaging to Produce Physically-Based Numerical Models for Concrete. Part I: Micromechanical Experiments

E.N. Landis[1], J.E. Bolander[2]
[1] University of Maine, Orono, Maine, [2] University of California, Davis, California,

Using 3D Microstructural Imaging to Produce Physically-Based Numerical Models for Concrete: lattice simulations

J.E. Bolander[2], E.N. Landis[1]
[1] University of Maine, Orono, Maine, [2] University of California, Davis, California,

Inverse analysis procedure for the characterisation of softening diagrams for FRC beams and panels

Ali Nour[1,2], Bruno Massicotte[1], Renaud De Montaignac[1], Jean-Philippe Charron[1]
[1] École Polytechnique de Montréal, Montréal, Québec, [2] Hydro Québec, Montréal, Québec,Canada

Numerical Modelling of Reinforced Concrete Beams Repaired with Polymer-Modified Mortar

L.M Mauludin, G. Guidi, F. Da Porto
Politeknik Negeri Bandung-Indonesia, University of Padova, Italy

Cracking Propagation Simulation of Concrete due to Rebar Corrosion

H. Nakamura, T.K. Khoa, N. Ueda, M. Kunieda
NagoyaUniversity, Japan

Statistical analysis of crack widths by virtual modeling of reinforced concrete beams

D. Novák, L. Fekete
Institute of Structural Mechanics, Faculty of Civil Engineering, Brno University of Technology, Brno, Czech Republic

Modeling of the behaviour of RC tie-beams reinforced by flat steel rebars: A comparison between 2D and 3D numerical simulations of the steel/concrete interface

T.S. Phan, J.-L. Tailhan, P. Rossi, J. Foulliaron
IFSTTAR Paris, France

Continuum damage mechanics based model for quasi-brittle materials subjected to cyclic loadings: application to concrete

B. Richard, F. Ragueneau, A. Delaplace, C. Oliver
LMT/ENS Cachan, CNRS/Université. Paris 6/ PRES UniverSud, France

Numerical modeling of cracking in fiber reinforced concretes

P. Rossi, T.S. Phan, J.-L. Tailhan
IFSTTAR Paris, France

Multiscale Modeling of Shear Failure in RC Slabs with Spatial Variability

A.B. Suma, H.G. Burggraaf, A.J. Bigaj-van Vliet, A.H.J.M. Vervuurt
TNO, Delft, The Netherlands

Probabilistic modelling of crack creation and propagation in concrete structures: some numerical and mechanical considerations.

J.-L. Tailhan, P. Rossi, T.S. Phan, J. Foulliaron
IFSTTAR Paris, France

A RC fibre beam element for full modelling of the bending-shear response by dual section approach

P. Tortolini, E. Spacone, M. Petrangeli
Department Civil Engineering of the "G. D'Annunzio" University , Pescara, Italy

Numerical methods for collapse analysis of RC framed structures with physical and geometrical nonlinearity

M. Ucci[1], M. V. Sivaselvan[2], E. Spacone[1]
[1] Dept. of Structural Engineering, University of Chieti-Pescara "G. d'Annunzio", Italy, [2] Dept. of Civil, Environmental and Architectural Engineering, University of Colorado at Boulder, CO, USA

Discrete Element Simulation of Concrete Fracture and Crack Evolution

Numerical Modeling
Strategies for Sustainable Concrete Structures

B. Beckmann, K. Schicktanz, M. Curbach

Institute of Concrete Structures, TU Dresden, Germany,
{Birgit.Beckmann,Kai.Schicktanz,Manfred.Curbach}@tu-dresden.de

A two-dimensional simulation of concrete behaviour using Discrete Element Method (DEM) is presented in this work. The main aim of this work is the modelling of the failure process and crack initiation. The failure process of a concrete specimen during a standard compression test is simulated with regard to high strain rates as they occur due to impact load. Crack patterns resulting from the simulation are shown and compared to laboratory experiments. It is shown, that the calculated peak load is independent from the particle number used in the simulation. The Poisson's ratio of the concrete specimen during load application is an inherent result of the simulation and is compared to experimental results.

Crack Elimination in Concrete Floors and Foundations

R. Cajka at al.

VSB – Technical University Ostrava, Czech Republic

Abstract

Using the rheological sliding joint is effective method to decrease the friction between deforming structure and subsoil. Convenient material for sliding joint is bitumen asphalt belt, widely available and reasonably priced material. Sliding joints were applied successfully on several buildings in Czech Republic in the undermined region where the subsoil has been deformed. But the application of slide joint is concededly much wider, e.g. pre-stressed foundations, creep and shrinkage, thermal strain and others. Original experiments of shear resistance of bitumen slide joint as a function of time dates from the 80th of last century. Material characteristic of bitumen belt has been changed significantly since that time and this fact demanded new experiments. At VSB – Technical University of Ostrava unique equipment was designed for shear resistance measuring. Renewed experiments for different types of bitumen belts passed in 2008. One of the important factor which affect the shear resistance is the temperature and that is way the experiments continues with measuring the shear resistance of slide joint as a function of temperature in air-conditioned room. In the paper first experiment results of temperature dependant shear resistance will be presented. Test results are used for analysis of stress/strain relation between concrete floor or foundation structure and subsoil.

Coauthors: Ph.D. students from Department of Building Structures, Faculty of Civil Engineering, VSB TU Ostrava

Effects of the Concrete Damage due to Corrosion of Steel Bars on the Static and Dynamic Response of PRC/RC Beams

R. Capozucca

Ass. Prof of Struct. Eng., Università Politecnica Marche, Ancona, Italy r.capozucca@univpm.it

Abstract

Accidental actions and environmental conditions may cause damage to concrete structural elements. The analysis of concrete beams affected by damage due to corrosion of steel bars represents a convenient approach to evaluate the degree of safe and the sustainable methods of rehabilitation. The present paper reports on experimentally investigation through dynamic and static tests on prestressed reinforced concrete (PRC) beams and reinforced concrete (RC) beams damaged by corrosion of steel bars. Testing has been carried out in order to verify damage degree correlated to microcracking of compressive concrete. The experimental program foresaw that PRC/RC beams were subjected to artificial reinforcement corrosion and successively to static loading with increasing applied loads to produce bending cracking. Dynamic investigation was developed both on undamaged and damaged PRC/RC beams measuring natural frequencies and evaluating vibration mode shapes. The analysis of experimental results compared with theoretical data, are shown and discussed.

Effects of carbonation on the lifetime of concrete structures and updating by Bayesain networks

B.Capra (1), A. Sellier (2), F. Deby (2), P.Rougeau (3)

(1) OXAND S.A.; 49 avenue F. Roosevelt; 77210 Avon, France
(2) Université de Toulouse ; UPS, INSA ; LMDC (Laboratoire Matériaux et Durabilité des Constructions) ; 135, avenue de Rangueil ; F-31 077 Toulouse Cedex 04, France.
(3) CERIB; Rue des Longs Réages; BP 30059; 28231 Epernon Cedex

Abstract

Concrete cover carbonation and chloride ingress are the main causes for concrete reinforcement corrosion. So, design of concrete cover has to be performed in such a way that the probability for the critical chloride concentration or for the carbonation front to reach the reinforcement for the expected service life remains lesser than an accepted value.

In current standards rules, this objective should be implicitly verified using concrete cover proposed. But the empiric methods used in these codes does not take into account accurately the various variability of environmental and material durability indicators involved in the depassivation processes (local carbon dioxide high concentration, excellent durability indicator for some new concretes, more or less quality control for other ones…).

To consider properly durability indicators, environmental parameters, and their respective variability, an empirical method is not sufficient. A probabilistic method using explicitly the parameters random distribution is more convenient.

To use such a method, three conditions are needed: A realistic physical modelling of the depassivation processes (carbonation or chloride ingress models); A statistical measure of the model unavoidable inaccuracy; A target probability level, and a realistic random distribution for other random parameter involves in the physical phenomena.

The target probability level can be chosen in accordance with previous probability of depassivation level calculable for conventional concrete respecting previous standard design rules in a "normal environment".

The models have to be as realistic as possible to minimize their own random inaccuracy, but not too much complex to be used in a standard code. On purpose two models are proposed, one for carbonation, another one for chloride ingress. Their parameters fitting need durability indicator tests, and their physical meaning allows using them in various environments and for different concretes. For example the carbonation model is able to take into account accelerated carbonation tests results to predict natural carbonation kinetic; chloride model is able to consider the bending isotherm variation with the cement type and the chloride diffusion coefficient dependence on the concrete formulation.

These models are based on numerous parameters whose values are not certain. In a design phase, it is possible to postulate a priori values and distribution laws for these variables. When experimental data are available for a given concrete formulation, carbonation tests or chloride diffusion tests allow following with time the evolution of certain parameters. The use of Bayesian techniques allow to update the distribution law parameters according to the observed data, their likelihood and the a priori data. When few data are available, Bayesian approaches are a mean to update the models according to the available information. In this article, this approach is used to update the evolution of the concrete cover design with regards to available experimental data.

Numerical modelling of reinforced concrete beam response to repeated loading including steel-concrete interface damage

A. Castel[1], R.I. Gilbert[2], S.J. Foster[2]

1- Professor, University of Nice, Nice, France.
2- Professor, University of New South Wales, Sydney, NSW, Australia.

Abstract

In reinforced concrete constructions, deflection control of is an important performance criterion for their serviceability and sustainability. Excessive concrete cracking resulting from excessive deformation is one of the most common causes of damage and results in huge annual cost to the construction industry.

The Finite-Element modeling proposed in this paper is dedicated to the calculation of beam deflection after cracking. By implementing a new constitutive law for concrete in tension, firstly, the cumulated deflection under permanent loading resulting from both concrete bending cracking and long term effects is predicted. Secondly, the elastic response of the already cracked beam under cyclic loading is calculated including tension stiffening effect.

Calculation are performed at serviceability stage only analyzing the coupled effects of the permanent loading and the live loading of structural members under normal operating conditions. Finite Element results are validated on several large size reinforced concrete beams under different permanent loading values and maximum live loading values during cycles.

Keywords: reinforce concrete, Finite Element modelling, tension stiffening, long term effects

Modelling of the reinforcing bars and prestressing tendons for containment buildings

Numerical Modeling
Strategies for Sustainable Concrete Structures

Aix-en-Provence, France
May 29-June 1, 2012

M. David[1,2], E. Lorentz[1], S. Michel-Ponnelle[1], J.-J. Marigo[2]

[1] LaMSID, EDF R&D, Clamart, France
[2] LMS, Ecole Polytechnique, Palaiseau, France

The containment concrete vessel is a major element in the safety assessment of a nuclear power plant: in accidental cases, it constitutes the third barrier preventing the escape of radioactive products in the environment. Since the containment building cannot be replaced, the prediction of its mechanical strength is a major concern for the energy producer. To answer this question, numerical simulations provide an important analysis tool which gives quantitative estimations of the stress states and crack openings.

The containment vessels are cylinder shaped, 50 meters high, about 1 meter thick, and are made of prestressed reinforced concrete. They are designed so that the concrete always stays in compression, hence preventing potential cracks from opening. However, in accidental ultimate loading stages, if the internal pressure becomes too large, cracks may open. In this case, the reinforcing bars and prestressing tendons play a crucial role in the containment efficiency of the structure, by limiting the crack opening. This effect is also strongly influenced by the behaviour of the steel-concrete interface. The proper modelling of the bars and tendons and of the steel-concrete bond is therefore very important to estimate the containment efficiency of the structure.

The method generally used to model bars and tendons relies on bar elements, i.e. 1D elements which only have elongation stiffness. This approach is not completely satisfactory, because it results in an ill-posed mathematical problem: the interaction between a 3D medium and a 1D element has no meaning in the framework of variational continuum mechanics [1]. In practice, this kind of model fosters high stress concentrations near the bar elements, and a slight mesh dependency.

Generally, for large concrete structures, the reinforcements take the form of 2D lattices. To describe such kinds of reinforcements, we propose a different approach: the reinforcements are modelled by membrane elements, while the degradation of the steel-concrete bond is described by cohesive elements. This simple model can be rigorously derived by using the method of separation of scales [2]. It is able to describe both the steel reinforcements and the prestressing tendons, depending on the level of details required by the analysis. Compared to detailed 3D computations, this model results in a much lower computational cost.

The model is implemented in the finite element code *Code_Aster* [3]. It is validated by extensive comparisons with 3D computations. We show that it can be used to accurately model the behaviour of reinforced concrete structures, and to estimate crack openings.

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Numerical study on load distribution in HC floors

P. Bernardi, R. Cerioni, N. Garutti, E. Michelini

Department of Civil and Environmental Engineering and Architecture,
University of Parma, Italy

Abstract

Precast prestressed hollow core units are widely used for ground and suspended floors in several types of building construction, representing an economic and flexible solution. Actually, these structures perform very well despite their limited weight, allowing to cover long spans and offering several advantages over traditional methods, such as cast in situ concrete, steel-concrete composite and timber floors.

Hollow core units are usually designed as simply supported elements subjected to bending and they are in practice connected to each other with cast-in-situ concrete joints, so to form a shear key without transmission of bending moment. These longitudinal joints play a fundamental role in transversal load distribution among panels, especially in presence of line loads acting parallel to floor span or concentrated point loads. The lateral load distribution relies on the shear key especially when HC floors are realized without a cast-in-situ concrete topping, as still occurs in many European countries. As a consequence, the design of the entire floor slab requires the knowledge of the load fraction supported by each panel, which is usually evaluated on the basis of simplified curves provided by design standards [1]. Actually, several former studies [2,3] have indicated that load distribution depends not only on span length and on load position over floor span, but also on the flexural and torsional stiffness of HC units. It has also been pointed out that the distribution of deflection, bending moment and shear force may differ greatly. As a consequence, no reliable methods are available for designers and numerical approach can represent a useful tool to afford the problem, taking into account all the involved variables.

In this paper, hollow core slabs with in-situ RC joints under concentrated and line loads are analyzed by adopting the finite element method. To this scope, different modeling techniques applied to complete floors are discussed and compared to standard distribution curves, as well as to experimental results. Particular attention has also been paid to longitudinal joint modeling, by considering different schematizations able to reproduce the hypothesized hinge behavior.

At the beginning, a simplified global FE model of the complete floors has been considered in order to focus on joint behavior and also to limit computational efforts. Subsequently, the model has been progressively refined so to introduce some additional variables, influencing the lateral load distribution among panels. The so obtained results have been compared to previous ones, so to evaluate the level of detail necessary to achieve reasonable degree of accuracy in HC floor design. Finally, NLFE analyses have also been carried out in order to simulate some significant experimental tests available in technical literature [4], focusing on the considered topic. Both the tests and the analyses describe the HC floor behavior under serviceability and ultimate conditions, up to failure. In numerical analyses, the non-linear behavior of the reinforced concrete has been described through 2D-PARC constitutive model [5], whose efficiency has already been proved for several concrete structures.

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Determination of the dynamic tensile response and dissipated fracture energy of concrete with a cohesive element model

F. Gatuingt[1], L. Snozzi[2], J.F. Molinari[2]

[1] *LMT-Cachan (ENS Cachan/CNRS/Université Paris 6/PRES UniverSud Paris), France fabrice.gatuingt@ens-cachan.fr*
[2] *LSMS, School of Architecture, Civil and Environmental Engineering (ENAC), ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE (EPFL), Switzerland*

The macroscopic modeling of the tensile response of concrete in dynamic has considerably evolved and the current constitutive laws are able to represent more and more complex phenomena. Nevertheless, in these approaches the different scales present in the structure of the material are not represented despite their strong influence on the macroscopic behaviour. For example it is usual to introduce in these models a dynamic increase factor directly in the macroscopic behaviour to represent the experimental data for loading strain rates exceeding 1 /s. This has to be done with care as it is not clear how important the dissipation at the structural level is. Indeed, the increase of the fracture energy with the strain rate may be caused, in the experiments, by a structural effect (at the concrete sample level) instead of a material one's. In the high dynamic regime, multiple cracking and micro-inertia effects in the fracture process zone are thought as the main factors for the rate dependency of concrete. However, the influence of the internal microstructure of concrete and the mechanisms that lead to different crack patterns when varying the loading rate, remain open questions. In order to give some answers to these questions, concrete has to be considered as a heterogeneous material where the nature of the heterogeneity depends essentially on the scale of observation.

In this work the influence of the heterogeneous meso-structure of concrete on the dynamic tensile response is analyzed. For this purpose a 2D geometrical model of concrete consisting of aggregates, interfacial transition zones and a matrix is modeled. We use a finite element framework with cohesive elements to explicitly represent the crack nucleation and growth. The debonding process in the cohesive elements is controlled by a traction separation law based on the popular linear extrinsic irreversible law proposed by Camacho and Ortiz [1]. This numerical approach has proved its efficiency on brittle material like ceramics [2] without an explicit meso-structure representation.

We validate our model by simulating a direct dynamic tension test of a concrete specimen. The role of the meso-structure and the influence of the loading rate are then analyzed. We especially focus on the evolution of the stress peak and the energy dissipated. We can observe that with a traction separation law independent of the strain rate we are not able to reproduce the macroscopic rate effect experimentally observed while the global dissipated energy is correctly simulated. We will also show the respective influences of the meso-structure and the loading rate on the variability of the stress peak in tension.

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Three dimensional constitutive law for concrete

R. Hammoud*, A. Yahia**, R. Boukhili*

*École Polytechnique de Montréal, Montréal, Québec, Canada
**Université de Sherbrooke, Sherbrooke, Québec, Canada

Abstract

Concrete has been widely used in various structural applications because of its high performance and good durability. Although concrete can be considered a continuum material on the macro-scale, it is a heterogeneous and anisotropic material on the micro-scale. Because of this heterogeneity and anisotropic behaviour, strength, stiffness, and ductility are strongly dependent upon the load path. Various finite element analyses have been carried out to evaluate three-dimensional behaviour of concrete. To ensure reliable analysis, realistic models describing the behaviour of concrete and efficient computational procedures are required. The objective of this study was to develop a constitutive law with hardening and softening parameters that can better describe the behaviour of normal concrete. Equivalent plastic strain serves as hardening variable and itself is a function of mean pressure, which can accurately assess the magnitude of permanent strain under various loads.

Strain softening causes the dissipation of plastic energy that is eventually transformed into fracture energy when major crack develop. These inelastic phenomena are described by plastic flow which its direction is determined by the gradient of the plastic potential, and which controls inelastic dilatancy in terms of the inelastic deformation behaviour of material. A new plastic potential is introduced and experimentally fitted to ensure better estimate of load direction. By overlaying the plastic potential on the Etse and Willam's yielding surface, both defined on the Haigh-Westergaard coordinate, it is possible to establish that, at the same strength parameter, the two curves do not undergo through the same stress states. For the evaluation of normal vectors, it is necessary that each surface goes through the current stress state to ensure adequate evaluation of normal vectors. Keeping the loading surface unchanged, the calculation related to the plastic potential need to be modify. The proposed constitutive model is validated through numerical experiments.

Keywords: Constitutive law, Failure, Elastic-plastic material.

Numerical modeling of the behaviour of UHPFRC

A.P. Lampropoulos and M.N. Soutsos

Department of Civil Engineering, University of Liverpool, Liverpool, L69 3GQ, UK

Abstract

Ultra High Performance Fibre Reinforced Concrete (UHPFRC) is a relatively new material with significant enhanced strength in both compression and tension and significant higher energy absorption in the post crack region. Its mix composition is not much dissimilar from that of normal strength concrete. The main difference is that the only aggregate that is used is silica sand. High dosage of steel fibres, up to 2% by volume, makes it a ductile material.

Finite Element Method, for simulating the behaviour of UHPFRC, required a constitutive law in both compression and tension that included both the strain-hardening and softening behaviour of the material. Cylinders were tested to determine the stress-strain relationship in compression. Direct tensile tests were also needed. The behaviour of the material in tension is of significant importance for the simulation of the behaviour of UHPFRC, as it is shows significant post crack energy absorption, and the existing procedures proposed in literature, that are based on load – deflection results from bending tests, cannot be used as they assume a linear stress distribution in the cross section.

The uniaxial stress - strain relationship in tension was found to be consisting of several linear parts, which included strain hardening, a subsequent plateau , and a significant post crack energy absorption softening branch. To validate the accuracy of the proposed material constitutive relationship and to investigate the 'size effect' of the specimens tested, a series of three point bending tests were performed on beams with different section depths. The beams were notched in the middle where LVDTs (Linear Variable Displacement Transducers) were placed to measure the crack mouth opening dimension (CMOD) in addition to the load - deflection relationship. These results were used to calibrate the numerical model so that is able to reliably predict the response of any size of specimen (i.e. to take into account size effects).

The ultimate aim of this work is to predict accurately the response of UHPFRC plates. The strain hardening behaviour of UHPFRC means that cracking occurs before the ultimate load is obtained. The cracked section has a reduced depth and this increases the risk of punching shear occurring. The proposed material model was used for the numerical simulation of these plates and the results were compared to plates of different thicknesses that were tested in the laboratory.

Using 3D Microstructural Imaging to Produce Physically-Based Numerical Models for Concrete.
Part I: Micromechanical Experiments

E.N. Landis[1], J.E. Bolander[2]

[1] *University of Maine, Orono, Maine, USA, landis@maine.edu*
[2] *University of California, Davis, California, USA, jebolander@ucdavis.edu*

The complex microstructure of concrete has traditionally led us to modeling approaches where model constants are based on either simple measurements or empirical curve fitting with experimental data. While this approach is certainly sound, and powerful tools have evolved, we seek here to make more direct links between measurable micromechanical properties and the computational models we use for performance prediction. The work described here represents progress towards this direct microstructure-model link.

In the micromechanical experiments we employ synchrotron-based x-ray microtomography, a 3D imaging technique that allows us to identify and measure different microstructural phases. Using a custom built load frame, we were able to make high resolution 3D images of small specimens subjected to split cylinder fracture. Through multiple scans of the same specimen with progressively higher levels of damage, we were able to measure internal cracking and damage evolution while simultaneously monitoring bulk load-deformation relationships. Using 3D image processing techniques, phase distributions, the porosity and pore structure are all measured, along with the complex network of cracks, the degree of fragmentation, and the 3D deformation fields. This paper focuses on the different microstructural measurements that can be made, and what we might infer about micromechanical properties.

As a first step toward linking these measurements with computational models, specimens were pre- pared with idealized aggregates consisting of spherical glass beads of two different surface properties. Upon 3D imaging, these aggregate particles were isolated and located in such a way that 3D lattice models could be meshed with aggregates in the same locations as in the real specimens. As discussed in the companion paper, comparisons between simulations can be made where both bulk-deformation response is matched, but also fracture and damage patterns. Further simulations predicted a relationship between strength and aggregate fraction that was confirmed by further experiments. We view this work as an important step in a movement towards more physical-based modeling.

Using 3D Microstructural Imaging to Produce Physically-Based Numerical Models of Concrete: Lattice Simulations

J.E. Bolander[1], E.N. Landis[2]

1 University of California, Davis, California, USA, jebolander@ucdavis.edu
2 University of Maine, Orono, Maine, USA, landis@maine.edu

Abstract

This paper describes the combined use of three-dimensional lattice models and tomographic imaging techniques to study pre-critical cracking in concrete materials. Model results are compared with 3-D maps of internal damage and crack growth provided by in situ load testing of split-cylinder microconcrete specimens within the tomographic setup. Microtomography provides high-resolution 3-D pictures of material structure and cracking at distinct stages of the loading history. Although the coarse domain discretizations considered in this study do not resolve such fine-scale features, the models provide a continuous event-by-event description of the 3-D fracture process and thus insight into the cause-and-effect relationships that determine material performance and failure.

As one example covered in the paper, lattice models are used simulate multiple, nominally identical specimens differing only in aggregate content and positioning. These simulations, which are analogous to the testing of replicate specimens in the laboratory, provide insight into the origins of strength variability of the composite material/structure. The model indicates that the arrangement of inclusions affects peak load, although additional factors (e.g. irregularities of specimen geometry) appear to be more influential in causing the scatter observed in the experimental results.

The lattice approach is also capable of modelling the scalar fields associated with potential flow. In previous work, the nodes used to represent the structural problem (i.e. displacements) are coincident with the nodes used to represent flow related quantities (e.g. moisture content and temperature). This sharing of nodes amongst the different element types is effective prior to cracking. Upon crack formation, however, the flow elements are oriented perpendicular to the simulated crack path, which complicates the modelling of crack-assisted flow and its dependence on crack opening. By defining the flow network on a dual lattice, the flow elements are aligned with potential cracks so that both pre- and post-cracking flow can be effectively simulated. This approach to modeling crack-assisted flow is presented, along with discussion of its use toward investigating the durability of concrete materials.

Inverse analysis procedure for the characterisation of softening diagrams for FRC beams and panels

Ali Nour[1,2], Bruno Massicotte[1], Renaud De Montaignac[1], Jean-Philippe Charron[1]

1 *École Polytechnique de Montréal, Montréal, Québec, H3C 3A7, Canada*
2 *Hydro Québec, Montréal, Québec, H2L4P5, Canada*

Abstract

The flexural performance of fibre reinforced concrete (FRC) materials is directly related to the stress-crack opening diagram (σ–w). This diagram is needed for structural design applications since it represents the energy change in the fracture process zone at the material level. Thus, the σ–w diagram is considered the characteristic material property of FRC materials. In practice, the simplest test method is to perform a direct tension test. Unfortunately, such test is complicated to perform since it is difficult to prepare the specimen, and to impose unambiguous boundary conditions in the setup. The alternative that is currently being studied exhaustively is the use of the experimentally obtained load-displacement bending response of some structural elements to determine the σ–w curve of the corresponding material through inverse analysis. Most investigators have focused on the behaviour of a notched beam under a three point bending load, whereas an inverse analysis with FRC panels is very scarce in the literature. In this paper, a novel inverse analysis procedure for the characterisation of the σ–w diagrams for FRC beams and panels is presented and validated. This procedure is based on a data fitting algorithm, for which the shape of the σ–w diagram is, a priori, free to vary. An analytical formulation that uses the σ–w curve as the input and provides the analytical load–displacement response for the beam or the panel is needed to match with the experimental results. For the case of FRC beams, an analytic formulation in the literature that provides, with satisfactory accuracy, the load–displacement response, for an arbitrary inputted σ–w diagram, is adopted. Since for FRC panels, to the authors' knowledge, such an analytic formulation is either scarce or does not exist, the authors developed recently a simple analytic formulation to investigate the post-crack behaviour of FRC panels using an arbitrary σ–w diagram as the input. The proposed post-crack behaviour of FRC panels is studied using the yield line theory, where the load deflection response is predicted based on the crack length parameter-normalized deflection relationship. It is worthy to mention that this procedure is being intensively used in the frame of sustainable development projects dealing with FRC and ultra performance fibre concrete (UPFC) materials. Application to the prediction of fibre reinforced concrete beam behaviour, with crack width prediction in service condition to ultimate concludes the paper.

Numerical Modelling of Reinforced Concrete Beams Repaired with Polymer-Modified Mortar

L.M Mauludin, G. Guidi, F. Da Porto

Politeknik Negeri Bandung-Indonesia, University of Padova-Italy, University of Padova, Italy

Abstract

This paper presents the results of finite element analyses on flexural behaviour of reinforced concrete beams repaired with polymer-modified mortar. The numerical models were calibrated on flexural tests carried out on eight concrete beams.

The main aim of the analyses was extending the study to different concrete and repair mortar properties and simulating the behaviour of repaired beams when subjected to cyclic loading. Parametric study was carried out to evaluate effectiveness and behaviour of repaired beams built and repaired with different materials, with different thickness of mortar repair and under static and cyclic flexural loading.

The numerical results showed that the repairing layer properties influence significantly the ultimate capacity of beams. The repair mortar is effective when its mechanical properties are similar or over those of the parent concrete. Thick repairs including the longitudinal reinforcement are the most effective repair method when beams are subjected to both static and fatigue loading. In general, the load bearing capacity of repaired beams is significantly reduced in case of cyclic loading compared to static loading.

Cracking Propagation Simulation of Concrete due to Rebar Corrosion

SSCS
Numerical Modeling
Strategies for Sustainable Concrete Structures

H. Nakamura, T.K. Khoa, N. Ueda, M. Kunieda

NagoyaUniversity, Japan

Abstract

Cracking of concrete due to rebar corrosion is a major source of deterioration of concrete structures. Such cracking typically accelerates the corrosion and deterioration processes, and can involve spalling of the concrete cover. It is necessary to assess internal damage from observable surface conditions during maintenance procedures. Therefore, it is desirable to establish a prediction method that can quantitatively evaluate internal crack propagation behavior and the rebar corrosion amount from observing surface cracks. it gives us maintenance strategy to achieve sustainable concrete structures.

Internal crack patterns due to rebar corrosion have mainly been investigated experimentally. Crack pattern have been also simulated numerically in which Finite Element Mthod is usually performed. Since the numerical tools give us useful information considering several conditions during life of structures, it is required to develop advanced numerical modeling for realistic evaluation of corrosion crack.

In this study, the simulation method developed by the authors is applied to evaluate internal and surface corrosion crack propagation under many conditions. The developed method is based on Rigid-Body-Spring Method (RBSM) with three-dimensional Voronoi particles. In the method, a three-phase material model including concrete, steel reinforcement, and corrosion products layer is proposed. For the corrosion products layer, internal expansion pressure due to corrosion expansion is modeled as an initial strain problem. Moreover, the effects of penetration of corrosion products into cracks, local corrosion and local penetration of corrosion products into cracks during the corrosion process can be considered.

The applicability of the model is shown by comparison with the experimental results. Then, the crack propagation is simulated several conditions such as rebar diameter, cover thickness, corrosion length, corrosion velocity, space of rebar for multi corrosion.

Statistical analysis of crack widths by virtual modeling of reinforced concrete beams

D. Novák, L. Fekete

Institute of Structural Mechanics, Faculty of Civil Engineering, Brno University of Technology, Brno, Czech Republic

1. Introduction

The paper is focused on virtual modeling of crack widths during concrete beams fracture. The basis for this work is an experimental work, where statistical characteristics of crack width were analyzed in detail [1]. It is a unique experiment on deep reinforced concrete beams subjected to four-point bending. The question arises if crack width statistics can be obtained numerically by nonlinear fracture mechanics simulation. This was stimulation for this research. The aim of the work was to compare crack widths using the simulated reinforced concrete beams with the values from the experiments.

For virtual modeling nonlinear fracture mechanics finite element analysis of concrete structures software ATENA 2D has been used [2]. Theoretical as well as practical application aspects are presented emphasizing the conceptual framework and key points of solution. As uncertainties of material play significant role in crack initiation process a Monte Carlo type randomization small-sample simulation Latin hypercube sampling, has been used as next step [3]. Efficient techniques of both nonlinear numerical analysis of concrete structures and stochastic simulation methods of Monte Carlo type have been combined in order to offer an advanced tool for assessment of realistic behavior of concrete structures from statistical and reliability point of views.
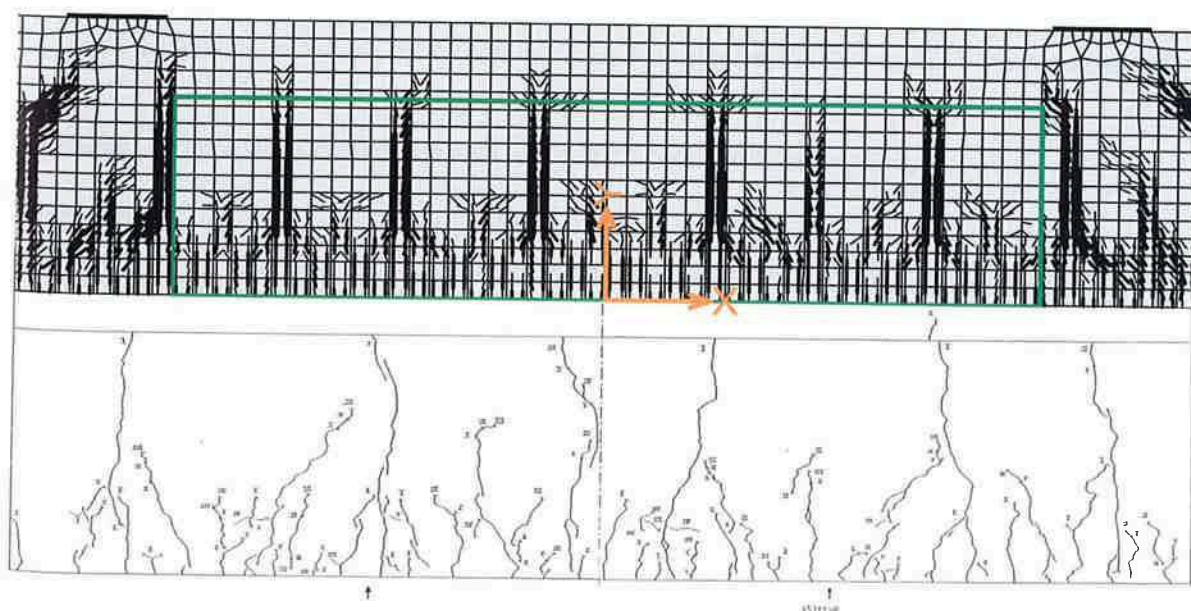

Figure 1: Crack width patterns – experiment vs. simulation

Crack widths were studied at nine cuts and statistical characteristics were calculated – mean crack width, maximum crack width and coefficient of variation. Experimental results versus numerical simulation were compared, good agreement was obtained. The paper discuss the differences between the behaviour of different material models (Sbeta model and fracture-plastic model Non-linear cementitious), crack models (fixed and rotated cracks) and between simulations with and without dead weight. Comparison with design specification is performed in the form of probability that allowable crack width (according to standard) will be exceeded.

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Modeling of the behaviour of RC tie-beams reinforced by flat steel rebars: A comparison between 2D and 3D numerical simulations of the steel/concrete interface

T.S Phan*[†], J.-L. Tailhan*, P. Rossi*, Ph. Bressolette[‡], . Mezghani[†], J. Foulliaron*

*French Institute of Science and Technology for Transport, Development and Networks (IFSTTAR) Paris East University, France
‡ Clermont University, Blaise Pascal University LaMI, EA3867, BP 206, 63000 Clermont, France † MATIERE☐ - Construction company, France
email : thanh-song.phan@ifsttar.fr, jean-louis.tailhan@ifsttar.fr, pierre.rossi@ifsttar.fr

The simulation of the behaviour of the steel-concrete interface is of primary importance for an accurate description of cracking processes in reinforced concrete structures and an improved prediction of their durability. In this paper, the methodology used to identify the mechanical behaviour of a steel-concrete interface in the case of a particular steel reinforcement is first mentioned. The methodology consists in simulating the statistical mechanical behaviour of RC tie-beams (170 x 10 x 10 cm), subjected to tension, using a probabilistic approach for the mechanical behaviour of the concrete and a deterministic model for the steel-concrete interface. The tie-beams are reinforced by a flat steel rebar which cross section is rectangular (22.5 x 5 mm).

In this work, the model simulating the concrete behaviour takes into account the inherent heterogeneity of the material and the consecutive scale effects on its mechanical properties (tensile strength f_t and Young's modulus E_c) via appropriate size effect laws and random distributions [1]. The steel-concrete interface is represented by contact elements which behaviour is modelled by a damage model taking into account the principal mechanical behaviour of physical phenomena of the interface: the cohesion and the slip. The obtained numerical results are compared with experiments [2]. The comparison is made in terms of global response (load-relative displacement curves), as well as local response (cracks opening, cracks spacing and number of cracks). And as far as the developed approach remains probabilistic, they are examined in a statistical way and the results seem to be relevant [3] [4]. In this work, a 3D numerical simulation of these RC tie-beams and its results will also be presented, and a comparison between the two approaches is performed. Finally, a discussion on the efficiency of both approaches (2D and 3D) is also proposed.

Keywords: Reinforced concrete, flat steel rebar, steel-concrete interface, cracking.

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Continuum damage mechanics based model for quasi-brittle materials subjected to cyclic loadings: application to concrete

B. Richard, F. Ragueneau, A. Delaplace, C. Oliver

LMT/ENS Cachan, CNRS/Univ. Paris 6/ PRES UniverSud,
61 Avenue du President Wilson, Cachan, France, {Benjamin.Richard}@lmt.ens-cachan.fr

Abstract

The events occurred in the world have shown the necessity to build constitutive models capable of predicting the response of a structure when subjected to cyclic - or seismic - loadings, particularly in the field of nuclear engineering. In civil engineering, concrete and steel are the most used materials. Material nonlinearities are mainly due to cracking.

The aim of that study is to propose an original concrete constitutive model allowing a refined description of mechanisms involved in the case of cyclic loadings. The formulation is based on a thermodynamical coupling between elasticity, damage, internal sliding and inelasticity. A full and progressive unilateral effect is also considered. Although further works is needed to validate this model, first applications show that the formulation is able to represent closed-loop bending tests not only in a quantitative way (load/displacement) but also in a qualitative way (damage pattern). The proposed model has also been applied to large-scale reinforced concrete structures subjected to synthetic accelerograms and the results clearly emphasize the power of such an approach.

Keywords: Unilateral effect, continuum damage mechanics, concrete, thermodynamics

Numerical modelling of cracking in fibre reinforced concretes

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P. Rossi, J.-L. Tailhan

Université Paris-Est, IFSTTAR, MAT, F-75732, Paris, France

Fibre reinforced concretes are more and more used in structural applications. One of the principal reasons of this statement is related to the existence of national (French, Japanese, Italian, German…) and international (Rilem, Fib…) recommendations concerning the design of structures using this type of material.

These recommendations are efficient for designing simple isostatic structures (beams and slabs) loaded in bending. But, for more complex hyperstatic structures or for others types of loading as shear and pushing, these recommendations are not enough physically based to propose relevant solutions. As a matter of fact, they are often too conservative and lead to an over consumption of matter. That is not good, especially if the problem of sustainable development is concerned.

In these cases, the best approach for designing structures in the respect of both safety and sustainable development is to use finite element analysis.
LCPC (newly IFSTTAR) develops a probabilistic discrete cracking model since 1985 (first paper in an international journal in 1987). This numerical modelling firstly developed for analyzing cracking of concrete structures has been then (1992) enriched to take into account cracking of fibre reinforced concrete structures.

In the present paper, an improvement of this probabilistic discrete cracking model devoted to the analysis of fibre reinforced concretes cracking is proposed.
In this new model:
- Cracks creation and propagation in the concrete are taken into account by using special interface elements which open when the normal tensile stress at its gravity centre reaches a critical value. The probabilistic aspect of the cracking process is then given by the fact that the critical value of the tensile stress is randomly distributed through the mesh.
- Just after the cracks creation, the fibres acting is taken into account by considering a linear decrease of the tensile stress in function of the crack opening. This post-cracking behaviour is modelled by using a damage model approach. Here, the probabilistic aspect consists in randomly distributing the post-cracking energy.

In the paper, the above numerical modelling is used to analyze the shear behaviour of a beam made with a steel fibre reinforced concrete. The simulations are compared with experimental results in terms of global behaviour of the beam and in terms of cracking process (cracks number, spacing and opening).

Multiscale Modeling of Shear Failure in RC Slabs with Spatial Variability

A.B. Suma[a], H.G. Burggraaf[a], A.J. Bigaj-van Vliet[a], A.H.J.M. Vervuurt[a]

[a] TNO, Delft, The Netherlands, alexander.suma@tno.nl

1. Introduction

Prediction of shear failure mechanisms in straight RC plates remains a difficulty in FEM modeling. Shear capacity of structures without shear reinforcement mainly depends on the composition, strength and quality of the concrete mixture. The macro scale homogenous models do not always describe the local behavior appropriately. Heterogeneous material properties and, on larger scale, randomly distributed material properties together with corrosion pitting, spall and material deterioration have a severe effect on the brittle failure strength. The ultimate capacity of slabs can be positively influenced by redistribution of stresses before ultimate failure occurs. However, modeling of concrete slab structures with non-uniform properties for shear failure prediction lacks experimental validation. Improvement is desired as these structures are often found in practice, where simulation accuracy goes along with disproportionate calculation times. Multiscale modeling is used in terms of local refinement of the mesh with different element types, where local material properties and conditions are directly related to the overall behavior. This study makes use of conventional calculation techniques to challenge complex problems.

1.1. Objectives

The objective of this study is to use the state-of-the-art modeling techniques and evaluate their use in practice. This will be done by evaluating the required level of local mesh refinement, size of refinement areas, and complexity of elements by means of calculation time, accuracy and reliability of results. As part of the investigation, results will be verified with experimental test results.
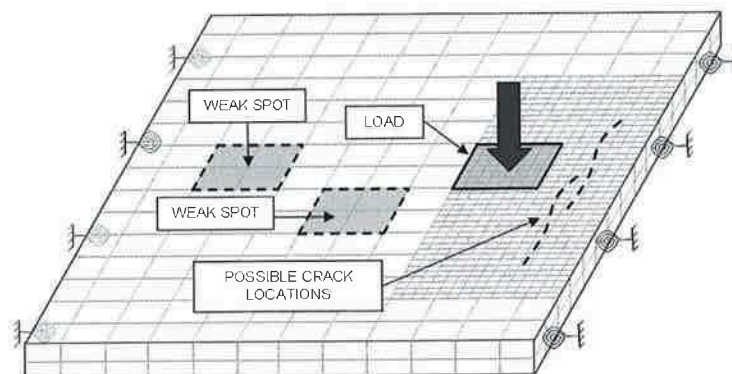

Figure 1: Model with spatial relation between weak spot(s), load location and shear crack location.

1.2. Subject of study

The subject of study is a RC slab without shear reinforcement with a concentrated load (Fig. 1). In relation to practice, the slab study is focused on brittle shear failure, where life time expectation needs to be estimated by means of FEM models. With more knowledge of mesh refinement and influence of local deficiencies, time consuming calculations of tunnel walls, bridge decks, building walls and floors slabs will be reduced. From this context, most relevant configurations for spatial variability are defined in terms of load location, cycling and magnitudes, weak spot location(s) and grade, and probable crack initiation location.

1.3. Methodology

The study case will be approached by making use of ATENA software. This package is well established for concrete modeling with shear failure mechanisms and cracking patterns. In addition, ATENA employs advanced constitutive models for concrete (incl. post-peak behavior for specific failure mechanism), based on damage mechanics, nonlinear fracture mechanics and plasticity theories with smeared crack approach, specific for computer simulation of reinforced structures (e.g. cracking of concrete is governed by the nonlinear fracture mechanics).

1.4. Research program

Investigations will start by modeling with relatively large elements to explore spatial relations and behavior in order to select most interesting cases. This is followed by modeling a more defined area around the probable cracks, weak spot(s), and load plane with a fine mesh consisting of solid elements. In a second phase, areas with linear and nonlinear behavior are selected, and replaced by shell elements and a refined mesh of solid element respectively. Iteratively, the size of the localized area and the level of refinement will be tested for optimized calculation time and level of accuracy.

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Probabilistic modelling of crack creation and propagation in concrete structures: some numerical and mechanical considerations.

J.L. Tailhan, P. Rossi, T. S. Phan, J. Foulliaron

Paris-East University, French Institute of Science and Technology for Transport, Development and Networks, 58 Bd Lefebvre, 75732 Paris cedex 15.

The numerical modelling of concrete cracking is a challenging issue in Civil Engineering. The development of models providing information on the characteristics of concrete cracks, for a given environment, loading and limit conditions set, is actually very popular. Cracks openings, lengths, orientations and spatial distributions are essential factors. Their impact on the long-term structural performance maintenance must be taken into account for an accurate prediction of structures life span.

Since the 90's, the French "Laboratoire des Ponts et Chaussées" (now named IFSTTAR) has developed a discrete probabilistic model [1] for an accurate description of the cracking processes in concrete structures. The model, which has been recently reworked, takes into consideration the inherent heterogeneity of the material and the consecutive scale effects on its mechanical properties via appropriate, and experimentally validated, size effect laws and random distributions. Since the model uses contact elements for the description of the kinematic discontinuities of the displacement field when cracks appear, the model can provide local information on both micro and macro cracks and it is well suited for modelling cracking patterns. In this framework of modelling of crack creation and propagation, the efficiency and the relevance of the approach, for a given scale of modelling, directly depends on the judicious choice of the couple of type of model/type of numerical support. This paper illustrates that approximating the description of crack propagation by the progressive creation of coalescent multiple crack planes by using a local elastic brittle behaviour necessarily induces the use of a quadratic element (for very fine refinements of meshes), and at the opposite, the use of an enriched model can allow the use of linear elements at a larger scale (i.e. for larger elements). The choice between these two strategies has an important and obvious impact on the richness of the local information obtained for cracking processes (micro and macro cracking). An illustration is proposed through the modelling of crack propagation in plane concrete structures and numerical results are compared to experimental results of tests performed at Ifsttar (concrete beams in bending and double cantilever beams).

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A RC fibre beam element for full modelling of the bending-shear response by dual section approach

P. Tortolini, E. Spacone, M. Petrangeli

Department Civil Engineering of the "G. D'Annunzio" University , Pescara, Italy

Abstract

The paper describe a fibre element with axial, bending and shear interaction for the static and dynamic analysis of reinforced concrete beams and columns. The element accuracy and numerical robustness make it a very useful tool in the seismic analysis of RC structures.

The element response is calculated by integrating a full 2D behaviour of the concrete fibres and the bi-axial arrangement of the longitudinal and transverse steel. The beam model is an evolution of the Petrangeli's element, [10], as they share the same solution strategies and overall element architecture and similar steel and concrete constitutive models. Both elements use an equilibrium based iterative approach to integrate the element stress-strain fields. The concrete constitutive model is an evolution of the microplane approach, modified to account for material heterogeneity. The model uses the plane sections remain plane hypothesis.

The major improvement of the new model relay on a static approach for the solution of the section shear field (fibre shear strains). The latter is obtained by imposing equilibrium, fibre by fibre, with adjoining sections following the Dual Section approach as proposed by Vecchio and Collins, [16]. Although this approach requires nesting of section iterations within the element solution, it is considered a substantial improvement with respect to the previous one that used predefined section shear functions (cinematic approach). This new approach ensures equilibrium and compatibility at both section and fibre level with improved capability of depicting the actual localization of axial and shear deformation within the reinforced concrete element.

The model is validated with two case studies based on experimental tests carried out at UNI San Diego on column specimens exhibiting a flexural and a shear failure under cyclic loading. Qualitative and quantitative agreement between model response and tests are quite impressive demonstrating the element capability to correctly depict the actual behaviour of R.C. members and their failure mechanisms under combined axial, bending and shear forces.

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Numerical methods for collapse analysis of RC framed structures with physical and geometrical nonlinearity.

M. Ucci[1], M. V. Sivaselvan[2], E. Spacone[1]

1 Dept. of Structural Engineering, University of Chieti-Pescara "G. d'Annunzio", Italy
{m.ucci, espacone}@unich.it
2 Dept. of Civil, Environmental and Architectural Engineering, University of Colorado at Boulder, CO, USA
siva@colorado.edu

Abstract

The use of numerical methods for nonlinear time-history analysis of reinforced concrete structures up to the ultimate and collapse limit states should consider second order effects. Structures subjected to seismic loading show a rapid growth of early cracking which can determine sudden loss of bearing capacity and, eventually, element failure. Although local collapse can be recognized as a significant event in the analysis, in order to track structural collapse at a global level, capacity design must be simulated. The progressive level of damage, along with element failures, affects dynamic behavior so that the structural scheme should be updated in time. Moreover, kinematic mechanisms can take place, even in case of highly redundant structures, due to the formation of plastic hinges. Such conditions likely imply large displacements and rotations of joints in space. According to spatial kinematics [1], the latter should be treated with particular attention, since they can produce numerical instabilities. In fact, some representations of finite rotations may lead to singularities and energetic inconsistencies, threatening adherence of the solution to the related physical problem. This fact depends on the non-Euclidean nature of the configuration space of rigid bodies in space. Therefore, a preliminary study has been conducted to determine the most suitable representation system for rigid body motion. Numerical results for an elastically restrained body have been carried out and compared. In a second phase, a physically nonlinear force-based element based on Spacone et al.[2] and complying with the chosen representation system has been formulated. A computational framework for testing the element has also been developed. Structure-preserving solution algorithms have been adopted, in order to ensure conservation of hamiltonian and other important first integrals characterizing the problem [3]. Numerical results show optimal convergence and energetic consistency throughout the solution.

Keywords: Geometrical nonlinearity, Frame analysis, Nonlinear dynamic analysis, Seismic analysis

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Session I-5:Chemical aging (chemical reactions and transfers)

Lattice discrete particle modeling of alkali-silica-reaction effects to concrete structures
Giovanni Di Luzio[1], Mohammed Alnaggar[2], Gianluca Cusatis[3]
[1]Assistant Professor, Department of Structural Engineering (DIS), Politecnico di Milano, Italy
[2]Research Assistant, Department of Civil and Environmental Engineering, Northwestern University, Evanston, USA
[3]Associate Professor, Department of Civil and Environmental Engineering, Northwestern University, Evanston, USA

The Alkali-Silica Reaction in Concrete: Structural Modeling and Numerical Simulation
R. Esposito, M.A.N. Hendriks
Delft University of Technology, The Netherlands

Bayesian reliability of reinforced concrete structure coupled with corrosion sensors
G. Lebon, C. Poisson, R. Devaux, V. Lamour
Cementys, Choisy-le-Roi, France

Concrete resistivity on small scale high performance concrete samples
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Facultad de Ingeniería, Universidad Nacional de Colombia

Simulation of the concrete chloride NT Build-492migration test
J. Lizarazo-Marriaga[1], J. Gonzalez[1], P. Claisse[2]
[1] Universidad Nacional de Colombia - [2] Coventry University- UK

A multiscale approach to diffusion phenomena in concrete
F. Nilenius [1,2], F. Larsson[2], K. Lundgren[1], K. Runesson[2]
[1] Department of Civil and Environmental Engineering, Chalmers University of Technology, [2] Department of Applied Mechanics, Chalmers University of Technology, Sweden

Contact elements, creep and anisotropy for the numerical modelling of concrete structures affected by internal swelling reaction
O. Omikrine-Metalssi[1], J.-F. Seignol[1], S. Rigobert[1], F. Toutlemonde[1] and L.-I. Boldea[2]
1Université Paris-Est, IFSTTAR, Paris, France - 2 Stucky, Lausanne, Switzerland

Assessment of service life and environmental impacts of chloride exposed concrete structures with repairs by cover replacement
A. Petcherdchoo
King Mongkut's University of Technology North Bangkok, Thailand

Prediction of Chloride Ingress into Concrete in a Marine Environment
Ian N. Robertson
University of Hawaii, Department of Civil Engineering, USA

Lattice model as a tool for modelling transport phenomena in cement based composites
B. Šavija, J. Pacheco, R.B. Polder, E. Schlangen
Microlab, Delft University of Technology, Delft, The Netherlands

Numerical tool for durability assessment of concrete structures subjected to aggressive environment
J. Mai-Nhu[1], A. Sellier[2], P. Rougeau[1], F. Duprat[2]
[1] *CERIB (Study and Research Centre for the French Concrete Industry),* [2] *Université de Toulouse, UPS, INSA, LMDC (Laboratoire Matériaux et Durabilité des Constructions)*

Modelling of the moisture transfer under wetting-drying cycles in cementitious material
Z. Zhang, M. Thiéry, V.Baroghel Bouny
IFSTTAR Paris, France

Lattice discrete particle modelling of alkali-silica- reaction effects to concrete structures

Giovanni Di Luzio1, Mohammed Alnaggar2, Gianluca Cusatis3

[1] *Assistant Professor, Department of Structural Engineering (DIS), Politecnico di Milano, Italy diluzio@stru.polimi.it*
[2] *Research Assistant, Department. of Civil and Environmental Engineering, Northwestern University, Evanston USA MohammedAlnaggar2012@u.northwestern.edu*
[3] *Associate Professor, Department. of Civil and Environmental Engineering, Northwestern University, Evanston USA gianluca@cusatis.us*

Abstract

A large number of structures especially in high humidity environments are endangered by Alkali-Silica Reaction (ASR). ASR is characterized by two processes: the first is gel formation resulting from contact between alkali and reactive silica in aggregates; the second is water imbibition into this formed basic gel which is the one responsible of the progressive swelling behavior. The swelling causes deterioration of concrete internal structure by cracking of reactive aggregate, mortar matrix and mortar aggregate contact surface, leading to loss of concrete strength and stiffness. Many research efforts were directed towards the evaluation, modelling and treatment of these phenomena but a comprehensive computational model is still lacking.

In this paper, the ASR effect is implemented within the framework of a mesoscale formulation that simulates concrete heterogeneity and ASR thermo-chemo-mechanical characteristics. The mesoscale model adopted is the Lattice Discrete Particle Model (LDPM), which simulates the mechanical interaction of coarse aggregate pieces through a system of three-dimensional polyhedral particles connected through lattice struts. LDPM has been calibrated and validated extensively with comparison to experimental data and it has shown superior capabilities in modelling concrete cracking and fracture.

The ASR expansion behavior is assumed to be totally a result of water imbibition into the formed ASR basic gel. For each aggregate, the two processes are simulated assuming that the aggregate particles are spheres and the permeability of the ASR gel is based on Fick's law. The gel formation rate, which directly depends on water supply to the reaction front, is calculated by a radial diffusion law. The rate of water imbibition is calculated using the thermodynamic equilibrium of water imbibition process. For a single aggregate, the model predicts the volume increase of the aggregate due to water imbibition.

The single aggregate model is then amalgamated within the LDPM framework by calculating the rate of change of each LDPM simulated aggregate radius assuming uniform aggregate volume change. The change in LDPM tetrahedron edge lengths are then calculated and applied to the facets along these edges as normal strains. Also the state of stress inside the LDPM meso-structure is used to redirect the applied normal strains to simulate expansion transfer reported in many experimental data.

Since LDPM simulates the heterogeneity and randomness characteristics of concrete, this formulation allows for precise and unique modelling of ASR effect including non-uniform expansions, expansion transfer and heterogeneous cracking. The model can replicate ASR cracking behavior even in free expansion tests. This is a capability that cannot be obtained within classical homogeneous and isotropic continuum based models. In addition, it reproduces reactive aggregate size and distribution effects on the ASR expansion considering temperature and stress state effects. The present model was validated based on the simulation of experiments for free and laterally passively restrained specimens under free expansion as well as subjected to axial load. The results showed good agreement with the experimental data.

The Alkali-Silica Reaction in Concrete: Structural Modeling and Numerical Simulation

R. Esposito, M.A.N. Hendriks

Delft University of Technology, The Netherlands

During their service life, concrete structures can be affected by chemical degradation processes. One of the most harmful processes is given by Alkali-Silica Reaction, which produces a hydrophilic and expansive gel. This reaction, which begins at microstructural level, may cause serious damage with consequent loss of structural capacity; the designer must be able to assess the safety at macrostructural level.

The gel formation and swelling is influenced by the environmental condition, as temperature and moisture. In a structural model these aspects can be taken in account through a kinetic law; one of the most known and used law was performed by Larive [1]. In an ASR-affected concrete structure also the interaction between gel and cement matrix is a relevant aspect. Experimental tests show that gel expansion into the concrete is influenced by the concrete porosity and the boundary condition (Larive [1], Multon and Toutlemonde [2]).

In the last 50 years various structural models have been developed and implemented in finite element codes. In early proposals the gel expansion is taken in account with a thermal equivalent approach. More advanced models have been developed by Ulm et al. [2], Bangert et al. [3], Saouma and Perrotti [4] and Comi et al. [5]. They are damage models in which the coupling between the chemical and mechanical aspects is considered.

The choice of mechanical properties and environmental parameters, on the basis of a literature review, for finite element analyses regarding ASR-affected concrete is discussed in this paper. The concepts are underlined by some examples.

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Bayesian reliability of reinforced concrete structure coupled with corrosion sensors

G. Lebon, C. Poisson, R. Devaux, V. Lamour

Cementys SAS, 29 avenue de la République, 94600 Choisy le Roi, France
www.cementys.com {gregorylebon,vincentlamour}@cementys.com

Reinforced concrete is widely used for durable construction in civil engineering. But the sustainability of reinforced concrete structure depends mainly of the corrosion of steel reinforcement. The degradation is induced by environmental actions and by the use of the structure (de-icing salt, atmospheric CO_2 or leaching). The corrosion affects severely the integrity of the structure and the visible consequences appear when the state of the structure is critical. To optimize the reparation or prevention costs, it is necessary to predict the risk of corrosion before that visual degradations appear.

Our first approach to assess such a risk is based on a simple diffusion model of chloride identified by insitu corrosion sensors. Fick's second law gives the chloride concentration along the concrete cover at considered time. The parameters of the law are the initial chloride concentration in the concrete, the chloride concentration of the environment, and the diffusion parameter of the concrete. A threshold on the chloride concentration gives the beginning of the corrosion of the reinforce steel. The lack of knowledge about these parameters makes more difficult the prognosis of a structure. Probabilistic modelling is necessary to evaluate the risk of corrosion. To enhance the accuracy of the diffusion model is necessary to decrease the uncertainty of model parameters as diffusion coefficient, critical concentration of chloride or the boundary conditions.

Anode ladder Corrosion sensors (CorroVolta) located in the concrete cover detect the progress of the chloride front at different depths (typically every centimetres). Eventually, this data will update the probability variables of the model by a Bayesian method. At a matter of fact, a Bayesian network is defined between selected parameters of the diffusive model. In our example, the diffusion parameter and the critical chloride concentration are chosen as unknowns. Discrete normal laws represent the initial repartition of unknown parameters. The detection of the initialisation of corrosion with CorroVolta sensors feeds the Bayesian actualisation of the variables. The update of these parameters gives a new prognosis of risk corrosion of the structure. The model is updated each time the corrosion initiation is detected by the sensor at known cover depth.

The proposed sensor assisted prediction model allows to estimate accurately the concrete cover affected by corrosion. Furthermore, reinforcement location is not known accurately: construction variability adds uncertainty about several millimetres upon concrete cover. Reliability computation takes into account this additional uncertainty to evaluate corrosion risk.

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Concrete resistivity on small scale high performance concrete samples

J. Lizarazo-Marriaga, C. A. Cortés

Facultad de Ingeniería, Universidad Nacional de Colombia

Abstract

Electrical resistivity is a non-destructive method that provides an indication of concrete permeability. The surface resistivity measured with a Wenner four-probe array is proportional to the ratio between the resultant potential difference between the inner two probes and a small current applied externally between the outer two probes. In order to keep the theoretical current flow and equipotential lines during a resistivity test, the mathematical aspects used to find the resistivity from the experimental observations assume that concrete is a semi-infinite and homogeneous volume. As standard concrete tests are carried out on small scale and in non-homogeneous samples due to carbonation the electrical field is distorted producing a constraint effect on resistivity measurements. This paper shows the results of a theoretical research carried out in order to quantify the size effect and the multilayered resistivity close to the surface in high performance concrete. To achieve this, finite element methods were used to assess the electrical field distortion.
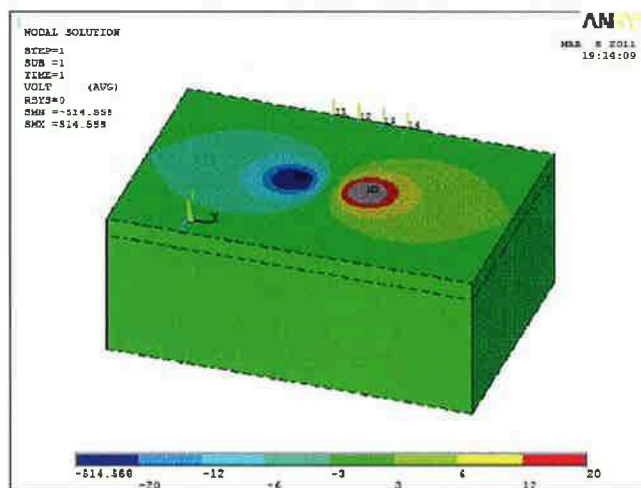
Figure 1: External electrical field on a concrete cubic specimen

Simulation of the concrete chloride NT build-492 migration test

Aix-en-Provence, France
May 29-June 1, 2012

J. Lizarazo-Marriaga[1], J. Gonzalez[1], P. Claisse[2],

[1] Universidad Nacional de Colombia
[2] Coventry University- UK

Abstract

Corrosion of steel reinforcement is the major cause of deterioration in concrete structures, where carbon dioxide and especially chlorides are the main causes of damage. The rate at which chloride ions diffuse through concrete is a major determinant of the durability of structures. The classical approach of ion transport in solutions states that if there is a difference in the concentration of ions in different regions this gradient produces a flow of ions, this movement is called diffusion. In the same way, if there is a difference of electric potential, this difference is called migration, electromigration or conduction.

The principle of electromigration tests is to apply a constant potential difference across a fully saturated sample. Usually they are performed in two chamber cells with the concrete in the middle and each cell full of a defined salt solution. As the chloride is the ion of interest and the pore solution of concrete contains sodium, potassium and hydroxyls, these species are the most used to fill the cells. The size of the concrete sample is usually a cylinder of 100 mm diameter and length about 15 to 50 mm. One of the most used migration test is the NORDTEST METHOD NT 492 approved as a standard in Finland in 1999.

The standard NT492 is extensively used around the world to determine the chloride diffusion coefficient. It assumes the chloride ions as isolated particles without any ionic interaction with other species. However, as chloride ions are charged particles, they interact with other species which affect the ionic flux. In order to investigate numerically the chloride penetration during a standard NT-492 experiment, in this paper simulations of the test has been carried out. For this, two different approaches have been used. First, the equations of the standard based on a mono-ion condition. And secondly, a finite difference coupled numerical multi-species model accounting for a binding isotherm and the ionic interaction caused by the species penetration the sample or contained in the pore solution.

A multiscale approach to diffusion phenomena in concrete

F. Nilenius[1,2,†], F. Larsson[2], K. Lundgren[1], K. Runesson[2]

[1] Department of Civil and Environmental Engineering, Chalmers University of Technology, Sweden
[2] Department of Applied Mechanics, Chalmers University of Technology, Sweden
[†] filip.nilenius@chalmers.se

1 Introduction

Chloride ions are harmful for concrete structures as the ions can initiate corrosion of embedded reinforcement bars. Modeling and simulation of chloride diffusion is therefore of interest in order to be able to predict time spans at which corrosion may be initiated.

In this contribution, a multiscale model for coupled chloride-moisture diffusion is proposed where the strongly heterogeneous mesoscale structure of concrete is accounted for. The model is based on the concept of a representative volume element (RVE) where the mesoscale constituents of concrete in terms of cement paste, ballast and the interfacial transition zone (ITZ) are contained. Here, the ITZ is interface between the cement paste and the ballast, having much higher porosity than the bulk cement paste. In the model it is assumed that the cement paste is permeable, the ballast is impermeable and the ITZ is highly permeable.

An algorithm for generating the mesoscale structure of concrete has been developed and examples of generated structures are shown in Figure 1. Main control parameters of the algorithm are ballast content and sieve curve. Note though, that since the modelled geometry is in 2D, it will not exactly correspond to concrete with a given (3D) sieve curve.
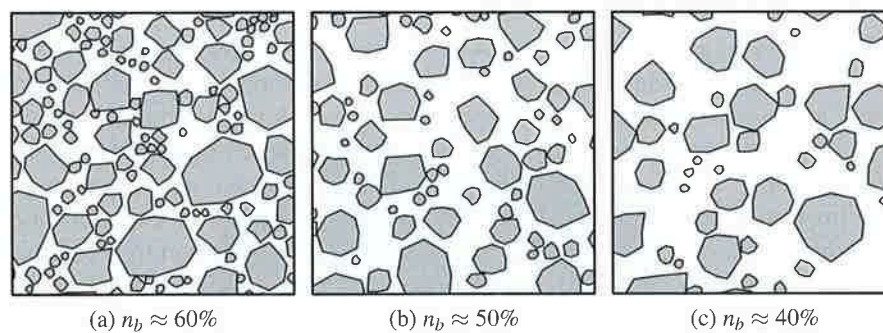

(a) $n_b \approx 60\%$ (b) $n_b \approx 50\%$ (c) $n_b \approx 40\%$

Figure 1: *Examples of different mesoscale structures generated by the algorithm. n_b denotes the ballast fraction.*

Computationally, the approach is to introduce the RVE in the Gauss-points on the macroscale domain in a so-called FE[2]-algorithm, with its principal structure depicted in Figure 2. In this manner, the idea is to let the RVE serve as a constitutive model for the macroscale.
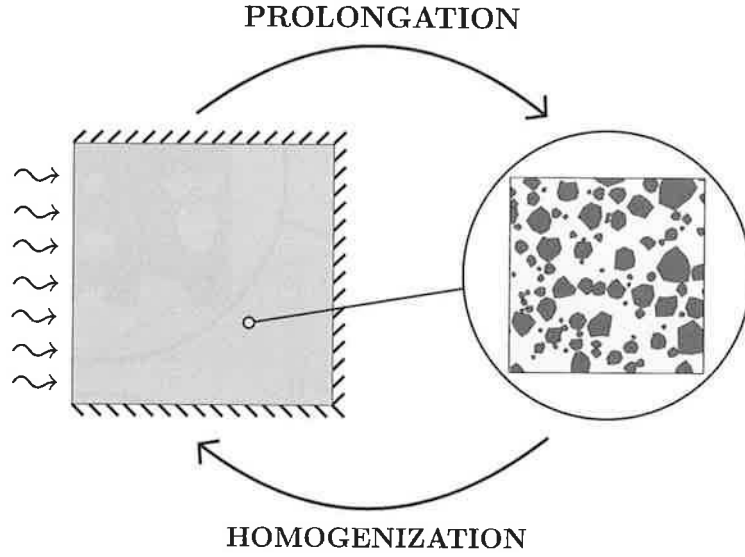
PROLONGATION

HOMOGENIZATION

Figure 2: *The RVE (right) is introduced in the Gauss-points on the macroscale (left). Macroscale quantities of $\bar{H}$ and $\bar{C}$ are used to set up Dirichlet boundary conditions (prolongation), a boundary value problem on the RVE is solved, and the solution is homogenized and sent back to the macroscale.*

2 Problem formulation

The multiscale framework used in this work was developed in Larsson et al. [1] for transient heat flow and is here adopted for coupled diffusion phenomena. Mathematically, the problem is formulated using the mass conservation laws stating that

$$\partial_t \Phi_H + \nabla \cdot J_H = 0 \quad \text{in } \Omega \times [0, T] \tag{1}$$
$$\partial_t \Phi_C + \nabla \cdot J_C = 0 \quad \text{in } \Omega \times [0, T] \tag{2}$$

where $\Omega \subset \mathbb{R}^3$ is an arbitrary spatial domain of unit thickness bounded by Γ, and where ∇ is the spatial gradient with respect to coordinates x in Ω. $\Phi_H(x,t)$ and $\Phi_C(x,t)$ denote the moisture and chloride ion content, respectively, and $J_H(x,t)$ and $J_C(x,t)$ denote the moisture- and chloride ion flux, respectively. The explicit choice of constitutive relations for the cement paste, used on the meso-scale, for the flux vectors is taken from Ababneh et al. [2]:

$$J_H(H,C;\nabla H,\nabla C) = -D_H(H)\nabla H - \varepsilon_C D_C(H,C)\nabla C \tag{3}$$
$$J_C(H,C;\nabla H,\nabla C) = -\varepsilon_H D_H(H)\nabla H - D_C(H,C)\nabla C \tag{4}$$

where H is the relative humidity in the cement pores and C is the chloride concentration. Furthermore, D_H and D_C are diffusive coefficients and ε_H and ε_C are coupling parameters.

3 Numerical example

In Figure 3, a numerical example of a two scale (FE^2) simulation is presented.
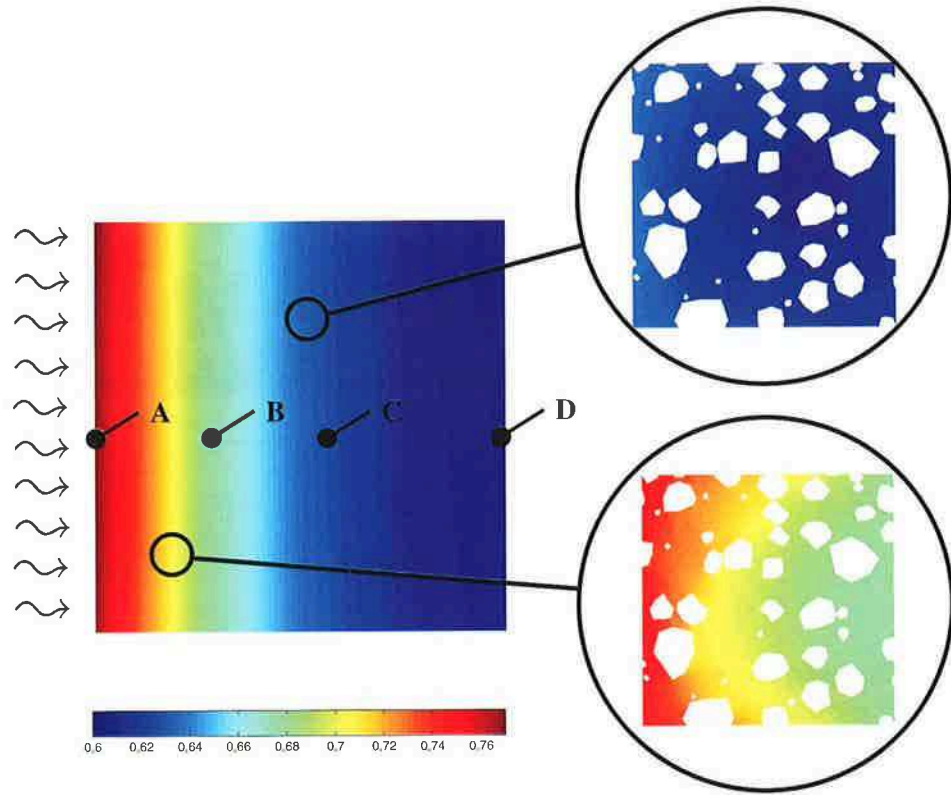
95

Figure 3: *Snapshot of transient solution to $\bar{H}$, for a given time step. The smooth solution on the macroscale (left) is obtained by homogenization of the non-smooth RVE responses (right).*

In Figures 4 and 5, the time evolution of $\bar{H}$ and $\bar{C}$ are presented from FE^2-simulations as shown in Figure 3.
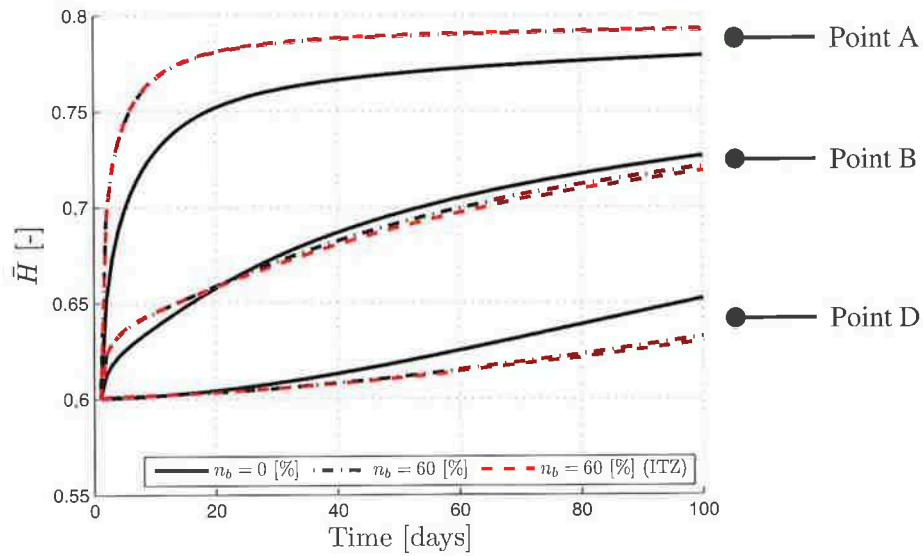

Figure 4: *Time evolution of $\bar{H}$ for varying values of n_b in the RVE, in different points in the macroscale domain. The red line has the ITZ included in the RVE. Point A,B and D are defined in Figure 3.*
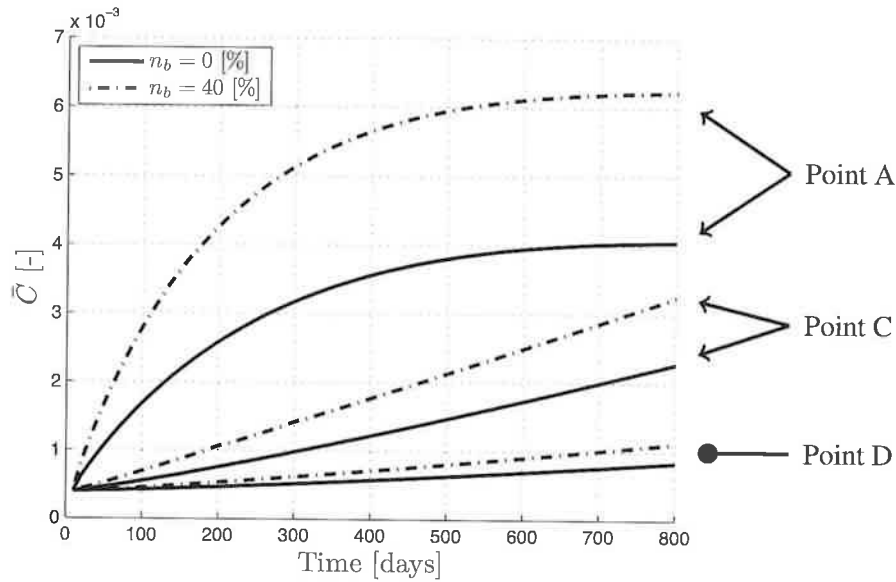
Figure 5: *Time evolution of $\bar{C}$ for varying values of n_b in the RVE, in different points in the macroscale domain. Point A,C and D are defined in Figure 3.*

4   Conclusions

By employing a multiscale method for modeling transport phenomena in concrete, the strongly hetero-geneous structure of the material can be accounted for. This method enables modeling of concrete as a heterogeneous material by actually consider it as a composition of three materials, namely the cement paste, ballast and ITZ. The aim here, using this model, is to better predict the over-all transport properties of concrete.

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Contact elements, creep and anisotropy for the numerical modelling of concrete structures affected by internal swelling reaction

O. Omikrine-Metalssi[1], J.-F. Seignol[1], S. Rigobert[1], F. Toutlemonde[1], L.-I. Boldea[2]

[1]Université Paris-Est, IFSTTAR, Paris, France
[2] Stucky, Lausanne, Switzerland

Abstract

Internal swelling reactions (ISR) which mainly consists in alkali-aggregate reaction (AAR) and/or delayed ettringite formation (DEF) are autogenous reactions that may affect the long term durability of concrete structures. They produce concrete expansion and generate cracking within structures and degradation of their mechanical behaviour. This phenomenon is worrying for affected structure owners as it deals with people safety and structure serviceability. Moreover, there is no practical way to stop reaction and only palliative actions can be proposed. Hence, prediction of concrete expansion, structural degradation and assessment of efficiency and schedule of repair works are crucial issues.

The modelling of these phenomena in CESAR-LCPC F.E. code was based on a sub program called "ALKA", for AAR, and presently relies on its newly developed extension called "RGIB" that allows modelling the behaviour of a structure affected by AAR or DEF. This program takes into account several coupled phenomena: influence of thermo-hygral conditions, effects of the early age thermal history, anisotropy of the imposed expansion related to the direction of concrete casting, damage resulting from cracking of the material, drying shrinkage and coupling between the expansion and the state of stresses. The developed sub program is applied by following two steps for each time step: firstly, RGIB calculates the reaction extent increment from the fields of temperature and humidity, and chemical parameters of the material, . Then, this reaction extent is introduced into the chemo-mechanical model, based on the assumption of prescribed chemical strains superimposed to mechanical deformations. In the case of DEF, this chemical strain is also affected by the early age thermal history, which can be assessed by a preliminary FE computation.

Many case studies have shown that it is necessary to model displacement discontinuities in the concrete, mainly to take into account two phenomena: firstly the modelling of the major cracks opening that result from interactions between pathology and mechanical behaviour of the structure, and secondly, the evaluation of the potential efficiency of stress release (e.g. sawing of dams), the procedure which consists in the creation of cutting lines in the structure for release of excessive compressive stresses (the possible re-closing of the cutting lines have to be ensured by allowing a residual stress in the surrounding concrete).

Furthermore, taking into account these phenomena and couplings in ISR modelling appears to be insufficient for the analysis of some types of structures, especially those subject to significant permanent loads, such as dams or large pre-stressed concrete structures. In this context, creep and its interaction with the development of ISR, particularly alkali-aggregate reaction, shall be accounted for.

This paper describes the algorithm development aimed to possibly combine contact elements and non-linear coupled models related to ISR modelling. It presents some illustrative cases to validate this model development. Moreover, the effect of stress on the anisotropy of expansion is highlighted. Finally, some validation cases of basic creep integration will be discussed.

Keywords: Internal swelling reactions (ISR), creep, cracks, numerical analysis, concrete dams, stress-release, anisotropy.

Assessment of service life and environmental impacts of chloride exposed concrete structures with repairs by cover replacement

Numerical Modeling
Strategies for Sustainable Concrete Structures

Aix-en-Provence, France
May 29-June 1, 2012

A. Petcherdchoo

King Mongkut's University of Technology North Bangkok, Thailand.

Abstract

This paper aims at assessing service life and environmental impacts of repaired concrete structure under chloride attack using the finite difference method. The quantitative prediction of chloride diffusion in concrete structures can mathematically be described using the Fick's second law, but the prediction of repaired concrete structures after repair by concrete cover replacement using the Fick's second law is restricted due to the complexity in solving the partial differential equations. Hence, a Crank-Nicolson based finite difference formulation is proposed to predict the remaining service life of repaired concrete structures. Furthermore, the environmental impacts, in terms of energy use and global warming categories, which can be used to indicate the sustainability of the structures, are also estimated based on the relationship between the application time of repair and the environmental impacts per repair action. Finally, a numerical example is presented.

Prediction of Chloride Ingress into Concrete in a Marine Environment

Ian N. Robertson

University of Hawaii, Department of Civil Engineering, 2540 Dole Street, Honolulu, Hawaii 96822, USA
email: ianrob@hawaii.edu

Abstract

Corrosion of reinforcing steel is a major contributor to early deterioration of concrete structures in a coastal environment. This paper presents results of a six year field monitoring study involving 25 reinforced concrete panels exposed to a marine environment. Seven different corrosion inhibiting admixtures were used in the study to compare their effectiveness at preventing or delaying onset of corrosion.

Chloride concentrations were measured at various depths below the concrete surface to obtain a chloride concentration profile approximately annually during the field exposure. LIFE-365, a numerical model to predict chloride ingress into concrete, was used to predict the chloride concentration profile for each specimen at each monitoring interval. Comparison of predicted and measured profiles indicate discrepancies which could lead to inappropriate design if LIFE-365 is applied using the default settings. Modifications to LIFE-365 are suggested to improve the prediction of chloride concentrations for the concrete mixtures considered in this test program.

This study was funded by the Hawaii Department of Transportation, Harbors Division, in order to evaluate commercially available corrosion inhibiting admixtures when used in concretes made with basalt aggregates common to Hawaii and other Pacific Islands. The corrosion-inhibiting admixtures included in this project were categorized into two types. Type 1 admixtures attempt to reduce the concrete permeability - Xypex Admix C-2000, latex modifier, Kryton KIM, fly ash, and silica fume were used in this study. Type 2 admixtures attempt to raise the chloride concentration threshold at which corrosion of the reinforcing steel is initiated - Darex Corrosion Inhibitor (DCI), Rheocrete CNI, Rheocrete 222+, and FerroGard 901 were used in this study.

Lattice model as a tool for modelling transport phenomena in cement based composites

B. Šavija, J. Pacheco, R.B. Polder, E. Schlangen

Microlab, Delft University of Technology, Delft, The Netherlands

Abstract

Reinforced concrete is a construction material of choice for structures exposed to severe environmental conditions. Due to relatively good durability characteristics and low price, its use is only going to increase in the future. However, due to different deterioration mechanisms (e.g. chloride or carbonation induced corrosion, sulphate or frost attack, etc.), it is inevitable that it deteriorates in time. There is an increasing need for reliable models which would enable reliable prediction of concrete durability.

A majority of these processes, if not all of them, involve transport of some agent (moisture, ions, heat, electrical current, etc.). Kinetics of these degradation mechanisms is controlled by different concrete mix properties, exposure conditions, curing, and so on. Analytical or numerical tools are therefore needed in order to optimize concrete mix proportions and construction practice, all in order to achieve the desired service life.

Lattice models have long been successfully used in modelling fracture processes in cement based materials [1]. In the model, specimens are modelled as a set of beam or truss elements. Realistic crack patterns and fracture properties can be easily obtained using these models. Also, composite nature of the material (concrete as mix of coarse aggregate, ITZ, and mortar) can be simulated with the lattice model [2]. Computer generated microstructure or microstructure obtained by scanning a real material can be used.

Recently, development of the lattice model as a tool for modelling transport processes in cement based materials has commenced. A two or three dimensional random (irregular) triangular lattice is used. In this case, the material is modelled as a set of one dimensional "pipes", through which the transport takes place. This makes it possible to model a two or three dimensional process using only one dimensional linear element. Cross sections of these elements are determined employing the Voronoi scaling method, previously proposed in the literature [3]. Since all the elements are one dimensional, computational effort needed to solve the system of resulting equations can be chiefly reduced. As with the fracture lattice model, it is possible to model the material on both the macro (homogeneous) and the meso scale (heterogeneous). In the paper, basic characteristics of the model- spatial discretization procedure, governing equations- are laid out. Examples for time independent (i.e. steady-state flow) problems at both the macro and the meso scale are presented and compared. Simulation results are then compared to the analytical solutions, and error estimates are given. Finally, conclusions on the model efficiency and the future prospective are given.

It is envisioned that this model will, in the future, be coupled with the fracture lattice model, which would enable taking cracking into account when modelling the transport of different species in cement based materials. This should enable more realistic estimates of the effect of cracking on durability of concrete exposed to different aggressive environments, ensuring that the influence of cracking is not over or underestimated.

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Numerical tool for durability assessment of concrete structures subjected to aggressive environment

Numerical Modeling
Strategies for Sustainable Concrete Structures

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May 29-June 1, 2012

J. Mai-Nhu[1], A. Sellier[2], P. Rougeau[1], F. Duprat[2]

[1] CERIB (Study and Research Centre for the French Concrete Industry), Research and Innovation Department, Materials Section, BP 30059, 28231 Epernon, FRANCE.
[2] Université de Toulouse, UPS, INSA, LMDC (Laboratoire Matériaux et Durabilité des Constructions), 135 Avenue de Rangueil, F-31 077 Toulouse Cedex 04, FRANCE.

Abstract

Mastering and optimising the durability of prefabricated products, whether they are structural, architectural or intended for sewerage, is without a doubt a major challenge for the entire profession.

Previous works carried out at CERIB and LMDC have already resulted in the creation of a predictive model for assessing the lifetime of reinforced concrete structures subjected to the phenomenon of carbonation.

In this research work, additional parameters of corrosion are being introduced such as the migration of chlorides in a saturated and unsaturated phase or the combination of this migration with the mechanism of carbonation and the corrosion of reinforcing bars according to wetting-drying cycles. A new experimental setup was developed to simulate wetting-drying cycles in controlled environmental conditions and to monitor the corrosion initiation for several types of concretes with different water/binder ratios and different types of binders.

In the same way, a model able to predict the performance of concretes in relation to the carbonation phenomenon in unsaturated phase was developed with a finite element analysis and multiphysics simulation.

The final goal is to come up with a comprehensive and more accurate model which takes into account all the most important coupled phenomena.

Modelling of the moisture transfer under wetting-drying cycles in cementitious material

Zhidong Zhang, Mickael Thiéry, Véronique Baroghel-Bouny

Paris-Est University, Paris; Materials Department, IFSTTAR, Paris, France

Abstract

In a realistic environment, cementitious materials are subjected to cyclic changes of relative humidity, such as from low level (40%-50%) to near water saturation. The description, quantification and study of moisture transport leads to the consideration of the hydraulic properties of unsaturated cementitious materials. This involves the relationship between the water content and the relative humidity, called the water vapour sorption isotherms (WVSIs). This function exhibits hysteresis, depending on whether the material is wetting (adsorption) or drying (desorption). Experimental results indicate cycles (scanning loops) remaining inside the area delimited by the boundary of the main desorption and adsorption curves obtained in the whole range of relative humidity.

The aim of this paper is to incorporate the hysteretic behaviour of WVSIs in a multiphase model simulating liquid water - water vapour - dry air flow in cementitious materials. There are two methods proposed. One we call 'direct shifting' method. The power functions developed by van Genuchten are used for least square fitting of experimental data of the main desorption and adsorption curves. The cyclic wetting and drying phenomena is described by direct shifting between desorption curve and adsorption curve. The numerical result shows this method suit for specimen undergoing high RH wetting progress (nearly saturated). The other method combines with an incremental relationship developed by Pedroso, which takes place of 'direct shifting' to describe the cyclic wetting and drying phenomena. In addition to the water sorption characteristics, the modelling of moisture transfer requires transport coefficients, as relative gas and liquid permeabilities, are derived from the knowledge of the WVSIs according to analytical models developed in the literature.

The mass loss (kinetics) and moisture profiles data, gained from experiments using gamma-ray attenuation measurements during the first wetting and drying cycle which were carried on the hardened cement pastes made of OPC (w/c 0.45 and 0.6) cylinderical specimens, are used to determine the intrinsic permeabilities and to validate the above model. The hysteretic behaviour of the materials can be investigated accoding the data gained from experiments and the main drying-wetting curves are fitted. Further more, a mass loss evolution under several drying-wetting cucles will be predicted. At the last, this paper describes and analyses phnomenon of the moisture transfer under the multi-cycles.

Keyword: wetting-drying cycles, moisture transfer, cementitious material

Session I-6:Coupling Problems

Investigation of the hygro-thermo-chemical modelling of concrete in unsaturated state conditions subjected to moderate temperatures
A.S. Chitez, A.J. Jefferson
Cardiff School of Engineering, Cardiff University, Cardiff, Wales, UK

A Thermo-chemo-mechanical numerical model applied to the design of sustainable structures
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UFRJ

Numerical Modelling for Corrosion Evaluation in RC Structures due to Climate Change Impacts
M. Gharib[1], S.J. Foster[2], A. Castel[3]
[1] *PhD Candidate, University of New South Wales, Australia -* [2] *Professor, University of New South Wales, Australia*
[3] *Professor, Université de Nice, France*

Experimental and numerical analysis of salt transport and crystallization in non-isothermal partly and fully saturated porous building materials
M. Koniorczyk, D. Gawin
Department of Building Physics and Building Materials, Technical University of Lodz, Lodz, Poland

Prediction of strength of concrete in long-lived concrete member
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Nagoya University, Graduate school of environmental studies, Japan

Modelling of Corrosion of Steel Reinforcement in Concrete – Fully Coupled 3D FE Model
J. Ožbolt[1,2], G. Balabanić[2], M. Kušter[3] and F. Oršanić[1,3]
[1]*IWB, University of Stuttgart, Stuttgart, Germany -* [2]*GF Rijeka, University of Rijeka, Rijeka, Croatia -* [3]*GF Zagreb, University of Zagreb, Croatia*

Thermo-hydro-mechanical modelling and simulation of fire induced spalling in concrete
M.T. Phan, S. Dal Pont, F. Meftah, S. Rigobert, P. Autuori, L. D'Aloia
MSME, Université Paris Est, France

Modeling of fluid transfers in cracking concrete: experimental constitutive laws and numerical probabilistic strategies
G.Rastiello, P. Rossi, J.-L. Tailhan, S. Dal Pont, C. Boulay
IFSTTAR Paris, France

Numerical modelling of fluid transfer in cracked reinforced concrete structures
G.Rastiello, J.-L. Tailhan, P. Rossi, C. Desmettre, J-P. Charron, S. Dal Pont
IFSTTAR Paris, France

Meso-mechanical study of high-temperature cracking in mortar and concrete specimens using fracture-based zero-thickness interfaces
M. Rodriguez, C.M. Lopez, I. Carol
ETSECCPB (School of Civil Engineering), UPC (Technical University of Catalonia), Barcelona, Spain

Chemo-Mechanical Micro Model for Alkali-Silica Reaction
Victor Saouma, Wiwat Puatatsananon
Dept. of Civil Engineering, University of Colorado

Role of Numerical Modelling of Reinforcement Corrosion for Sustainable Concrete Structures
Henrik Stang[1], Michael D. Lepech[2] and Mette Geiker[1,3]
[1] Technical University of Denmark, [2] Stanford University, [3] Norwegian University of Science and Technology

Investigation of the hygro-thermo-chemical modelling of concrete in unsaturated state conditions subjected to moderate temperatures

A.S. Chitez, A.J. Jefferson

Cardiff School of Engineering, Cardiff University, Cardiff, Wales, UK

Abstract

In this study a finite element numerical model is described which is used to investigate the moisture transfer in unsaturated concrete subjected to moderate temperatures through both phenomenological and mechanistic approaches. The numerical results are validated with experimental findings available in the literature. The approaches differ in the complexity of the constitutive equations used to describe moisture transport mechanisms. This elaborateness is responsible for a higher degree of non-linearity of the system and for the difficulty of choosing the input material parameters. The phenomenological approach[1,2,3] gives a relatively simplified description of the diffusion model since it encompasses in a single flux term all the existing means of fluid transport within concrete. The moisture diffusion analysis has one primary variable: the relative humidity (H) or the moisture content (w). To couple the thermal effect a heat transfer equation is introduced adding temperature T as supplementary variable. The mechanistic approach uses separate mass balance equations for each individual phase (dry air, water vapour, liquid water) to which an enthalpy balance equation is attached for the thermal effect[5,6]. In the current study simplified assumptions are made based on previous research results[7,8] and the system is reduced to two sets of equations with capillary pressure (p_c)/degree of saturation (S_w) and temperature (T) as independent variables. In both approaches the switch between the first possible variables is made by means of sorption isotherm and capillary curve respectively.

The numerical investigation is intended to highlight the issues raised by the diversity of constitutive laws found in literature describing the material characteristics related especially to moisture transfer in concrete. Attention is focused particularly upon the expression of the permeability function of the water phase and the effective diffusivity of vapour within air. The numerical findings are compared with relative humidity versus time experimental curves at different concrete depths for specimens with various water-cement ratios. These expressions are highly non-linear and the predicted response shows considerable sensitivity to their values and controlling parameters. In addition the hygro-thermal model appears to be responsive to the moisture and heat transfer coefficients responsible for the boundary convection fluxes.

Also in this investigation due to the inconsistencies between the numerical and experimental values of relative humidity at the end of self-desiccation a comparison of two hydration models was performed. One model considers the hydration rate dependent on the chemical affinity and relative humidity[6] while in the other the hydration rate is obtained considering the hydration degree as an exponential function of an equivalent time derived from maturity method[9]. In this way the chemical coupling was added to the model.

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A Thermo-chemo-mechanical numerical model applied to the design of sustainable structures

Eduardo M. R. Fairbairn[1], Fernando L. B. Ribeiro[1], Marcos M. Silvoso[2],
Romildo D. Toledo Filho[1]

[1]COPPE/UFRJ, [2]FAU/UFRJ

Abstract

In this paper we present a parallel finite element implementation of a thermo-chemo-mechanical model dedicated to the analysis of massive structures. The code is developed for distributed memory parallel architectures and simulates the layered construction of hydropower plants. The optimized code permits the consideration of complex geometries with a fine discretization of power houses and spillways. We present two applications of the model: the first one is the analysis of the construction phase of a spillway gate pier of the Tokoma hydropower plant, which is being constructed in Venezuela, and the second one simulates the construction of a general spillway considering two different materials, a conventional concrete and a concrete made with the partial substitution of cement by a blend of sugar cane bagasse ash and rice rusk ash, which can reduce CO_2 emissions.

Numerical Modelling for Corrosion Evaluation in RC Structures due to Climate Change Impacts

M. Gharib[1], S.J. Foster[2], A. Castel[3]

1- PhD Candidate, University of New South Wales, Australia.
2- Professor, University of New South Wales, Australia.
3- Professor, Université de Nice, France.

Abstract

For sustainable development, performance-based durability analysis of reinforced concrete (RC) structures is needed to ascertain serviceability, and strength, performance over time as a result of deterioration processes. Performance based durability design is not only needed at the initial design stage but also, based on updated state data, at subsequent in-service stages. This allow for continued updating and assessment throughout the life of the structure to implement optimal maintenance schedules. In this regard, corrosion due to chloride ingress and carbonation are generally the more concerning processes indicating susceptibility to deterioration.

In this paper, a model is proposed for coupling chloride ingress and carbonation in concrete. The model is capable of predicting onset of corrosion, focusing on the initiation phase. It is assembled by simulation of chloride ion, carbon dioxide, moisture and oxygen concentrations via multi-mechanistic transport into concrete with diffusion and conviction mechanisms. A numerical solution is employed through finite element modelling to solve the coupled system using governing mass conservation and heat transfer equations. The developed model is compared with existing models and is verified by experimental results.

The model proposed may be utilised to assess the impacts of climate change in the presence of sustained mechanical loading, for changes in atmospheric CO_2 concentration, temperature and relative humidity. Some examples are given.

Keywords: Durability, reinforced concrete, corrosion, carbonation, diffusion

Experimental and numerical analysis of salt transport and crystallization in non-isothermal partly and fully saturated porous building materials

M. Koniorczyk, D. Gawin

Department of Building Physics and Building Materials, Technical University of Lodz, Lodz, Poland

Abstract

Water and salt are wildly recognized as a major factor of porous materials damage, therefore a lot of experimental and theoretical studies are devoted to them. One of the most adverse phenomenon which is related to the salt and moisture presence in the pore system of building materials is salt crystallization. It might be responsible for two kinds of building material damage. One is efflorescence of salt on the surfaces and the other is the additional pressure, which is produced during the crystallization. The maximum value of the pressure, which is generated during salt crystallization is described by the equation [1]:

$$\Delta p = \frac{RT}{V_m} \ln\left(\frac{a}{K}\right)$$

where a is ion activity product, K is the equilibrium constant, T is absolute temperature, R is gas constant.

The mathematical model of salt, moisture and energy transport was derived and based on it the computer code was developed [2]. The salt phase change kinetics is taken into account while modeling. Crystals grow in pores when the solution is supersaturated. Solution supersaturation ratio is the function of the ion activity product, which is calculated based on the Pitzer ion interaction model.

The mercury intrusion porosimetry tests were performed in order to study the influence of salt crystallization on the internal structure of porous medium e.g. porosity, permeability, pore size distribution. To get additional information about the shape of pores two intrusion-extrusion cycles were carried out.

To solve the set of governing, differential equations the finite element and finite difference methods are used. The numerical validation of the developed software for various density of finite elements and time intervals, was carried out. Three different rate laws are assumed for the modeling the salt phase change kinetics. The drying and cooling-warming of cement mortar containing salt solution, have been simulated using the developed software. The changes of salt concentration in the pore solution and the amount of precipitated salt due to variation of boundary conditions are analyzed. The crystallizing salt generates the additional tensile stress in the surface layer, what might be responsible for its splitting.

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Prediction of strength of concrete in long-lived concrete member

I. Maruyama, G. Igarashi

Nagoya University, Graduate school of environmental studies, Japan

Abstract

Distribution and time dependent behaviour of concrete strength and related properties of concrete are predicted in aged-concrete structural member which suffers from relatively high temperature and drying condition. This condition is assuming the member in nuclear power plant.

For the prediction or evaluation of this, hydration-model-based numerical evaluation tool is proposed. This system is composed of models of rate of hydration, phase composition, heat production, specific heat, compressive strength and Young's modulus, vapor desorption isotherm, coupled heat and moisture transfer.

Each model parameters are determined through experimental data. This system is aiming for the structural member which can not be accessed or can not be evaluated by the core sampling test. Using non-destructive data or quality control sample's data, this system might illustrate the distribution and development of concrete strength in structural member properly.

In this paper, a samples calculation results for concrete members exposed to high temperature condition (65 °C) and room temperature condition is discussed.

During construction period, water in concrete is evaporates from the both surfaces and then water content on the surface become low and become relatively high in internal part. Assuming that the member is attached to high temperature facilities and there is no water movement on the surface after 1 year from the casting and the facilities begin to run at the same time, re-distribution of water content is observed. Due to the temperature distribution in specimen, water in the centre is moved to both surfaces, and strength development on the high temperature side is produced. Finally the weakest strength is found on the surface of room temperature side.

On the contrary, concrete member which is not attached to high temperature facilities, strong drying is observed on the high temperature side. And resultantly, the weakest part is found on the high temperature side.

As a result, strength development as well as distribution is quite sensitive to the boundary condition, and this concludes that the evaluation of structural member under such special condition needs precise boundary conditions.

Modelling of Corrosion of Steel Reinforcement in Concrete – Fully Coupled 3D FE Model

J. Ožbolt[1,2], G. Balabanić[2], M. Kušter[3] and F. Oršanić[1,3]

[1]*IWB, University of Stuttgart, Stuttgart, Germany*
[2]*GF Rijeka, University of Rijeka, Rijeka, Croatia*
[3]*GF Zagreb, University of Zagreb, Zagreb, Croatia*

Abstract

Reinforced concrete structures, which are exposed to aggressive environmental conditions, such as structures close to the sea or highway bridges and garages exposed to de-icing salts, often exhibit damage due to corrosion. Damage is usually manifested in the form of cracking and spalling of concrete cover caused by expansion of corrosion products around reinforcement. The reparation of corroded structure is related with relatively high direct and indirect costs. Therefore, it is of great importance to have a model, which is able to realistically predict influence of corrosion on the safety and durability of RC structures.

To estimate reduction of the cross-section of reinforcement and to predict the increase of the volume of corrosion product it is necessary to know the corrosion rate e.g. corrosion current density in the corrosion unit. The calculation of corrosion current density and its consequence for concrete structures requires modelling of the following physical and electrochemical processes: (1) transport of capillary water, oxygen and chloride through the concrete cover; (2) immobilization of chloride in the concrete; (3) transport of OH^- ions through electrolyte in concrete pores, (4) cathodic and anodic polarization, (5) calculation of corrosion rate and (6) transport of corrosion products. These processes are coupled with the mechanical properties of concrete (damage), which have significant influence on transport processes and consequently on the corrosion rate. Moreover, the corrosion products have two to seven time large volume than the steel. This generates stresses and can cause cracking of concrete cover.

In the present contribution a 3D chemo-hygro-thermo-mechanical model for concrete is presented [1,2]. In the model the interaction between non-mechanical properties (distribution of temperature, humidity, oxygen, chloride and rust) and mechanical properties of concrete (damage), is accounted for. The mechanical part of the model is based on the microplane model. The strong and weak formulations and implementation into a 3D finite element code are discussed. The application of the model is illustrated on numerical examples in which the transient 3D finite element analysis of RC specimens is carried out. First example includes only initiation phase of corrosion and shows the influence of damage of concrete on depassivation time of reinforcement. To investigate the influence of environment conditions and concrete properties on corrosion rate of reinforcement, in the second example are simulated processes before and after depassivation of reinforcement. Comparison between numerical and experimentally observed corrosion rates shows that the model is able to realistically predict corrosion of reinforcement.

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Thermo-hydro-mechanical modelling and simulation of fire induced spalling in concrete

M.T. Phan[1], S. Dal Pont[3], F. Meftah[2], S. Rigobert[3], P. Autuori[4],
L. D'Aloia-Schwartzentruber[5]

1 MSME, Université Paris-Est Marne-la-Vallée, France, Minh-Tuyen.phan@univ-Paris-est.fr
2 LMMGC, Université Cergy-Pontoise, Neuville-sur-Oise, France, Fekri.Meftah@u-cergy.fr
3 IFFSTAR-LCPC, 58 boulevard Lefebvre 75732 Paris, France, {dalpont,rigobert}@lcpc.fr
4 Bouygues TP, Challenger -1 avenue Eugène Freyssinet, 78061 Saint-Quentin-en-Yvelines, France,
P.autuori@bouygues-construction.com
5 CETU, 25 avenue François Mitterrand, 69674 Bron, France, laetitia.daloia@developpement-durable.gouv.fr

Abstract

This paper presents a coupled thermo-hydro-mechanical (THM) model enriched with a buckling-type criterion for progressive spalling. In the first part of the paper, a general fully coupled multi-phase THM model describing the behaviour of concrete at moderate and high temperatures is presented. Then the spalling criterion and its numerical implementation in the framework of the finite element method are presented. Finally, a simple 1D numerical example will illustrate the effectiveness of the implemented numerical approach.

Modelling of fluid transfer in concrete: experimental constitutive laws and numerical probabilistic strategies

G. Rastiello[1], J.-L. Tailhan[1], P. Rossi[1], S. Dal Pont[1], C. Boulay[1]

[1]IFSTTAR, Paris-East University, France, {giuseppe.rastiello, rossi, tailhan, dalpont, boulay}@ifsttar.fr

The aim of this paper is to present a three-dimensional finite element fully coupled thermo-hydro-mechanical probabilistic strategy to model fluid transfer in cracking concrete. The concrete is considered as a partially saturated porous medium and, as common in the multi-phase theory, it is treated as a three-phase system composed by the voids of the skeleton filled with liquid water and gas (two miscible species: dry air and water vapour).

Although in conventional analyses a homogeneity assumption is commonly adopted for solid skeleton properties and transfer properties, an appropriate approach for thermo-hydro-mechanical modelling of concrete should not ignore a proper description of its heterogeneous nature. Such a heterogeneity makes inevitable the presence of micro/macro cracks and, as well known in the literature, it is strictly related to scale effects in concrete mechanical response.

In the model, herein presented, material heterogeneities are taken into account through a probabilistic approach considering some mechanical characteristics as randomly distributed fields.

Concrete mechanical cracking is modelled by means of the probabilistic model first proposed by [6] and more recently by [7,8]. This approach allows describing the growth of a pre-existing flaw as well as to predict the genesis and formation of cracks in an initially flaw-free structure subjected to tension. The macroscopic model for tensile cracking is capable at the same time of providing information on the local response (i.e., cracks), taking into account scale effects as well as the heterogeneous nature of concrete via appropriate, experimentally validated, size effect laws and via a statistical distribution of mechanical properties.

The coupling with the thermo-hydraulic model is assured by the use of experimental constitutive laws allowing to relate, when cracking occurs, crack geometry (orientation, opening, ...) to a local variation of hydraulic properties. These constitutive laws has been obtained by means of the experimental protocol for real-time measurements of the transfer properties evolution of a concrete sample under tensile loading (Brazilian test) first presented by [1] for electric resistivity and more recently by [5] for hydraulic conductivity and permeability.

The model is implemented in a new finite element code for multi-physics numerical analysis. It is based on a staggered solution procedure [2,3,4], which allows to split the overall model into four small sub-models, one for each type of problem (mechanical, thermal and hydraulic), and to solve subsequently the corresponding block of equations for the correspondent set of field variables, while the other variables of the problem are temporarily frozen at predicted values. Interaction effects between blocks are treated as additional external forces. The full coupling of the problem is preserved by means of a suitable multi-level iterative scheme.
After validation of the code by means of some case study examples, some capabilities of the numerical model and of the proposed probabilistic approach in modelling of cracking of concrete structures are finally illustrated and discussed.

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Numerical modelling of fluid transfer in cracked reinforced concrete structures

G. Rastiello[1], J.-L. Tailhan[1], P. Rossi[1], C. Desmettre[2], J.-P. Charron[2], S. Dal Pont

[1]IFSTTAR, Paris-East University, France, {giuseppe.rastiello, rossi, tailhan, dalpont}@ifsttar.fr
[2]Ecole Polytechnique de Montréal, Montréal, QC, Canada, {clelia.desmettre, jean-philippe.charron}@polymtl.ca

Reinforced concrete structures durability is strongly affected by flow of fluids, gas and pollutants. The presence of cracks weakens the resistance of the porous matrix of concrete and constitutes preferential flow path for aggressive components and thus accelerate its deterioration. Various phenomena can occur: corrosion of the steel reinforcements, carbonation, alkalis-aggregate reaction, scaling and sulphate attack. Therefore, when dealing with life expectancy of structures (dams, nuclear power plants vessels, waste storage structures, tunnels, ...) the prediction of the genesis and formation of cracks in concrete, the description of their growth and the prediction of their impact in concrete transport properties are of crucial importance.

In this paper, the numerical probabilistic strategy for thermo-hydro-mechanical modelling of concrete cracking presented in [7] is applied to model fluid transfer in a cracked reinforced concrete structure.

The concrete is considered as a partially saturated porous medium and it is treated as a three-phase system composed by the voids of the skeleton filled with liquid water and gas [2,4]. Mechanical cracking is modelled by means of the probabilistic model proposed by [6,8,9]. This approach allows describing the growth of a pre-existing flaw as well as to predict the genesis and formation of cracks in an initially flaw-free structure subjected to tension. The macroscopic model for tensile cracking is capable at the same time of providing information on the local response (i.e., cracks), taking into account scale effects as well as the heterogeneous nature of concrete via appropriate, experimentally validated, size effect laws and via a statistical distribution of mechanical properties. When cracking occurs, crack geometry (orientation, opening, ...) is related to a local variation of hydraulic properties (conductivity, permeability, ...) by means of experimental constitutive laws obtained through the experimental protocol for real-time measurements of the transfer properties of a concrete sample under tensile loading presented by [1, 5]. The model is implemented in a new finite element code for multi-physics numerical analysis.

In order to validate the modelling strategy on a real structural case, the experience presented by [3] is numerically simulated. In [3], a water permeability device was developed to estimate the water flow in plain and cracked reinforced concrete under tensile loading. The testing specimen consists of a steel reinforcing bar (diameter 11 mm) and the surrounding concrete (length = 610 mm and prismatic cross-section of 90 x 90 mm2) submitted to tensile loads in a reinforced concrete structure. An elastomeric membrane is installed on four of the six faces of the specimen in order to avoid water leakage during the permeability test. It provides, at the same time, a unidirectional water flow through the specimen. Two aluminium boxes are fixed against the elastomeric membrane and each box is linked to a tank by a system of tubes for water circulation. Water is put under pression upstream while the atmospheric pressure is downstream and seeps though the specimen from the inlet tank to the outlet tank. During the test, the real pressure gradient applied to the specimen is measured and the water flow through the specimen is evaluated in real-time.

A comparison between experimental and numerical results, in terms of water flux seeping through the specimen and permeability coefficient, is finally presented and discussed.

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Meso-mechanical study of high-temperature cracking in mortar and concrete specimens using fracture-based zero-thickness interfaces

M. Rodriguez, C.M. Lopez, I. Carol

ETSECCPB (School of Civil Engineering), UPC (Technical University of Catalonia) Campus Nord UPC, Edif D2, 08034 Barcelona, Spain

Abstract

Multiscale, and in particular, meso-mechanical analysis of heterogeneous and quasi-brittle materials such as concrete or rock has emerged as a powerful tool for the modeling of the fracture processes under different loading situations. The group of Mechanics of Materials at UPC (Barcelona, Spain) has been developing such tools with the distinctive feature of the way of representing a key ingredient of concrete behavior: cracking. All lines in the FE mesh are considered as potential crack lines, via systematic use of zero-thickness interface elements, and equipped with traction-separation constitutive models based on principles of non-linear fracture mechanics. In the simplest scenario, the matrix phase is considered elastic or linear viscoelastic, and both the continuum and the interfaces may or may not incorporate the variation of their parameters with time (aging effect). This approach has been implemented in the context of a general 2D/3D FEM code with features such as construction/excavation, coupled THMC analysis, etc. The polygonal geometry of the particles (larger aggregates) is generated numerically using Voronoï/ Delaunay theory. This meso-mechanical model has proven to yield very realistic results, such as distributed microcrack, coalescence, localization and average stress-strain curves for concrete specimens. Applications developed focus primarily on concrete mechanics and durability (drying shrinkage, external sulfate attack), but also expand to sandstone rock and even biological materials (trabecular bone) [1,2,3].

In this paper, attention is focused on the on-going extension of the model to the analysis of thermal mismatch effects in mortar and concrete subject to high temperatures up to 800 C. As a first approach to this scenario, the material is considered as a two-phase composite, with different thermal expansion laws for matrix and particles, whereby the mismatch generates cracks which are captured by the interface elements. The computational results are verified with the experimental observations reported in the literature [4,5] for uniform temperature distribution, and is then extended to the non-uniform temperature distribution to the prediction of thermal spalling under heating using different temperature-time evolution.

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Chemo-Mechanical Micro Model for Alkali-Silica Reaction

Victor Saouma, Wiwat Puatatsananon,

University of Colorado, Boulder USA & Ubon Ratchathani University, Thailand

Abstract

We present a two-stage numerical model for ASR/stress analysis in concrete. A finite difference model is used to simulate the coupled diffusion of alkali into concrete and then the subsequent ASR gel into pores surrounding the aggregates, finally a finite element one is subsequently used to perform a nonlinear analysis. This model is invoked from the master finite difference one resulting in a coupled chemo-mechanical simulation of ASR affected concrete with aggregates of different shapes and sizes. Throughout this analysis, we keep track of the vertical and lateral expansion of the concrete with time, which in turn are transformed into equivalent anisotropic coefficients of ASR expansion.

Finally, accuracy of the model is assessed through comparison with simulated laboratory tests.

Role of Numerical Modelling of Reinforcement Corrosion for Sustainable Concrete Structures

Henrik Stang[1], Michael D. Lepech[2] and Mette Geiker[1,3]

[1] *Technical University of Denmark*
[2] *Stanford University*
[3] *Norwegian University of Science and Technology*

Abstract

With a focus on numerical modeling of reinforcement corrosion and the associated structural deterioration, this paper connects numerical models in order to operationalize design and maintenance for sustainability. A framework was established consisting of two types of models: (i) probabilistic deterioration models combining one or several deterioration mechanisms with a suite of limit states and (ii) probabilistic life cycle assessment (LCA) models for measuring the impact of a given repair, rehabilitation, or strengthening. As such, numerical deterioration models of reinforced concrete comprise a major component of this design approach.

Numerical modelling of reinforced concrete deterioration is used to stochastically estimate the time to the first repair (from the time of initial construction) and – given the structural condition after a repair – the time to any subsequent repair. Novel numerical models of initiation and propagation of reinforcement corrosion are discussed.

These deterioration models are coupled with impact models of a given repair, rehabilitation, or strengthening activity based on a process-based LCA of individual repair activities. Impacts can be environmental, social, and economic in nature. Both types of models (material deterioration or LCA) are formulated stochastically so that the time to repair and total sustainability impact are described by a probability density function. This leads to a fully probabilistic calculation of accrued cumulative impacts (which can be annualized) throughout the service life of a structure from the time of initial construction up to the time of functional obsolescence (end of life). Results facilitate rational decision-making by infrastructure stakeholders when designing to meet sustainability targets.

Session I-7:Other Problems

Relationship between cement alkalis and ASR-based expansion
Mohammad S Islam[a] and Nader Ghafoori[b]
[a,b]Civil and Environmental Engineering Department, University of Nevada Las Vegas, Las Vegas, USA

Prediction of aggregate reactivity based on a modified polynomial model
Mohammad S Islam[a] and Nader Ghafoori[b]
[a,b]Civil and Environmental Engineering Department, University of Nevada Las Vegas, Las Vegas, USA

Modeling the engineering performance of self-compacting concrete to produce precast piles
Mohammed Sonebi[1], Richard Morton[2], Su Taylor[1]
[1]School of Planning, Architecture and Civil Engineering Queen's University Belfast, Belfast, UK - [2]Bullivant Taranto Ltd, Precast Company, Tandragee, UK

Bond behavior of plain bars subjected to uniaxial lateral tension
B.H. Xu, X. Zhang, Z.M. Wu
State Key Laboratory of Coastal and Offshore Engineering, Dalian University of Technology, China

Characteristics and Prediction of Autogenous Shrinkage in Concrete Made with Low-Heat Cement and GGBS
S. Yoshida[1], T. Nawa[2], F. Taguchi[1], T. Ogura[3]
[1]Civil Engineering Research Institute for Cold Region, [2]Hokkaido University, [3]Nittets Cement Co.Ltd, Japan

Relationship between Cement Alkalis and ASR-based Expansion

Mohammad S Islam, Nader Ghafoori

Civil and Environmental Engineering Department, University of Nevada Las Vegas, Las Vegas, USA
Corresponding author: Nader Ghafoori, Professor, Department of Civil and Environmental Engineering, University of Nevada Las Vegas. nader.ghafoori@unlv.edu

Abstract

The main objective of this study was to examine the influence of three dosages of cement alkalis, namely, 0.42%, 0.84% and 1.26% Na2Oeq, on the expansion of mortar bars made with five different aggregate sources due to alkali-silica reactivity (ASR) at the immersion ages of 14, 28 and 56 days. The previously suggested Kolmogorov-Avrami-Mehl-Johnson (K-A-M-J) model was utilized to interpret the ASR classifications of the investigated aggregates. Additionally, an improved K-A-M-J model was developed to better predict the degree of reactivity of the trial aggregates. The study revealed that the ASR-induced expansion increased with an increase in cement alkalis, and the percent increase in expansion due to elevated cement alkalis was more at the early immersion age than that experienced at the extended immersion ages. When compared to the original K-A-M-J model, the proposed statistical model showed a better correlation with the findings of the experimental method and the reactivity suspected based on aggregate mineralogy.

Key words: alkali-silica reactivity; cement alkali; ASR expansion; mortar bars; immersion age; modified K-A-M-J model

Prediction of Aggregate Reactivity based on a Modified Polynomial Model

Mohammad S Islam, Nader Ghafoori

Civil and Environmental Engineering Department, University of Nevada Las Vegas, Las Vegas, USA
Corresponding author: Nader Ghafoori, Professor, Department of Civil and Environmental Engineering, University of Nevada Las Vegas. nader.ghafoori@unlv.edu

Abstract

This paper explored the alkali-silica reactivity (ASR) of thirteen aggregate sources by using the expansion limits of ASTM C 1260. Based on the previous research findings, the ASR-induced expansions over the immersion age of 14 days were fitted in a polynomial equation of second degree with three terms having three distinct regression variables of A2 (the leading coefficient), A1 (the second coefficient), and A0 (constant). The A1 coefficients were plotted against the A2 coefficients to evaluate the degree of alkali-silica reactivity of the trial aggregates based on the trend of the curve generated by these aggregate groups. Additionally, A0, A1 and A2 coefficients were correlated with the 14-day ASR-induced expansions. A modified polynomial model, based on the values of A2 parameter, was proposed to better interpret ASTM C 1260 results. The output of the study showed that the existing polynomial model was nearly unable to confirm the actual results of ASTM C 1260. However, the proposed polynomial model showed a better prediction of ASTM C 1260 results on the degree of alkali-silica reactivity of the trial aggregate sources.

Keywords: alkali-silica reactivity, mortar bar, ASR-induced expansion, aggregate mineralogy, polynomial model.

Modeling the engineering performance of self-compacting concrete to produce precast piles

Mohammed Sonebi[1], Richard Morton[2], Su Taylor[1]

(1) School of Planning, Architecture and Civil Eng., Queen's University Belfast, Belfast, UK
(2) Bullivant Taranto Ltd, Precast Company, Tandragee, UK

Abstract

This investigation aims to model the engineering performance of self-compacting concrete (SCC) to produce precast piles with grade C40/50. A factorial design was carried out to model the influence of mix parameters on the fresh and hardened properties such as filling ability, passing ability, segregation, and compressive strength that are important for the successful development of SCC. The parameters considered in the study were the content of binder, the type of binder, water-to-binder ratio (W/B), and sand-to-aggregate ratio (S/A). Twelve mixes were prepared to derive the statistical models. The models of fresh properties and compressive strengths were established. The influences of W/B, binder content, type of binder and the S/A were characterised and analysed using polynomial regression which can identify the primary factors and their interactions on the measured properties. The results of the modelling and surface responses of the engineering performance were discussed in this paper.

Bond behavior of plain bars subjected to uniaxial lateral tension

Aix-en-Provence, France
May 29-June 1, 2012

B.H. Xu, X. Zhang, Z.M. Wu

State Key Laboratory of Coastal and Offshore Engineering, Dalian University of Technology, China

Abstract

This paper presents the results of an experimental study undertaken to evaluate the characteristics of the local bond stress-slip response of plain bars embedded in concrete under uniaxial lateral tension. A total of 87 (150 x 150 x 150 mm) specimens were tested, which are divided into several series according to the different compressive strength and plain bar diameter. The tension is uniformly imposed on steel plates bonded on parallel surfaces of cube pull-out specimens. The maximum lateral tension applied in the test is equal to 80% of the uniaxial tensile strength (f_t) of concrete. It was found that the ultimate bond strength monotonously decreases by 46% when the lateral tension reaches $0.8\,f_t$. The slip corresponding to the ultimate bond strength increases with the increase of lateral tension. Based on the experimental results of this study, a model for the local bond stress-slip response of plain bars embedded in concrete is proposed, and constitutive relationships that describe its characteristic behavior were developed.

Key words: bond strength; plain bars; lateral tension; bond stress-slip

Characteristics and Prediction of Autogenous Shrinkage in Concrete Made with Low-Heat Cement and GGBS

S. Yoshida[1], T. Nawa[2], F. Taguchi[1], T. Ogura[3]

[1]Civil Engineering Research Institute for Cold Region, [2]Hokkaido University, [3]Nittets Cement Co.Ltd Japan

Abstract

Recently, investment in the development of new infrastructure has decreased because of higher maintenance and replacement costs related to the increase of old social capital stock in Japan. Against this background, there is a strong need to promote more efficient infrastructure development through measures such as ensuring the long-term durability of structures to extend their service life. The key to ensuring the long-term durability of concrete structures is to make the concrete used for them more durable, and for this reason it is important to study concrete with a low water-cement ratio range. However, such concrete has a variety of inherent problems, including an increased likelihood of thermal and shrinkage cracking and the need to secure workability.

The authors previously conducted studies on enhancing the performance of concrete by modifying cement and using mineral admixtures. The results indicated that the use of ground granulated blast-furnace slag (GGBS) as a substitute for part of highly pulverized belite-based cement (low-heat cement) improved strength, heat generation characteristics, frost resistance, chloride penetration resistance and other properties as well as the durability of the concrete, thereby enabling enhanced concrete performance. As concrete made using binders with such properties is expected to exhibit low-heat generation properties and long-term strength development in addition to long-term durability, it is regarded as very useful for application to relatively large structures such as piers and abutments of long bridges and retaining walls constructed under severe environments where frost and salt damage may occur. With the use of such binders, the amount of CO_2 generated in the cement production process can be reduced. In this regard, a reduction in the environmental burden related to the construction industry can be expected.

However, it should be noted that concrete with a low water-binder ratio range undergoes significant autogenous shrinkage, and that the use of finer GGBS results in greater autogenous shrinkage. The occurrence of initial cracking leads to crucial issues in securing long-term durability. Accordingly, this study sought to investigate and predict autogenous shrinkage in concrete made with highly pulverized belite-based cement and GGBS with a low water-binder ratio.

The results indicated that the degree of autogenous shrinkage depended on the binder type and the water-binder ratio. It was also found that autogenous shrinkage was reduced when higher volumes of SO_3 were added to GGBS, and this was true even when the fineness of the slag was increased. In addition, a prediction equation for estimating autogenous shrinkage of concrete made with belite-based cement and GGBS was proposed in consideration of the effects of various factors on such shrinkage.

Sessions II:

Structural applications and Sustainability

Session II-1:Bridges

Numerical Modeling of the Mechanical behavior of bridge Decks with Precast Parapets
M. Namy, J.-P. Charron, and B. Massicotte
Ecole Polytechnique de Montreal, Montreal, Canada

Use of nonlinear finite element models for structural evaluation of concrete box girder bridges
E.Yildiz[1], B.Massicotte[2]
[1] CIMA+ Société d'ingénierie, Montréal, Canada, [2] École Polytechnique de Montréal, Montréal, Canada

Predicting the Shear Behaviour of Solid Slab Bridges using Nonlinear Finite Elements
D. Conciatori, B. Massicotte
École Polytechnique de Montréal, Montréal, Canada

Cracking analysis of concrete structure elements reinforced by flat steel rebars
T.S. Phan, J.-L. Tailhan, P. Rossi, J. Foulliaron
IFSTTAR Paris, France

CO_2-Optimization of PC precast bridges by hybrid heuristics
J.V. Martí, V. Yepes, F. González-Vidosa, J. Alcalá
ICITECH, Universitat Politècnica de València, Spain

Numerical modeling of the mechanical behaviour of bridge decks with precast parapets

AM. Namy, J.P. Charron [(*)] and B. Massicotte

Ecole Polytechnique de Montréal, Department of Civil, Geological and Mining Engineering
P.O. Box 6079, Station Centre-Ville, Montreal (Quebec) Canada, H3C 3A7
[(*)] *Corresponding author: jean-philippe.charron@polymtl.ca*

Abstract

In the framework of a 4-years industrial project, new designs of precast bridge parapets made with fibre reinforced concretes (FRC) and novel anchorage methods to connect the parapet to the underneath slab were developed. In order to study the mechanical performance of a bridge deck with precast parapets in comparison to cast in place parapets, an experimental program of quasi-static tests was carried out on 3 full-scale specimens of 6-m length including the external girder, slab and parapets. A tridimensional non-linear finite elements model was developed in the project to reproduce the stiffness, ultimate strength, crack pattern and failure mode of the bridge deck with precast and cast in place parapets. The paper will first focus on the comparison of finite element calculations and experimental results. Then the results of a numerical parametric study conducted on various configurations of bridge deck will be discussed.

Use of nonlinear finite element models for structural evaluation of concrete box girder bridges

Aix-en-Provence, France
May 29-June 1, 2012

E.Yildiz[1], B.Massicotte[2]

1 – CIMA+ Société d'ingénierie,Montréal, Canada
2 - École Polytechnique de Montréal, Montréal, Canada

Abstract

Most of the bridges in Canada are built before 1980s. The type of concrete and the reinforcement detailing prescribed in codes at that time are such that structures need major investments for maintenance and rehabilitation. In this process many structural evaluations are carried out based on well-known structural analysis and strength calculation methods. The methods prescribed in codes are mainly oriented for designing new structures. Although they have generally proven to be safe, they maybe sometime inappropriate when used in bridge evaluation. In some case they fail in identifying the appropriate failure mode and lead to inadequate strengthening whereas in other cases they can underestimate the actual strength and lead unnecessary repairs.

The paper is based on a typical 1960's multi-cellular reinforced concrete bridge showing typical defects such as extended cracking and insufficient reinforcement. Two main issues are considered: the strength of pier caps that are deep and massive elements, and the strength of the box girder webs that are considered as slender members in which shear and bending interact.

Nonlinear finite elements were used to study these issues. The first study presented in this paper deals with the strength and behaviour of the pier caps. The failure modes before and after strengthening are studied. The emphasis will be put on the contribution of nonlinear analysis in identifying the inadequate behaviour of the existing structure and the proper strengthening technique adopted.

The second portion of the paper considers the importance of the flexural-shear cracking over the spans. The finite element models used allows to observe the progression of the shear cracks versus the applied load amount and the associated failure modes.

The paper emphasis will be on how nonlinear finite element models can be used to properly identify the failure modes and to optimise the strengthening solutions in order to limit the costs and maximize the structural reliability.

Predicting the Shear Behaviour of Solid Slab Bridges using Nonlinear Finite Elements

D. Conciatori, B. Massicotte

École Polytechnique de Montréal, Montréal, Canada

Abstract

Catastrophic collapse of Concorde Bridge in 2006 near Montreal raised the issue shear stress concentration in straight and skewed concrete concrete slab bridges. These bridge have been traditionally designed without shear reinforcement. Questions were raised concerning the reliability of existing bridges and also on the design guidelines of new bridges.

Straight and skewed solid concrete slab bridges are modeled using linear and nonlinear finite element models to highlight shear forces that develop in slab bridges, particularly at the corners. Various types of loads are applied in order to understand the elastic and plastic behavior of the corner force in service conditions and near ultimate. A parametric study is carried out on several configurations of simply supported slabs with geometries covering one to four lane bridges of 3 to 20 m spans and with skew angles ranging from 0° to 60°. The analyses show that corner forces develop locally and the actual design of straight and skew concrete slab bridges is not influenced by the corner forces. A redistribution of corner forces is observed near ultimate limit states with apparition of shear crack bringing ductility at this failure mode. The analyses indicate that these corner forces appear along the free edge with depth about a half-thickness of the concrete slab. This justifies reinforcing the free edge by stirrup, when the design propose a reinforcement.

For existing bridges, the analyses show that strength obtained using a beam type behavior is too conservative for estimating the actual shear strength of slab bridges where wheel loads allows a better redistribution than assumed using elastic analysis.

Cracking analysis of concrete structure elements reinforced by flat steel rebars

T.S Phan[*†], J.-L. Tailhan[*], P. Rossi[*], Ph. Bressolette[‡], F. Mezghani[†], J. Foulliaron[*]

[*]French Institute of Science and Technology for Transport, Development and Networks (IFSTTAR) Paris East University, France
‡ Clermont University, Blaise Pascal University LaMI, EA3867, BP 206, 63000 Clermont, France † MATIERE□ - Construction company, France
email : thanh-song.phan@ifsttar.fr, jean-louis.tailhan@ifsttar.fr, pierre.rossi@ifsttar.fr

This paper presents a cracking analysis of a new reinforcement method based on the use of flat steel rebars instead of classical circular high adhesion. The objective of this method of reinforcement is to optimize the use of materials and to better distribute the cracking processes in the concrete elements. The analysis is performed in the case of the beam-slabs subjected to four point bending. The results are analysed in terms of cracking processes of the concrete as well as at the level of the steel-concrete interface. The dimensions of the concrete prismatic specimens are 330 x 15 x 80 cm. The reinforcement is made of flat steel which cross section is rectangular (22.5 x 5 mm).

The behaviour of the concrete is represented by an explicit probabilistic cracking model ([1], [4]) taking into account two major characteristics of the concrete: heterogeneity, on the one hand, and its sensitivity to scale effects, on the other hand. The mechanical properties (tensile strength f_t and Young's modulus E_c) are randomly distributed and dependent on the volume of material stressed (size effect laws). The behaviour of the flat steel rebars remains elastic as far as only the service limit state is here considered. The steel-concrete interface is represented by contact elements which behaviour is modelled by a deterministic damage model taking into account cohesion and slip at the level of the interface. To identify the parameters of this interface model, a methodology based on an inverse analysis approach is used. This methodology has been made by simulating the statistical mechanical behaviour of RC tie-beams (170 x 10 x 10 cm) subjected to tension and made of the same concrete and reinforced by the same flat steel rebars. The results have been compared with experiment [2] and are relevant ([5], [6]).

The obtained numerical results of the beam-slabs are also compared with experiments [3]. The comparison is made in terms of global response (load-relative displacement curves), as well as cracking process (cracks opening, cracks spacing and number of cracks).

Keywords: Reinforced concrete, flat steel rebar, steel-concrete interface, cracking.

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CO$_2$-Optimization of PC precast bridges by hybrid heuristics

J.V. Martí, V. Yepes, F. González-Vidosa, J. Alcalá

ICITECH, Universitat Politècnica de València. Spain.

Abstract

Precast concrete (PC) construction technology presents economic opportunities when high production volumes are possible with a corresponding saving in costs. Nevertheless, today there are additional social and environmental benefits for using PC. Engineers have taken advantage of this technology by specifying designs which utilize standards beams (Fig. 1). In this context, structural optimization of this type of large and repetitive structures is an area of much research interest due to the large amount of materials required for their manufacturing process. Following this line of work, the present authors' research group has recently reported on heuristic techniques for the CO2 and cost optimization of several concrete structures [1-9].
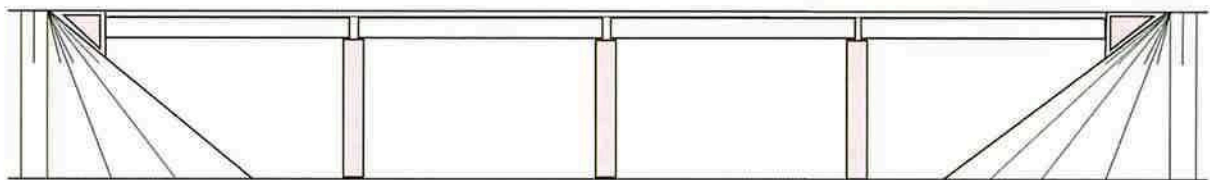
Figure 1: PC precast road bridge longitudinal profile

This paper describes a methodology for the design of PC precast road bridges, with double U-shape cross-section which integrates an upper reinforced concrete slab for the road traffic (Fig. 2). The procedure used to solve the problem is a variant of the simulated annealing, which is applied to two objective functions: the embedded CO2 emissions and the economic cost of these structures at different stages of materials production, manufacturing, transportation and construction. The module computed the objective functions of a solution and checked all the relevant limit states. The problem involved 59 discrete design variables for the geometry of the beam and the slab, materials in the two elements and active and passive reinforcement. Results first indicate that embedded emissions and cost are closely related, and that more environmentally-friendly solutions than the lowest cost solution are available at a reasonable cost increment.
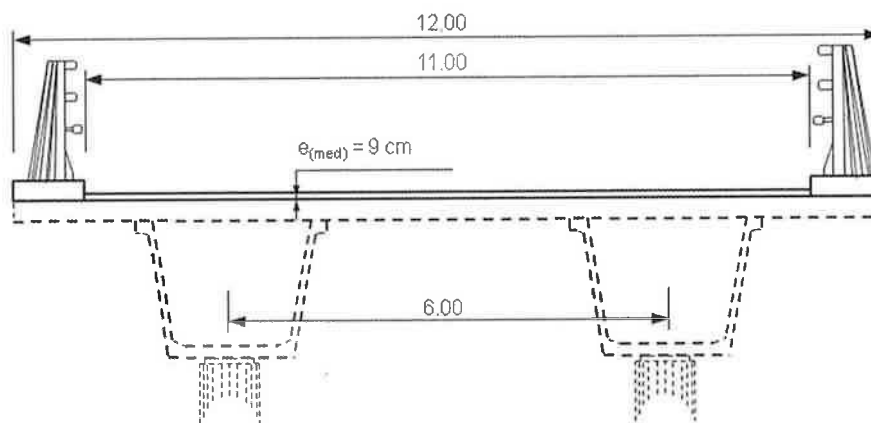
Figure 2: Double U-shape cross-section

Acnkowledgements

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Session II-2:Buildings

Numerical Modelling of Deconstructable Composite Beams with Bolted Shear Connectors
M.A. Bradford & Y.-L. Pi
Centre for Infrastructure Engineering & Safety, University of New South Wales, UNSW Sydney, Australia

Experimental and numerical analysis of advanced cementitious composites for sustainable roof elements
M. Di Prisco, G. Zani
Politecnico di Milano, Italy

Optimized and Sustainable Earthquake Resistant Engineered Cementitious Composites Buildings
Bora Gencturk[1] and Amr Elnashai[2]
[1] Research Associate (currently assistant professor, University of Houston) - [2] Bill and Elaine Hall Endowed Professor, Department Head - Department of Civil and Environmental Engineering, University of Illinois at Urbana-Champaign, USA

Advanced Construction Stage Analysis of High-rise Building Considering Creep and Shrinkage of Concrete
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Use of HPFRC for Sustainable Seismic Hazard Mitigation
C.-C. Hung[1], S. El-Tawil[2]
[1) Department of Civil Engineering, National Central University, Taiwan - 2) Department of Civil and Environmental Engineering, University of Michigan, Ann Arbor, MI, USA.

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Numerical Modeling of FRP- Confined Square RC Columns under Axial load and Biaxial Bending
A.R. Rahai[1], H. Akbarpour[2]
[1,2] Department of Civil and Environmental Engineering, Amirkabir University of Technology, Iran

Reliability of Ancient RC Structures by Means of Numerical Modeling

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DISIG University of Cagliari, Italy

Seismic Performance Evaluation of Reinforced Concrete Building with Static Pushover Analysis

K. Tounsi[*], H. Aknouche[**]
*Superior National School of Public Works, ENSTP, Algiers - ** National Centre of Applied Research in Earthquake Engineering, CGS, Algiers, Algeria*

Decreases to the Carbon Dioxide Impermeability of Polyurethane Waterproof Membranes Caused by Weathering and Concrete Substrate Cracking

M. Tsukagoshi[*], T. Ueda[*], K. Tanaka[**]
University of Tokushima, Japan[*], Tokyo Institute of Technology, Japan[**]

Mechanical Analysis and Simplified Models of Concrete Block Infill Walls under Out-of-Plane Action

Wei-qiu Zhong[1], Ming-shu Gang[1], Xian-hui Cai[2]
[1] Faculty of Infrastructure Engineering, Dalian University of Technology, Liaoning - [2] Department of Engineering Mechanics, Faculty of Vehicle Engineering and Mechanics, Dalian University of Technology, Liaoning, China

Numerical Modelling of Deconstructable Composite Beams with Bolted Shear Connectors

M.A. Bradford & Y.-L. Pi

Centre for Infrastructure Engineering & Safety, University of New South Wales, UNSW Sydney, NSW 2052, Australia

Abstract

Composite beams of steel and concrete are commonplace in engineering structures, taking advantage of the favourable compressive strength of the concrete slab and the favourable tensile strength of the steel girder in a symbiotic fashion. Mechanical shear connection between these two components is essential to realise the increased strength and stiffness of composite beams above those of the slab and steel girder alone. Because of this, headed mechanical stud shear connectors have found close to universal acceptance in contemporary buildings and bridges in providing robust shear connection between the slab and girder, being installed very economically by rapid welding procedures.

Paradigms related to sustainability and full life-cycle assessment in building construction and usage are being introduced in many nations, and unfortunately composite beams with headed stud connectors are not able to be decommissioned easily and efficiently during deconstruction or building modification. One means of circumventing this drawback is to use high strength bolts to provide the shear connection in lieu of headed connectors welded to the steel girder's top flange, which can be unbolted to deconstruct the building or to alter part of it structurally. Surprisingly, this form of shear connection has received little attention in published comprehensive research outcomes, despite its attractiveness for deconstruction as well as structural retrofit.

This paper describes an efficient finite element method of analysis of composite beams with structural steel joists and ordinary Portland cement concrete slabs which are joined by high strength bolted shear connectors. It incorporates material non-linearity in these three elements of the beam, drawing on empirical representations of the shear connection response that may be obtained from standard push testing. By making recourse to comprehensive experimental investigations undertaken in the United States some forty years ago, the numerical model is shown to agree well with test results for full-scale beams.

Since the carbon footprint of a building transcends the materials of its original construction because of full life-cycle performance which includes its deconstruction, the use of bolted shear connectors with ordinary Portland cement slabs reduces the carbon footprint of a building that uses welded headed stud connectors with ordinary Portland cement slabs for which deconstruction is problematic. The numerical technique developed in the paper provides an efficacious tool of analysis for composite beams with welded headed stud connectors.

# Experimental and numerical analysis of advanced cementitious composites for sustainable roof elements

M. di Prisco, G. Zani

Department of Structural Engineering, Politecnico di Milano, Italy

Sandwich technology potential can be maximized by coupling the exceptional mechanical characteristics of Textile Reinforced Mortars (TRM) and UHPFRC with the insulation capability of a XPS foam layer (Fig.1). The coupling of a low stiffness material with cementitious composite layers brittle at a specific strain threshold, could give back a composite panel characterized by multi-cracking phenomena and high inertia. Due to the internal actions acting on the horizontal bearing component, the insulating core should ensure an adequate shear transfer, able to keep the TRM layer mainly in tension and the FRC plate mainly in compression and in local bending. This configuration makes lighter structures possible because it fully exploits the material used and, secondly, makes them more environmental friendly because recycled materials can be used. In the paper, the attention is focused on the problems inherent with the experimental evaluation of individual materials constitutive relations and on the non-linear finite elements modelling of the bending behaviour of the composite. The UHPFRC upper layer consisted of a 25 mm thick plate made of a self compacting cementitious material reinforced with 1.2% by volume of straight high carbon steel fibers. The fibers had a length l_f of 13 mm, a diameter d_f of 0,16 mm and hence an aspect ratio (l_f/d_f) of about 80. The intrados layer of the sandwich beam is made of a 6 mm thick fine grained concrete matrix, reinforced with two layers of alkali resistant glass fabrics (warp / weft wire weight and spacing are respectively 640 / 1200 tex and 5 / 7.1 mm). Experimental and numerical simulations were carried out according to Finite Element Method (FEM), as implemented in Diana 9.4.3 code.
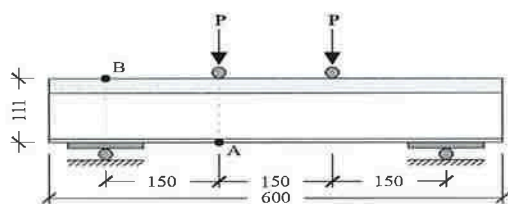
Figure 1: (a) Four point bending test setup; (b) experimental test

The comparison between experimental and numerical results is presented in Fig. 2. The simulation is able to fit the experimental results in terms of initial stiffness and ultimate load, in particular on the load-displacement curve (Fig. 2a), where the displacement represents the deflection measured under the loading knives, depurated from support crushing and local deformation of polystyrene.

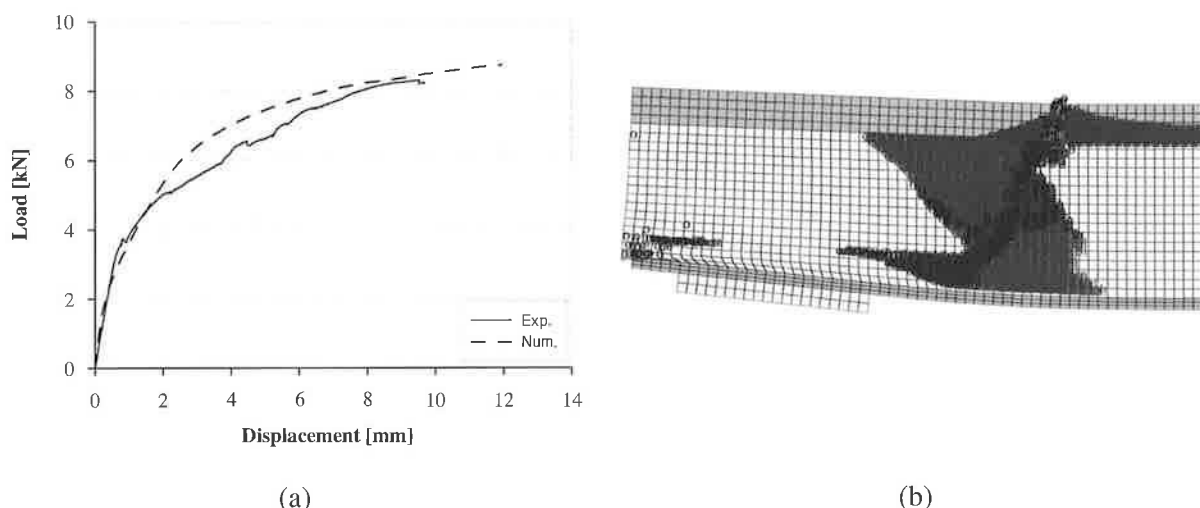(a)   (b)

Figure 2: Numerical simulations: (a) load-displacement and (b) sandwich crack pattern

Concrete cracking started quite early, but the loss of stiffness was mainly related to delamination, cracking and crushing of the sandwich core, as shown in Fig. 2b. Delamination and crushing occurred at the bottom left corner, while under the loading knife a UHPFRC crack localization with a propagation inside the polystyrene core was observed. The careful simulation by Finite Element allows the designer to highlight the critical resistant mechanism and therefore to calibrate the best geometrical coupling of the three materials in relation with serviceability and ultimate strains. The results are instrumental in the design of new precast roof elements able to favour sustainability either in the production process and during the whole life cycle of the structure.

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Optimized and Sustainable Earthquake Resistant Engineered Cementitious Composites Buildings

Aix-en-Provence, France
May 29-June 1, 2012

Bora Gencturk(1) and Amr Elnashai(2)

(1)   Research Associate (currently assistant professor, University of Houston, USA)
(2)   Bill and Elaine Hall Endowed Professor, Department Head
Department of Civil and Environmental Engineering Department, University of Illinois at Urbana-Champaign, USA

Abstract

Lifecycle Cost Analysis provides a powerful tool to balance initial design and construction cost, maintenance and operation. Engineered cementitious composites (ECC) are high performance concrete mixes that are significantly more expensive than reinforced concrete (RC). In this paper, constitutive relationships that capture the difference in behavior between the two materials, ECC and RC are developed and applied to earthquake design in an optimization framework. A whole lifecycle cost model is developed and used to assess the results from analytical simulation of the two types of structure when subjected to severe earthquake motion. It is concluded that ECC buildings are indeed a most viable and often superior solution, in spite of their higher initial cost.

Advanced Construction Stage Analysis of High-rise Building Considering Creep and Shrinkage of Concrete

T. Ha, S. Lee

Daewoo E&C, Suwon, Gyeonggi-do, South Korea

Construction stage analysis for reinforced concrete structures is usually applied to bridges, of which the structural stability during construction is as much important as for the finished structure. This requirement is equally applicable to high-rise reinforced concrete buildings. Long-termed construction period of high-rise building may induce axial shortening of the structure over several hundred millimetres at higher levels of the building during construction. For buildings with mass eccentricity or irregularity, the differential shortening combined with applied moment could also make the building move laterally due to the mechanism similar to bimetallic strip. The amount of axial or lateral movement can be ignored for ordinary buildings but is very important to high-rise buildings, since they cause adverse effects to the construction and performance of elevators and façade, and also develop locked-in forces in outriggers or belt trusses which are vital to the lateral resistance of the high-rise buildings.

In this research, a construction stage analysis program was developed and used to predict and to solve the problems during the construction of the KLCC Tower, a 58-story reinforced concrete building (refer to Figure 1). The program can create or import 3-dimensional structural model of a building for analysis. The user defines the time-dependent material properties like modulus of elasticity, creep, and shrinkage of concrete according to ACI 209, 318, and 363. Other creep and shrinkage models such as CEB MC90-99, B3, and GL2000 are currently being incorporated into the program for a possibility of better prediction of building movement. The amount of reinforcement is also input to consider the effect of load redistribution between steel and the surrounding concrete for RC and SRC members. The construction sequence of a building is modelled by assigning birth date or extinction date to each element of the structural model for self-weight and to other additional loading stages. In the process of analysis, the model is analysed at each construction stage for member forces and deformation, and the intermediate results are stored and used as datum values for the next construction stage analysis. As a result, the building is simulated for its movement and forces for all stages of construction best possible. In the case of the KLCC Tower, developed program was used (1) to set the preset amount at each level for axial shortening, (2) to reduce the supporting duration of the temporary prop under a massive transfer girder, and (3) to predict the building verticality at the time of elevator construction and the remaining lateral movement until target time. Material testing for the modulus of elasticity, specific creep, and ultimate shrinkage of concrete was performed to update the accuracy of the prediction. Three types of field monitoring for actual movement of the building was also performed: strain measurement of column deformation using vibrating wire gauge, optical survey for lateral movement, and 3-dimensional laser scanning of as-built shape of the building for axial and lateral movement (refer to Figure 2). The results of field monitoring confirmed the predicted value of the building movement.
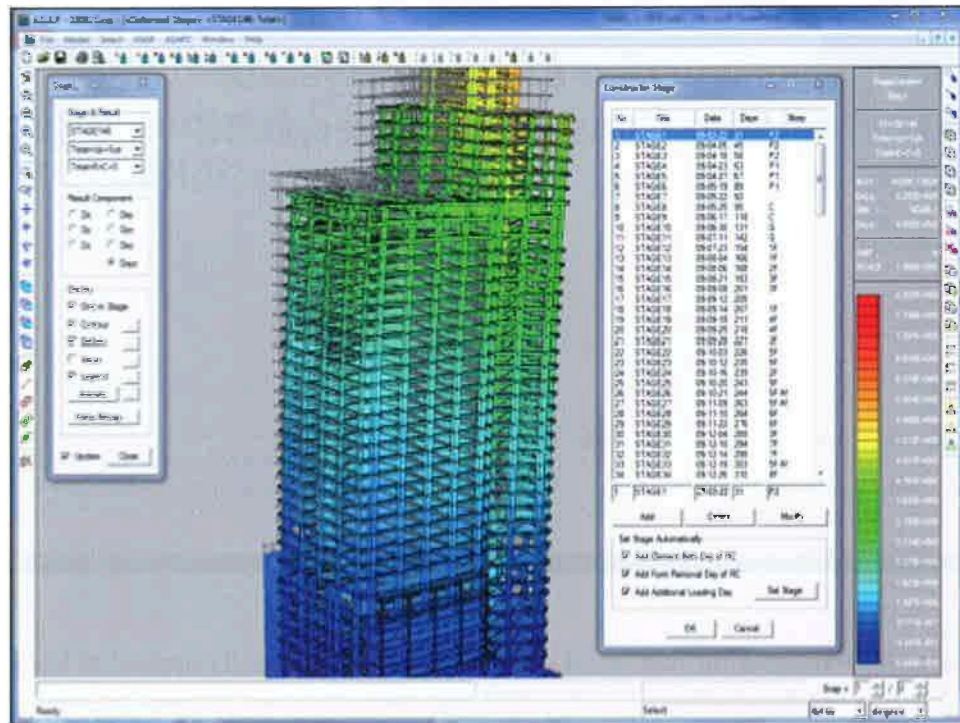
Figure 1 – User interface of construction stage analysis program under development
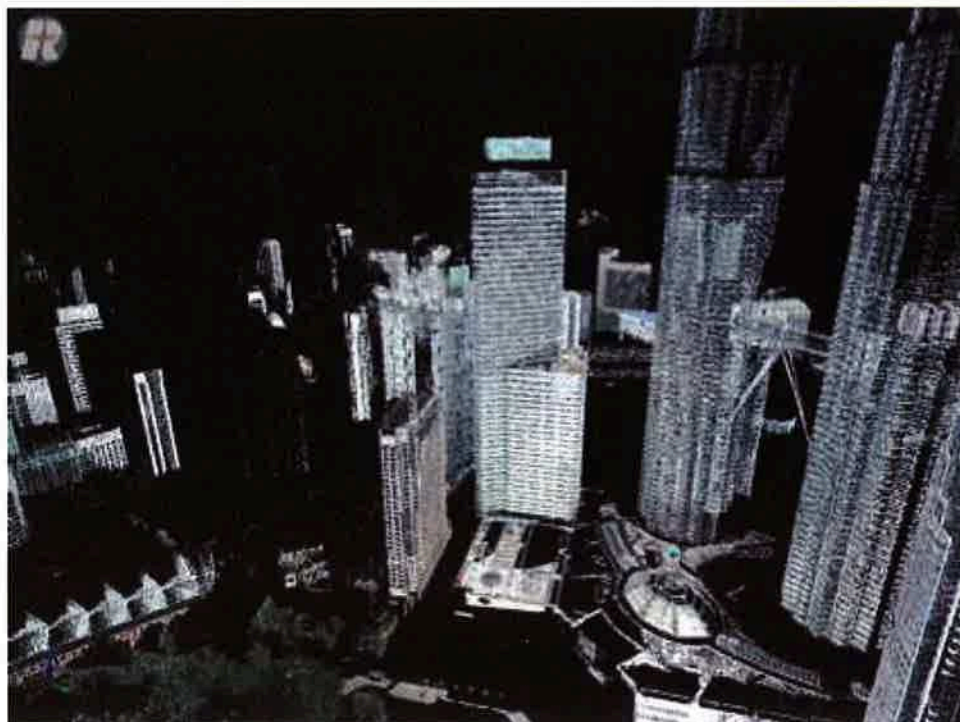

Figure 2 – Result of 3-dimensional laser scanning of KLCC Tower

Use of HPFRC for Sustainable Seismic Hazard Mitigation

C.-C. Hung[1], S. El-Tawil[2]

1) Department of Civil Engineering, National Central University, Taiwan
2) Department of Civil and Environmental Engineering, University of Michigan, Ann Arbor, MI, USA.

Abstract

High performance fiber reinforced concrete (HPFRC) is a type of cementitious material that exhibits tensile strain hardening behavior accompanied by the development of multiple hair-line cracks. HPFRC has many advantages over conventional concrete materials including enhanced ductility, shear resistance, crack control, and damage tolerance. The study herein investigates using HPFRC for sustainable seismic hazard mitigation. The premise is that the use of HPFRC instead of regular concrete will result in substantial reduction in damage due to a design earthquake, reducing the need for repair and/or replacement after the event. To this end, detailed finite element models are used to assess the seismic performance of a HPFRC coupled wall system. The performance is discussed through various performance indicators, including system response parameters, crack patterns, and energy absorbing capacity. The ability of using HPFRC for reducing permanent damage in structures and its use for sustainable hazard mitigation is also discussed.

Numerical modelling of UHPC structural members reinforced with fibres and rebars

P. Lussou

Lafarge Centre de Recherche, France

The current reference document for the design of UHPC structural members is the "interim recommendations" of AFGC-SETRA. As this document doesn't consider the possibility of mixing fibers and reinforcing bars, there is not yet a generally admitted way of modelling this kind of composite structures. The objective of this study is to compare several computation strategies for structural members made of UHPC with several types of reinforcement. Two types of structural members are considered: beams and plates; each of them is reinforced by a combination of fibers (steel, PVA or glass) and rebars (steel or composite) or glass fiber mesh.

In order to support this benchmark, a set of seven beams has been tested in the laboratory of the University of Lyon. Strain gages were placed on the steel bar and on concrete in the middle section of the beam. Image-based measurement of concrete strain was also carried out in order to evaluate crack width. These beams were made of UHPC and were reinforced with PVA fibers and a steel bar. Concerning, plates, in order to calibrate the robustness of the computation methods, several geometries and reinforcing solutions have been considered (plate with stiffening ribs reinforced with steel bars, fiber glass mesh etc).

For each computation, the structural member is described by using either structural finite elements (fiber beams or multilayer plates) or full 3D description. The paper will present in details the technical choices concerning the Finite Elements Method.The simulations results are shown in terms of force-displacement curves compared to test results. A special focus is put on the serviceability and safety criteria.

Numerical Assessment of the Thermal Performance of Structural Precast Panels

J. Keenahan, K. Concannon, D. Hajializadeh, C. McNally

University College Dublin, Ireland

Abstract

With the increasing cost of energy the need to provide energy efficient buildings continues to grow. In 2003 the EU introduced the Energy Performance of Buildings Directive and this was enforced by all member states by 2006. The need to continually improve thermal performance has lead to member states implementing their own national initiatives, and from next year the National Standards Authority of Ireland will specify that all certified sandwich panel products comply with the incoming building regulations. The incoming building regulations stipulate that all sandwich panels achieve a U-Value of 0.15 W/m^{2}K, a reduction from the current value of 0.25 W/m^{2}K. This is a significant challenge and requires that there be no significant heat loss through the panel.

This paper presents the results of a collaborative project with a sandwich panel manufacturer whereby the thermal performance of a number of concrete panels was assessed. Each sandwich panel contained an inner concrete wythe of 150mm thickness, a 120mm layer of phenolic foam insulation and a 90mm thick outer layer of .concrete. For structural reasons it is necessary to use connectors between the inner and outer concrete wythes, but these connectors have the potential to allow heat loss. In this study 2 connector types were used: 1 manufactured using FRP, the other with stainless steel. A control (non-structural) panel was manufactured containing no connectors. The thermal performance of each panel was assessed through experimental hot-box testing to determine U-values. This was complemented by a series of images taken using a thermal camera to show areas of heat loss. In addition the U-values were also determined using a theoretical numerical approach and a thermal finite element analysis (using MSC Patran) was conducted to determine the heat flux through the panel.

The results showed that the connector type has a significant influence on the thermal performance of the sandwich panels, and that those containing steel connectors were not capable of providing the required U-value. The relative performance of the various panel types was consistent between analysis methods, as the finite element, the numerical and experimental approaches were in agreement. In addition, the heat losses observed through the thermal imaging camera were consistent with the heat losses predicted by the finite element analysis. It is proposed then that the use of numerical and finite element approaches has a valuable role in the design of thermally efficient sandwich panels. The experimental testing required is time consuming and requires significant effort. The analysis approach described above will make the design process more efficient and facilitate the construction of energy efficient buildings.

Modeling of Progressive Collapse in Reinforced Concrete Structure

Numerical Modeling
Strategies for Sustainable Concrete Structures

A.R. Rahai[1], M. Banazadeh[1], M.R. Seify Asghshahr[1]

[1] Department of Civil Engineering, Amirkabir University of Technology (Tehran Polytechnic), Iran ,
{rahai,mbanazadeh,m_seify}@ aut.ac.ir

Abstract

Progressive collapse is the complete failure of the structure or of a major part of it when one or several load-bearing elements fail suddenly. One of the scenarios that guidelines such as GSA (General Service Administration) and DOD (Department of Defense) propose for progressive collapse analysis of structures is the instantaneous removal of a column in different locations; this kind of analysis is assumed to be independent of the cause of damage. Bombing, explosion and sudden external impacts can be the cause of damage. Behaviour of structure after column removal can be investigated through static and dynamic analysis.

Model of 5-story RC structure developed using OpenSees software and designed based on current concrete codes. The modelling method was verified using the experimental and analytical studies done in Northeastern University and Amirkabir University of Technology, respectively. In addition to material nonlinearity, geometric nonlinearity is considered in analysis because large deformations occur in structure after column removal. The nonlinear force based elements are used for accurate modelling of the structure. Service loads for progressive collapse analysis of structure are calculated based on GSA guideline.

In this research after removing the column from the model, at first redistribution of the forces to other elements is investigated through a linear static and nonlinear dynamic analysis. Response of structure in linear static analysis is evaluated by demand to capacity ratios (DCR). Then plastic deformations in elements during the nonlinear dynamic analysis are evaluated. Finally the effects of the duration of element removing as well as the location of the removed elements are discussed.

Keywords

Progressive Collapse, Reinforced Concrete Structure, Nonlinear Dynamic Analysis, Instantaneous Removal, OpenSees Software

Numerical Modeling of FRP- Confined Square RC Columns under Axial load and Biaxial Bending

A.R. Rahai[1], H. Akbarpour[2]

[1,2] *Dep. of Civil and Environmental Engineering, Amirkabir University of Technology, Iran, {rahai,hakbarpour}@aut.ac.ir*

Abstract

Rehabilitation of RC buildings after a lot of destructive earthquakes becomes a considerable point in structural engineering. Application of fiber-reinforced polymer (FRP) sheets for strengthening of the RC elements such as those columns which are commonly under biaxial eccentric loading is known as a more effective technique. This paper presents the results of a numerical modeling of square RC columns using of both the finite element analysis (FEA) and the fiber method modeling (FMM). This iterative procedure predicts the location of the natural axis at every step and updates the stiffness matrix of elements produced with the principle virtual work. For this reason, the cross-section is divided into a number of small fibers and a step-by-step loading is applied. Strains of all fibers are calculated and the elemental stiffness matrix as a function of strain distribution states as well as the stress-strain relation of each material has been regenerated. Finally, interaction diagrams of a bi-direction eccentric loaded square column are plotted. The results compare with the experimental study has conducted by El Sayed and El Maaddawy at United Arab Emirates University. It shows that the results of the numerical model are in a good agreement with experimental results.

Keywords: Biaxial Bending, Square RC Columns, Interaction Diagram, fiber-reinforced polymer

Reliability of Ancient RC Structures by Means of Numerical Modeling

S. Tattoni, F.Stochino

DISIG University of Cagliari, Italy

Abstract

Within the framework of the Italian National Project PRIN-2006-08 "Architecture and Structures in Italy after the 2nd World War (1945-1965) – "Procedures and Techniques for Upgrading and Rehabilitation" the research team of Cagliari, leaded by Prof. Antonello Sanna, was particularly involved in Reinforced Concrete Structures.

In sustainability theme it is very important to know if the historical existing structures may be used nowadays or they must be refurbished or, even, demolished and reconstructed.

The critical approach to the comprehension of the structural behaviour of such buildings requires to immerse in the shoes of the original designers. In fact they had to rely only on tables and slide rules for safety assessment. The first step to reach the targets of the I.N. Project was the reconstructions of the original concept design by means of documental research. Then it was possible to describe the computation models (usually very simplified) developed by the original designer.

The following step was to compare the original computation models with the current constructions codes. The question was if current codes are more or less on the safe side. Generally it was proved that no significant variations appears between old and current codes in safety assessment. The only significant differences arise from original designers' mistakes.

At last the whole structures have been analyzed in a more sophisticated manner by means of modern computational numerical methods (FEM). The comparison between the results obtained by these last methods and the original ones allows a better understanding of the behaviour, and in such cases to discover unsuspected resources of the structures.

As an exemplification of the above mentioned procedures two significant cases, both in Cagliari, are presented in this work. The CasMez pavilion, a folded plate RC structures, and the San Domenico Church, a meaningful example of the interaction between modern and ancient architecture.

Figure 1: Picture of CasMez pavilion (left) and San Domenico Church (right).

Seismic Performance Evaluation of Reinforced Concrete Building with Static Pushover Analysis

K. Tounsi[*] , H. Aknouche[**]

*   *Superior National School of Public Works, ENSTP, Algiers, Algeria*
* * *National Centre of Applied Research in Earthquake Engineering, CGS, Algiers, Algeria*

Abstract

The aim of this presentation is to investigate the nonlinear performance of reinforced concrete framed building which is taken as a representative structure of the mid-rise RC buildings currently designed in Algeria under the new seismic Code RPA99/2003.

The global and the local frames behaviour are studied under several earthquake ground motions. Nonlinear Static **"Pushover"** Analysis using various lateral load patterns was also performed.

The seismic performance of the structure is determined on the basis of its damage state under an earthquake ground motion. For this purpose, inelastic dynamic and nonlinear static analyses are used to calculate the damage state *"inter-storey drifts"*.

Damage Index from the nonlinear time history analysis is compared with those obtained by Pushover Analysis procedure.

Keywords

Seismic performance, Non linear analysis, Pushover, RPA99/2003, Damage state.

Decreases to the Carbon Dioxide Impermeability of Polyurethane Waterproof Membranes Caused by Weathering and Concrete Substrate Cracking

M. Tsukagoshi*, T. Ueda*, K. Tanaka**

University of Tokushima, Japan, Tokyo Institute of Technology, Japan**

Numerical Modeling
Strategies for Sustainable Concrete Structures

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Abstract

Concrete structures, to a certain extent, are intrinsically durable. However, in recent years they have been being required to resist carbonation to meet the demand for extended service lives of buildings. For this reason, waterproofing membranes having CO_2-shielding performance are employed as a means to prevent carbonation of concrete substrates.

However, little attention has currently been paid to the problem of cracking under such membranes, which is difficult to completely eliminate in reinforced concrete buildings. It's often the case that waterproofing membranes are adhered to concrete substrates.

Therefore, cracking occurring in concrete substrate which has been coated with such a membrane is a concern because the membrane on the crack elongates and decreases the shielding effect. In addition, almost all waterproofing membranes are composed of organic materials, which gradually are deteriorated by ultra violet radiation, heat and rain. This deterioration further elongates and thins the waterproofing membranes across the cracks making them more permeable to CO_2, and thereby accelerating carbonation.

The purpose of this study is to investigate the carbonation resistance of waterproofing membranes applied to the concrete surface, particularly the changes to the membrane's shielding effectiveness caused by substrate cracking and deterioration due to weathering.

The study examines test specimens of concrete beams coated with membranes of various thickness, stressed to produce a 1.0mm wide crack, and exposed to the outdoors for five years in Yokohama, Japan. In particular, carbonation around the cracked zones of the specimens is examined. The study finds that the thickness of waterproofing membranes is significant. Membranes with a thickness of 0.5mm allow carbonation to proceed along the cracks. Within the parameters of this study, a membrane with a thickness of 1.0mm or more appears to resist carbonation of concrete around crack.

The changes in the CO2 permeability of deteriorated waterproofing membranes are also investigated. On the basis of these observations, a numerical simulation method is developed in order to predict the influence on carbonation caused by the degradation of the membranes. Note that, carbon dioxide gas is assumed to permeate in the following three stages : (1) CO2 gas diffuses and permeates through a waterproofing membrane; (2) CO2 gas and air mutually diffuse in the space in the crack; and (3) CO2 gas diffuses into concrete. It is the stage (1) process which is the focus of the consideration of the changes caused by the deterioration of the membrane.

Carbonation was simulated using a simple model incorporating the extension of a waterproofing membrane across cracking, and the results were compared with test results. The numerical modeling appears useful and capable of evaluating the carbonation phenomenon in cracked substrate concrete.

Mechanical Analysis and Simplified Models of Concrete Block Infill Walls under Out-of-Plane Action

Wei-qiu Zhong[1] , Ming-shu Gang[1], Xian-hui Cai[2]

1 Faculty of Infrastructure Engineering, Dalian University of Technology, Dalian 116023, Liaoning, China
2 Department of Engineering Mechanics, Faculty of Vehicle Engineering and Mechanics, Dalian University of Technology, Dalian116023, Liaoning, China

Abstract

In big earthquakes, the whole collapse of infill walls often happened. It is essential to analyze mechanical performance of infill walls under out-of-plane action and to study out-of-plane capacity of infill walls for the serious damage results. Furthermore, another problem should be penetrated into: what kinds of simplified models are appropriate to calculate out-of-plane capacity of infill walls. In the present paper, the concrete block infill walls were analyzed by ANSYS software and the deformation in plane was ignored. Hence the issue of out-of-plane action was transformed to the issue of plane strain. Two kinds of concrete block infill walls were numerically simulated in nonlinear way and analyzed. One kind was rigidly connected to top beams, and the other was connected to top beams with steel bar. Under uniformly distributed load and displacement between floors, the infill wall cracked. In the process of cracking, the stress changed and failure modes were inspected. The arching effect of rigidly connected walls was obviously represented in the late cracking period. However, the arching action did not exist for the infill walls connected with steel bar, and the capacity of this kind was obviously smaller than rigid connection one. Based on this, different simplified models for four circumstances were proposed: the infill walls rigidly connected on top can be considered with arch model of three hinges under uniformly distributed load, and can be considered with arch model of two hinges under displacement between floors. The walls separated from top beams and connected by steel bar can be simplified by hinge joints on the top and consolidation on the bottom model for two kinds of action.

Session II-3:Nuclear structures and storages

Cracks distance and opening in reinforced concrete membranes: codes predictions vs. experimental measurements
P. Bisch, S. Erlicher
Egis Industries, Montreuil, France

A new Creep model for NPP containment behaviour prediction
A.Foucault
EDF R&D, Clamart, France, LaMSID,UMR EDF/CNRS 2832, Clamart, France

Dunkerque LNG Terminal : tanks design
Maryline Verbauwhede, Louis Marracci
Bouygues Travaux Publics, Saint-Quentin en Yvelines, France

Modelling of leak tightness degradation of reinforced containment vessels due to aging and cracking mechanisms
Mahsa Mozyan-Kharazi

Finite Element Analysis of Thermal Restraint at Early Concrete Ages, Exemplified by Cooling Tower Shell Structure
Dipl.-Ing. K. Turner, Dipl.-Wirtsch.-Ing. D. Schlicke and Prof. Dr.-Ing. habil. N. V. Tue
Graz University of Technology, Institute for Structural Concrete, Austria

Cracks distance and opening in reinforced concrete membranes: codes predictions vs. experimental measurements

M. Rachidi, P. Bisch, S. Erlicher

EGIS Industries, 4 rue Dolores Ibarruri, TSA 50012, 93188 Montreuil cedex, France

Abstract

An important aspect of reinforced concrete structure analysis for design purposes is the evaluation of crack distances and openings [1-5]. This kind of information is required for checking the structure against the serviceability limit state. In the practical applications, in particular for walls in nuclear buildings, the evaluation of crack openings should be based on an accurate and robust procedure.

In this paper, we use a procedure of crack assessment articulated in two phases: (i) evaluation of stresses and strains by a finite element (FE) model where reinforced concrete walls and slabs are represented by shell elements with a suitable macroscopic nonlinear constitutive rule; (ii) computation of crack distances and openings from stresses computed at the previous step, by using a procedure inspired to Eurocode 2 formulas [6] and to the cracked membrane theory of Kaufmann [1]. The choice of decoupling these two coupled aspects of the crack analysis is motivated by the need of a numerically not too expensive procedure for industrial applications.

Observe that phase (ii) is not carried out by merely using the formulas of Eurocode 2, because, by the authors' knowledge, they mainly concern the case of cracks in reinforced concrete beams and not the case of membranes. Hence, in the case of membranes a comparison is needed between Eurocode predictions and experimental results. The experimental results used here come from the experimental campaign carried out in the framework of the National French Project CEOS.FR [7-9] on a reinforced concrete wall subjected to shear load.

A new Creep model for NPP containment behaviour prediction

A.Foucault

EDF R&D, Clamart, FRANCE
LaMSID,UMR EDF/CNRS 2832, Clamart, FRANCE

Abstract

Electricité de France (EDF) - the French main electricity production and distribution company - manages 59 nuclear power plants (NPP) in France. Some of these NPP are based on the concept of Pressurized Water Reactor (PWR), where the radioactive protection is ensured by a double concrete containments vessel.

In order to deal with the security and durability of these concrete structures, engineers require numerical tools to predict delayed strains. Indeed, creep and shrinkage cause cracking, losses of pre-stress and redistribution of stresses in the structures.
The numerical simulations of delayed strains are actually performed on the FE software Code_Aster [4] with the constitutive model BETON_UMLV_FP, developed by Benboudjema[2]. This paper will only deal with the creep part of the hydro-mechanical model [2], which includes the description of drying, shrinkage, creep and cracking phenomena.
It is assumed that the creep process can be split into a spherical and a deviatoric part as assumed by [1,2,6,7]. This concept has been motivated by experimental results [3], which have shown a proportional link between stress and strain according to this decomposition in two parts.

The feedback on using the creep part of this constitutive model and also some recent experimental results [4] highlight theoritical points to review its formulation. The experimental results of Brooks[4] on uniaxial creep tests show a slower creep rate over the 30-years of records. In contrast, the BETON_UMLV_FP model assumes on the deviatoric part a constant creep rate long-term. Moreover, the lack of interaction between spherical and deviatoric parts of creep strains leads to a non-controlled evolution of the apparent Poisson's ratio.

The proposed improvements on BETON_UMLV_FP model are based on the works of Sellier and Buffo-Lacarrière [6]. The deviatoric and spherical parts of creep strains are modelled by Burger's chains with a non-linear term introduced on the Maxwell level. The viscosity depends on creep strain. However, our approach considers the effects of the tensor of creep strain and not only the spherical one.

This model is integrated through an implicit scheme into the Finite Element software Code_Aster. The analysis of the long-term behaviour of concrete samples has been done. The result of the comparison between numerical results and measured deformations on French NPP containment will be discussed.

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Dunkerque LNG Terminal: tanks design

M. Verbauwhede [1], L. Marracci [2]

Bouygues Travaux Publics, [1] Ingénierie Béton France, [2] Bureau d'Etudes

Abstract

The consortium composed of Entrepose Projets and Bouygues Travaux Publics has won a tender held by Dunkerque LNG, subsidiary of EDF, to design and build the three cryogenic LNG (liquefied natural gas) storage tanks of methane terminal of Dunkerque (Dunkirk) in Northern France. Each of the tanks has a working capacity of 190.000 m3. Their main dimensions are 91 m in diameter and 50 m height. They are among the largest "full containment tanks" built in the world, composed of an internal 9% Nickel steel inner tank which will contain the LNG at a temperature of -163°C, thanks to an insulation system composed of perlite, foamglas, fiberglass, etc..., and of an outer concrete structure (prestressed wall, reinforced dome and raft). Bouygues Travaux Publics will build the concrete structures and carry out the soil improvement. Construction should start at the beginning of 2012.

This paper will present numerical methods used during the design phase, both for structural design and concrete design.

The structural design had to cope with soft soil with significant settlements and important design seismic accelerations (0.30 g pga).

The following numerical models were used for structural design:
- Static models :
    - Axi-symmetrical model
    - Full 3D model for non axi-symmetrical loads
    - Geotechnical non linear model, which analyses construction phases and different service configurations (tests, tank drainage, consolidation), enables the soil improvement design and evaluates soil settlement
- Dynamic models for seismic analysis, which consider both full and empty tanks:
    - 3D non linear model for soil structure interaction and impedance matrix determination
    - Global seismic model which determines global response of the structure, taking into account soil structure interaction and liquid structure interaction
    - Detailed model for determination of seismic forces in the raft
    - Detailed model for determination of seismic forces in the dome and the top platform
- Thermo-mechanical model: this model copes with a major leakage of LNG across the steel inner tank which results in the progressive filling of the concrete outer tank. This configuration is studied via a non linear coupled thermo-mechanical model in which reinforcement rebars are modeled taking into account concrete mechanical and thermal properties variation against temperature, concrete non linear behavior and cracking.

- Specific thermodynamic and structural analysis for overfilling scenario for which it has to be demonstrated that the damage of the roof under the corresponding over pressure will occur in the first place enabling the over pressure to be dissipated and the containment of LNG still being ensured by the outer concrete wall and raft.
- Thermal models for fire and LNG leakage on roof studies

Concrete mix study in design phase will use a thermo-mechanical finite element model to assess early thermal behavior of concrete. The purpose is to optimize the concrete formula and concreting methodology. CO_2 emissions will be reduced by using equivalent cement content method in order to reduce cement content.

Durability will also be integrated in this approach by incorporation of pulverized fuel ash.
Model results will be compared with measurements on full scale mock ups of relevant parts of tanks and with in-situ measurements in the final structure itself.

Modelling of leak tightness degradation of reinforced containment vessels due to aging and cracking mechanisms

M.Mozyan-Kharazi

Abstract

One of the main functions of a pressure containment vessel is its capacity to provide sufficient leakage tightness. This is obtained either by placing a liner covering the entire surface of the vessel, or by a thicker reinforced concrete wall. Periodically, the tightness of containments vessels is verified by means of tests, by injecting pressurized air into the vessel. The test is considered successful if the measured leakage is bellow licencing limit.

In most cases, test results are positive (bellow limits). But leakage measures indicate that some vessels maintain a steady rate even over several decades, while for others the leakage rate increases with time. The reasons behind these increases are more or less well known.

The purpose of this paper is to present a set of numerical models accompanied by a study methodology to help experts understand those mechanisms most responsible for leakage tightness degradation of prestressed reinforced concrete pressure containment vessels without liner.

An important feature of this work is that the solution proposed is adapted to the study of full size reactor buildings. Most research work dealing with this matter offers sophisticated modelling techniques, but their complexity and cost make it that they are only suitable for local studies. In our opinion it is essential to simultaneously encounter all phenomena behind tightness decay, in order to be able to compare simulation results with test measures. This is mandatory to demonstrate the efficiency of the technique, in order to provide reliable engineering analysis tools that can be used to improve design codes for future constructions, or develop retrofitting solutions to improve or maintain leakage tightness of existing reactor buildings.

In this methodology, the gas flow across a concrete wall is classified in three parts: flow due to the natural porosity of material; accelerated flsow through microcracks, and macrocracks. In the last case, both open and reclosed cracks are accounted for. In this approach, it is considered that the gas phase consists only of dry air. Transport through the unsaturated sound and microcracked concrete is calculated by Darcy's law. In case of discrete cracks, it is with Poiseuille-flow equation that leakage is estimated. In unsaturated sound concrete, permeability is defined by both intrinsic porosity and hydric state of concrete (degree of saturation). In unsaturated damaged concrete, permeability also depends on the mechanical state. That is why, prior to permeability and leakage calculations, thermo-hydric and mechanical analyses are performed to determine saturation degrees and damage states. These analyses use thermo-hydro-mechanical models which include moisture and heat transfer, creep, shrinkage, damage and cracking in concrete.

Simulations are performed by coupling the finite elements program Code_Aster®, and the fluid mechanics program ECREVISSE, both developed by EDF.

Different experimental elementary tests are studied to check the validity of mechanical, thermal, hydric and hydraulic models individually and when coupled. Finally a large scale structural application is studied in order to assess the model's ability to simulate a complex case.

Finite Element Analysis of Thermal Restraint at Early Concrete Ages, Exemplified by Cooling Tower Shell Structure

SSCS 2012

Numerical Modeling
Strategies for Sustainable Concrete Structures

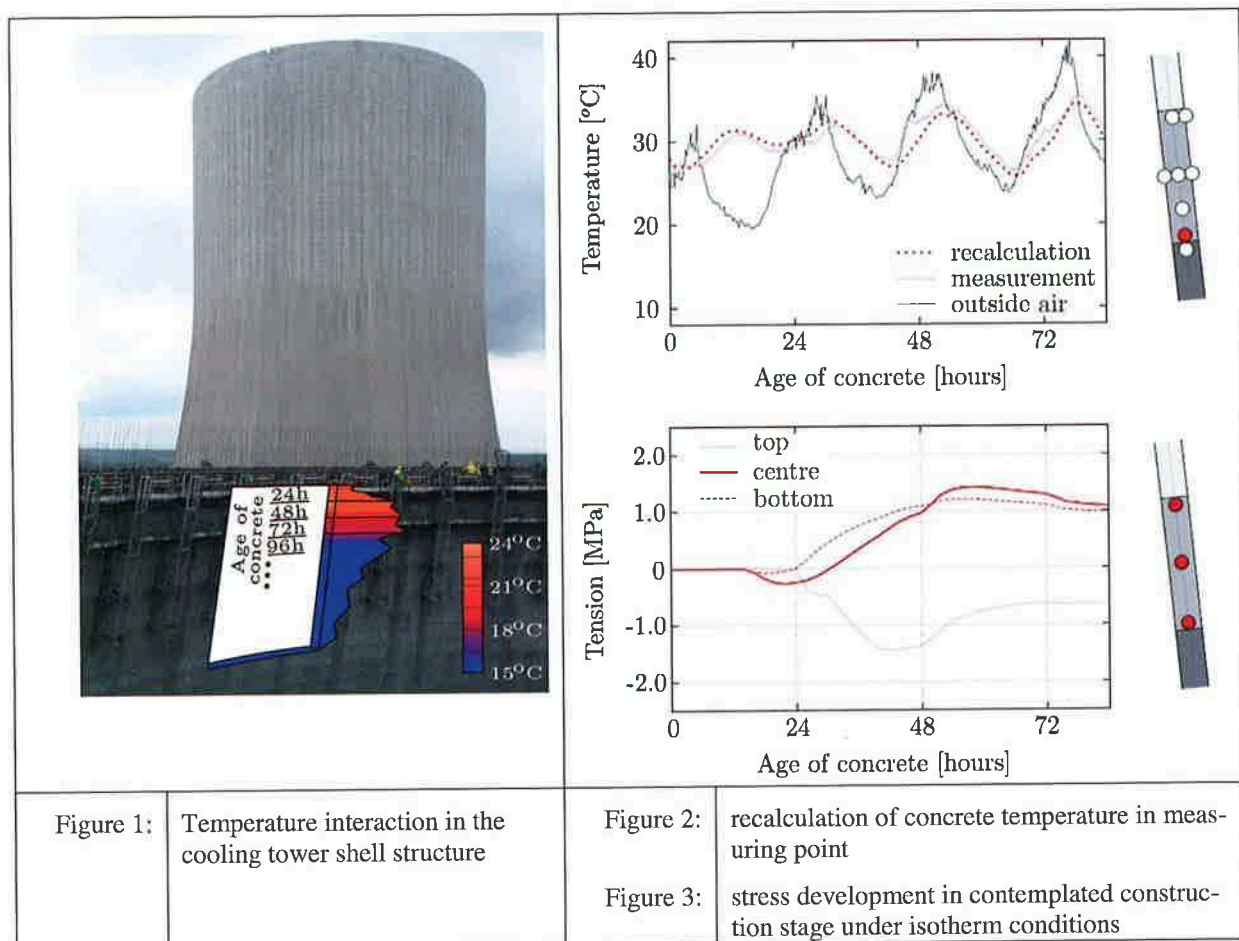Aix-en-Provence, France
May 29-June 1, 2012

Dipl.-Ing. K. Turner, Dipl.-Wirtsch.-Ing. D. Schlicke
and Prof. Dr.-Ing. habil. N. V. Tue

Graz University of Technology, Institute for Structural Concrete, Austria

Abstract

By reason of thermal restraint structural concrete elements are exposed to an increased risk of cracking during the hardening process. The use of new concrete compositions and extraordinary structural member dimensions require comprehensive research. In order to determine possible effects on serviceability we depict a way to simulate the behaviour of concrete at early ages.

The presented calculation model was developed for detailed investigation of thermal and mechanical interactions in a construction stage of a cooling tower. The calculation model allows the reproduction of the temperature development in the member. Based on the prevailing temperature it is able to simulate the evolution of the mechanical characteristics and the resulting restraint stresses properly.

Figure 1:	Temperature interaction in the cooling tower shell structure
Figure 2:	recalculation of concrete temperature in measuring point
Figure 3:	stress development in contemplated construction stage under isotherm conditions

It is useful to link heat dissipation and the development of the concrete's strength properties to the hydration degree. Performed material analyses provided corresponding knowledge of the hardening process. Temperature measurements in the structure were executed additionally. Furthermore thermal boundary conditions, assembly situation and construction progress were taken into consideration.

The contribution is focused on the implementation of the material behaviour in the calculation model and their adjusting to the obtained measurement data for achieving conclusive results.

Session II-4:Tunnels

Analysis of cracking due to shrinkage restraint in a concrete tunnel
M. Briffaut, A. Bonnet, B. Bahrami, F. Benboudjema, L. D'Aloia
LMT, ENS CACHAN, France / CETU, Bron, France

The study of interaction between sprayed concrete and steel support in a rock-TBM tunnelling using 3D-FEM model
G.D. Kang, Y.S. Kwak, I.M. Lee
Daelim Industrial Company, Korea University, Korea

Analysis of cracking due to shrinkage restraint in a concrete tunnel

M. Briffaut, A. Bonnet, B. Bahrami, F. Benboudjema, L. D'Aloia

LMT, ENS CACHAN, France / CETU, Bron, France

Abstract

Cracking in concrete structures can reduce drastically its serviceability, since it increases the permeability and diffusivity. Therefore, it leads to a faster penetration of liquid/gas (which is prejudicial if the tightness must be guaranteed like in water reservoir or dams, nuclear and gas containment, tunnel etc …) and aggressive agents (chloride, CO_2 … leading to corrosion, in bridges, beams, column etc …). Cracking may be due to the (self or external) restraint of autogeneous, drying and thermal shrinkage.

This study concerns the prediction of cracking due to restraint of shrinkage in a concrete tunnel. The objective is twofold. First, the effect of fibres (two types of organic fibres and one type of steel fibre) has been studied (via experience and numerical simulations) and compared to a solution using anti-crack mesh. Secondly, an analysis has been performed in order to investigate the effect of autogeneous, thermal and drying shrinkage.

Since several phenomena are involved (hydration, thermal, drying, shrinkage, creep, cracking), an important experimental program has been carried out. It consists to measure "classical" thermo-mechanical parameters (hydration heat, autogeneous shrinkage, dilatation coefficient, Young's modulus …), which are needed for the numerical simulations as input data. Ring tests have been also performed: a concrete ring is cast around a brass one. Therefore, the shrinkage of concrete is restrained by the metallic ring, which is representative on an external restraint. The time of cracking (which allows for quantifying the potential of cracking) and evolution of strains in the inner brass ring (which allows for identifying creep parameters) are measured. At this time, drying shrinkage has not been taken into account (it is currently under investigation). These experimental results show (for the studied mix designs), that the solution using steel fibres cracks the latest, with the smallest crack opening. Splitting tests show also that its tensile strength is the most important. Besides, the presence of fibres does not seem to modify the creep of concrete.

A numerical model has been developed to predict early age cracking. All major phenomena have been modelled (hydration, drying, heat, evolution of mechanical parameters, thermal and autogeneous shrinkage, basic creep …). For the prediction of cracking, a simple elastic damage model is used. Numerical simulations have been performed in order to predict the behaviour of a concrete tunnel lining (50 cm width) for 2 different concrete mixes and different types of fibres (polypropylene, steel). The results highlight that:

- A cracking pattern, close to the one observed usually on tunnel lining, has been obtained (see Figure 1)

- Crack opening depends upon the type of fibers;

- Drying can be neglected at early-age for such massive structures;

- Creep plays a significant role: stresses are relaxed and less damage is predicted;

- Finally, meeting both technical and environmental requirements and ensuring the durability of the structure can be a great challenge when choosing a concrete mix for tunnel lining.
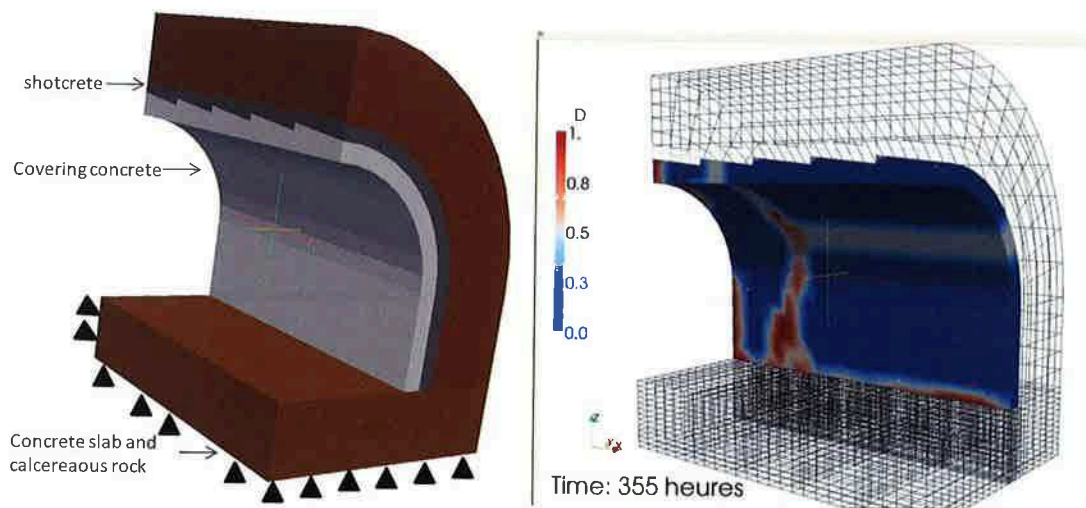

Figure 1: Cracking due to the restraint of autogeneous and thermal shrinkage in a concrete tunnel

The study of interaction between sprayed concrete and steel support in a rock-TBM tunnelling using 3D-FEM model

G.D. Kang, Y.S. Kwak, I.M. Lee

Daelim Industrial Company, Korea
Korea University, Korea

1. Introduction

Recently in Korea, the need for underground public utility is increasing and projects of deep and long rock tunnels are being proposed. The construction of tunnel and underground space come to the fore and as the reason of greening the cities, thought to be the main way to realize *the green growth policy* which has the aim of reducing CO_2 emissions. In this point of view, the blasting noise and vibration should be minimized, so *the mechanized tunneling* is preferred and considering deep and sound rock condition, the open tunnel boring machine(TBM) could be the optimum method of excavation. But the open TBM method has the problem of *jamming* when in a complex geological condition or fractured zone, the *modern gripper TBM* which has partial shield at the tunnel face and automated supporting system is thought to be the best solution.

Sprayed concrete is the main support of tunnel that forms an immediate and intimate bond with the excavated rock surface that interacts actively with the ground, steel support, and rock bolts. A properly applied sprayed concrete lining is equivalent in strength, impermeability and durability to conventional cast in place concrete. In this study, using 3D-FEM model(see figure 1&2) the interaction between sprayed concrete and ring beam as the advance of tunnel face is performed. The curing time of sprayed concrete is applied by changing the deformation modulus as soft to hard considering advance rate of tunnel face and the interaction behavior with the ring beam is analyzed by the deformation convergence. Also, the combination of sprayed concrete and steel support are proposed and the effect of inner pressure which enhances the support resisting level.
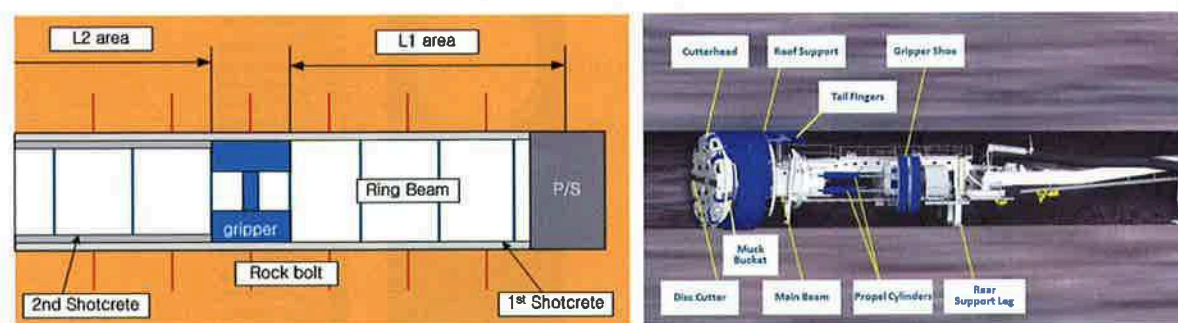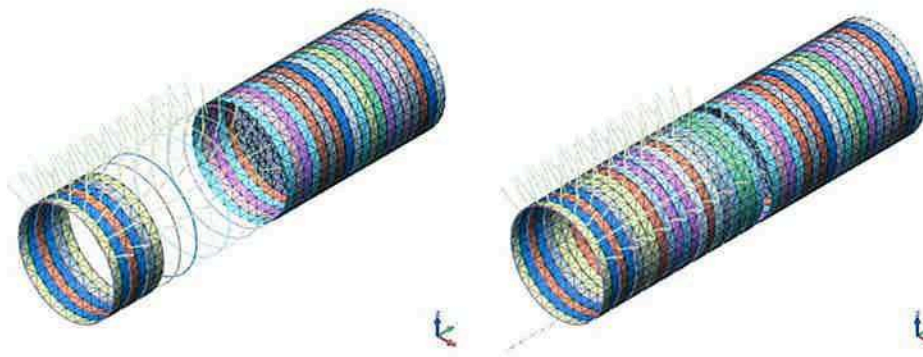

Figure 1: Schematic diagram of 3D-model

Figure 2: Sprayed concrete model with curing time(left-without sprayed concrete in L1 area: case-1, right- with sprayed concrete in L1 area: case-2)

2. The interaction between sprayed concrete and steel support

The stress distribution of sprayed concrete is shown at figure 3. As a result, the bending stress of sprayed concrete at L1 area is very much increased compared to that of L2 area. The arching effect with the advance of tunnel face redistributes more loads to sprayed concrete than steel support compared to spray concrete only in L2 area, and it means that to penetrate poor ground condition there should be another reinforcing methods in addition. In this study, using increased inner pressure to steel support it is possible to stabilize the excavated ground as shown at figure 4(plastic zone decreased with inner pressure) and this method should carry L1 area of sprayed concrete, the accelerating agency should be added to shorten the curing time.
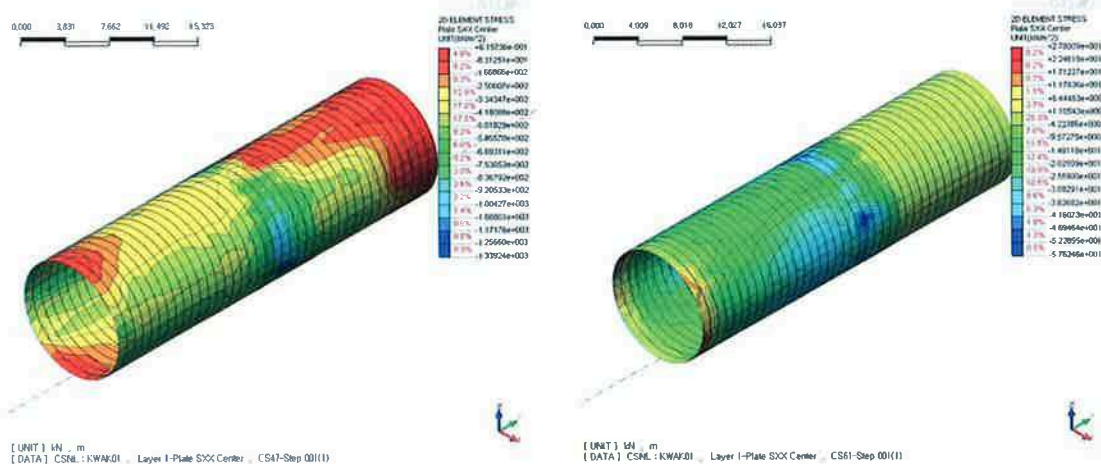
Figure 3: Stress distribution of sprayed concrete case-1&2
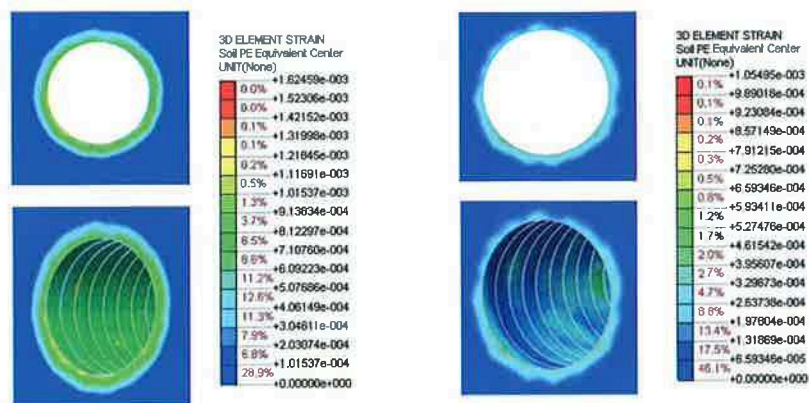
Figure 4: Plastic zone before (left) and after (right) inner pressure applied

174

Session II-5: Other applications

Construction phasing of a dam spillway: thermo-mechanical simulation

M. Azenha, R.M. Lameiras, J. Barros, A. Costa

ISISE, Institute for Sustainability and Innovation in Structural Engineering
University of Minho, Guimarães, Portugal

Abstract

The construction phasing of massive concrete elements is an issue that frequently raises doubts to practitioner engineers in regard to the risks of thermal cracking. A sustained estimation of temperature and self-induced stress development that occurs at early ages can only be achieved by numerical simulation with thermo-mechanical models, through which scenarios of construction phasing/scheduling can be compared.

The recourse to such approach consists on the initial computation of the temperature field, and subsequent evaluation of the corresponding stresses. The thermal field is calculated considering the variable environmental temperature, the exothermal and thermally activated nature of cement hydration reactions, as well as the adequate modelling of boundary conditions. The stress field is determined for each time step considering the corresponding temperature variation and the thermal dilation coefficient of concrete. The evolution of E-modulus and the creep behaviour at early ages are of particularly importance, and are also carefully estimated.

Tis paper deals with the assessment of the temperature and stress development in the construction of a 27.5m long wall integrated dam spillway, with a thickness that attains a maximum of 2.8m. This wall has a total height of 15m, and is constructed by stages. Particular attention is devoted to a segment of the construction, in which a 2.5m tall concreting was performed, and internal cooling of concrete was made with recourse to prestress sheaths into which air was blown by industrial fans. Parts of this casting phase were monitored by temperature sensors (thermocouples and thermistors) and vibrating wire strain gages.

The paper encompasses an initial description of the studied structure, along with the corresponding environmental conditions and a brief description of the monitored temperatures and strains. A summary discussion of laboratory characterization tests is also made, and the overall properties of the studied concrete are provided. The main focus of the paper is then centred in the description of modelling strategies and their discussion in view of the available laboratory testing and the in-situ conditions of the spillway wall.

Fatigue life of fire damaged concrete cylinders repaired with carbon fibre reinforced polymer subjected to cyclic loading in compression

Y.K Guruprasad, Ananth Ramaswamy

Department of Civil Engineering, Indian Institute of Science, Bangalore, India

Abstract

This study looks at concrete cylinders of 25MPa cylinder compressive strength, 150mm in diameter and 300mm in height, exposed to temperatures of 715 degress Celcius for a duration of 4 hours and 2 hours respectively , 550 degress Celcius for a duration of 4 hours, cooled and thereafter repaired with CFRP wrap was subjected to cyclic loading in compression to assess the fatigue life of these cylinders with fire damage.

The concrete cylinders which were subjected to fire damage at different temperatures and duration as indicated above were wrapped with CFRP. It was observed that the concrete cylinders subjected to fire damage at temperatures of 715 degress Celcius for 4 and 2 hours and 550 degress Celcius for 4 hours had cracked extensively and had very low compressive strength of the order of about 20 to 50 % of the corresponding control cylinders in compression. When these fire damaged cylinders were wrapped with CFRP and subjected to cyclic loading in compression, these cylinders failed at significantly large number of cycles close to the number of cycles at which the cylinders which were not subjected to fire damage and without CFRP wrap(control cylinders) had failed under cyclic loading in compression.

This indicated that the fire damaged concrete when well confined by the CFRP can result in a substantially improved fatigue life.

A finite element model has been developed for predicting the behaviour of fire damaged unrepaired and repaired cylinders with CFRP under cyclic compression loading.

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Design of UHPC Wind Turbines

FX. Jammes, X. Cespedes, J. Resplendino, FJ. Ulm

Setec tpi, 42/52, quai de la Râpée, 75 583 Paris cedex 12, France

Abstract

Ultra-High Performance Concrete (UHPC) has proven an asset for bridge design as it significantly reduces the quantities of material used. However, UHPC has not been applied yet to wind turbine technology. Wind turbine design is mostly based on the use of steel, which is not proven to be the most effective material in terms of cost and durability. In recent years, some authoritative studies have shown the advantages of building reinforced concrete towers and a number of companies have adopted this solution *[1]*. The purpose of this paper is to go even further by considering UHPC as the best steel substitute available. The project is mainly adapted from a Master's thesis achieved by FX. Jammes in 2009 and supervised by Professor Ulm at the Massachusetts Institute of Technology *[2]*.
J. Resplendino, an international expert of UHPC, played a key role in the relevancy of the research as well as X. Cespedes who helped to develop the most innovative FE models.

First, the unique characteristics of UHPC in terms of fatigue are highlighted. For current offshore projects where the tower height is of primary concern, fatigue represents an important limit for a steel design. Therefore, the superiority of UHPC over steel in this field definitely makes it a more appropriate material.

Then a design of the mast using UHPC in the case of onshore conditions is suggested. The design loads are adapted from the literature and their values were validated by experts from the most specialized design organisations *[3]*. The accuracy of the design is validated through two main finite element models. Hence, the structure is globally checked by being modelled as a cantilever beam according to the beam theory. Local verifications have been carried out through a very innovative finite element model based on the shell theory. These models were developed in close collaboration with the Setec tpi R&D department led by X. Cespedes.

Finally, a revolutionary construction sequence is proposed in order to reveal the easiness of the erection process and to justify that UHPC could be directly applied by construction companies. The prefabrication, the jacking-up, and the fastening of the elements are more particularly considered.

The ultimate objective is to demonstrate that UHPC is an attractive substitute to steel for the erection of wind turbine masts.

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Numerical modelling strategies for safety assessment and rehabilitation of concrete dams

Pierre Léger[1], Ph.D, Eng, Lucian Stefan, M.Sc.A., Martin Leclerc, M.Eng, Eng.

Department of Civil, Geological and Mining Engineering, École Polytechnique de Montréal, Montréal University Campus, P.O. Box 6079, Station CV, Montreal, PQ H3C 3A7
[1] *Phone: (514) 340-4711 (ext. 3712), Fax :(514) 340-5881, E-mail: pierre.leger@polymtl.ca*
Pierre Léger CORRESPONDING AUTHOR

Concrete dams are major strategic infrastructures to produce renewable energy and control floods. In developed countries construction of new dams is limited. The challenge has been put in extending the service life of existing dams. Figure 1 shows the increase in service lives of existing dams that could be brought by implementing effective remedial actions, repair strategies, and protection systems. However, innovative and economic remedial work must be based on (i) an effective diagnostic and prognostic of past, present and expected structural behaviours, (ii) advanced knowledge of damaged, repair, and composite materials, (iii) suitable decision models based on cost-benefit analysis of different remedial actions, and (iv) appropriate construction methods and quality control procedures (Fig. 2).

This paper first presents the difference in CO_2 foot print of new dams (where it is possible to minimize cement consumption) and existing dams. The benefit of extending the service life of existing structures is discussed. The emphasis is then put on typical concrete hydraulic structures such as spillways for which innovative numerical modeling strategies have been developed. They were furthermore implemented in dedicated computer program CADAM-3D and complementary module GM-Dam to assess the structural stability of existing and repaired structures (Fig.3). Spillways are complex three-dimensional concrete structures often being unreinforced or with limited reinforcement. Multiple cracking directions can develop in spillways due to three-dimensional loading patterns (water and uplift pressures, ice impact, earthquake, ...). There is a lack of simplified computational methods to asses the safety of lightly reinforced hydraulic structures. The safety factors, widely used by the profession, were developed based on beam theory and global equilibrium. However, there is no direct way to include the effect of non prestressed reinforcement in the evaluation of these factors. The finite element analyses (FEA) can be used but in a progressive safety evaluation strategy simplified tools based on beam theory are initially preferred by practical engineers. FEA are particularly difficult to converge when water penetration and cracking occurs. The paper presents innovative robust methodologies for sectional analyses and safety factors computation of arbitrary cracked sections of spillway piers accounting for concrete cracking, the presence of passive reinforcements and uplift pressures.

A three-dimensional extension of the gravity method is developed accounting for biaxial moment interactions (P-M_x-M_y), presence of passive reinforcements, in-plane concrete cracking and 3D updating strategy for uplift pressures. The kernel of arbitrary cross sections is computed for a planar bi-dimensional extension of the so called "middle third" criterion extensively used for the location of the resultant where no-tension could be developed. The structural shear strength is evaluated by summing the shear resistance of concrete (friction and cohesion) and the shear resistance of reinforcements working as anchors. Cracked sectional analyses of reinforced spillway piers are shown as application examples.

There is a wide interest to develop efficient and robust tools for computation of safety indicators and strength evaluation of lightly reinforced hydraulic structures. The proposed methodology is very useful for practical engineers as it offers an accessible approach for the rational consideration of reinforcement bars in existing/repaired or new hydraulic structures. A decision can be made based on safety factors computed

for plain and lightly reinforced structure, because the amount of participation of the steel bars to the structural overall strength is clearly quantified. Using the proposed computational tools, the periodic safety assessments of concrete hydraulic structures, required by regulatory agencies, could be done efficiently. To implement repair strategies for extending their service life, recommendations could be established in a convenient approach using parametric analyses for initial cost – benefit evaluations of different repair strategies.
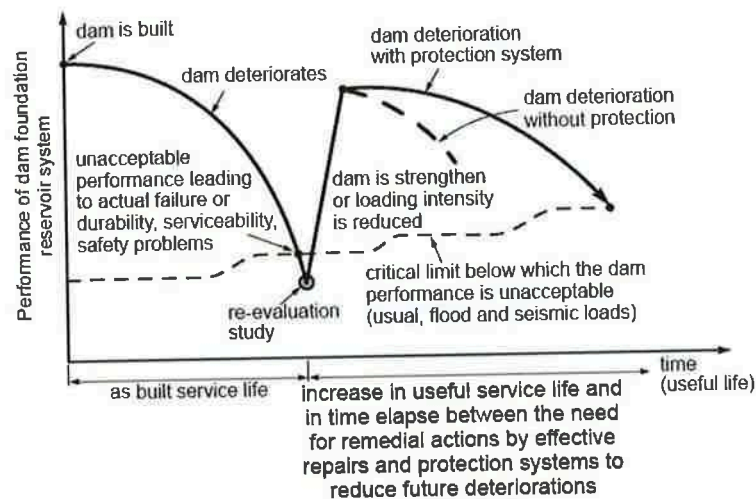

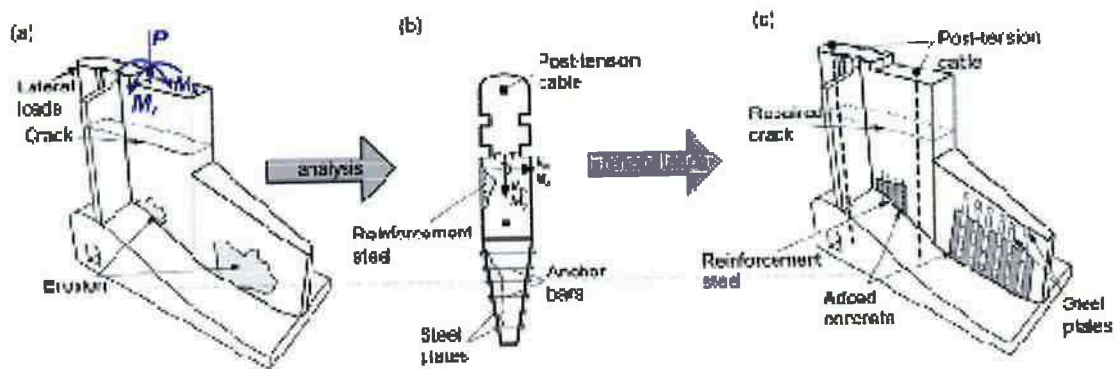Figure 1 – Rehabilitation to increase useful life of dams (adapted from Emmons 1994).

Figure 2 – Structural analysis and rehabilitation of concrete hydraulic structures.
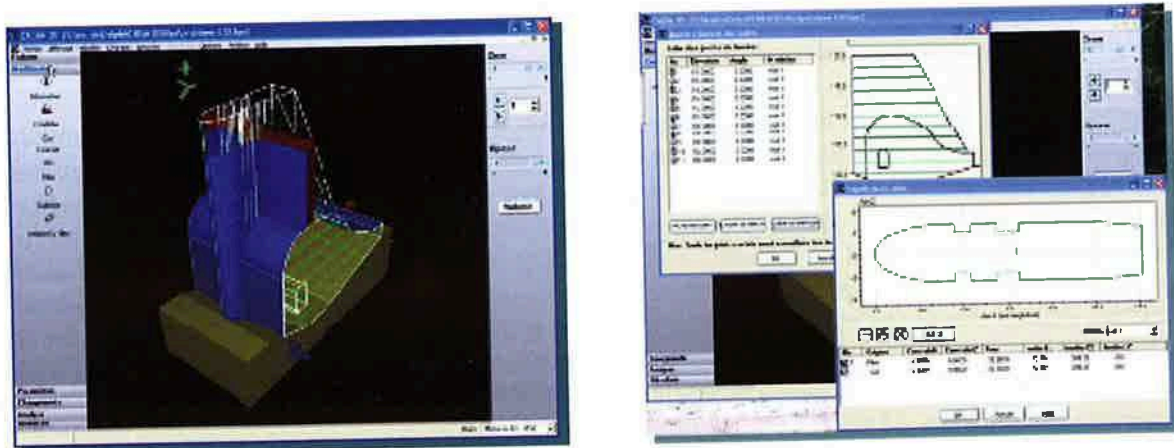

Figure 3 – Computer program CADAM-3D developed to assess the structural safety of hydraulic structures.

Explicit Nonlinear Finite Elements for the Design of Concrete Structures: Application to Hydraulic Structures

M. Ben Ftima, B. Massicotte

École Polytechnique de Montréal, Montréal, Canada

Abstract

Nonlinear finite elements for concrete structures have seen a remarkable advancement in the last half century with more emphasis on constitutive modelling of reinforced and non-reinforced concrete. Applications were restricted to the analysis of simple structures (beams, columns, slabs …etc.), comparisons to experimental tests, and rarely extended to the design of complex structures.

Many reasons lie behind this fact. The first is the difficulty to implement such analyses for complex structures: large computation time with respect to conventional linear analyses, and convergence problems generally related to concrete softening. The second important reason is the complexity of the concrete material and the existence of a multitude of models and theories in the literature. Finally, there is a lack in the literature and international codes concerning the reliability framework and the limit state design using nonlinear analyses. The current work presents solutions to these issues. To address the first problem, the quasi-static explicit solver algorithm is presented in this paper, as an alternative to the conventional static implicit solver. Effectiveness of the explicit solver algorithm compared to the standard implicit one is demonstrated. It is shown through validations that, analysis of complex models with highly nonlinear behaviour is possible without the need for iterations. To address the second and third problems, a methodology that uses nonlinear finite elements analysis for determining a global resistance factor for the design of reinforced concrete structures is suggested. A new reliability approach is introduced, which takes into account the uncertainties of the material properties and the performance of the concrete model used in the calculations. In the proposed approach, the global resistance factor is computed following a procedure in which the coefficient of variation of the calculated resistance is estimated using Rosenblueth's point estimate method.

Finally, the application of nonlinear finite elements is presented for the case of large hydraulic structures. The structure of draft tube, typical component of a powerhouse, is chosen as candidate for this application. It is a large concrete structure with low reinforcement ratios, complex geometry and highly nonlinear behaviour due to thermal loads and concrete-rock interaction. Analyses and design verification were conducted on a model with more than one million degrees of freedom. Comparisons are made with an existing powerhouse at service load, and showed good correlation for the cracking pattern, mainly due to thermal effects. It is shown that thermal effects could lead to a decrease in the structural resistance with a premature shear failure. Effect of shear reinforcement, a practice which is uncommon for this type of structures, is illustrated. It showed an interesting increase in the structural resistance with the use of minimal shear reinforcement.

Keywords: nonlinear analysis, finite element, reinforced concrete, explicit algorithm, global safety factor, limit state design, hydraulic structures, size effect.

Experimental and numerical studies on the behaviour of concrete sandwich panels

G. Metelli, N. Bettini, G. Plizzari

DICATA,University of Brescia, Italy

Abstract

Precast concrete panels are often used for the façades of modern warehouses and commercial malls. During the last two decades, they have generally been made of two concrete layers with interposed thermal insulating polystyrene boards. Traditionally, perimeter concrete ribs allow the weight of the external concrete layer to be transferred to the internal thus causing unavoidable thermal bridges which reduce the energy performance of the building. In the sandwich cladding panel, the two concrete layers can be linked by low-conductivity shear connectors crossing through the insulation layer, thus ensuring the overall thermal efficiency of the building.

The research study presented in the paper aims to better understand the behaviour of a concrete sandwich panels (CSP) realized by the use of pultruded glass fibre connectors. A wide numerical research program is presented, focusing on the stresses and deformations caused by dead load, thermal gradient and differential concrete shrinkage through the panel thickness.

Material properties and local shear behaviour of the connector were experimentally studied with preliminary tests.

The preliminary experimental campaign on the mechanical behavior of FRP connector shows a tensile strength ranging from 130 MPa to 160 MPa, depending on the fibers orientation. The tensile strength is weakly affected by the temperature with a decrease by 25% when temperature rises up to 100°C from 23°C. The shear strength is greater than 6.0 kN.

A 3D finite element analyses show the remarkable role of the position of the panel constraints (to the structure) on the shear action distribution among the connectors: when only the dead load is present, the outermost connectors are stressed by greatest shear force (that is reduced in the inner ones), thus confirming that the typical uniform distribution of the dead load among the connectors cannot be adopted for design purposes.

Results of several numerical analyses carried out with a thermal heating equal to 45°C or a thermal cooling of -25°C after a drying shrinkage actions ranging from 15 days to 1 year time, show that a young CSP could suffer from external wythe heating while an older one from cooling. The vertical shear action on the outermost connectors reaches a value close to 73% of the maximum shear strength under the effects of dead load, 15 days shrinkage and +45°C heating of external concrete wythe.

As the thermal gradient and drying shrinkage act like eigen-strains applied to the concrete wythes, an increase of the connector number at the outer panel ends does not markedly reduce the stress in the connectors. Furthermore, the presented 3D numerical model shows that the differential drying shrinkage (within the wythe thickness) due to the different humidity between the environment and the concrete-to-insulation interface, is responsible of out of plane imperfection of the CSP.

Comparison of Deterministic and Probabilistic Design (environmental aspects)

P. Štěpánek, I. Laníková, P. Šimůnek,

Faculty of Civil Engineering, Brno University of Technology, Brno, Czech Republic

Abstract

1. Introduction

The building industry is one of the largest consumers of material and energy resources and ranks among the largest producers of waste and harmful emissions. Therefore, it is useful to design a structure so that its environmental impact is minimal. To find the best possible design for a structure or member without a negative effect on the reliability system as a whole it is necessary to use a suitable optimisation method. The reliability of a structure can be expressed in accordance with the standard [1] via the commonly used partial reliability factor method, and also via the use of fully probabilistic methods in connection with that same standard and the standard [2].

The impact of structure on the environment should be assessed from the viewpoint of lifecycle of this ones. The methodology of life cycle assessment is defined in standards ISO 14040-14049. This methodology includes the following stages for a particular structure: the construction process, utilisation and the end of its life cycle.

The optimisation problem of the concrete structure may be, e.g. according to [3], defined by the target function

$$\{f(\{A_s\})\} = f(\min E_{tot}, \min C_{tot}, \max S_{tot}), \tag{1}$$

where E_{tot} is the gross environmental impact, C_{tot} is the gross cost and Stot is the gross socio-cultural quality. In a case when the Life Cycle Assessment of a structure is taken into account, it is possible to express

$$E_{tot} = E_{constr} + E_{oper} + E_{dem}, \tag{2}$$

$$C_{tot} = C_{constr} + C_{oper} + C_{dem}, \tag{3}$$

where E_{constr}, E_{oper}, E_{dem} are the environmental impacts for the construction, operation and demolition phases respectively; C_{constr}, C_{oper}, C_{dem} are the costs for the construction, operation and demolition phases respectively.

2. Case study – a prestressed concrete pole

A prestressed pole made from spun concrete was designed. The geometry of the pole is displayed in Figure 1.

The target function criteria involve economic, ecological and structural aspects (according to eq. (2)) in terms of life cycle of pole. The gross socio-cultural quality Stot was neglected. The target function describes the costs of the execution of 1 pole, the environmental impact being expressed in terms of

primary energy consumption, equivalent global warming potential, equivalent acidification potential and equivalent photochemical ozone creation potential. The problem is a multicriterial one and all the above-mentioned aspects should be minimised. The method of weighted sums should be applied; the problem then becomes monocriterial and a suitable optimisation algorithm can be selected. However, the terms of the objective function have different units and thus cannot be directly summed; for that reason they must first be normalized by the chosen reference values.

Restrictive conditions are formulated by the principles of standards [1] according to the reliability conditions of ultimate limit state (within normal force load and the bending moment) and serviceability limit state (deflection, crack origin and crack widths)

Design and assessment were carried out with software based on the algorithms determined and mentioned in [4]. This software was set up primarily for use in the partial factor method but then was modified for application in fully probabilistic design. The Monte Carlo simulation method was used to calculate the reliability, modified by the Latin Hypercube Sampling method (LHS). The statistical distributions of the material characteristics and some geometric characteristics were provided by the producer of the poles, while the uncertainties of the resistance model R and the calculation of the effect of loading E were taken from the recommendation in [5]. A description of the calculation is given in [6].

The design was based on the assumption that the geometry of the pole is unchangeable (it is determined by the mold in which it is produced); only the thickness of the concrete, the number of prestressed strands and the passive reinforcement (number of bars, length of bars) were allowed to be changed.
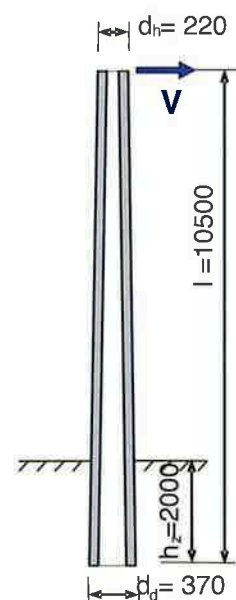

Figure. 1 Geometry of the pole

3. Results

From all the observed aspects the most advantageous proposal is the pole with the maximum amount of prestressed wire and lower concrete section thickness, which was designed using the probability-based method.

The proposals demonstrate that the probability-based method requires less reinforcement as compared with the partial safety factor method.

Materially-optimised structures seem to be environmentally-friendly without there being any explicitly prescribed goal of taking ecological aspects into account. This is because material savings mean less pollution. It is therefore preferable to choose a higher degree of reinforcement to reduce the volume of concrete.

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Conference Secretariat

Mrs Nadget BERRAHOU-DAOUD
Tel. + 33 1 44 58 24 29 - Fax + 33 1 44 58 24 79
e-mail : afgc@enpc.fr

www.sscs2012.com

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