Control of Cracking and Durability of Reinforced Concrete Structures

4th ConCrack Workshop
Engineering and Standard issues

Borislava Nikolova, Fabio Taucer, Jacky Mazars
2014
Abstract

This report contains technical and scientific information presented at the 4th workshop "Control of Cracking and Durability of Reinforced Concrete Structures", held on 20-21 March 2014 at the Joint Research Centre, Ispra, Italy. Co-sponsored by the Joint Research Centre, this event was the fourth of a series of "Control of Cracking" workshops (ConCrack) organised by the French research programme CEOS.fr. This programme was the framework set up by French professionals to make a decisive step in the predictive capacity of models to describe the state of cracking of buildings and civil engineering works, with the final objective of developing tools for designers and support the evolution of standards. The main purpose of the workshop was to improve engineering practices related to the cracking process in special massive concrete structures, thus enhancing the prediction of crack evolution during the service life of special structures. The international scientific and engineering community acknowledged the significance of the research findings and the practical results presented at the workshop enabling the exchange of expert know-how and codification. There was a strong motivation among participants to pursue further research work on the topic of cracking and durability of massive concrete structures, addressing aspects of cost, safety and sustainability.
Foreword

This report contains technical and scientific information presented at the 4th workshop “Control of Cracking and Durability of Reinforced Concrete Structures”, held on 20-21 March 2014 at the Joint Research Centre, Ispra, Italy. Co-sponsored by DG JRC, this event was the fourth of a series of “Control of Cracking” workshops (ConCrack) organized by the French national research programme CEOS.fr each year since the beginning of the programme in 2008.

The control of cracking has a direct impact on the durability and sustainability of structures, hence on the overall quality of the construction works and the quality of life of Europeans as outlined in COM (2012)433 “Strategy for the sustainable competitiveness of the construction sector and its enterprises”, communicated by the Commission to the European Parliament and the Council. Predicting expected crack patterns is crucial for the safety of critical infrastructures.

We gratefully acknowledge the workshop lecturers, the members of CEOS.fr and especially Prof. Jacky Mazars for the contribution, coordination and support to the workshop.

The contribution of Martin Poljansek for the graphic design of communication materials is appreciated.

More information can be found at the official web page of the CEOS.fr at http://ceosfr.org/.

Borislava Nikolova
Fabio Taucer
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1 Introduction

This report presents the outcomes from the 4th workshop “Control of Cracking and Durability of Reinforced Concrete Structures”, held on 20-21 March 2014 at the Joint Research Centre, Ispra, Italy. The workshop was preceded by CEN/TC250/SC2/WG1 and CEN/TC250/Sub-Committee 2 meetings on 18th and 19th of March 2014.

Co-sponsored by the Joint Research Centre, this event was the fourth of a series of “Control of Cracking” workshops (ConCrack) organised by the French research programme CEOS.fr. This programme was the framework set up by French professionals to make a decisive step in the predictive capacity of models to describe the state of cracking of buildings and civil engineering works, with the final objective of developing tools for designers and support the evolution of standards.

Organised in one day and half, the programme was divided in five sessions with presentations and discussions on the results of CEOS.fr research project and other European/International projects on crack control, followed by a round table entitled “What for the future?” regarding the CEOS.fr proposals related to standardisation.

This document corresponds to deliverable D.2 “Durability/Sustainability of concrete structures” related to Project 615 - PNR-Eurocodes “Pre-Normative Research and support to the implementation of the Eurocodes” of the Joint Research Centre. This project aims at pre-normative research exploiting the experimental results of ELSA and its network of European partners for developing safety standards. This includes assessment and retrofit of new and existing structures and critical infrastructure, increased loading due to climate change adaptation, further harmonization of NDPs and the new generation of Eurocodes.
2 Objectives of the 4th Workshop “Control of Cracking and Durability of Reinforced Concrete Structures”

Started in 2008, the joint national research programme CEOS.fr is now under finalisation. With the aim of making a significant step forward in the engineering capabilities for predicting the expected crack pattern of special structures under anticipated in-service or extreme conditions, the principal objectives of the workshop were to:

- present and discuss the main results obtained during the CEOS.fr programme and related research in Europe;
- propose and discuss standards rules for special construction works on the basis of lessons learnt from these results;
- discuss the opportunity of complementary research at European level.

The organisation of the workshop is relevant to the JRC activities in pre-normative research and support to the implementation of the Eurocodes. The main purpose was to provide scientific, technical and organisational support to standardisation works.

2.1 Scientific issues

The topic of “durability-tightness-corrosion” was one of the main aspects affecting the serviceability and ultimate capacity of reinforced concrete infrastructures. Based on the outcomes of the experimental research and within the framework of industrial projects, the following issues were discussed:

- What are the safety margins for severe events (beyond design events) and what is the related damage?
- It is necessary to establish a link between crack width and durability by taking into account the influence of cover, concrete quality, exposition class, link corrosion, and tightness.
- The effect of physical phenomena of probabilistic scale effects, non-uniform strains through thickness, and heating-cooling effects on tensile stresses at early age, should be accounted for in a better way when determining cracking and durability.

2.2 Practical implementation

A number of important issues related to the collected data during the experimental campaigns carried out with the framework of CEOS.fr were raised and discussed in order to further develop the present state of work for practical implementation:
Numerical experimentation provides useful insights for a better understanding of the physical phenomena.

There is a need to revisit and update the design procedures for durability, including characteristic values, safety factors, etc.

It is recommended to prepare engineering guidelines based on test results and numerical simulation.

Discussion with European experts should be promoted with the purpose of converging on commonly agreed procedures for crack estimation.

2.3 Standardisation proposals

One of the main aims of the CEOS.fr programme was to propose further rules for assessing crack width and crack spacing in special concrete structures. Given the results obtained from the experimental programme it was ascertained that for massive structures the fib Model Code for Concrete Structures 2010 (MC 2010) is in better compliance with experimental results than Eurocode 2 (EC2). This comparison resulted in proposed adjustments to existing formulae and proposals to develop enhanced methods for coupling numerical calculations and engineering formulae. This is presented in detail in Appendix E “A brief overview of the outcomes of the project and associated proposals”.

2.4 Further project opportunities

ConCrack4 has set an important milestone towards the control of cracking in reinforced concrete structures; however, is not the end of the journey. It is proposed to organize a new research programme in cooperation with European researchers, once the output from CEOS.fr has been assimilated by the scientific community.

The vehicle for the new programme, that will include additional benchmark tests, could be the Horizon 2020 Framework Programme for research and innovation or other European vehicles. The contribution of industry, in particular of critical infrastructure owners and operators, will be crucial for the success of future activities.

The CEOS.fr group will take the initiative to organise before the end of 2014 a meeting to discuss ways for continuing the research programme. Any suggestions and ideas from those who might be interested will be appreciated.
3 General conclusions and recommendations

The main purpose of the workshop was to improve engineering practices related to the cracking processes in special massive concrete structures, thus enhancing the prediction of crack evolution during the service life of special structures. Cracking formation is a problem with substantial impact on the vulnerability and resilience of critical infrastructures such as transportation systems, dams, nuclear facilities, underwater and high-pressure subjected structures as well. The protection against cracking caused by natural or man-made hazards plays an important role for the safety and sustainability of these structures and can be improved only by research and innovation.

The international scientific and engineering community acknowledged the significance of the research findings and the practical results presented at the workshop. Based on the results obtained in the CEOS.fr programme framework, two stages must be now addressed:

- need to perfect the analysis on cracking in massive structure including early age effects and durability approaches
- work on the transfer of information and knowledge towards research, standards, training and design

The workshop enabled the international engineering community to exchange research results, expert know-how and codification. There was a strong motivation among participants to pursue further research work on the topic of cracking and durability of massive concrete structures, addressing aspects of cost, safety and sustainability.

Therefore, an European project stimulating the research in this direction should be set up in order to improve the understanding of the cracking phenomena and to facilitate and speed up the integration of advanced approaches for cracking assessment. The results from the research activities combined with innovative model analysis would develop a reasonable proposal for revision of the design codes in order to improve significantly the service life of the structures. Given the importance of the critical infrastructures utility (capacity, safety and efficiency), this initiative would furthermore contribute to the competitiveness and sustainability of the construction sector.
References

CEOS.fr – A synthesis of the first year work.
http://ceosfr.org/telechargement/International/CEOS-SYNTHÈSE.pdf
Appendix A

A. Poster and Flyer for the 4th workshop “Control of cracking and durability of reinforced concrete structures”
CONCRACK 4

4th Workshop on
Control of Cracking and Durability of Reinforced Concrete Structures
Engineering and Standard Issues

20-21 March 2014
JRC Ispra - Italy

AND SUPPORTED BY

JOINT RESEARCH CENTRE
EUROPEAN COMMISSION

CEOS.fr
FRENCH NATIONAL RESEARCH PROGRAMME

DRI
MINISTÈRE DE L’ÉCOLOGIE, DU DéVELOPPEMENT DURABLE ET DE L’ÉNERGIE
Participants

The participation in the Workshop is by invitation only from the Organising committee.

Will be invited mainly:
- members of the CEOS.fr research program
- members of the CEN/TC250/Sub-Committee 2
- members of fib Task Group 4
- participants from JRC Ispra

Event Registration

The application for participation is individual. The invited participants are requested to register online at:
https://jrc-meeting-registration.jrc.ec.europa.eu

The registration site is open from 16 December 2013. The deadline for application at the workshop registration site is 3 March 2014, 12:00 CET.

Shortly after application, a confirmation of registration acceptance will be sent to the applicant by the Organising Committee.

Attendance Fees

No registration/attendance fees are requested from the participants. Participants are responsible for their own travel, accommodation and subsistence costs, which will not be reimbursed by the European Commission.

The Workshop secretariat will provide further information to the participants about travel and accommodation arrangements.

Workshop Material

Relevant materials will be distributed to the participants.

Venue, dates and social events

18-21 March, 2014, at the Auditorium conference room 11, building 58c, Joint Research Centre, via Enrico Fermi 2749, 21027 Ispra (VA), Italy

The Organising Committee invites the participants to a working dinner (see the programme for more details)

Language

English (no translation will be provided).

Organising Committee

Artur V. Pinto, Fabio Taucer, Pierre Pégéon, Borislava Nikolova, Geraldine Sachs
Joint Research Centre – European Commission

Jacky Mazars, Pierre Labbé, Philippe Bisch
CEOS.fr French research programme

Brice Delaporte
IREX

With the Support of

Joint Research Centre
European Commission
CEOS.fr
French National Research Programme
DRI
Ministère de l’Ecologie, du Développement durable et de l’Energie

Further Information

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CONCRACK 4
4th Workshop on
Control of Cracking and Durability of Reinforced Concrete Structures
Engineering and Standard issues

20-21 March 2014
JRC Ispra - Italy

ORGANISED AND SUPPORTED BY

JOINT RESEARCH CENTRE
EUROPEAN COMMISSION
CEOS.fr
FRENCH NATIONAL RESEARCH PROGRAMME
DRI
MINISTÈRE DE L’ECOLOGIE, DU DÉVELOPPEMENT DURABLE ET DE L’ÉNERGIE
Control of cracking and durability of reinforced concrete structures

Cracking is an inherent phenomenon to concrete structures. However, its control is essential in order to ensure serviceability of structures throughout time and therefore it is a major concern for durability and sustainability.

The French national research programme CEOS.fr (www.ceosfr.org) whose name can be translated as “Behaviour and assessment of special construction works concerning cracking and shrinkage” aims at dealing with this issue, particularly for special works (specific use, specific shape and size, specific requirements for loading or durability, etc.), coupling numerical modelling and experimental approaches and those elaborated by design engineers/practitioners. The issue of cracking during and after an earthquake is also addressed.

This programme was the framework set up by French professionals involved in Building and Civil Engineering works to make a decisive step in the predictive capacity of models to describe the states of cracking in such construction works, with the final objective to develop tools for designers and to provide rational background to the evolution of standards covering them.

Objectives

Co-sponsored by Joint Research Centre, this event is the fourth of a series of “Control of Cracking” workshops (ConCrack) organised each year since the beginning of the programme in 2008.

In this framework the principal objectives of the workshop are:
- To present and to discuss the main results obtained during the CEOS.fr programme and related works in Europe.
- Based on these results, to propose and to discuss standard rules for reinforced concrete massive elements.
- To discuss the opportunity of complementary research efforts at European level.

Main Topics

The workshop will include presentations on:
- Outlines of major CEOS.fr outcomes
- European works on crack control
- Lessons learned from CEOS.fr on massive structures and proposals for standards
- Standard activities

More details on the workshop sessions and program can be found at the website at: http://www.ceosfr.org/.

The workshop will be preceded by CEN/TC250 Sub-Committee 2 meeting which will take place at the Joint Research Centre in Ispra on 18-19 March 2014. This meeting is intended for the members of this Sub-Committee.

Programme “ConCrack 4”

<table>
<thead>
<tr>
<th>Thursday, March 20</th>
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<tbody>
<tr>
<td>09:00 – 09:30</td>
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<tr>
<td>A. Pinta (DG JRC, European Commission)</td>
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<td>CEOS.fr general overview</td>
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<tr>
<td>P. Labbé, EDF – Fr of CEOS.fr</td>
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<td>09:30 – 10:15</td>
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<td>Chairs: G. Mancini, F. Taucer</td>
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<td>10:15 – 10:45</td>
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<td>10:45 – 11:15</td>
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<td>S. Erlicher (Epis)</td>
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<td>P. Bisch (Epis)</td>
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<td>11:45 – 12:15</td>
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<td>A. Sellier/L. Buffo-Lacarrière (LMDC-INSA Toulouse)</td>
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<td>12:15 – 12:45</td>
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<td>C. Rospars (IFSTTAR-EDF SEPTEN-3SR)</td>
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Session 1

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<td>14:20 – 14:40</td>
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<td>J. Mazars (Grenoble INP-Scientific director CEOS.fr)</td>
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<td>14:40 – 15:00</td>
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<td>B. Belletti (University of Parma)</td>
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<td>15:00 – 15:20</td>
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<td>J. M. Bairan et al. (UPC Barcelona)</td>
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<td>15:20 – 16:00</td>
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<td>V. Cervenka (Cervenka consulting)</td>
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<td>15:40 – 16:10</td>
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16:20 – 16:40 International Benchmark ConCrack

16:40 – 17:10 Experimental tests of thick shear walls at the ELSA laboratory

16:50 – 17:10 Shear and flexure cracking in partially pre-stressed concrete

17:10 – 17:30 Creep and shrinkage prediction according to the new fib Model Code 2010

17:30 – 18:15 ELSA tour

20:00 Working Dinner for all participants

Friday, March 21

| Session 3 | European works on crack control |
|-------------------|
| 09:00 – 09:25 | Crack control for beams |
| J. Cortade (CEOS.fr partner) |
| 09:25 – 09:50 | Crack control for shear walls |
| P. Bisch (EGIS) |
| 09:50 – 10:15 | Crack control at early age and long term operation |
| F. Barré (GdS) |
| 10:15 – 10:35 | Proposal for standards |
| J-M. Torrenti (IFSTTAR) |
| 10:35 – 11:55 | Coffee break |
| 14:20 – 14:40 | Simulation of crack propagation in ConCrack benchmark |
| V. Cervenka (Cervenka consulting) |
| 14:40 – 15:00 | Finite element modelling of RC walls with smeared crack models |
| B. Belletti (University of Parma) |
| 15:00 – 15:20 | A filament beam model for the thermo-mechanical analysis of RC structures. Simulation of the Concrack2 RL1 test |
| J. M. Bairan et al. (UPC Barcelona) |
| 15:20 – 16:00 | Simulation of crack propagation in ConCrack benchmark |
| V. Cervenka (Cervenka consulting) |
| 15:40 – 16:10 | Coffee break |

16:20 – 17:10 Working Dinner for all participants

17:30 – 19:00 Round table

20:00 Working Dinner for all participants
Appendix B

B. Programme of the workshop
# PROGRAMME

## Thursday, March 20

<table>
<thead>
<tr>
<th>Time</th>
<th>Event</th>
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| 09:00 – 09:30 | Welcome addresses  
A. Pinto, DG JRC, European Commission  
CEOS.fr general overview  
P.Labbé, EDF – Pt of CEOS.fr |
| 09:30 – 10:15 | CEOS.fr experimental programme  
L. Demilecamps (Vinci) |
| 10:15 – 10:45 | Coffee break |
| 10:45 – 11:15 | Generic considerations on cracking based on tie experiments  
S. Erlicher (Egis) |
| 11:15 – 11:45 | Cracking on shear walls  
P. Bisch (Egis) |
| 11:45 – 12:15 | Cracking on massive elements at early age  
A. Sellier/L. Buffo-Lacarrière  
(LMDC-INSAToulouse) |
| 12:15 – 12:45 | Cracking on massive elements in bending  
C. Rospars (IFSTTAR-EDF SEPTEN-3SR) |
| 13:00 – 14:15 | Lunch break |
| **Session 2** | **International benchmark and presentations from participants**  
Chairman : H. Ganz, P.Negro |
| 14:20 - 14:40 | International Benchmark ConCrack  
J. Mazars (Grenoble INP-Scientific director CEOS.fr) |
| 14:40 – 15:00 | Finite element modelling of RC walls with smeared crack models  
B. Belletti (University of Parma) |
| 15:00 – 15:20 | A filament beam model for the thermo-mechanical analysis of RC structures.  
Simulation of the Concrack2 RL1 test  
J. M.Bairan et al. (UPC Barcelona) |
| 15:20 – 15:40 | Simulation of crack propagation in ConCrack benchmark  
V. Cervenka (Cervenka consulting) |
| 15:40 – 16:10 | Coffee break |
### Session 3: European works on crack control
**Chairman:** S. Leivestad, J. Molina

<table>
<thead>
<tr>
<th>Time</th>
<th>Topic</th>
<th>Speaker/Institution</th>
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<tbody>
<tr>
<td>16:10 – 16:30</td>
<td>Experimental tests of thick shear walls at the ELSA laboratory</td>
<td>P. Pegon (DG JRC, European Commission)</td>
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<tr>
<td>16:30 – 16:50</td>
<td>Cracking of RC members- influence of cover, $\varphi/\rho_{ef}$ ratio, stirrup spacing and the addition of recycled steel fibres</td>
<td>A. Perez Caldentey (UP Madrid)</td>
</tr>
<tr>
<td>16:50 – 17:10</td>
<td>Shear and flexure cracking in partially pre-stressed concrete</td>
<td>A. Mari et al. (UPC Barcelona)</td>
</tr>
<tr>
<td>17:10 – 17:30</td>
<td>Creep and shrinkage prediction according to the new fib Model Code 2010</td>
<td>F. Acosta, H. Müller (KIT Karlsruhe)</td>
</tr>
<tr>
<td>17:30 – 18:15</td>
<td>ELSA tour</td>
<td>F. Taucer (DG JRC, European Commission)</td>
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#### Friday, March 21

### Session 4: Lessons learned from CEOS.fr on massive structures and proposition for standards
**Chairman:** G. Balazs, B. Nikolova

<table>
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<tr>
<th>Time</th>
<th>Topic</th>
<th>Speaker/Institution</th>
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<tbody>
<tr>
<td>09:00 – 09:25</td>
<td>Crack control for beams</td>
<td>J. Cortade (CEOS.fr partner)</td>
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<tr>
<td>09:25 – 09:50</td>
<td>Crack control for shear walls</td>
<td>P. Bisch (EGIS)</td>
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<tr>
<td>09:50 – 10:15</td>
<td>Crack control at early age and long term operation</td>
<td>F. Barré (GdS)</td>
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<td>10:35 – 10:55</td>
<td>Coffee break</td>
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### Session 5: Standards activities and codification
**Chairman:** J-A Calgaro, S. Dimova

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<th>Time</th>
<th>Topic</th>
<th>Speaker/Institution</th>
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<tbody>
<tr>
<td>11:25 – 11:55</td>
<td>Possible ways of codification for control of cracking</td>
<td>G. Balazs (Budapest University of Technology – Immediate Past President of fib)</td>
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### Session 6: What for the future?
**Chairman:** M. Fardis

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<tr>
<th>Time</th>
<th>Topic</th>
<th>Speaker/Institution</th>
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<tbody>
<tr>
<td>11:55 – 12:05</td>
<td>How to valorize CEOS.fr ?</td>
<td>C. La Borderie (University of Pau)</td>
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<tr>
<td>12:05 – 12:55</td>
<td>Round table</td>
<td>Chairman: M. Fardis (University of Patras)</td>
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<tr>
<td>13:00 – 14:30</td>
<td>Lunch break</td>
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Organised in one day and half, the programme of the workshop comprised five sessions with presentations and discussions followed by a round table entitled “What for the future?”. The full programme of the workshop is included in Appendix B. The working sessions were dedicated to the results and the outcomes of the CEOS.fr research programme, the international benchmark ConCrack organised in the framework of CEOS.fr and crack control related research European projects. The round table aimed to contribute to standardisation activities and proposals.

The workshop gave an opportunity to prepare and disseminate background material including a USB key with the presentations of the CEOS.fr team, a booklet with “A brief overview of the outcomes of the project and associated proposals” (Appendix E) and a brochure including the programme of the workshop (Appendix B) and the abstracts of the international presentations (Appendix F).

**B.1. Session 1: Outlines of major CEOS.fr outcomes**

The core of CEOS.fr consisted of an extensive experimental research programme on full-scale beams, similar 1/3 scale beams, 1/3 scale shear walls and ties. During the ConCrack 4 workshop, the research teams involved in the project presented:

- the main results and experimental data obtained
- the analyses carried out on the basis of these results and data
- the main lessons learnt and the conclusions drawn.

The questions and discussions on the full-scale beams were focused on the observations reported by the research teams on the early cracking and the associated tensile strength in the concrete. The CEOS.fr outputs suggest that scale effects should presumably be taken into account in the analyses of this phenomenon.

The questions arisen regarding the shear walls and the ties concerned the crack direction angle and the crack opening. Dispersion of concrete tensile strength and the concurrent scale effect were also discussed. The proposals made by the CEOS.fr teams for the crack spacing and the crack width formula, may be considered as development of the previous formula proposed by G. Balazs.

**B.2. Session 2: Presentations from ConCrack benchmark participants**

During 2011, the international scientific community was invited to participate at a benchmark based on blind simulation of the response of various mock-ups tested in the framework of the CEOS.fr programme. In this session, three out of 18 participants presented their results and comments, showing how efficient their numerical tools were:

- to manage the modelling (2D FEM) of monotonic and cyclic shear loading,
- to perform a good 3D approach for early age effects using filament beams,
- to simulate cracking in special structures under various loading types.

The discussion led to highlight:

- the need to introduce uncertainties in nonlinear calculations,
when filament beams are used, the need to consider average crack spacing as input,
the possibility to continue the calculation beyond cracking to estimate the risk of corrosion.

B.3. Session 3: European works on crack control

Four high-level presentations were done in this session:
- an overview of two experimental tests (SAFE and TESSH) on thick shear walls performed at the ELSA laboratory;
- the incidences of various indicators on cracking: cover, $\phi / \rho_{\text{eff}}$ ratio, stirrups spacing and addition of recycled fibres, based on three experimental campaigns carried out at the Polytechnic University of Madrid;
- the effect of partially prestressed concrete on shear and flexure cracking obtained from numerical analysis on beams with a non-linear shear-flexural filament beam model;
- new formulations for the prediction of shrinkage and creep integrated in the \textit{fib} Model Code 2010, which extend the range of applicability while using in each case a single constitutive approach.

This session was followed by a visit to the ELSA laboratory giving opportunity to see in person the experiments of the TESSH programme.

B.4. Session 4: Lessons learned from CEOS.fr on massive structures and proposition for standards

In this session, CEOS.fr members presented proposals for the evolution of standards on:
- Cracking of ties and beams, introducing scale effects – an issue that provoked discussion mainly in relation on how to apply it.
- Shear walls, for which the reinforcement web generates questions on the best way for evaluation of the crack width. Another subject of discussion was crack rotation resulting from the evolution of local stresses caused by global loading and out of plane loading effects.
- Early age effects related to restrained shrinkage, causing where cracking which evolves without reaching a stabilized state. A point of discussion concerned the minimum reinforcement to be adjusted as a function of the reduction of concrete strength in massive elements due to scale effects.

B.5. Session 5: Standards activities and codification

The first presentation, given by the Chairman of CEN/TC250/SC2, drew attention to the main lines of evolution of Eurocode 2.
The second presentation, given by the past president of fib, outlined how 10 years of development contributed in particular for Service Life States, on various subjects such as:

- unacceptable deformation or deflexion,
- excessive cracking,
- excessive vibrations,
- reversed cyclic loading increasing slip bond and crack width.

The discussion added some other interesting topics such as: water and gas tightness and scale effects.


Seven experts participated in the round table chaired by M. Fardis (University of Patras), G. Mancini (Politecnico di Torino, Chairman of CEN/TC250/SC2), P. Labbé (EDF, CEOS.fr), J.M. Torrenti (IFFSTAR), J.F. Coste (consultant), G. Balazs (Budapest University of technology, fib immediate past President) and A. Pinto (JRC).

Following the objectives of the workshop, the main purpose was to provide scientific, technical and organisational support to standardisation works.
Appendix C

C. Evaluation of the impact and effectiveness of the workshop
Dear workshop participant,

This questionnaire is a part of our efforts to evaluate the quantity and quality of the information we provide in workshops like the one you have just attended and to ensure that the information is helping you in your day-to-day work. We would like to ask you to spend about 5-10 minutes of your time to answer the following questions.

Questions:

1. Are you attending this workshop as
   □ Speaker          □ Participant

2. Your professional position is ... (select all that apply)
   □ Public authority
   □ Private body with delegated official tasks in the field of construction
   □ Certification body
   □ Specification writer (i.e. national standardization body)
   □ CEN/TC250 member
   □ University
   □ Employee in a private company
   □ Other(s): ________________________________

3. Your country: ______________________________________

4. Please rate this workshop in terms of meeting your needs or expectations
   □ Very Good     □ Good         □ Average    □ Poor

Please tell us how much you disagree or agree with the following statements:
5. The registration process and all logistics matters were handled efficiently
   □ Agree □ Average □ Disagree

6. The workshop facilities were comfortable and appropriate
   □ Agree □ Average □ Disagree

7. The workshop materials provided were appropriate and helpful
   □ Agree □ Average □ Disagree

8. The participants to the workshop were:
   □ Too many □ Just the right number □ Too few
   □ Other ____________________________

9. The length of the workshop sessions was
   □ Too long □ Just about right □ Too short
   □ Other ____________________________

10. How would you rate the quality of the information presented?
    □ Very Good □ Good □ Average □ Poor

11. Overall, how would you rate the quality of this workshop?
    □ Very Good □ Good □ Average □ Poor

12. How could this workshop be improved?
    __________________________________________
C.1. Participants

This workshop was addressed to researchers and professionals involved in building and civil engineering works related to crack control. Therefore the intended participants were among the:

- members of the CEOS.fr research program
- members of the CEN/TC250/Sub-Committee 2
- members of fib Task Group 4
- JRC Ispra

In total, 60 participants from 12 countries (EU Member States and Switzerland) attended the workshop. Distribution of the number of participants per country is given in  Fig. C.1. There was a good balance between the French and the European participation in the workshop.

![Fig. C.1 Number of the participants per country](image-url)
Appendix C

The CEOS.fr workshop brought together professionals involved in different fields of the buildings sector. The delegates were representatives from research institutes, universities, industry and other institutions concerned with cracking control in special structures. Figure D.1 shows the distribution of the participants according to their professional background.

C.2. Evaluation of the workshop (presentations, materials)

An evaluation questionnaire was distributed to the participants of the event to evaluate the impact and effectiveness of the workshop (Appendix C). The participants were asked to express their opinion on certain aspects of the workshop and to give additional comments as appropriate.

37 filled in forms were collected at the end of the workshop. The received data was analysed and conclusions were drawn for four groups of questions.

As a whole, the workshop was evaluated as very effective in terms of meeting participants’ expectations. 76% of the answers were very good and 24% good. As regards to the scale of the event, 95% agreed there were “just the right number” of participants.

The workshop was comprised by six thematic sessions and a concluding round. 89% of the participants evaluated the length of the workshop sessions as “just about right”. Figure 3.3 shows the very positive estimation of the quality of the information presented. After the workshop all presentations are being uploaded at the CEOS.fr website (www.ceosfr.org).

Fig. C.2 Professional position of the participants
Appendix C

29

The following materials were distributed to the participants:

- A USB key including all the presentations of the CEOS.fr team (Session 1 and Session 4)
- Brochure including the programme of the workshop and the abstracts of the presentations in Sessions 2, 3 and 5 (Appendix F)
- A brief overview of the outcomes of the project and associated proposals (Appendix E)

95% of the participants agreed the workshop material provided was appropriate and helpful.

C.3. Evaluation of the organisation

The workshop was organised by the Joint Research Centre with the support of the CEOS.fr French national research programme and the DRI Ministere de l'ecologie, du development durable et de l'energie, as part of a series of activities related to pre-normative research and support to the implementation of the Eurocodes.

The event took place at the Auditorium conference room in building 58 in JRC at Ispra. 97% of the participants found the facilities comfortable and appropriate. The registration process and all logistics materials were evaluated very positively in 86% of the filled in questionnaires.

C.4. General satisfaction and comments

Figure 3.4 summarises the answers of the participants about the overall quality of the workshop. As it can be seen on the chart, the event was absolutely positively evaluated with 76% “very good” and 24% “good” marks.
The analysis of the satisfaction reviews and the additional comments give a valuable input to the quality management of the workshop and will be used for improving the performance in future events.

Fig. C.4 Overall evaluation of the quality of the workshop
Appendix D

D. French National Research Programme CEOS.fr
Appendix D

D.1. General overview

Cracking is an inherent phenomenon to concrete structures. However, its control is essential in order to ensure the serviceability of structures throughout time and therefore it is a major concern for durability and sustainability.

CEOS.fr is a four-year French research programme which name can be translated as “Behaviour and assessment of special structures concerning cracking and shrinkage”. In the context of the CEOS.fr project, are considered as “special” those structures that are not covered by current engineering practice, either because their sizes are unusual (very massive structures in particular) or because of unusual in-service requirements (life duration, leak tightness …) or special requirements related to the protection against external threats or hazards (extreme or beyond design earthquakes). The issue of cracking during and after an earthquake was also addressed. The research programme aimed at coupling numerical modelling with experimental approaches and development of standards.

D.2. Objectives

This programme was the framework set up by French professionals involved in building and civil engineering works to make a decisive step in the predictive capacity of models to describe the state of cracking in such construction works, with the final objectives to:

- contribute to reference documents (fib, CEB);
- develop appropriate engineering tools for designers;
- provide rational background to the evolution of standards covering them.

D.3. Scope of the project

CEOS.fr general philosophy consists of running concurrently conventional experimentation, numerical modelling and engineering approach. The project was organized on a cross theme method. Three different types of physical phenomena were considered for research:

- Cracking under monotonic load cases
- Thermo-hydro-mechanical behaviour
- Cyclic or seismic load cases

Three approaches were adopted to investigate these loading types:

- Modelling (material, structure)
- Experimental testing and monitoring
- Engineering practices

The experimental programme included five series of 29 large (real-scale and 1/3-scale) specimens subjected to the above mentioned different and representative loading cases. All experimental data was made available to the project partners and the scientific community through a common website platform.
D.4. Partners

CEOS.fr is a collective research programme that relied on input from 41 stakeholders including owners, designers, contractors, civil engineering and consulting companies, research institutes, universities, metrology and measuring technology firms, consultants and financially supported of the French Ministry in charge of sustainable development.

D.5. Conclusions

The main purpose of the French National Project CEOS.fr was to improve engineering practices related to the cracking process in reinforced concrete and in prestressed concrete massive structures, thereby enhancing the prediction of crack evolution during the life of the structure.

The CEOS.fr project identified two major findings, when compared with common concrete elements. It appeared that on average, the *fib* Model Code for Concrete Structures 2010 (MC 2010) is more appropriate to massive element design than Eurocode 2, provided that further to the project outcomes some formulae are adapted.

The International Scientific and Engineering Community acknowledged the significance of the research findings of the national CEOS.fr project, organised by the French Institute of Research and Experiments (IREX). This enables the international community to benefit from the learning gained by the French research and engineering community.

More details and the key outcomes of the project are presented in “A brief overview of the outcomes of the project and associated proposals” (Appendix E).
Appendix E

E. A brief overview of the outcomes of the projects and associated proposals
FRENCH NATIONAL RESEARCH PROGRAM

Behaviour and assessment
of massive structures: cracking and shrinkage

A brief overview of the outcomes
of the project and associated proposals
I. CEOS.fr GENERAL OVERVIEW

The majority of concrete structures have to fulfil a number of structural functions beyond that of simple resistance. These include behavioural requirements for: stability, reinforced concrete cracking, deformability, water and air leak-tightness, and sustainability.

Most European concrete structures today are designed in accordance with Eurocode 2 (EC2), which uses a performance-based approach related to durability and functionality at Serviceability Limit State (SLS).

For massive and more general special structures, the EC2 standard rules do not fully reflect the complete behaviour of massive elements, for which Thermo-Hydro-Mechanical (THM) effects, scale effects and structural effects induce crack pattern such as crack spacing and crack width. For massive slabs and walls, shrinkage and creep are prevalent at an early and long-term age. This approach may lead to structures that are not optimised, especially for concrete reinforcement.

To address these concerns, the French Civil Engineering Community decided in 2008 to launch a joint national research programme project, CEOS.fr, with the aim of making a significant step forward in the engineering capabilities for predicting the expected crack pattern of special structures under anticipated in-service or extreme conditions.

The aims of the CEOS.fr project are to:
- Develop numerical non linear and damage models, to simulate concrete behaviour under load and imposed deformation;
- Provide engineering guidelines to optimise the design of special concrete structures;
- Propose further rules for crack width and crack spacing assessment in special concrete structures, in addition to EC2 or fib Model Code 2010 (MC2010).

Are considered as “special” structures:
- Structures that are not covered by the conventional engineering practice:
  - Very massive \( h_0 \geq 400 \text{ mm} \), where \( h_0 \) is the notional size of the cross section (cf. EC2-1 § 3.1.4)
  - Unusual in-service requirements (life duration, leak tightness …)
  - Unusual requirements relating to the protection against external threats or hazards

II. CEOS.fr PROGRAMME

Three themes have been progressed from February 2008 up to 2013, namely:
- Modelling: applying existing numerical models and developing specific computer models;
- Testing: implementing tests on large scale models (full scale beams and 1/3 scale shear walls); with boundary state clearly defined and accurate measurements of crack development made;
- Engineering: rules or guidelines developed on test results and computer simulation.

A. Modelling and simulation

As part of the first CEOS.fr international benchmarking in December 2009, the existing models and their performance were tested and compared.

Two further workshops were held: ConCrack2 in June 2011 on crack control and ConCrack3 in March 2012 on THM. These forums were dedicated to the exchange of researchers’ know-how’ and available modelling tools.

1. MEFISTO research programme

In parallel, the MEFISTO research project was launched in 2008 by the French National Agency for Research (ANR). As a result of CEOS.fr collaboration with the MEFISTO project, it was possible to develop models, which consider the following topics and approaches:
- Modelling of effects under monotonic loading in connection with the global performance of the material (strain-strain model) and the local damage process (trajectory and width of cracks);
- Modelling of THM coupled effects on early age concrete and assessment of induced stresses and local damage;
- MEFISTO also provided support to CEOS.fr for the design and construction of full and 1/3 scale test bodies.

2. Numerical experiments and simulations

Numerical modelling played a key role in the interpretation of test result data obtained from the cracking of massive elements at an early
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Ispra, 20-21 March 2014
Behaviour and assessment of massive structures: cracking and shrinkage

age, and of 1/3 scale shear walls. Comparison of model numerical results, with the experimental data obtained from instrumentation, has provided an improve understanding of the physical phenomena due to Scale effects in massive structures. As a consequence, it was possible to use modelling and other simulation tools to extend the range of the experimental programme results through numerical “virtual” modelling of the physical processes.

B. Testing
Specific tests on various full or 1/3 scale test bodies were performed as part of the CEOS.fr project. These included:

1. Tests on full-scale prismatic blocks

- Tests under monotonic loading on 7 blocks, RL1 to RL7 (test body dimensions: 6,1 m × 1,6 m × 0,80 m). Before loading, the blocks were matured with free deformations during at least one month then under loading in bending on a 4-point flexural bench. The blocks were made of different concrete mixes and have various reinforcements and concrete cover.

- Tests on 3 blocks subject to restrained shrinkage (test body dimensions: 6 m × 0,50 m × 0,80 m), RG8 (2% reinforcement, concrete cover = 50 mm), RG9 (0,6% reinforcement, concrete cover = 50 mm) and RG10 (2% reinforcement and an increased cover c = 70 mm instead 50 mm for other blocks).

2. Tests on 1/3 scale concrete blocks under continuous loading
(test body dimensions: 1,90 m × 0,25 m × 0,44 m)
The purpose of these tests was to highlight the Scale effect in comparison with full-scale test bodies and to check the validity for massive structures of EC2 clauses and crack width and spacing assessment relationships.

3. Tests on shear walls at 1/3 scale with different concrete mix and reinforcement
(test body dimensions: 4,2 m × 1,05 m × 0,15 m)

- 1 wall under non alternate loading
- 3 walls under alternate loading

4. Tests on ties
- 2 ties (test body dimensions: 3,20 m × 0,135 m × 0,135 m) with one reinforcement bar
- 2 ties (test body dimensions: 3,20 m × 0,17 m × 0,17 m) with one reinforcement bar
- 3 ties (test body dimensions: 3,20 m × 0,355 m × 0,355 m) with 4 Re-bars
- 2 ties (test body dimensions: 3,20 m × 0,355 m × 0,355 m) with 8 Re-bars
All test bodies were comprehensively instrumented in order to locate and follow crack propagation and measure crack spacing and width. Test data, including measurements from Digital Image Correlation (DIC) instrumentation, provides confidence in the reliability of the test results, and is recorded in a database.

In addition to the measurement of the external alternating cyclic loads and associated displacement by Linear Variable Differential Transformer (LVDT) sensors, each test body was comprehensively equipped with varied and numerous sensors, including:

- Long base optical extensometers, placed externally on one side and embedded in the test body, providing data and information on global strains (marked Optical fiber on the figure),
- Vibrating wires embedded in the test body concrete (marked CV on the figure), providing data and information on local concrete strain,
- Embedded temperature and optical sensors, based on Fibre Bragg Grating (FBG),
- Bragg optical local strain sensors, located on reinforcement bars. Sensor resolution ≤ 1 µm/m,
- Electrical strain gauges located on reinforcement bars, plus one gauge embedded within the concrete.

In addition to the above, Digital Image Correlation (DIC) is used for all RL blocks and shear wall test blocks, enabling measurement of the crack pattern with a resolution of 0.05 mm for massive blocks and 0.06 mm for shear walls.

C. Engineering

Over the course of the CEOS.fr project, the suitability of EC2 and MC2010 formulae and clauses has been assessed, and the codes ability to predict the behaviour of test bodies has been assessed, by comparing the numerical predictions against the CEOS.fr experimental test results and numerical simulations. This comparison has resulted in proposed adjustments to existing formulae for massive concrete structures, and proposals to develop enhanced methods for coupling numerical calculations and engineering formulae.
III. KEY OUTCOMES OF THE CEOS.fr Project

1. Cracking of shear walls
   a. Non-alternate loading test

The influence of the following factors has been assessed during the non alternate test loading, with the spacing $S_r$ between cracks compared to EC2 and MC2010 formulae based results. In addition to this approach, other results from the SAFE experiment (ISpra) have been re-analysed, especially at Ultimate Limit State (ULS), with the CEOS.fr outcomes demonstrating consistent agreement with the SAFE results.

![Fig. 04. Damaged central part of shear wall 3 under non-alternate loading and crack pattern according to DIC interpretation.](image)

- Concrete cover calculation
  The results of the shear wall tests show that it is advisable to use, for calculation purposes, either the cover for each rebar layer or the mean value of the two covers in the both directions. Of the two approaches, the second (mean value) solution is considered to be simpler to apply.

- Angle $\theta$
  This is the angle between the reinforcement in the x-direction and the direction of principal tensile stress. If the reinforcement layers are in accordance with the good engineering practice, an error in angle $\theta$ assessment does not result in a significant error in the assessment of crack spacing and crack width.

- Structural Tensile resistance of concrete $f_{ctm}$
  The test results show that the mean structural tensile resistance $f_{ctm}$ is 40% less than the theoretical value $f_{ctm}$ when the first crack occurs. This reduction is due to the 3D effects for massive elements, resulting in stress variations across the section. Scale effects between $f_{ctm}$ measured on specimens under laboratory conditions and $f_{ctm}$ results observed on the large concrete volume of the tested shear walls are also a factor which contributes to reducing $f_{ctm}$ in tested shear walls. In addition to these scale effects, the effect of concrete struts working in compression may also decrease the tensile strength.

  The value of $f_{ct}$ demonstrates some impact (approximately 20%) on $S_r$ value and cannot be neglected, although it should be noted that both EC2-1 and MC2010 do not take this parameter into account.

  The crack width $w_d$ has been measured for comparison with EC2 and MC2010 calculations.

- Influence of reinforcement ratio
  For n°4 test, the global reinforcement ratio decreases from 1% down to 0,8% while it is observed that $S_r$ increases up to 22%. However, the application of code formulae leads to an opposite variation. This is due to the formula giving the effective area, which appears not to be appropriate.
b. Alternate and non-alternate loading tests

θ varies around 10% according to the test pushing direction and is not dependent on f_{ct}'. The value of S_{r,max} is dependent on the value of f_{ct}', which is not considered either by the EC2-1 or MC2010 formulae.

Cracks close up during alternating loading when around zero the pushing alternates. In reverse, cracks do not close up for non-alternating tests when unloading.

Test results show that cracks close during the alternate load test, when the load is approximately zero, while cracks do not close during non-alternate load tests.

Crack width increases with the loading during the cyclic testing.

2. Cracking of massive ties

a. Tensile strength

The results from tie tests demonstrate that the first cracks appear in the concrete cross section under a lower tensile load than predicted by the conventional tensile stress expression 0,7 f_{ct}: e.g. values of 1 or 2MPa compared to the 3MPa predicted. In the case of thick concrete elements, the three dimensional distribution of strains over the cross section and resultant tensile stresses before cracking modify the apparent tensile strength of the homogeneous concrete cross section. This tensile strength appears, due to scale effect to be lower than the effective tensile stress. The restrained shrinkage of concrete due to reinforcement bars also causes concrete pre-tension and consequently early cracking.

b. Crack spacing

The maximum spacing, S_{r,max}, measured between cracks at stabilized stage is less than that predicted by the EC2-1 - expression (7.11) applied to large ties, which overestimates this spacing.

\[
S_{r,max} = 3,4c + 0,8 \cdot 1,0 \cdot 0,425 \sigma / \rho
\]

The maximum spacing calculated from the MC2010 – expression 7.6-4 with no distinction made between ties and beams appears to provide spacing values with greater agreement with the test results:

\[
l_{r,max} = k \cdot \sigma + \frac{1}{4} \cdot \sigma_{\text{cm}} \cdot \frac{\rho \sigma}{\rho} s_{\text{eff}}
\]

\[
l_{r,max} = 1 \cdot \sigma + \frac{1}{4} \cdot 1,8 \cdot \sigma
\]

\[
S_{r,max} = 2 l_{r,max} = 2c + 0,277 \sigma / \rho_{\text{eff}}
\]

c. Crack width

The maximum crack width measured is close to the value calculated from EC2-1 or MC2010, which suggests that the relative mean strain might be underestimated by these standard and code.

3. Cracking of massive beams in bending and crack spacing

a. RL beams with free deformation

For 1/3 scale beams, the test results demonstrate that the mean crack spacing and width at the stabilised cracking stage, are consistent with the crack spacing and width calculated using the MC2010 formulae (cf. fig. 05). It is noted that the beam size corresponds to test results and on site observations used to establish the codes. The average crack width measured values provide a scattered distribution, partly explained by THM effects.

b. RG beams with restrained deformation

Processing of experimental results of RG beams in bending with restrained deformations are still in progress and are not yet available.

4. Cracking of massive elements and THM effects at an early age

The most significant finding from the CEOS.fr project is an improved understanding of the THM effects at an early age. At an early age the massive elements are submitted to non-uniform strains, which induce cracking at this stage. This effect is unavoidable in practice and is generated by:

- Temperature gradients between the core and the surface of the massive element.
- Internal strains generated by the temperature profile, shrinkage and creep.
In addition, assessment and interpretation of the test results for massive elements has improved the understanding of the influence of two phenomena: 3D effects as the massive elements are always submitted to 3D non-uniform strains and probabilistic scale effect.

**a. RL beams (free deformation)**

Two types of early age behaviour are observed on fig. 06:

- Either there is no visible cracks at early age on the surface of the concrete but the instrumentation analysis shows that internal cracks develop at early age (RL1 beam);

- Or cracks appear on the surface at early age (RL6 beam).

In addition, tensile resistance of thick elements is apparently lower than the tensile strength calculated in accordance with EC2-1-1 \( f_{ct,0.05} = 0.7 f_{ct,m} \):

\[
f_{ct,0.05} \approx 0.5 f_{ct,m}
\]

This is due to the 3D stress distribution in the cross-section and the Scale effect, since the cross-section of the massive beam is significantly larger than the cross-section of specimens tested in laboratory and used to calibrate the EC2-1 formula. Then the real \( f_{ct,0.05} \) value is more likely to be reached in a massive structure.
b. RG beams with restrained deformation

- Early age THM Effects
  These experiments demonstrate early age cracking with THM effects, which result from a temperature increase during the concrete setting, a temperature decrease and restrained shrinkage. During the test, 400 hours duration, 3 to 4 cracks appeared in the central beam sections, but the stabilised cracking stage was never reached. Cracks were detected by the instrumentation (strain gauges, LVDT, fibre sensors). The maximum and minimum crack width test results from RG8 (with 2% reinforcement), maximum crack width 107 μm, was less than that obtained from RG9 (with 0.6% reinforcement), maximum crack width 126 μm.

Modelling of THM effects has simulated the test results taking account of the same temperature variation profile derived from tests on RG beams and of the scale effect calculated from the Weibull theory. This modelling is performed in order to assess the influence of the main parameters: early age creep, reinforcement cover and % reinforcement.

In simulating the effect of the non-uniform strains, resulting from the 3D deformation of the concrete section, the 3D effect is taken into account. However, the variation and concentration of tensile concrete strains are not the only phenomena that could explain the concrete cracking and reduced tensile strength observed.

To explain the effects seen on massive structures it is necessary to assume that the mean tensile strength is reduced compared with the split test, and that the stress distribution is non-uniform, mainly due to the Probabilistic Scale effect (referred to in MC2010 clause 7.12.5.4): the volume of concrete submitted to high tensile stresses is larger compared to that submitted to tensile stresses in a specimen under tensile test (cf NF EN 12390-6 split tensile test). In this example, the likelihood that the tensile strength

The main result of the above simulation test is recognition that the compressive stresses developed during the heating of the concrete are not negligible and must be taken into account for an accurate assessment. The compressive strength reduces the tensile stresses during the cooling phases. To ensure that the compressive stresses are not overestimated, it is important to take account of the autogeneous shrinkage and the creep at early age, which reduce the compressive stress during the heating phase as demonstrated from the test measurements.

5. 3D effect and Probabilistic Scale effect

Another important result from the mock-up tests and simulations is an increased understanding that the mean value of the mean tensile strength is reduced. This effect is due to the combination of the 3D effect and Probabilistic Scale effect phenomena.
value $f_{ct,0.05}$ is met for massive structures, is much greater than in a test specimen.

The probabilistic scale effect can be simulated by using the Weibull theory and the weak value of the tensile strength can be mainly explained by the use of a simplified approach based on this theory (see P. Rossi and al. 1994, Scale effect on concrete in tension and A. Sellier, Mefisto project, Reference in Annex).

### Other results from existing site structures

For long term results related to drying shrinkage and creep, a review of in-service measurement data from the monitoring and visual checks of existing structures has been used to supplement the above CEOS.fr test results. This data has been sourced from cooling towers, Nuclear Power Plant (NPP) containment and associated large scale models such as the MAEVA model for NPP inner containment, concrete nuclear waste containers, cantilever prestressed decks, bridge piers, etc.

### IV. PROPOSALS TO SUPPLEMENT CODES AND STANDARDS FOR MASSIVE CONCRETE STRUCTURES ——

#### A. Shear walls

1. **Crack spacing** $S_{r,max}$

For the calculation of $S_{r,max}$, it is proposed that the value of $S_{r,max,x}$ and $S_{r,max,y}$ used in the formulae takes into account, either the cover of each layer of rebar or the mean value of the two covers in the two directions.

2. **Mean $\varepsilon_{\perp}$ strain and Crack width**

It is proposed that the relative mean $\varepsilon_{\perp}$ strain and the crack width $w$ shall be calculated in the direction orthogonal to the crack. In the absence of EC2-1 supporting reference, a formula is proposed for the calculation of these two parameters.

3. **Minimum reinforcement**

Walls are defined in two categories:

- Walls without specific cracking requirement
- Walls with specific cracking requirement

For the first category, the minimum reinforcement prescribed by EN-1992-1-1 § 9.6, or other appropriate dedicated rules are considered to be sufficient.

For the second category, where THM or concrete delayed deformation effects impact on crack control, the minimum reinforcement shall not be solely based on SLS crack width calculation, but has to be justified independently from SLS load cases. It is proposed that a rule is developed to assess the amount of reinforcement required, capable of balancing the concrete tensile areas in the section. CEOS.fr proposes to use the results and analysis from actual on site ties of existing structures, validated using the Weibull theory and 3D effects.

It is concluded that a reduced $f_{ct,0.05}$ is required, dependent on concrete thickness: In the absence of a more accurate demonstration, the simplified approach described in the following tables 1 and 2 may be adopted.

#### B. Large Ties under tensile loads or restrained strains

1. **Crack spacing**

Statistical analysis of 130 tests results, including ties tested under the CEOS.fr project, demonstrates that the MC2010 expression (7.6.4): $S_{r,max} = 2\varepsilon_{r,max} = 2\varepsilon + 0.277 \frac{\phi}{\rho_{s,ef}}$

appears to provide a more accurate estimate than the corresponding formula from EC2-1.

NOTE: in the absence of MC2010 supporting reference, EC2-1 expression may be used assuming the value $k_2 = 0.5$ instead of 1

$$S_{r,max} = k_3\varepsilon + k_4k_2\varepsilon_4 \Phi / \rho = 3.4\varepsilon + 0.17 \Phi / \rho$$

2. **Minimum reinforcement**

If no 3D calculation is available, the relationship given in EC2-1 (7.1) may be used with $k$ and $k_c$ coefficients derived according to measurements obtained from tensile areas of in-service structures (see the following table 1).
Comportement et Evaluation des Ouvrages Spéciaux vis-à-vis de la fissuration et du retrait

It is proposed to apply a reduction factor to reinforcement due to the scale effect for slabs or walls whose thick layer height in tension is $h_t$ and crack spacing ranging from $h_t$ to 2 $h_t$ according to table 2.

**Table 2. Reinforcement reduction factors due to the scale effect**

<table>
<thead>
<tr>
<th>$h_t$</th>
<th>$f_{ck} = 40$ MPa</th>
<th>$f_{ck} = 60$ MPa</th>
<th>$f_{ck} = 80$ MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.5</td>
<td>0.7</td>
<td>0.8</td>
</tr>
<tr>
<td>0.30 m</td>
<td>0.4</td>
<td>0.55</td>
<td>0.75</td>
</tr>
<tr>
<td>&gt; 0.3 m</td>
<td>0.4</td>
<td>0.55</td>
<td>0.75</td>
</tr>
</tbody>
</table>

C. Beams in bending

1. **Common beams**

MC2010 formulas are applicable for:
- Calculation of $l_r$, max under loading
- Calculation of crack with $w_d$
- Minimum reinforcement

2. **Large beams—massive elements**

Four stages are distinguished:
- The un-cracked staged
- The crack formation stage
- The stabilised cracking stage
- The steel yielding stage

At an early age, the first crack resulting from the THM effects can be seen. Scale effect is taken into account by reducing the $f_{ctm}$ value in accordance with ratio range 0.5 to 0.7.

At an early age, the first crack resulting from the THM effects can be seen. Scale effect is taken into account by reducing the $f_{ctm}$ value in accordance with ratio range 0.5 to 0.7. A new proposed approach to calculate $\varepsilon_{sm}$ – $\varepsilon_{cm}$ is derived from the formula given in MC2010 § 7.6.5.2 “Deformations due to bending with or without axial force” § 7.6.5.2.2 “Simplified

\[ \sigma_{sr} = (1-\beta)/E_3 \]

\[ \sigma_{sr} = \frac{1-\beta}{E_3} \]

\[ \Delta l/l \]

\[ \Delta l/l = \text{defined in equ. 7.6-6} \]

Fig. 08. Simplified load-strain relation for a centrically reinforced member subjected to tension

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method for RC structures\(^a\) where deflections are checked by the following interpolation between an uncracked (I) and a fully cracked (II) state of the member:

\[
\alpha = \zeta \alpha_{II} + (1 - \zeta) \alpha_I \quad \text{where} \quad \zeta = 1 - \beta \left(\frac{\sigma_{sr}}{\sigma_s}\right)^2.
\]

Using this principle it is possible to calculate \(\varepsilon_{sm} - \varepsilon_{cm}\). The advantage of this approach is that it will show the crack formation stage, transforming the horizontal line 2 into an inclined line. For point A (see above figure) the value of \(\sigma_{sr}\) will be taken as the minimum \(f_{ct,\text{scale}}\) corresponding to a volume of the member limiting sizes to 1.25 m:

\[
\text{For point B} \quad f_{ct} = f_{ct,0.95}.
\]

It is assumed that:

\[
\varepsilon = \zeta \varepsilon_{II} + (1 - \zeta) \varepsilon_I \quad \text{where} \quad \zeta = 1 - \beta \left(\frac{\sigma_{sr}}{\sigma_s}\right)^2.
\]

\(\varepsilon_i\) is the strain in the non cracked stage and \(\varepsilon_{II}\) the strain in the cracked stage. So \(\varepsilon_i\) defines point A and \(\varepsilon_{II}\) is used for the stabilised cracking stage beginning at point B. For line 2 that stands in the crack formation stage, a linear adjustment is made between points A and B.

### D. Shrinkage & creep and THM assessment of mass concrete structures at an early age and long-term age

EN1992-2 provides the designer with the option to adapt the deformation formulae using correction factors, introduced to take into account pre-construction or in-service measurements through the structures life. The use of correction factors an underlying principle within the CEOS.fr project proposals. Use of pre-construction measurements is recommended for special (massive) structures. In the absence of applicable test results, it is recommended that higher safety factors be adopted for the detailed design.

MC2010 § 5.1.10 gives the designer the option to adapt the deformation formulae to take account of temperature effects (in the range of variation range from 0°C to 80 °C). Temperature effects can modify the relative humidity ratio and can also have an impact on the:

- Kinetic of drying,
- Amplitude of basic creep,
- Amplitude of the autogeneous shrinkage.

In the absence of measurements that support the temperature effect results, it is recommended that the requirements of Model-Code 2010 be applied.

#### 1. Shrinkage

No modifications are proposed to the autogeneous shrinkage assessment clauses in EN1992 or MC2010, given the autogeneous shrinkage values and kinetic are not specific to massive concrete structures.

The kinetic of drying shrinkage, as given by the EN1992-1-1 formula, is considered to be too rapid and hence is not relevant for thick structures. The EN1992-2 formulae have a limited validity range and the asymptotic limit can result in over estimated deformation values.

The asymptotic and kinetic values in the MC2010 formulae are considered more suitable, although MC2010 expression presents a discontinuity for high relative humidity ratio related to shrinkage for \(RH < 99.\beta_{s1}\) and swelling for \(RH > 99.\beta_{s1}\). In-service measurements from cooling towers subject to increased humidity, do not demonstrate such a discontinuity.

The CEOS.fr project proposes to adapt the MC2010 § 5.1.9.4.4 for drying shrinkage at high relative humidity ratio by introducing the notion of saturation state, used in EN1992-2.

#### 2. Creep

The main result of the assessment of prestressed wall structures is the recognition of the importance of distinguishing between the two creep phenomena, basic creep and drying creep. These two types of creep do not exhibit the same kinetic or behaviour under bi- or tri-axial prestressing. The strains due to basic creep result mainly from an increase in the initial strains due to prestressing. The strains due to drying creep result mainly from an increase in the drying shrinkage. The CEOS.fr project proposes to adapt the MC2010 § 5.1.9.4.3 creep formulae retaining the two types of creep.
3. Experimental identification procedure
In order to assess the delayed strains with greater accuracy, experimental measurements should be used to identify the parameters that are included in the models for creep and shrinkage. An approach, based on the experimental determination of coefficients altering the $\beta$ coefficients in MC2010 formulae, should be used both for shrinkage and for creep.

4. Thermo-mechanical effects at an early age
During the concrete setting of thick elements, the temperature increase during the heating phase due to cement hydration during concrete setting can be assessed in the core of the element as a quasi-adiabatic temperature. This temperature is corrected by a reduction factor $\beta_T$, which is dependent on the actual geometry and on the thermal properties of the formworks.

$$T_{\text{max}} - T_{\text{initial}} = \beta_T \cdot \Delta T_{\text{adiabatic}} = \beta_T \cdot \frac{Q_{\infty}}{\rho \cdot C}$$

$T_{\text{max}}$ is the maximum temperature reached, the initial temperature when the concrete is poured in the formworks. $Q_{\infty}$ is the maximum hydration heat of the cement; $Q_{\infty}$ takes account of additions such as silica fumes. $\rho C = 2500$ kJ/m$^3$

![Example of reduction coefficient $\beta_T$ calculation](image)

For a simplified approach, the reduction factor $\beta_T$ can be assessed according to the nomogram/diagram provided by the technical guide published by LCPC/IFSTTAR – August 2007.

Example:
EP = 0,50 m
Cement content 400kg/m$^3$
$T_{\text{adiab}} = 71^\circ C$

$T_{\text{initial}} = 18^\circ C$

$Q_{\infty} / \rho C = 53^\circ C$

$Q_{\infty} = 332$ kJ/kg

$Q_{\infty} = Q_{41} \Rightarrow \beta_T = 0,7$

$T_{\text{max}} - T_{\text{init}} = 0,7 \times 53^\circ C \approx 37^\circ C$

Three temperature differences are identified to estimate and to limit:
- The difference between the core and the surface (mainly during or immediately after the heating phase or after the formwork removal or after the curing effect);
- The mean temperature difference between the mean temperature of one new concrete lift and the temperature of the previous concrete lift, which supports the new lift (mainly 10 to 30 days depending on the element thickness);
- The mean temperature difference between the two concrete elements, which have different thickness and are poured at the same time.

The three temperature differences can be assessed with reasonable agreement, using graphs, graphs, graphs.
nomograms or by simple thermal calculations, taking into account the hydration properties of the cement and the cement ratio.

These assessments show non-uniform stresses due the effect of self-equilibrate stresses and allow an estimate of the concrete tensile area or volume. The minimal concrete tensile strength is dependent upon of this tensile area.

The temperature differences are generally too small to lead to the stabilised concrete cracking phase. Mainly due to shrinkage, two types of cracks can appear at an early age:
- Cracks on concrete facing resulting from the difference of temperature between core and surface which can be limited by standard methods (curing),
- Internal and external cracks resulting from the global cooling of the concrete element, more specific to massive concrete elements.

Crack formation formulae are normally applied. In this case, the minimal reinforcement, which results is considered to be sufficient when calculated with the reduced concrete tensile area and with reduced concrete tensile strength due to the scale effect as described above.

5. Combined effects of load and imposed deformation

- Minimum reinforcement
The reinforcement determined by the mechanical loading shall be checked under the THM effects at an early age or at long term in the corresponding massive element.

The checking under THM effects can be determinant when the loading and the THM effects induce reinforcements in two different directions or in two different faces of the element.

- Crack width limitation
The crack width resulting from early age cracking is calculated according to MC2010 requirements

$$w_d = 2l_{s,max}(e_{sm} - e_{cm} - e_s)$$

with

$$l_{s,max} = c + \frac{1}{4} \frac{f_{ctm}}{r_{bms}} \frac{\rho_s}{\rho_{s,ef}}$$

with \(f_{ctm}\) and \(r_{bms} = 1.8f_{ctm}\), since there is no influence of the scale effect on shear effects and rebar anchorage.

But the scale effect is contributing to the mean strain: at the stabilized cracking stage under load, the volume subject to the scale effect is limited to the distance between cracks; then the influence of the scale effect decreases and the tensile strength increases from \(f_{ct, scale1}\) up to \(f_{ct, scale2}\) values that are calculated according to the Weibull approach as described in III.5 and IV.C.2.

The relative mean strain is given by the following expressions:

$$e_{sm} - e_{cm} - e_s = \frac{\sigma_s - \beta \sigma_{str}}{E_s} + \eta_r \cdot e_{sh}$$

(MC2010 § 7.6-5) and

$$\sigma_{pr} = \frac{f_{ctm}}{\rho_{s,ef}} (1 + \alpha_r \rho_{s,ef})$$

(MC2010 § 7.6.6)

where \(f_{ctm}\) is replaced by \(f_{ctw} = (f_{ct, scale1} + f_{ct, scale2})/2\)

It is proposed to give \(\eta_r\) a value less than 1, dependent on the value of the deformation restraint factors that would be determined according to a method yet to be defined and on the cracking stage met during the cycle life of the concrete element.

V. CONCLUSION

The main purpose of the French National Project Ceos.fr is to improve engineering practices related to the cracking process in reinforced concrete and in prestressed concrete massive structures, thereby enhancing the prediction of crack evolution during the life of the structure.

The project has focussed on massive reinforced concrete elements. Tests have been performed during about one year in three areas:
- Cracking under monotonic loading case on beams: the purpose of this test is to calibrate available models and establish their applica-
Comportement et Evaluation des Ouvrages Spéciaux vis-à-vis de la fissuration et du retrait

Comportement et Evaluation des Ouvrages Spéciaux vis-à-vis de la fissuration et du retrait

Behaviour and assessment of massive structures: cracking and shrinkage

The CEOS.fr management team acknowledges sincerely Jean-François Coste for his valuable contribution to the present synthesis paper of the CEOS.fr program.

ANNEXES

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Appendix F

F. Abstracts of the presentations in sessions 2, 3 and 5
It is well known that RC walls, thanks to their dimensions and their in-plane disposition, give a high stiffness and a high resistance to buildings, reducing the interstorey drift values at damage limit state and providing enough strength and ductility at collapse. The linear or non-linear structural analysis of RC structural wall systems is usually carried out by modelling RC walls with equivalent beam elements or with membrane, plate or shell elements.

In Italy, specific standard code prescriptions for the design of RC walls have become mandatory only since the publication of the new building code D.M. 2008, in accordance with Eurocode 8 rules. As a consequence, in the design practice, the structural analysis of RC walls systems, especially when software aided, is carried out as they were RC frames. Indeed, the traditional structural analysis of frame systems is well known in engineering practice and it is also used to carry out safety verifications of ductile wall systems (coupled or uncoupled) and dual systems (frame or wall equivalent), by transforming the walls behaviour to an equivalent columns behaviour. Due to the geometrical features of RC walls, the Bernoulli hypotheses are not suitable for the description of the actual walls behaviour, even in case of ductile walls, because walls are principally constituted of discontinuity regions. The shear resistance (especially near supports and floors), the flexural bending resistance and the curvature ductility determination (especially of composite wall cross sections like “U”, “L” and “C” shapes) requires a-priori assumptions to be performed with beam modelling. Standard codes suggest to use variable inclination truss models or a strut and tie model only for the evaluation of the shear resistance of shear walls.

The structural analysis of RC walls with plate or shell elements modelling is currently adopted to carry out linear and non-linear dynamic or equivalent static analyses of wall systems or dual systems. The wall modelling with plate or shell elements is sometimes preferred to the equivalent beam modelling because the position of the stiffness centroid and the eccentricity between the mass and the stiffness centroid can be automatically evaluated at every story level of the building (also in case of wall cross sections like “U”, “L” and “C” shapes). Output results have to be post-processed and transformed into generalized stresses (N, M, V) of equivalent beam

1 DICATeA – University of Parma, Italy
sections in order to meet the Standard Code verification. These numerical manipulations can be unknown to commercial software users.

The presentation will focus on the prediction of the non-linear behaviour of several RC walls systems (ductile walls, shear walls, post-tensioned walls, casted in-situ or precast walls) with membrane or multi-layered shell elements and total strain smeared crack models.

The new Model Code 2010 provides safety formats for non-linear analysis that ensure, in case of verifications assisted by FE methods, design resistances having the reliability level required by Codes for the structural verifications. In the framework of new Model Code 2010, the presentation will focus on alternative procedures to satisfy performance requirements and compliance criteria for RC walls resisting systems (modelled with shell elements) that circumvent the use of generalized stresses (N, M, V). The proposed verifications can be performed in terms of displacements, material stresses and crack opening values limitations for damage limit state verifications and in terms of displacements, strain verifications for confined, un-confined concrete and for steel in tension and compression (considering also rebars buckling phenomena and second’ order effects in general) for ultimate limit state verifications.

Numerical results obtained with DIANA Code and ABAQUS Code will be presented; without loss of generality a multi-layered shell element model, developed at the University of Parma using the finite element code ABAQUS will be illustrated. The analyses with ABAQUS Code let to adopt PARC_CL model, implemented in the user subroutine UMAT.for, for the description of the mechanical non-linearity.

In the presentation a case study of a multi-story building will be shown to demonstrate that for ductile walls the structural response at collapse can be predicted with similar level of accuracy by adopting shell element models or distributed plasticity models or lumped plasticity models.

However, the modelling with shell elements and smeared crack models can be more powerful, if compared to other approaches, for the structural assessment of shear walls and walls building characterized by both brittle shear or torsional failure and ductile bending failure.

Thus in the presentation the case studies of the Concrack 4 shear wall and of a ductile wall tested at the University of Brescia will be presented to illustrate that the shell elements modelling with smeared crack models can properly describe the state of cracking of both ductile and shear walls.

Strut and tie models are well known in the design practice at macro-level, the proposed approach implies the use of total strain crack models at micro-level: bridging the gap between macro and micro perspectives is a promising challenge for a comprehensive conceptual design of RC wall structures which unifies stress equilibrium conditions, strain compatibility conditions, constitutive laws of concrete and steel and their interaction.
A FILAMENT BEAM MODEL FOR THE THERMO-MECHANICAL ANALYSIS OF RC STRUCTURES. SIMULATION OF THE RL1 TEST

Jesús BAIRÁN, María Delia CRESPO, Denise FERREIRA and Antonio MARI²

Early age stresses arise from the restraint to the volumetric changes (such as those produced by the temperature development and autogeneous shrinkage) that develop from the hydration process of the cement. Such restraint can be caused either by non-linear strains distributions, by internal (reinforcement) or external restraints. Although the volumetric strains at early ages produce 3D effects, in case of beams and columns, it can be considered that the moisture and thermal flow produced are essentially longitudinal, except at the elements ends.

CEOS.fr has carried out an experimental campaign for benchmark proposes in order to evaluate the simulation skills of the models to describe the cracking phenomenon of RC structures. In this communication the simulation of one of the experimental tests - the large RC beam specimen loaded in bending after free shrinkage (RL1 test) – carried out by means of thermo-mechanical filament beam model, is presented. Such a model is able to reproduce the strain and stress states of tridimensional reinforced and prestressed concrete frame structures since early ages.

A blind stage simulation with this model was presented for participation in the ConCrack2 Benchmark and, after divulgation of the experimental results a post-diction simulation was re-made with some updated parameters. These include better approximations of the thermal boundary conditions, ambient temperatures, initial temperature of concrete and less tension stiffening. Numerical results from the 1D model in terms of temperature development, displacements, stresses, strains and crack patterns are compared with the experimental result. The predictions made by other participant teams are also contrasted, covering a wide range of geometrical modelling and mechanical assumptions. Beam elements presented one of the most successful performances at the blind stage, thus becoming a very interesting option for the design stage, because of their conceptual simplicity, capability to adequately capture complex structural behaviours and computational efficiency,

Key words: Temperature, early ages, cracking, concrete, shrinkage, filament, beam, model.

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SIMULATION OF CRACK PROPAGATION IN CONCRACK BENCHMARK

Vladimir CERVENKA

A suitable control of cracking of young concrete often determines the durability and the reliability of concrete structures. A hydro-thermo-mechanical approach is presented for analysis of reinforced concrete structures applicable in engineering practice. The multi-physics problem is solved by a staggered analysis that consists of two steps. The moisture and heat transport analysis is performed and the results are time dependent moisture and temperature fields in all material points. These resulting fields are then used in a stress analysis to calculate stresses, crack patterns and crack width. The whole model is implemented in finite element software.

It should be noted that the concrete cracking is effected by its volume changes due to chemical processes during the cement hydration and drying also by actions of externally applied loading forces. The modelling of this process requires implementation of constitutive models for transport as well as for crack propagation. Due to its complexity and induced uncertainty the model should be verified in order to allow its reliable application. It was the aim of the ConCrack benchmark to provide a forum for such validation.

Figure 1: Beam RG8 with restrained shrinkage

3 Cervenka consulting, Prague
The example of Beam RG8 in ConCrack benchmark was designed for investigation of crack development in early time stages after casting. The specimen was produced under well controlled conditions, Figure 1. The deformation of concrete specimen is restrained by special steel devices.

The numerical simulation provided the history of crack propagation and a large amount of supporting data about the stress and strain fields, which can explain the crack development.

An example from practical application of this approach in case of a massive concrete structure in a power plant is shown for illustration.
EXPERIMENTAL TESTS OF THICK SHEAR WALLS AT THE ELSA LABORATORY
Pierre PEGON

The presentation will give an overview of two test campaigns on thick shear walls performed at the ELSA Laboratory: SAFE ("Structures Armées Faiblement Elancées", contract with EDF & COGEMA) and TESSH (TEst on Strong SHear wall, EU-FP7 IRIS project).

1) SAFE

The campaign was performed in 1997-1998 on shear walls with thickness 16cm (4 walls) and 20cm (9 walls). It consists of Pseudo Dynamic tests, and the objective of the tests was to apply design earthquake repeatedly, increasing its intensity up to the ruin of the structure. The differences between each test were the Pseudo-dynamic mass, the vertical force and the steel detailing. Details about the running of the tests (the maximum capacity in shear was 7MN), instrumentation and available documentation will be given, together with an interpretation of the experimental results in term of stiffness and damping.

2) TESSH

The campaign was performed in 2012 on 5 identical shear walls with thickness 40cm. It consists of cyclic tests which were repeated two times on two wall specimens. In the first series the amplitude of the cycles was always increasing up to collapse. In the second series, two cycles were first performed to approach the plasticity limit of the steel at given amplitude followed by series of cycles performed starting from smaller amplitudes up to collapse. Three stereo photogrammetric rigs were used to take pictures during the tests, to monitor each face of the wall and to measure the displacements of the loading system. Details about the running of test (the maximum capacity in shear was 12MN) and instrumentation will be given, together with an interpretation of the experimental results in term of stiffness and damping and some results in terms of crack patterns, opening and sliding.

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CRACKING OF REINFORCED CONCRETE ELEMENTS: INFLUENCE OF COVER, $\phi/\rho_{ef}$ RATIO, STIRRUPS SPACING AND ADDITION OF RECYCLED STEEL FIBERS

Alejandro PÉREZ CALDENTEY$^5$, Giancarlo GROLI$^6$

The results obtained from 3 experimental campaigns carried out at the Structures Laboratory of the Civil Engineering School of the Polytechnic University of Madrid are briefly presented and analysed. The campaigns include basic cracking tests of beams subject to constant bending moment designed to separate the effect of cover and $\phi/\rho_{ef}$ ratio, tests designed to evaluate the effect of stirrups and a series of identical tests of beams manufactured with recycled steel fibres in order to evaluate the efficiency of this type of fibre in reducing the crack width opening.

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A further experimental campaign is presented involving supports subjected to imposed deformations with and without fibres in an effort to study the cracking effects in jointless structures.
From this experience some ideas are advanced with regard to why cover affects crack width and why this should not be a concern for durability reasons.

Potential practical applications are then discussed, including how to extend the length of jointless structures and how to reduce the amount of reinforcement in water retaining structures by using fibres.
Partially prestressed concrete, which is an effective means for crack control and other service performance, is gaining newly interest in practical design; in part, motivated by the development of new performance based design codes. Among the main advantages of partially prestressed concrete, it should be mentioned the more freedom that it provides the designer to optimize structures in terms of specific needs of each project, reduction of material and weight. On the other hand, it also provides more ductility, in comparison to fully prestressed concrete elements, and allows redistribution of internal forces, among other advantages.

However, the behaviour of cracked partially prestressed concrete is complex, resulting non-linear even at service load levels; for this reason, adequate methodologies and models are needed for its full application in engineering practice, and, in particular for shear sensitive concrete structures. Among these topics, it can be mentioned cracking verification under bending and shear loading, where the influence of different variables are to be defined, such as the prestressing degree, spacing of amount of transversal reinforcement, longitudinal reinforcement, crack inclination, etc.

In this presentation, a review of the state of art regarding cracking in prestressed concrete elements under bending and shear is presented. The current design tendencies of different contexts are analysed and discussed, and the topics where higher discrepancies exists both in research and codes are identified. For this purpose, numerical studies on existent experimental tests on partially prestressed concrete beams are replicated with a nonlinear shear-flexural filament beam model, in which the most relevant variables affecting shear cracking behaviour are discerned. Furthermore, a parametric study is performed with this model in order to investigate the influence of several parameters on the flexural and shear cracking response of partially prestressed isostatic I-shaped beams at scale of ¼ of typical bridge girders: web width, prestress level and configuration, cover, quantity and disposition of longitudinal and transversal reinforcement. Time-dependent analyses are also performed to study the influence of creep and shrinkage on the cracking response. This parametric study led to the design of an experimental campaign to be carried out in the near future at UPC in the framework of Research Project ‘Performance-based-design of partially prestressed concrete structures. Proposal of new design methodology, experimental verification and design criteria’, financed by the Spanish Ministry of Economy and Competitivity.
Since the release of MC 1990 considerable progress in concrete technology has taken place. New types of concrete, in particular self-compacting concrete and high strength concrete up to $f_{cm} = 120$ MPa, are produced in practice today on a routine basis.

Expanding the range of validity of the models without appealing to split them and to use different models for different types of concretes represents a significant challenge for the conception of a code type model. However, within MC 2010 for a given concrete behaviour to be modelled, one single constitutive approach has been chosen, which represents an optimum, when applied for differed types of concrete. Of course, the type of concrete must be taken into account by the introduction of certain factors within the corresponding formulas, but the basic mathematical relation of the constitutive approach or model, respectively, remains unchanged.

Under this background, the new fib Model Code 2010 presents new formulations for the prediction of shrinkage and creep extending the range of applicability while using in each case a single constitutive approach.

**Shrinkage modelling**

In contrast to the previous prediction model in the MC1990, this new model subdivides the total shrinkage into a drying shrinkage component and an additional basic shrinkage component, which was necessary to ensure sufficient prediction accuracy for normal (NSC) and high strength concrete (HSC). The significance of basic shrinkage in high strength concrete becomes apparent in Fig. 3 which shows the development of shrinkage components with time for NSC and HSC.

General approach:

$$\varepsilon_{cs}(t,s) = \varepsilon_{cbs}(t) + \varepsilon_{cbs}(t,s)$$

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8 *KIT Karlsruhe*
Figure 3: Time development of shrinkage

Creep modelling

As long as creep deformation is considered exclusively for NSC, we do not lose much accuracy by not separating creep into its basic and drying components. As for the model of shrinkage, if the model for creep should also integrate the prediction for HSC, we need to consider the fact that the influence of the increase in strength affects in different ways, both magnitude and kinetics of basic creep and drying creep as may be seen in Fig. 4.

General approach:

$$\varphi(t, t_0) = \varphi_{bc}(t, t_0) + \varphi_{dc}(t, t_0)$$

Figure 4: Time development of creep
Appendix F

SC2 ACTIVITY FOR NEW MANDATE

Giuseppe MANCINI

The main idea is to present the intense activity that SC2 is managing since about two years.

The presentation can be summarized as follows:

- Analysis of implementation needs envisaged during the use of EN 1992's, like contained in an official document approved by CEN TC250/SC2;
- Organization of SC2 to manage the process of revision of EN1992's: creation of WG1 and of 10 TG's, between which the main subjects of revision/implementation have been divided;
- Analysis of comments received by NMB's (National Member Body) and their treatment within the WG1;
- Present activity within the TG's and first proposals available on the floor;
- Timetable for the next 18 months, that will be crucial for the preparation of a first draft of EN1992;
- New proposed format for the next generation of code for concrete structures.

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\(^9\) Politecnico di Torino, Chairman CEN/TC250/SC2
POSSIBLE WAYS OF CODIFICATION FOR CRACKING

György L. BALÁZS

Introduction

Cracks occur in concrete, reinforced concrete, prestressed concrete elements whenever the deformation exceeds the tensile capacity of concrete. This can happen already in early stages after casting or later at any time. Some of the cracks can be avoided by technological measures, others have to be controlled by reinforcement.

Proper functioning of a reinforced concrete structures strongly depends on the development of internal cracks (their existence can be recognized e.g by acoustic emission measurements) and the external cracks (that we can observe on the surface of the element). Both groups of cracks have their importance.

Discussion

The cracking phenomenon itself, as well as the crack width and crack spacing that we actually use as parameters to control cracking in the practice, are influenced by many parameters. Of course, we know the existence of these parameters, however, their weight and importance are sometimes under or overestimated.

Present cracking formulas are mainly based on observations with small or relatively small elements. The careful measurements by the CEOS Project, using large size elements, can considerably contribute to the modelling and future codification of the cracking phenomenon.

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