Ductal®: from materials to structures

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Content

• Highlight Gilles extensive and deep contribution to UHPC material development up to his involvement on iconic projects

• Focus on the back analysis method to assess fiber contribution for the post cracking tensile stress

• Key stages of UHPC history from the assessment of fire properties, assessment of structural behavior through pilot projects (crack analysis), shrinkage, etc. up to most recent advanced mix development

• Gilles’ footprint on iconic projects as Mucem, Jean Bouin, FLV

• Gilles’ human contribution, empowering everybody in the labs combining an amazing teamwork experience with the search for excellence
UHPC

UHPC : Ultra High Performance Concrete

Enhancement of:
- homogeneity
- compactness
- microstructure
- micro-fibre compatibility
Ductal®

Ductal® = large range of UHPC

- Ductal® is a registered trademark owned by LafargeHolcim that covers all the range of UHPC products
- Ductal® mixes are patented material customized for specific needs

Performances

- Strong: up to 250 MPa in compressive strength and 50 MPa in flexural strength
- Lifetime of structures is higher than 150 years
- High durability properties
- Constant properties over time
Genesis of UHPC

Reinforced / Prestressed concrete: compliance of detailings (cover of rebars, spacing between rebars, bending radius of stirrups, …) leads to large and not optimized sections

Durability: ordinary concrete is sensible to aggressive agent ingress (carbonation, chloride attacks, freeze / thaw cycles) → reinforcement must be protected by the concrete

A solution: remove the rebars and develop a high durable and strong concrete
Genesis of Ductal®

1996: first extensive project in France (nuclear plant)
A total of 2,400 metallic girders were replaced by prestressed girders in Ductal
History of Ductal®

1994
First Bouygues patents « BPR » (metallic fibres)

1995
Agreement Bouygues / Lafarge / Rhodia (common development, co-ownership)
The worldwide brand Ductal® is registered

1997
First Ductal® patent (metallic fibres)

1998
New Ductal® patent (organic fibres)

2000
New Ductal® patent (fire resistant with PP fibres)

2004
Rhodia withdraws from the co-ownership

2005 - 2011
R&D projects focussed on surface treatment

2007
First 100% Lafarge patent UHPC by Lafarge

2008 - 2014
R&D projects focussed on 100% Lafarge formulations

04/2014
Agreement with Bouygues on the use of jointly owned patents and Ductal® trademark

Gilles is one of inventors for several Ductal patents
Ductal®: range of tailor-made mixes

Large range of applications by mastering the rheology

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Since ancient times, fibres have been used to reinforce brittle materials

Exodus 5:6,
*And Pharaoh commanded the same day the taskmasters of the people, and their officers, saying, we shall no more give the people straw to make brick, as heretofore: let them go and gather straw for themselves*

Egyptians used straw to reinforce mud bricks, but there is evidence that asbestos fiber was used to reinforce clay posts about 5000 years ago.
Early 19th century, patent on steel fibers as reinforcement
Several patents on fibre geometries

H. Hooked ends fibre
Fibres concrete

• During the early 1960s in the United States, the first major investigation was made to evaluate the potential of steel fibres as reinforcement for concrete. Since then, a substantial amount of research, development, experimentation, and industrial application of steel fibre reinforced concrete has occurred.

• Use of glass fibres in concrete was first attempted in the USSR in the late 1950s. Development of alkali-resistant glass fibres containing zirconia has led to a considerable number of commercialized products (for example architectural cladding panels).

• Initial attempts at using synthetic fibres (nylon, polypropylene) were not as successful as those using glass or steel fibres. However, better understanding of the concepts behind fibre reinforcement, new methods of fabrication, and new types of organic fibres have led researchers to conclude that both synthetic and natural fibres can successfully reinforce concrete.
Fibres concrete: rheological considerations

Whatever their type nor geometry, addition of fibres tends to degrade the rheological behaviour of concrete.

Can we explain such impact with basic considerations?
Fibres concrete: rheological considerations

As for aggregate, it is a question of fibre packing

Tara Donovan
Untitled (Pins)
UHPC: mechanical consideration

Cracking mechanisms of plain concrete: a certain potential of crack bridging provided by aggregates

Cracking mechanisms of macro fibre concrete: no impact on tensile strength but large crack bridging potential
UHPC: mechanical consideration

Cracking mechanisms of micro fibre concrete: increase of apparent tensile strength but small crack bridging potential

- micro-crack growth delayed by microfibres
- macro-crack growth
- bridging and branching
- Micro fibre-reinforced concrete
- Concrete
- fibre bridging
- postpones development and prevents widening of micro-crack
- Region where microfibres act
UHPC: mechanical consideration

Pure tension: two main categories, strain softening or hardening
UHPC : Back analysis method

From pure tension to flexural response:

Uni-axial response

Flexural response

Deflection hardening

Multiple cracking

Matrix cracking

Deflection softening

Single crack

Matrix cracking

Load

Deflection
Back analysis method

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From concrete nanoscale to structure
celebrating Gilles Chanvillard’s memory

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UHPC: Back analysis method for thin plates

Thanks to Gilles, it is now common to characterize the tensile behaviour of fibre-reinforced concrete by bending tests rather than by direct tensile tests. Then it is fairly common today to apply reverse analysis to extract the tensile constitutive equation of the material. For the case of thin plates showing a bending hardening behaviour, Gilles developed an explicit method (which does not need any numerical solver) allowing performing reverse analysis into equivalent strain. This method starts with an experimental moment-deflection relationship to get tensile stress-strain constitutive relationship. The great advantage of this explicit approach is to be easy to program and it allows to quickly manually adjust a constitutive material relationship on the experimental results without any data pre-treatment.

Figure 2: Schematic representation of the non linear distribution of the curvature
UHPC: Back analysis method for thin plates

Figure 1: Strain and stress distribution over the height of a section

Normal force is obtained by integrating the stress distribution over the section:

$$N_i = \int_S \sigma \cdot b \cdot dz - \frac{b}{\chi_i} \int_{\varepsilon_i}^{\varepsilon_c} \sigma(\varepsilon) \cdot d\varepsilon \quad \text{avec} \quad dz = \frac{d\varepsilon}{\chi_i}$$
UHPC: Back analysis method for thin plates

\[
M_{i+1}^- = \frac{b}{(\chi_{i+1})^2} \left( \int_{\varepsilon_{i+1}}^{\varepsilon_i} \sigma(\varepsilon) \varepsilon \, d\varepsilon + \int_0^{\varepsilon_i} \sigma(\varepsilon) \varepsilon \, d\varepsilon \right) = \frac{b}{(\chi_{i+1})^2} \int_{\varepsilon_{i+1}}^{\varepsilon_i} \sigma(\varepsilon) \varepsilon \, d\varepsilon + \left( \frac{\chi_i}{\chi_{i+1}} \right)^2 M_i^-
\]

The integral term has won a power compared to normal force calculation. The trapezoidal rule method is then no longer acceptable. A variant of Simpson's method is then preferred:

\[
\int_{\varepsilon_{i+1}}^{\varepsilon_i} \sigma(\varepsilon) \varepsilon \, d\varepsilon = \frac{\sigma(\varepsilon_{i+1}) \cdot (2 \cdot \varepsilon_{i+1} + \varepsilon_i) + \sigma(\varepsilon_i) \cdot (2 \cdot \varepsilon_i + \varepsilon_{i+1})}{6} \times (\varepsilon_i - \varepsilon_{i+1})
\]

Using (3), compressive stress moment in (11) becomes:

\[
M_{i+1}^+ = \frac{b}{(\chi_{i+1})^2} \int_{\varepsilon_{i+1}}^{\varepsilon_i} \sigma(\varepsilon) \varepsilon \, d\varepsilon = \frac{E \cdot b \cdot (\varepsilon_{i+1})^3}{3 \cdot (\chi_{i+1})^2} = \frac{E \cdot b}{3 \cdot (\chi_{i+1})^2} \left[ \varepsilon_{i+1} \left( \frac{1 - \alpha_{i+1}}{\alpha_{i+1}} \right) \right]^3
\]

Finally, with \( \chi_{i+1} = -\varepsilon_{i+1} \cdot (\alpha_{i+1} \cdot h)^{-1} \), (12), (13) and (14) allow to evaluate the moment at \( "i+1" \)
UHPC: Back analysis method for thin plates

Figure 3: Screen capture of an spreadsheet allowing adjusting the tensile constitutive equation through the cursors in order to reproduce the experimental results.
Iconic project: Mucem

Mucem museum, France / Architect: Rudy Ricciotti
Iconic project: Mucem
Iconic project: Mucem

- Straight column and Y column were tested
- Modeling and testing were consistent for straight column but unsafe for Y column (larger deflection than expected)

A testing device// failure mode: UHPC or massive head ➔
Iconic project: Mucem
Iconic project: Mucem

Fibre orientation and distribution
Iconic project: Mucem

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Iconic project: Mucem

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From concrete nanoscale to structure
celebrating Gilles Chanvillard’s memory
5-6 July 2016
Champs-sur-Marne, France
Iconic project: Mucem
Iconic project: Jean-Bouin stadium

Jean Bouin stadium, France / Architect: Rudy Ricciotti
Iconic project: Jean-Bouin stadium

• Facade: triangle perforated panels, up to 8m x 2.4m
• Roof: waterproof panels + glass inclusions, same dimensions. Ribs devices used for drainage of water
• Isostatic panels support, specific designed hinges
Iconic project: Jean-Bouin stadium
Iconic project: Jean-Bouin stadium

Ductility and safety factors…
Iconic project: Jean-Bouin stadium
Iconic project: Jean-Bouin stadium

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Iconic project: Jean-Bouin stadium

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Iconic project: Fondation Louis Vuitton

Fondation Louis Vuitton (France) / Architect: Frank Gehry
Iconic project: Fondation Louis Vuitton

- Total area: 9,326 m²
- Panels: 18,737
- Dimensions: 1.5m x 0.4m x 25mm
  - 40% of the panels are flat
  - 60% of the panels are curved and all different

Vacuum system for pouring the curved panels
Iconic project: Fondation Louis Vuitton
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Iconic project: Fondation Louis Vuitton
A deep tribute for Gilles Chanvillard

Thank you Gilles!