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Australia's Global University

Exploring the Future of Ultra-High Performance Concrete (UHPC) Bridge Construction: Advancements, Challenges, and its Role in Critical Infrastructure Development

Professor Stephen Foster

Faculty of Engineering, UNSW Sydney

UHPC materials and structures, Budapest, 27 August 2024

Impact on Sustainability

- In March 2023, the Intergovernmental Panel for Climate Change (IPCC) released its sixth synthesis report (AR6) outlining challenges associated with climate change.
- It is recognised that “human activities … have unequivocally led to global warming, with average global surface temperature reaching 1.1°C above 1850–1900 in 2011–2020”
- The solution lies in climate resilient development through a combination of adaptation and actions to reduce GHG emissions.
- These goals cannot be delivered without ready and speedy uptake of disruptive technologies and alignment of these with societal needs.
- How ready are we? Do our codes and practices support this?

Once upon a time someone said “*cement contributes 8% of global C0$_2$ emissions*” … what happens next …

CBS NEWS

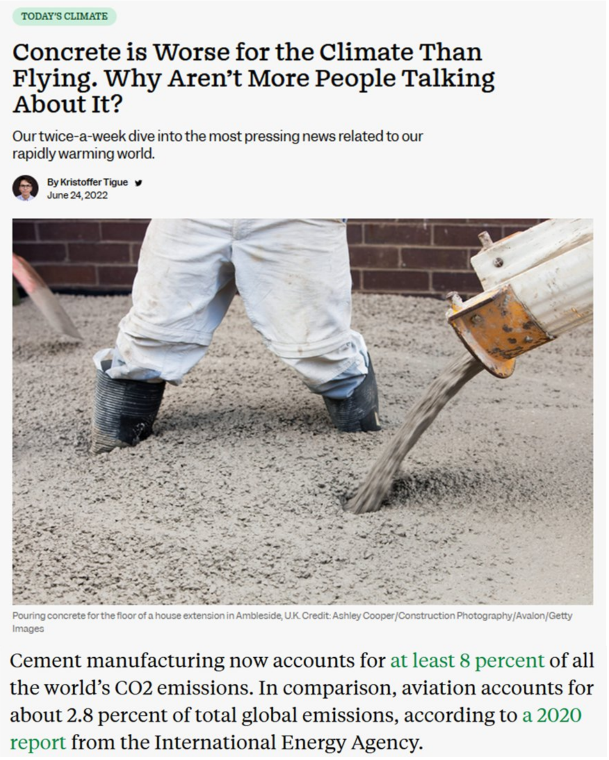
CBS MORNINGS ›

Cement industry accounts for about 8% of CO2 emissions. One startup seeks to change that.

EDITORIAL | 28 September 2021

Concrete needs to lose its colossa carbon footprint

Concrete will be crucial for much-needed climate-resilient construction. But the industry must set out its plan for decarbonization.



TODAY'S CLIMATE

Concrete is Worse for the Climate Than Flying. Why Aren’t More People Talking About It?

Our twice-a-week dive into the most pressing news related to our rapidly warming world.

By Kristoffer Tigue
June 24, 2022

Pouring concrete for the floor of a house extension in Ambleside, U.K. Credit: Ashley Cooper/Construction Photography/Avalon/Getty Images

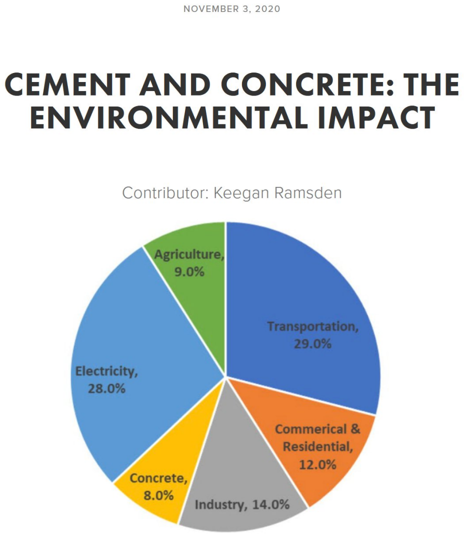
Cement manufacturing now accounts for at least 8 percent of all the world’s CO2 emissions. In comparison, aviation accounts for about 2.8 percent of total global emissions, according to a 2020 report from the International Energy Agency.

Concrete needs to lose its colossal carbon footprint

Concrete will be crucial for much-needed climate-resilient construction. But the cement industry must set out its plan for decarbonization.

Versatile and long-lasting, concrete buildings and structures are in many ways ideal for climate-resilient construction. But concrete has a colossal carbon footprint — at least 8% of global emissions caused by humans come from the cement industry alone[3].

Cement manufacturing (such as that at this plant in Russia) accounts for 8% of the world's carbon dioxide emissions. Credit: Getty



NOVEMBER 3, 2020

CEMENT AND CONCRETE: THE ENVIRONMENTAL IMPACT

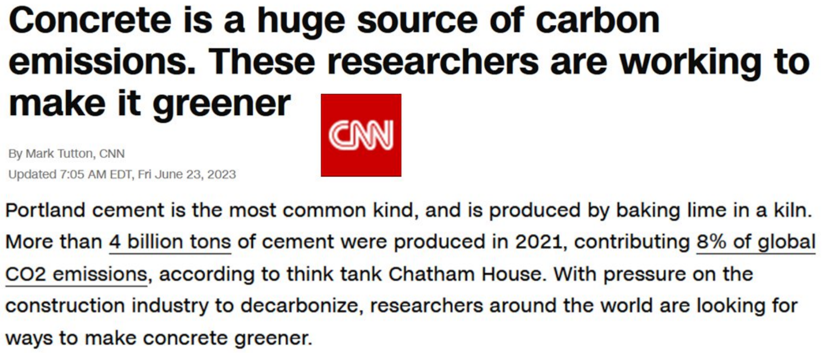
Contributor: Keegan Ramsden

Climate change: The massive CO2 emitter you may not know about

17 December 2018

By Lucy Rodgers
BBC News

Cement is the source of **about 8% of the world's carbon dioxide (CO2) emissions,** according to think tank Chatham House.



Concrete is a huge source of carbon emissions. These researchers are working to make it greener

By Mark Tutton, CNN
Updated 7:05 AM EDT, Fri June 23, 2023

Portland cement is the most common kind, and is produced by baking lime in a kiln. More than 4 billion tons of cement were produced in 2021, contributing 8% of global CO2 emissions, according to think tank Chatham House. With pressure on the construction industry to decarbonize, researchers around the world are looking for ways to make concrete greener.

Chatham House Report

Johanna Lehne and Felix Preston
Energy, Environment and Resources Department | June 2018

Making Concrete Change Innovation in Low-carbon Cement and Concrete

Each year, more than 4 billion tonnes of cement are produced, accounting for around 8 per cent of global CO$_2$ emissions

Concrete: the most destructive material on Earth

After water, concrete is the most widely used substance on the planet. But its benefits mask enormous dangers to the planet, to human health - and to culture itself

- A brief history of concrete: from 10,000BC to 3D printed houses
- Editor’s pick: best of 2019. We’re bringing back some of our favorite stories of the past year. Support the Guardian’s journalism in 2020

by Jonathan Watts

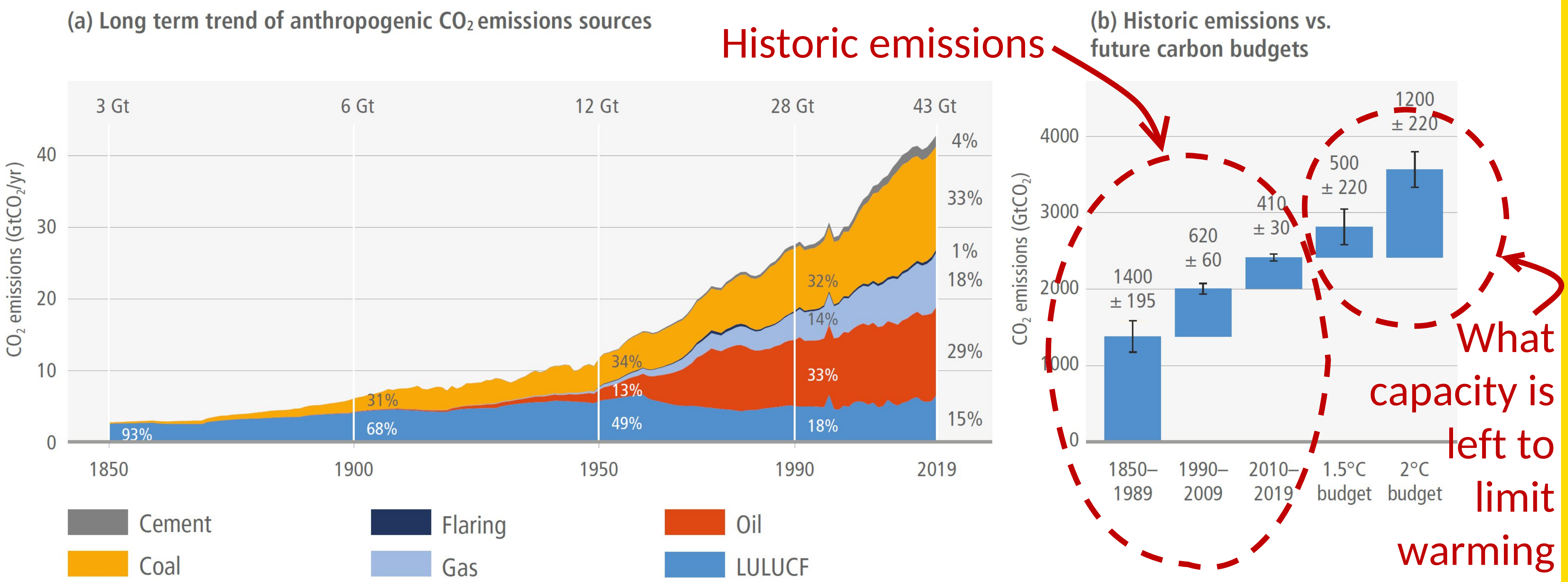
Concrete: the most destructive material on Earth - podcast

Technical Summary

WGIII

Working Group III contribution to the
Sixth Assessment Report of the
Intergovernmental Panel on Climate Change

WMO UNEP



(a) Long term trend of anthropogenic CO_2 emissions sources

(b) Historic emissions vs. future carbon budgets

Historic emissions

What capacity is left to limit warming

Figure TS.3 | Historic anthropogenic CO_2 emission and cumulative CO_2 emissions (1850–2019) as well as remaining carbon budgets for limiting warming to 1.5°C (>67%) and 2°C (>67%). Panel (a) shows historic annual anthropogenic CO_2 emissions ($GtCO_2\ yr^{-1}$) by fuel type and process. **Panel (b)** shows historic cumulative anthropogenic CO_2 emissions for the periods 1850–1989, 1990–2009, and 2010–2019 as well as remaining future carbon budgets as of 1 January 2020 to limit warming to 1.5°C and 2°C at the 67th percentile of the transient climate response to cumulative CO_2 emissions. The whiskers indicate a budget uncertainty of ±220 $GtCO_2$-eq for each budget and the aggregate uncertainty range at one standard deviation for historical cumulative CO_2 emissions, consistent with WGI. {Figure 2.7}

Source: https://www.ipcc.ch/report/sixth-assessment-report-working-group-3/

WGIII

Working Group III contribution to the
Sixth Assessment Report of the
Intergovernmental Panel on Climate Change

WMO UNEP

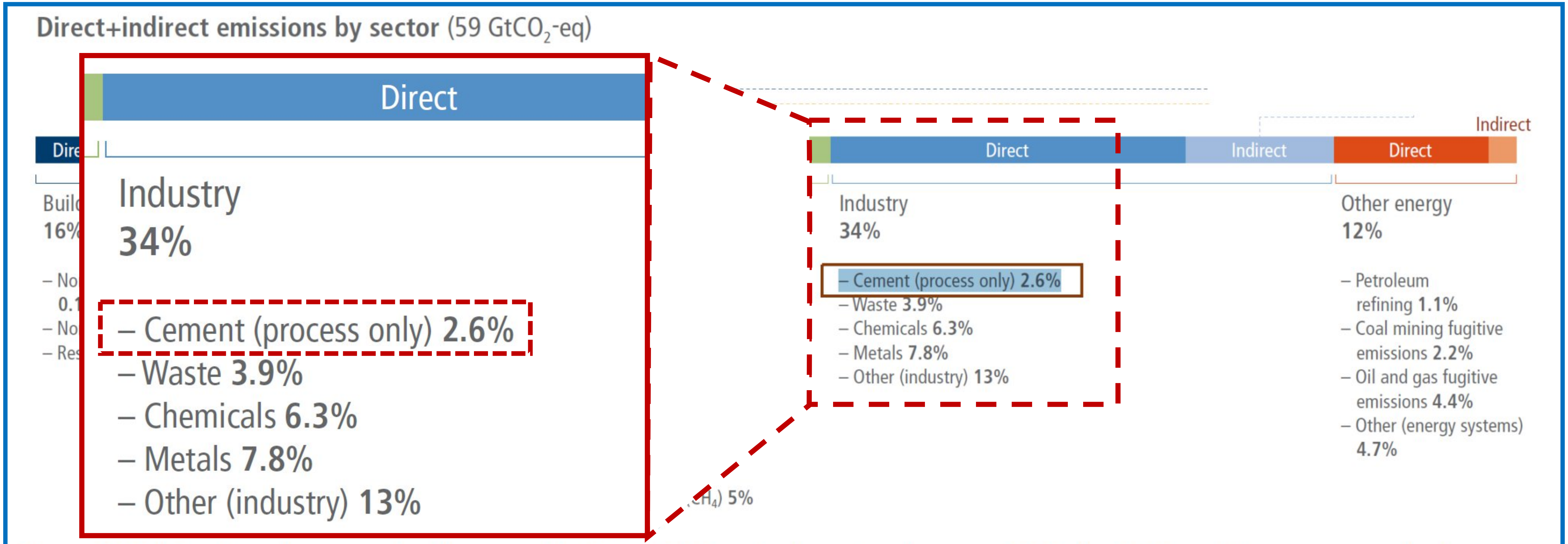


Figure TS.6 | Total anthropogenic direct and indirect GHG emissions for the year 2019 (in $GtCO_2$-eq) by sector and subsector.

Source: https://www.ipcc.ch/report/sixth-assessment-report-working-group-3/

UNSW SYDNEY

Global C

Robbie Andrew[1]

GCP-CEM: The G

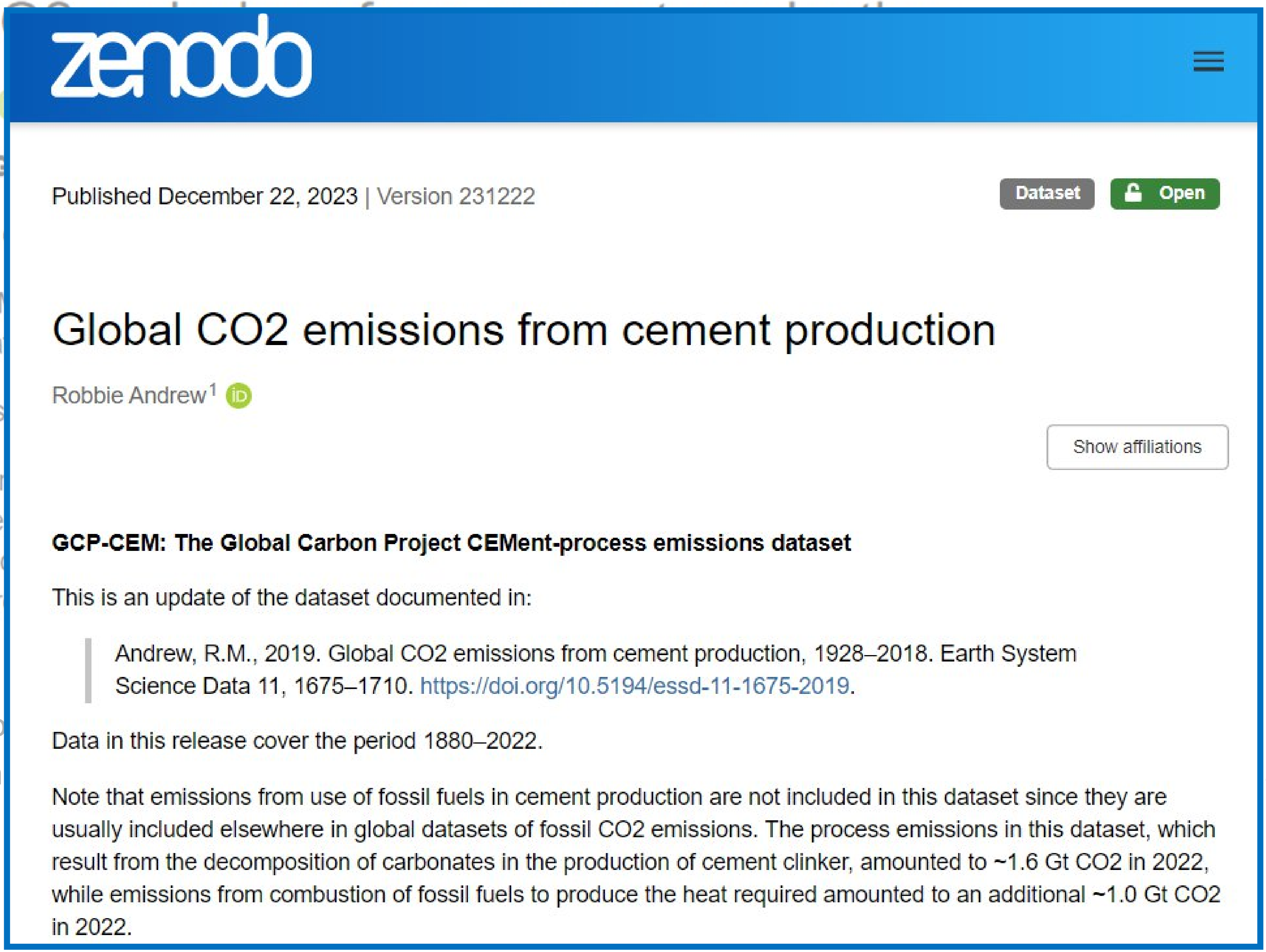
This is an update

Andrew, R.M.
Science Da

Data in this releas

Note that emissio
usually included e
result from the de
while emissions fr
in 2022.

Total world pro
Decomposition al emissions)



Published December 22, 2023 | Version 231222

Global CO2 emissions from cement production

Robbie Andrew[1]

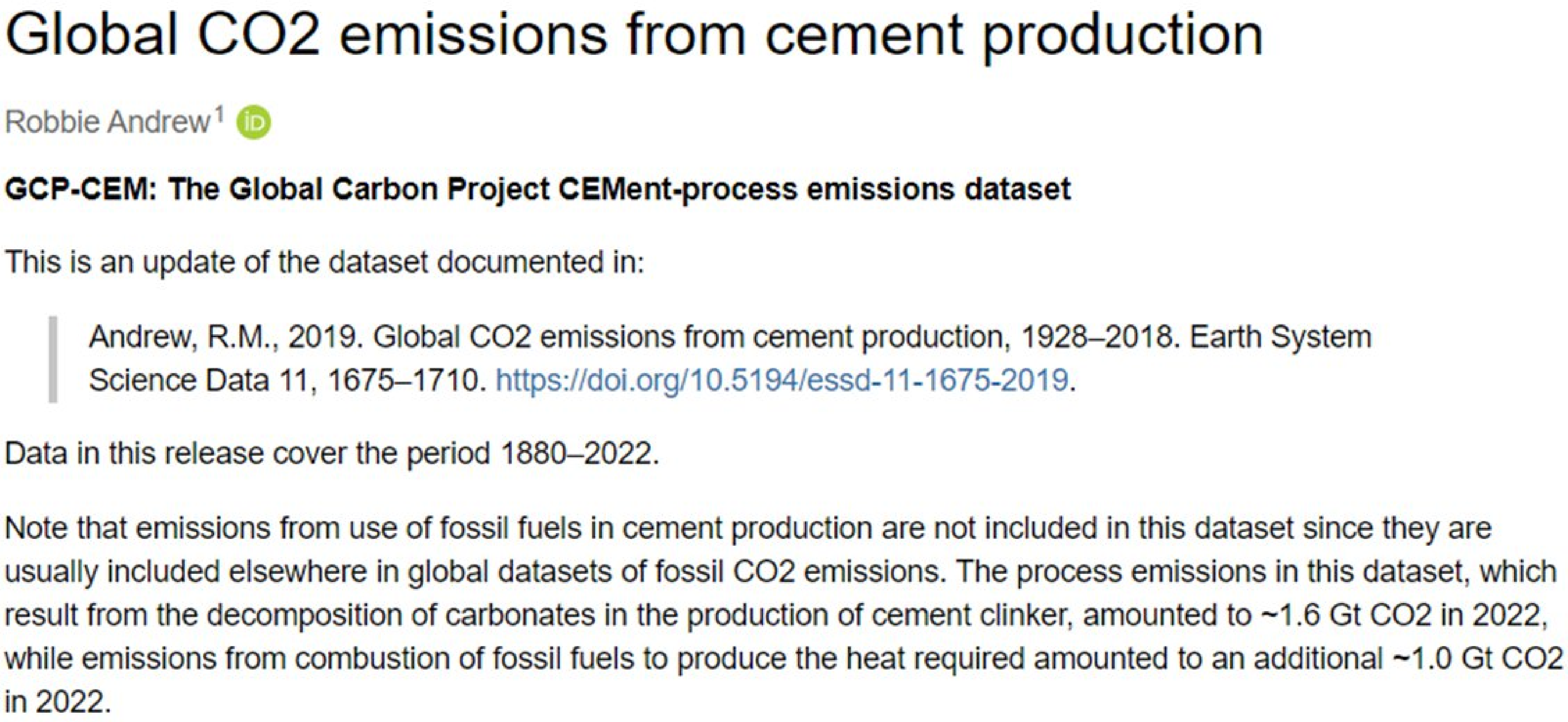
GCP-CEM: The Global Carbon Project CEMent-process emissions dataset

This is an update of the dataset documented in:

> Andrew, R.M., 2019. Global CO2 emissions from cement production, 1928–2018. Earth System Science Data 11, 1675–1710. https://doi.org/10.5194/essd-11-1675-2019.

Data in this release cover the period 1880–2022.

Note that emissions from use of fossil fuels in cement production are not included in this dataset since they are usually included elsewhere in global datasets of fossil CO2 emissions. The process emissions in this dataset, which result from the decomposition of carbonates in the production of cement clinker, amounted to ~1.6 Gt CO2 in 2022, while emissions from combustion of fossil fuels to produce the heat required amounted to an additional ~1.0 Gt CO2 in 2022.



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Total world production of CO_2 in 2019 = **44 Gt CO_2**

Decomposition of carbonates **1.6 Gt CO_2** + fossil fuel for energy **1.0 Gt CO_2** = **2.6 Gt CO_2** (**5.9%** of total emissions)

Total world production of CO_2-eq (or GHG) = **59 Gt CO_2-eq** in 2019 (IPCC: 2022 WGIII Report)

CO_2-eq emissions from cement CO_2 emissions = **2.6 Gt CO_2-eq** (**4.4%** of total GHG emissions)

Ways to achieving a low carbon building industry

Substitution:	Replacement of a higher carbon material with a lower one that gives the same or improved performance.
Reuse:	Adaption and reuse of existing infrastructure assets
Sequestration:	Embedding carbon dioxide in the environment (terrestrial sequestration), within geological formations (geological sequestration) or in materials used in the building and infrastructure construction (industrial sequestration)
Capture:	Direct carbon capture, storage, and reuse
Dematerialisation:	Higher strength, higher performance materials; efficiency gains.

Some Background to UNSW Research in UHPC

An investigation into the behaviour of Prestressed Reactive Powder Concrete Girders Subject to Non-Flexural Actions. Yen Lei “Jackie” Voo PhD 2004 (Supervisors: Foster, Gilbert)

Post PhD formed a company DURA Technology (capitalisation US$15 million)

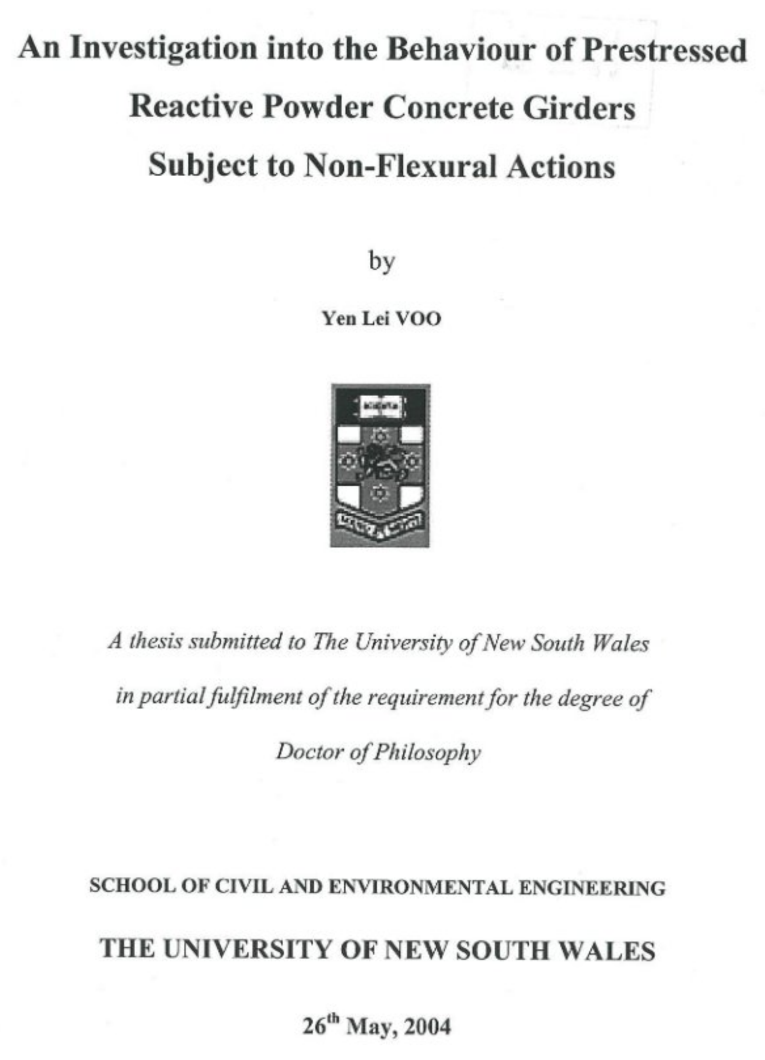
Short-term and time-dependent flexural behaviour of steel fibre-reinforced reactive powder concrete. Robyn Warnock PhD 2005 (Supervisors: Gowripalan, Gilbert)

An Investigation into the Behaviour of reactive Powder Concrete Columns. Adnan Malik PhD 2007 (Supervisor: Foster)

Behaviour of high-Strength and Reactive Powder Concrete Columns Subjected to Impact. Luan “Ryan” Huynh PhD 2011 (Supervisor: Foster)

Non-destructive methods for determining fibre distribution and orientation in SFRC and UHPFRC structures. Lakshminarayanan Mohana Kumar PhD 2023 (Supervisors: Foster, Aboutanios)

UHPC Prestressed Girders Failing in Shear



An Investigation into the Behaviour of Prestressed
Reactive Powder Concrete Girders
Subject to Non-Flexural Actions

by

Yen Lei VOO

A thesis submitted to The University of New South Wales
in partial fulfilment of the requirement for the degree of
Doctor of Philosophy

SCHOOL OF CIVIL AND ENVIRONMENTAL ENGINEERING

THE UNIVERSITY OF NEW SOUTH WALES

26th May, 2004

UHPC – Applications – Impact Resistance

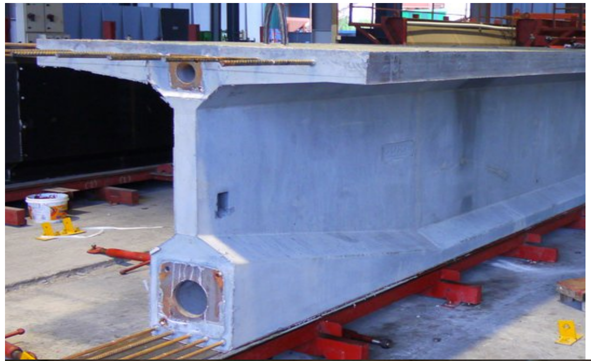
HSC Column – 3rd Impact

RPC Column – 3rd Impact


Pakistan
PB
HP
UK
UP
Nepal
AR
RJ
BR
ML
NL
GJ
India
WB
Myanmar (Burma)
OR
MH
6
TS
KA
AP
Bay of Bengal
ian Sea
TN
KL
Laccadive Sea
East China Sea
11
Philippine Sea
Thailand
South China Sea
Vietnam
Philippines
Gulf of Thailand
122
aysia
10
Indonesia
Banda Sea
Arafura Sea
Papua New Guinea

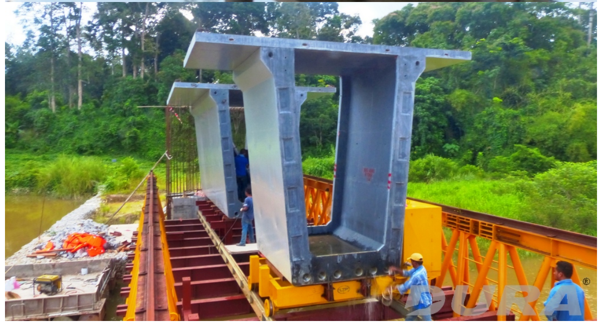
Types of UHPFRC Bridges

Type 1: Integral beam deck



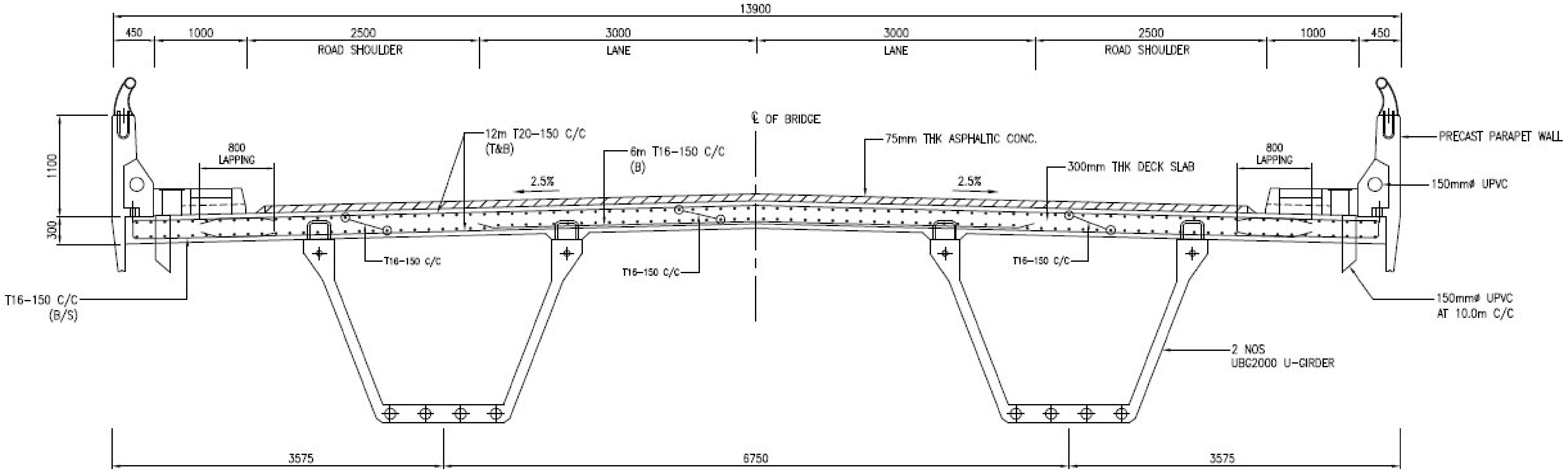
Type 2: Composite UHPFRC beam
 in-situ NSC deck

Type 3: UHPFRC box girder

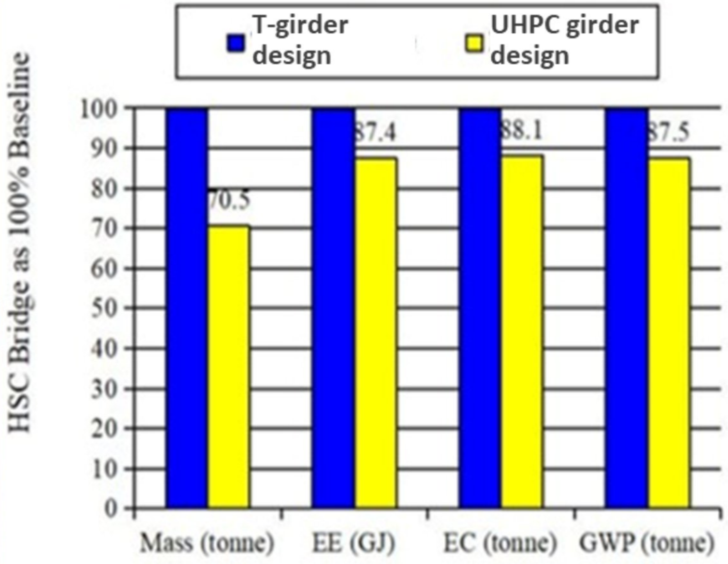


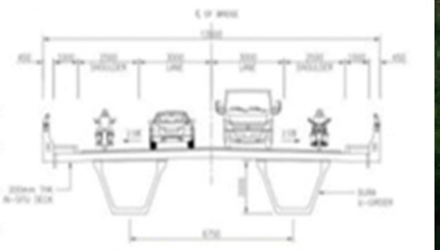
Type 4: U trough girder

Cross-section of KB-KT Bridge

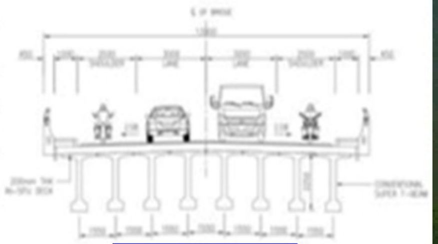


420 metre KB-KT Bridge

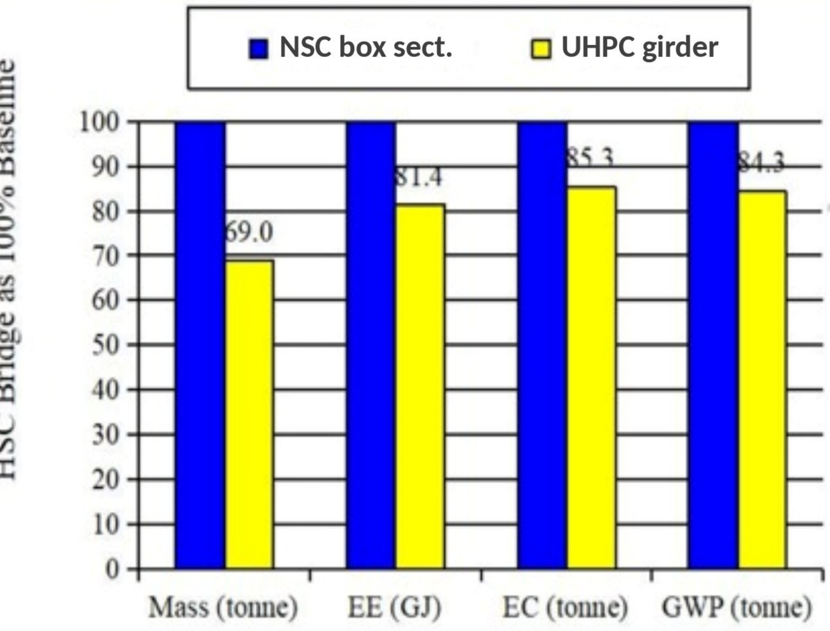


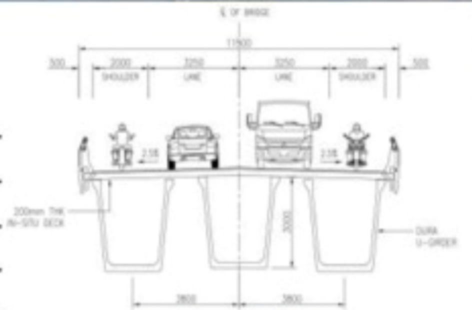


UHPC Bridge

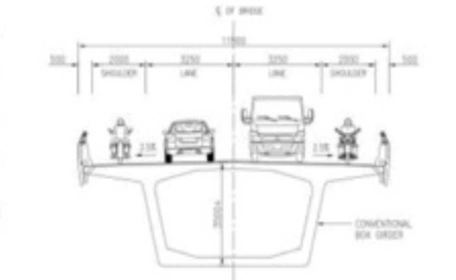


NSC Bridge





UHPC girder



UHPC box section

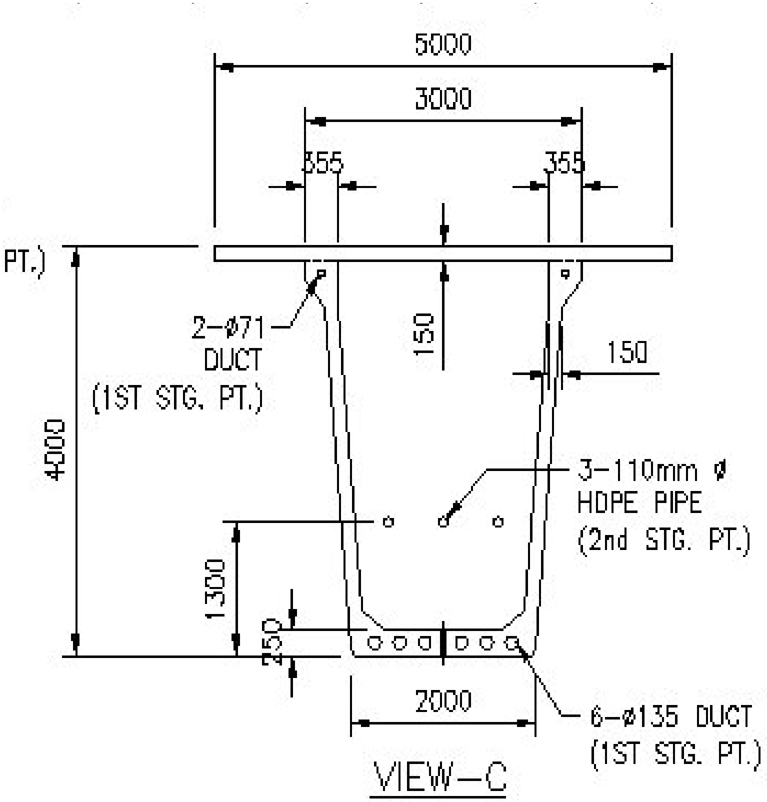
Manong Bridge, Perak (2018-2019)

Lambor Bridge, Malaysia

Negeri Sembilan Bridge – 51.5 metres

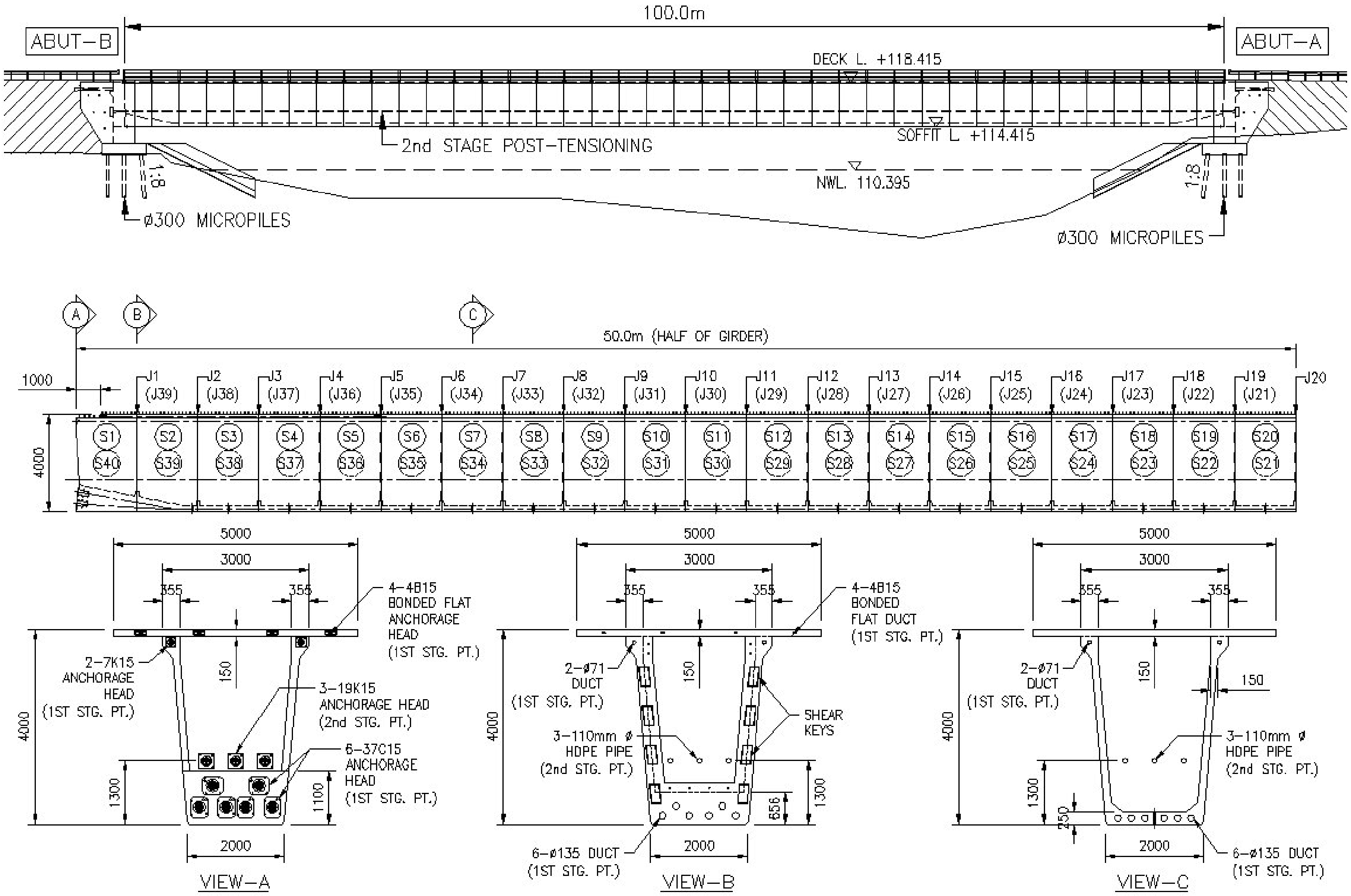
Negeri Sembilan Bridge – 51.5 metres

Ultra High Performance Concrete

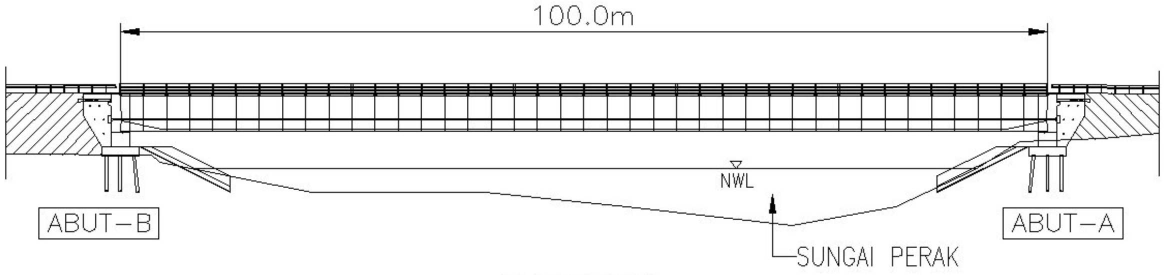


100 metre Span UHPC Batu 6 Segmental Box Girder Bridge, Malaysia

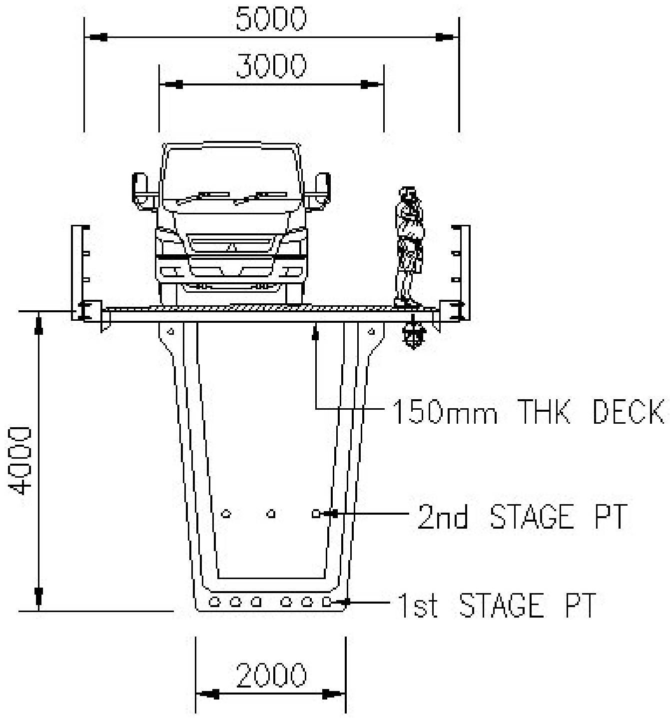
150 MPa Concrete; very high levels of prestress (4x that of conventional construction); light-weight; lighter foundations; lower carbon emissions in transport; etc.


100.0m
ABUT–B
ABUT–A
DECK L. +118.415
SOFFIT L. +114.415
2nd STAGE POST–TENSIONING
NWL. 110.395
1:8
1:8
ø300 MICROPILES
ø300 MICROPILES
A
B
C
50.0m (HALF OF GIRDER)
1000
J1 (J39)
J2 (J38)
J3 (J37)
J4 (J36)
J5 (J35)
J6 (J34)
J7 (J33)
J8 (J32)
J9 (J31)
J10 (J30)
J11 (J29)
J12 (J28)
J13 (J27)
J14 (J26)
J15 (J25)
J16 (J24)
J17 (J23)
J18 (J22)
J19 (J21)
J20
4000
S1 S40
S2 S39
S3 S38
S4 S37
S5 S36
S6 S35
S7 S34
S8 S33
S9 S32
S10 S31
S11 S30
S12 S29
S13 S28
S14 S27
S15 S26
S16 S25
S17 S24
S18 S23
S19 S22
S20 S21
5000
3000
355
355
150
4000
1300
1100
2000
4–4B15 BONDED FLAT ANCHORAGE HEAD (1ST STG. PT.)
2–7K15 ANCHORAGE HEAD (1ST STG. PT.)
3–19K15 ANCHORAGE HEAD (2nd STG. PT.)
6–37C15 ANCHORAGE HEAD (1ST STG. PT.)
VIEW–A
5000
3000
355
355
150
4000
1300
656
2000
4–4B15 BONDED FLAT DUCT (1ST STG. PT.)
2–ø71 DUCT (1ST STG. PT.)
SHEAR KEYS
3–110mm ø HDPE PIPE (2nd STG. PT.)
6–ø135 DUCT (1ST STG. PT.)
VIEW–B
5000
3000
355
355
150
150
4000
1300
250
2000
2–ø71 DUCT (1ST STG. PT.)
3–110mm ø HDPE PIPE (2nd STG. PT.)
6–ø135 DUCT (1ST STG. PT.)
VIEW–C

UHPC Segments for 100 metre span Box Girder Batu 6 Bridge crossing Sungai Perak - Malaysia



ELEVATION

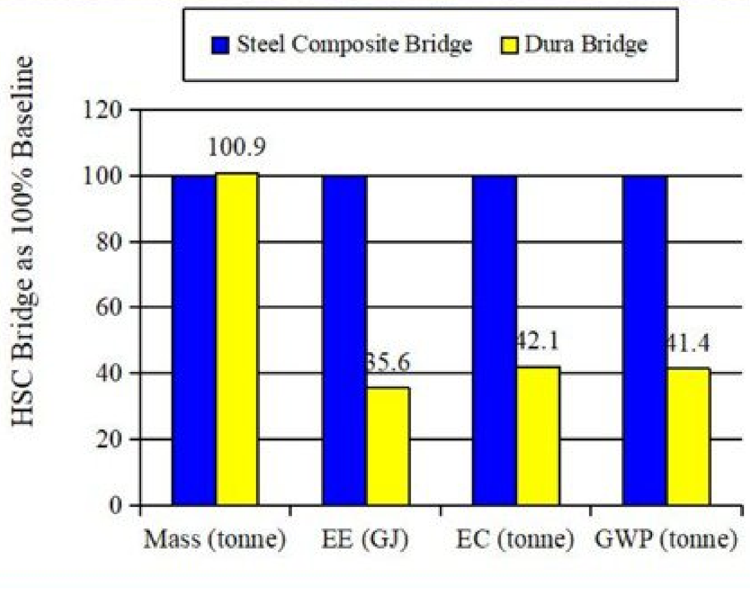


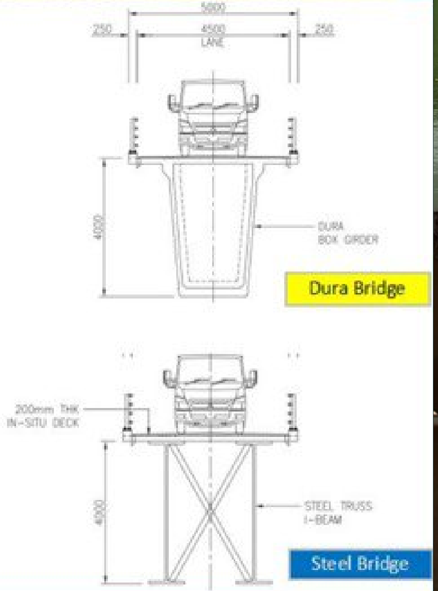
TYP. SECTION OF BRIDGE MIDSPAN

100% assembled – before stressing


Freyssinet

100 m span box girder Batu 6 Bridge - Sungai Perak - Malaysia





Ulu Geroh Bridge – 25 metres

Location: Ulu Geroh, Kampar, Perak, Malaysia

Client: JKR Kinta

Function: River crossing river to indigenous community

Structure: Single span 25m x 3.5m UHPdC integral beam-deck system.

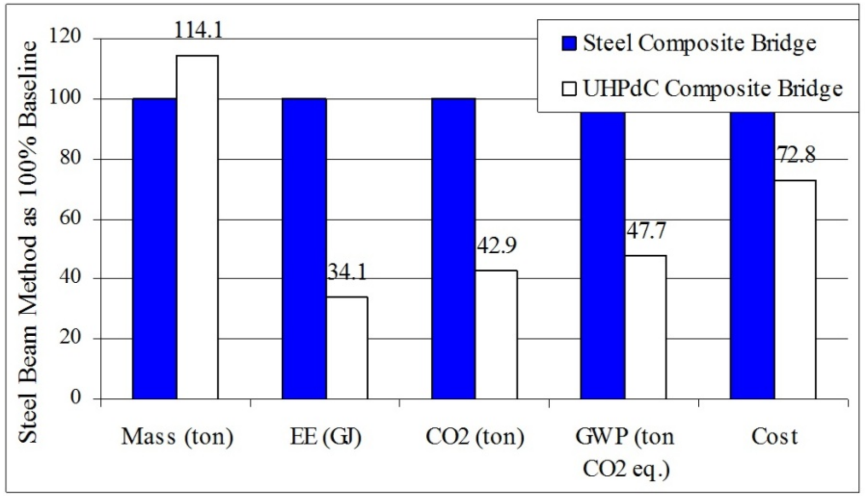
Design Load: Full HA + 30HB loadings (BD37/01)

Construction Period: 3 months.

Ulu Geroh, Kampar, Perak, Malaysia

50 Metre Span Road Bridge

Total time from start of fabrication to completion of abutments 79 days!



Construction and Environmental Impact Assessment of Langat River 105 Metre Span UHPC Composite Bridge

Jhen Shen Tan[1], Yen Lei Voo[1,2], Stephen J. Foster[3], Balamurugan A. Gopal[4], Hui Teng Ng[1]

1: Dura Technology Sdn. Bhd
2: Adj. Professor, Faculty of Science and Technology, Swinburne University of Technology, Victoria, Australia
3: Professor, Faculty of Engineering, The University of New South Wales, UNSW Sydney, Australia
4: Public Work Department of Malaysia

Table 4: EE and EC of NSC 32/40, steel bar, UHPC-1.5%SF and NSC 50/60.

Material	SD (kg/m^3)	EEF (MJ/kg)	ECF ($kgCO_2/kg$)	EE (GJ/m^3)	EC ($kgCO_2/m^3$)
NSC 32/40	2350	0.88*	0.123*	2.07	289
Steel	7850	29.2*	2.59*	229	20332
UHPC-1.5%SF	2420#	3.83	0.468	9.278#	1130#
NSC 50/60	2370#	1.05	0.170	2.49#	405#

*Source from: * [6]; # Table 5*

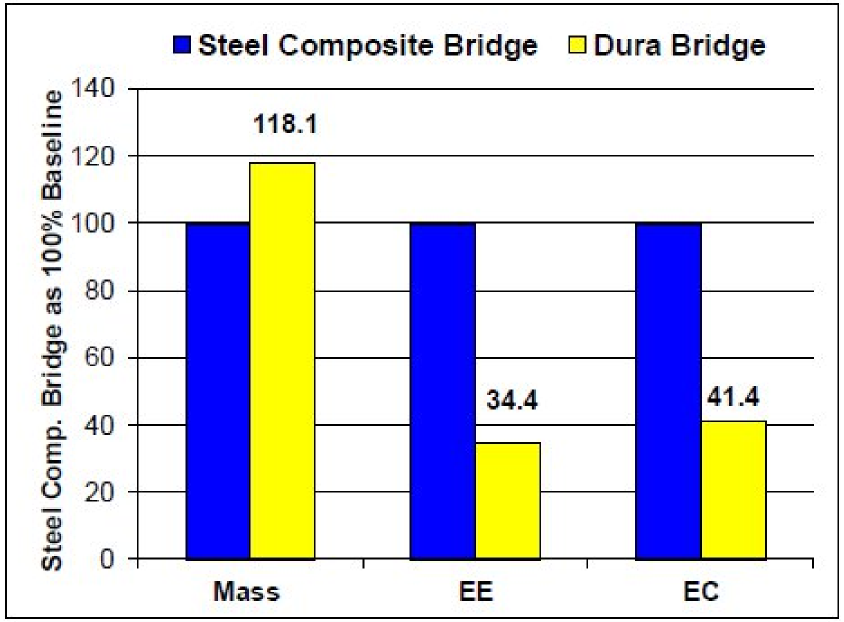
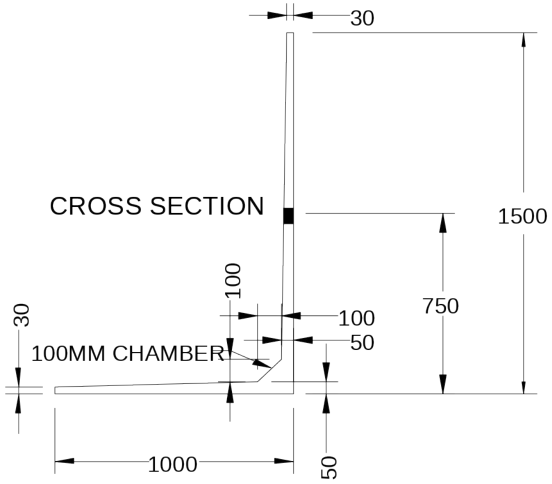


Figure 4: Mass, EE and EC comparison


SAFETY FIRST
UTAMAKAN KESELAMATAN

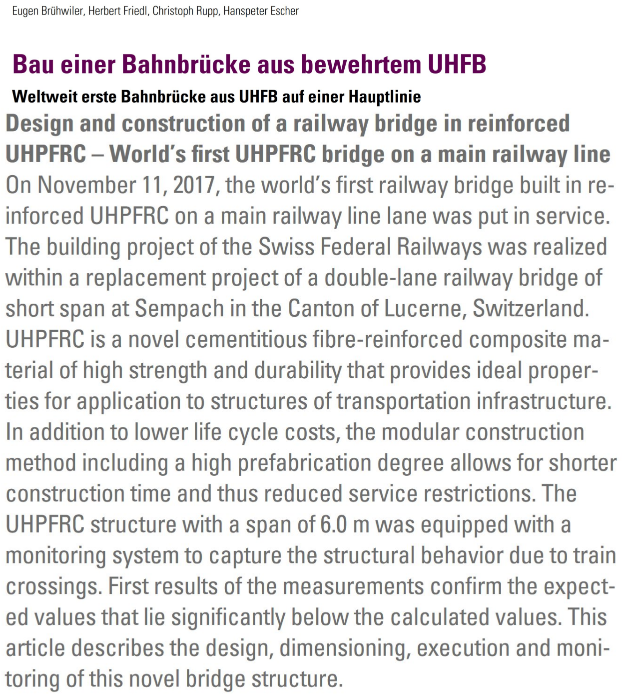
UHPC Retaining Walls - 2009



25 kPa Surcharge Loading

Environmental Impact Calculation

https://onlinelibrary.wiley.com/doi/epdf/10.1002/best.201900010



Eugen Brühwiler, Herbert Friedl, Christoph Rupp, Hanspeter Escher

Bau einer Bahnbrücke aus bewehrtem UHFB

Weltweit erste Bahnbrücke aus UHFB auf einer Hauptlinie

Design and construction of a railway bridge in reinforced UHPFRC – World's first UHPFRC bridge on a main railway line

On November 11, 2017, the world's first railway bridge built in reinforced UHPFRC on a main railway line lane was put in service. The building project of the Swiss Federal Railways was realized within a replacement project of a double-lane railway bridge of short span at Sempach in the Canton of Lucerne, Switzerland. UHPFRC is a novel cementitious fibre-reinforced composite material of high strength and durability that provides ideal properties for application to structures of transportation infrastructure. In addition to lower life cycle costs, the modular construction method including a high prefabrication degree allows for shorter construction time and thus reduced service restrictions. The UHPFRC structure with a span of 6.0 m was equipped with a monitoring system to capture the structural behavior due to train crossings. First results of the measurements confirm the expected values that lie significantly below the calculated values. This article describes the design, dimensioning, execution and monitoring of this novel bridge structure.

Bild 3 Straßenunterführung Unterwalden nach Abschluss der Bauausführung (Dezember 2017)

Road underpass Unterwalden after construction (December 2017)

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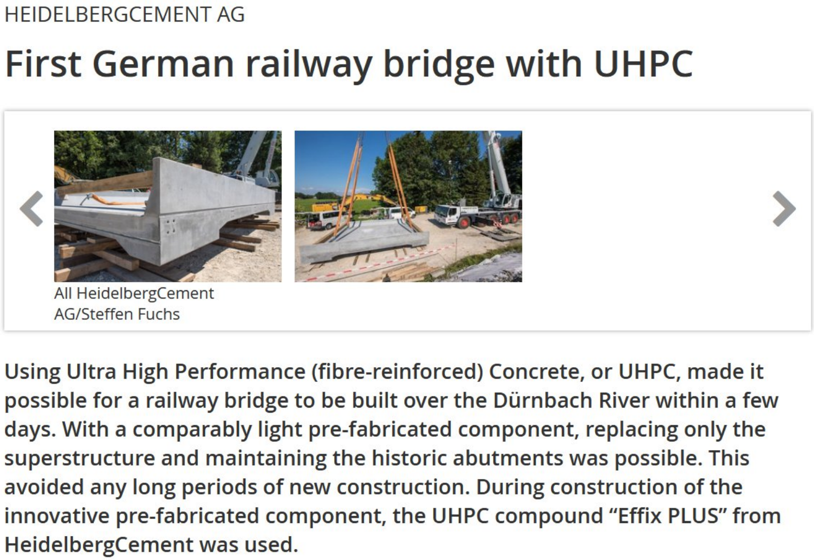
https://www.zkg.de/en/artikel/zkg_First_German_railway_bridge_with_UHPC-3562139.html



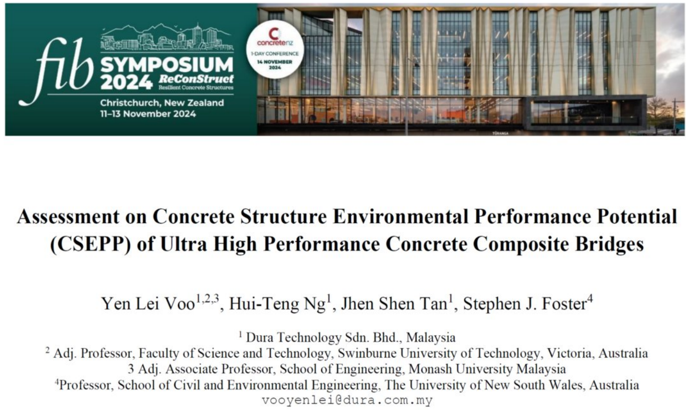
HEIDELBERGCEMENT AG

First German railway bridge with UHPC

All HeidelbergCement AG/Steffen Fuchs

Using Ultra High Performance (fibre-reinforced) Concrete, or UHPC, made it possible for a railway bridge to be built over the Dürnbach River within a few days. With a comparably light pre-fabricated component, replacing only the superstructure and maintaining the historic abutments was possible. This avoided any long periods of new construction. During construction of the innovative pre-fabricated component, the UHPC compound "Effix PLUS" from HeidelbergCement was used.

Crossing of RTS Link using UHPC design - Singapore



Assessment on Concrete Structure Environmental Performance Potential (CSEPP) of Ultra High Performance Concrete Composite Bridges

Yen Lei Voo[1,2,3], Hui-Teng Ng[1], Jhen Shen Tan[1], Stephen J. Foster[4]

[1] Dura Technology Sdn. Bhd., Malaysia
[2] Adj. Professor, Faculty of Science and Technology, Swinburne University of Technology, Victoria, Australia
[3] Adj. Associate Professor, School of Engineering, Monash University Malaysia
[4] Professor, School of Civil and Environmental Engineering, The University of New South Wales, Australia
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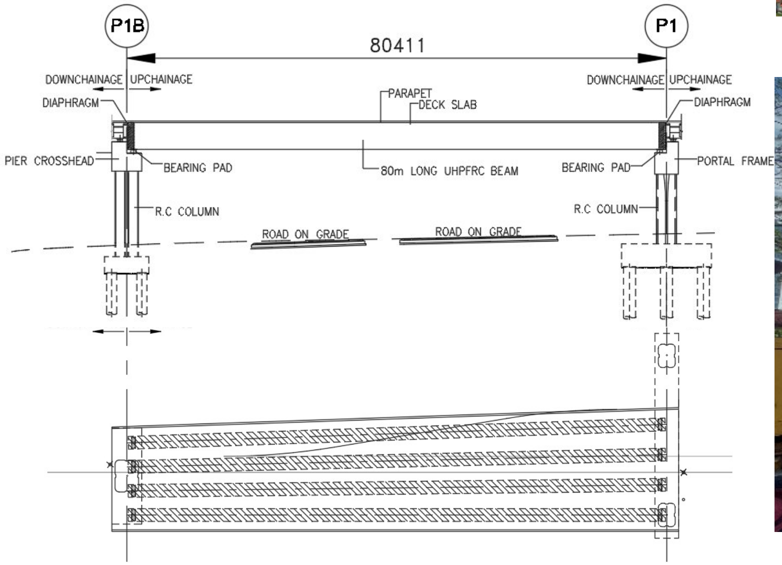


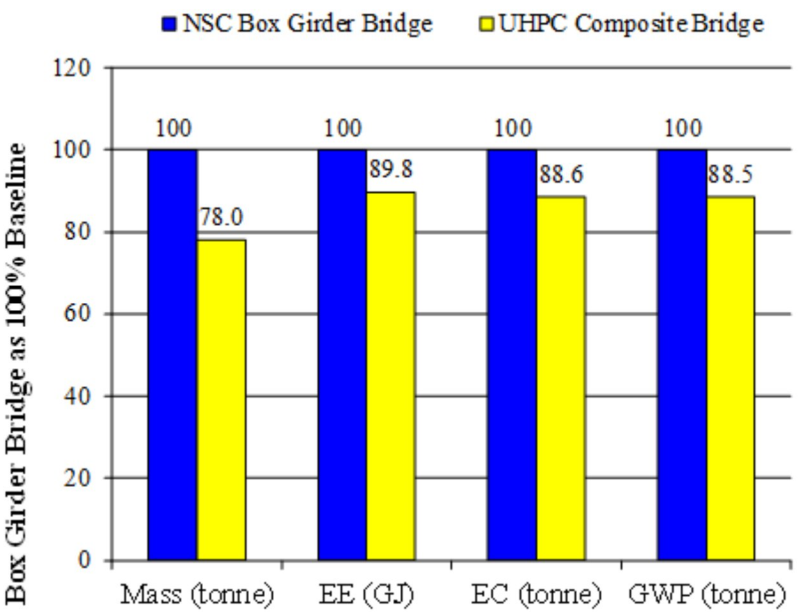
Lead consultants: AECOM (Southeast Asia)

Designers: Jurutera Perunding Riz, Malaysia

Manufacturer: DURA Technology, Malaysia

Conforming NSC design: 2-spans of approximately 40 metres each

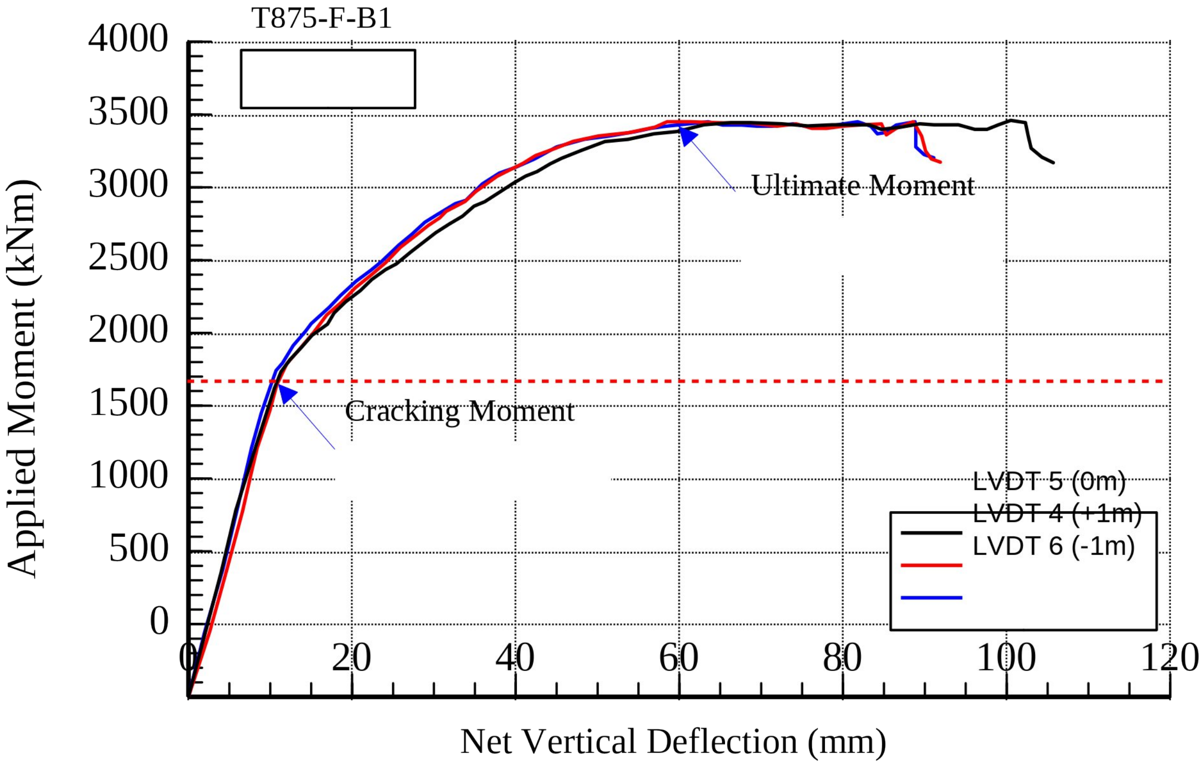
Alternative design: 1-span of approx. 80 metres (requiring 1 less pier).




DURA


DURA
Ultra High Performance Construction Material
EAST

Flexural Behaviour



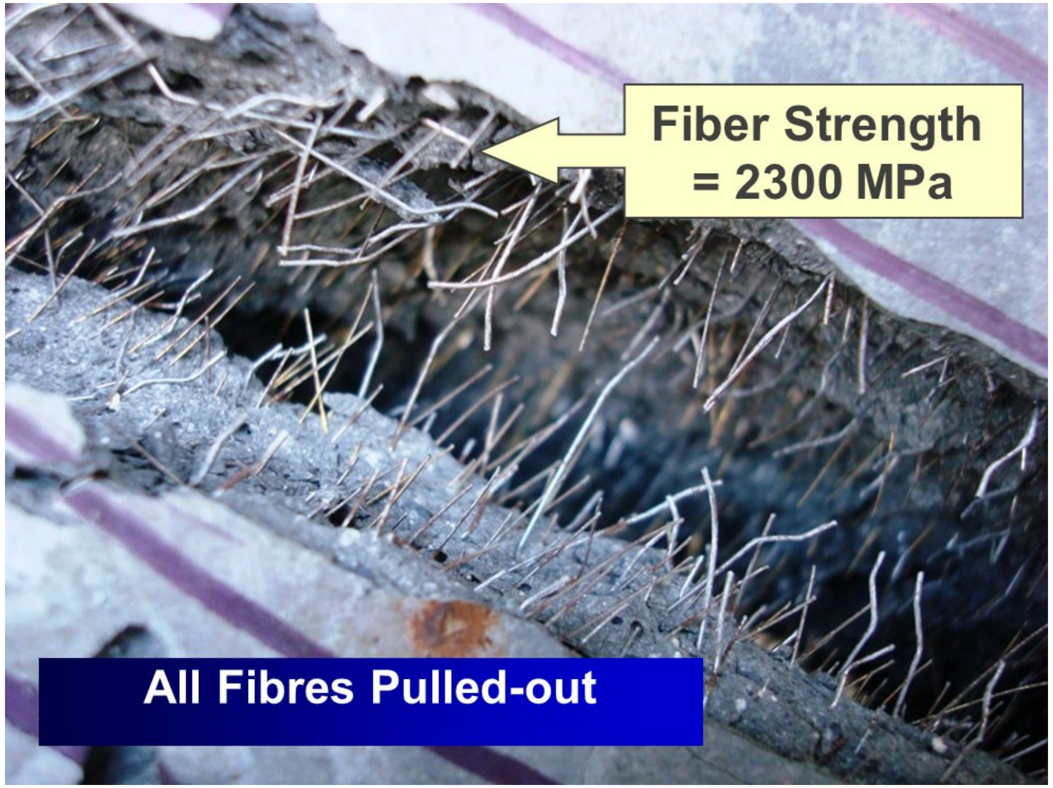
EAST

Critical diagonal shear crack

P = 2800 kN

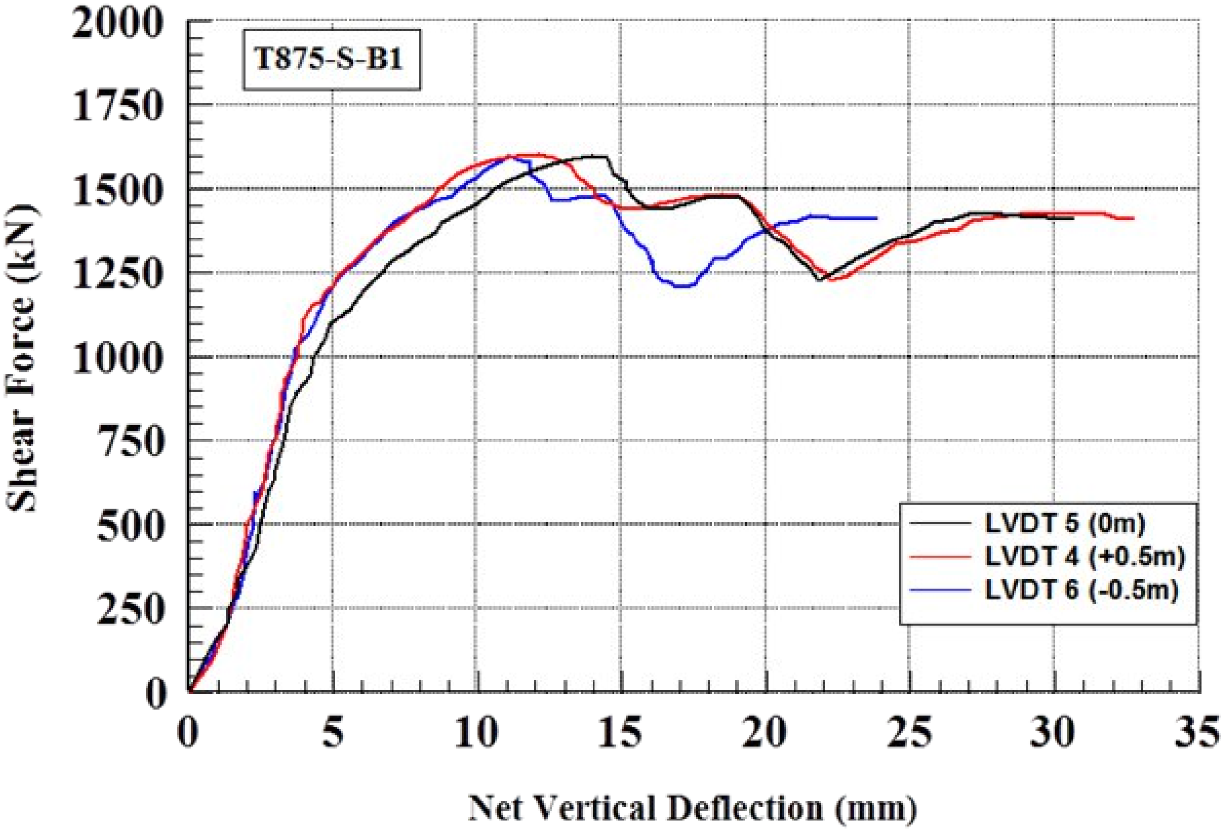
Fracture Surface

Load-deflection



Fiber Strength = 2300 MPa

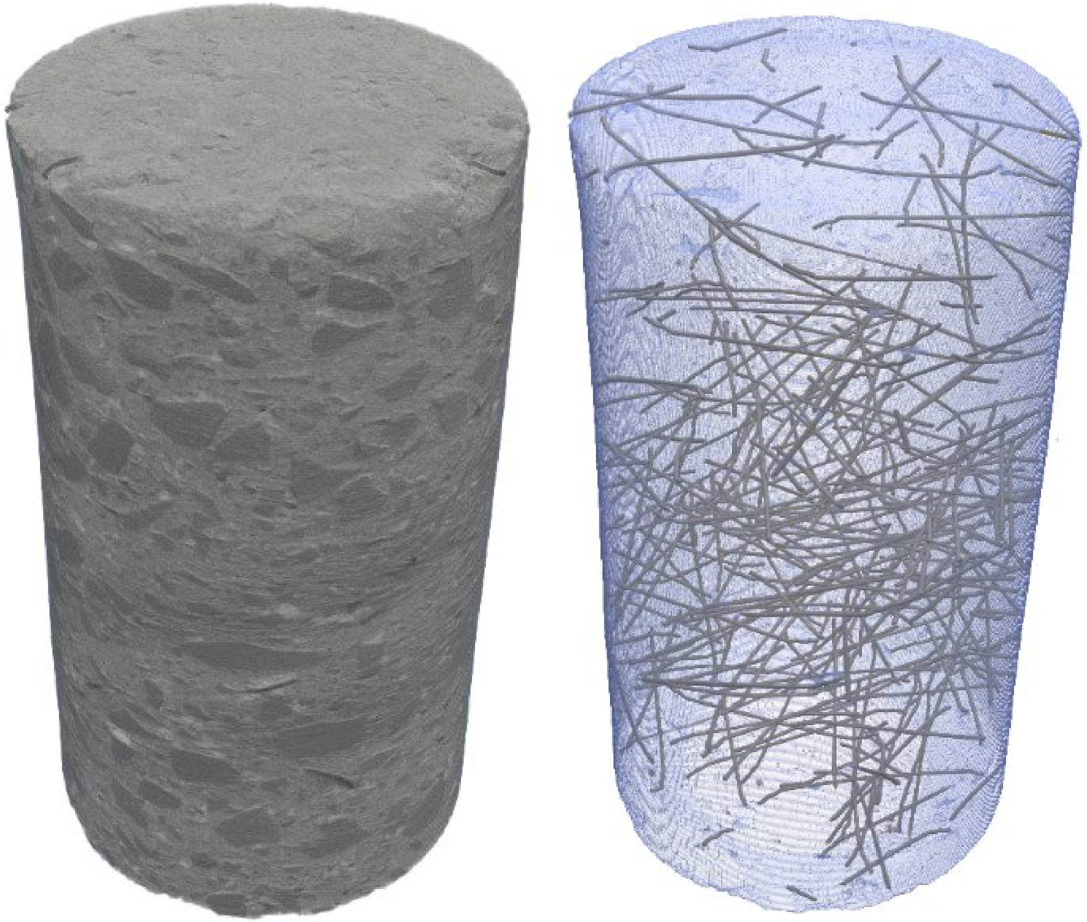
All Fibres Pulled-out



Fibre Orientation State is Three Dimensional!

- Much like the state of stress, fibre orientation state is also three dimensional!
- Isotropic, planar, and unidirectional fibre orientation states are all special cases, as in the case of stress.
- Yet, isotropic or other simpler fibre orientation states are assumed during design.
- Fibre orientation measurements and corrections are made in terms of the **orientation factor**, which is a 1D parameter.

We need to more fully understand the 3D fibre orientation state and incorporate in design?



3D rendering of tomogram of a SFRC cored specimen

Norwegian University of Science & Technology

Technical Paper

Giedrius Žirgulis*
Oldřich Švec
Mette Rica Geiker
Andrzej Cwirzen
Terje Kanstad

Variation in fibre volume and orientation in walls experimental and numerical investigations

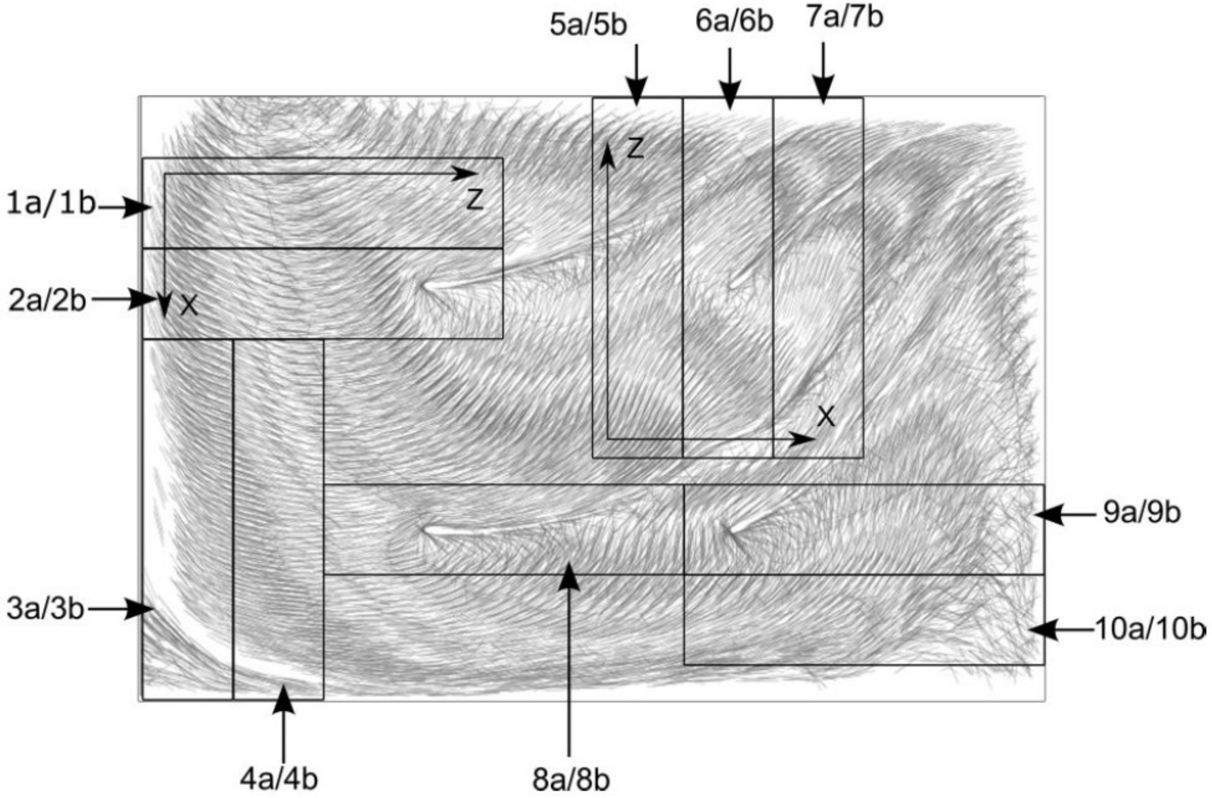


Fig. 8. Results of numerical simulations of fibre orientation in the FRSCC wall. The directions of the X and Zaxes in the vertically and horizontally sawn beams and the names of sawn beams are indicated.

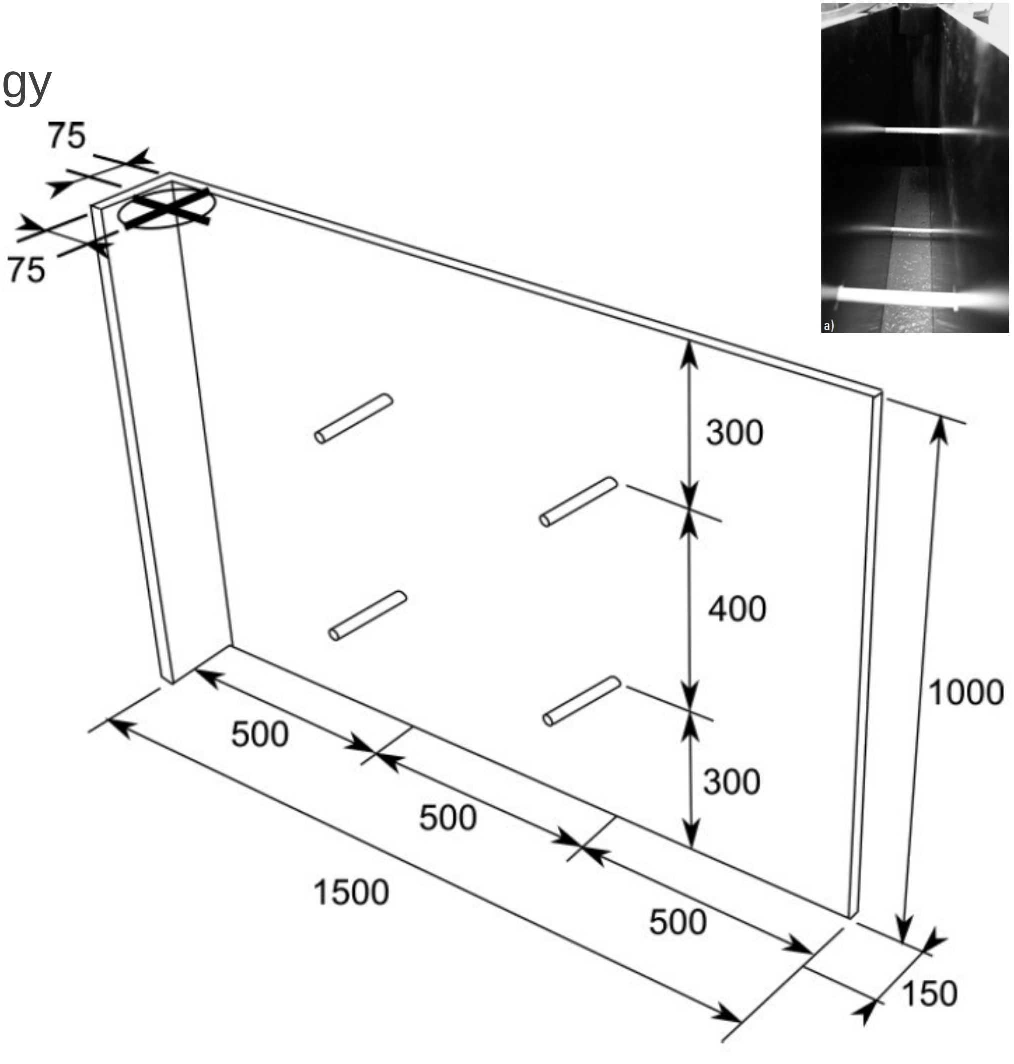
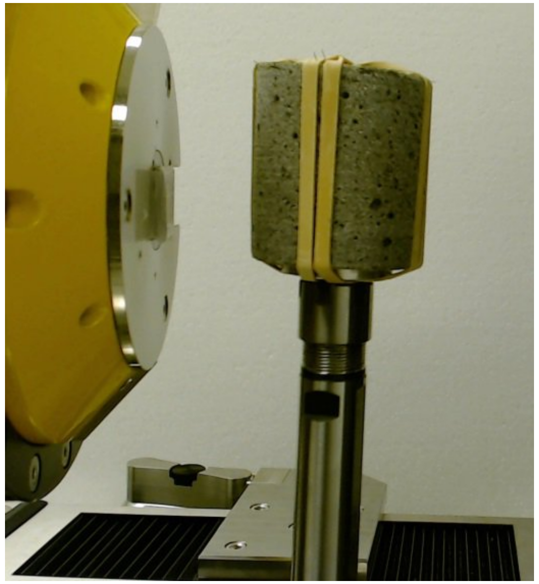
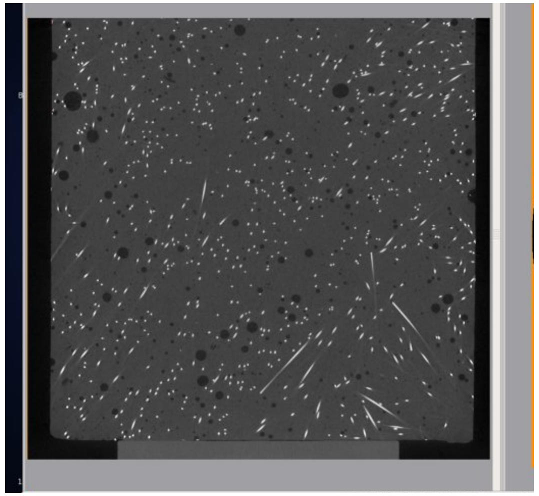


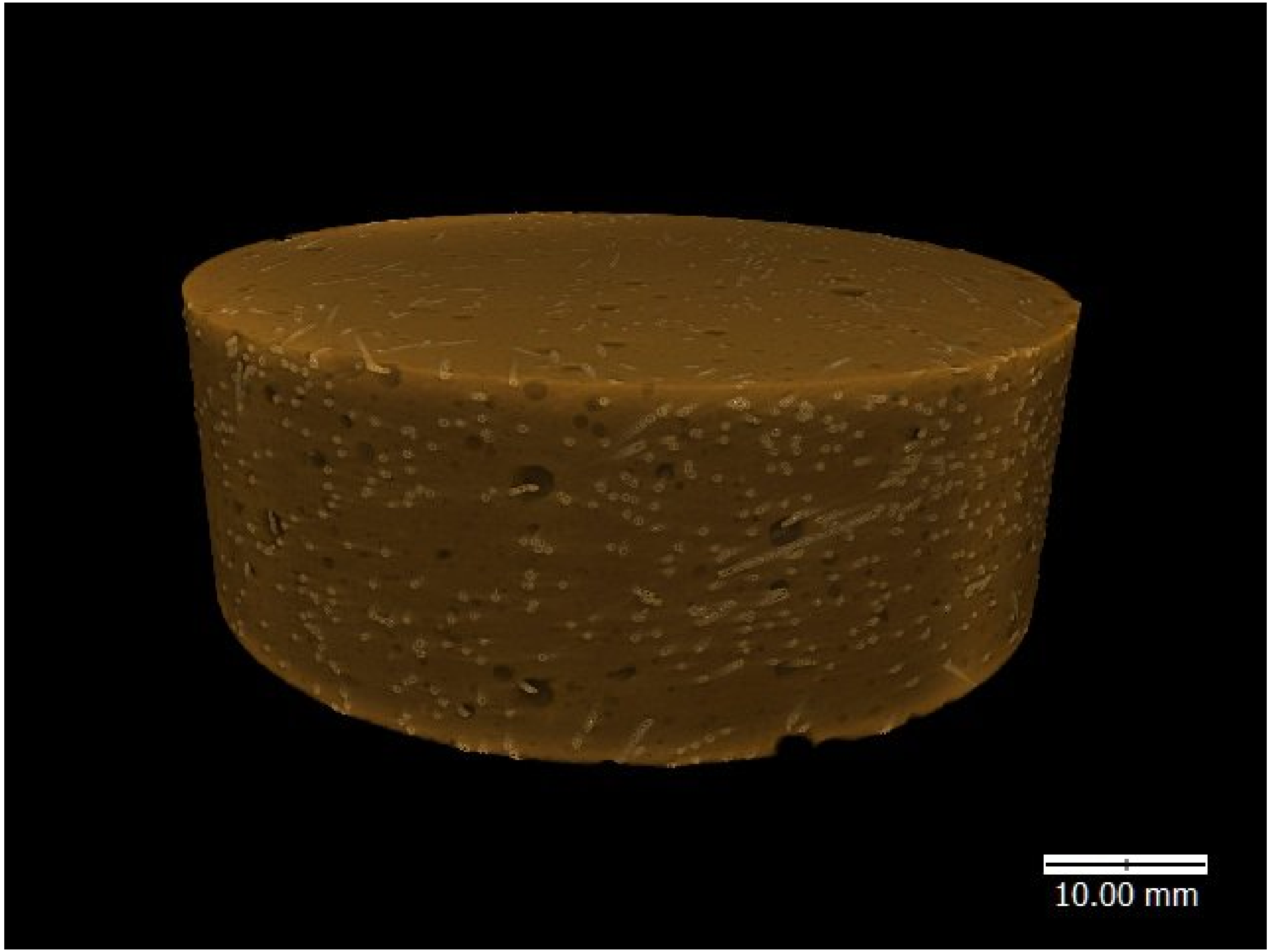
Fig. 3. Formwork dimensions, casting point and positions of four formwork tie bars (dims. in mm)

X-ray MicroCT on UHPFRC

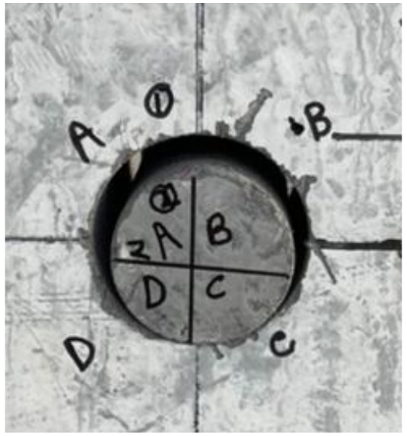
2% straight fibres: 13 mm long 0.2 mm diameter







Core Analysis: Bukit Merah Dam Bridge Girders

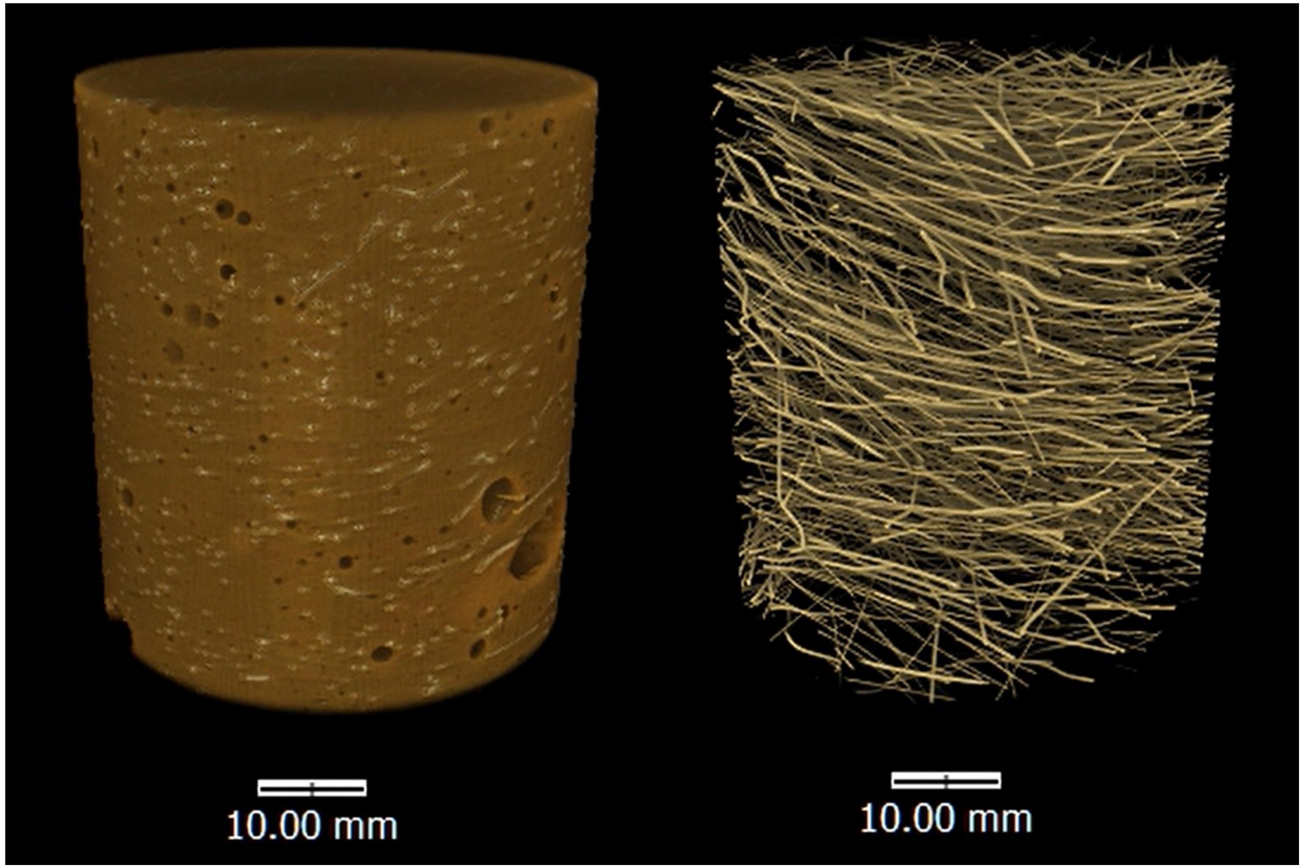


(a) (b)

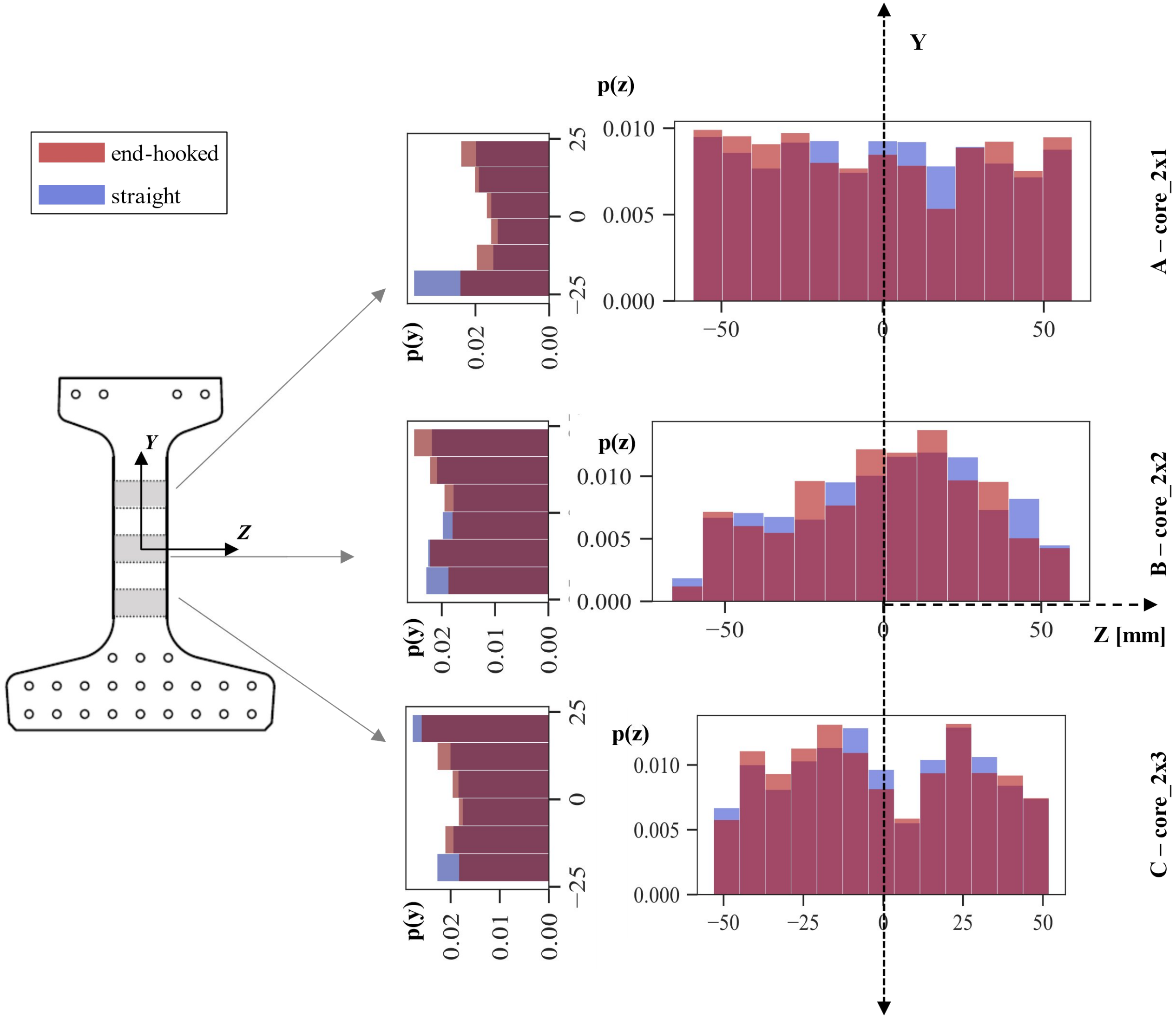
(c) (d)

Fig. 5 Coring: (a) location on the web, (b) zoomed view, (c) global coordinate system, and (d) fibre orientation measured with respect to the co-ordinate system

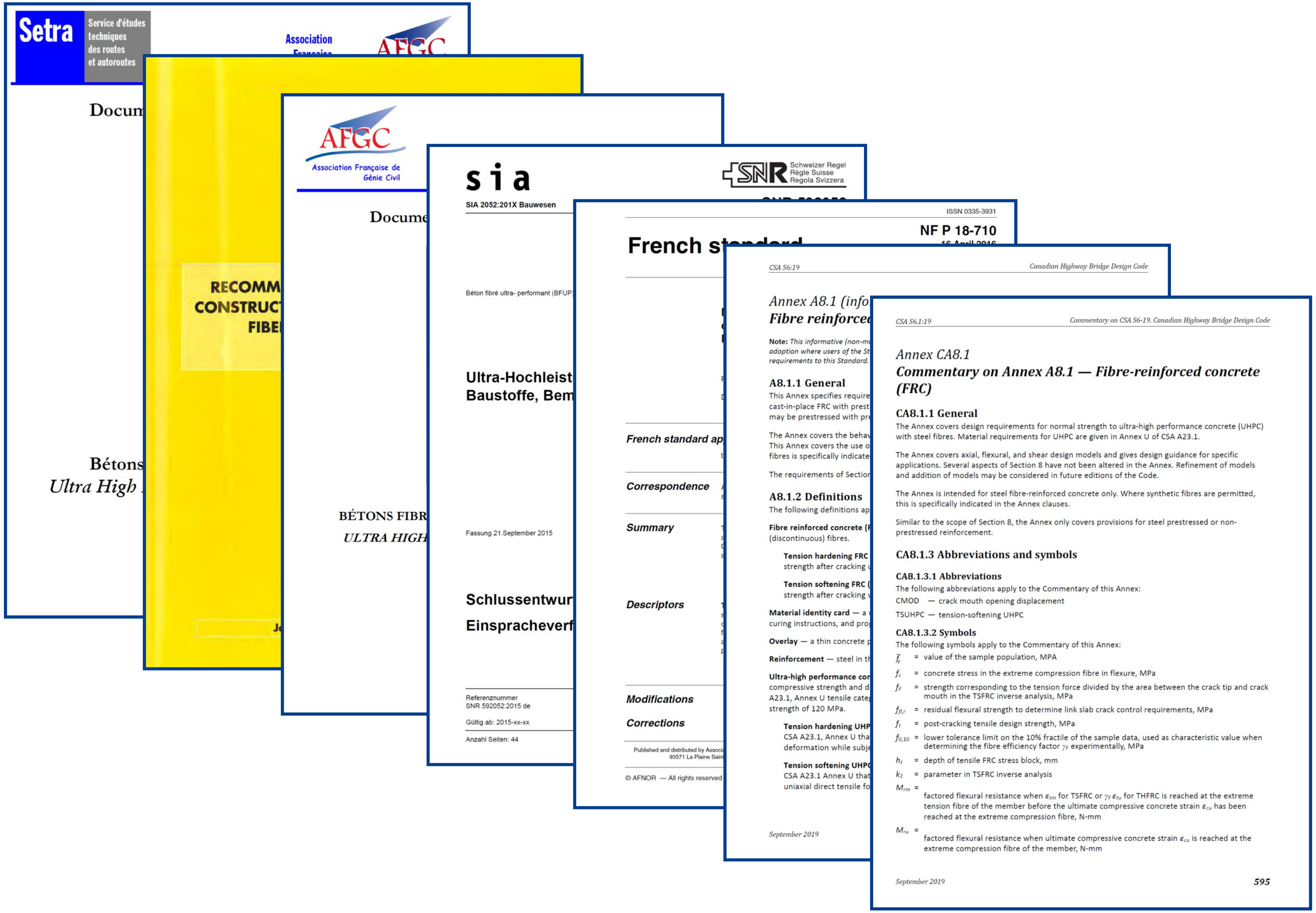
Core Analysis: Bukit Merah Dam Bridge Girders



Core Analysis: Bukit Merah Dam Bridge Girders



Standards and Guidelines



CSA S6.1:19 — Commentary on CSA S6-19, Canadian Highway Bridge Design Code

Annex CA8.1

Commentary on Annex A8.1 — Fibre-reinforced concrete (FRC)

CA8.1.1 General

The Annex covers design requirements for normal strength to ultra-high performance concrete (UHPC) with steel fibres. Material requirements for UHPC are given in Annex U of CSA A23.1.

The Annex covers axial, flexural, and shear design models and gives design guidance for specific applications. Several aspects of Section 8 have not been altered in the Annex. Refinement of models and addition of models may be considered in future editions of the Code.

The Annex is intended for steel fibre-reinforced concrete only. Where synthetic fibres are permitted, this is specifically indicated in the Annex clauses.

Similar to the scope of Section 8, the Annex only covers provisions for steel prestressed or non-prestressed reinforcement.

CA8.1.3 Abbreviations and symbols

CA8.1.3.1 Abbreviations

The following abbreviations apply to the Commentary of this Annex:

CMOD — crack mouth opening displacement

TSUHPC — tension-softening UHPC

CA8.1.3.2 Symbols

The following symbols apply to the Commentary of this Annex:

$\bar{f}_c$ = value of the sample population, MPA

f_c = concrete stress in the extreme compression fibre in flexure, MPa

f_F = strength corresponding to the tension force divided by the area between the crack tip and crack mouth in the TSFRC inverse analysis, MPa

$f_{fl,r}$ = residual flexural strength to determine link slab crack control requirements, MPa

f_t = post-cracking tensile design strength, MPa

$f_{0,10}$ = lower tolerance limit on the 10% fractile of the sample data, used as characteristic value when determining the fibre efficiency factor γ_F experimentally, MPa

h_t = depth of tensile FRC stress block, mm

k_2 = parameter in TSFRC inverse analysis

M_{rm} = factored flexural resistance when ε_{tm} for TSFRC or $\gamma_F \varepsilon_{tu}$ for THFRC is reached at the extreme tension fibre of the member before the ultimate compressive concrete strain ε_{cu} has been reached at the extreme compression fibre, N-mm

M_{ru} = factored flexural resistance when ultimate compressive concrete strain ε_{cu} is reached at the extreme compression fibre of the member, N-mm

September 2019 595

Technical Notes and Theses

Ultra-High Performance C

A State-of-the-Art Repor

Bridge Community

PUBLICATION NO. FHWA-HRT-13-060

U.S. Department of Transportation
Federal Highway Administration

Research, Development, and Technology
Turner-Fairbank Highway Research Center
6300 Georgetown Pike
McLean, VA 22101-2296

TECHNOTE

Design and Constructi
Field-Cast UHPC Conn

FHWA Publication No: FHWA-HRT-19-011

FHWA Contact: Ben Graybeal, HRDI-40, ORCID: 0000-0002-3694-1369, 202-49
benjamin.graybeal@dot.gov

This document is an update to *Design and Construction of Field-Cast UHPC C*
(FHWA-HRT-14-084).

Introduction

Advancements in the science of concrete materials have led to the development of a new class of cementitious composites called ultra-high performance concrete (UHPC). UHPC exhibits mechanical and durability properties that make it ideal for use in new solutions to pressing concerns about highway-infrastructure deterioration, repair, and replacement.[1,2] The use of field-cast UHPC details that connect prefabricated structural elements in bridge construction has captured the attention of bridge owners, specifiers, and contractors across the country. These connections can be simpler to construct and can provide more robust long-term performance than connections constructed through conventional methods.[3] This document provides guidance on the design and deployment of field-cast UHPC connections.

UHPC

UHPC is a fiber-reinforced, portland cement–based product with advantageous fresh and hardened properties. Through advancements in superplasticizers, dry-constituent gradation, fiber reinforcements, and supplemental cementitious materials, UHPC outperforms conventional concrete. Developed in the late 20th century, this class of concrete has emerged

as a capable replacem
structural materials in a

The Federal Highway A
defines UHPC as follows

UHPC is a cementiti
composed of an
of granular const
cementitious materi
and a high percen
internal fiber reinf
the mechanical p
include compressive
21.7 ksi (150 MPa)
cracking tensile s
0.72 ksi (5 MPa).[1] UH
pore structure that
significantly enhanci
to conventional conc

An alternative name for
formance fiber-reinforc

TABLE OF CONTENTS:

U.S. Department of Transportation
Federal Highway Administration

Research, Development
Turner-Fairbank Highwa
6300 Georgetown Pike,
www.fhwa.dot.gov/rese

Ultra High Performance Fibre
Reinforced Concrete
applied in Railway Bridges

LITERATURE STUDY

submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE

in

STRUCTURAL ENGINEERING

by

J.V. de Geus
born in Dirksland, The Netherlands

TUDelft
Concrete Structures
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Faculty CEG, Delft University of Technology
Delft, the Netherlands
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Structural Design with Ultra-High
Performance Concrete

PUBLICATION NO. FHWA-HRT-23-077 OCTOBER 2023

U.S. Department of Transportation
Federal Highway Administration

Research, Development, and Technology
Turner-Fairbank Highway Research Center
6300 Georgetown Pike
McLean, VA 22101-2296

Design for Shear

Web cracking model

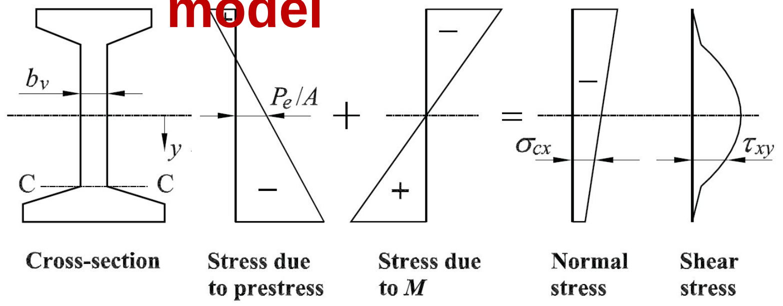
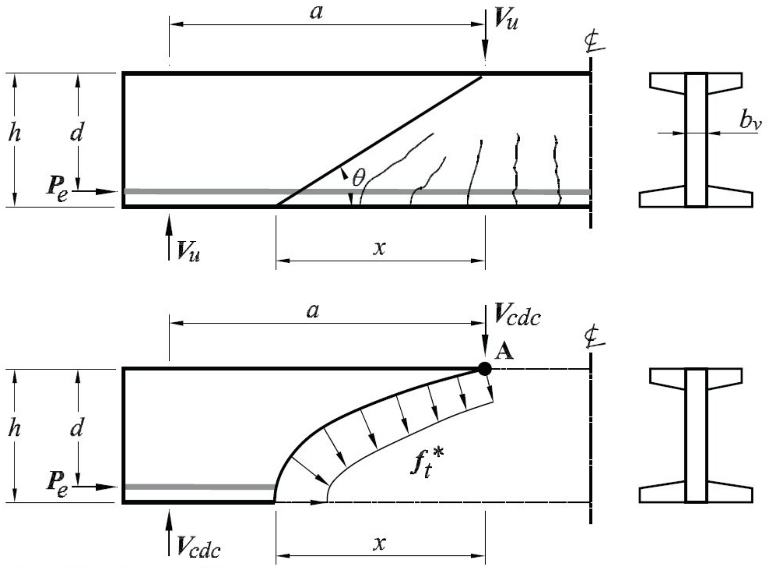


FIGURE 3 Stress distributions on an uncracked section.[42]



DOI: 10.1002/suco.202300738

ARTICLE

Crack sliding model

Design of UHPC prestressed girders for shear

Stephen J. Foster[1] | **Evan Bentz**[2]

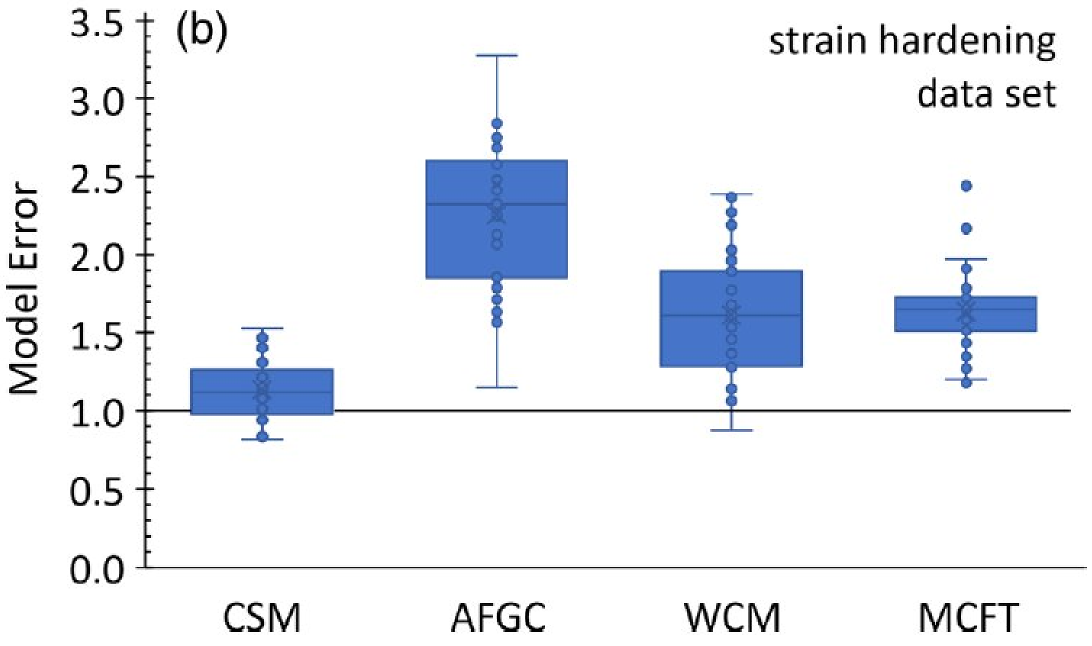


FIGURE 5 Summary statistics for models considered for (a) full data set of 62 tests and (b) reduced data set of 35 strain hardening tests.

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https://onlinelibrary.wiley.com/doi/epdf/10.1002/suco.202300738

Design for Shear

SMCFT Equations

$$V_{uc} = k_v \sqrt{f_{cm}}\, bz$$

$$V_{us} = \frac{A_{sv}}{s_w} f_{sy.f}\, z \cot\theta$$

$$k_v = \frac{0.4}{1 + 1500\varepsilon_x} \times \frac{1300}{1000 + \boxed{k_{dg} z}}$$

= 50 mm

$$\varepsilon_x = \frac{M/z + 0.5V\cot\theta}{2E_s A_s}$$

$$V_{fib} = 0.8\gamma_F \phi_F f_{tf} b_{vs} d_v \cot\theta$$

Additional fibres equation

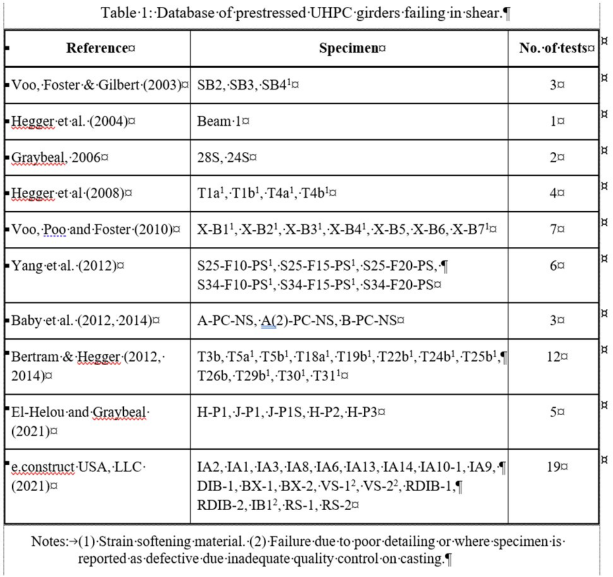


Table 1: Database of prestressed UHPC girders failing in shear.

Reference	Specimen	No. of tests
Voo, Foster & Gilbert (2003)	SB2, SB3, SB4^1	3
Hegger et al. (2004)	Beam 1	1
Graybeal, 2006	28S, 24S	2
Hegger et al (2008)	T1a^1, T1b^1, T4a^1, T4b^1	4
Voo, Poo and Foster (2010)	X-B1^1, X-B2^1, X-B3^1, X-B4^1, X-B5, X-B6, X-B7^1	7
Yang et al. (2012)	S25-F10-PS^1, S25-F15-PS^1, S25-F20-PS, S34-F10-PS^1, S34-F15-PS^1, S34-F20-PS	6
Baby et al. (2012, 2014)	A-PC-NS, A(2)-PC-NS, B-PC-NS	3
Bertram & Hegger (2012, 2014)	T3b, T5a^1, T5b^1, T18a^1, T19b^1, T22b^1, T24b^1, T25b^1, T26b, T29b^1, T30^1, T31^1	12
El-Helou and Graybeal (2021)	H-P1, J-P1, J-P1S, H-P2, H-P3	5
e.construct USA, LLC (2021)	IA2, IA1, IA3, IA8, IA6, IA13, IA14, IA10-1, IA9, DIB-1, BX-1, BX-2, VS-1^2, VS-2^2, RDIB-1, RDIB-2, IB1^2, RS-1, RS-2	19

Notes: → (1) Strain softening material. (2) Failure due to poor detailing or where specimen is reported as defective due inadequate quality control on casting.

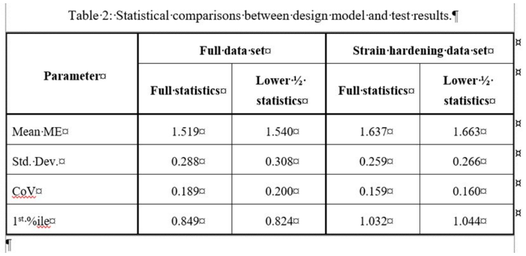
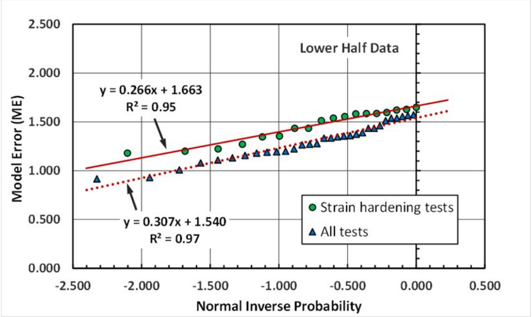
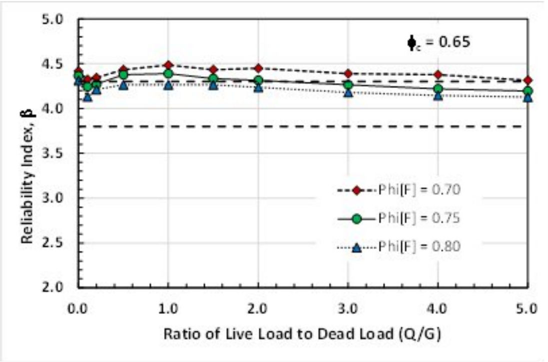
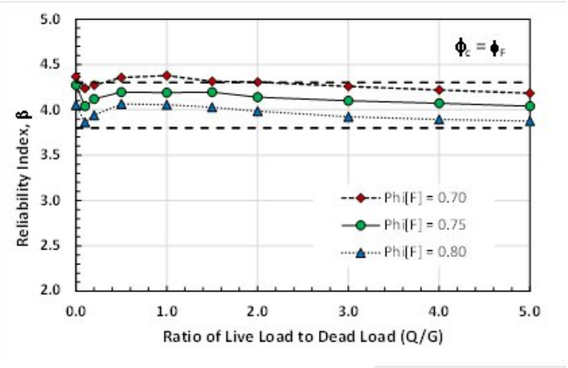


Table 2: Statistical comparisons between design model and test results.

Parameter	Full data set		Strain hardening data set	
	Full statistics	Lower ½ statistics	Full statistics	Lower ½ statistics
Mean ME	1.519	1.540	1.637	1.663
Std. Dev.	0.288	0.308	0.259	0.266
CoV	0.189	0.200	0.159	0.160
1st %ile	0.849	0.824	1.032	1.044







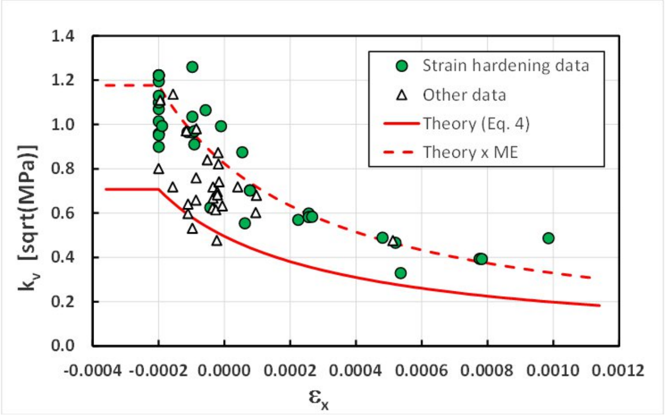


Fig. 3: Comparison of size effect predicted by Eq. (4) to test data.

DOI: 10.1002/suco.202300738

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Design of UHPC prestressed girders for shear

Stephen J. Foster[1] | **Evan Bentz**[2]

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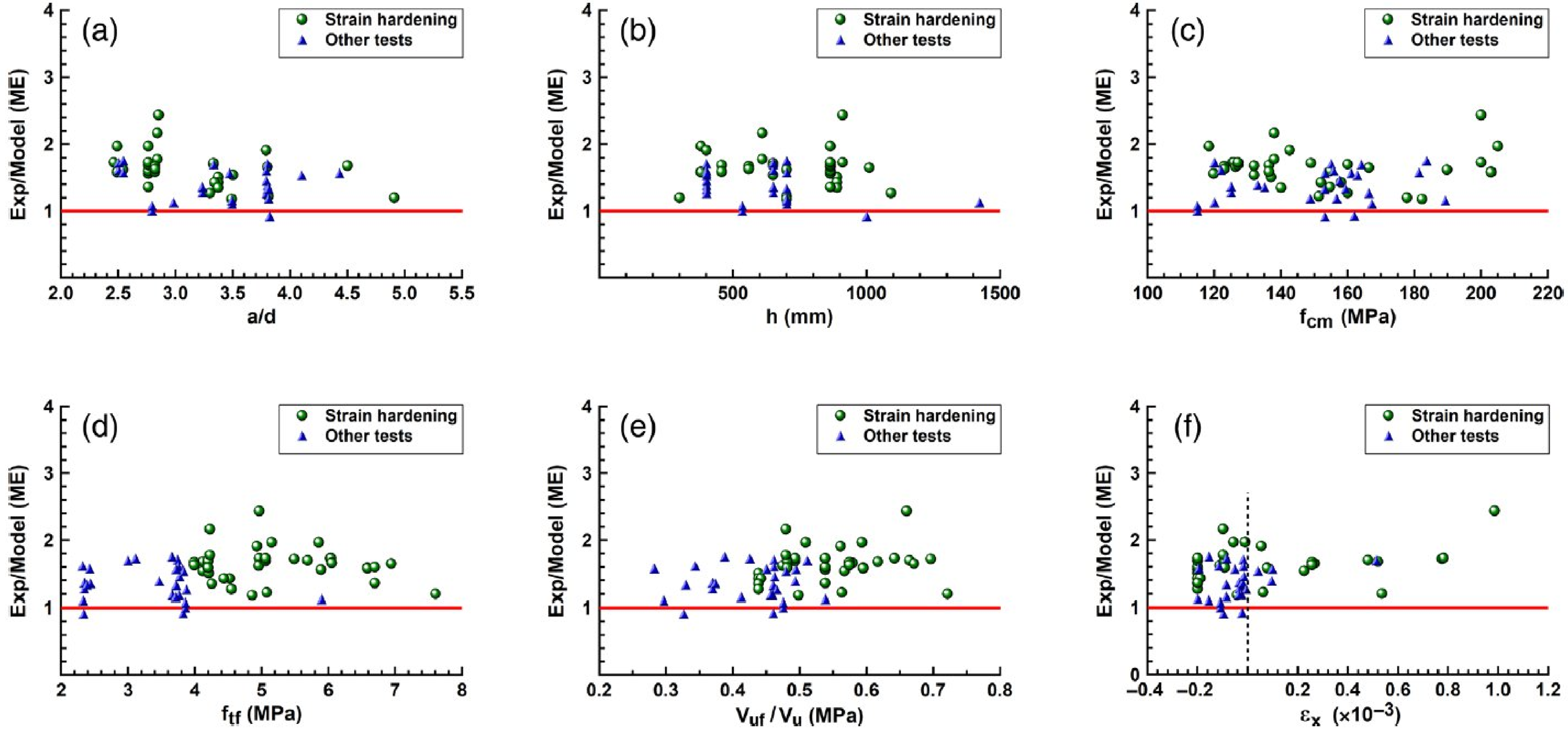

FIGURE 9 Comparison of experimental-to-predicted shear strength for MCFT model for prestressed UHPC girders against: (a) *a*/*d*, (b) overall depth *h*, (c) concrete strength, (d) fiber component stress, (e) ratio of shear carried by fibers component to calculated shear strength and (f) mid-height strain parameter.

Behaviour of Steel–PVA UHPC under High Temperatures

Materials and Structures (2016) 49:769–782
DOI 10.1617/s11527-015-0537-2

ORIGINAL ARTICLE

High temperature behaviour of hybrid steel–PVA fibre reinforced reactive powder concrete

Sriskandarajah Sanchayan · Stephen J. Foster

Received: 17 July 2013 / Accepted: 20 January 2015 / Published online: 30 January 2015

Abstract Reactive powder concrete (RPC) with dense microstructure are found to perform poorly at elevated temperatures due to a build-up of pore pressure that causes explosive spalling. This paper presents the results of an experimental investigation of the behaviour of six RPC mixes containing hybrid steel and polyvinyl alcohol (PVA) fibres, following exposure to high temperatures up to 700 °C. Residual compressive strength, static elastic modulus and ultrasonic pulse velocity measurements were carried out for all the RPC mixes. A mix containing hybrid steel–PVA fibre is proposed as suitable for high-temperature applications based on these results. Further tests were conducted for the mix at a hot state using a specially designed furnace–loading frame assembly. The hot-state elastic modulus, free thermal strains (FTS) and transitional thermal creep (TTC) were measured at the hot state. Residual compressive strength results for all the mixes indicated an initial increase in strength up to 300 °C, followed by a drastic drop. No apparent changes in elastic modulus and ultrasonic pulse measurements were observed till 300 °C, after which both dropped sharply. RPC containing only either steel fibres or only PVA fibres showed some form of instability, which was explosive in some cases. RPC with no fibres was also susceptible to explosive behaviour; however, the addition of hybrid fibres seemed to have beneficial effects. A mix containing equal volumes of steel and PVA fibres occupying a total fraction of 2 % by volume was found to give the best results. The FTS of that mix was similar to that of siliceous aggregate concretes, and the TTC was significant above 250 °C.

Keywords Reactive powder concrete · UHPC · Steel fibres · PVA fibres · Elevated temperature · Fire

1 Introduction

Concrete technology is constantly evolving, raising the limit of concrete compressive strength. In the 1990s concrete with compressive strengths of 200 MPa, and greater, and with improved durability were developed [1]; these concretes are in a class known as ultra-high-performance concrete (UHPC). Much of its improved mechanical properties and durability characteristics are due to its dense and homogeneous microstructure, and the presence of steel fibres. RPC uses low *w/c* ratios, in the range 0.17–0.21. The dense microstructure is achieved by optimizing the packing density of the mix by incorporating fine particles such as silica fume and/or silica flour. Such packing density optimization at lower

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s.sriskandarajah@unsw.edu.au

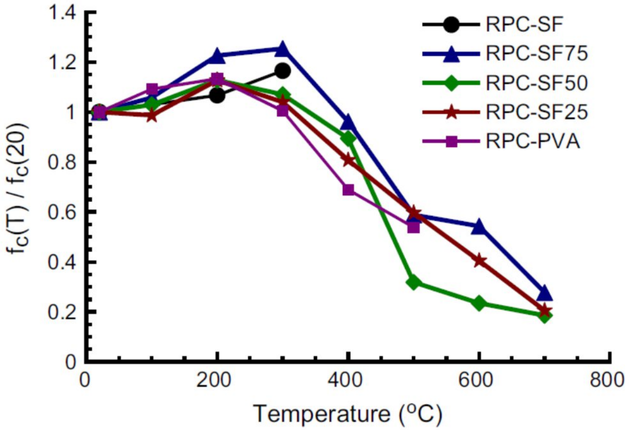


Fig. 7 Residual compressive strength

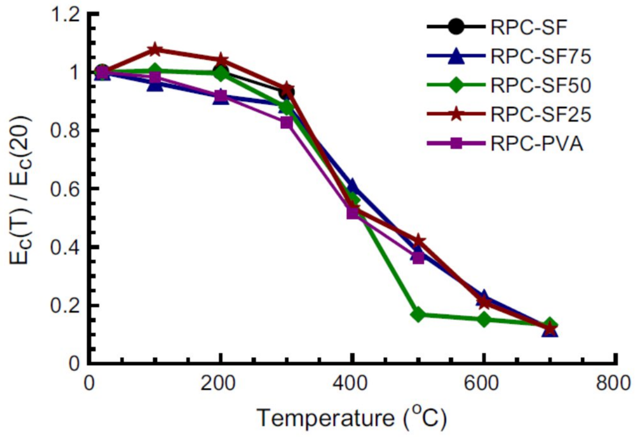


Fig. 8 Residual elastic modulus

Behaviour of Steel–PVA UHPC under High Temperatures

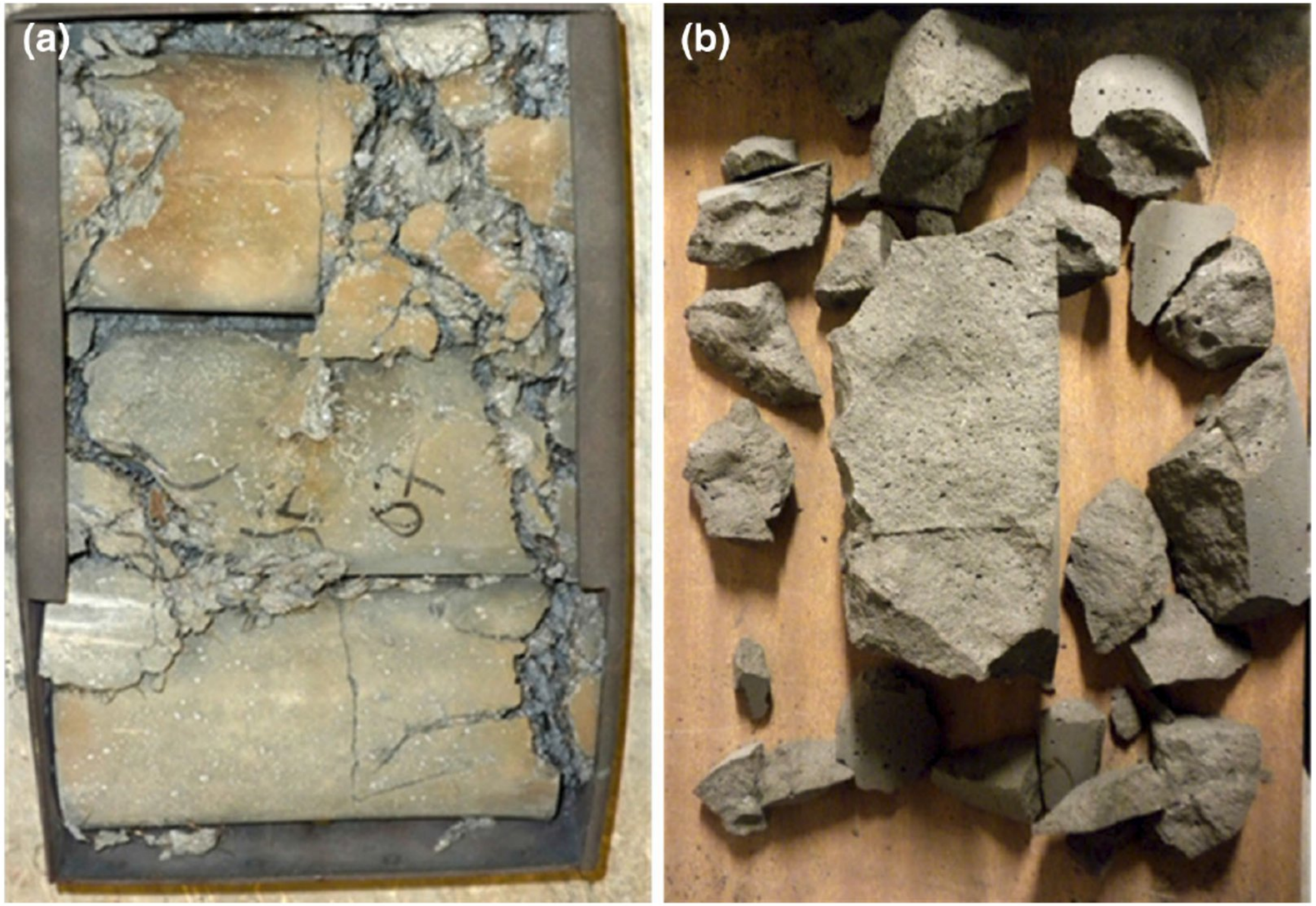
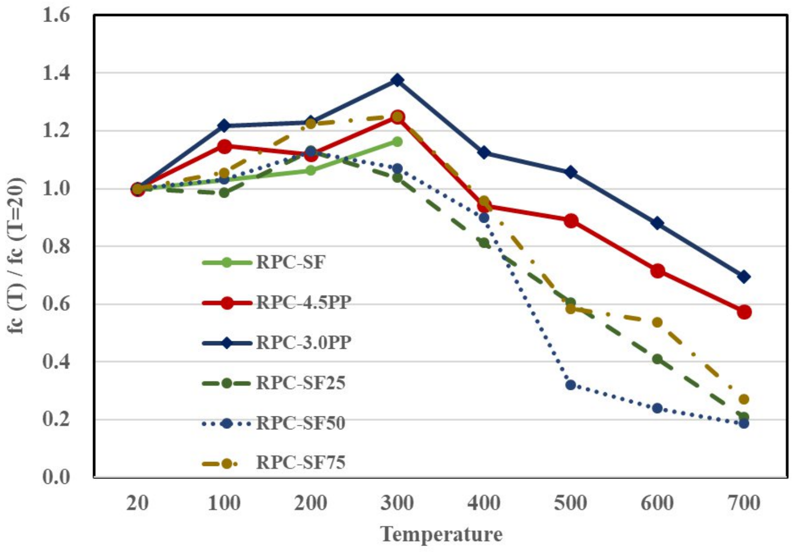


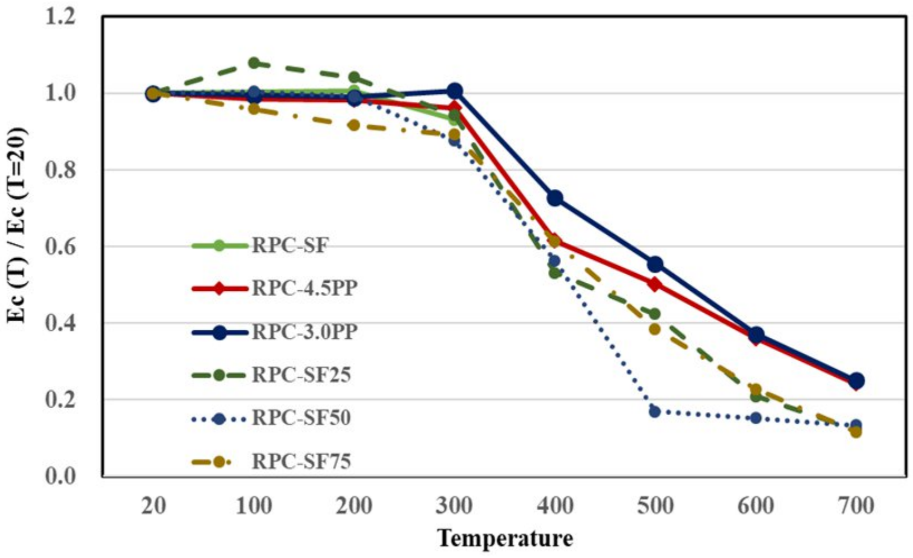
Fig. 4 Exploded cylinders, after heated to approximately 400 °C. **a** RPC–SF mix and **b** RPC–P mix

Behaviour of Steel–PP UHPC under High Temperatures

Constituent	RPC-SF	RPC-3.0PP	RPC-4.5PP
Cement	1	1	1
Silica Fume	0.25	0.25	0.25
Sydney Sand	1.1	1.1	1.1
Superplasticiser	0.062	0.062	0.062
Steel Fibre	0.172	0.146	0.13
PP Fibre	-	0.004 (3 kg/m^3)	0.005 (4.5 kg/m^3)
Water	0.17	0.15	0.15



Residual Compressive Strength



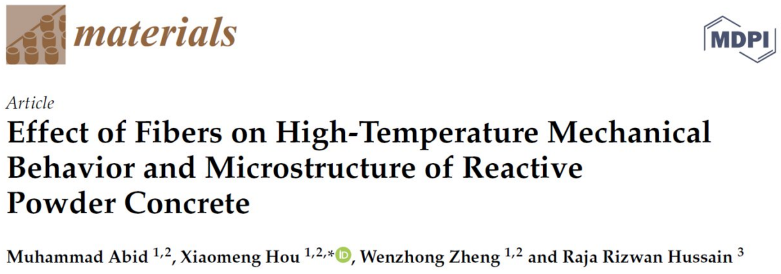
Residual Elastic Modulus

Spawned Literature on UHPC under High Temperatures

High temperature behaviour of hybrid steel–PVA fibre reinforced reactive powder concrete

Authors	Sriskandarajah Sanchayan, Stephen J Foster
Publication date	2016/3/1
Journal	Materials and Structures
Volume	49
Issue	3
Pages	769-782
Publisher	Springer Netherlands

Total citations Cited by 131



materials MDPI

Article

Effect of Fibers on High-Temperature Mechanical Behavior and Microstructure of Reactive Powder Concrete

Muhammad Abid [1,2], Xiaomeng Hou [1,2,*], Wenzhong Zheng [1,2] and Raja Rizwan Hussain [3]

ELSEVIER

Engineering Structures
Volume 185, 15 April 2019, Pages 122-140

Comparative fire behavior of reinforced RPC and NSC simply supported beams

Xiaomeng Hou [a, b], Pengfei Ren [a, b], Qin Rong [c], Wenzhong Zheng [a, b], Yao Zhan [a, b]

ELSEVIER

Construction and Building Materials
Volume 205, 30 April 2019, Pages 321-331

Creep behavior of steel fiber reinforced reactive powder concrete at high temperature

Muhammad Abid [a, b], Xiaomeng Hou [a, b], Wenzhong Zheng [a, b], Raja Rizwan Hussain [c], Shaojun Cao [a, b], Zhihao Lv [a, b]

Solid State Phenomena
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Revised: 2017-12-14
Accepted: 2017-12-14
Online: 2018-02-28

UHPC Reinforced by Hybrid Fibers and its Resistance to High Temperature Loading

RYDVAL Milan[1,a*], ČÍTEK David[1,b], KOLÍSKO Jiří[1,c] and PAVLÍK Zbyšek[2,d]
[1]Klokner Institute – CTU in Prague, Solinova 7, 16608 Prague 6, Czech Republic
[2]Faculty of Civil Engineering – CTU in Prague, Thakurova 7, 16628 Prague 6, Czech Republic
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DURA Fire Testing

Conclusions

- UHPC's superior strength and durability compared to that of traditional concrete have enabled the creation of longer, slimmer, and more visually appealing bridges, enhancing both aesthetic and structural aspects.
- While challenges such as limited professional expertise and the need for standardized practices remain, the advantages of UHPC, particularly in constructing bridges in remote locations, are clear.
- Increased educational and policy efforts are needed to maximize the potential of UHPC in bridge construction and wider infrastructure developments.
- Better understanding of the in-place material, specifically the orientation and distribution of the fibres and their impact on strength.