



Bulletin 95



Fibre Reinforced Concrete: From Design to Structural Applications

Proceedings of the *ACI-fib-RILEM* International
Workshop - FRC2018

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Technical report

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Proceedings of the ACI-*fib*-RILEM
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Any publication not having met the above requirements will be clearly identified as a preliminary draft.

fib Bulletin 95 is published as a technical report and is a collection of contributions to a workshop that was co-sponsored by the *fib* and the American Concrete Institute (ACI). The authors have presented their individual views. Although these contributions have not been discussed in any of the *fib*'s working bodies, the subject matter is highly topical and believed to be of general interest to members of the *fib*.

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Authors by chapter

Chapters	Main Authors	DOI
1	Plückelmann, S. ; Breitenbücher, R.	https://doi.org/10.35789/fib.BULL.0095.Ch01
2	Li, L.; Cao, M.	https://doi.org/10.35789/fib.BULL.0095.Ch02
3	Vrijdaghs, R.; di Prisco, M.; Vandewalle, L.	https://doi.org/10.35789/fib.BULL.0095.Ch03
4	Galeote, E.; Blanco, A.; Cavalaro, S.H.P.; de la Fuente, A.	https://doi.org/10.35789/fib.BULL.0095.Ch04
5	Galeote, E.; Blanco, A.; Cavalaro, S.H.P.; de la Fuente, A.	https://doi.org/10.35789/fib.BULL.0095.Ch05
6	Juhasz, K.P.; Schaul, P.; Winterberg, R.	https://doi.org/10.35789/fib.BULL.0095.Ch06
7	Javadian, A.; Mahdavi, A.; Benamrane, O.; Majeed, M.; Aoude, H.	https://doi.org/10.35789/fib.BULL.0095.Ch07
8	Chelha, F.; Alam, S. Y.; Bendimerad, A.Z.; Loukili, A.	https://doi.org/10.35789/fib.BULL.0095.Ch08
9	Ferrara, L.; Asensio, E.C.; Lo Monte, F.; Snoeck, D.; De Belie, N.	https://doi.org/10.35789/fib.BULL.0095.Ch09
10	Ortiz-Navas, F.; Scaroni, L.; Navarro-Gregori, J.; Serna-Ros, P.	https://doi.org/10.35789/fib.BULL.0095.Ch10
11	Ortiz-Navas, F.; Navarro-Gregori, J.; Serna Ros, P.; Leiva Herdocia, G.	https://doi.org/10.35789/fib.BULL.0095.Ch11
12	Barros, J.A.O.; Foster, S.J.	https://doi.org/10.35789/fib.BULL.0095.Ch12
13	De Smedt, M.; De Wilder, K.; Anastasopoulos, D.; Reynders, E. ; De Roeck, G.; Vandewalle, L.	https://doi.org/10.35789/fib.BULL.0095.Ch13
14	Winterberg, R.; Rodríguez, L.M.; Cámara, R.J.; Abad, D.S	https://doi.org/10.35789/fib.BULL.0095.Ch14
15	Galeote, E.; Blanco, A.; de la Fuente, A.	https://doi.org/10.35789/fib.BULL.0095.Ch15
16	Meda, A.; Rinaldi, Z.; Spagnuolo, S.; De Rivaz, B.; Giamundo, N.	https://doi.org/10.35789/fib.BULL.0095.Ch16
17	Juhasz, K.P.; Schaul, P.	https://doi.org/10.35789/fib.BULL.0095.Ch17
18	Yao, Y.; Bakhshi, M.; Nasri, V.; Mobasher, B	https://doi.org/10.35789/fib.BULL.0095.Ch18
19	Conforti, A.; Trabucchi, I.; Tiberti, G.; Plizzari, G.A.; Caratelli, A; Meda, A.; Moro, S.; Hunger, M.	https://doi.org/10.35789/fib.BULL.0095.Ch19
20	Massicotte, B.; Cordoni, N.	https://doi.org/10.35789/fib.BULL.0095.Ch20
21	Pourzarabi, A.; Colombo, M.; Martinelli, P.; di Prisco, M.	https://doi.org/10.35789/fib.BULL.0095.Ch21
22	Zani, G.; Colombo, M.; Failla, C.; di Prisco, M.	https://doi.org/10.35789/fib.BULL.0095.Ch22
23	Trabucchi, I.; Conforti, A.; Tiberti, G.; Plizzari, G.A.; Winterberg, R.	https://doi.org/10.35789/fib.BULL.0095.Ch23
24	Bernard, E. S.	https://doi.org/10.35789/fib.BULL.0095.Ch24
25	Dancygier, A.N.; Karinski, Y.S..	https://doi.org/10.35789/fib.BULL.0095.Ch25

26	Fantilli, A.P.; Tondolo, F.	https://doi.org/10.35789/fib.BULL.0095.Ch26
27	Frazão, C.; Barros, J.; Bogas, A.; Pilakoutas, K.; de Sousa, C.M.	https://doi.org/10.35789/fib.BULL.0095.Ch27
28	Kitazawa, K.; Sato, Y.; Naganuma, K.; Kaneko, Y.	https://doi.org/10.35789/fib.BULL.0095.Ch28
29	Monte, R.; de la Fuente Antequera, A.; Dominigues de Figueiredo, A.	https://doi.org/10.35789/fib.BULL.0095.Ch29
30	Aoude, H.; Li, Y.; Bastami, R.; Ibrahim, F.M.	https://doi.org/10.35789/fib.BULL.0095.Ch30
31	Poveda, E.; Ruiz, G.; Cifuentes, H.; Yu, R.C.; Zhang, X.X.	https://doi.org/10.35789/fib.BULL.0095.Ch31
32	Antroula, G.; Stavroula, P.	https://doi.org/10.35789/fib.BULL.0095.Ch32
33	Ranjbarian, M.; Mechtcherine, V.	https://doi.org/10.35789/fib.BULL.0095.Ch33
34	Bernard, E. S.	https://doi.org/10.35789/fib.BULL.0095.Ch34
35	Vieira, M.M.; Cavalaro, S.H.P.; Aguado, A.	https://doi.org/10.35789/fib.BULL.0095.Ch35
36	Amin, A.; Gilbert, R.I.	https://doi.org/10.35789/fib.BULL.0095.Ch36
37	Berrocal, C.G.; Lundgren, K.; Löfgren, I.	https://doi.org/10.35789/fib.BULL.0095.Ch37
38	de la Fuente, A.; Cavalaro, S.H.; Bairán, J.M.	https://doi.org/10.35789/fib.BULL.0095.Ch38
39	Zanotti, C.; Randl, N.; Gar, P.S.; Far, B.K.; Steiner, M.	https://doi.org/10.35789/fib.BULL.0095.Ch39
40	Turgeon-Mallete, V.; Sorelli, L.; Conciatori, D.; Réthore, J.	https://doi.org/10.35789/fib.BULL.0095.Ch40
41	Ding, Y.; Li, D.; Zeng, W.	https://doi.org/10.35789/fib.BULL.0095.Ch41
42	Fargier-Gabaldon, L.B.; Al-Tameemi, M.; Parra-Montesinos, G.J.	https://doi.org/10.35789/fib.BULL.0095.Ch42
43	Plückelmann, S.; Breitenbücher, R.	https://doi.org/10.35789/fib.BULL.0095.Ch43
44	Fantilli, A.P.; Nishiwaki, T.; Lisi, V.; Longo, M.	https://doi.org/10.35789/fib.BULL.0095.Ch44
45	Look, K.; Mark, P.	https://doi.org/10.35789/fib.BULL.0095.Ch45
46	Valente, T.; Barros, J.; Lourenço, L.	https://doi.org/10.35789/fib.BULL.0095.Ch46
47	Lucchini, S.S.; Facconi, L.; Minelli, F.; Plizzari, G.A.	https://doi.org/10.35789/fib.BULL.0095.Ch47
48	Redaelli, D.; Nseir, J.Y.	https://doi.org/10.35789/fib.BULL.0095.Ch48
49	Rossi, P.; Davian-Desnoyers, D.; Tailhan, J.L.	https://doi.org/10.35789/fib.BULL.0095.Ch49
50	Charron, J.P.; Desmetre, C.; Cantin Bellemare, E.	https://doi.org/10.35789/fib.BULL.0095.Ch50
51	Loser, R.; Justs, J.; Lura, P.	https://doi.org/10.35789/fib.BULL.0095.Ch51
52	Bastami, R.; Li, Y.; Algassem, O.; Aoude, H.	https://doi.org/10.35789/fib.BULL.0095.Ch52
53	Randl, N.; Mészöly, T.	https://doi.org/10.35789/fib.BULL.0095.Ch53

Foreword

This bulletin presents a compilation of the papers presented at the 3rd International workshop on Fibre-Reinforced Concrete, "FRC2018, from Design to Structural Applications". The workshop was a joint ACI - Rilem - *fib* event, which expresses inter-federation collaboration and broad expertise.

The aim of the workshop was to provide state-of-the-art information on recent progress in term of specifications development, actual applications, and to expose users and researchers to tomorrow's challenges in the design and construction of a wide variety of structural applications. The topic is thus fitting and is a clear supplement to the work of *fib* TG4.1 "Fibre-reinforced concrete". The aim of TG4.1 is to make theoretical and practical developments in the field of fibre-reinforced concrete materials technology, rheology and materials characterisation and modelling and to present these developments in code-type formulations.

Recently, it was decided to merge the work of TG4.1 and TG4.2 "Ultrahigh performance fibre reinforced concrete" to prepare one joint bulletin. At the time of writing, this bulletin is being finalised. Also, a framework bulletin for the *fib* Model Code MC2020 will be prepared.

I'm very grateful to Fausto Minelli (University of Brescia, Italy), for making the colossal effort to convert this collection of papers into an *fib* bulletin. And many thanks to Corinne Bottollier-Dépois for formatting this bulletin.

Tor Arne Martius-Hammer

Deputy chair of Commission 4: *Concrete and Concrete Technology*

Preface

The first international FRC workshop supported by RILEM and ACI was held in Bergamo (Italy) in 2004. At that time, a lack of specific building codes and standards was identified as the main inhibitor to the application of this technology in engineering practice. The workshop aim was placed on the identification of applications, guidelines, and research needs in order for this advanced technology to be transferred to professional practice.

The second international FRC workshop, held in Montreal (Canada) in 2014, was the first ACI-*fib* joint technical event. Many of the objectives identified in 2004 had been achieved by various groups of researchers who shared a common interest in extending the application of FRC materials into the realm of structural engineering and design. The aim of the workshop was to provide the State-of-the-Art on the recent progress that had been made in term of specifications and actual applications for buildings, underground structures, and bridge projects worldwide.

The rapid development of codes, the introduction of new materials and the growing interest of the construction industry suggested presenting this forum at closer intervals. In this context, the third international FRC workshop was held in Desenzano (Italy), four years after Montreal. In this first ACI-*fib*-RILEM joint technical event, the maturity gained through the recent technological developments and large-scale applications were used to show the acceptability of the concrete design using various fibre compositions.

The growing interests of civil infrastructure owners in ultra-high-performance fibre-reinforced concrete (UHPFRC) and synthetic fibres in structural applications bring new challenges in terms of concrete technology and design recommendations. In such a short period of time, we have witnessed the proliferation of the use of fibres as structural reinforcement in various applications such as industrial floors, elevated slabs, precast tunnel lining sections, foundations, as well as bridge decks. We are now moving towards addressing many durability-based design requirements by the use of fibres, as well as the general serviceability-based design. However, the possibility of having a residual tensile strength after cracking of the concrete matrix requires a new conceptual approach for a proper design of FRC structural elements.

With such a perspective in mind, the aim of FRC2018 workshop was to provide the State-of-the-Art on the recent progress in terms of specifications development, actual applications, and to expose users and researchers to the challenges in the design and construction of a wide variety of structural applications.

Considering that at the time of the first workshop, in 2004, no structural codes were available on FRC, we have to recognize the enormous work done by researchers all over the world, who have presented at many FRC events, and convinced code bodies to include FRC among the reliable alternatives for structural applications. This will allow engineers to increasingly utilize FRC with confidence for designing safe and durable structures.

Many presentations also clearly showed that FRC is a promising material for efficient rehabilitation of existing infrastructure in a broad spectrum of repair applications. These cases range from sustained gravity loads to harsh environmental conditions and seismic applications, which are some of the broadest ranges of applications in Civil Engineering.

The workshop was attended by researchers, designers, owner and government representatives as well as participants from the construction and fibre industries. The presence of people with different expertise provided a unique opportunity to share knowledge and promote collaborative efforts. These interactions are essential for the common goal of making better and sustainable constructions in the near future.

The workshop was attended by about 150 participants coming from 30 countries. Researchers from all the continents participated in the workshop, including 24 Ph.D. students, who brought their enthusiasm in FRC structural applications.

For this reason, the workshop Co-chairs sincerely thank all the enterprises that sponsored this event. They also extend their appreciation for the support provided by the industry over the last 30 years which allowed research centers to study FRC materials and their properties, and develop applications to making its use more routine and accepted throughout the world. Their important contribution has been essential for moving the knowledge base forward.

Finally, we appreciate the enormous support received from all three sponsoring organizations of ACI, *fib* and Rilem and look forward to paving the path for future collaborations in various areas of common interest so that the developmental work and implementation of new specifications and design procedures can be expedited internationally.

June 2018

Bruno Massicotte, Fausto Minelli, Barzin Mobasher, Giovanni Plizzari

Contents

Foreword	i
Preface	ii
1. Mechanical characterization	1
Round-Robin Test on Various Test-Methods for Flexural Behavior of Steel Fiber Reinforced Sprayed Concretes	2
Plückelmann, S. ;Breitenbücher, R.	
https://doi.org/10.35789/fib.BULL.0095.Ch01	
A new multi-scale hybrid fiber reinforced cement-based composites	12
Li, L.; Cao, M.	
https://doi.org/10.35789/fib.BULL.0095.Ch02	
A sectional approach for the bending creep of FRC based on uniaxial tension creep tests	20
Vrijdaghs, R.; Di Prisco, M.; Vandewalle, L.	
https://doi.org/10.35789/fib.BULL.0095.Ch03	
Optimized quality control procedure with the Barcelona test and the inductive method for FRC	30
Galeote, E.; Blanco, A.; Cavalaro, S.H.P.; de la Fuente, A.	
https://doi.org/10.35789/fib.BULL.0095.Ch04	
Influence of the beam size on the residual strength of high performance fibre reinforced concrete	40
Galeote, E.; Blanco, A.; Cavalaro, S.H.P.; de la Fuente, A.	
https://doi.org/10.35789/fib.BULL.0095.Ch05	
Influence of test methodology on the applicability of test results of fibre reinforced concrete for design	50
Juhasz, K.P.; Schaul, P.; Winterberg, R.	
https://doi.org/10.35789/fib.BULL.0095.Ch06	
Parameters affecting the properties of plain and fiber reinforced self-consolidating concrete.	60
Javadian, A.; Mahdavi, A.; Benamrane, O. ;Majeed, M.; Aoude, H.	
https://doi.org/10.35789/fib.BULL.0095.Ch07	

Mechanical characterization of fiber reinforced floor screeds: Influence of glass fibers on shrinkage and cracking mechanisms Chelha, F.; Alam, S. Y.; Bendimerad, A.Z.; Loukili, A. https://doi.org/10.35789/fib.BULL.0095.Ch08	70
An application oriented state-of-art and research-need perspective on self-healing fibre-reinforced cementitious composites Ferrara, L.; Asensio, E.C.; Lo Monte, F.; Snoeck, D.; De Belie, N. https://doi.org/10.35789/fib.BULL.0095.Ch09	80
2. Shear	90
Experimental study of shear transfer in polypropylene fibre-reinforced concrete using pre-cracked push-off specimens Ortiz-Navas, F.; Scaroni, L.; Navarro-Gregori, J.; Serna-Ros, P. https://doi.org/10.35789/fib.BULL.0095.Ch10	91
Shear crack behaviour and shear deformation of polypropylene fibre-reinforced concrete slender beams Ortiz-Navas, F.; Navarro-Gregori, J.; Serna Ros, P.; Leiva Herdocia, G. https://doi.org/10.35789/fib.BULL.0095.Ch11	101
Fibres as shear reinforcement in RC beams: an overview on assessment of material properties and design approaches Barros, J.A.O.; Foster, S.J. https://doi.org/10.35789/fib.BULL.0095.Ch12	111
Experimental investigation of shear-critical prestressed steel fibre reinforced concrete beams De Smedt, M.; De Wilder, K.; Anastasopoulos, D.; Reynders, E. ; De Roeck, G.; Vandewalle, L. https://doi.org/10.35789/fib.BULL.0095.Ch13	121
3. Bridges/Elevated Slabs/Precast Elements/Tunnel Linings	132
Segmental Lining Design using Macro Synthetic Fibre Reinforcement Winterberg, R.; Rodríguez, L.M.; Cámara, R.J.; Abad, D.S https://doi.org/10.35789/fib.BULL.0095.Ch14	133
Effect of reinforcement configuration on the ductility requirements of real-scale slabs Galeote, E.; Blanco, A.; de la Fuente, A. https://doi.org/10.35789/fib.BULL.0095.Ch15	143

Experimental Behaviour of Precast Tunnel Segments in Steel Fiber Reinforcement with GFRP Rebars Meda, A.; Rinaldi, Z.; Spagnuolo, S.; De Rivaz, B.; Giamundo, N. https://doi.org/10.35789/fib.BULL.0095.Ch16	153
Opportunities for synthetic fibre reinforcement in concrete tramlines Juhasz, K.P.; Schaul, P. https://doi.org/10.35789/fib.BULL.0095.Ch17	163
Closed-form Solutions for Interaction Diagrams of Hybrid Fiber-Reinforced Tunnel Segments Yao, Y.; Bakhshi, M.; Nasri, V.; Mobasher, B. https://doi.org/10.35789/fib.BULL.0095.Ch18	173
An experimental study on the use of polypropylene macrofibers in precast segments for hydraulic and metro tunnel lining Conforti, A.; Trabucchi, I.; Tiberti, G.; Plizzari, G.A.; Caratelli, A; Meda, A.; Moro, S.; Hunger, M. https://doi.org/10.35789/fib.BULL.0095.Ch19	185
Design of precast prestressed SFRC T-girders for accelerated sustainable bridge construction Massicotte, B.; Cordoni, N. https://doi.org/10.35789/fib.BULL.0095.Ch20	195
FRC Hybrid slabs: reliability of Model Code approaches Pourzarabi, A.; Colombo, M.; Martinelli, P.; di Prisco, M. https://doi.org/10.35789/fib.BULL.0095.Ch21	205
Optimization of partially prefabricated HyFRC slabs Zani, G.; Colombo, M.; Failla, C.; di Prisco, M. https://doi.org/10.35789/fib.BULL.0095.Ch22	215
Structural behavior of precast tunnel segments with macro- synthetic fibers during TBM operations: a numerical study Trabucchi, I.; Conforti, A.; Tiberti, G.; Plizzari, G.A.; Winterberg, R. https://doi.org/10.35789/fib.BULL.0095.Ch23	225

4. Seismic and Special Loading Conditions	235
Seismic Performance of Fibre Reinforced Concrete in the Absence of Bars	236
Bernard, E. S. https://doi.org/10.35789/fib.BULL.0095.Ch24	
RC Beams with Steel Fibers - Towards Better Determination of their Minimum Conventional Reinforcement Ratio	246
Dancygier, A.N.; Karinski, Y.S.. https://doi.org/10.35789/fib.BULL.0095.Ch25	
Residual crack width in RC and R/FRC ties subjected to repeated loads	254
Fantilli, A.P.; Tondolo, F. https://doi.org/10.35789/fib.BULL.0095.Ch26	
An experimental investigation on the post-cracking behaviour of Recycled Steel Fibre Reinforced Concrete	262
Fração, C.; Barros, J.; Bogas, A.; Pilakoutas, K.; de Sousa, C.M. https://doi.org/10.35789/fib.BULL.0095.Ch27	
Finite Element Analyses of Seismic Response of a 22-story RC Wall Building subjected to Drying Shrinkage Cracking and Application of SCRPPC	272
Kitazawa, K.; Sato, Y.; Naganuma, K.; Kaneko, Y. https://doi.org/10.35789/fib.BULL.0095.Ch28	
Closed loop control in crushing test for fibre reinforced concrete pipes	282
Monte, R.; de la Fuente Antequera, A.; Dominigues de Figueiredo, A. https://doi.org/10.35789/fib.BULL.0095.Ch29	
Effect of synthetic fibers on the quasi-static and blast behaviour of reinforced concrete beams	292
Aoude, H.; Li, Y.; Bastami, R.; Ibrahim, F.M. https://doi.org/10.35789/fib.BULL.0095.Ch30	

Strain-based fatigue failure criterion for steel-fiber reinforced concrete	302
Poveda, E.; Ruiz, G.; Cifuentes, H.; Yu, R.C.; Zhang, X.X. https://doi.org/10.35789/fib.BULL.0095.Ch31	
Performance of Ductile FRCC under Cyclic Loads and Non-Linear FE Simulation	310
Antroula, G.; Stavroula, P. https://doi.org/10.35789/fib.BULL.0095.Ch32	
Cyclic Damage on PVA Microfibre Embedded in Cementitious Matrix in Alternating Tension-Compression Regime	321
Ranjbarian, M.; Mechtcherine, V. https://doi.org/10.35789/fib.BULL.0095.Ch33	
5. Service Conditions and Durability	330
Reduction of Flexural Crack Widths Using Synthetic Fibres in Reinforced Concrete	331
Bernard, E. S. https://doi.org/10.35789/fib.BULL.0095.Ch34	
Influence of chloride-initiated corrosion on the surface aspect of steel fibre reinforced cementitious composites	341
Vieira, M.M.; Cavalaro, S.H.P.; Aguado, A. https://doi.org/10.35789/fib.BULL.0095.Ch35	
Serviceability Limit State Design of SFRC Members	351
Amin, A.; Gilbert, R.I. https://doi.org/10.35789/fib.BULL.0095.Ch36	
The effect of fibres on corrosion of reinforced concrete	361
Berrocal, C.G.; Lundgren, K.; Löfgren, I. https://doi.org/10.35789/fib.BULL.0095.Ch37	
Influence of the Post-Cracking Residual Strength Variability on the Partial Safety Factor	371
de la Fuente, A.; Cavalaro, S.H.; Bairán, J.M. https://doi.org/10.35789/fib.BULL.0095.Ch38	

Comparability of bond tests for repair and retrofit of concrete structures with Fiber Reinforced Concrete Zanotti, C.; Randl, N.; Gar, P.S.; Far, B.K.; Steiner, M. https://doi.org/10.35789/fib.BULL.0095.Ch39	381
Characterization and Prediction of Microcracking in Reinforced UHPFRC Beams under Bending Turgeon-Mallette, V.; Sorelli, L.; Conciatori, D.; Réthore, J. https://doi.org/10.35789/fib.BULL.0095.Ch40	391
Investigation of fiber effect on the geometrical property of crack and water permeability of cracked concrete Ding, Y.; Li, D.; Zeng, W. https://doi.org/10.35789/fib.BULL.0095.Ch41	401
Evaluation of Effective Moment of Inertia for Calculation of Short-Term Deflections of Steel Fiber Reinforced Concrete Flexural Members Fargier-Gabaldon, L.B.; Al-Tameemi, M.; Parra-Montesinos, G.J. https://doi.org/10.35789/fib.BULL.0095.Ch42	411
6. Structural Applications and Rehabilitation	421
Experimental Investigation of Hybrid Concrete Elements with Varying Fiber Reinforcement under Concentrated Load Plückelmann, S.; Breitenbücher, R. https://doi.org/10.35789/fib.BULL.0095.Ch43	422
The behaviour of concrete columns confined by UHP-FRCC jacketing Fantilli, A.P.; Nishiwaki, T.; Lisi, V.; Longo, M. https://doi.org/10.35789/fib.BULL.0095.Ch44	432
A holistic calculation and design tool for structural SFRC members Look, K.; Mark, P. Longo, M. https://doi.org/10.35789/fib.BULL.0095.Ch45	442
FRCcalc - Software for design of fiber reinforced concrete elements according to MC2010 recommendations Valente, T.; Barros, J.; Lourenço, L. https://doi.org/10.35789/fib.BULL.0095.Ch46	452

Retrofitting a full-scale two-story hollow clay block masonry building by Steel Fiber Reinforced Mortar coating Lucchini, S.S.; Facconi, L.; Minelli, F.; Plizzari, G.A. https://doi.org/10.35789/fib.BULL.0095.Ch47	462
7. HPFRC	473
Structural behavior of prestressed Ultra-High Performance Fibre-Reinforced Concrete beams with and without openings: comparison between experimental results and finite element modelling techniques. Redaelli, D.; Nseir, J.Y. https://doi.org/10.35789/fib.BULL.0095.Ch48	474
Use of a Probabilistic Explicit Cracking Model for Analysing the mechanical behaviour of an Ultra-High Performance Fibre Reinforced Concrete (UHPFRC) Beam Subjected to Shear Loading Rossi, P.; Davian-Desnoyers, D.; Tailhan, J.L. https://doi.org/10.35789/fib.BULL.0095.Ch49	484
UHPFRC Precast slabs and field-cast joints of the Isabey-Darnley pedestrian bridge Charron, J.P.; Desmettre, C.; Cantin Bellemare, E. https://doi.org/10.35789/fib.BULL.0095.Ch50	494
Practical considerations on the application of the recent SIA 2052 guidelines on testing of Ultra-high-performance fiber-reinforced concrete Loser, R.; Justs, J.; Lura, P. https://doi.org/10.35789/fib.BULL.0095.Ch51	504
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1) MECHANICAL CHARACTERIZATION

Round-Robin Test on Various Test-Methods for Flexural Behavior of Steel Fiber Reinforced Sprayed Concretes

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Abstract

According to the actual European standard EN 14487-1 the potential of steel fiber reinforced sprayed concrete is characterized by flexural strength tests (first peak, ultimate and residual). In most cases, this is performed by a four-point bending test on beam specimens, specified in EN 14488-3. As an alternative test method, a three-point bending test on square panels with notch is recommended by EFNARC. It is argued as main benefit of the latter test method, that the geometry and dimensions of the panels are equal to those of specimens used for measuring the energy absorption capacity according to EN 14488-5. Hence, the specification of the ductility of fiber reinforced concretes according to EN 14487-1 in terms of residual strength and energy absorption capacity can be achieved preparing only one type of specimen. Furthermore, the EFNARC guideline points out a smaller scatter of test results, compared to the beam tests according to EN 14488-3.

Before the EFNARC method will be considered in EN 14487-1, the relevant CEN TC 104/WG10 requests for adequate proofs. These were performed within a round-robin test (RRT) on testing the flexural behavior of steel fiber reinforced sprayed concrete by the standardized EN 14488-3 method as well as by the proposed EFNARC method. The aim of this RRT was to investigate the comparability and correlation between the two test methods. Furthermore, the scatter of both methods was assessed. The RRT has been organized by Ruhr University Bochum, in whose labs the steel fiber reinforced sprayed concrete specimens (beams according to EN 14488-3 and square panels according to EFNARC guideline) were produced using a robotic spraying machine. The specimens were then tested in five independent laboratories Europe-wide. The results of this RRT are presented in detail. With regard to the residual strength, the relevant material parameter for steel fiber reinforced sprayed concrete, a tendency towards a slightly lower scatter was detected for the EFNARC test method.

Keywords

Sprayed concrete, steel fibers, round-robin test, flexural behavior

1 Introduction

The specification of the ductility of fiber reinforced sprayed concrete according to EN 14487-1 is ascertained by the classification of its residual strengths and/or energy absorptions capacity. In most cases, the residual strengths will be determined if the concrete characteristics are used in a structural design model. According to EN 14487-1, the determination of flexural strengths has to be performed by a four-point bending test on beam specimens specified in EN 14488-3. The residual strengths are classified by a minimum strength level defined for specific intervals of deflection according to EN 14487-1.

With regard to the main field of application of fiber reinforced concrete (i.e. rock stabilization in tunneling) further information concerning the concrete's energy absorption capacity can be essential. The energy absorption capacity has to be determined by performing a bending test on square panels, which are supported on their four edges and loaded centrally with a point load. This test method is specified in EN 14488-5 and was developed by the “National Rail-way Company (SNCF)” in order to simulate the typical loading scenario in terms of biaxial bending. By analogy to the classification of residual strengths, the energy absorption classes are also defined in EN 14487-1.

In EN 14487-1 it is explicitly pointed out that a direct comparison between the two different methods for the specification of ductility by means of residual strengths and energy absorption capacity is not feasible. Depending on project-specific requirements related to the quality of the concrete it could be necessary to perform both test methods. Consequently, in this case, two different types of specimens have to be prepared and tested under different testing conditions.

As an alternative test method to the four-point bending test on beams according to EN 14488-3, a three-point bending test on square panels with notch is recommended by EFNARC. The respective guideline was published in 2011. In this guideline, a series of arguments for performing the EFNARC method instead of the EN 14488-3 method are indicated. As an example, it is argued as main benefit of the EFNARC test method, that the geometry and dimensions of the panels are equal to those of specimens used for measuring the energy absorption capacity according to EN 14488-5. Hence, only one type of specimen has to be prepared for the determination of both material characteristics. Moreover, the EFNARC guideline points out a smaller scatter of test results compared to the beam tests according to EN 14488-3. However, if the scatter of results within the EFNARC test method is lower compared to the EN 14488-3 method remains to be examined, particular as in both guidelines it is noted that there is a lack of information in terms of precision. Even though it is a matter of fact, before the EFNARC test method will be considered in EN 14487-1, the relevant CEN TC 104/WG10 requests for adequate proofs. These were performed within a round-robin test (RRT) on testing the flexural behavior of steel fiber reinforced sprayed concrete by the standardized EN 14488-3 method as well as by the proposed EFNARC method. The aim of this RRT, that was organized and coordinated by the Institute for Building Materials of the Ruhr University Bochum, was to investigate the comparability and correlation between the two test methods. Furthermore, the scatter of both methods was assessed.