# RESULTS OF BLIND COMPETITION

**Simulation of three-point bending of beams with conventional reinforcement and fibres**

## 1. Introduction

This document presents the results of the blind competition carried out within the scope of the fib Working Group WG 2.4.2 *Modelling of Fibre Reinforced Concrete Structures*. The object of the benchmark was to predict the behaviour of a T cross section steel fibre reinforced concrete beam with conventional longitudinal (R/SFRC) and without conventional shear reinforcement in the shear span where the beam is predicted to fail in shear.

This benchmark and the rules of the competition were announced at the end of the year 2019. Information about the properties of the materials at the age of 7 and 14 days was communicated in the last week of January and first week of February 2020. A total of thirty six participants submitted the results of numerical simulations. The 9th of March experiments were conducted on two twin beams for the appraisal of the predictive performance of the submitted simulation proposals. The experiments were transmitted in real time through a youTube channel. In the weeks following to that, the experimental results and those of the participants have been analysed.

The following sections present the name of participants, the experimental results, numerical results and performance of the numerical predictions.

## 2. Name of participants

Table 1 includes a list of the participants and their affiliation, sorted by alphabetical order.

Table 1. List of participants and affiliation, sorted by alphabetical order

| Name of the participants | Affiliation(s) |
|---|---|
| Alejandro Nogales[1], Nikola Tošić[2], Albert de la Fuente[2] | [1]Smart Engineering Ltd, UPC Spin-Off, Barcelona, Spain [2]Civil and Environmental Engineering Department, Universitat Politècnica de Catalunya, Barcelona, Spain |
| Alexander Kagermanov | [1]University of Applied Science Rapperswil, Switzerland |
| Antonio A. Cristian | [1]Technical University of Civil Engineering of Bucharest |
| Barzin Mobasher[1], Devansh Deepak Patel[1], Chidchanok Pleesudjai[1] | [1]Material Model ASU Team |
| Camille A. Issa[1], Najwa Hani[1] | [1]Lebanese American University |
| Christoph Betschoga[1], Michael Huß, Yolcu Sever, Nguyen Duc Tung | [1]Institute of Structural Concrete, Graz University of Technology, Graz, Austria |
| Dong Xiang[1] | [1]Tongji University, China |
| George Markou[1] | [1]Faculty of Engineering, University of Pretoria, Hatfield, South Africa |
| Gerrit E. Neu[1], Michael Hofmann[1], Günther Meschke[1] | [1]Institute for Structural Mechanics, Ruhr University of Bochum, Germany |

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| Gili L. Sherzer[1], Younes F. Alghalandis[1], Karl Peterson[1], Giovanni Grasselli[1] | [1]University of Toronto, Canada |
| Giulio Zani[1], Matteo Colombo[1], Marco di Prisco[1] | [1]Politecnico di Milano, Department of Civil and Environmental Engineering |
| Hiroki Ogura[1], Minour Kunieda[2] | [1]Shimizu Corporation, Japan<br>[2]Gifu University, Japan |
| Inkyu Rhee[1], Jae-Min Kim[1] | [1]Department of Civil Engineering, Chonnam National University, Gwangju, South Korea |
| Jaime Planas[1], Beatriz Sanz[1], José M. Sancho[2] | [1]Dep. Ciencia de Materiales, ETS de Ingenieros de Caminos, Canales y Puertos, Universidad Politécnica de Madrid, Madrid, Spain<br>[2]Dep. Estructuras de Edificación, ETS Arquitectura, Universidad Politécnica de Madrid, Madrid, Spain |
| Jan Červenka[1] | [1] Červenka Consulting |
| Jia-Qi Yang[1], Zhiyuan Li[1], Peizhao Zhou[1], Chongfeng Xie[1] | [1]Department of Civil Engineering, Tsinghua University, Beijing, China |
| José Joaquín Ortega[1] | Universidad de Castilla-La Mancha, Spain |
| Josef Landler[1], Sören Faustmann[1], Oliver Fischer[1] | [1]Technical University of Munich, Department of Civil, Geo and Environmental Engineering, Munich, Germany |
| Lex van der Meer[1], Kris Riemens[1], Srinidhi Ramadas[1], Yue Dai[1] | [1]ABT, The Netherlands |
| Luís M.P. Matos[1], António V. Gouveia[2] | [1]Department of Civil Engineering, University of Minho<br>[2]Department of Civil Engineering, Polytechnic Institute of Viseu |
| Marcos A. da Silva[1], Luiz C. de Almeida[1], Leandro Mouta Trautwein[1] | [1]Universidade Estadual de Campinas, School of Civil Engineering, Architecture and Urbanism, Laboratório de Modelagem Estructural e Monitoração, Campinas-SP, Brazil |
| Mário Pimentel[1], Rui Valente[1] | [1]University of Porto, Faculty of Engineering, Porto, Portugal |
| Mladena Lukovic[1], Dawei Gu[1], Erik Schlangen[1] | [1]TU Delft, The Netherlands |
| Mohmaed Hamza[1], Hamed Salem[2] | [1]Applied Science International, Cairo, Egypt<br>[2]Structural Engineering Department, Cairo University, Egypt |
| Monday Isojeh[1] | [1]Hatch Limited |
| Osvaldo L. Manzoli[1], Luís A.G. Bitencourt Jr.[2], Yasmin T. Trindade[2] | [1]São Paulo State University, Department of Civil Engineering, Bauru-SP, Brazil<br>[2]University of São Paulo, Department of Structural and Geotechnical Engineering, São Paulo-SP, Brazil |
| Peter K. Juhasz[1], Peter Schaul[1] | [1]JPK Static Ltd, Department of Construction Materials and Technologies , Budapest University of Technology and Economics |
| Pim van der Aa[1], Ab van den Bos[1] | [1]Diana FEA BV |
| Rafael A. Sanabria[1] | [1]Universidade Estadual de Campinas, Laboratorio de Modelagem Estrutural e Monitoração, Brazil |
| Rutger Vrijdaghs[1] | [1]Department of Civil Engineering, KU Leuven, Belgium |
| Saeid Mehrpay[1], Tamon Ueda[2] | [1]Hokkaido University, Japan |

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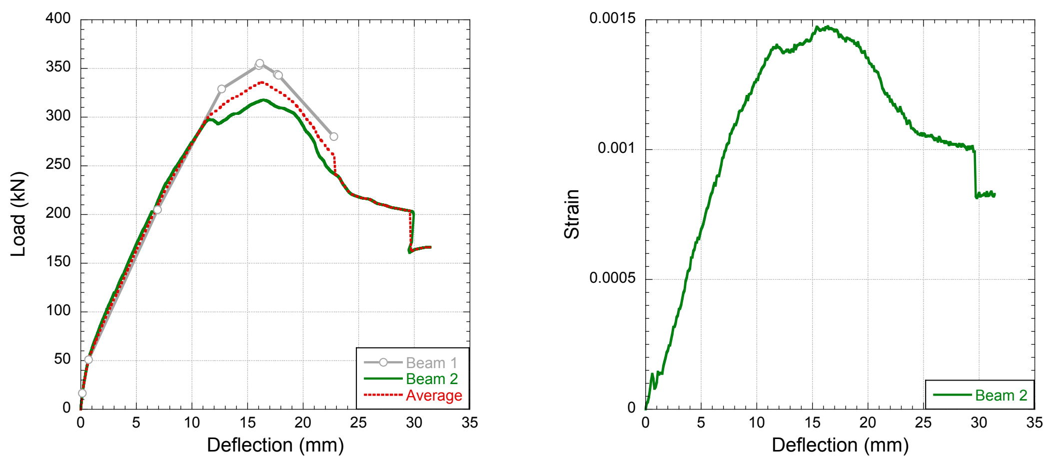
|---|---|
| | [2]Shenzhen University, PR China |
| Shen Le[1,2], Ding Miao[1,2], Yang Bo[1,2] | [1]School of Civil Engineering, Chongquing, China<br>[2]Key Laboratory of New Technology for Construction of Cities in Mountain Area, Chongquing University, China |
| Song Jin[1], Yating Tai[1], Yun Tian[1], Chenghuan Lin[1], Xiyao Zhao[1], Meng Zhang[1], Qingqing Wu[1], Jikai Zhou[1] | [1]College of Civil and Transportation Engineering, Hohai University |
| Tiago Valente[1], Inês Costa[1], Lúcio Lourenço[1], Christoph de Sousa[1], Felipe Melo[1], Cristina Frazão[1] | [1]CiviTest-Pesquisa de Novos Materiais para a Engenharia Civil, Lda., Vila Nova de Famalicão, Portugal |
| Zhongyue Tracy Zhang[1], Frank J. Vecchio[1] | [1]University of Toronto, Canada |
| Ziyang Zhang[1], Linyou Zhang[1], Weiting Chen[1], Yong Li[1] | [1]Department of Bridge Engineering, Southwest Jiaotong University, Chengdu, China |


## 3. Experimental results

Two beams were subjected to eccentric bending. Figure 1 displays the experimental results. Unfortunately, the record of strain of the first beam was lost.

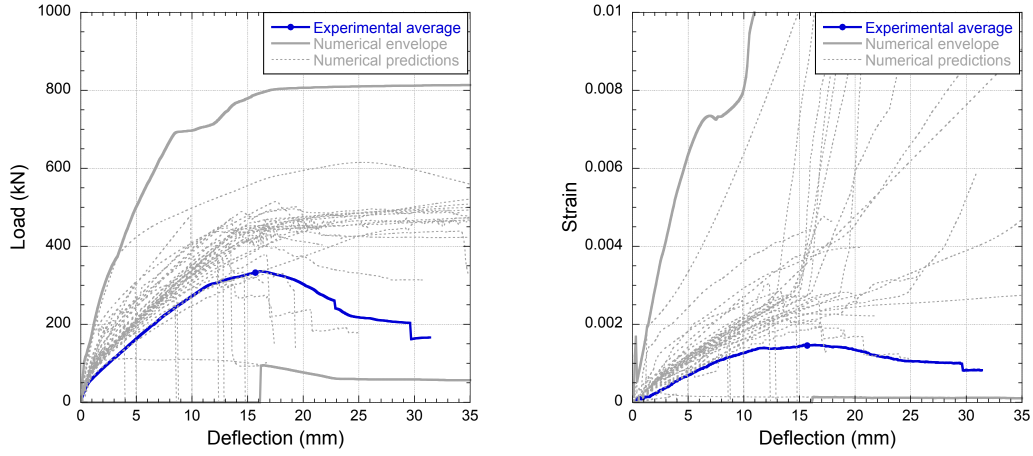



(a) (b)

Figure 1. Experimental results and average curves of load versus deflection (a) and strain versus deflection (b)

## 4. Results of the simulations

Figure 2 shows the experimental average, numerical envelope and numerical predictions of all participants for the curves of load versus deflection and strain versus deflection. The results are displayed up to the deflection corresponding to the end of the experiments. Note that the curves of strain of Participants 13 and 34 have been excluded from the graphic, as they are out of the range of results of the remaining participants.




(a) (b)

Figure 2. Experimental results, numerical envelope and numerical predictions of all participants of load versus deflection (a) and strain versus deflection (b)

## 5. Predictive performance of the simulations

For each participant, the predictive performance was computed after performing the tests, according to the following:

1. The experimental average was computed from the results of the two beams (see corresponding paragraph).

2. The numerical results of each participant were compared with the experimental average, up to the experimental peak load.

3. The error $Err_F$ of the numerical prediction was calculated as:

$$Err_F = \frac{1}{n}\sum_{\kappa}\left(\frac{|F_{exp}^{\kappa} - F_{num}^{\kappa}|}{F_{exp}^{\kappa}}\right) \quad (1)$$

where $\kappa$ corresponds to the records, $F_{exp}^{\kappa}$ is the experimental value of load for record $\kappa$, $F_{num}^{\kappa}$ the numerical value, and n are the number of scan readings. An equivalent equation is used to compute the error of the strain $Err_{\varepsilon}$.

4. The relative error of the maximum load $\Delta F/F$ was computed as:

$$\Delta F/F = \frac{|F_{exp}^{max} - F_{num}^{max}|}{F_{exp}^{max}} \quad (2)$$

where $F_{exp}^{max}$ is the maximum load of the average of experiments and $F_{num}^{max}$ is the maximum load of the numerical prediction. A similar expression is used to compute the relative error of the strain $\Delta\varepsilon/\varepsilon$, considering the strain corresponding to the maximum load of experiments, $\varepsilon_{F_{exp}^{max}}$, and strain corresponding to the maximum load of the numerical prediction, $\varepsilon_{F_{num}^{max}}$, and the relative error of the deflection $\Delta u/u$, considering the corresponding $u_{F_{exp}^{max}}$ and $u_{F_{num}^{max}}$.

5. The score of each participant was calculated considering the error of the numerical curves with respect to the average of the experiments and the relative errors of the maximum load, strain and deflection corresponding to the maximum load, according to the following expression:

$$Score = 0.35\,\Delta F/F + 0.15\,Err_F + 0.25\,\Delta\varepsilon/\varepsilon + 0.1 Err_\varepsilon + 0.15 \Delta u/u \qquad (3)$$

Table 2 includes the predictive performance of the simulations of the 36 participants. Note that the order of participants is random and does not coincide with that of that of Table 1, for the sake of confidentiality. One of the participants presented results for two models, marked as *a* and *b*.

Table 2. Predictive performance of the results presented by the participants, shown in random order.

| Partici-pant no. | Rel. error of $F_{max}$ $\Delta F/F$ (%) | ERR force-deflection $Err_F$ (%) | Rel. error of strain at $F_{max}$ $\Delta\varepsilon/\varepsilon$ (%) | ERR strain-deflection $Err_\varepsilon$ (%) | Rel. error of deflect. at $F_{max}$ $\Delta u/u$ (%) | Score (%) | Classif. |
|---|---|---|---|---|---|---|---|
| 1 | 16.12 | 59.71 | 22.70 | 86.05 | 47.83 | 36.05 | 6 |
| 2 | 14.34 | 62.43 | 18.60 | 83.45 | 49.69 | 34.83 | 5 |
| 3 | 18.09 | 34.06 | 84.04 | 77.77 | 16.15 | 42.65 | 10 |
| 4 | 51.88 | 44.91 | 2486 | 60.18 | 356.5 | 705.8 | 32 |
| 5 | 4.417 | 9.356 | 201.8 | 260.9 | 3.106 | 79.96 | 21 |
| 6 | 7.973 | 89.26 | 12.45 | 122.3 | 69.57 | 41.96 | 9 |
| 7 | 41.93 | 27.09 | 1824 | 78.23 | 136.0 | 503.0 | 31 |
| 8 | 32.99 | 77.10 | 41.78 | 54.37 | 18.63 | 41.79 | 8 |
| 9 | 42.55 | 89.62 | 86.10 | 102.7 | 38.51 | 65.90 | 17 |
| 10 | 1.270 | 6.135 | 33.56 | 23.50 | 4.348 | 12.76 | 1 |
| 11 | 83.12 | 122.0 | 129.9 | 59.78 | 57.76 | 94.52 | 24 |
| 12a | 53.73 | 35.02 | 1562 | 70.48 | 223.0 | 455.1 | 29 |
| 12b | 34.85 | 32.26 | 182.9 | 80.08 | 0.000 | 70.76 | 19 |
| 13 | 60.80 | 29.14 | 1.659e+05 | 2.020e+04 | 241.0 | 4.355e+04 | 36 |
| 14 | 70.55 | 23.65 | 2376 | 136.3 | 831.7 | 760.7 | 34 |
| 15 | 8.847 | 53.34 | 28.99 | 64.63 | 23.60 | 28.35 | 2 |
| 16 | 13.48 | 42.25 | 43.63 | 57.98 | 24.84 | 31.49 | 3 |
| 17 | 42.22 | 46.37 | 92.66 | 75.46 | 147.8 | 74.62 | 20 |
| 18 | 11.68 | 21.01 | 109.7 | 66.46 | 23.60 | 44.86 | 11 |
| 19 | 42.66 | 22.38 | 112.1 | 29.47 | 40.37 | 55.31 | 14 |
| 20 | 32.98 | 29.90 | 226.9 | 87.49 | 6.211 | 82.44 | 22 |
| 21 | 9.844 | 27.78 | 95.48 | 138.6 | 18.01 | 48.04 | 13 |
| 22 | 28.74 | 105.5 | 89.36 | 90.55 | 78.88 | 69.11 | 18 |
| 23 | 49.19 | 52.64 | 93.35 | 64.81 | 20.50 | 58.01 | 15 |
| 24 | 30.44 | 14.41 | 332.8 | 64.10 | 24.84 | 106.2 | 26 |
| 25 | 66.59 | 45.88 | 56.46 | 59.22 | 72.05 | 61.03 | 16 |
| 26 | 30.34 | 48.69 | 49.33 | 43.07 | 23.60 | 38.10 | 7 |
| 27 | 46.45 | 38.31 | 1199 | 86.52 | 86.34 | 343.5 | 27 |
| 28 | 35.35 | 31.33 | 1464 | 121.5 | 30.43 | 399.7 | 28 |
| 29 | 53.46 | 58.72 | 167.1 | 135.8 | 9.317 | 84.27 | 23 |
| 30 | 41.35 | 16.64 | 4040 | 834.3 | 167.1 | 1135 | 35 |
| 31 | 78.28 | 30.08 | 2498 | 517.3 | 215.5 | 740.5 | 33 |

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|---|---|---|---|---|---|---|---|
| 32 | 39.16 | 24.89 | 90.62 | 54.91 | 10.56 | 47.17 | 12 |
| 33 | 13.12 | 7.442 | 81.23 | 54.63 | 3.106 | 31.95 | 4 |
| 34 | 42.87 | 27.05 | 1.955e+09 | 1.622e+08 | 346.6 | 5.049e+08 | 37 |
| 35 | 147.5 | 168.4 | 966.5 | 32.34 | 983.9 | 469.3 | 30 |
| 36 | 98.55 | 99.73 | 97.34 | 104.9 | 99.38 | 99.18 | 25 |

Figure 3 shows the score of participants. Note that the scores of Participants 13 and 34 have been excluded from the graphic, as they are out of the range of results of the remaining participants.

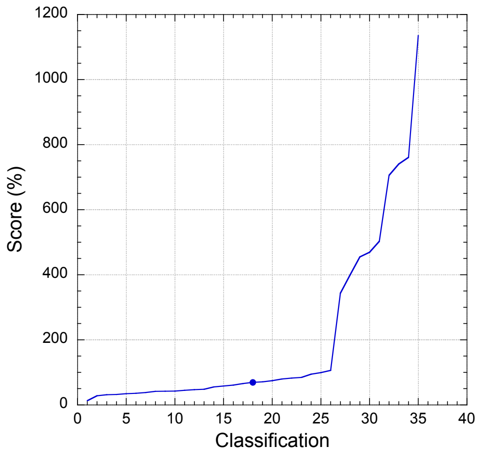


Figure 3. Score of participants

The best score, i.e., the minimum, is 12.76%, which corresponds to Participant 10, Alexander Kagermanov, from the University of Applied Science Rapperswil, Switzerland. Since the organization of this competition did not obtain explicit permission to publicly disclose the classification of now-winner participant by identifying his/her name (or the name of team's members) and corresponding affiliation, those that want to know their classification in the pole should contact directly the organization by email (beatriz.sanz@upm.es).

17 April 2020

Joaquim Barros (Convener)

Beatriz Sanz (Deputy convener)