The Challenges and Opportunities of New Materials and Advanced Numerical Tools for the Development of Innovative and Sustainable Built Environment

Joaquim Barros
Full Professor
barros@civil.uminho.pt

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University of Minho

SUMMARY

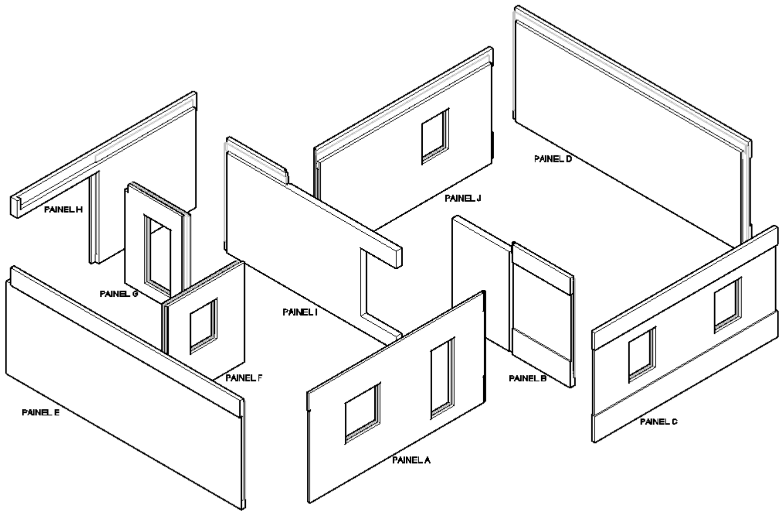
1 – MOTIVATION

- ✓ Explore the potentialities of materials of complementary properties and functionalities for developing more sustainable constructions systems, such is the case of fiber reinforced cement-based materials (FRC) and fiber reinforced polymers (FRP);

- ✓ How reliable are existing advanced numerical approaches for assisting on the optimum use of FRC and FRP regarding innovation and sustainability on the built environment – the role of Blind Simulation Competitions.

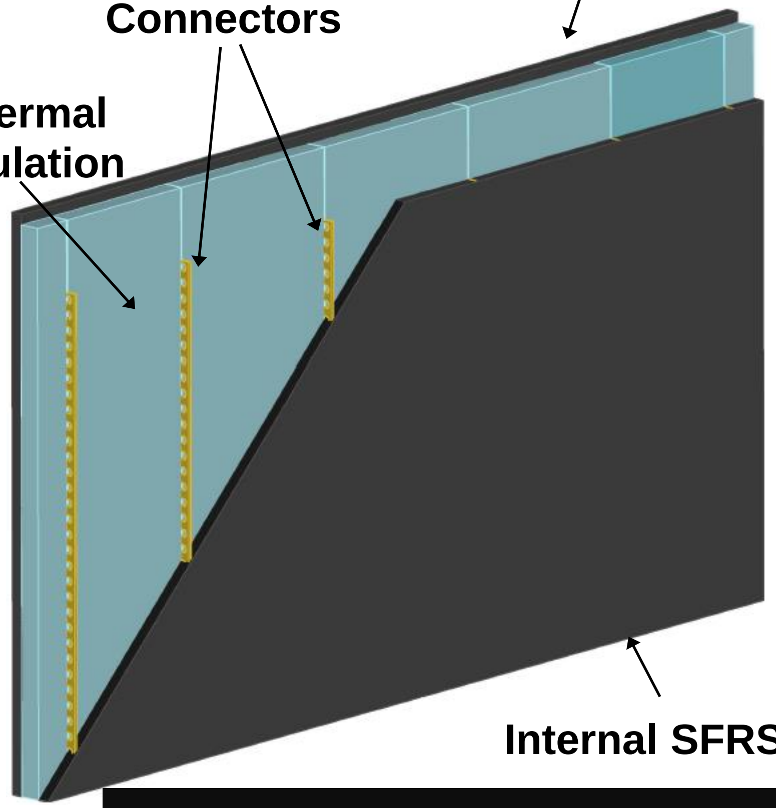
2 – MATERIALS OF COMPLEMENTARY FUNCTIONALITY FOR THE DEVELOPMENT OF INNOVATIVE CONSTRUCTION SYSTEMS

2.1 - LEGOUSE

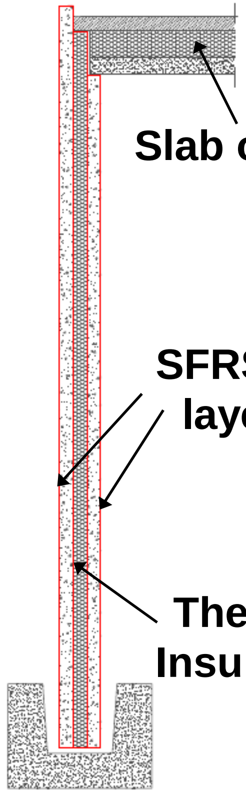


doi.org/10.1016/j.compstruct.2013.06.015

doi.org/10.1016/j.compstruct.2013.06.022



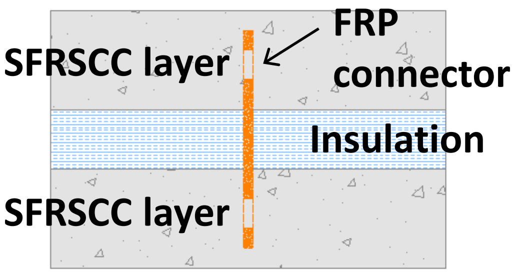
PERSPECTIVE OF A SANDWICH PANEL

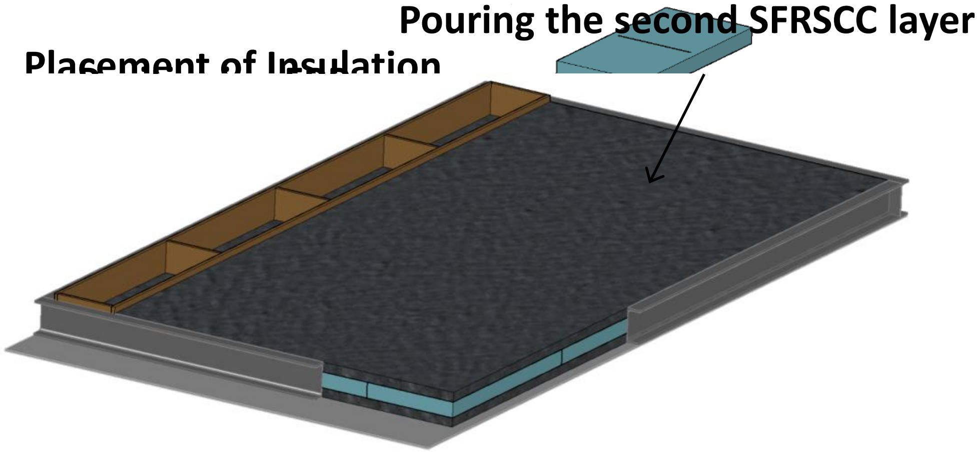


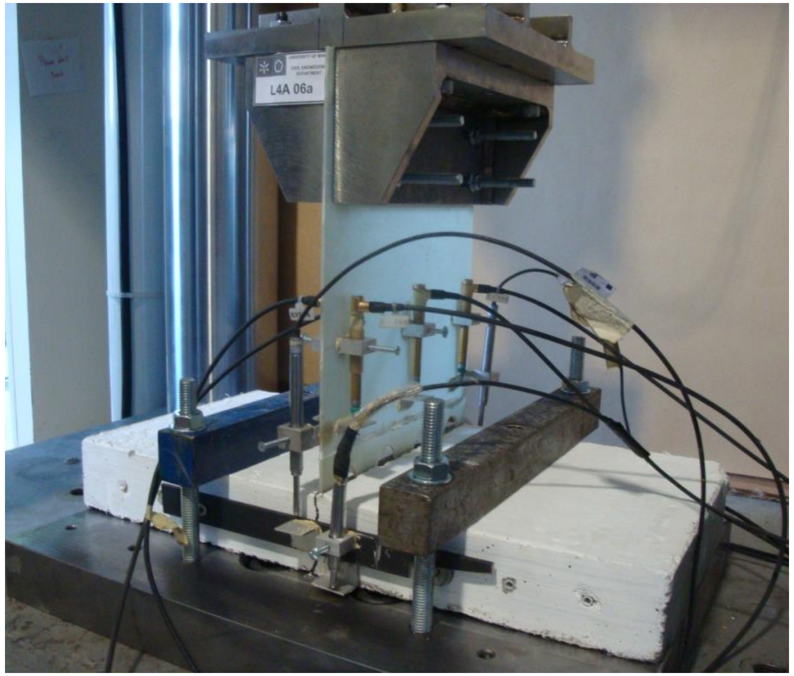
CROSS SECTION

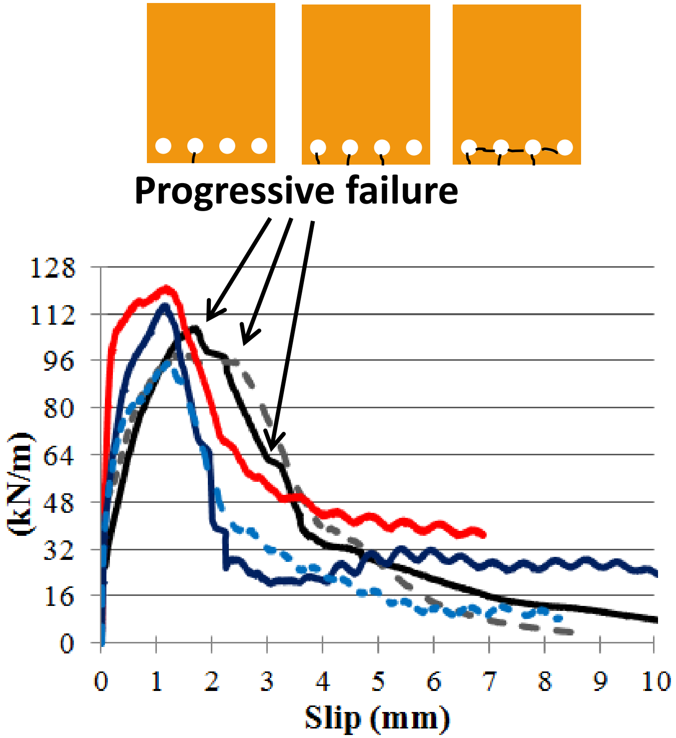
2.1 - LEGOUSE

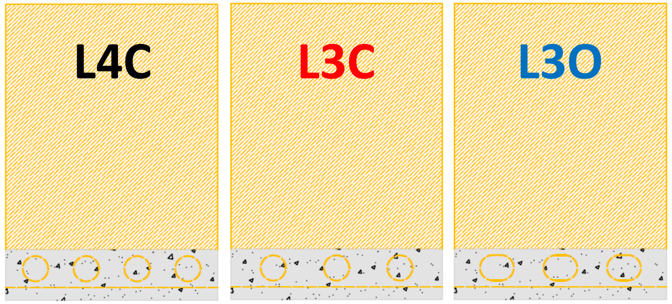
Simply perforated plates:









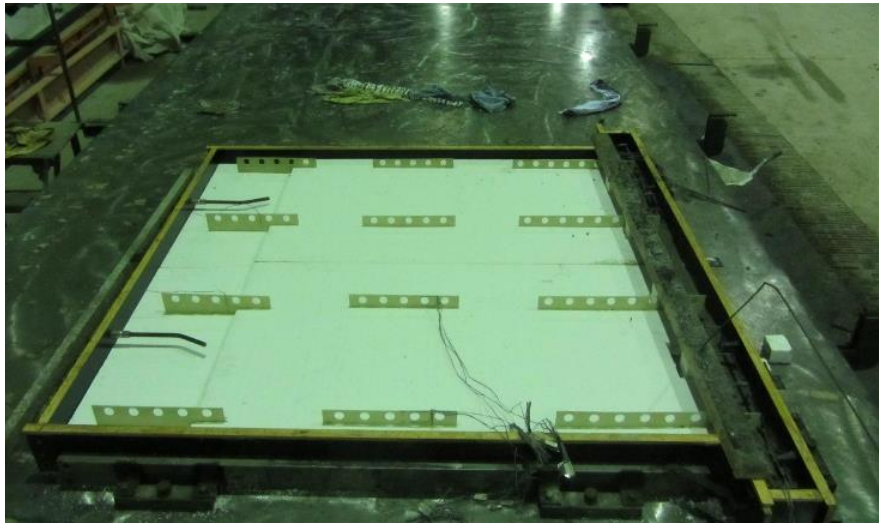


doi.org/10.1016/j.conbuildmat.2017.12.021

doi.org/10.1016/j.conbuildmat.2018.02.141

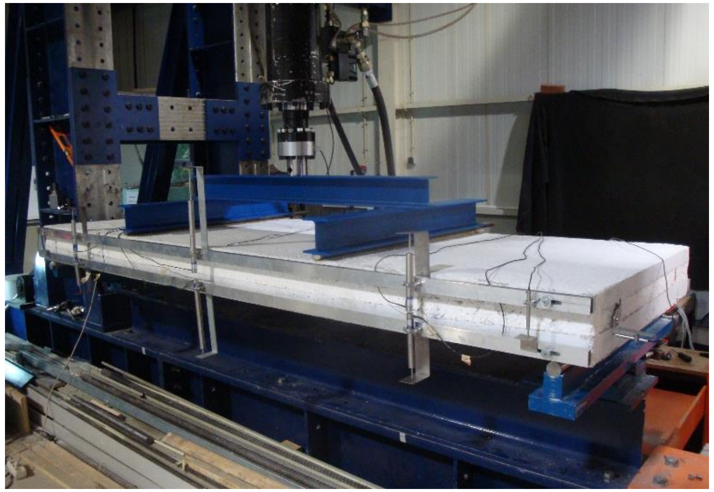
2.1 - LEGOUSE

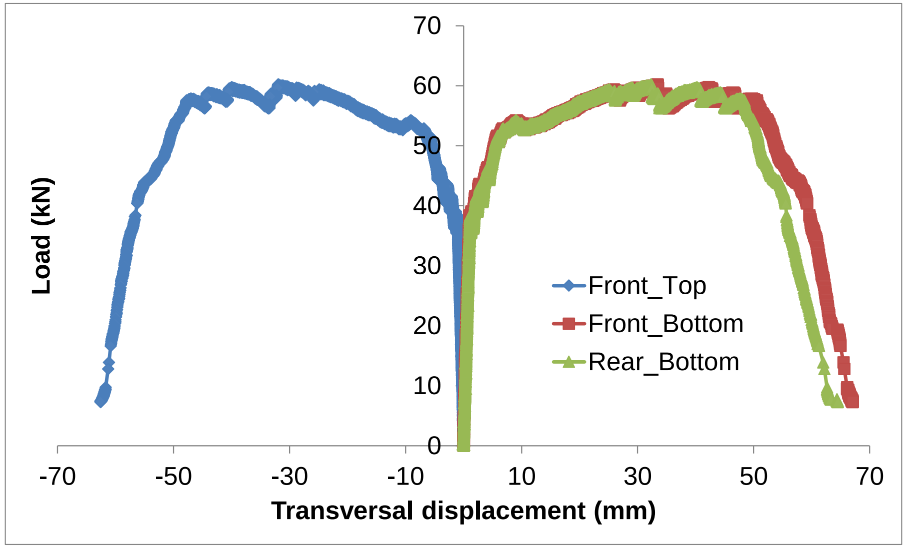
Construction of sandwich panels prototypes for testing programs

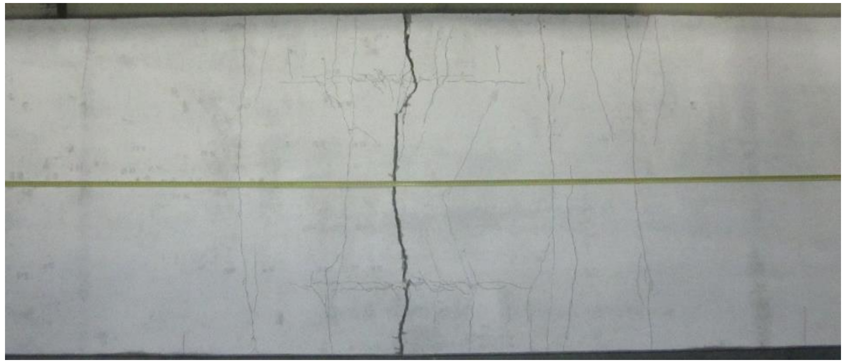


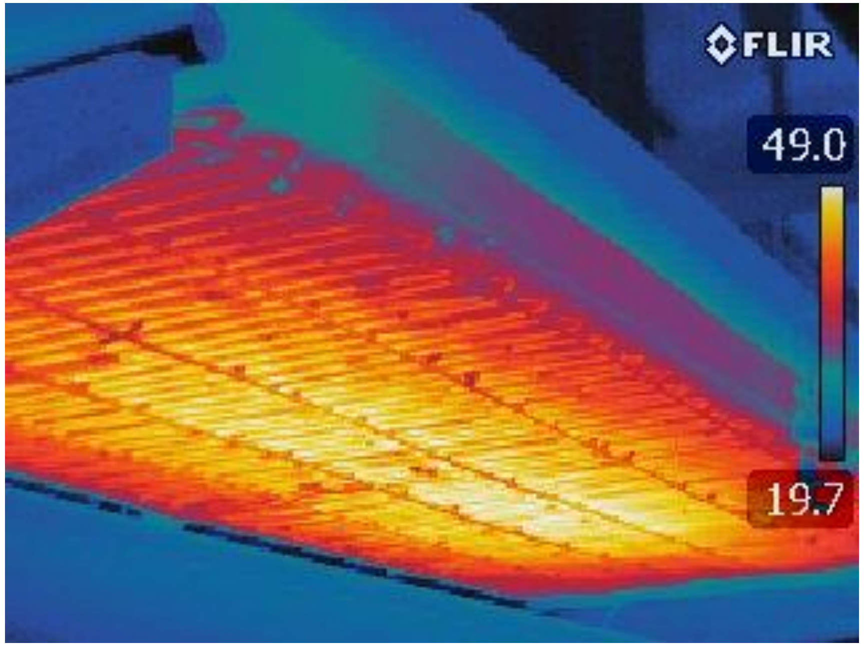
2.1 - LEGOUSE

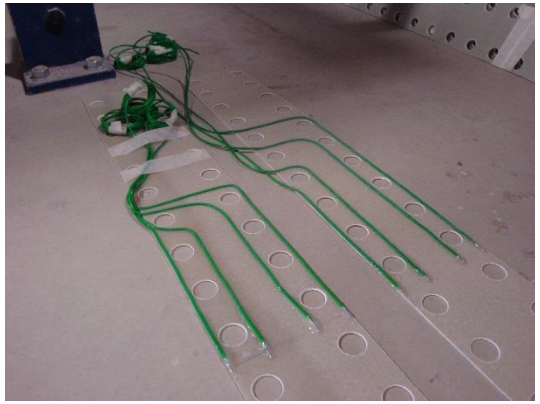
Testing real scale sandwich panels prototypes

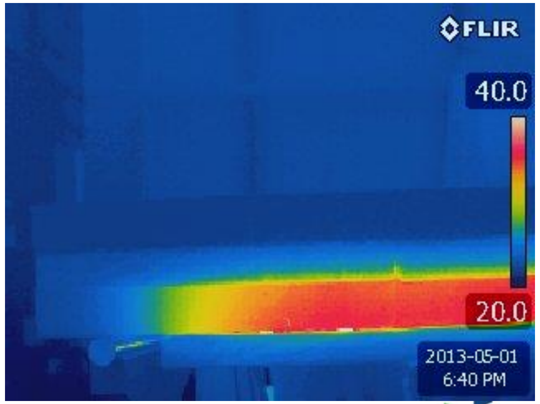






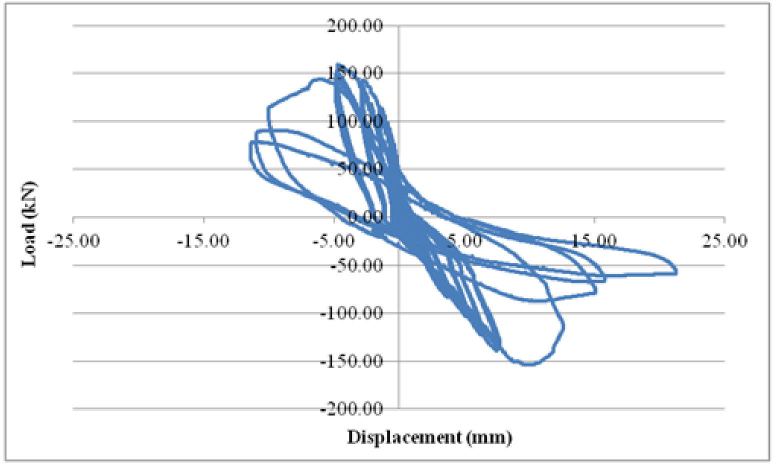


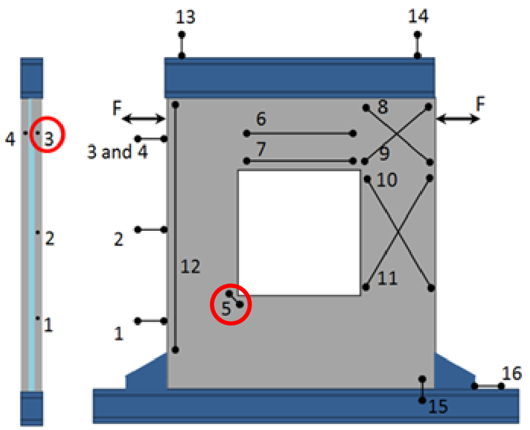




2.1 - LEGOUSE

Pseudo-static in-plane cyclic tests





doi.org/10.1016/j.engstruct.2021.112149

2.1 - LEGOUSE

Construction of real scale prototype





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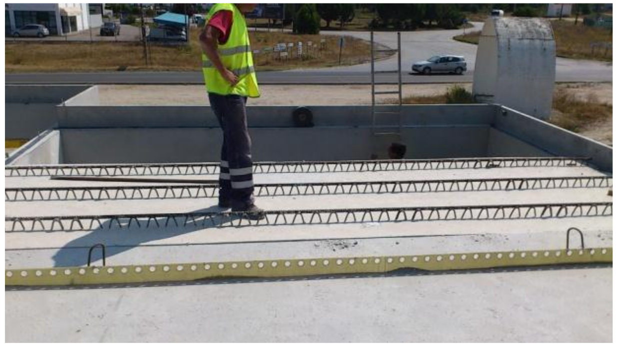
Construction of real scale prototype





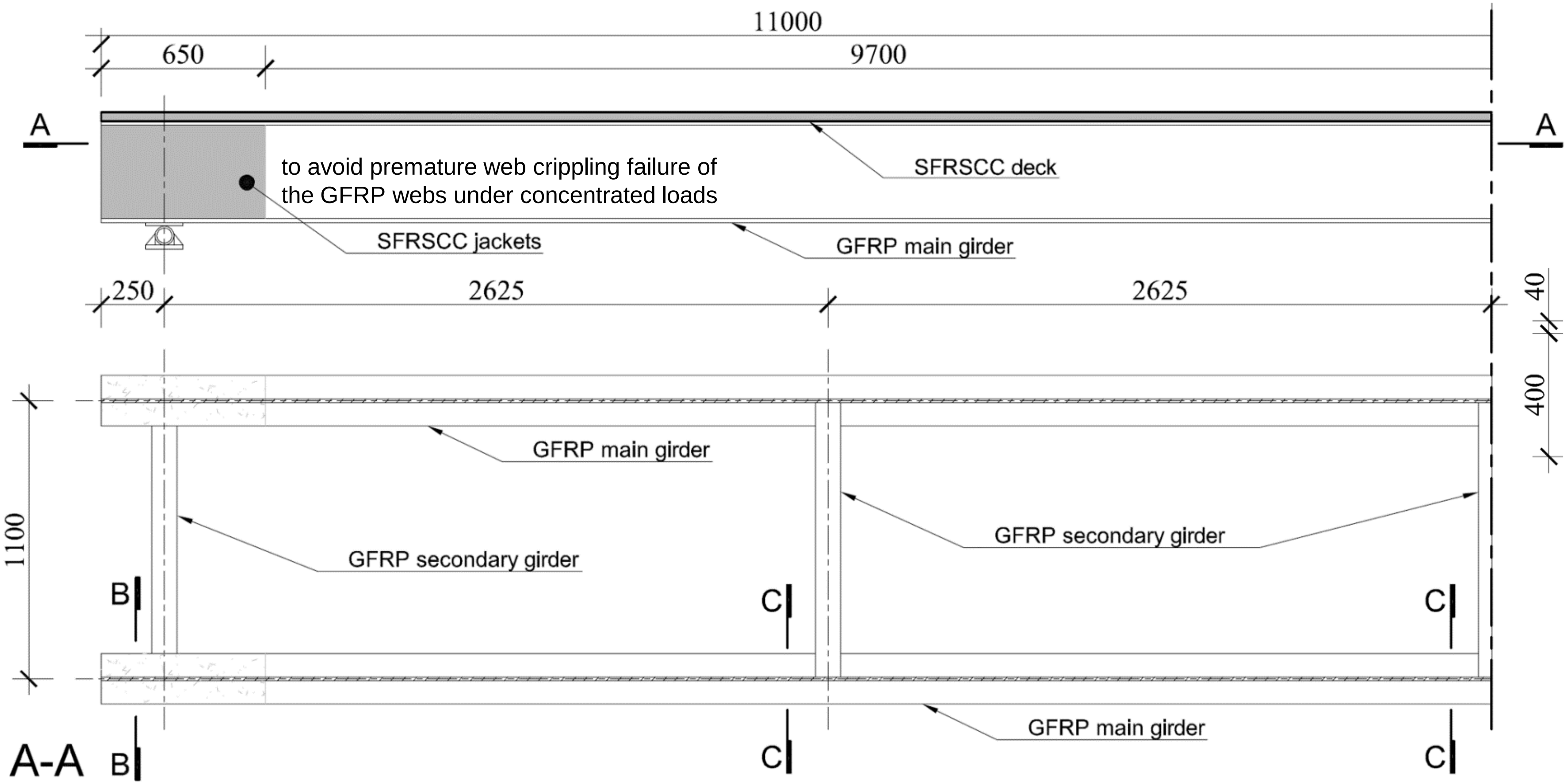
2.1 - LEGOUSE

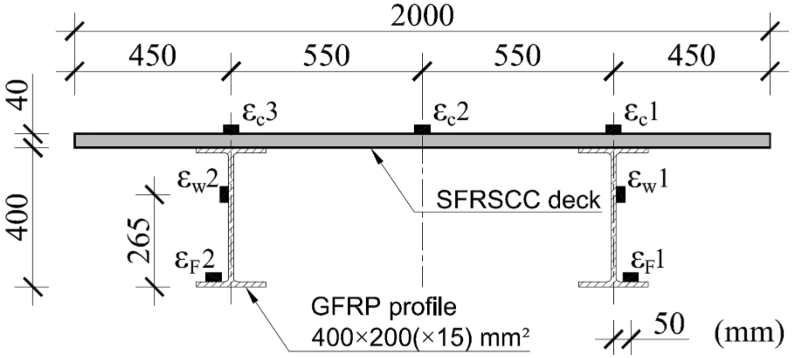
Construction of real scale prototype

Real scale prototype of 100 m² area, capable of hosting 6 persons, built in the Portuguese city of Rio Maior.

Two weeks are required to build completely this modular construction, with a final cost per m² of 400€.

2.2 - PONTALUMIS





Mechanical properties of the GFRP main girders (avg. ± std. dev.)..

GFRP	$E_{L,t}$ [GPa]	$E_{T,c}$ [GPa]	G_{LT} [GPa]	$f_{tu,L}$ [MPa]	$\tau_{u,LT}$ [MPa]	ρ [kN/m^3]
Webs	23.98 ± 1.61	4.55 ± 0.52	3.49 ± 0.43	278.90 ± 23.78	20.42 ± 1.15	18.0
Flanges	35.71 ± 1.83	3.57 ± 0.36	-	336.94 ± 37.51	-	

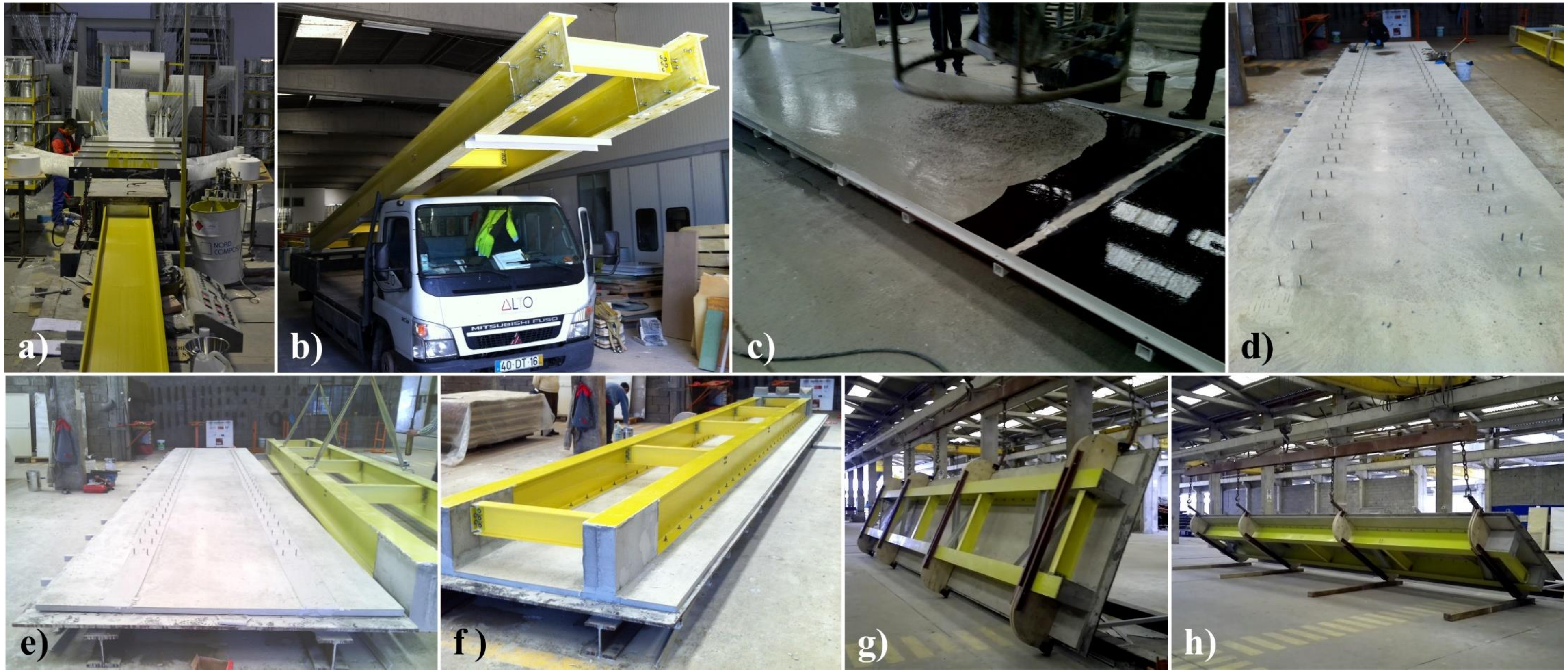
doi.org/10.1016/j.engstruct.2011.05.005
doi.org/10.1016/j.compstruct.2013.11.018

2.2 - PONTALUMIS

Construction of the real scale prototype

Mechanical properties of the SFRSCC (avg. ± std. dev.).

$E_{c,28}$ [GPa]	f_{cm} [MPa]	$f_{ct,L}$ [MPa]	$f_{eq,2}$ [MPa]	$f_{eq,3}$ [MPa]	$f_{R,1}$ [MPa]	$f_{R,2}$ [MPa]	$f_{R,3}$ [MPa]	$f_{R,4}$ [MPa]
37.75±1.31	75.95±10.03	6.21±1.25	10.42±2.42	10.56±2.40	10.17±2.16	10.27±2.34	9.71±2.26	9.01±2.15



(a) manufacturing the GFRP profiles; (b) Transportation of the GFRP component; (c) casting the SFRSCC deck; (d) applying the stainless steel anchors and the epoxy layer; (e,f) placing the GFRP grid; (g,h) placing the footbridge on the final position

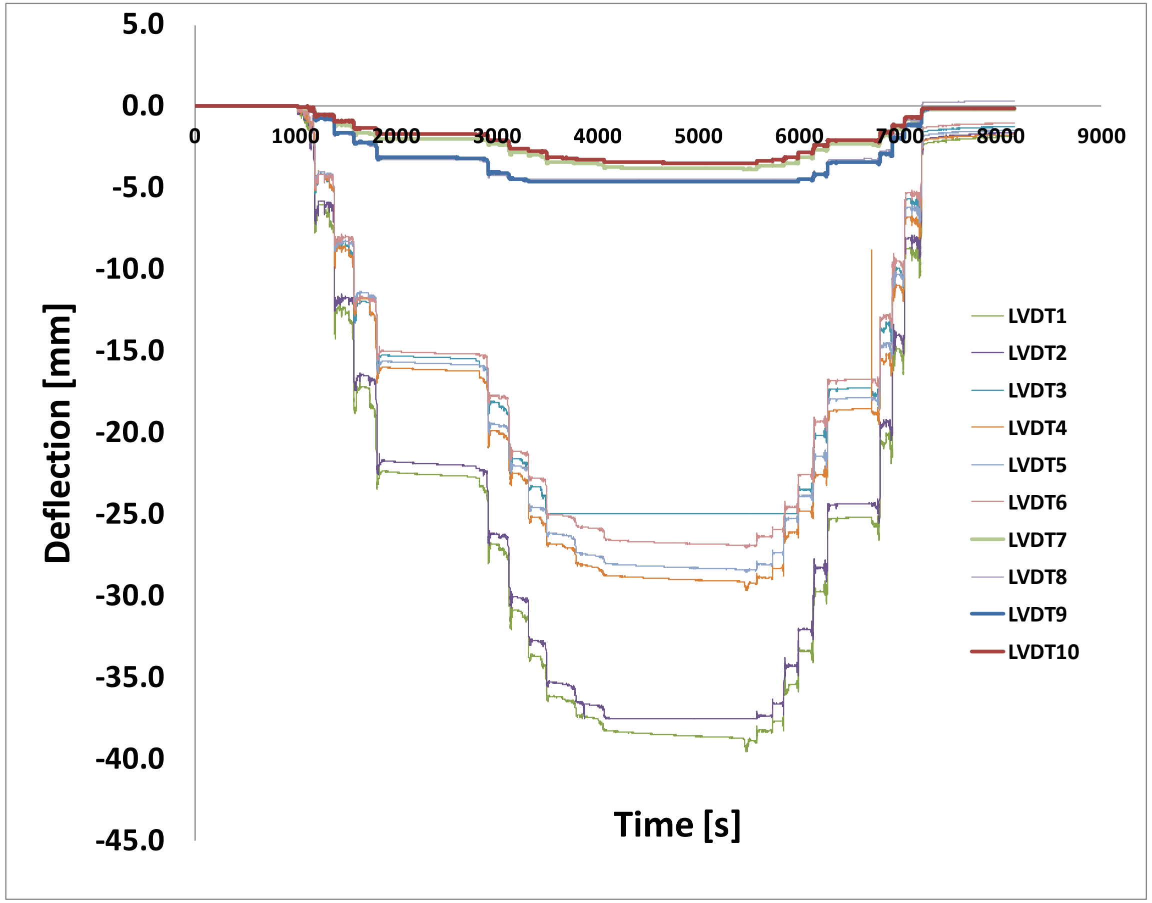
2.2 - PONTALUMIS

Tests on the real scale prototype

a) Uniformly distributed load along the entire span, centerd with the deck in a width of 1.20m

b) Uniformly distributed load in the central part of the span, in a length of about 2.7m, across the entire width of the deck

c) Uniformly distributed load in the central part of the span, in a length of about 5.1m, across the entire width of the deck

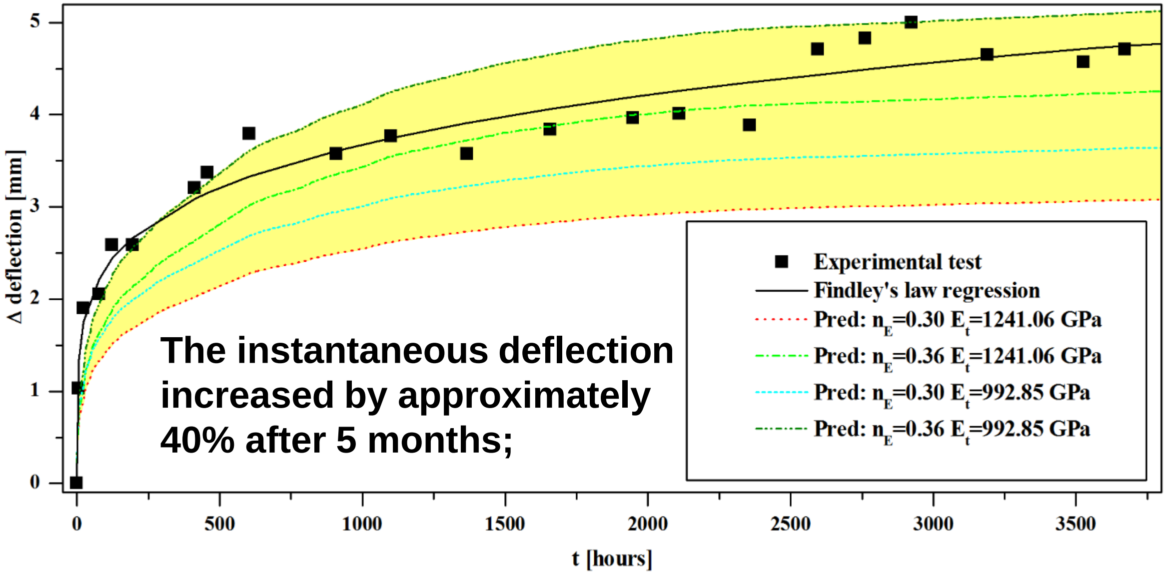


8.8 kN/m^2, **76% higher** than the characteristic load preconized in Eurocode 1 for footbridges (5 kN/m^2)

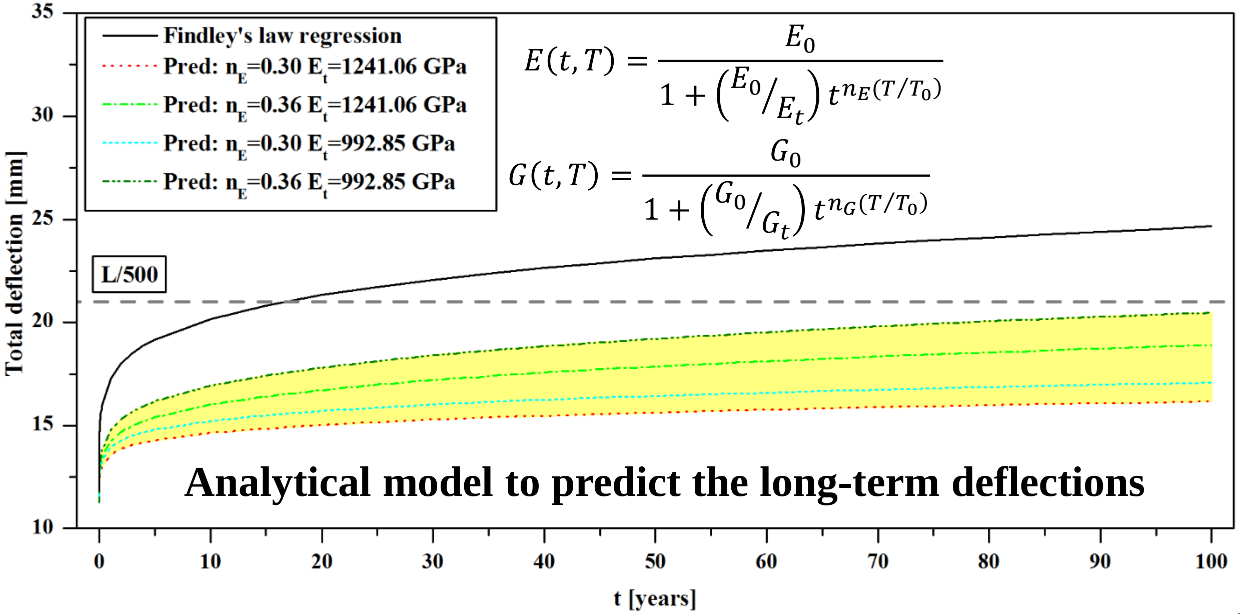
2.2 - PONTALUMIS

Tests on the real scale prototype

***q* = 1.49 kN/m²** (30% of the characteristic live load for footbridges defined in Eurocode 1)

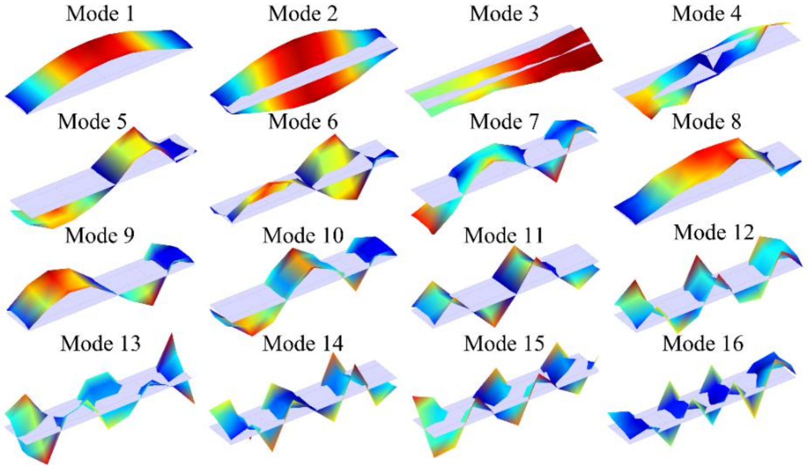


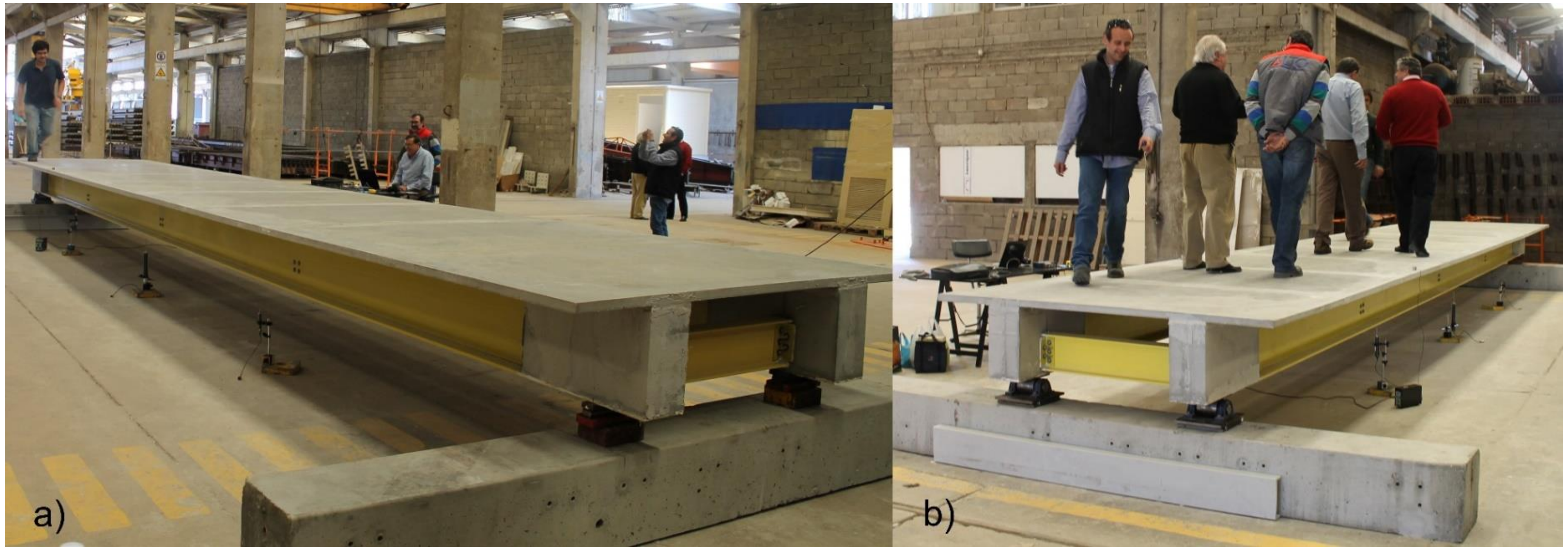
The Findley's power law predicted appropriately (R^2=0.963) the time deflection evolution: $\Delta(t) = \Delta_0 + m \cdot t^n$ **with *m*=0.945 and *n*=0.197**



2.2 - PONTALUMIS

Tests on the real scale prototype





Mode	Frequency		Damping ratio	
	Mean [Hz]	CoV [%]	Mean [%]	CoV [%]
1	6.40	0.28	1.89	18.69
2	8.16	0.01	1.26	11.77
3	12.13	0.63	1.96	16.28
4	20.78	12.28	1.57	62.08
5	22.16	6.14	0.92	20.59
6	23.74	0.09	0.76	11.65
7	31.11	0.28	1.74	13.29
8	42.37	0.10	0.70	11.21
9	45.96	0.06	0.53	11.62
10	51.69	0.14	0.47	14.21
11	60.21	0.04	0.79	24.45
12	68.29	0.05	0.43	14.99
13	69.24	0.25	0.17	26.56
14	77.18	0.06	0.57	19.01
15	80.62	0.30	1.00	24.57
16	88.61	0.12	0.47	19.45

Pedestrian response tests: Very low probability of pedestrian discomfort due to the structural vibrations

Modal identification test: results of the first 16 mode shapes with ambient excitation.

doi.org/10.1016/j.compstruct.2015.07.041

doi.org/10.1016/j.compstruct.2014.08.009

2.2 - PONTALUMIS

Pedestrian bridge

The developed pedestrian bridge is in service since 2015 over the River Cáster in the Portuguese city of Ovar (S. Silvestre bridge)

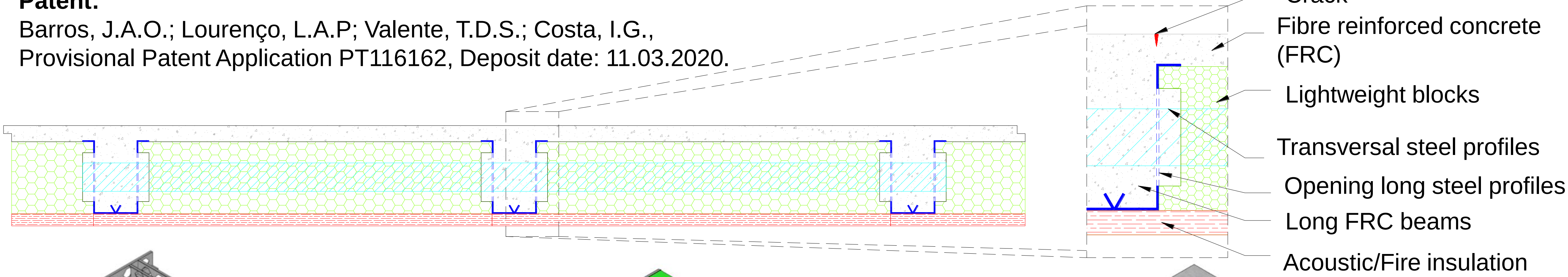
The results of this project confirmed the potential of the proposed hybrid GFRP-SFRSCC structural system for footbridge applications.

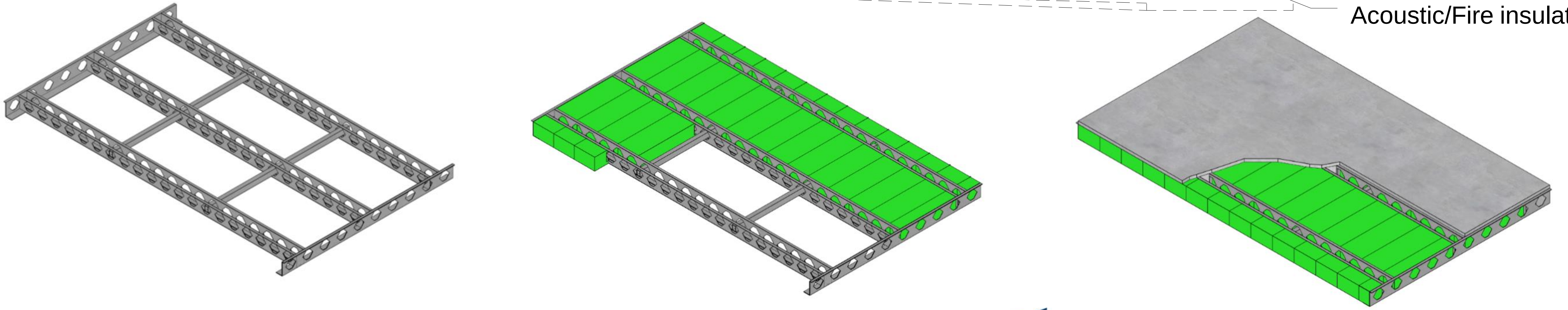
2.3 - PRESLABTEC

New slab system for the construction of building pavements

Website: http://civitest.pt/preslabtec/en_gb/

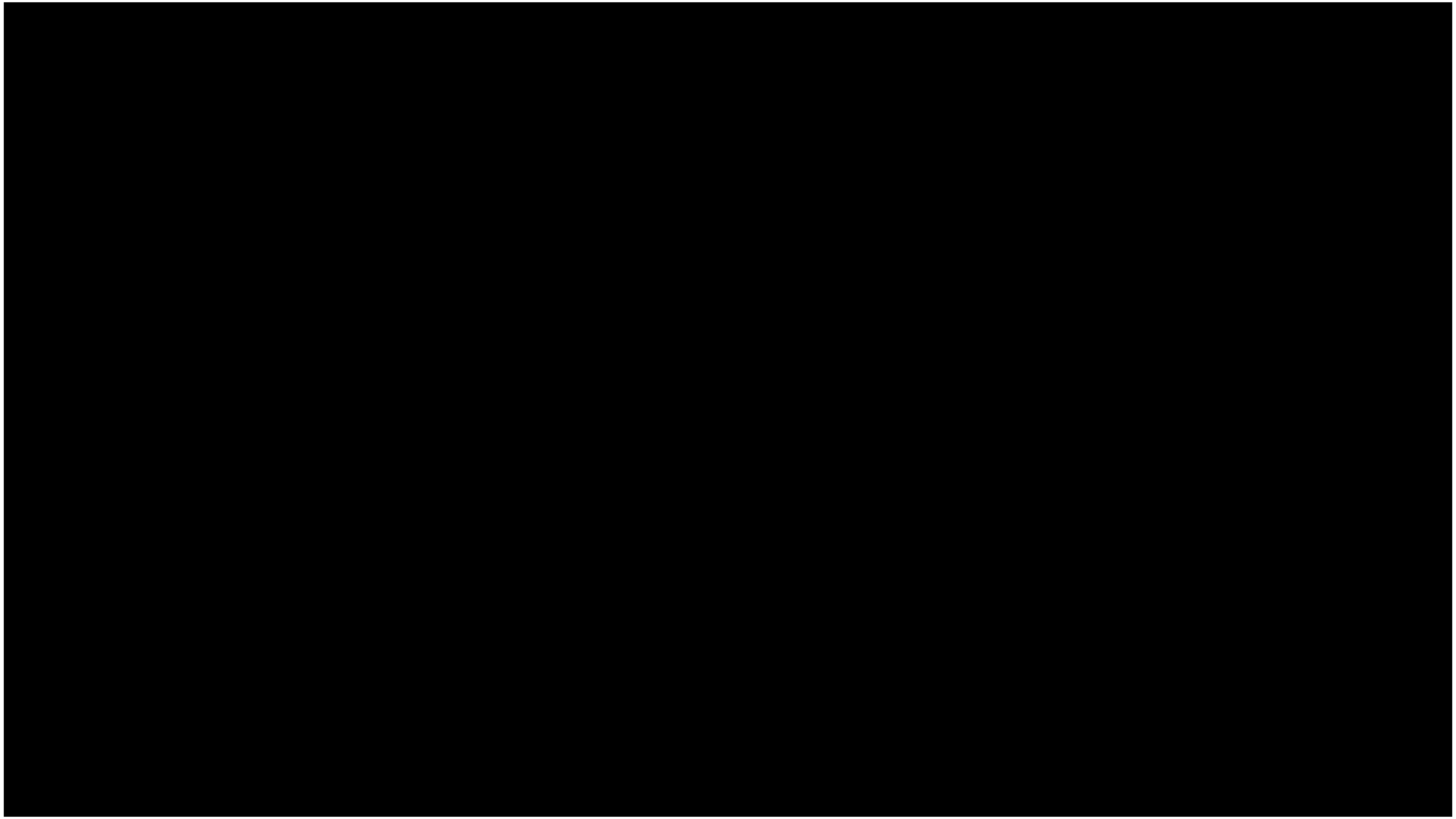
Patent:
Barros, J.A.O.; Lourenço, L.A.P; Valente, T.D.S.; Costa, I.G., Provisional Patent Application PT116162, Deposit date: 11.03.2020.





2.3 - PRESLABTEC

Demonstrating the structural performance by experimentally testing prototypes of real scale (bending tests)



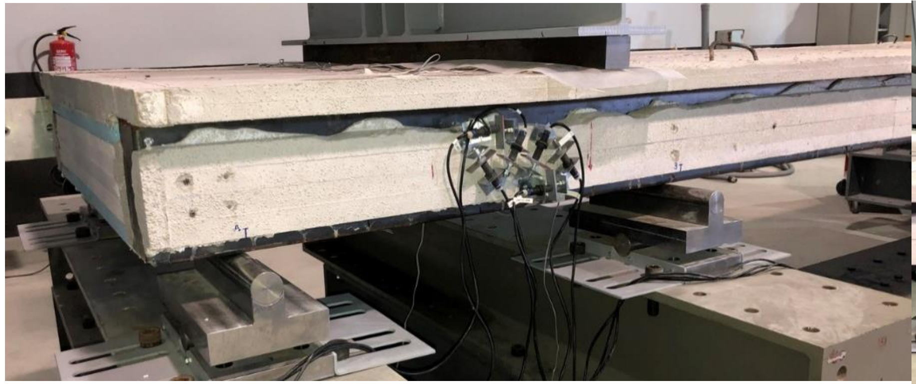
2.3 - PRESLABTEC

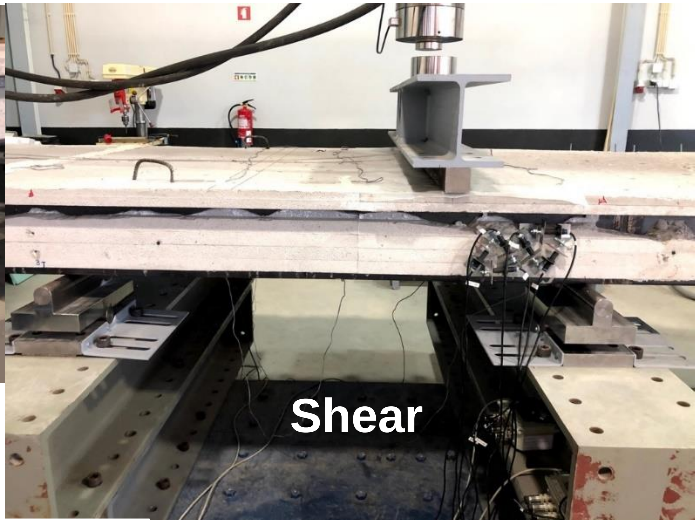
Technical data of the tested prototype

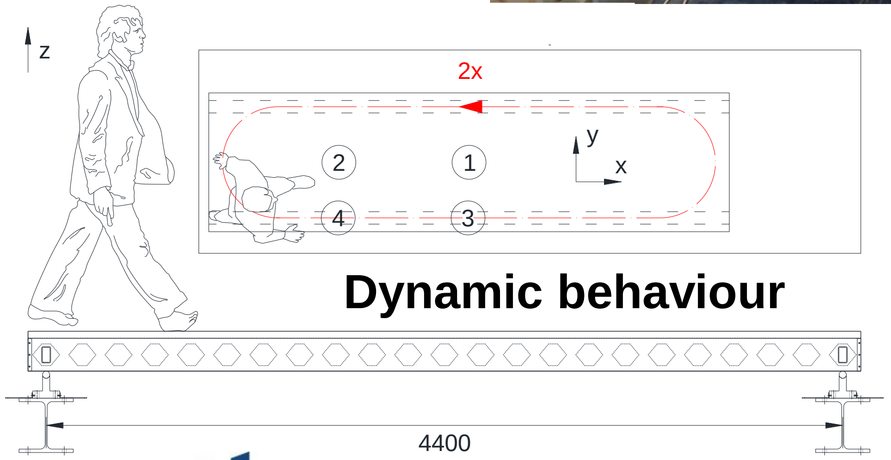
- Dead weight: **210kg/m²**;
- Content of FRC: **0.08m³/m²**;
- Content of steel in the form of cold formed steel profiles: **18.21 kg/m²**;
- At the maximum load, when the test was interrupted, the prototype was supporting an equivalent load of **44kN/m²** with a ductile flexural failure mode.
- Linear phase, followed by an elasto-cracked stage of relatively high amplitude and small loss of stiffness up to the yield initiation of the longitudinal steel profiles, with subsequent hardening phase of very ductil behaviour.

2.3 - PRESLABTEC

Tests with prototypes of real scale

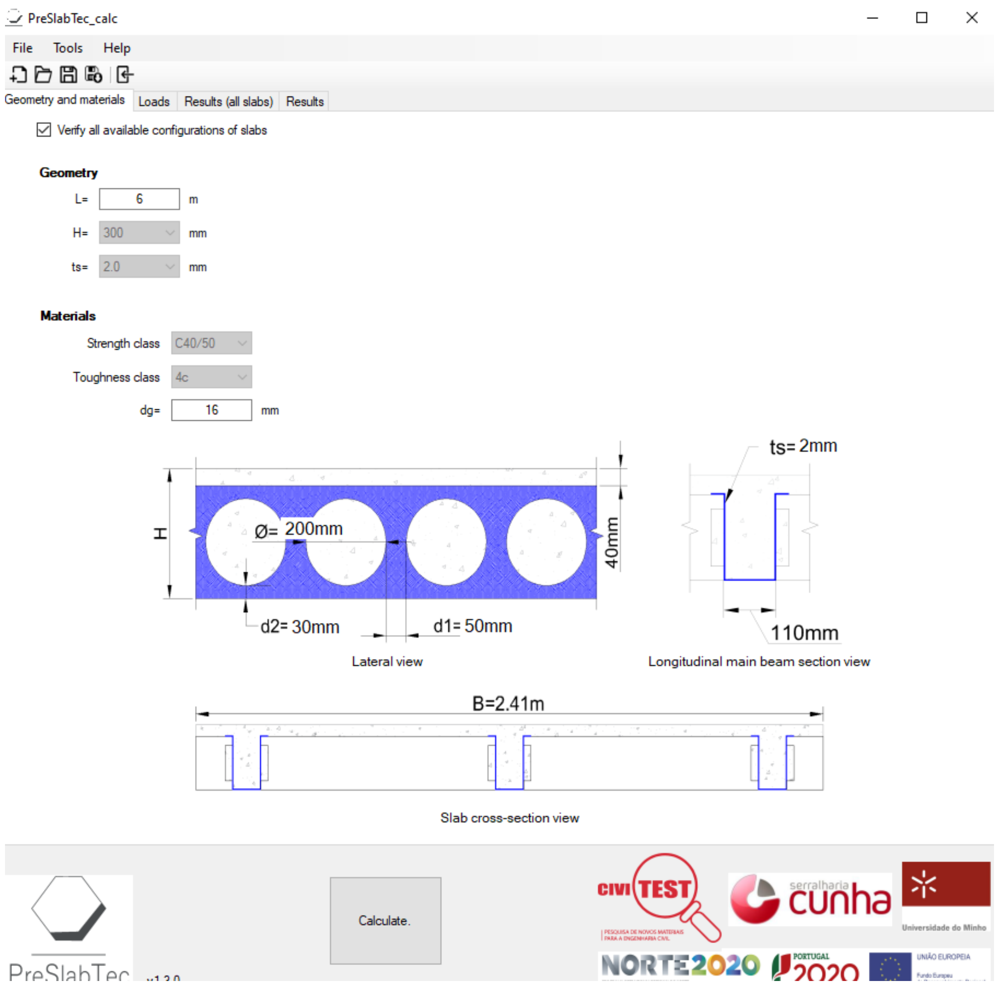






2.3 - PRESLABTEC

PreSlabTec_calc



PreSlabTec_calc

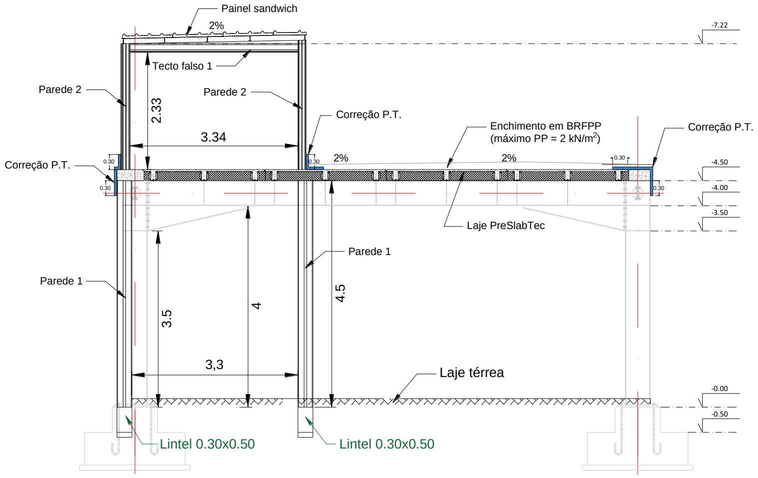
File Tools Help

Geometry and materials | Loads | Results (all slabs) | Results

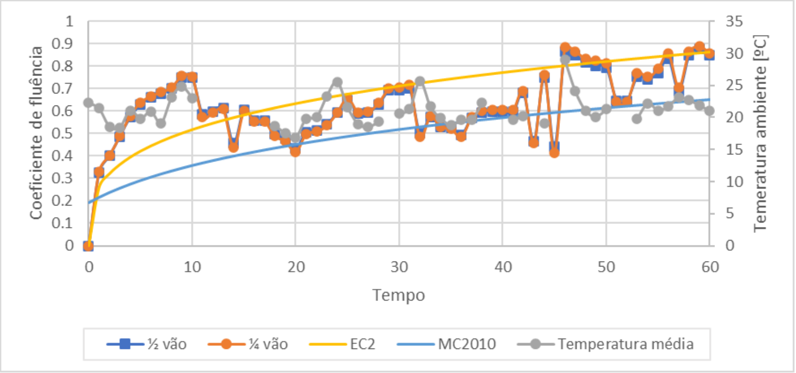
Height [mm]	ts [mm]	Strength class	Toughness class	Maximum instantaneous deflection (SLS) [mm]	Check deflection (SLS)	Check concrete compressive stress (SLS)	Check steel tensile stress (SLS)	Check bending (ULS)	Check shear (ULS)	Deta result
220	1.5	C40/50	4c	9.95	✓	✓	✓	✗	⚠	v res
220	1.5	C40/50	5b	8.95	✓	✓	✗	✗	⚠	v res
220	1.5	C40/50	6a	8.83	✓	✓	✗	✗	⚠	v res
220	2	C40/50	4c	8.78	✓	✓	✗	✗	⚠	v res
220	2	C40/50	5b	8.15	✓	✓	✓	✗	⚠	v res
220	2	C40/50	6a	8.07	✓	✓	✓	✗	⚠	v res
220	3	C40/50	4c	7.48	✓	✓	✓	✓	✓	v res
220	3	C40/50	5b	7.19	✓	✓	✓	✓	✓	v res
220	3	C40/50	6a	7.16	✓	✓	✓	✓	✓	v res
260	1.5	C40/50	4c	5.52	✓	✓	✗	✗	⚠	v res
260	1.5	C40/50	5b	5.15	✓	✓	✓	✗	⚠	v res
260	1.5	C40/50	6a	5.11	✓	✓	✓	✗	⚠	v res
260	2	C40/50	4c	5.07	✓	✓	✓	✗	⚠	v res
260	2	C40/50	5b	4.86	✓	✓	✓	✗	⚠	v res
260	2	C40/50	6a	4.84	✓	✓	✓	✗	⚠	v res
260	3	C40/50	4c	4.55	✓	✓	✓	✓	✓	v res
260	3	C40/50	5b	4.47	✓	✓	✓	✓	✓	v res
260	3	C40/50	6a	4.46	✓	✓	✓	✓	✓	v res
300	1.5	C40/50	4c	3.45	✓	✓	✓	✗	⚠	v res
300	1.5	C40/50	5b	3.36	✓	✓	✓	✗	⚠	v res
300	1.5	C40/50	6a	3.35	✓	✓	✓	✗	⚠	v res
300	2	C40/50	4c	3.28	✓	✓	✓	✓	✓	v res
300	2	C40/50	5b	3.25	✓	✓	✓	✓	✓	v res
300	2	C40/50	6a	3.25	✓	✓	✓	✓	✓	v res
300	3	C40/50	4c	3.06	✓	✓	✓	✓	✓	v res
300	3	C40/50	5b	3.05	✓	✓	✓	✓	✓	v res
300	3	C40/50	6a	3.05	✓	✓	✓	✓	✓	v res

2.3 - PRESLABTEC

Pilot unit



A prototype of 12m span length is being tested according to the Eurocode 1 load conditions for long term deflection assessment.



3 – MODELLING AND DESIGN

3.1 – Main models for the simulation and design of FRC structures

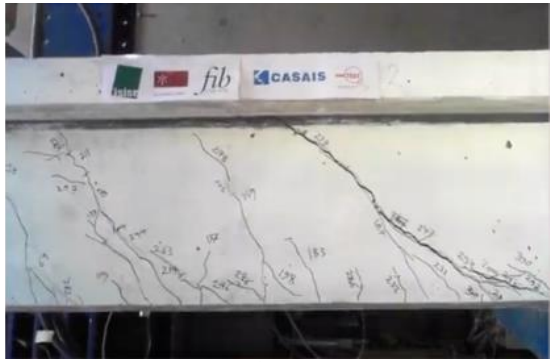
- Smeared Crack Models (SCM)
- Discrete Crack Models (DCM)
- Concrete Damage Plasticity (CDP)
- Lattice Discrete Particle Models (LDPM)
- Others: based on moment-rotation, partition-of-unity, rigid-body-spring, and three-phase approaches

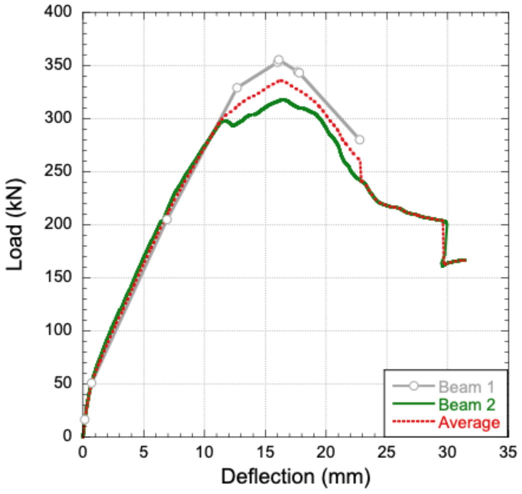
For design, the most used are SCM and CDP.

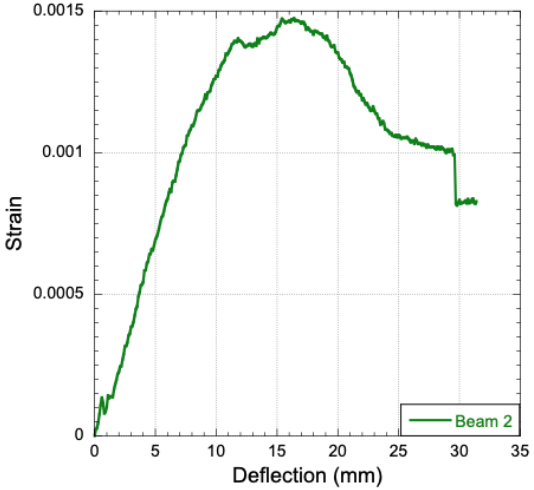
3.2 – 1st BLIND SIMULATION COMPETITION (BSC)

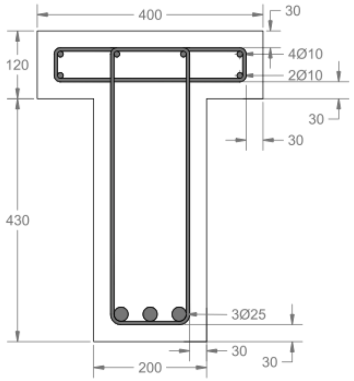
Organized by the *fib* WP 2.4.1
Modelling of Fibre Reinforced Concrete Structures

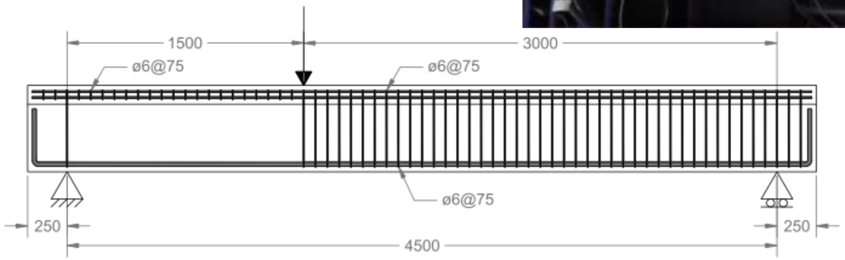
doi.org/10.1002/suco.202000345

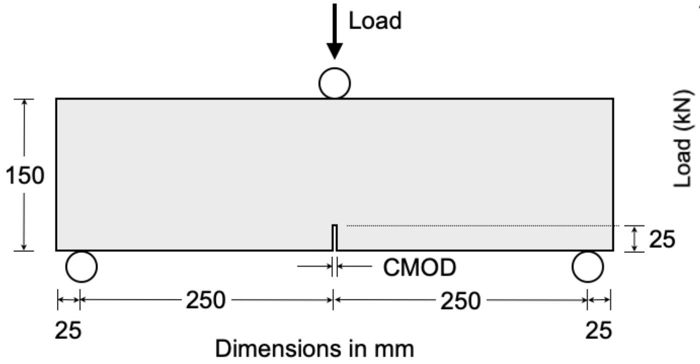


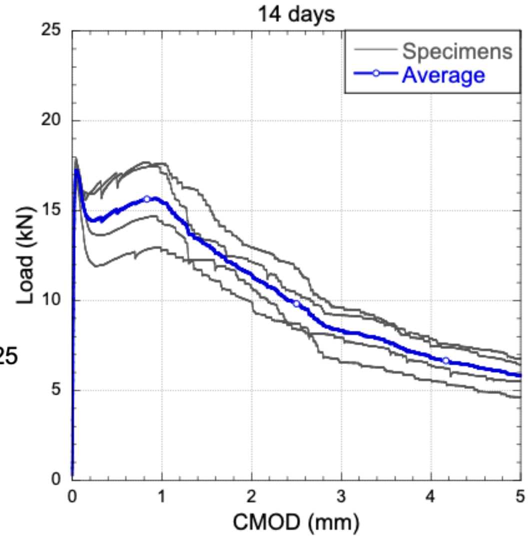


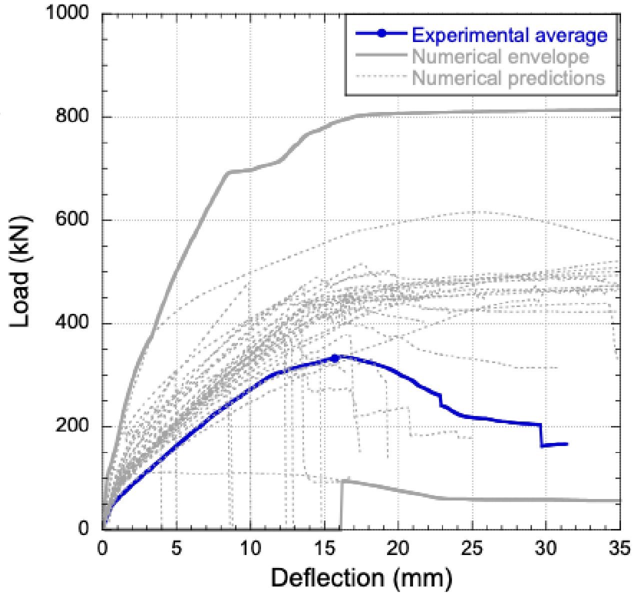


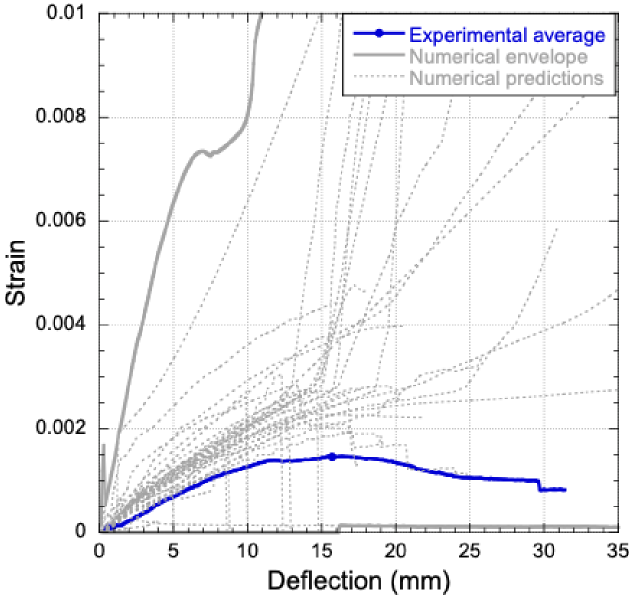






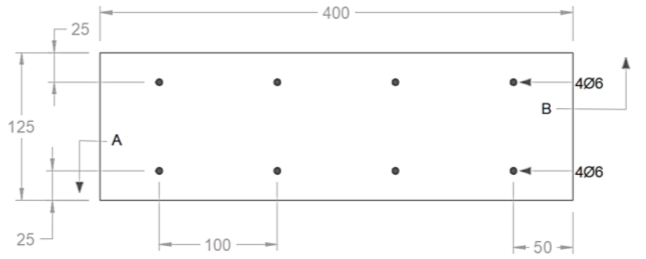


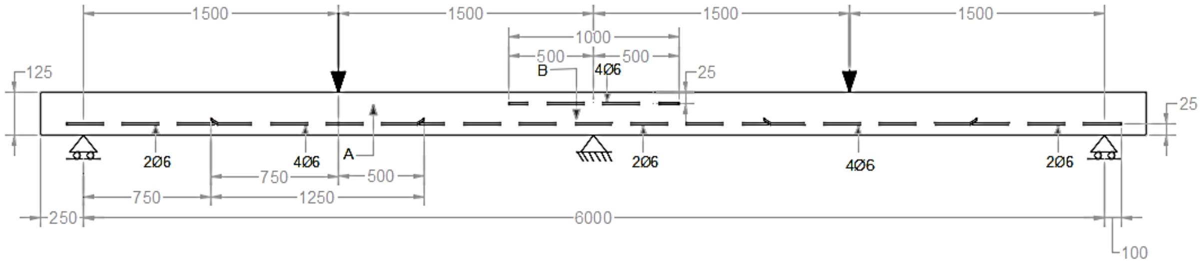


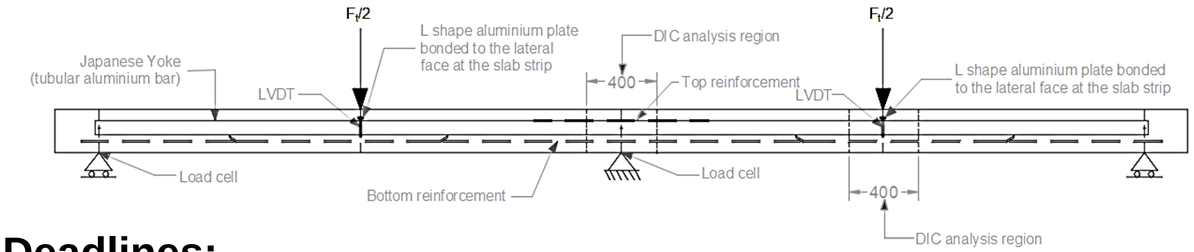


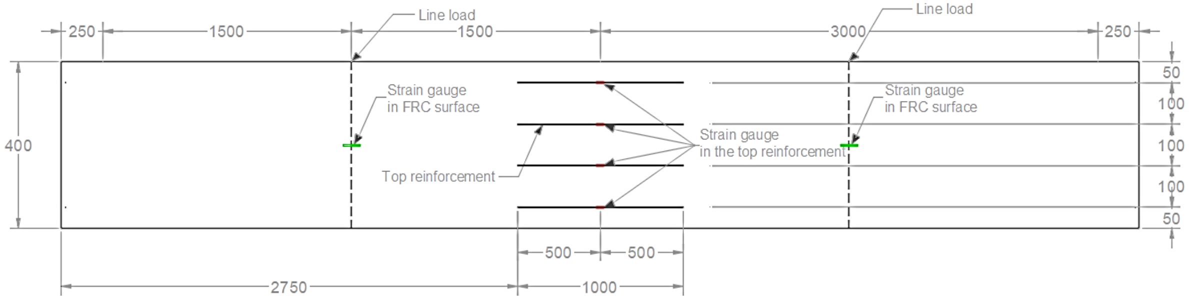
Despite the provided experimental data for the definition of the relevant models' parameters, inaccuracies on the load capacity, deflection and strain at peak load have attained 40%, 113% and 600%, respectively

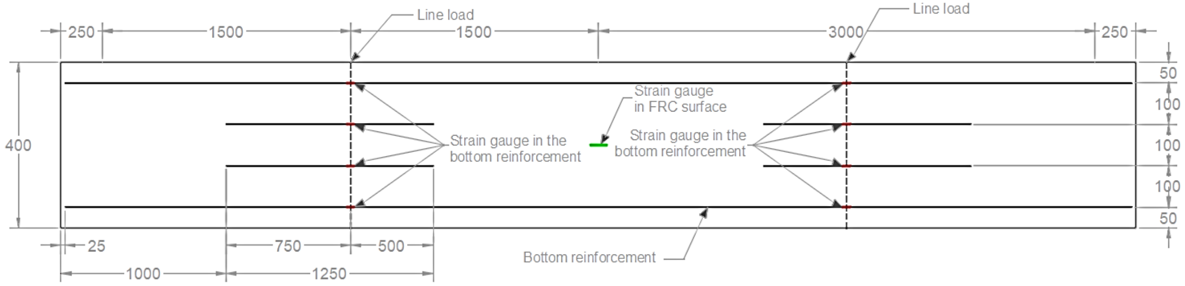
3.2 – 2nd BLIND SIMULATION COMPETITION (BSC)











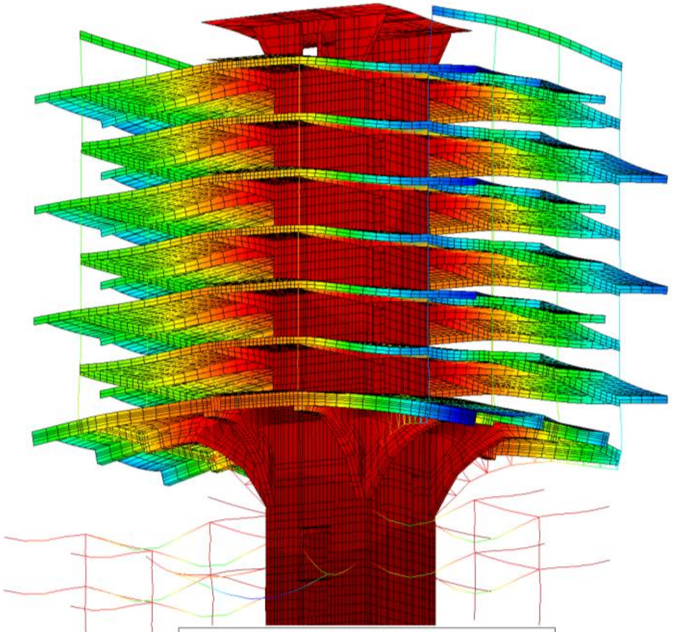
Deadlines:

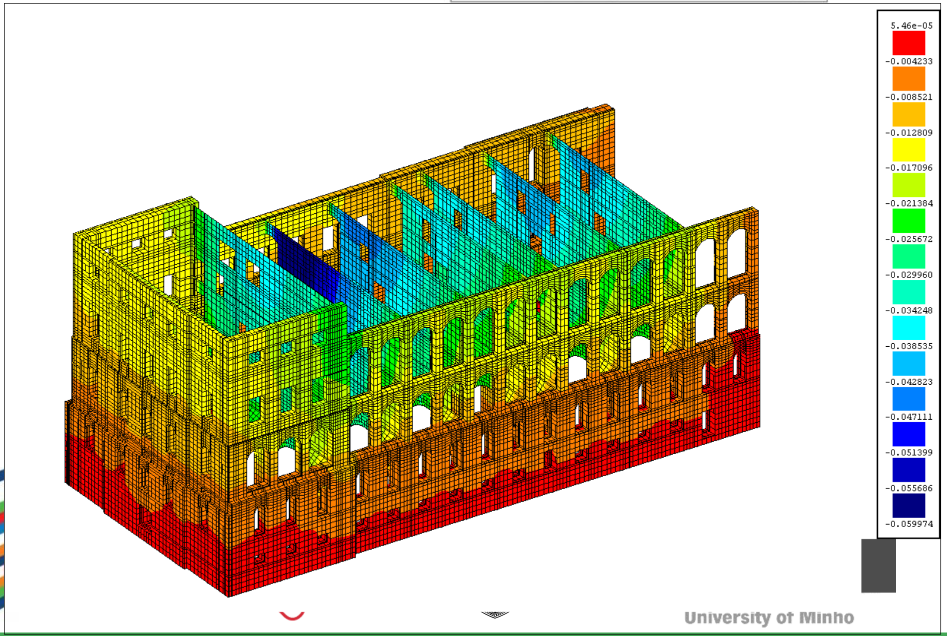
1) Information about the material properties will be provided up to 15/11/2021.
2) Participant must submit their report up to 23h:59 of 31/12/2021 (Spain time).
3) Experiments will be conducted on the 10 and 14 January 2022.
4) Conclusions about processing of results will be communicated by the end of February 2022.

3.3 – Design applications

This design is being made by **FEMIX** software, written in C and C++ code

- Includes a large **library** of types of **finite elements** (FE);
- Set of point, line and surface **(non-)linear springs** to model diverse contact conditions with the supports;
- Several types of **interface FEs** to model inter-element contact;
- **Embedded line FE** to model reinforcement bars;
- **Special embedded FE** for simulating fibers in FRCC context;
- **Static** and **dynamic** analysis, with material **linear** or **nonlinear** behavior;

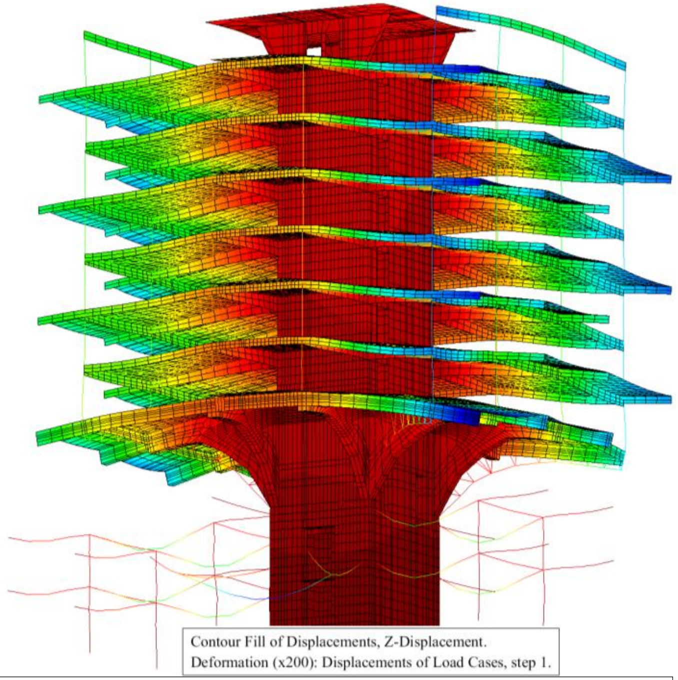

Contour Fill of Displacements, Z-Displacement.
Deformation (x200): Displacements of Load Cases, step 1.

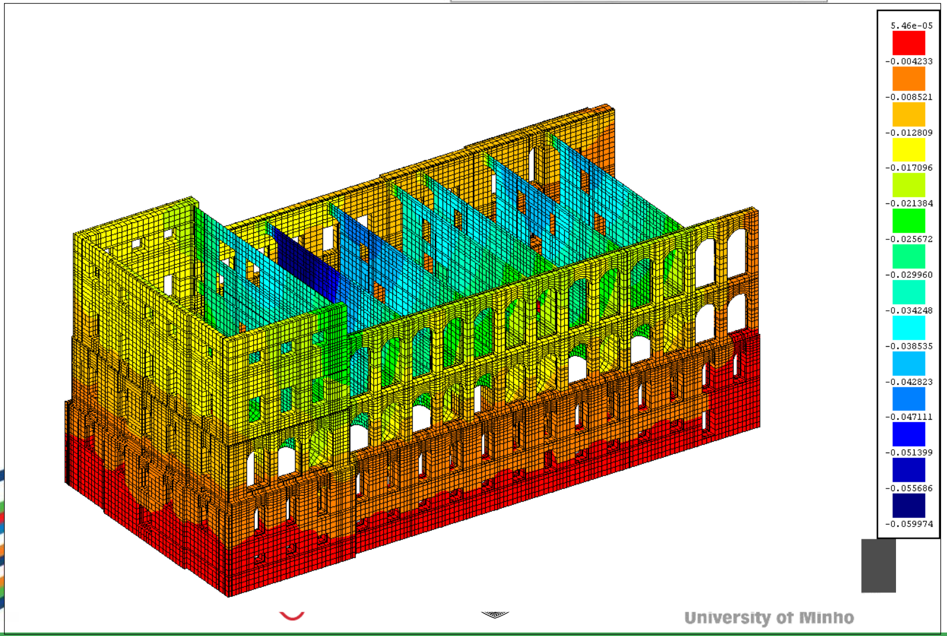


3.3 – Design applications

This design is being made by **FEMIX** software, written in C and C++ code

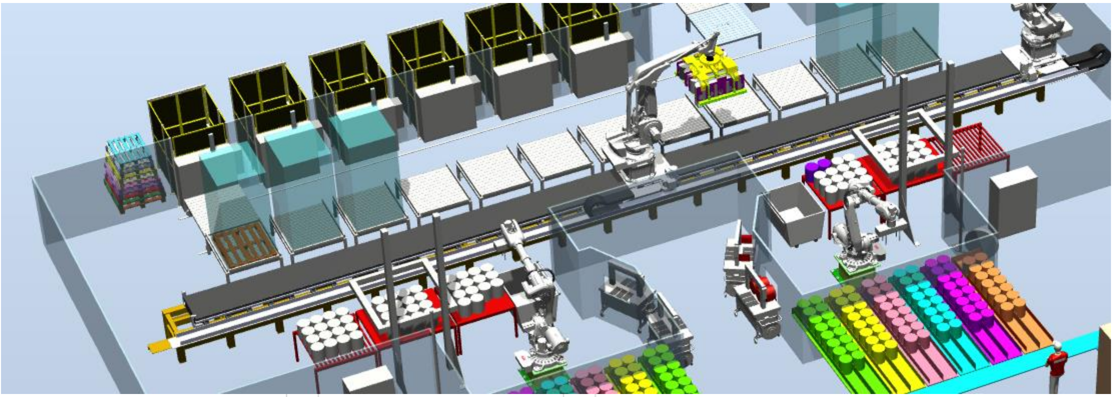
- In the **same analysis several nonlinear models** may be simultaneously considered;
- **Time dependent phenomena** like concrete maturation including creep and shrinkage;
- Newton-Raphson method, arc-length techniques and path dependent or independent algorithms;
- Direct and preconditioned conjugate gradient methods;
- Pre- and Post-processing by using **GiD**.

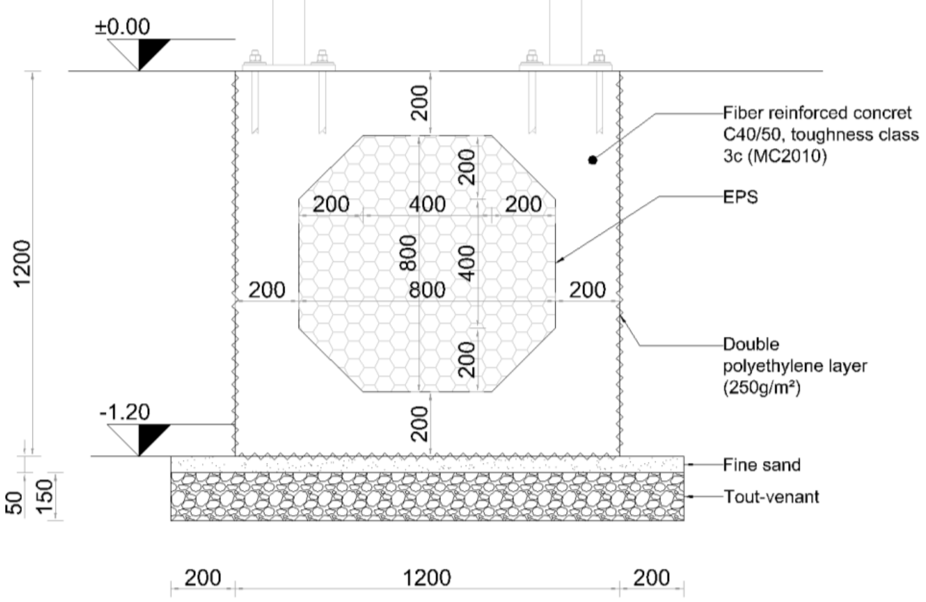




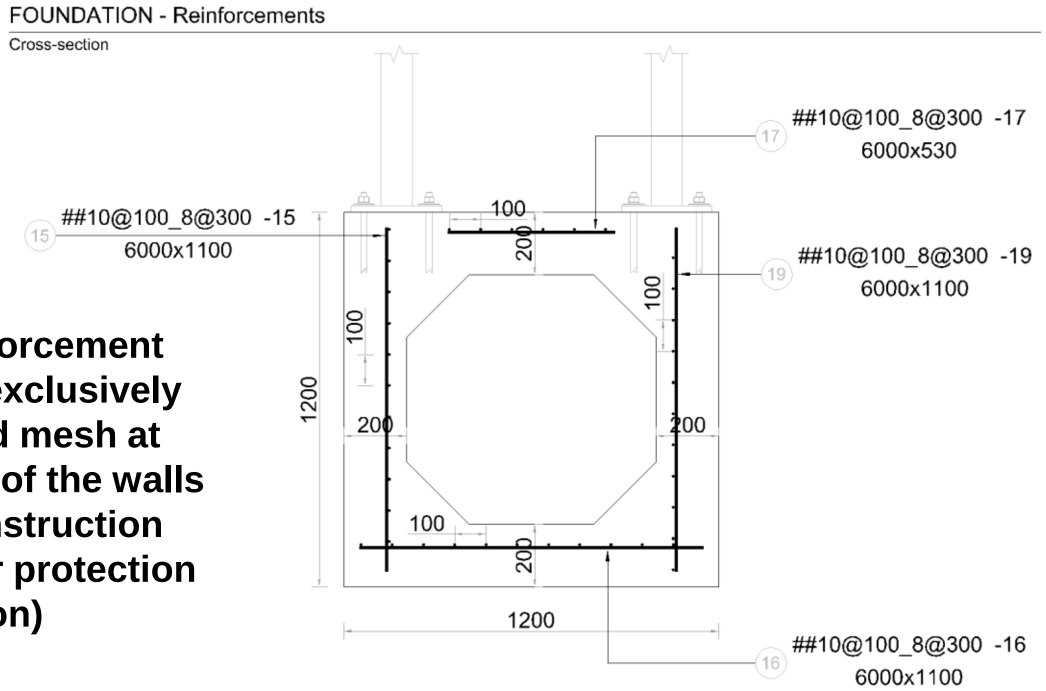
3.3 – Design applications

Integrating hybrid reinforced concrete technology and advanced fEM-based numerical modelling for crack control in long concrete foundations without joints.





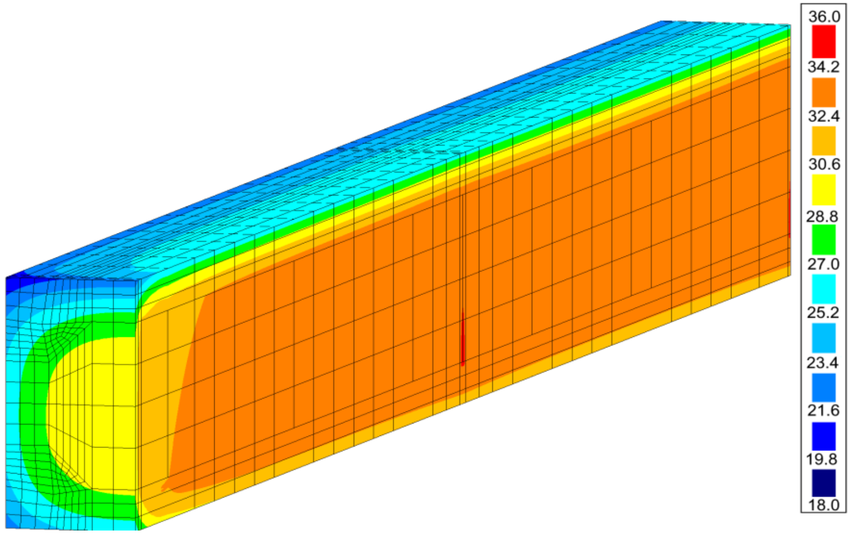
Fiber reinforcement for using exclusively a steel grid mesh at mid depth of the walls (faster construction and higher protection to corrosion)



(dimensions in mm)

3.3 – Design applications

Thermo-mechanical model that considers the FRC maturation, creep, shrinkage and cracking



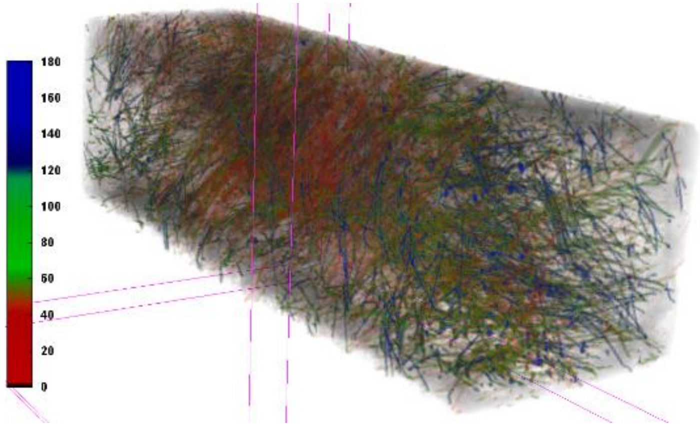
FRC design; testing and quality control; monitoring and structural design by Civitest:

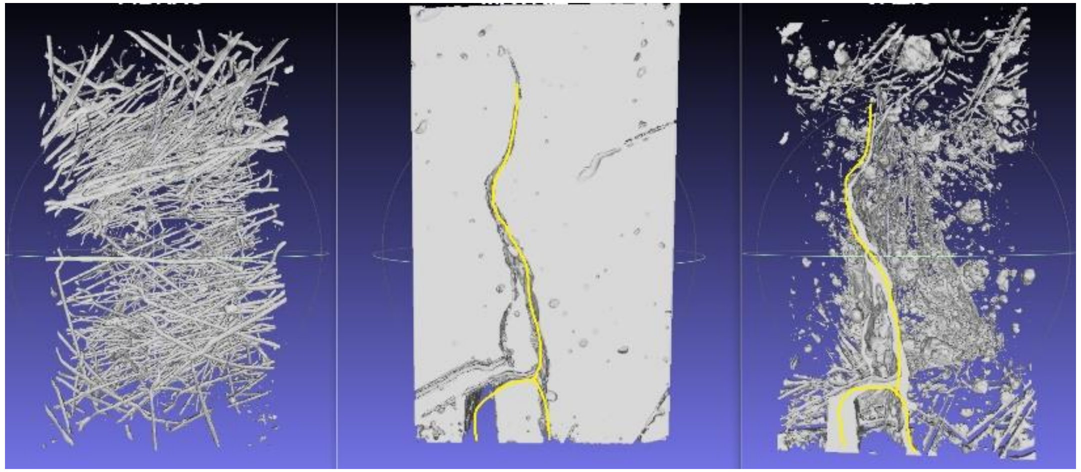
https://www.civitest.pt/en/services/

3.4 – *Design challenges and opportunities*

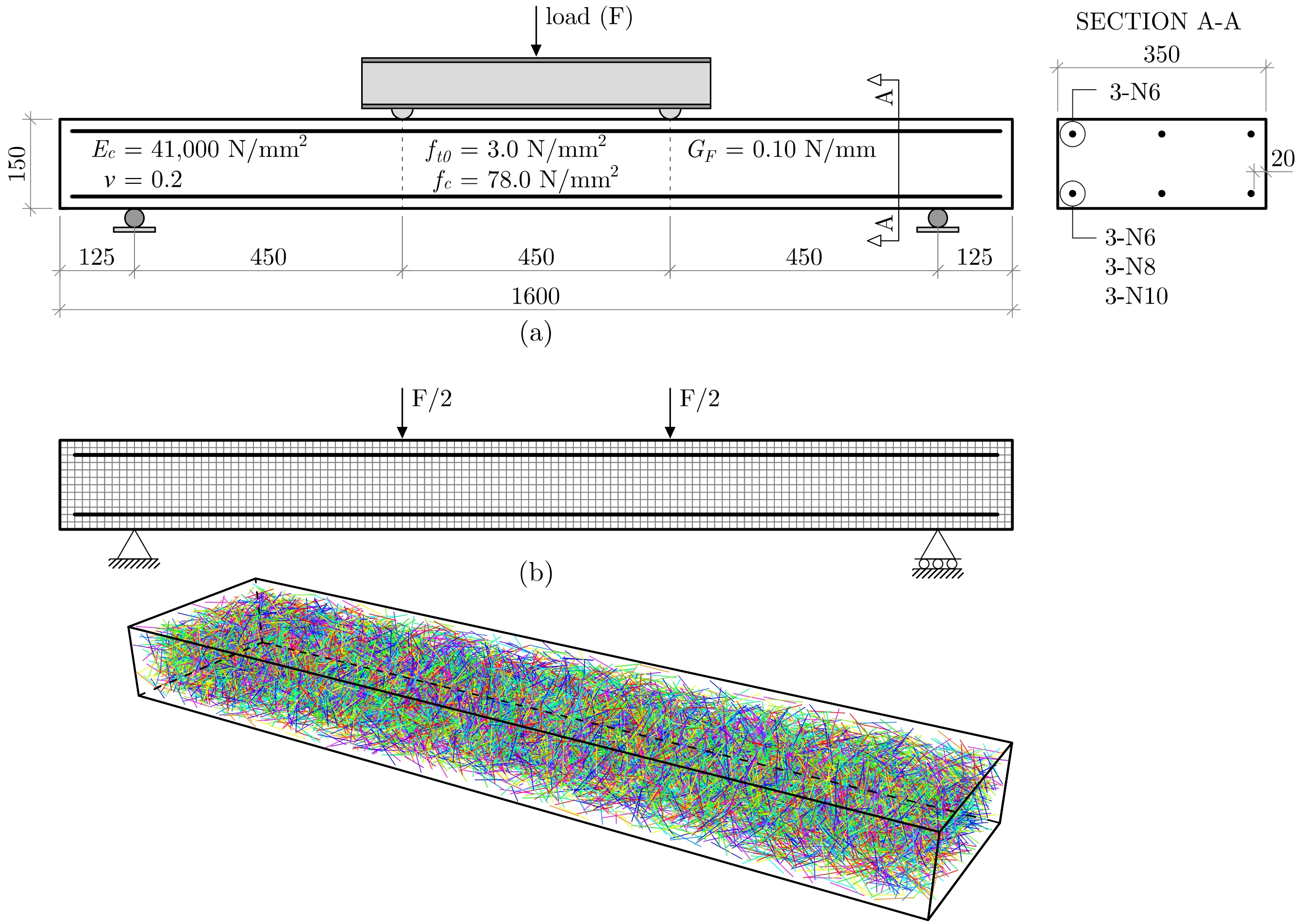
- ✓ Web-based information platform that includes a database ecosystem with artificial intelligence (AI) techniques for collecting the results of BSC and reliable experimental results of the scientific community in a continuous and dynamic feeding;
- ✓ Parametric studies and sensitivity analysis should be carried out for assessing the influence of the models' parameters on their predictive performance;
- ✓ Reliable methodologies for FEM-based design of FRC structures should be developed by modelling explicitly the fibres and the cracks and using an holistic vision of their structural behaviour and AI techniques

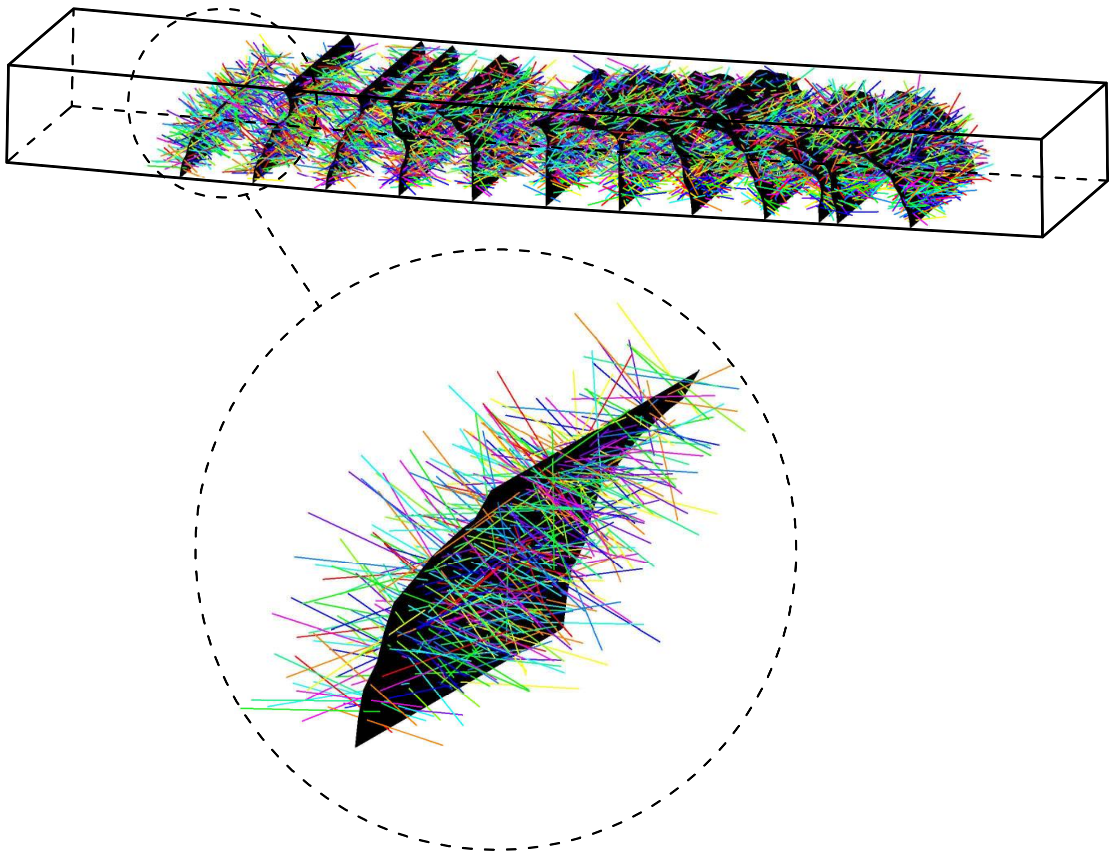
Database with information from assessing FOD, such is the case of computed tomography scanning (CTS):

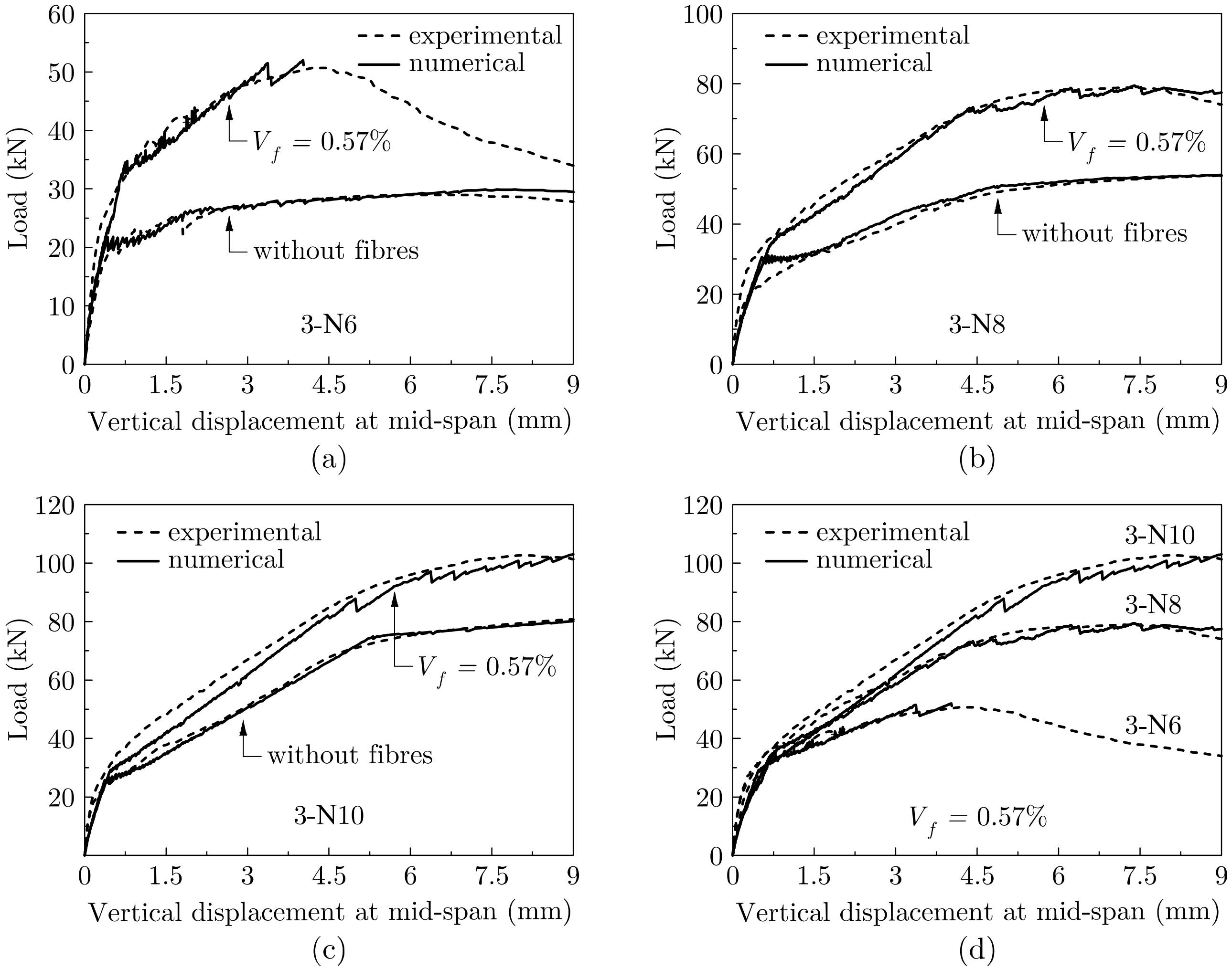




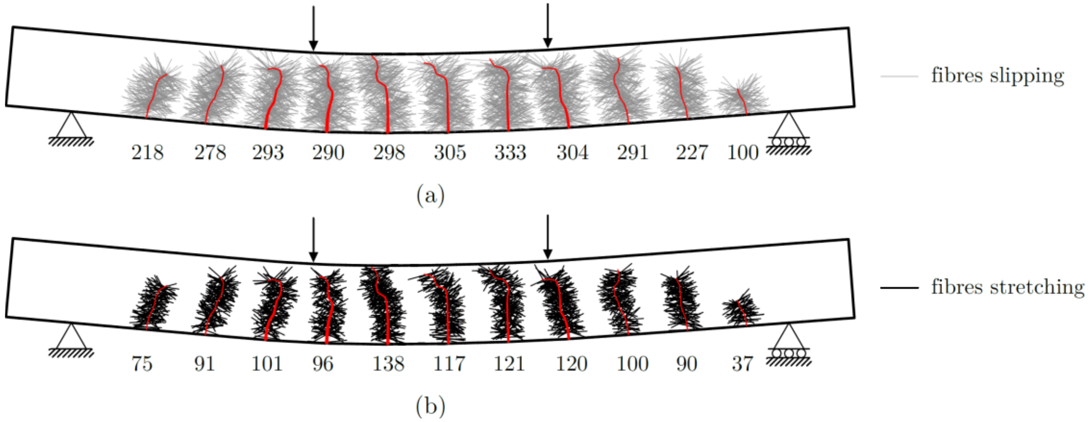
The Embedded Strong Discontinuities (ESD) approach, a class of DCM, with explicit representation of fibers and cracks have a very high potential for reliable simulations, as is being demonstrated:







(a) (b) (c) (d)

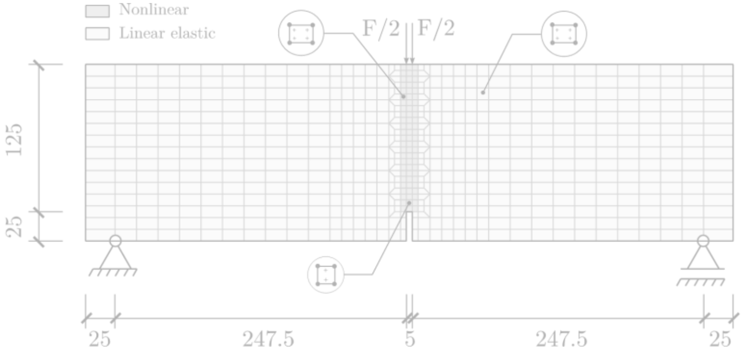


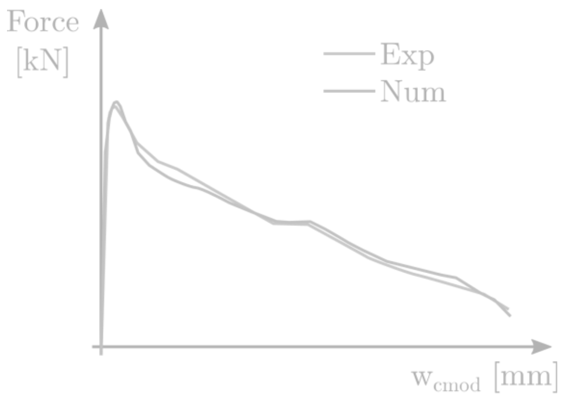
(a) (b)

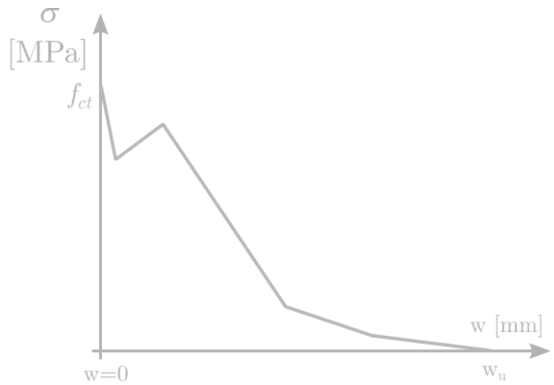
doi.org/10.1016/j.cma.2020.112879

COFIT: Motivation

- Chacterise the tensile behaviour of FRC (σ-*w* relationwship)
- Determine the necessary fracture parameters to simulate, analyse and design FRC structures







Develop a practical, efficient and automatised tool capable of determining these properties in a optimised way

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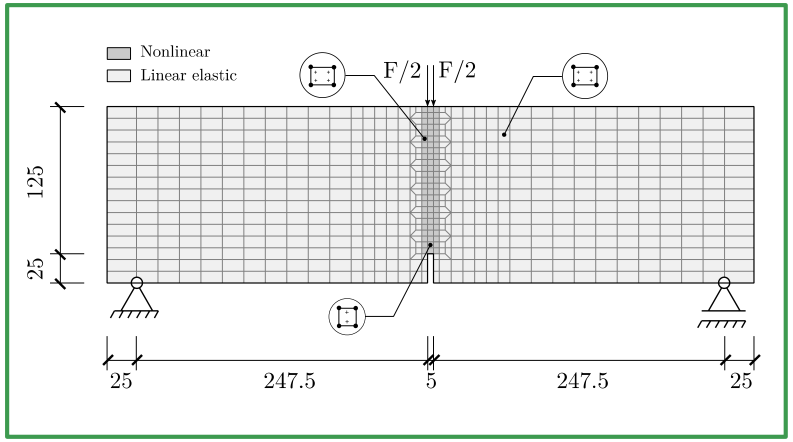
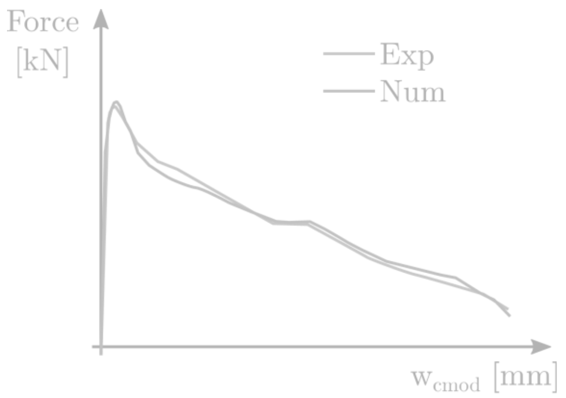
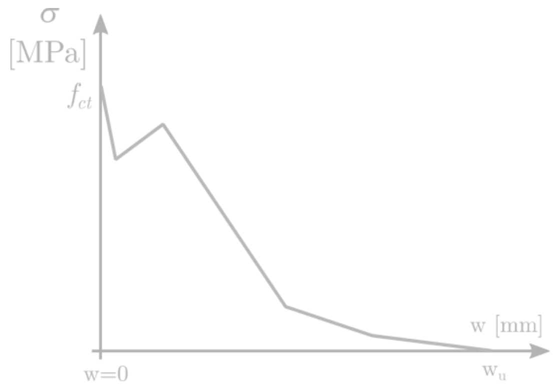
FEM model







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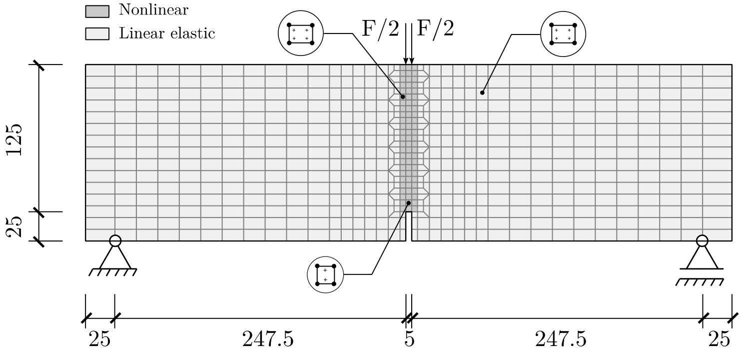
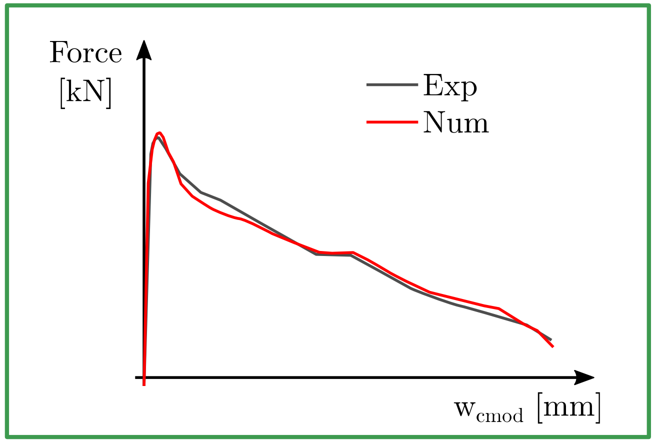
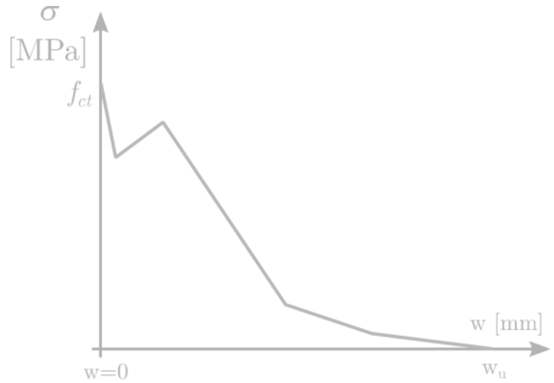


Check response





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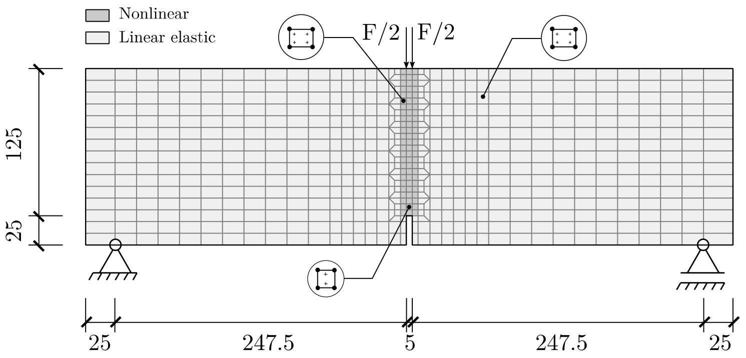
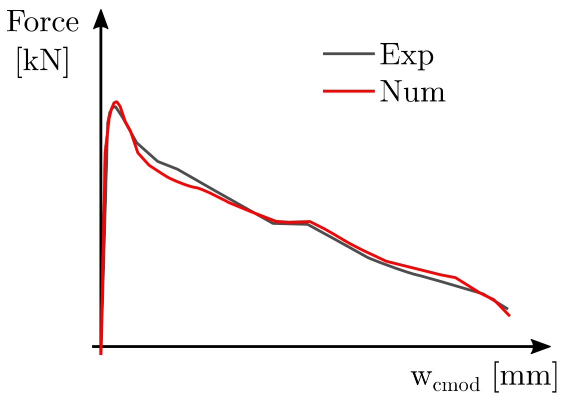
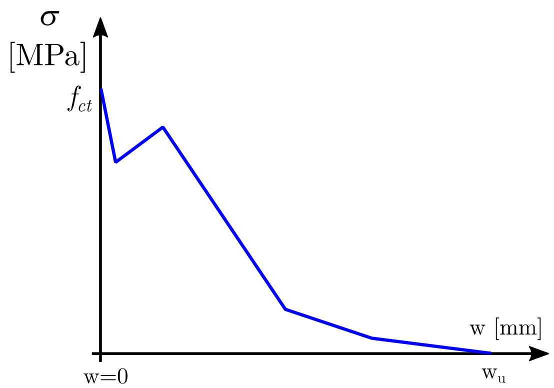




Modify parameters



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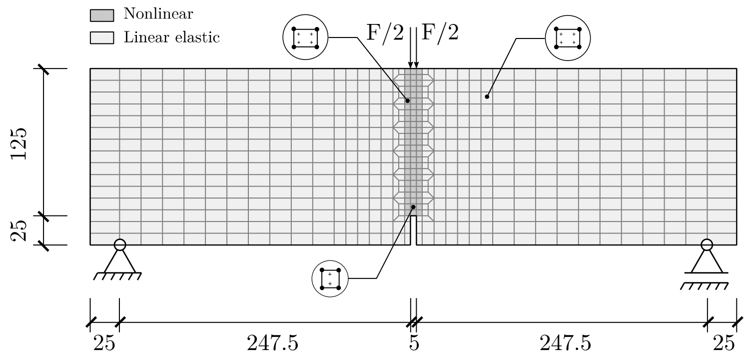
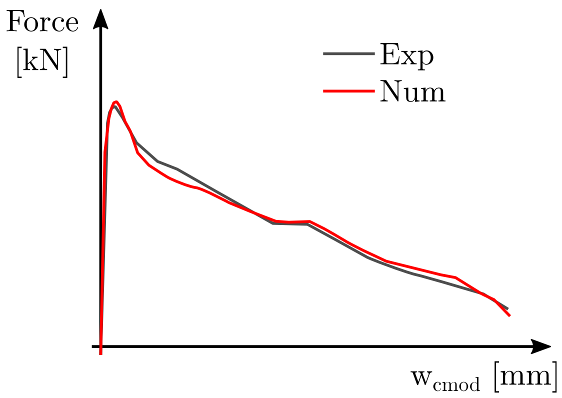
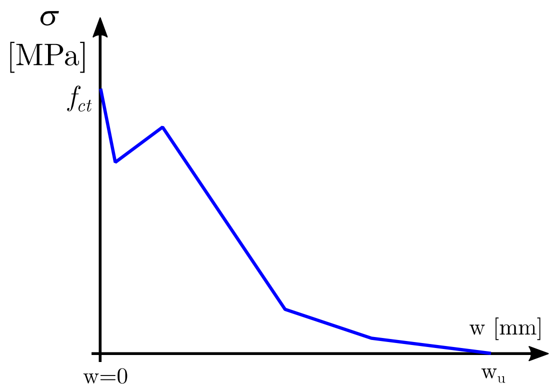






Develop a practical, efficient and automatised tool capable of determining these properties in a optimised way

COFIT: Main features

doi.org/10.1016/j.engfracmech.2021.107613

2 problem types

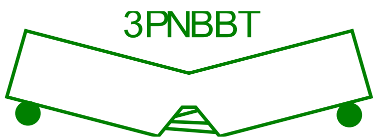
Include/exclude *fct* and/or *Ec* from the IA procedure

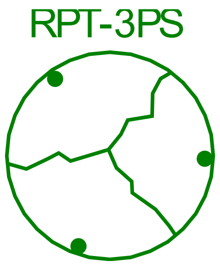
Possible implementation of additional models due to **modular architecture**

fx Numerical response based on **analytical models** reducing computational time

COFIT: Main features

2 problem types





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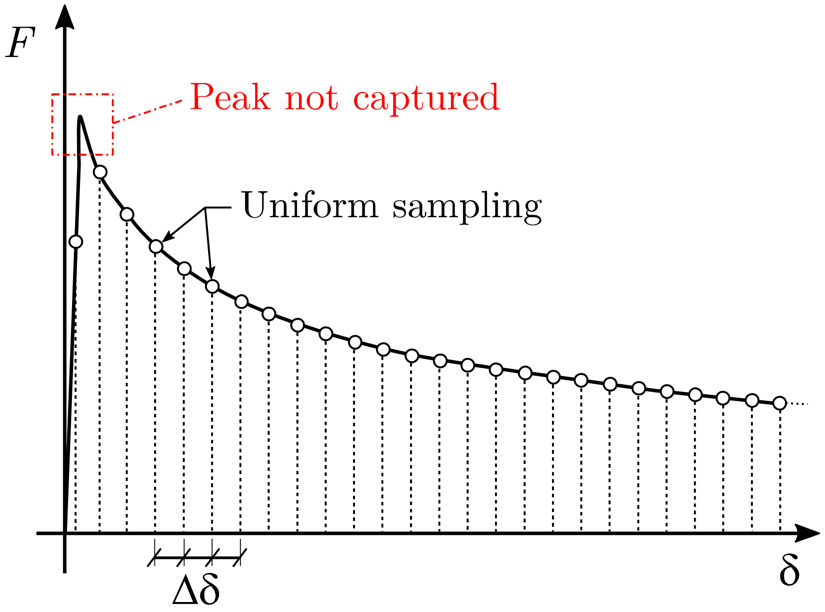
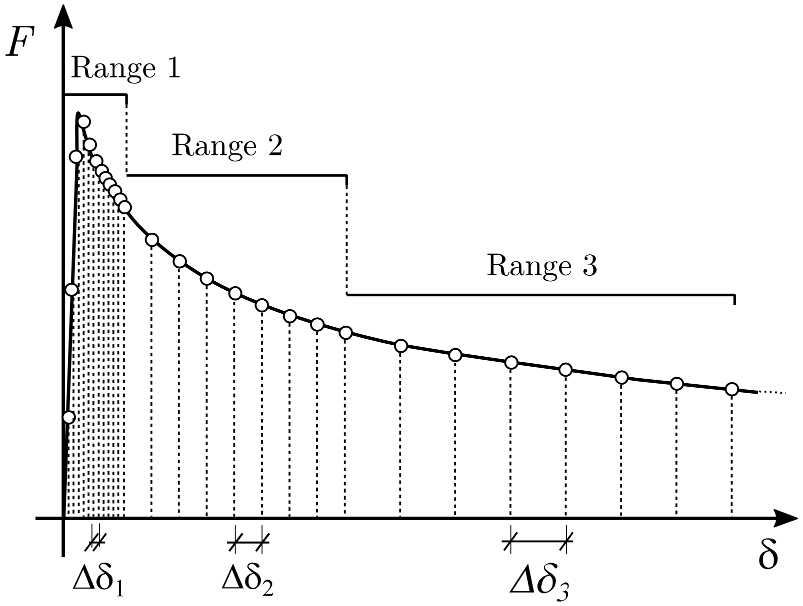
COFIT: Main features

Custom discretisation of the experimental curve



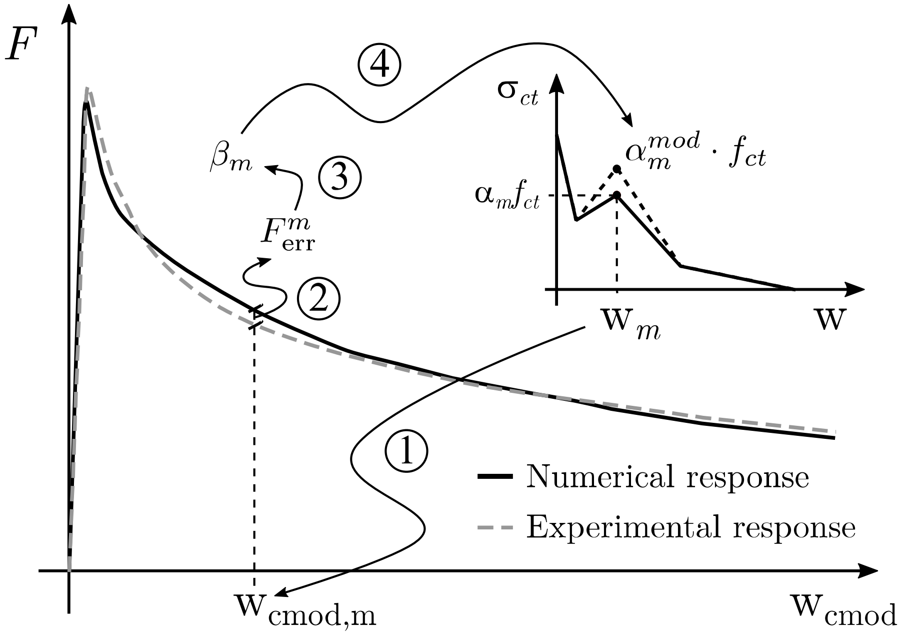
Uniform sampling approach



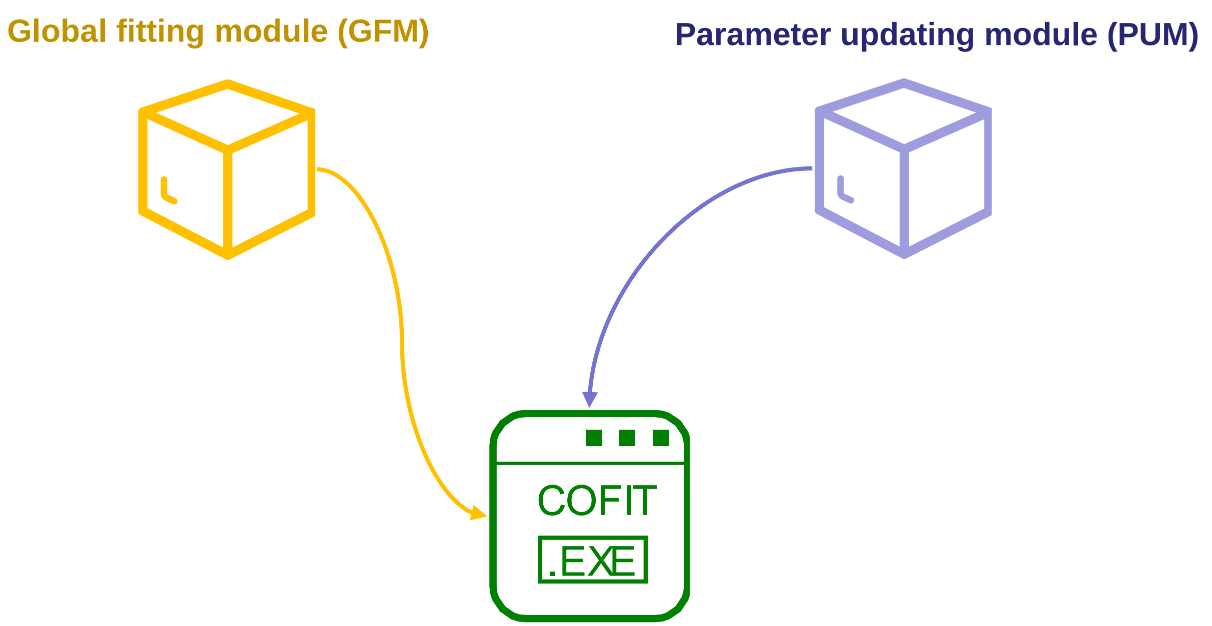
Custom method with specification of different sampling in different regions of the response

COFIT: Main features

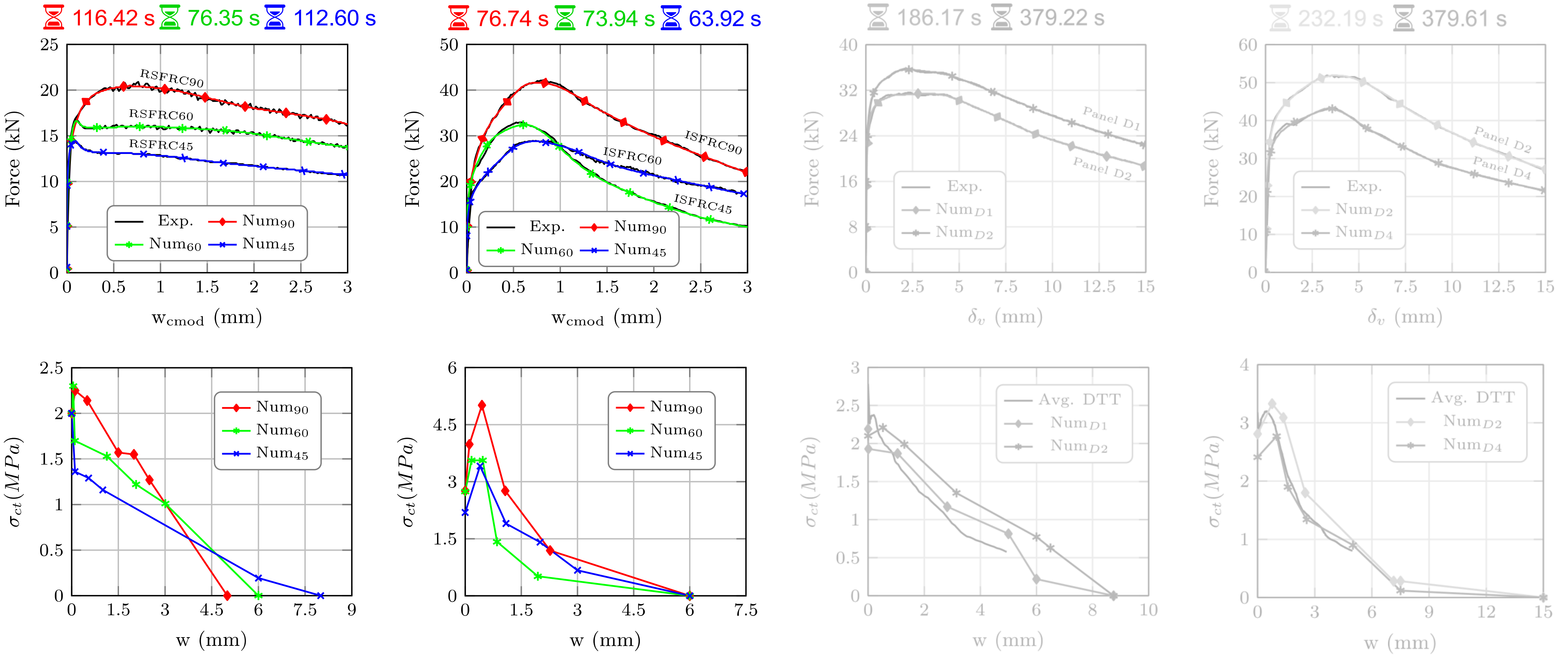
Automatic variable updating based on numerical-experimental error



- ## COFIT: Theoretical aspects – underlying algorithms



COFIT: Performance assessment



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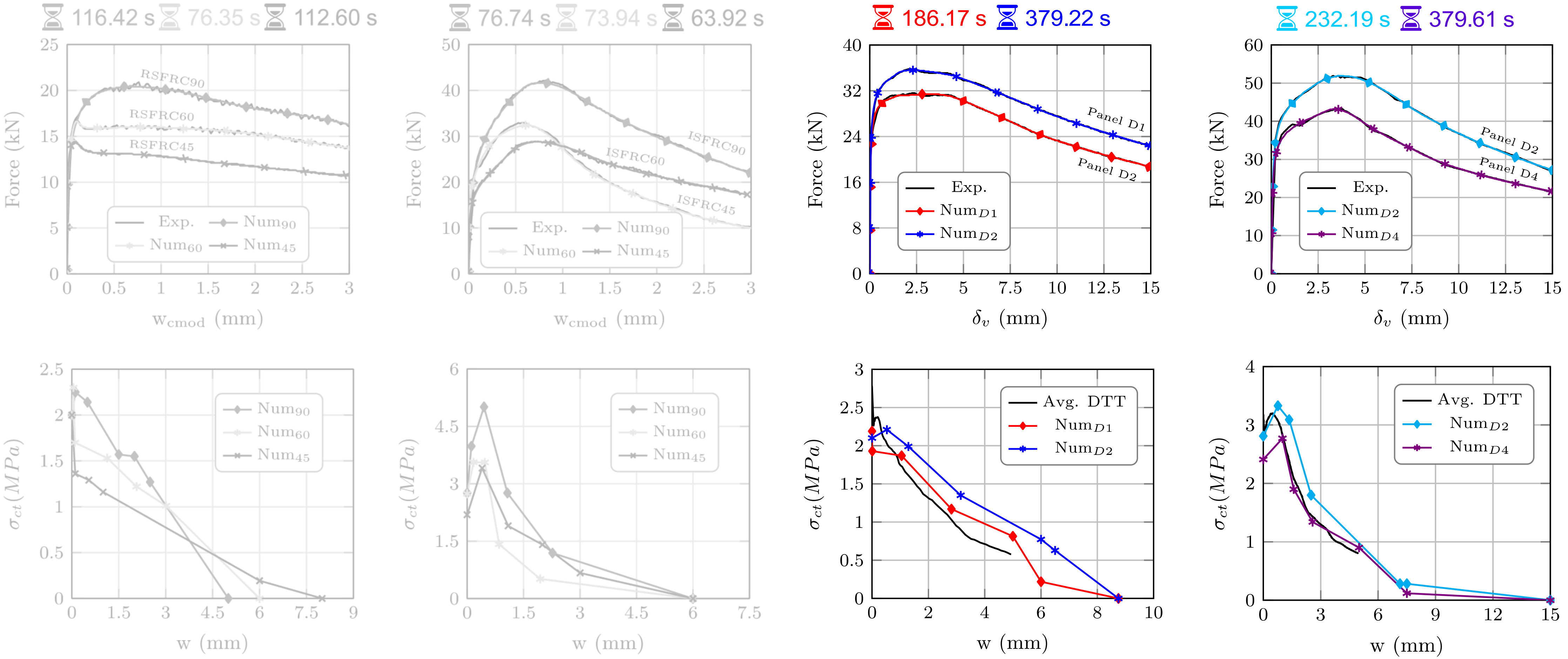

4 - CONCLUSIONS

Challenges and opportunities :

- AI techniques on the FRC mix design that consider the production characteristics and the structural, durability, functional and LCA requirements;
- Advanced data base for assisting on the design and use of local resources, promoting circular economy.
- Pre-fabrication based on robotics for producing with high quality control and according to advanced design tools in order to minimize natural resources, time, costs and accidents;
- Modular construction with assembling, disassembling and reuse potentialities;
- Safe connections systems for efficient assembling and disassembling of constructive elements of modular constructions;
- Building Information Modeling (BIM) Integration;
- Reliable design tools that consider the behavior of FRC from casting to SLS and ULS conditions;
- Incorporation of self-powered sensors during the prefabrication process for increasing the functional performance of the built environment, maintenance plans, and to provide well-timed information to minimize the devastating effects of extreme events;

ACKNOWLEDGEMENTS

The author acknowledges:

- **The support provided by the FCT through the project FemWebAI - Integrated approach for reliable and advanced analysis and design of sustainable construction systems in fiber reinforced concrete, with reference PTDC/ECI-EST/6300/2020;**
- **The CiviTest company by the shared information regarding the design examples;**
- **The collaboration of the fib WG2.4.1 in the BSC.**