FRPlongDur

POCI-01-0145-FEDER-016900 (PTDC/ECM-EST/1282/2014)

Seminário de Conclusão do Projeto FRPLongDur

(E-BOOK DAS APRESENTAÇÕES)

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Preface

The FRPLongDur research project (reference no. POCI-01-0145-FEDER-016900) was financed by national funds through FCT and co-financed by the European Regional Development Fund (FEDER) through the Competitiveness and Internationalization Operational Program (POCI), and Lisbon Regional Operational Program.

This project had as participating institutions at the University of Minho and the National Civil Engineering Laboratory. It also had the participation of Empa - Swiss Federal Laboratories for Materials Science and Technology.

FRPLongDur aimed at contributing to the knowledge on the long-term behavior and durability of reinforced concrete elements strengthened with CFRP (Carbon Fiber Reinforced Polymers) laminates according to the EBR (Externally Bonded Reinforcement) and NSM (Near Surface Mounted) reinforcement techniques, under the effect of aging in a real environments. The work involved: (i) an extended experimental program, with the creation of five experimental stations distributed throughout Portugal country, involving different environments (Elvas, Guimarães, Lisbon, Serra da Estrela and Viana do Castelo), where test specimens at three scales (material, connection and structure) were installed to evaluate its performance during the time; (ii) the development of numerical simulations, based on the results obtained in the monitoring carried out; and, (iii) making recommendations for the project.

On the last 30th of October 2020, the seminar to conclude the FRPLongDur project took place in a Webinar mode, in which the main results were presented. The present eBook summarizes the presentations carried out.

The organizing committee

José Sena Cruz | Luís Correia | Ricardo Cruz | Susana Cabral-Fonseca

Project FRPLongDur: Motivation, objectives, execution

José Sena Cruz

Seminário de Conclusão do Projeto FRPlongDur

(POCI-01-0145-FEDER-016900(PTDC/ECM-EST/1282/2014)

October 30th, 2020

José Sena Cruz

Universidade do Minho

Technical Data

Universidade do Minho

Empa Materials Science and Technology

Title:	**FRPLongDur –** Long-term structural and durability performances of reinforced concrete elements strengthened in flexure with CFRP laminates
Main Institution:	**UMinho**
Other patterns:	National Laboratory of Civil Engineering (**LNEC**) **Empa** - Swiss Federal Laboratories for Materials Science and Technology
Coordinator:	José Sena-Cruz
Team:	**J. Sena Cruz**, S. Cabral-Fonseca, J. Michels, P. Fernandes, J.R. Cruz, J. Gallelo Martin, M. Rezazadeh, L. Correia, C. Czaderski
Financing Institution:	FCT - Portuguese Foundation for Science and Technology
Reference:	PTDC/ECM-EST/1282/2014
Period:	June 2016 to October 2020
Budget:	199.983,00€ (127.579,00 to ISISE/UM)

Outline

- ❑ **Motivation**
- ❑ **Objectives**
- ❑ **General methodology**
- ❑ **Dissemination/Outputs**
- ❑ **Acknowledgments**

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Motivation

Universidade do Minho

Motivation > *Strengthening - Why?*

I. To eliminate structural problems or distresses which result from:

- **unusual loading or exposure conditions;**
- **inadequate design;**
- **or poor construction practices.**

Distresses may be caused by overloads, fire, flood, foundation settlement, DETERIORATION RESULTING FROM ABRASION, FATIGUE EFFECTS, CHEMICAL ATTACK, WEATHERING, INADEQUATE MAINTENANCE, etc.

II. To be conform to current codes and standards.

III. To allow the feasibility of changing the use of a structure to accommodate a different use from the present one.

Motivation > *Increased need of rehabilitation*

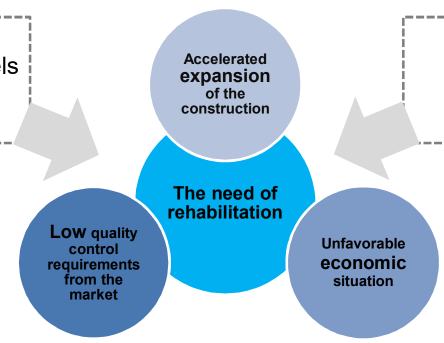
China, US and India
(57% of this investment)

Trends in the Construction Industry

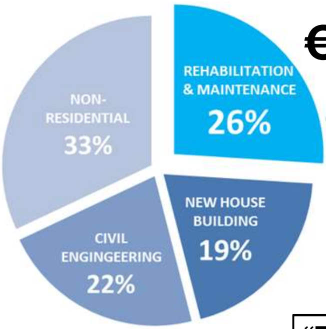
10.8B US$ (2017) — GLOBAL INVESTMENT → **17.5B** US$ (2030) (+62%)

Climatic changes:
Increase in atmospheric CO2 levels
Increase in the temperature
Increase water levels

New policies/actions:
Green deal
Circular economy
Low-carbon economy



Motivation > *Increased need of rehabilitation*



€305bn on rehabilitation and maintenance in 2012 (EU27) *(European Construction Industry Federation 2013)*

INE, CENSOS 2011

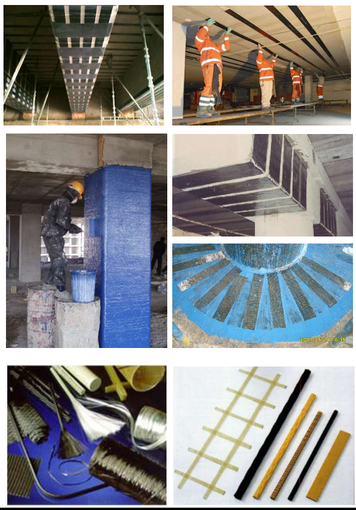
Estado de conservação dos edifícios

"The Federal Highway Administration (FHWA) estimates that to eliminate the US nation's bridge deficient backlog by 2028, we would need to invest **$20.5bn** annually, while only $12.8bn is being spent currently."
(ASCE Infrastructure Report Card 2013)

Motivation > *FRP systems as strengthening solutions*

Fiber Reinforced Polymer (FRP) materials

- The FRP's has been used in Civil Engineering applications due to:
  - Lightweight
  - Good mechanical properties (stiffness and strength)
  - Corrosion-resistant
  - Good fatigue behavior
  - Easy application
  - Virtually endless variety of shapes



Motivation > *Strengthening techniques*

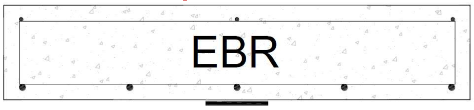
- The implementation of a **FRP-based structural strengthening system** requires the following main components:
  1. **FRP:** reinforcing material (**CFRP**)
  2. **ADHESIVE:** bonding agent of the reinforcing material (**Epoxy adhesive**)
  3. **SUPPORT:** RC element to be strengthened

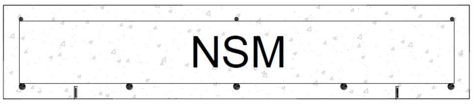
Motivation > *Strengthening techniques*

Courtesy of S&P Clever Reinforcement

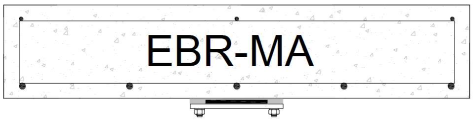
Motivation > *Strengthening techniques studied*

Passive techniques





Active techniques



Motivation > *S&P Prestressing Systems – Main Components*

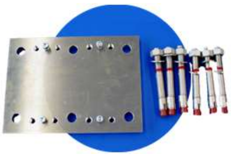
Clamp unit

Guides

Frame

Hydraulic cylinder

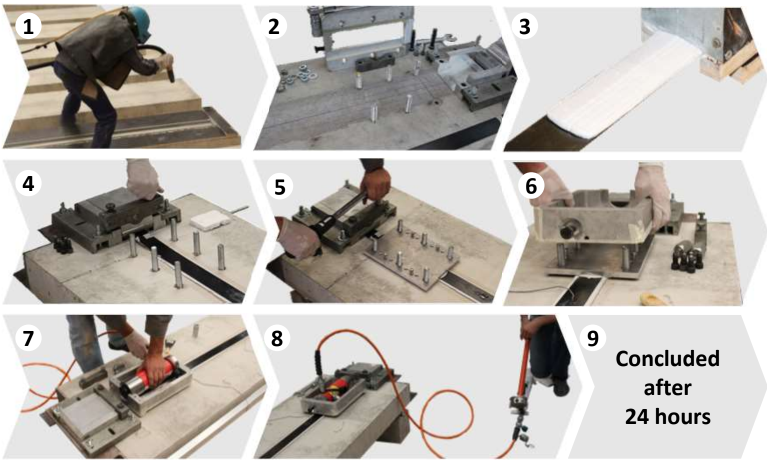
Steel plate anchors (MA)



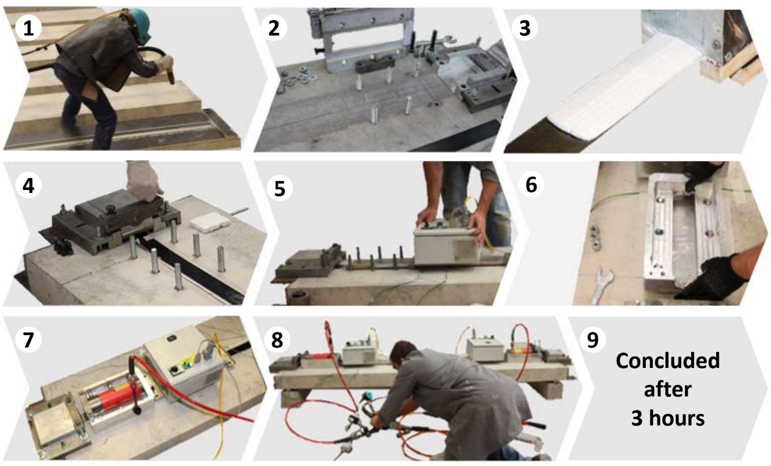
Heating device (GA)

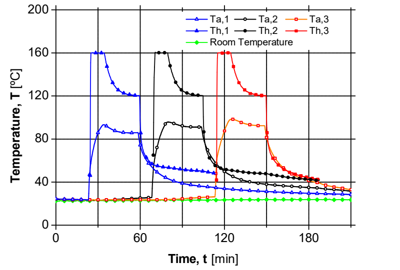
Hydraulic pump

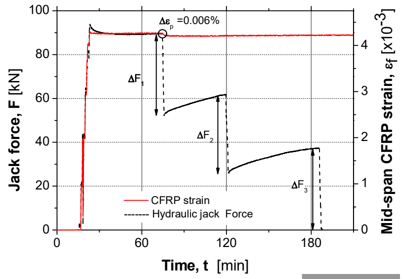
Motivation > *S&P Prestressing Systems – MA System*



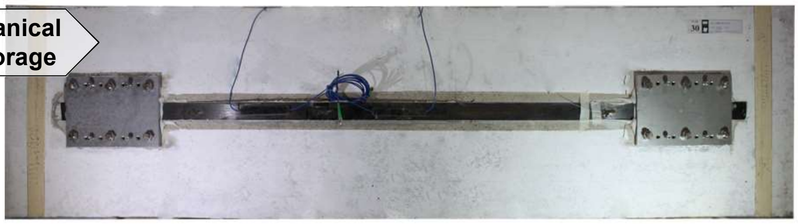
Motivation > *S&P Prestressing Systems – GA System*







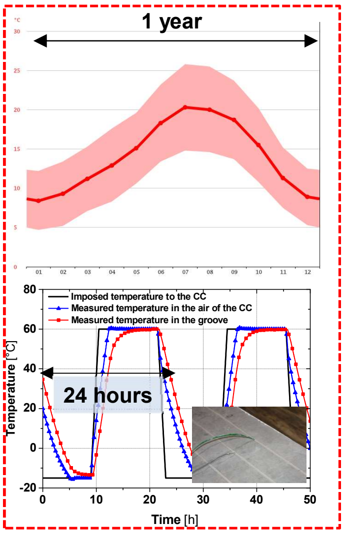
Motivation > *S&P Prestressing Systems – MA vs. GA System*



Motivation > *Knowledge on the durability related topics*

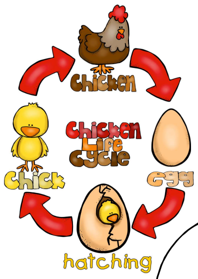
- Although **FRP composites have been successfully used** in the **automotive**, **marine**, **wind energy**, and **aerospace sectors**, there are critical differences where compared with **Civil Engineering applications** in terms of:
  - Loading conditions
  - Environmental conditions
  - Types of materials used
  - Processes
- A **huge variety** of different **constituent materials** are commercially available.
- In many situations, **there is an absence of standards** for the **characterization of the durability**.
- Difficulties in testing: **artificial accelerated** *versus* **real/natural aging**.

Motivation > *Artificial accelerated ageing tests vs. real outdoor ageing conditions*



Are we **pushing too much** our **accelerated ageing tests** at the **LAB**, that at the end they **are not representative** of the **real behaviour**?

Real chicken life cycle



Accelerated chicken life cycle

- **2 weeks at 48 °C ?**
- **1 week at 58 °C ?**
- **1 day at 68 °C ?**
- **1 hour at 78 °C ?**
- **10 minutes at 100 °C!!!**

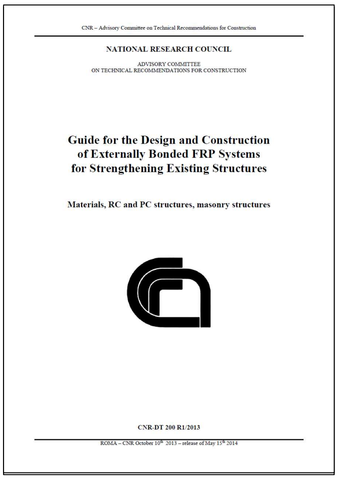
Motivation > *Knowledge on the durability related topics*

- **Degradation factors** are **all agents that act** on the material, component or structure and that may **cause alterations on its performance**. The main degradation factors can be classified according to two categories:

Environmental degradation factors	Mechanical degradation factors
▪ **Moisture** ▪ **Chemicals** ▪ **Thermal effects** ▪ **UV exposure**	▪ **Static loading**: creep, relaxation ▪ **Dynamic loading**: fatigue, vibrations, impact

- **Degradation mechanisms** are characterized by a sequence of **chemical**, **mechanical** and/or **physical changes**, leading to the **alteration** of **one or more mechanical properties** of the material, component or structure in a **harmful way** when exposed to a degradation factor or a combination of them.

Motivation > *Current codes*


CNR – Advisory Committee on Technical Recommendations for Construction

NATIONAL RESEARCH COUNCIL

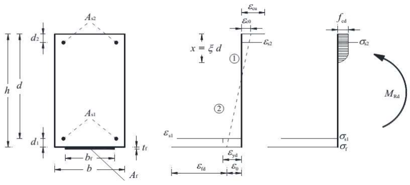
ADVISORY COMMITTEE ON TECHNICAL RECOMMENDATIONS FOR CONSTRUCTION

Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Existing Structures

Materials, RC and PC structures, masonry structures

CNR-DT 200 R1/2013

ROMA – CNR October 10th 2013 – release of May 15th 2014



$$\varepsilon_{fd} = \min\left\{\eta_a \cdot \frac{\varepsilon_{fk}}{\gamma_f}, \varepsilon_{fdd}\right\}$$

$$X_d = \eta \cdot \frac{X_k}{\gamma_m}$$

η → $= \eta_a$ (ULS)

η → $= \eta_a \cdot \eta_l$ (SLS)

Table 3-2– Environmental conversion factor η_a for different exposure conditions or FRP systems.

Exposure conditions	Type of fiber/resin	η_a
Internal	Glass/Epoxy	0.75
	Aramid/Epoxy	0.85
	Carbon/Epoxy	0.95
External	Glass/Epoxy	0.65
	Aramid/Epoxy	0.75
	Carbon/Epoxy	0.85
Aggressive environment	Glass/Epoxy	0.50
	Aramid/Epoxy	0.70
	Carbon/Epoxy	0.85

Objectives

Objectives

- **The FRPLongDur aims** *at contributing for the knowledge* ***on long-term structural behaviour*** *and* ***durability performance*** *of RC elements strengthened in flexure with* ***CFRP laminates*** *according to the* ***EBR*** *and* ***NSM techniques****, under various* ***REAL ENVIRONMENTS****, and* ***compared this performance*** *with the ones obtained by using* ***artificial accelerated ageing protocols****.*

EXPERIMENTAL ASSESSMENT

- **Different techniques**
- **Different scales**
- **Different environmental conditions**

MODELLING

- **Multi-physics**
- **Short and time-dependent**

ARTIFICIAL
vs.
REAL AGEING

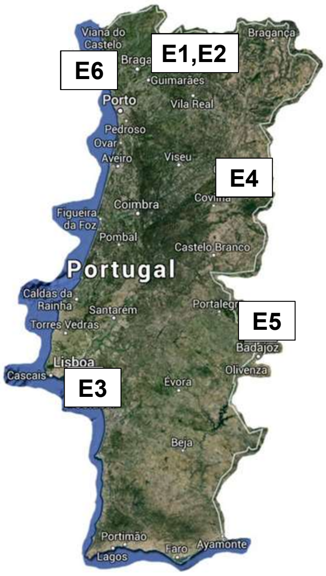
Institute for Sustainability and Innovation in Structural Engineering

Universidade do Minho

General methodology

Universidade do Minho

General methodology > *Techniques, scales, experimental stations*



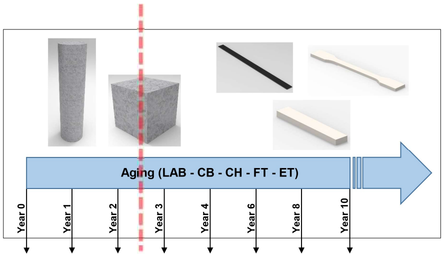
TECHNIQUES
- EBR
- NSM
- MA & GA

SCALE
- Material
- Bond
- RC slabs

Experimental Station

EXPERIMENTAL STATIONS (6)
- Reference Specimens (E1, E2) – UMinho
- Ageing induced by carbonation (E3) – Lisbon@LNEC
- Ageing induced by freeze/thaw attack (E4) – Serra da Estrela@EDP
- Ageing induced by elevated temperatures (E5) – Elvas@S&P
- Ageing induced by chlorides from sea water (E6) – V.Castelo@APDL

General methodology > *Techniques, scales, experimental stations*



Set of specimens to be tested up to the failure

EPOXY & CFRP LAMINATE

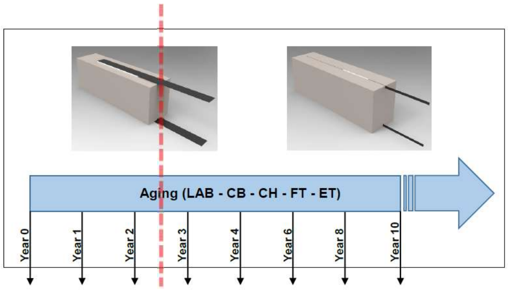
COMPOSITION
- Chemical composition
- Chemical resistance
- Density
- SEM

MORPHOLOGY
- Microscopy

HYDROTHERMAL PROPERTIES
- Water absorption

THERMAL PROPERTIES
- DSC
- DMA

MECHANICAL PROPERTIES
- Tensile properties
- Flexural properties

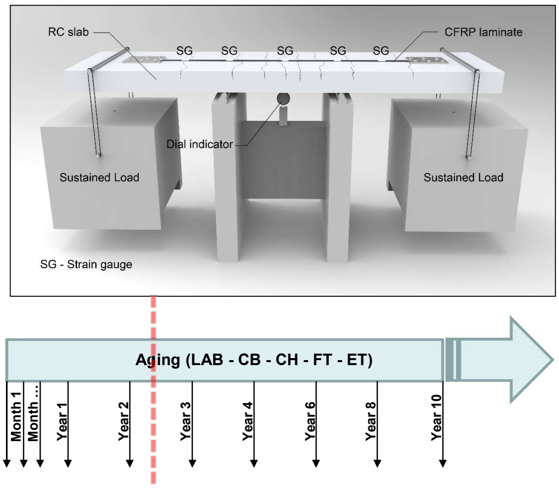


Set of specimens to be tested up to the failure

PULLOUT/LAP-SHEAR SPECIMENS

- Maximum pullout force (F_{max})
- Slip at F_{max}
- Bond strength
- $\tau - s$
- Degradation

General methodology > *Techniques, scales, experimental stations*

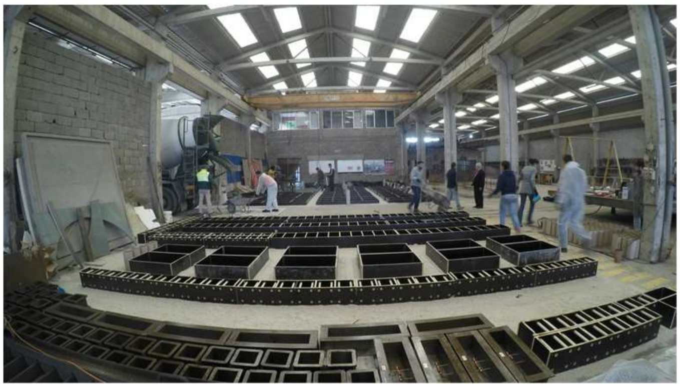


SLABS – Evolution of

- **Deflection**
- **FRP strain**
- **Concrete strain**
- **Bond degradation**

General methodology > *Specimens' preparation & Installation*

- **Concrete specimens:**
  - Single concrete mixture batch of 12 m^2
  - C30/37 XC4(P) d_{max}12.5 S4
  - **140** cylinders 150/300
  - **90** cubes 200 mm of edge
  - **90** cubes 200/200/400 [mm]
  - **30** slabs 120/600/2600 [mm]
- **Laminates:**
  - **258**: S&P 10×1.4 [mm]
  - **86**: S&P 50×1.4 [mm]
- **Epoxy adhesive:**
  - **342** Epoxy S&P
  - **342** Epoxy Sika



General methodology > *Specimens' preparation & Installation*

1. **Installation of the slabs**
2. **Installation of the bond specimens**
3. **Installation of the materials**
4. **Installation of the fencing**

General methodology > *Specimens' preparation & Installation*

Experimental Station E4 – Seia/Barragem da Lagoa Comprida (EDP)

General methodology > *Specimens' preparation & Installation*

Laboratory environments

Outdoor environments

Dissemination/Outputs

Dissemination/Outputs

❑ Advanced training:

- PhD theses (**1**):
  - "*Multi-scale investigation on durability and long-term behavior of concrete structures strengthening with CFRP laminates according to the EBR and NSM techniques*." PhD Thesis of José Ricardo Loureiro Cruz, PhD Program on Civil Engineering, University of Minho.

- Master theses (**4**):
  - "*Exploring the use of hybrid FRP Composites on retrofitting of RC beam-column joints*." MSc Thesis of Zahir Mohammad Emtair Namourah, Advanced Masters in Structural Analysis of Monuments and Historical Constructions (SAHC), University of Minho. September, 2019.
  - "*Elementos de betão reforçados com laminados de CFRP: aderência e comportamento à flexão*." MSc Thesis of João Nuno Ferros Boaventura, Integrated Master in Civil Engineering, University of Minho. December, 2018. [in Portuguese]
  - "*Numerical simulation of RC slabs strengthened with pre-stressed CFRP laminates*." MSc Thesis of Gao Hongchen Jacey, Advanced Masters in Structural Analysis of Monuments and Historical Constructions (SAHC), University of Minho. July 2016.
  - "*Estruturas de betão armado reforçadas com laminados de CFRP: caracterização da aderência e do comportamento em flexão*." MSc Thesis of João Nuno Ferros Boaventura, Integrated Master in Civil Engineering, University of Minho. December 2016. [in Portuguese]

Dissemination/Outputs

❑ ISI Papers in International Journals: (**10**)

1. Cruz, J.R.; Seręga, S.; Sena-Cruz, J.; Pereira, E.; Kwiecień, A.; Zając, B. (2020) "Flexural behaviour of NSM CFRP laminate strip systems in concrete using stiff and flexible adhesives" ***Composites Part B: Engineering***, 195: 108042 1-18. DOI: https://doi.org/10.1016/j.compositesb.2020.108042
2. Cruz, J.R.; Sena-Cruz, J.; Rezazadeh, M.; Seręga, S.; Pereira, E.; Kwiecień, A.; Zając, B. (2020) "Bond behaviour of NSM CFRP laminate strip systems in concrete using stiff and flexible adhesives" ***Composite Structures***, 250: 112369 1-18. DOI: https://doi.org/10.1016/j.compstruct.2020.112369
3. Correia, L.; Barris, C.; França, P.; Sena-Cruz, J. (2019) "Effect of Temperature on Bond Behavior of Externally Bonded FRP Laminates with Mechanical End Anchorage." ***Journal of Composites for Construction***, 23(5): 04019036-1 - 04019036-12. DOI: https://doi.org/10.1061/(ASCE)CC.1943-5614.0000961
4. Ribeiro, F.; Sena-Cruz, J.; Branco, F.; Júlio, E. (2019) "3D finite element model for hybrid FRP-confined concrete in compression using modified CDPM." ***Engineering Structures***, 190: 459–479. DOI: https://doi.org/10.1016/j.engstruct.2019.04.027
5. Soares, S.; Sena-Cruz, J.; Cruz, J.R.; Fernandes, P. (2019) "Influence of Surface Preparation Method on the Bond Behavior of Externally Bonded CFRP Reinforcements in Concrete." ***Materials***, 12(3) 414: 1–20. DOI: https://doi.org/10.3390/ma12030414
6. Ribeiro, F.; Sena-Cruz, J.; Branco, F.; Júlio, E. (2018) "Hybrid FRP jacketing for enhanced confinement of circular concrete columns in compression." ***Construction & Building Materials***, 184: 681–704. DOI: https://doi.org/10.1016/j.conbuildmat.2018.06.229
7. Barris, C.; Correia, L.; Sena-Cruz, J. (2018) "Experimental study on the bond behaviour of a transversely compressed mechanical anchorage system for externally bonded reinforcement." ***Composite Structures***, 200:871–890. DOI: https://doi.org/10.1016/j.compstruct.2018.05.084
8. Ribeiro, F.; Sena-Cruz, J.; Branco, F.G.; Júlio, E. (2018) "Hybrid effect and pseudo-ductile behaviour of unidirectional interlayer hybrid FRP composites for civil engineering applications." ***Construction & Building Materials***, 171:871–890. DOI: https://doi.org/10.1016/j.conbuildmat.2018.03.144
9. Coelho, M.; Neves, L.; Sena-Cruz, J. (2018) "Designing NSM FRP systems in concrete using partial safety factors." ***Composites Part B: Engineering***, 139:12-23. DOI: https://doi.org/10.1016/j.compositesb.2017.11.031
10. Fernandes, P.; Sena-Cruz, J.; Xavier, J.; Silva, P.; Pereira, E.; Cruz, J.R. (2018) "Durability of bond in NSM CFRP-concrete systems under different environmental conditions." ***Composites Part B: Engineering***, 138: 19–34. DOI: https://doi.org/j.compositesb.2017.11.022

Dissemination/Outputs

❑ Papers/Presentations in International Conferences: (12)

- Sena-Cruz, J.; Cruz, J.C.; Correia, L.; Cabral-Fonseca, S; Michels, J.; Czaderski, C. (2019) "Long-term structural and durability performances of reinforced concrete elements strengthened in flexure with CFRP laminates: a research project", IABSE Symposium Guimarães 2019 - Towards a Resilient Built Environment Risk and Asset Management, March 27-29, Guimarães, 1006-1014 pp. URI: http://hdl.handle.net/1822/60198
- Correia, L.; Sena-Cruz, J.; França, P. (2019) "Behaviour of RC structures strengthened with prestressed CFRP laminates: a numerical study", IABSE Symposium Guimarães 2019 - Towards a Resilient Built Environment Risk and Asset Management, March 27-29, Guimarães, 276-283 pp. URI: http://hdl.handle.net/1822/60194
- Cruz, J.R.; Sena-Cruz, J.; Borojevic, A.; Kwiecień, A.; Zając, B. (2018) "Influence of adhesive type on the flexural behaviour of RC slabs strengthened with NSM-CFRP systems", 9th International Conference on Fibre-Reinforced Polymer (FRP) Composites in Civil Engineering (CICE2018), July 17-19, Paris, 8 pp. URI: http://hdl.handle.net/1822/55647
- Correia, L.; Barris, C.; Sena-Cruz, J. (2018) "Temperature effect on the bond behaviour of a transversely compressed mechanical anchorage system", 9th International Conference on Fibre-Reinforced Polymer (FRP) Composites in Civil Engineering (CICE2018), July 17-19, Paris, 8 pp. URI: http://hdl.handle.net/1822/55669
- Sena-Cruz, J.; Correia, L.; Barris, C. (2018) "Behaviour of Metallic Anchorage Plates for Prestressing CFRP Laminates Under Room and Elevated Temperatures", 40th IABSE Conference – Engineering the Developing World, April 25-27, Kuala Lumpur, 111-118. URI: http://hdl.handle.net/1822/55708
- Sena-Cruz, J.; Correia, L.; França, P.; Michels, J.; (2017) "Short and long-term behaviour of RC slabs strengthened with prestressed CFRP laminate strips", 39th IABSE Symposium – Engineering the Future, September 21-23, Vancouver, 8 pp. URI: http://hdl.handle.net/1822/50508
- Sena-Cruz, J.; Michels, J.; Correia, L.; Harmanci, Y.; Silva, P.; Gallego, J.; Fernandes, P.; Czaderski, C.; França, P. (2017) "Recent contributions from UMinho and Empa on durability issues of flexural strengthening of RC slab with EB CFRP laminates", 4th Conference on Smart Monitoring, Assessment and Rehabilitation of Civil Structures (SMAR2017), September 13-15, Zurich, 8 pp. URI: http://hdl.handle.net/1822/50505
- Soares, S.; Cruz, J.R.; Fernandes, P.; Sena-Cruz, J. (2017) "Bond behavior of EBR CFRP systems in concrete: influence of surface preparation", 6th Asia-Pacific Conference on FRP in Structures (APFIS2017), 19 a 21 de julho, Singapura, 5 pp. URI: http://hdl.handle.net/1822/50502
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- Sena-Cruz, J.; Fernandes, P.; Coelho, M.; Silva, P.; Granja, J.; Benedetti, A.; Azenha, M.; Neves, L. (2016) "Bond on NSM CFRP systems: recent contributions of UMinho on durability, quality control and design", Eighth International Conference on Fibre-Reinforced Polymer (FRP) Composites in Civil Engineering (CICE2016), December 14-16, Hong Kong, 912-917 pp. URI: http://hdl.handle.net/1822/43901
- Cruz, J.R.; Borojevic, A.; Sena-Cruz, J.; Pereira, E.; Fernandes, P.; Silva, P.; Kwiecien, A. (2016) "Bond behaviour of NSM CFRP-concrete systems: adhesive and CFRP cross-section influences", Eighth International Conference on Fibre-Reinforced Polymer (FRP) Composites in Civil Engineering (CICE2016), December 14-16, Hong Kong, 930-935 pp. URI: http://hdl.handle.net/1822/43903
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Dissemination/Outputs

❑ Papers/Presentations in National Conferences: (10)

- Correia, L.; Sena-Cruz, J.; França, P. (2018) "Estudos numéricos de lajes de betão armado reforçadas à flexão com laminados de CFRP pré-esforçados." Encontro Nacional Betão Estrutural - BE2018, 7 a 9 de novembro, Laboratório Nacional de Engenharia Civil, Lisboa, 10 pp. URI: http://hdl.handle.net/1822/58387
- Ribeiro, F.; Sena-Cruz, J.; Branco, F.G.; Júlio, E. (2018) "Comportamento à compressão de pilares circulares de betão confinados por sistemas compósitos de FRP híbridos." Encontro Nacional Betão Estrutural - BE2018, 7 a 9 de novembro, Laboratório Nacional de Engenharia Civil, Lisboa, 10 pp. URI: http://hdl.handle.net/1822/58385
- Ribeiro, F.; Sena-Cruz, J.; Branco, F.G.; Júlio, E. (2018) "Comportamento à compressão de pilares circulares de betão confinados por sistemas compósitos de FRP híbridos." Encontro Nacional Betão Estrutural - BE2018, 7 a 9 de novembro, Laboratório Nacional de Engenharia Civil, Lisboa, 10 pp. URI: http://hdl.handle.net/1822/58385
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Acknowledgments

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Acknowledgments > *Companies*

S&P Clever Reinforcement Ibérica, Lda

edp

APDL

Sika

Artecanter Indústria Criativa

Pré-fabricados tecnipor

VIALAM

HILTI

Novo Modelo Europa, S.A.

Acknowledgments > *Funding agencies/programs*

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FCT Fundação para a Ciência e a Tecnologia — COMPETE — POPH — QREN — UNIÃO EUROPEIA Fundo Social Europeu

IB-S INSTITUTO DE CIÊNCIA E INOVAÇÃO PARA A BIO-SUSTENTABILIDADE

Durability of materials

Susana Cabral-Fonseca

Conclusion Seminar
FRPLongDur Project
30 October 2020

LONG-TERM STRUCTURAL AND DURABILITY PERFORMANCES OF REINFORCED CONCRETE ELEMENTS STRENGTHENED IN FLEXURE WITH CFRP

MATERIALS DURABILITY

Susana Cabral-Fonseca
Laboratório Nacional de Engenharia Civil

POCI-01-0145-FEDER-016900
PTDC/ECM-EST/1282/2014

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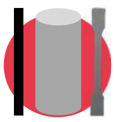
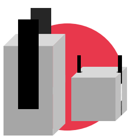
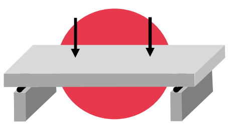
1. Introduction 2. Materials 3. Methods 4. Results 5. Conclusions



Materials
(Concrete, adhesive and CFRP)



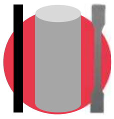
Bond Specimens
(EBR and NSM)



Slabs under sustained load
(EBR and NSM)

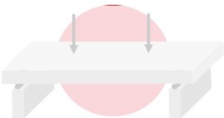
Experimental stations

- **E1**: Reference (indoor)
- **E2**: Immersion in water
- **E3**: Outdoor - carbonatation
- **E4**: Outdoor - freeze-thaw attack
- **E5**: Outdoor - elevated temperatures
- **E6**: Outdoor - chloride exposure



Materials
(Concrete, adhesive and CFRP)

Bond Specimens
(EBR and NSM)



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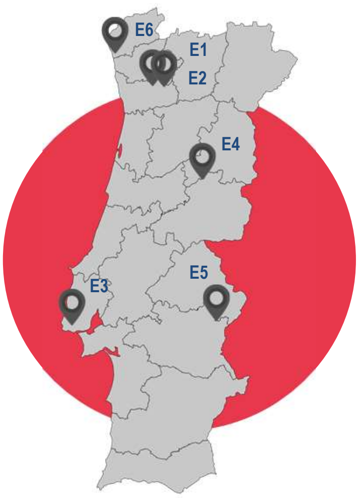

1. Introduction 2. Materials 3. Methods 4. Results 5. Conclusions

Concrete: C30/37 XC4(P) Cl 0,4 D 12,5 S4

Two epoxy adhesives: ADH1 and ADH2

CFRP laminate (two width): L10 and L50

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1. Introduction 2. Materials 3. Methods 4. Results 5. Conclusions

T0: initial characterisation

T1 & T2: one and two years of ageing in different experimental stations

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Concrete

T0 @ Concrete

- COMPRESSIVE PROPERTIES
  Compressive strength: NP EN 12390-3:2011
  Modulus of elasticity: NP EN 12390-13:2014
- TENSILE PROPERTIES (PULL-OFF TEST)
  ASTM D 4541:2017

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1. Introduction 2. Materials **3. Methods** 4. Results 5. Conclusions

Concrete

T1 & T2 @ Concrete

- COMPRESSIVE PROPERTIES
  Compressive strength: NP EN 12390-3:2011
  Modulus of elasticity: NP EN 12390-13:2014
- TENSILE PROPERTIES (PULL-OFF TEST)
  ASTM D 4541:2017
- DEEP OF CARBONATION
  LNEC E 391:1993

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Adhesives

T0 @ Adhesives

- CHEMICAL COMPOSITION by FTIR
  ASTM E 1252:2013
- DIFFERENTIAL SCANNING CALORIMETRY (DSC)
  ISO 11357-1:2016 and ISO 11357-2:2020
- DYNAMIC MECHANICAL ANALYSIS
  ISO 6721-1:2019 and ASTM E 1640:2014
- WATER ABSORPTION BEHAVIOUR
  At three different temperatures: 20 ºC, 40 ºC and 60 ºC
- TENSILE PROPERTIES
  EN ISO 527-2:2012

FTIR

DSC

DMA

Adhesives

T1 & T2 @ Adhesives

- DYNAMIC MECHANICAL ANALYSIS
  ISO 6721-1:2019 and ASTM E 1640:2014
- TENSILE PROPERTIES
  EN ISO 527-2:2012

DMA – Dual cantilever configuration


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CFRP
T0 @ CFRP
T1 & T2 @ CFRP
• TENSILE PROPERTIES
EN ISO 527-5:2009
CFRP Strip
Clip Gauge
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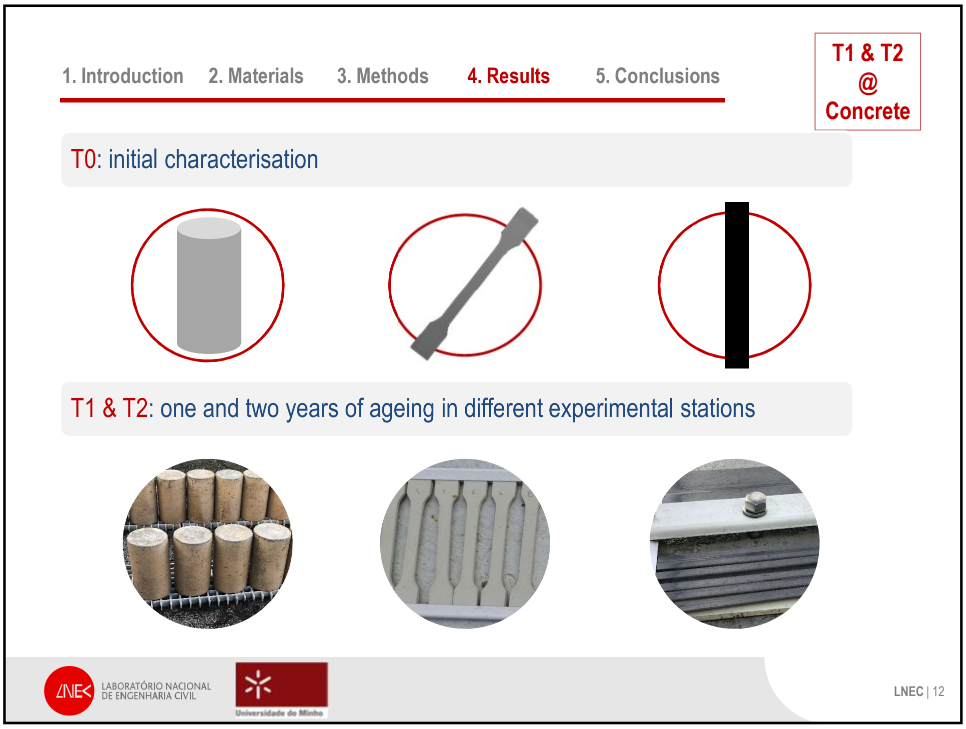
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T1 & T2 @ Concrete
T0: initial characterisation
T1 & T2: one and two years of ageing in different experimental stations
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T0
@
Concrete

T0: Initial characterisation

T1 & T2: one and two years of ageing in different experimental stations

T0
@
Concrete

Compressive properties of concrete (28 days)	
Compressive strength [MPa] (CoV [%])	Modulus of elasticity [GPa] (CoV [%])
41.5 (4.4)	29.1 (4.7)

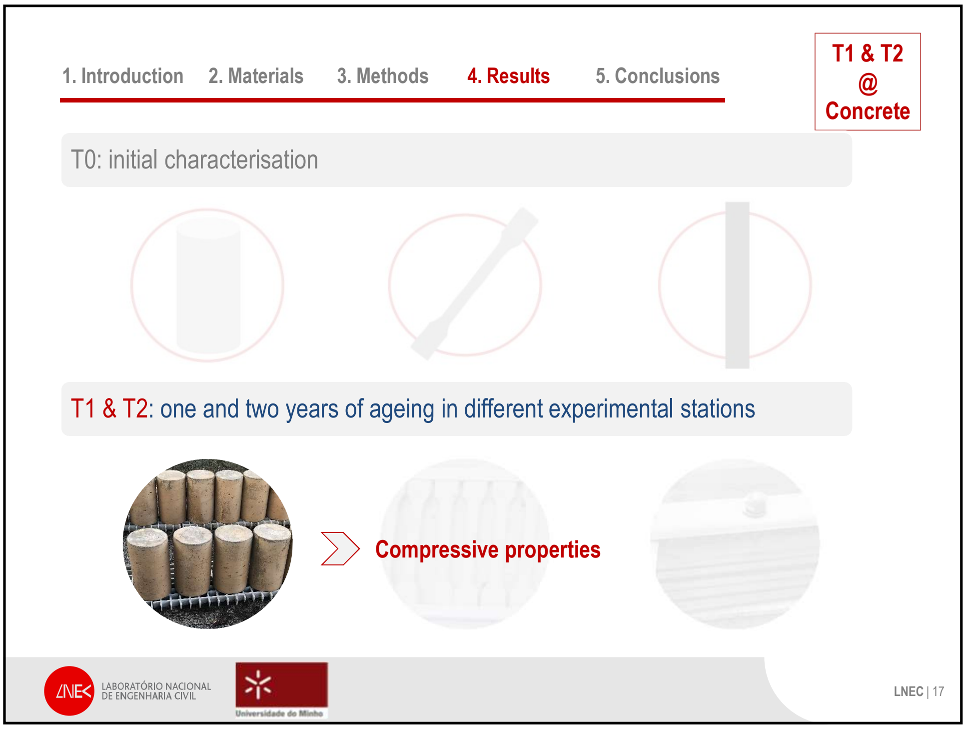
T0 @ Concrete

Tensile strength, by Pull-off [MPa] (CoV [%])
3.4 (13.3)

T1 & T2 @ Concrete

T0: initial characterisation

T1 & T2: one and two years of ageing in different experimental stations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T1 & T2 @ Concrete
T0: initial characterisation
T1 & T2: one and two years of ageing in different experimental stations
Compressive properties
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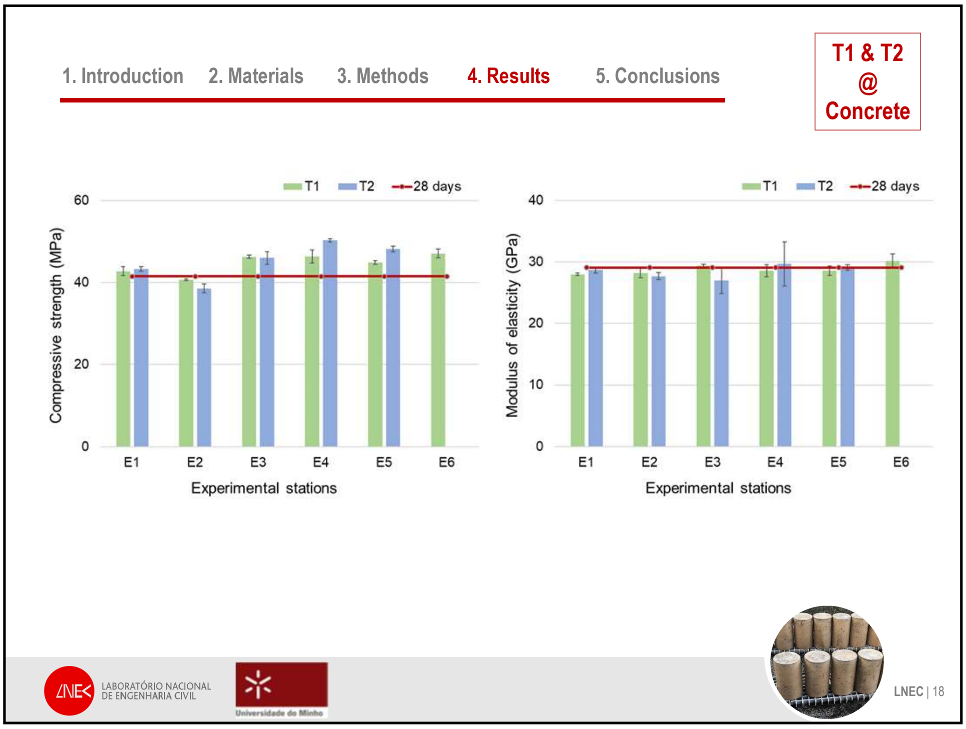
1. Introduction
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3. Methods
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T1 & T2 @ Concrete
T1
T2
28 days
Compressive strength (MPa)
0
20
40
60
E1
E2
E3
E4
E5
E6
Experimental stations
Modulus of elasticity (GPa)
0
10
20
30
40
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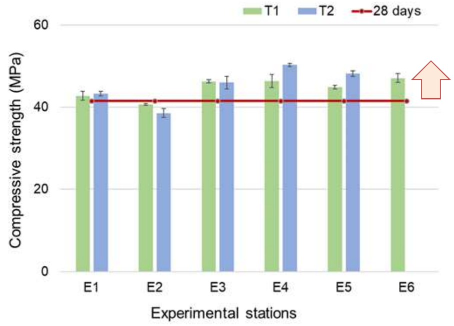
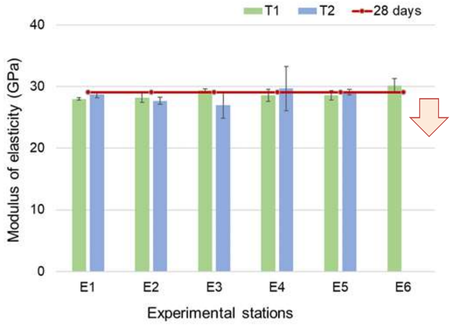
T1 & T2 @ Concrete





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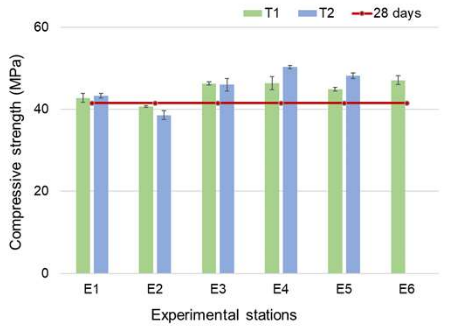
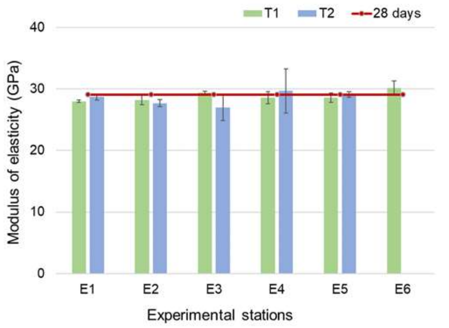
1. Introduction 2. Materials 3. Methods **4. Results** 5. Conclusions

T1 & T2 @ Concrete



	E2/E1	E3/E1	E4/E1	E5/E1	E6/E1
T1	- 4.9	+ 8.2	+ 8.4	+ 4.9	+ 10.0
T2	- 10.9	+ 6.2	+ 16.2	+ 11.3	

Variation (%)



	E2/E1	E3/E1	E4/E1	E5/E1	E6/E1
T1	+ 0.7	+ 5.0	+ 2.1	+ 2.1	+ 7.9
T2	- 3.5	- 5.9	+ 3.5	+ 1.4	

Variation (%)

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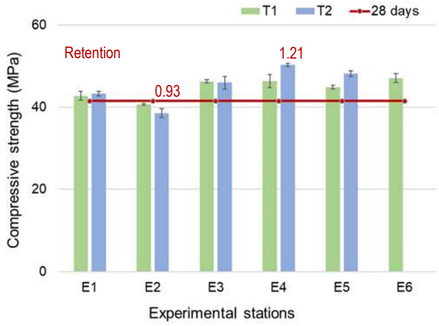
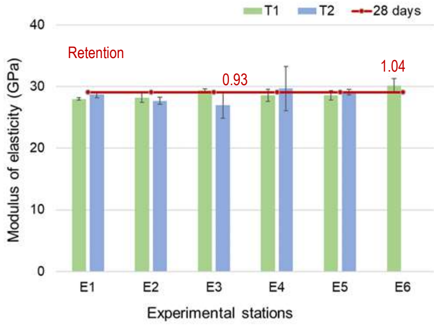
T1 & T2 @ Concrete





	E2/E1	E3/E1	E4/E1	E5/E1	E6/E1
T1	- 4.9	+ 8.2	+ 8.4	+ 4.9	+ 10.0
T2	- 10.9	+ 6.2	+ 16.2	+ 11.3	

Variation (%)

	E2/E1	E3/E1	E4/E1	E5/E1	E6/E1
T1	+ 0.7	+ 5.0	+ 2.1	+ 2.1	+ 7.9
T2	- 3.5	- 5.9	+ 3.5	+ 1.4	

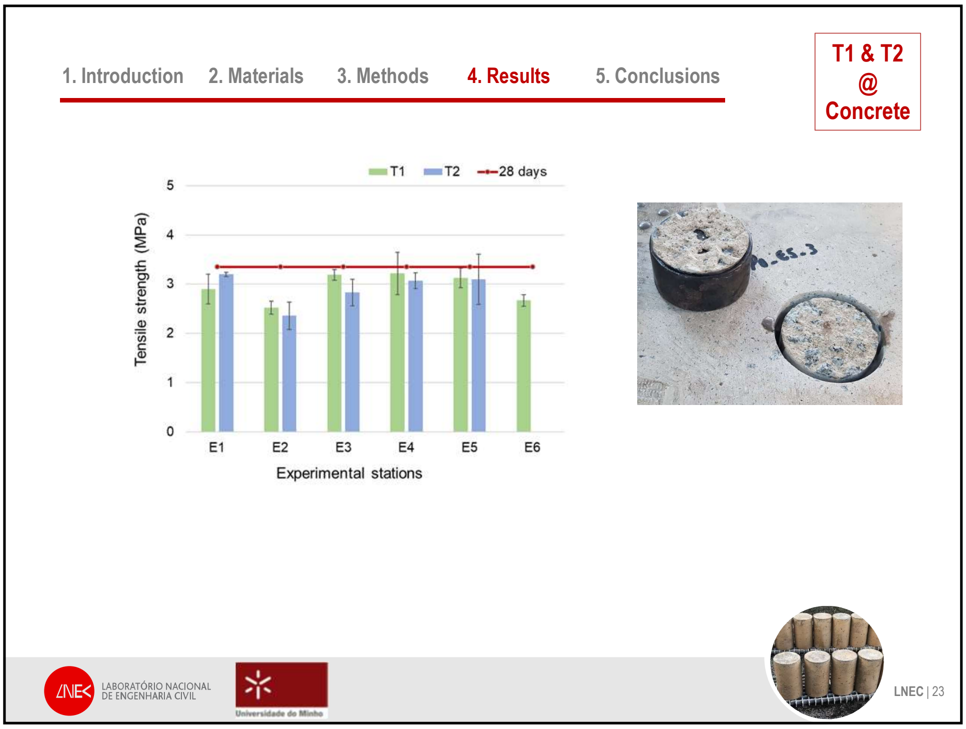
Variation (%)

T1 & T2 @ Concrete

T0: initial characterisation

T1 & T2: one and two years of ageing in different experimental stations

Tensile properties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T1 & T2 @ Concrete
T1
T2
28 days
Tensile strength (MPa)
5
4
3
2
1
0
E1
E2
E3
E4
E5
E6
Experimental stations
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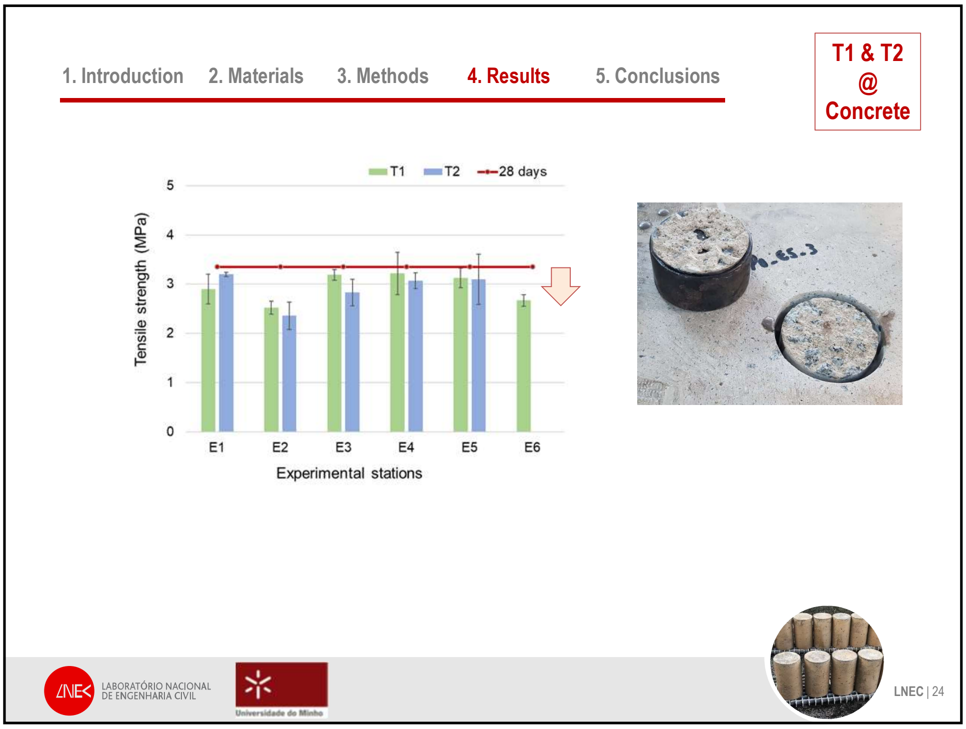
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T1 & T2 @ Concrete
T1
T2
28 days
Tensile strength (MPa)
5
4
3
2
1
0
E1
E2
E3
E4
E5
E6
Experimental stations
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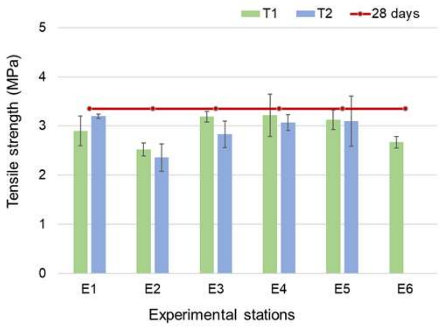
T1 & T2 @ Concrete



	E2/E1	E3/E1	E4/E1	E5/E1	E6/E1
T1	- 13.1	+ 10.0	+ 11.2	+ 8.1	- 7.9
T2	- 26.3	- 11.8	- 4.3	- 3.2	

Variation (%)

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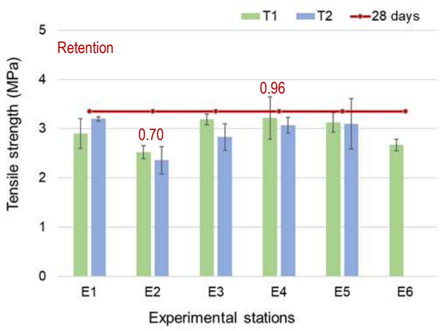
T1 & T2 @ Concrete



	E2/E1	E3/E1	E4/E1	E5/E1	E6/E1
T1	- 13.1	+ 10.0	+ 11.2	+ 8.1	- 7.9
T2	- 26.3	- 11.8	- 4.3	- 3.2	

Variation (%)

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T1 & T2 @ Concrete

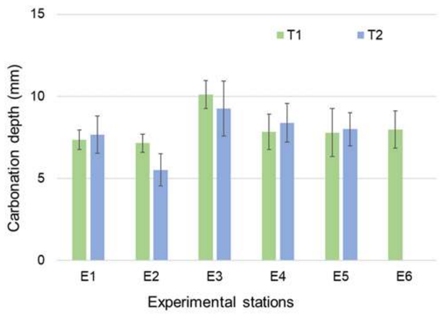
T0: initial characterisation

T1 & T2: one and two years of ageing in different experimental stations

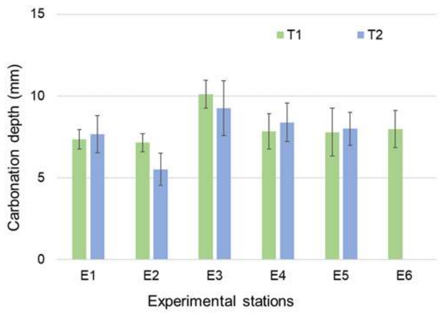
Deep of carbonation

1. Introduction 2. Materials 3. Methods **4. Results** 5. Conclusions

T1 & T2 @ Concrete



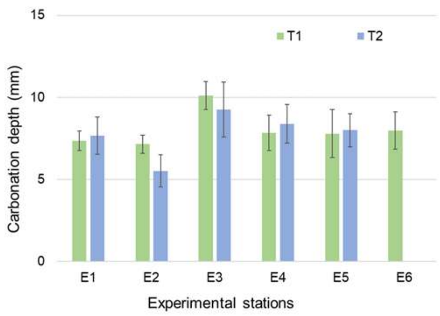
T1 & T2 @ Concrete



	E2/E1	E3/E1	E4/E1	E5/E1	E6/E1
T1	- 2.7	+ 37.4	+ 6.7	+ 6.0	+ 8.7
T2	- 28.0	+ 20.6	+ 9.4	+ 4.3	

Variation (%)

T1 & T2 @ Concrete



	E2/E1	E3/E1	E4/E1	E5/E1	E6/E1
T1	- 2.7	+ 37.4	+ 6.7	+ 6.0	+ 8.7
T2	- 28.0	+ 20.6	+ 9.4	+ 4.3	

Variation (%)

T0 @ Adhesives

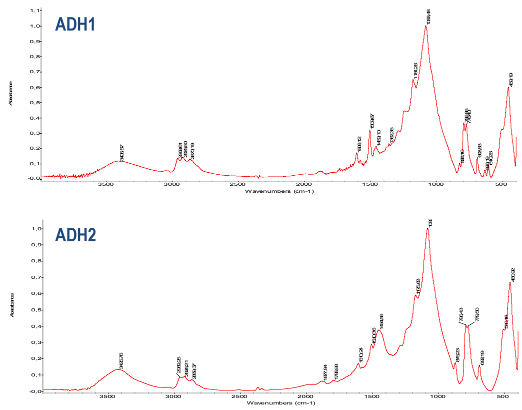
T0: Initial characterisation

T1 & T2: one and two years of ageing in different experimental stations

T0 @ Adhesives

Chemical composition

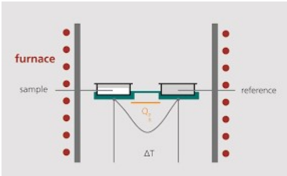
Epoxy based resins with silica fillers



28 days of cure at 23 ºC

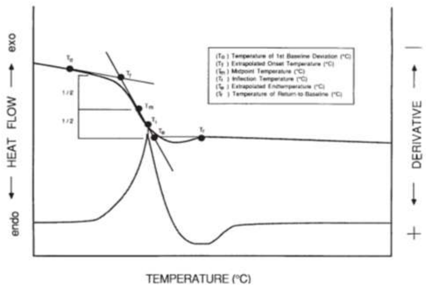
T0 @ Adhesives

Differential Scanning Calorimetry (DSC)



Small test specimens

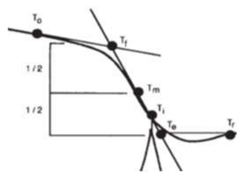
T_g determination from calorimetric curve

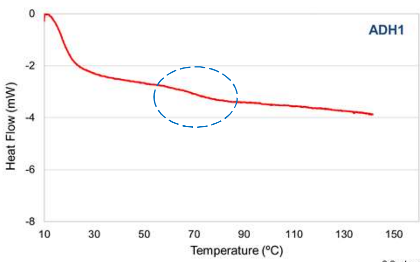


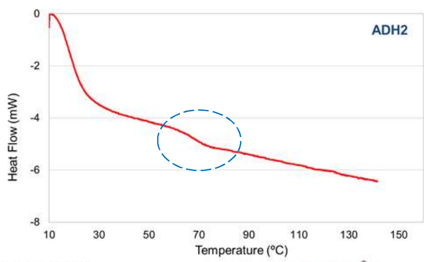
T0 @ Adhesives

Differential Scanning Calorimetry (DSC)

small test specimens
+
adhesives with a high content of mineral filler
=
little definition of the experimental curve "step"







28 days of cure at 23 ºC

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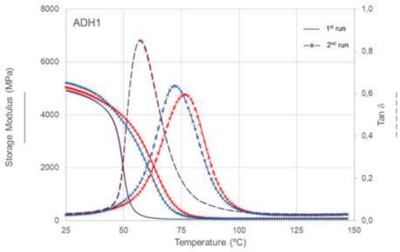
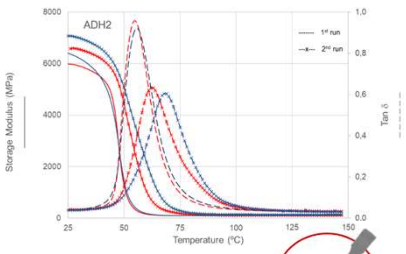
T0 @ Adhesives

Dynamic Mechanical Analysis (DMA)

28 days of cure at 23 °C

Adhesive	Glass Transition Temperature [ºC] (CoV [%])			
	T_g [E'_{onset}]		T_g [tan δ]	
	1st run	2nd run	1st run	2nd run
ADH1	46.2 (0.3)	50.6 (3.5)	57.0 (0.2)	74.3 (3.0)
ADH2	44.3 (1.0)	45.7 (0.4)	55.3 (0.8)	65.4 (4.7)





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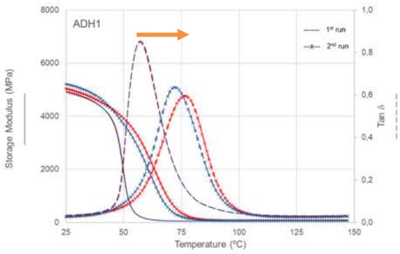
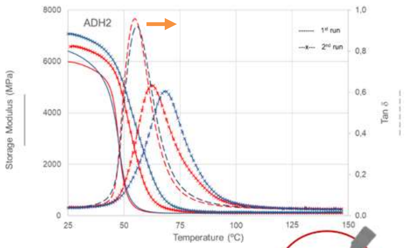
T0 @ Adhesives

Viscoelastic properties

28 days of cure at 23 °C

Adhesive	Glass Transition Temperature [ºC] (CoV [%])				
	T_g [E'_{onset}]		T_g [tan δ]		
	1st run	2nd run	1st run	2nd run	
ADH1	46.2 (0.3)	50.6 (3.5)	57.0 (0.2)	74.3 (3.0)	↑ 30%
ADH2	44.3 (1.0)	45.7 (0.4)	55.3 (0.8)	65.4 (4.7)	↑ 18%





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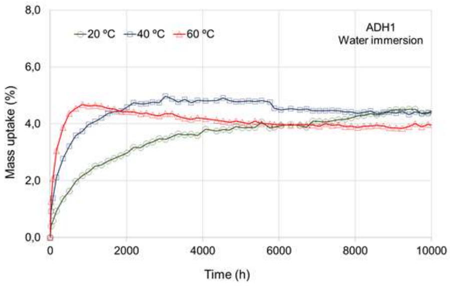
T0 @ Adhesives

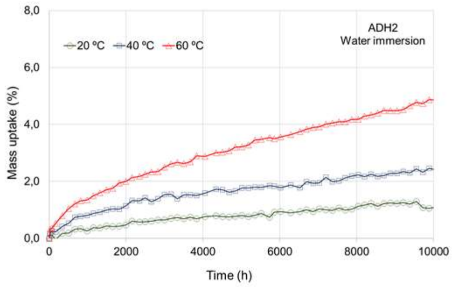
Water absorption behaviour

Water absorption [ADH1]

>

Water absorption [ADH2]





After 28 days of cure at 23 ºC: immersions in water at 20 ºC, 40 ºC and 60 ºC

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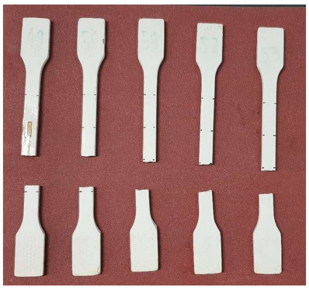
T0 @ Adhesives

Mechanical properties

28 days of cure at 23 ºC

Adhesive	Tensile properties		
	Tensile strength [MPa] (CoV [%])	Modulus of elasticity [GPa] (CoV [%])	Strain at break [$\times10^{-3}$] (CoV [%])
ADH1	19.9 (3.0)	6.50 (3.0)	4.0 (6.2)
ADH2	24.8 (7.0)	7.99 (8.2)	4.5 (20.0)



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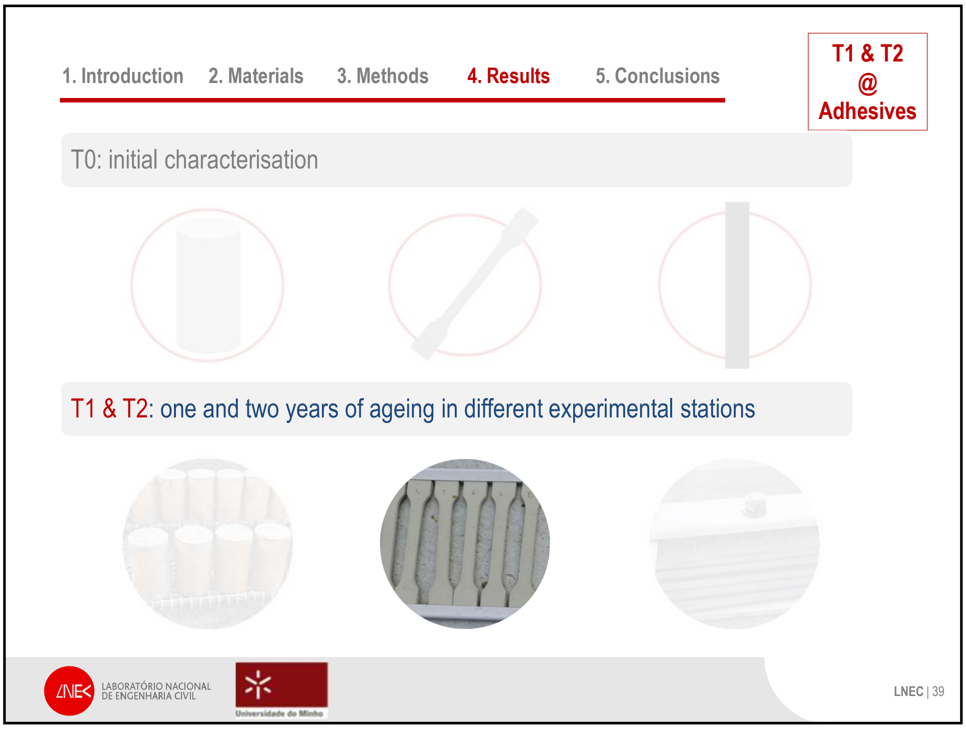
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T1 & T2 @ Adhesives
T0: initial characterisation
T1 & T2: one and two years of ageing in different experimental stations
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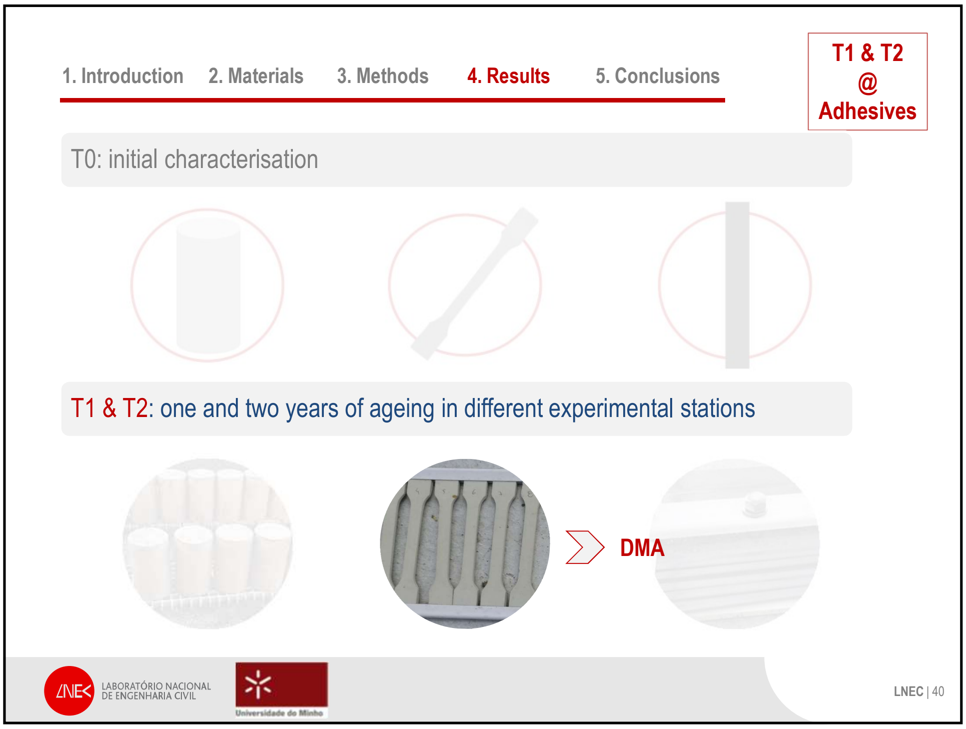
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T0: initial characterisation
T1 & T2: one and two years of ageing in different experimental stations
DMA
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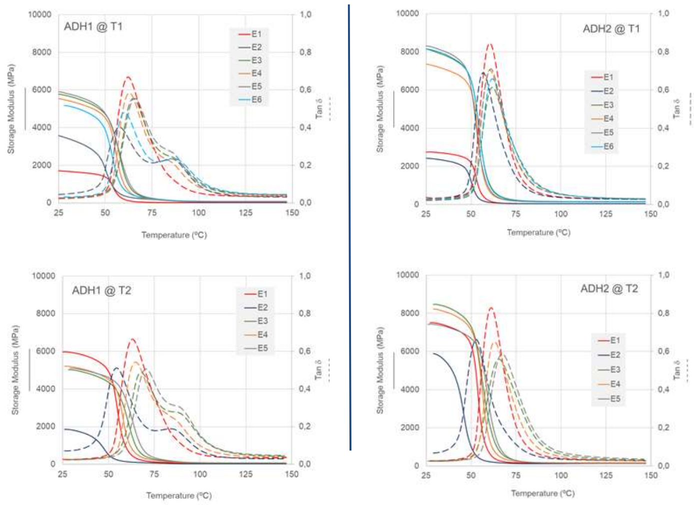
T1 & T2 @ Adhesives



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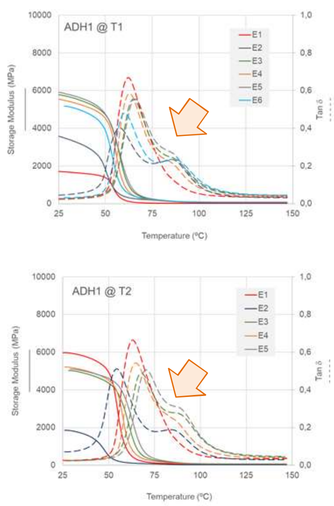
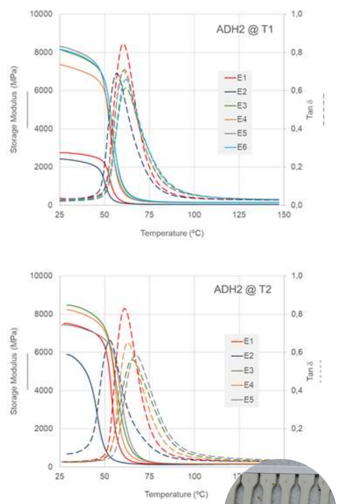
T1 & T2 @ Adhesives

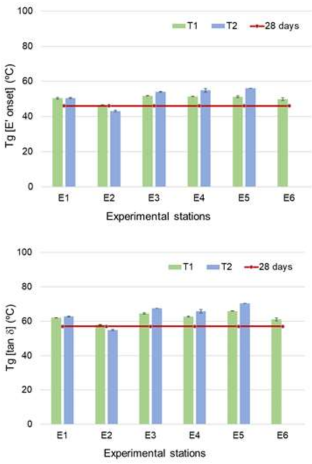


Presence of water inside the adhesive

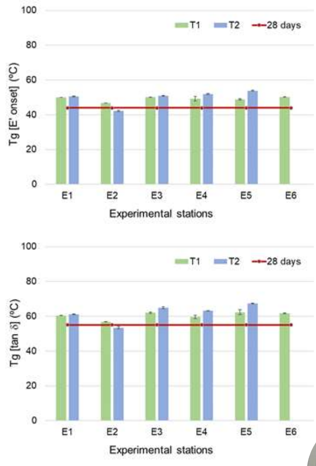


T1 & T2 @ Adhesives

ADH1

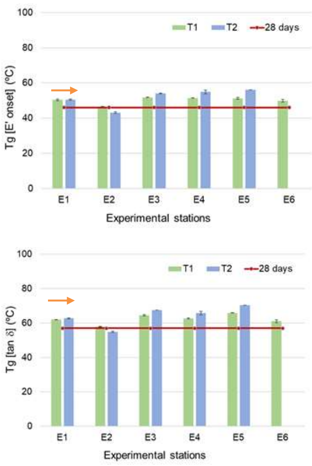


ADH2

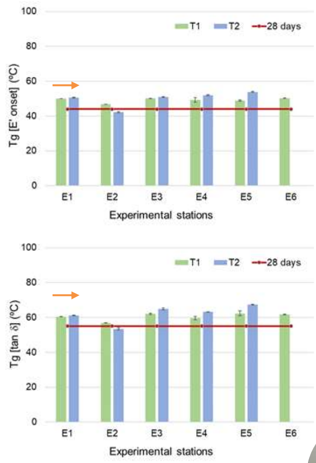


T1 & T2 @ Adhesives

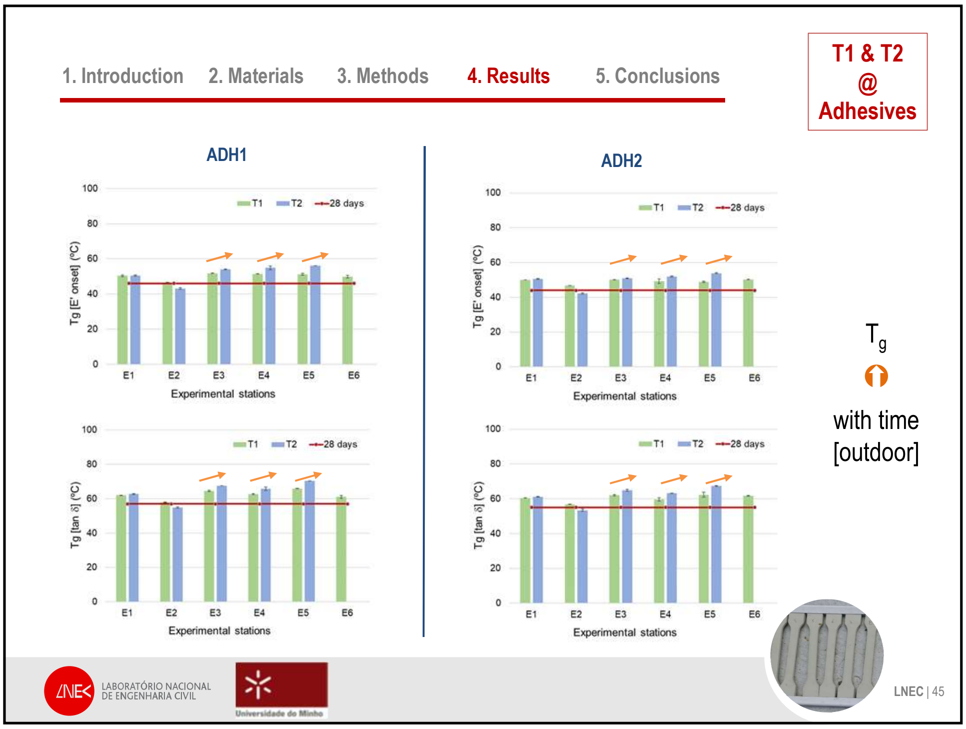
ADH1



ADH2



T_g constant with time [Ref]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T1 & T2 @ Adhesives
ADH1
ADH2
T1
T2
28 days
Tg [E' onset] (ºC)
Tg [tan δ] (ºC)
E1
E2
E3
E4
E5
E6
Experimental stations
Tg
with time [outdoor]
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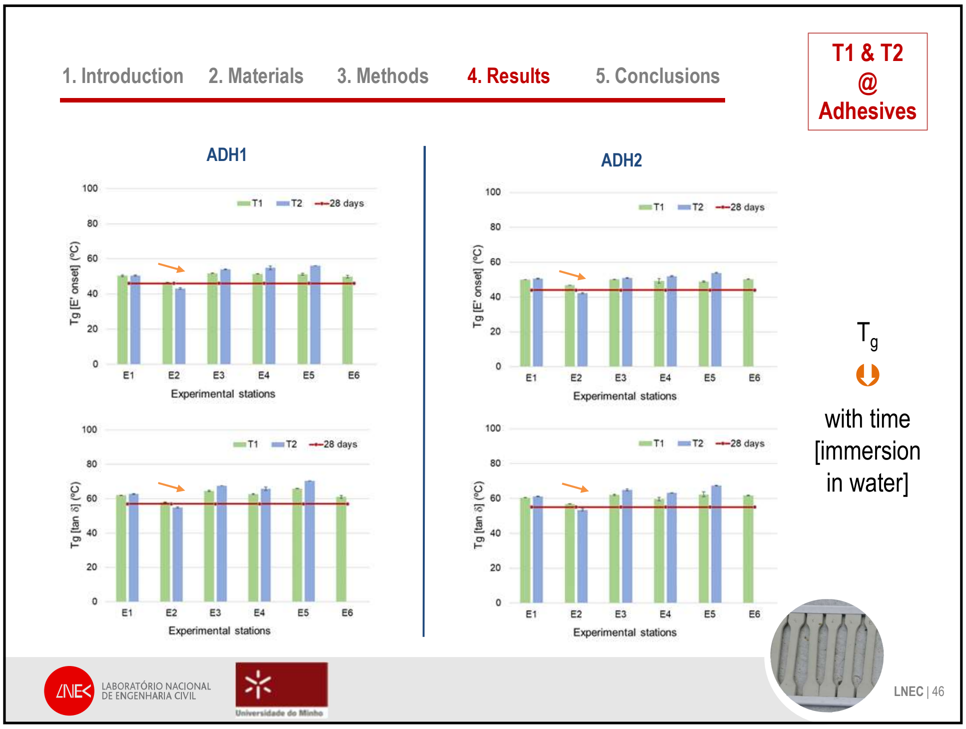
1. Introduction
2. Materials
3. Methods
4. Results
5. Conclusions
T1 & T2 @ Adhesives
ADH1
ADH2
T1
T2
28 days
Tg [E' onset] (ºC)
Tg [tan δ] (ºC)
E1
E2
E3
E4
E5
E6
Experimental stations
Tg
with time [immersion in water]
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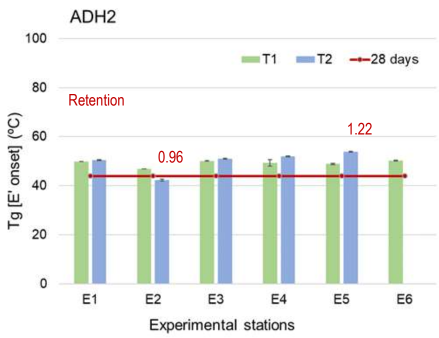
T1 & T2 @ Adhesives

	E2/E1	E3/E1	E4/E1	E5/E1	E6/E1
T1	- 7.5	+ 2.9	+ 2.2	+ 1.6	- 0.9
T2	- 14.6	+ 7.0	+ 8.7	+ 11.3	

Variation (%)



	E2/E1	E3/E1	E4/E1	E5/E1	E6/E1
T1	- 6.2	+ 0.4	- 1.3	- 2.1	+ 0.7
T2	- 16.3	+ 1.0	+ 2.9	+ 6.6	

Variation (%)

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T1 & T2 @ Adhesives

T0: initial characterisation

T1 & T2: one and two years of ageing in different experimental stations

TENSILE PROPERTIES

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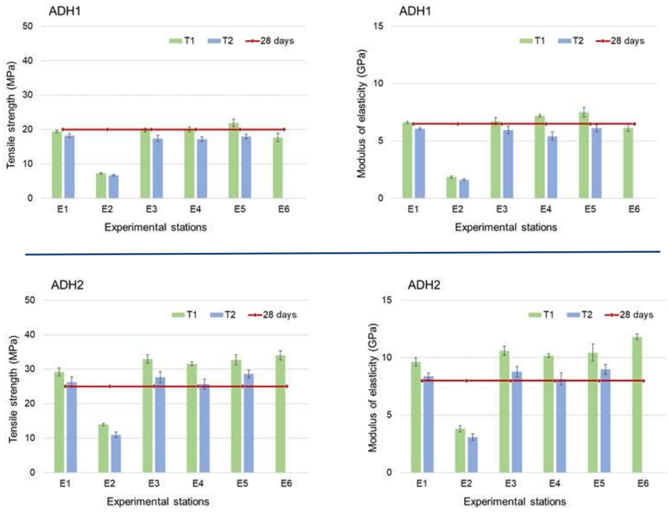
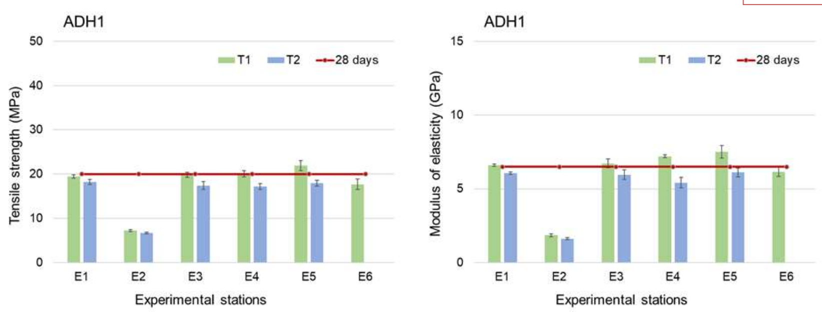
T1 & T2 @ Adhesives



T1 & T2 @ Adhesives



	E2/E1	E3/E1	E4/E1	E5/E1	E6/E1
T1	- 62.8	+ 1.9	+ 3.3	+ 12.5	- 9.0
T2	- 63.5	- 4.5	- 5.6	- 1.5	

Variation (%)

	E2/E1	E3/E1	E4/E1	E5/E1	E6/E1
T1	- 71.9	+ 2.0	+ 9.2	+ 13.8	- 6.7
T2	- 73.3	- 1.7	- 10.6	+ 0.7	

Variation (%)

T1 & T2 @ Adhesives

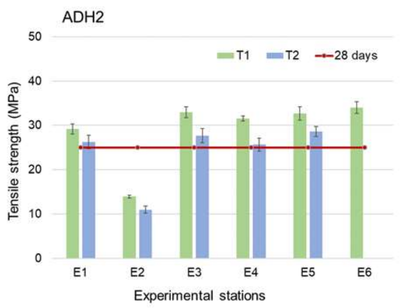
	E2/E1	E3/E1	E4/E1	E5/E1	E6/E1
T1	- 62.8	+ 1.9	+ 3.3	+ 12.5	- 9.0
T2	- 63,5	- 4.5	- 5.6	- 1.5	

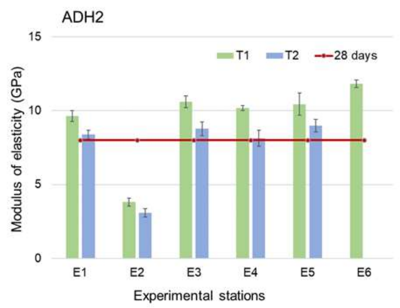
Variation (%)

	E2/E1	E3/E1	E4/E1	E5/E1	E6/E1
T1	- 71.9	+ 2.0	+ 9.2	+ 13.8	- 6.7
T2	- 73.3	- 1.7	- 10.6	+ 0.7	

Variation (%)

T1 & T2 @ Adhesives





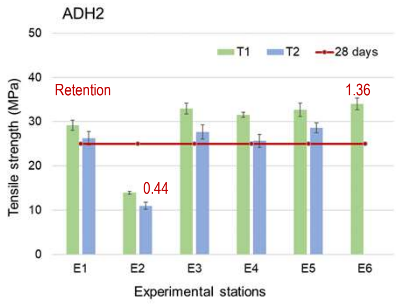
	E2/E1	E3/E1	E4/E1	E5/E1	E6/E1
T1	- 52.3	+ 13.0	+ 8.1	+ 12.1	+ 16.5
T2	- 58.2	+ 5.6	- 2.1	+ 9.0	

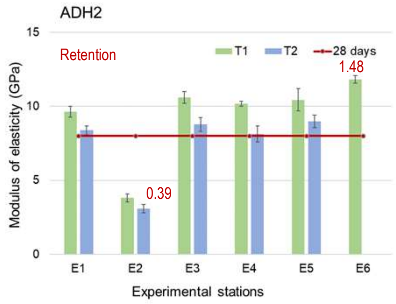
Variation (%)

	E2/E1	E3/E1	E4/E1	E5/E1	E6/E1
T1	- 60.5	+ 10.0	+ 5.5	+ 8.3	+ 22.6
T2	- 63.2	+ 4.7	- 2.8	+ 7.3	

Variation (%)

T1 & T2 @ Adhesives





	E2/E1	E3/E1	E4/E1	E5/E1	E6/E1
T1	- 52.3	+ 13.0	+ 8.1	+ 12.1	+ 16.5
T2	- 58.2	+ 5.6	- 2.1	+ 9.0	

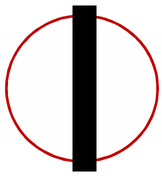
Variation (%)

	E2/E1	E3/E1	E4/E1	E5/E1	E6/E1
T1	- 60.5	+ 10.0	+ 5.5	+ 8.3	+ 22.6
T2	- 63.2	+ 4.7	- 2.8	+ 7.3	

Variation (%)

T0 @ CFRP

T0: Initial characterisation



T1 & T2: one and two years of ageing in different experimental stations

T0 @ CFRP

CFRP	Tensile properties		
	Tensile strength [MPa] (CoV [%])	Modulus of elasticity [GPa] (CoV [%])	Strain at break [$\times 10^{-3}$] (CoV [%])
L10	2.40×10^3 (3.9)	164 (1.2)	15 (4)
L50	2.53×10^3 (10.1)	190 (9.3)	13 (14)

T1 & T2 @ CFRP

T0: initial characterisation

T1 & T2: one and two years of ageing in different experimental stations

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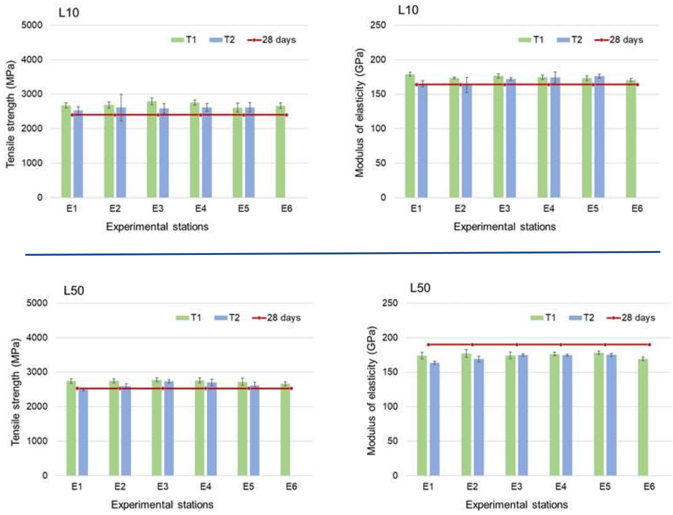
T1 & T2 @ CFRP



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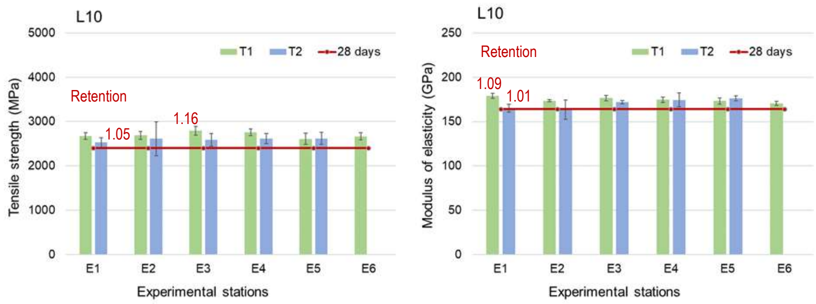
T1 & T2 @ CFRP



	E2/E1	E3/E1	E4/E1	E5/E1	E6/E1
T1	+ 0.5	+ 4.4	+ 3.1	- 2.3	- 0.2
T2	+ 3.4	+ 2.5	+ 3.5	+ 3.6	

Variation (%)

	E2/E1	E3/E1	E4/E1	E5/E1	E6/E1
T1	- 3.1	- 1.3	- 2.4	- 3.2	- 4.7
T2	- 1,0	+ 4,1	+ 5.5	+ 6.7	

Variation (%)

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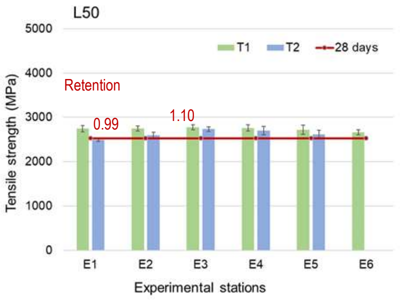
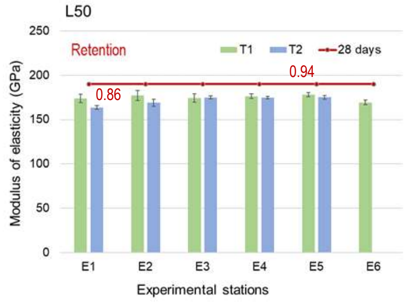
T1 & T2 @ CFRP



	E2/E1	E3/E1	E4/E1	E5/E1	E6/E1
T1	+ 0.1	+ 1.1	+ 0.4	- 1.0	- 3.0
T2	+ 3.9	+ 9.5	+ 8.2	+ 4.8	

Variation (%)



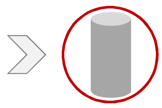
	E2/E1	E3/E1	E4/E1	E5/E1	E6/E1
T1	+ 1.8	+ 0.2	+ 1.4	+ 2.5	- 2.6
T2	+ 3.3	+ 7.0	+ 7.0	+ 7.0	

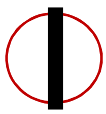
Variation (%)

Initial characterization > Concrete

Compressive strength: 41.5 MPa
Modulus of elasticity: 29.1 GPa

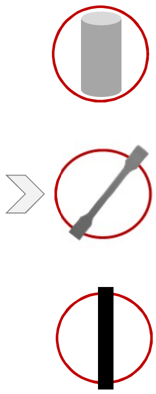
Tensile strength, by Pull-off: 3.4 MPa





Initial characterization > Adhesives

		ADH1	ADH2
Composition		Epoxy based resins with silica fillers	
Water absorption	20 ºC	+++ (~5%)	+ (~1%)
	40 ºC	+++ (~5%)	+ (~2%)
	60 ºC	+++ (~5%)	+ (~5%)
Tg (ºC)	E' onset	46.2	44.3
	Tan δ	57.0	55.3
Tensile properties	Tensile strength (MPa)	19.9	24.8
	Modulus of elasticity (GPa)	6.50	7.99
	Strain at break (%)	4.0	4.5



Initial characterization > CFRP laminates

Tensile strength (GPa): 2.40 – 2.53
Tensile modulus (GPa): 164 – 190

Durability > Concrete

Ei @ E1:

- Compressive strength ↓ immersion in water [E2]
  ↑ outdoor [E3, E4, E5, E6]
- Tensile strength (pull-off) ↓ [E2, E3, E4, E5, E6]



Retention (@ 28 days):

- Compressive strength:
  Min: [E2@T2] = 0.93 Max: [E4@T2] = 1.21
- Compressive modulus of elasticity:
  Min: [E3@T2] = 0.93 Max: [E6@T1] = 1.04
- Tensile strength:
  Min: [E3@T2] = 0.93 Max: [E6@T1] = 1.04

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Durability > Adhesives > Glass Transition Temperature

Ei @ E1:

For both adhesives:

- Tg ↓ immersion in water [E2]
  ↑ outdoor [E3, E4, E5, E6]



Retention (@ 28 days):

ADH1 Min: [E2@T2] = 0.94 Max: [E5@T2] = 1.22

ADH2 Min: [E2@T2] = 0.96 Max: [E5@T2] = 1.22

Durability > Adhesives > Glass Transition Temperature

Ei @ E1:

For both adhesives:

- Tg ↓ immersion in water [E2]
  ↑ outdoor [E3, E4, E5, E6]

Retention (@ 28 days):

ADH1 Min: [E2@T2] = 0.94 Max: [E5@T2] = 1.22

ADH2 Min: [E2@T2] = 0.96 Max: [E5@T2] = 1.22

Durability > Adhesives > Tensile properties

Ei @ E1:

ADH1 Tensile properties ↓ [E2, E3, E4, E5, E6]

ADH2 Tensile properties ↓ [E2]
↑ [E3, E4, E5, E6]

Retention (@ 28 days):

ADH1
Tensile strength Min: [E2@T2] = 0.33 Max: [E5@T1] = 1.09
Tensile modulus Min: [E2@T2] = 0.25 Max: [E5@T1] = 1.16

ADH2
Tensile strength Min: [E2@T2] = 0.44 Max: [E6@T1] = 1.36
Tensile modulus Min: [E2@T2] = 0.39 Max: [E6@T1] = 1.48

Durability > Adhesives > Tensile properties

Ei @ E1:

ADH1 Tensile properties ↓ [E2, E3, E4, E5, E6]

ADH2 Tensile properties ↓ [E2]
↑ [E3, E4, E5, E6]

Retention (@ 28 days):

ADH1
Tensile strength Min: [E2@T2] = 0.33 Max: [E5@T1] = 1.09
Tensile modulus Min: [E2@T2] = 0.25 Max: [E5@T1] = 1.16

ADH2
Tensile strength Min: [E2@T2] = 0.44 Max: [E6@T1] = 1.36
Tensile modulus Min: [E2@T2] = 0.39 Max: [E6@T1] = 1.48



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Durability > CFRP laminates

Ei @ E1:

- Tensile properties => variations less than 10%

Retention (@ 28 days):

- Tensile strength:

  Min: [L50, E1@T2]: 0.99 Max: [L10, E3@T1], L: 1.16

- Tensile modulus:

  Min: [L50, E1@T2]: 0.86 Max: [L10, E1@T1]: 1.09



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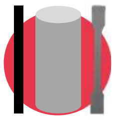
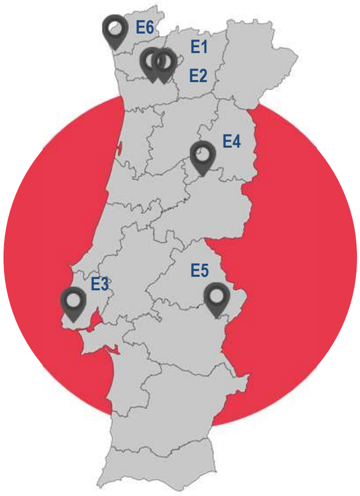


Materials
(Concrete, adhesive and CFRP)

T3
T4
…
T10



Prediction models
Correlation with accelerated tests in lab

Acknowledgments > Companies

S&P Clever Reinforcement Ibérica, Lda
edp
APDL
Sika
Artecanter Indústria Criativa
Pré-fabricados tecnipor
VIALAM
HILTI
Novo Modelo Europa, S.A.

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Durability of bond with EBR and NSM strengthening techniques

Ricardo Cruz

Durability of bond with EBR and NSM strengthening techniques

Durabilidade da aderência das técnicas EBR e NSM

October 30th, 2020

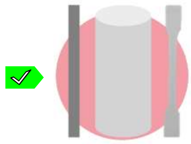
Ricardo Cruz

Universidade do Minho

Outline

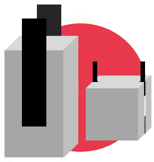
- ❑ **Introduction/Motivation/Objectives**
- ❑ **Experimental program**
  - ❑ Brief description
  - ❑ Environment characterization
  - ❑ Specimen's geometry and test configuration
- ❑ **Results at T0**
- ❑ **Results during the time:**
  - ❑ Results T1/Results T2 – evolution including T0
  - ❑ Failure modes
  - ❑ Reduction factors
- ❑ **Conclusions**

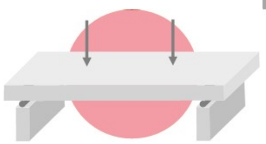
Introduction/Motivation/Objectives



Materials
(Concrete, epoxy, and CFRP)

Bond Specimens
(EBR and NSM)





Slabs under
sustained load
(EBR and NSM)

Exposure to outdoor environmental actions

E1: Reference (indoor)
E2: Immersion in water
E3: Outdoor - carbonatation
E4: Outdoor - freeze-thaw attack
E5: Outdoor - elevated temperatures
E6: Outdoor - chloride exposure

Numerical and Analytical Simulations

Comparison with accelerated ageing studies performed in laboratory

Design Recommendations

❑ **Objective**: to evaluate de **durability** of bond between **CFRP laminates** and **concrete** under **real outdoor conditions** by comparing with **reference environments**.

Experimental program

❑ **Main objective:** to determine **along the time** and depending on the **type of environment of exposure condition**, mainly, the evolution of **specimen's stiffness**, **bond strength** and **failure modes**.

❑ **Main steps:**
- **Specimens production**
  - Casting
  - EBR sand blasting / NSM groove's opening
  - Strengthening
  - Storage before installation
- **T0 tests**
- **Installation**
- **Visits to Experimental Stations**
- **T1 Collecting – T1 Tests**
- **Visits to Experimental Stations**
- **T2 Collecting – T2 Tests**

T0 ⇩ **After the production of the specimens to determine it's initial mechanical properties**

T1 **T2** ⇩ ⇩ **After 1 (T1) and 2 (T2) years of exposure to the environments (E1 – E6)**

Experimental program

- Specimen's production

Casting

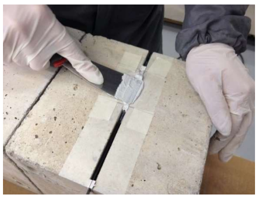
→

EBR – Sandblasting

NSM – Groove's opening

CFRP placement

EBR



NSM

→

Storage inside the laboratory until the installation

Experimental program

- Installation

Reference environments

E1@UMinho

20 °C / 55% RH

E2@UMinho

Immersion in water at 20 °C

Experimental program

- Installation

Real outdoor environments

Orientation of exposure: <u>Sunrise-sunset</u>

Specimens placed together side by side to avoid the risk of tipping

Placement of a grid between the specimens and the ground

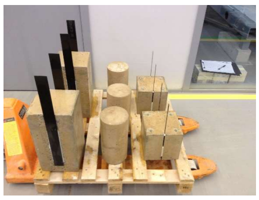
Experimental program

- Collecting and storage before test – T1 and T2

Collecting
E3-E6

Storage during two weeks for humidity control
E3-E6

Test immediately after removing from water
E2



Experimental program

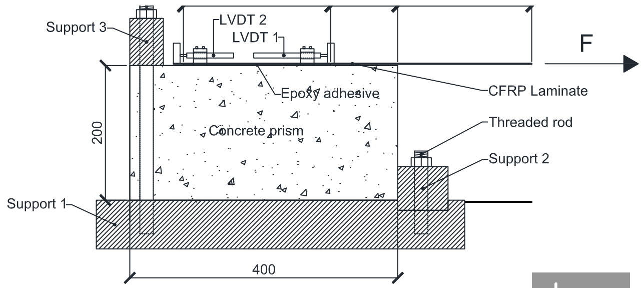
- ❑ **Specimen geometry and test configuration**

EBR

Concrete prism: 200×200×400 mm^3
CFRP laminate: 50×1.2 mm^2
Bond length: 220 mm

Properties to be evaluated:

- Force *versus* slip
- Maximum Force (F_{max})
- Slip at F_{max}
- Bond strength τ_{max}
- Local bond slip law $\tau - s$
- Failure modes



Experimental program

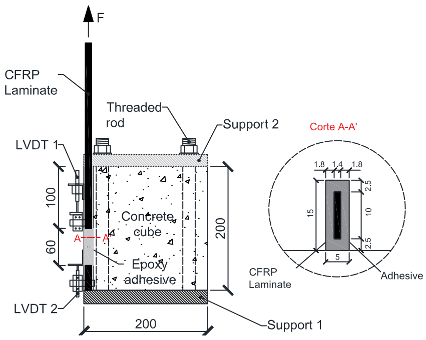
- ❑ **Specimen geometry and test configuration**

NSM

Concrete cube: 200×200×200 mm^3
CFRP laminate: 10×1.4 mm^2
Bond length: 60 mm

Properties to evaluate:

- Force *versus* slip
- Maximum Force (F_{max})
- Slip at F_{max}
- Bond strength τ_{max}
- Local bond slip law $\tau - s$
- Failure modes

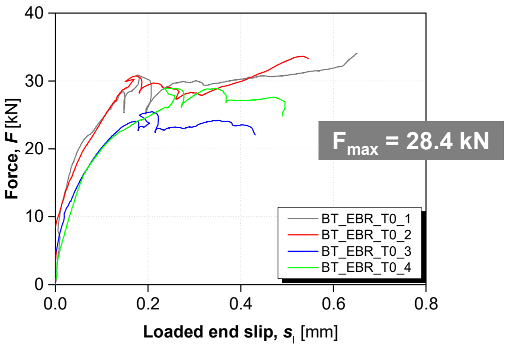


Results at T0

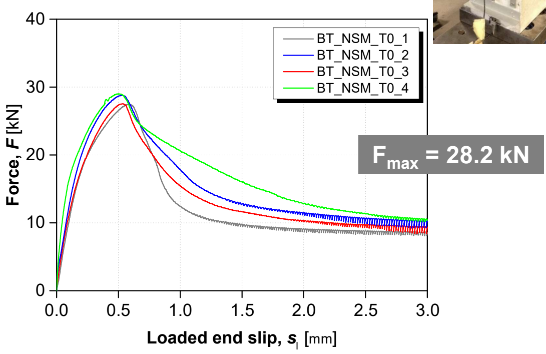
- Curves pullout force *versus* slip

T0

EBR



NSM

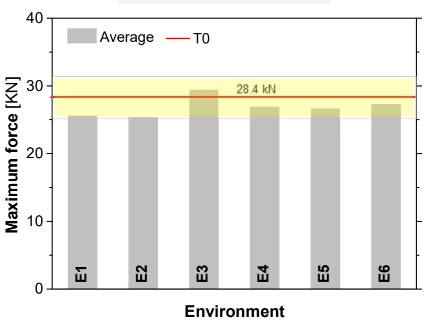


Results during the time

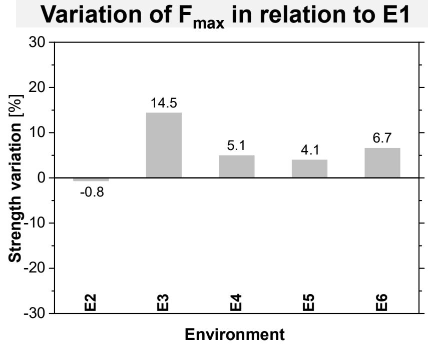
- EBR - F_{max}

T1

Maximum force



Variation of F_{max} in relation to E1



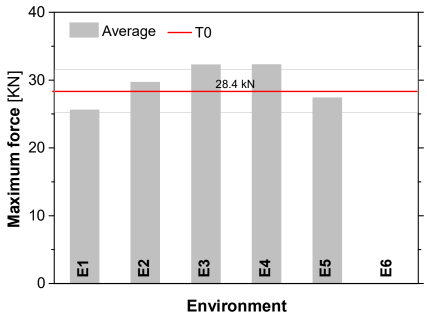
F_{max} increased in relation to E1, specially in E3

Results during the time

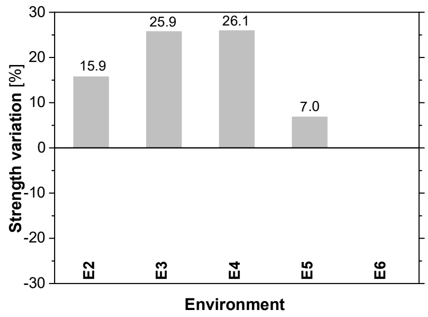
❑ **EBR - F_{max}**

T2

Maximum force



Variation of F_{max} in relation to E1



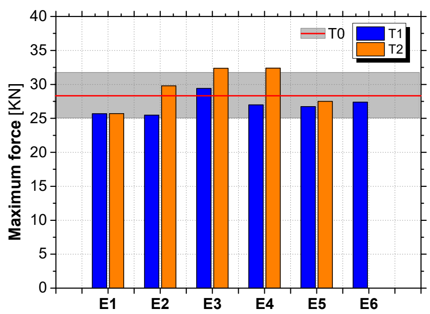
F_{max} increased in relation to E1 in environments, mainly in E3 and E4

Results during the time

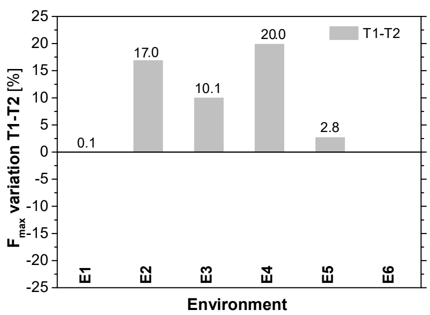
❑ **EBR - F_{max}**

T1 **T2**

Maximum force



Variation of F_{max} from T1 to T2



- **In E1, the F_{max} is similar in T1 and T2**
- **F_{max} increased in all environments mainly in E2 and E4**

Results during the time

- **EBR – Failure modes in each environment**

T1	T2

E1 – E6

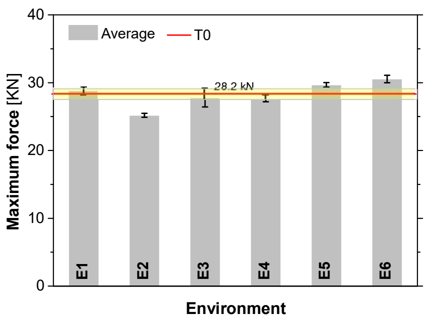
C
Cohesive failure of concrete

Results during the time

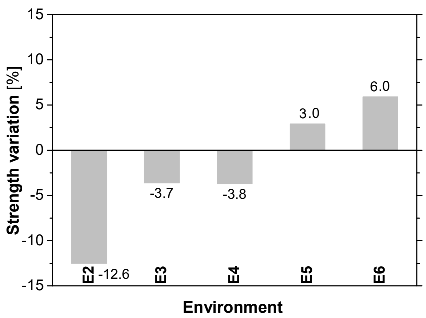
- **NSM - F_{max}**

T1

Maximum force



Variation of F_{max} in relation to E1



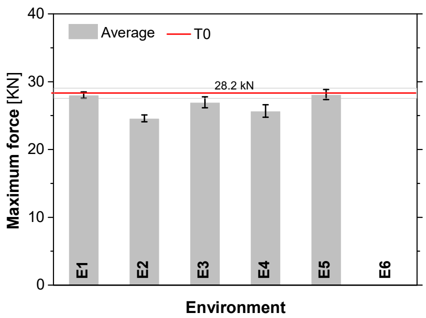
- **F_{max} reduced in E2 (mainly), E3 and E4**
- **F_{max} slightly increased in E5 and in E6**

Results during the time

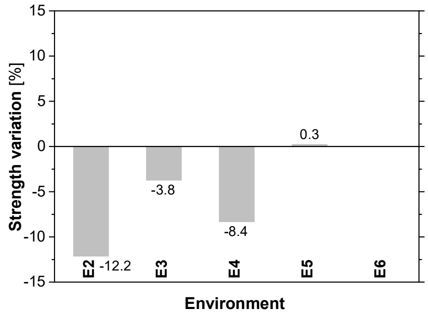
❑ **NSM - F_{max}**

T2

Maximum force



Variation of F_{max} in relation to E1



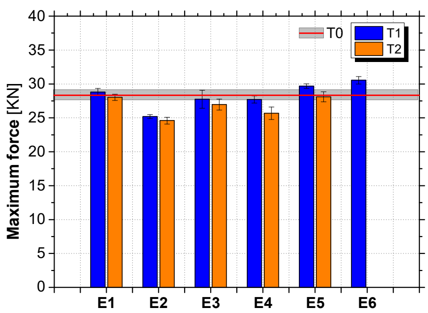
- **F_{max} reduced E2 (mainly), E3 and E4**
- **In E5, F_{max} is similar to E1**

Results during the time

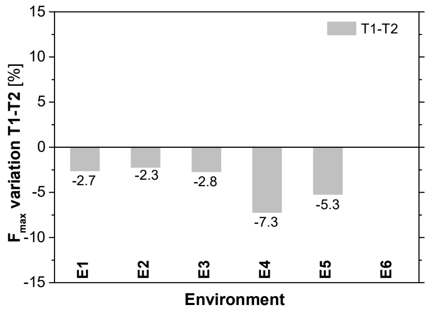
❑ **NSM - F_{max}**

T1 **T2**

Maximum force



Variation of F_{max} from T1 to T2



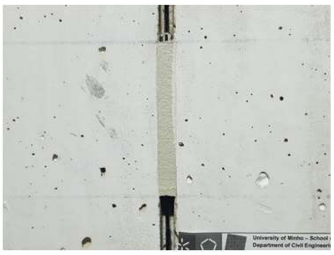
- **A slightly decrease of F_{max} was observed in E1, E2 and E3 environments and a higher reduction was observed in E4 and in E5**

Results during the time

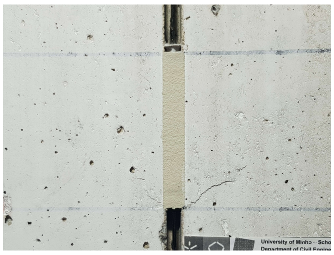
- NSM – Failure modes in each environment

T1	T2

E1	E3	E5	E4



I-FA
Debonding at CFRP-Adhesive interface



I-FA + CC
Debonding at CFRP-Adhesive interface with concrete cracking

I-FA + CS
Debonding at CFRP-Adhesive interface with concrete splitting

Results during the time

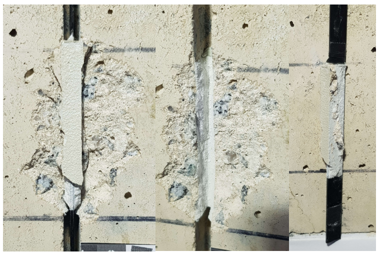
- NSM – Failure modes in each environment

T1	T2

E2

I-AC + CS
Debonding at Adhesive-Concrete interface with concrete splitting

I-FA + C-C + CS
Debonding at CFRP-Adhesive interface and cohesive failure of concrete with concrete splitting



C-A + CS
Cohesive failure of adhesive with concrete splitting

Environmental retention factors

- **Retention factors based on de evolution of F_{max} from T0 to T1 and T2**

EBR

Environment	RF_T1	RF_T2
E1	0.90	**0.90**
E2	0.90	1.05
E3	1.04	1.14
E4	0.95	1.14
E5	0.94	0.97
E6	0.96	-

NSM

Environment	RF_T1	RF_T2
E1	1.02	0.99
E2	0.89	**0.87**
E3	0.98	0.96
E4	0.98	0.91
E5	1.05	1.00
E6	1.08	

Conclusions

- From **T0 to T1**, F_{max} **decreased in EBR** technique and **remains almost constant** in the case of **NSM** technique.
- The **bond strength** tends to **slightly increase** in the case of **EBR** technique with the **environmental exposure conditions**, while in the case of **NSM** technique, the **bond strength tends to decrease**.
- The **water immersion** affects more the **NSM** specimens than **EBR** specimens.
- The dominant **failure mode** in **EBR** technique remained the same regardless the type of **environmental exposure condition**.
- The several **failure modes** characterize the **NSM** technique, being the debonding at CFRP/adhesive dominant failure.
- Up to **2 years of exposure**, **retention factors of strength** still remain higher than **~0.9**.

Acknowledgments

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Acknowledgments > *Companies*

S&P Clever Reinforcement Ibérica, Lda

edp

APDL

Sika

Artecanter Indústria Criativa

Pré-fabricados tecnipor

Vialam

Hilti

Novo Modelo Europa, S.A.

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- This work was supported by **FEDER** funds through the Operational Program for Competitiveness Factors – **COMPETE** and National Funds through **FCT** (Portuguese Foundation for Science and Technology) under the project **FRPLongDur** POCI-01-0145-FEDER-016900 and partly financed by the project POCI-01-0145-FEDER 007633SFRH/BD/80682/2011.

Durability and long-term behaviour of slabs strengthened according to EBR and NSM techniques

Luís Correia

Durability and long-term behaviour of slabs strengthened according to EBR and NSM techniques

October 30th, 2020

Luís Correia

Universidade do Minho

Outline

- Introduction
- Specimens definition
- Experimental Program
- Short-term study
- Long-term study
- Conclusions
- Acknowledgments

Introduction

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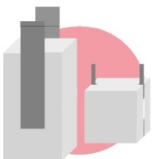
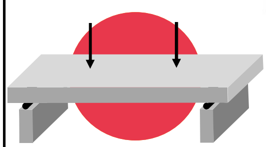
Introduction > *FRPlongDur Project*

EXPERIMENTAL PROGRAM

Materials
(Concrete, epoxy, and CFRP)



Bond Specimens
(EBR and NSM)



Slabs under sustained load
(EBR and NSM)

Exposure to outdoor environmental actions

E1: Reference (Indoor)
E2: Immersion in water
E3: Outdoor - carbonatation
E4: Outdoor - freeze-thaw attack
E5: Outdoor - elevated temperatures
E6: Outdoor – chloride exposure

Numerical and Analytical Simulations

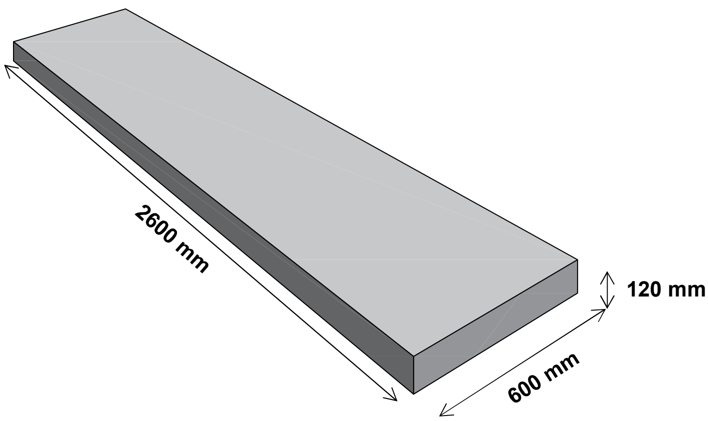
Comparison with accelerated ageing studies performed in laboratory

Design Recommendations

Specimens definition

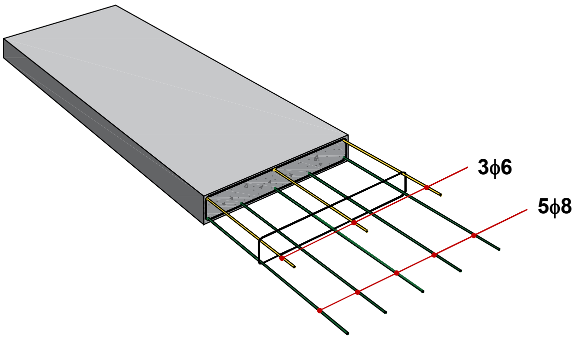
Universidade do Minho

Specimens definition > *Reinforced Concrete Slabs*



- **Geometry**
  - Real scale
- **Concrete**
  - f_{cm} = 41.5 MPa (@ time T0)
  - E_{cm} = 29.1 GPa (@ time T0)

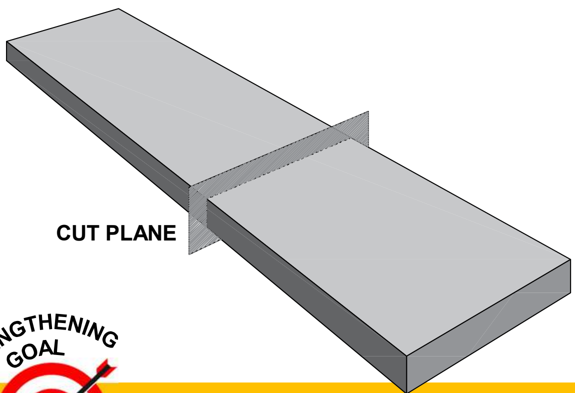
Specimens definition > *Reinforced Concrete Slabs*

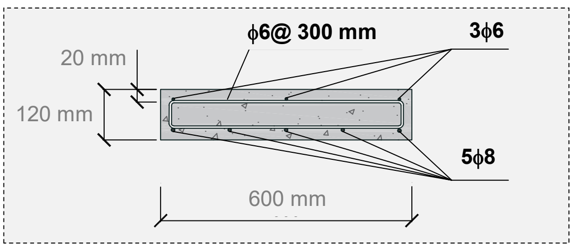


- **Geometry**
  - Real scale
- **Concrete**
  - f_{cm} = 41.5 MPa (@ time T0)
  - E_{cm} = 29.1 GPa (@ time T0)
- **Steel**

(Ø8/Ø6)
  - f_y = (528 / 581) MPa (@ time T0)
  - f_t = (687 / 698) MPa (@ time T0)
  - E_s = (241 / 228) GPa (@ time T0)

Specimens definition > *Reinforced Concrete Slabs*



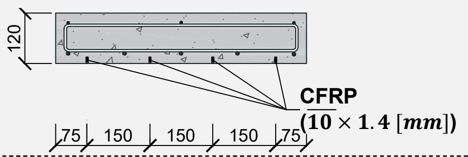


Cross Section

Double the Ultimate Load ≈ 60 kN

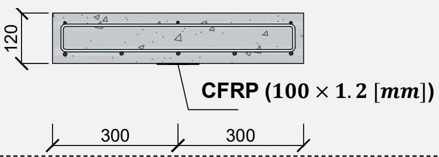
Specimens definition > *Reinforced Concrete Slabs*

Non-prestressed NSM Solution



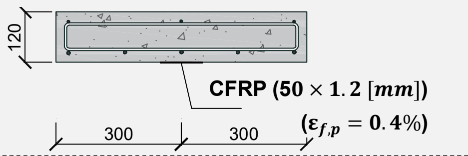
Cross Section

Non-prestressed EBR Solution



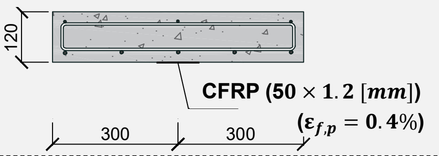
Cross Section

Prestressed EBR Solution (MA System)



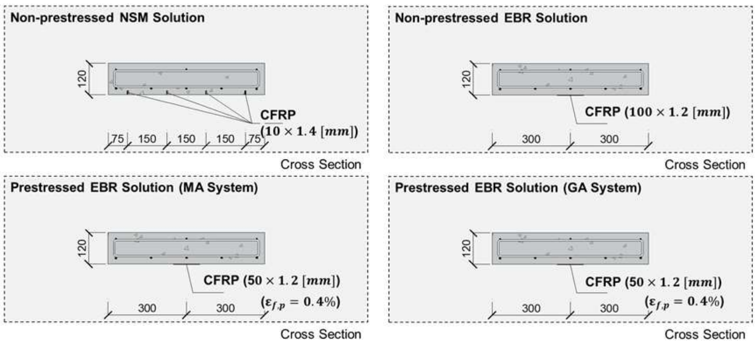
Cross Section

Prestressed EBR Solution (GA System)



Cross Section

Specimens definition > *Reinforced Concrete Slabs*



❑ **CFRP**

$(10 \times 1.4\ [mm])$

- f_f = 2005 MPa (@ time T0)
- E_f = 164 GPa (@ time T0)

$(100 \times 1.2\ [mm])$

- f_f = 2620 MPa (@ time T0)
- E_f = 188 GPa (@ time T0)

$(50 \times 1.2\ [mm])$

- f_f = 2526 MPa (@ time T0)
- E_f = 190 GPa (@ time T0)

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Experimental Program

Experimental Program > *Short and Long-term study*

Long-term

Creep tests in 6 different environments

6 × NSM | EBR | MA | GA

START ⟷ **10 years**

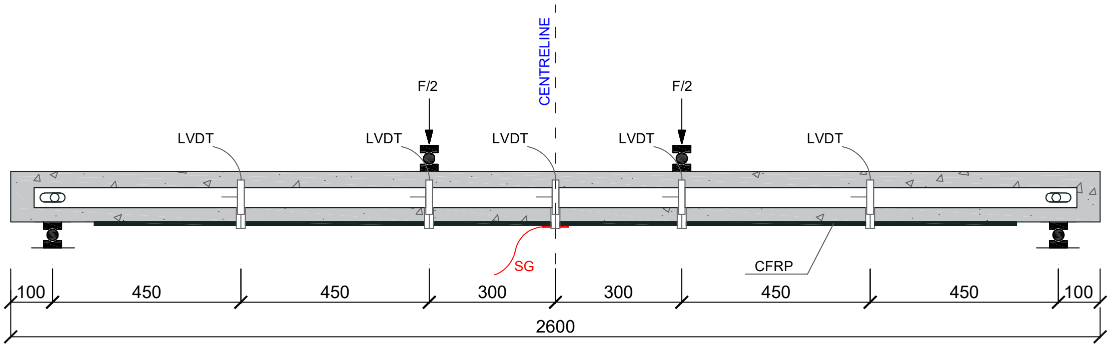
(time) **T0** **T1** **T2** T3 T4 T5 T6 T7 T8 T9 T10

Short-term

Flexural tests up to failure

REF | NSM | EBR | MA | GA

Experimental Program > *Short-term study (test set-up)*



Short-term

Flexural tests up to failure

REF NSM EBR MA GA

Experimental Program > *Short-term study (test set-up)*

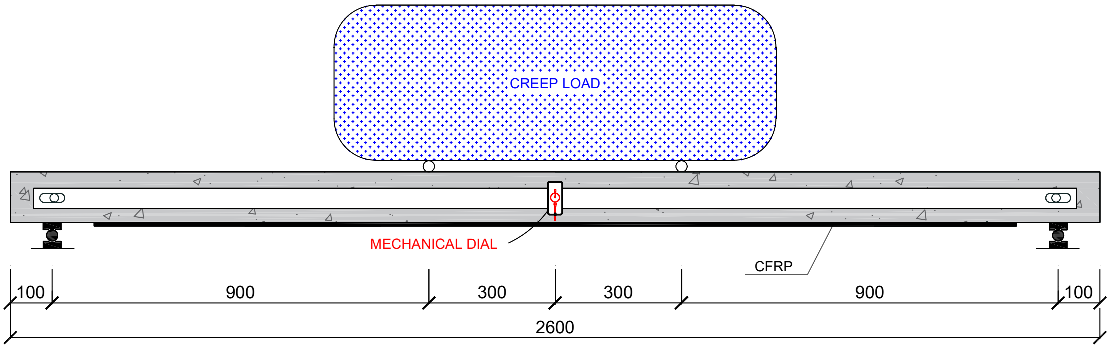
Short-term

Flexural tests up to failure

REF NSM EBR MA GA

Durability and long-term behaviour of slabs strengthened according to EBR and NSM techniques **L. Correia | 15**

Experimental Program > *Long-term study (test set-up)*



Long-term

Creep tests in 6 different environments

6 × **NSM** **EBR** **MA** **GA**

Durability and long-term behaviour of slabs strengthened according to EBR and NSM techniques **L. Correia | 16**

Experimental Program > *Long-term study (test set-up)*

Long-term

Creep tests in 6 different environments

6 × **NSM** **EBR** **MA** **GA**

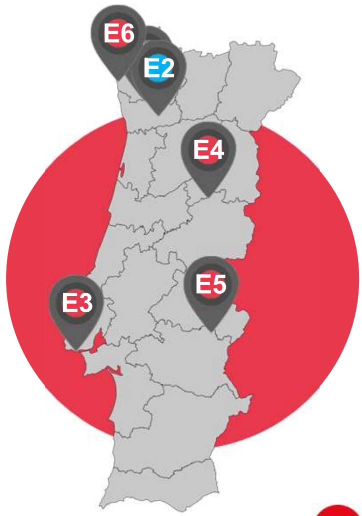
Experimental Program > *Long-term study (test set-up)*

Long-term

Creep tests in 6 different environments

6 × **NSM** **EBR** **MA** **GA**

E1	**Lab.** (20ºC & 55% RH)
E2	**Lab.** (20ºC & 100% RH)
E3	**Outdoor** (Lisbon)
E4	**Outdoor** (Serra da Estrela)
E5	**Outdoor** (Elvas)
E6	**Outdoor** (Viana do Castelo)



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Short-term study

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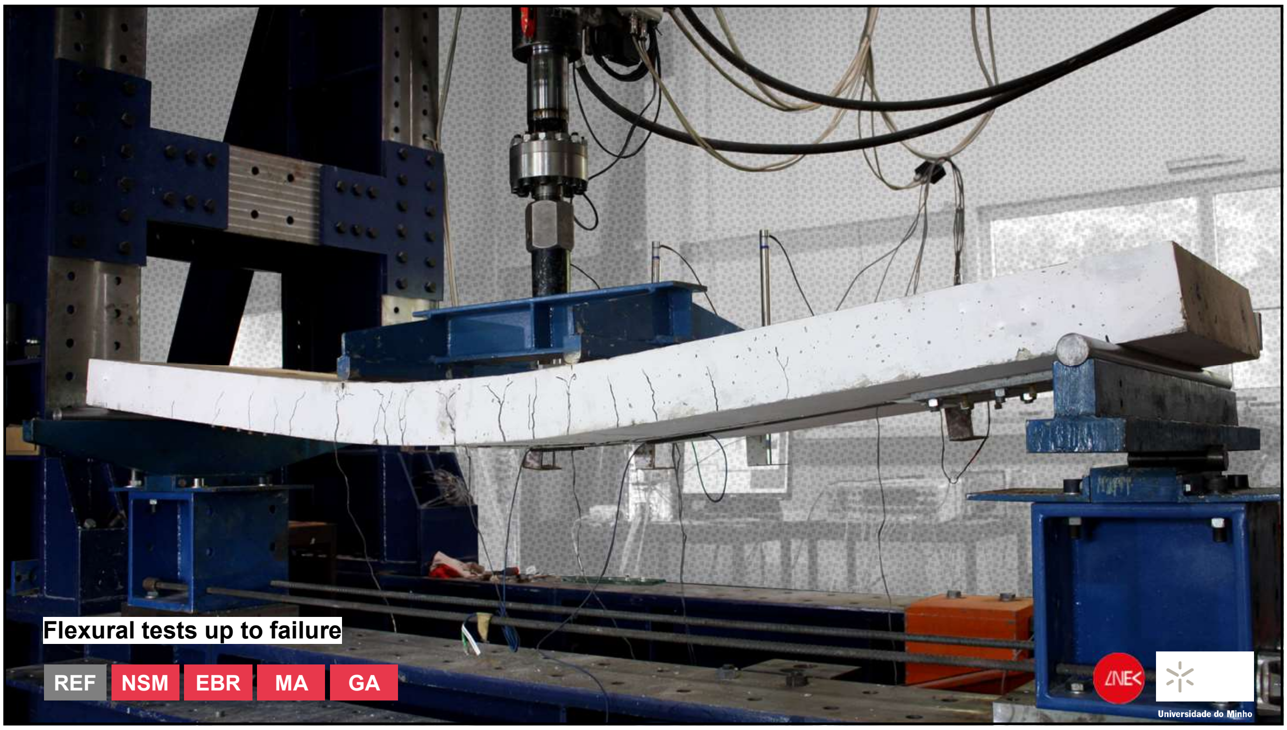
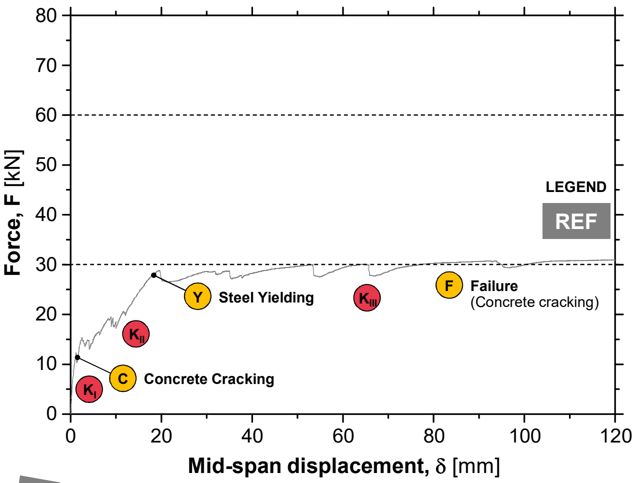
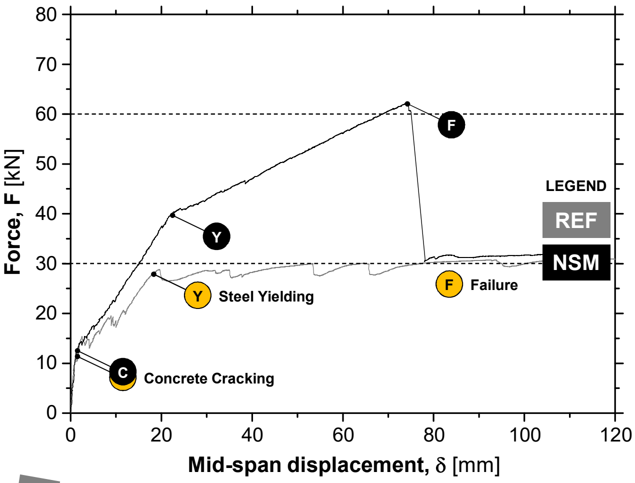


Short-term study > *Force / Mid-span displacement*



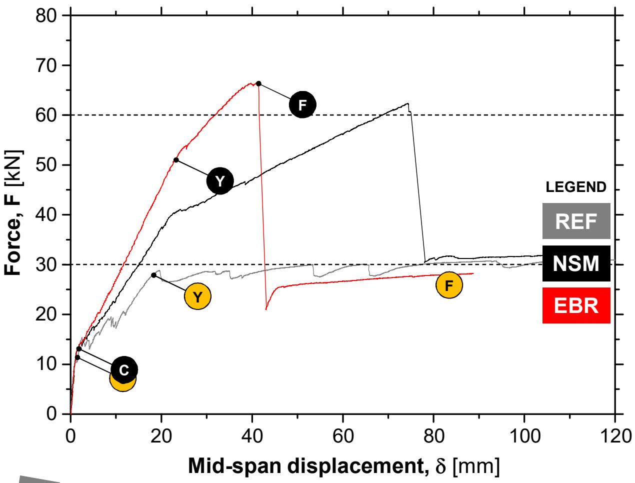
Short-term study > *Force / Mid-span displacement*



NSM

- C Similar Load
- Y Higher load
- F CFRP rupture

Short-term study > *Force / Mid-span displacement*



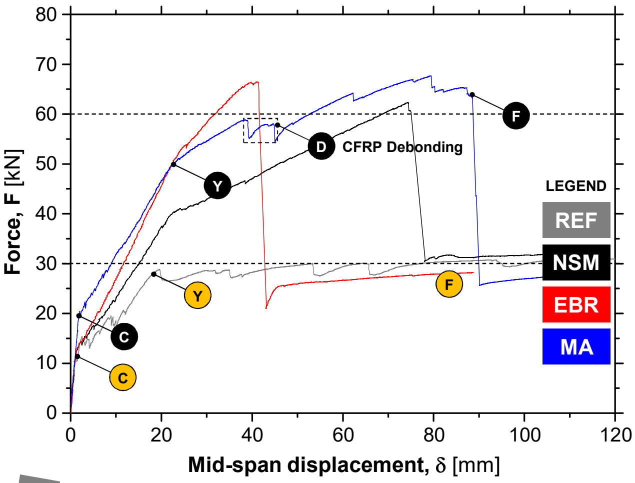
NSM

- C Similar Load
- Y Higher load
- F CFRP rupture

EBR

- C Similar Load
- Y Higher load
- F CFRP debonding

Short-term study > *Force / Mid-span displacement*



NSM

- C Similar Load
- Y Higher load
- F CFRP rupture

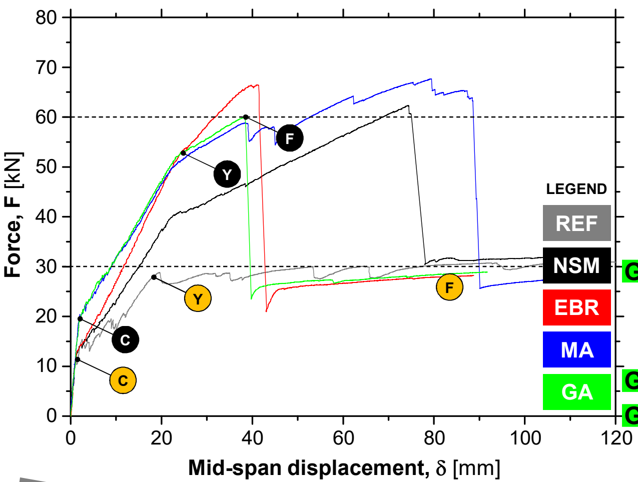
EBR

- C Similar Load
- Y Higher load
- F CFRP debonding

MA

- C Higher Load
- Y Higher load
- F CFRP rupture

Short-term study > *Force / Mid-span displacement*



NSM

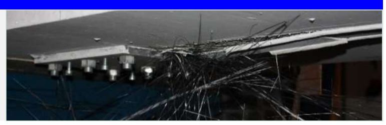
- C Similar Load
- Y Higher load
- F CFRP rupture

EBR

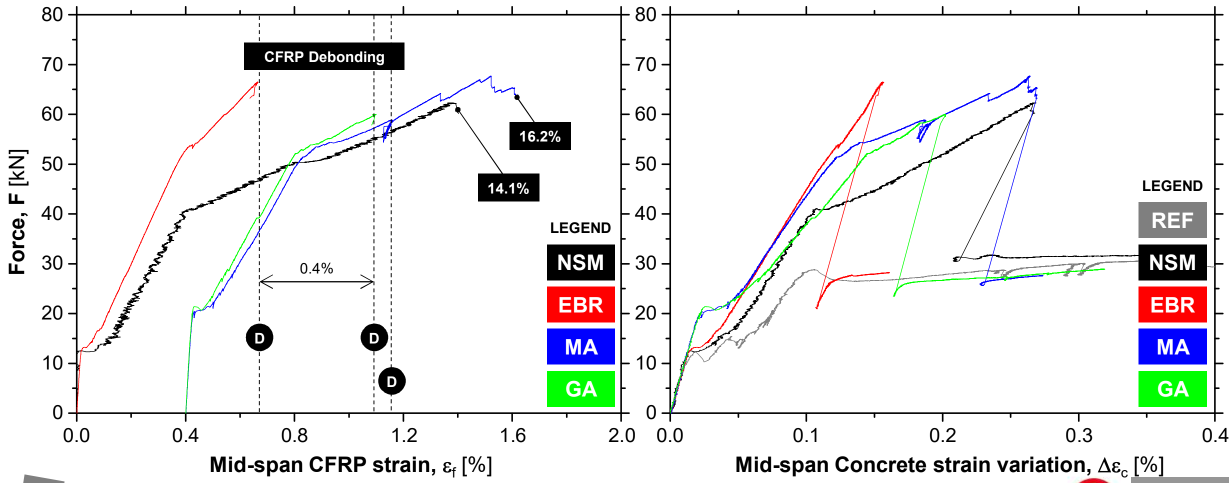
- C Similar Load
- Y Higher load
- GA F CFRP debonding

MA

- GA C Higher Load
- GA Y Higher load
- F CFRP rupture



Short-term study > *Force / Mid-span Strain*

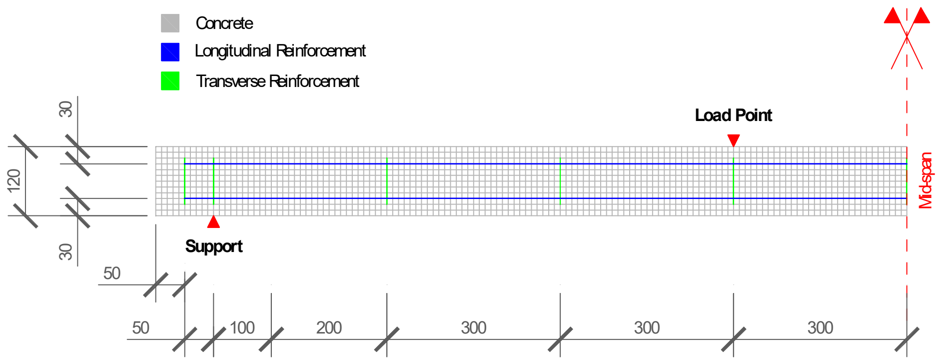


Short-term study > *Numeric Simulations (Model geometry and Mesh)*

- Slabs were simulated as a plane state problem
- Different FE meshes were used

Slab:

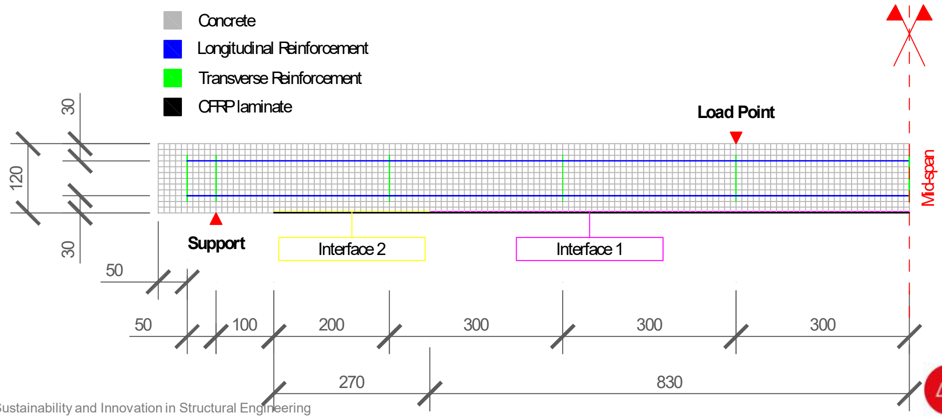
REF



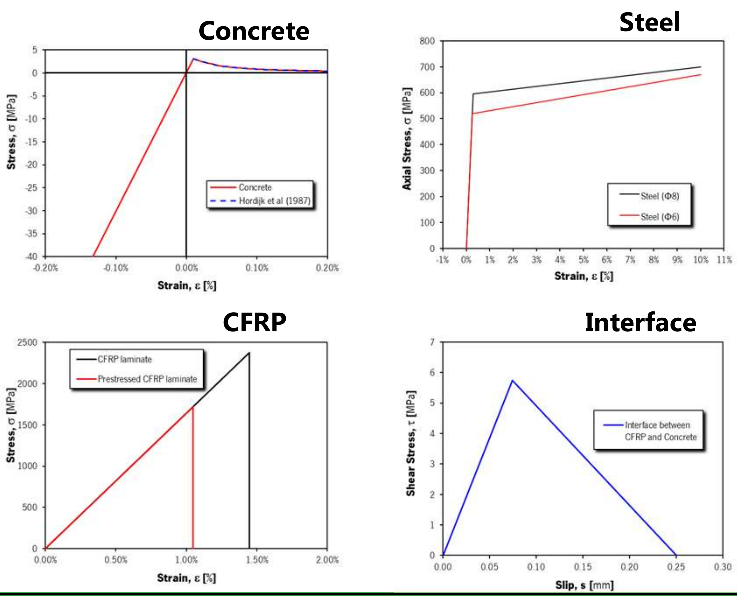
Short-term study > *Numeric Simulations (Model geometry and Mesh)*

- Slabs were simulated as a plane state problem
- Different FE meshes were used

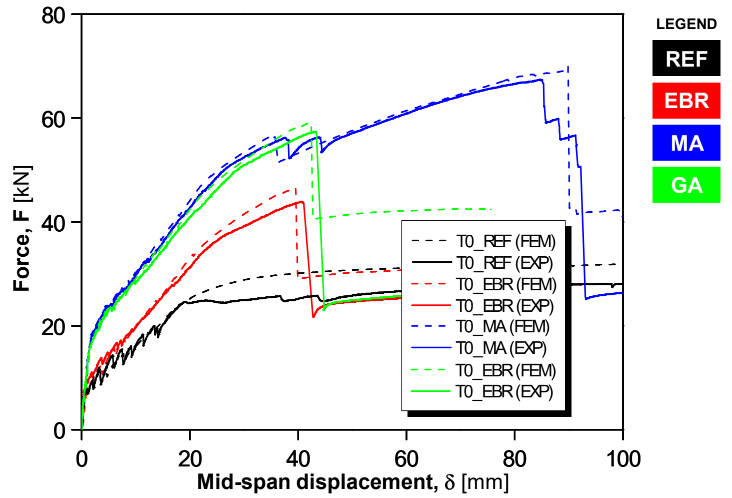
Slab:
EBR
MA
GA



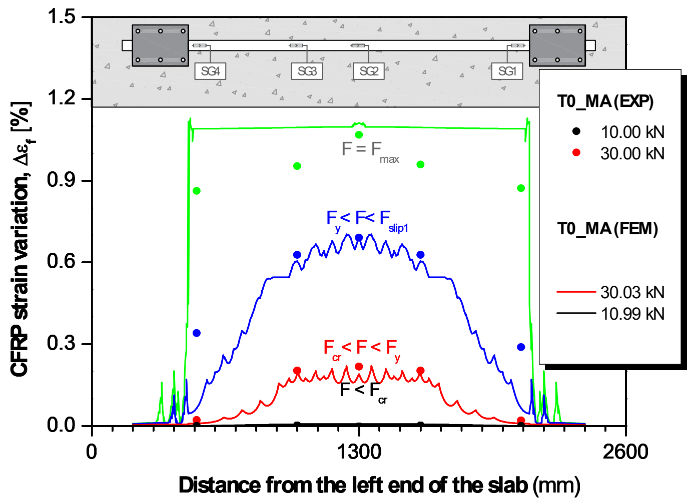
Short-term study > *Numeric Simulations (Constitutive Material Models)*



Short-term study > *Numeric Simulations (Force – Mid-span displacement)*



Short-term study > *Numeric Simulations (CFRP strain variation with MA system)*



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Long-term study

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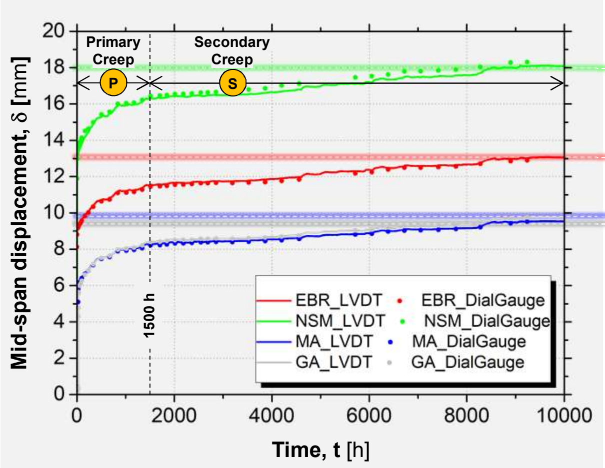
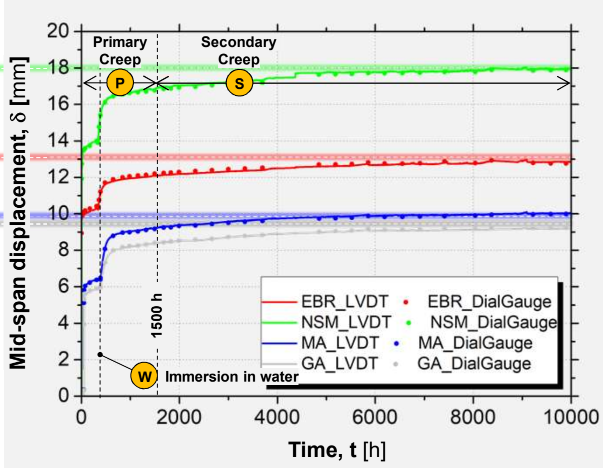
Long-term study > *Mid-span displacement (E1 and E2 environments)*

E1 : Lab. (20ºC & 55%RH)

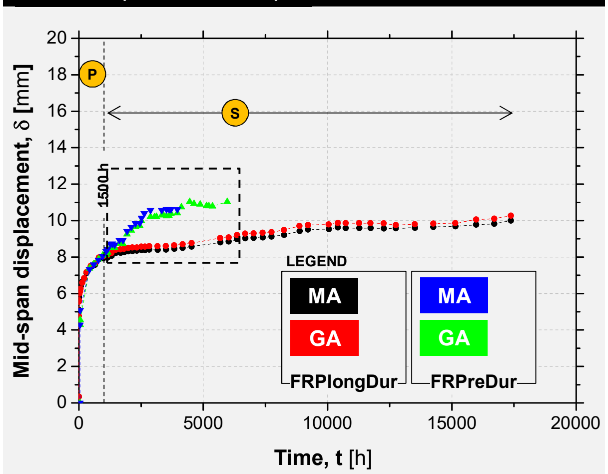


E2: Immersion in water (20ºC & 100% RH)

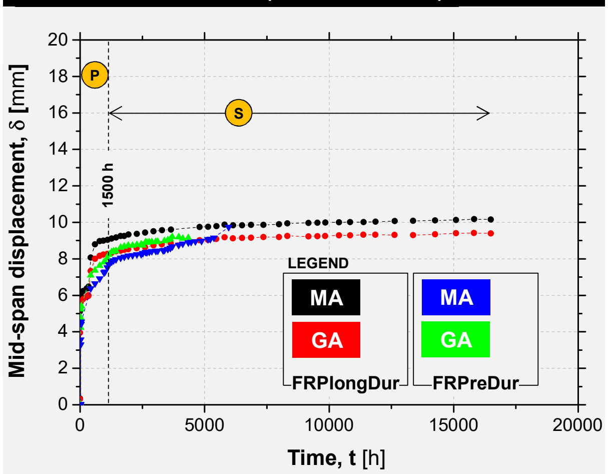


Long-term study > *Mid-span displacement (E1 and E2 environments: previous results)*

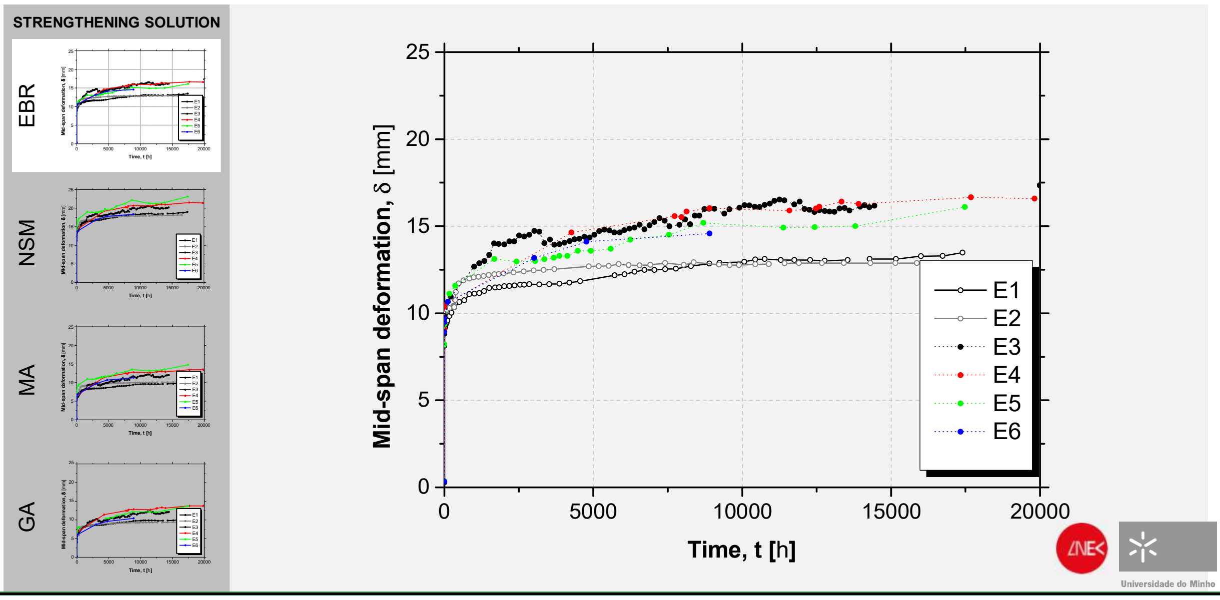
E1 : Lab. (20ºC & 55%RH)



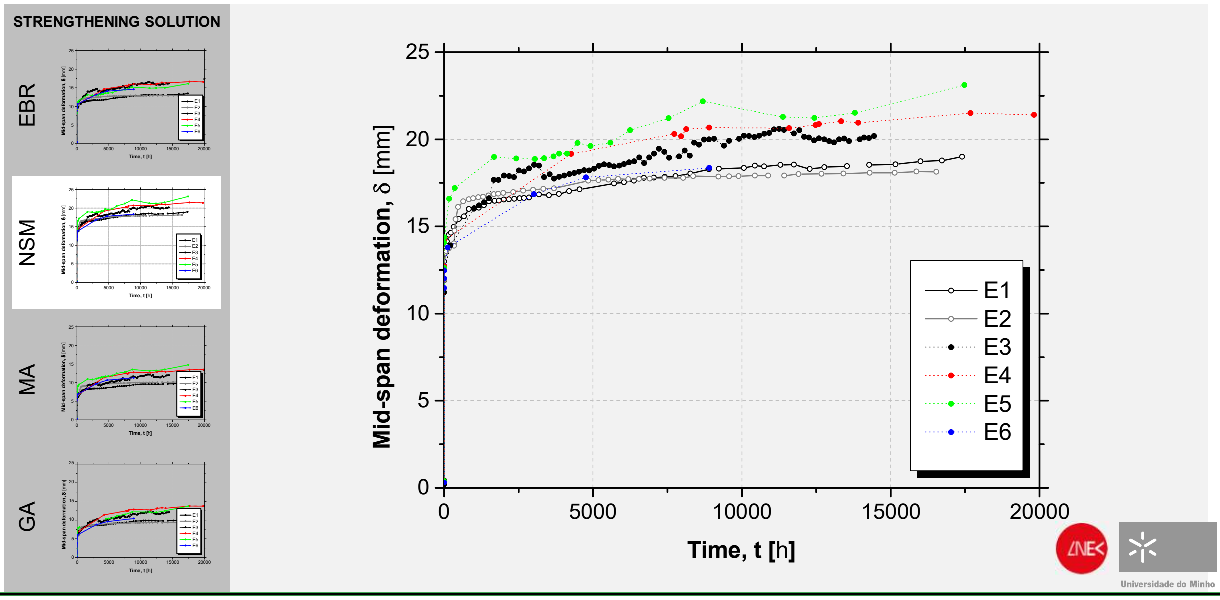
E2: Immersion in water (20ºC & 100% RH)



Long-term study > *Environment influence (Creep displacements)*

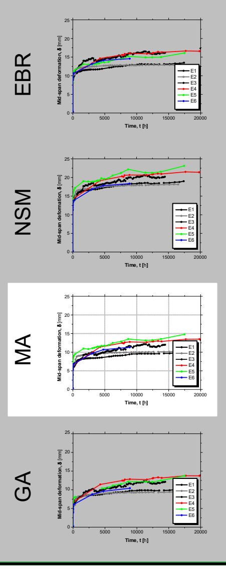


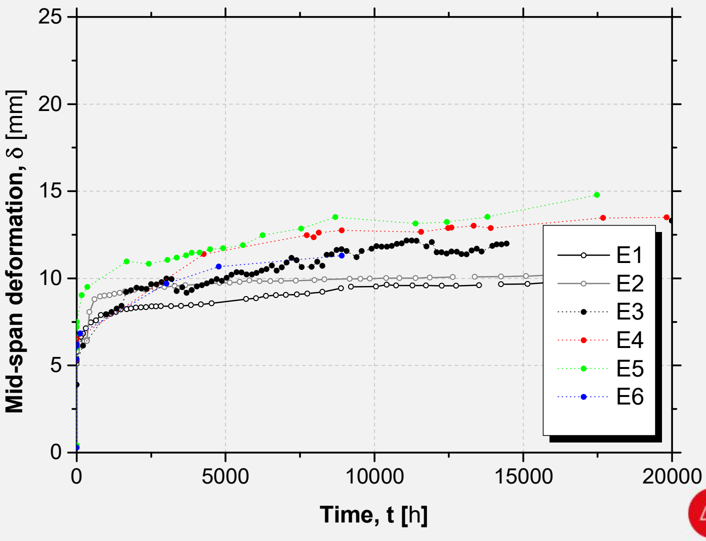
Long-term study > *Environment influence (Creep displacements)*



Long-term study > *Environment influence (Creep displacements)*

STRENGTHENING SOLUTION





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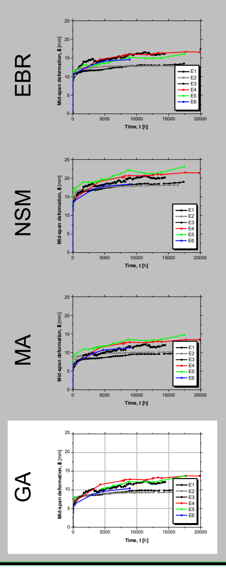
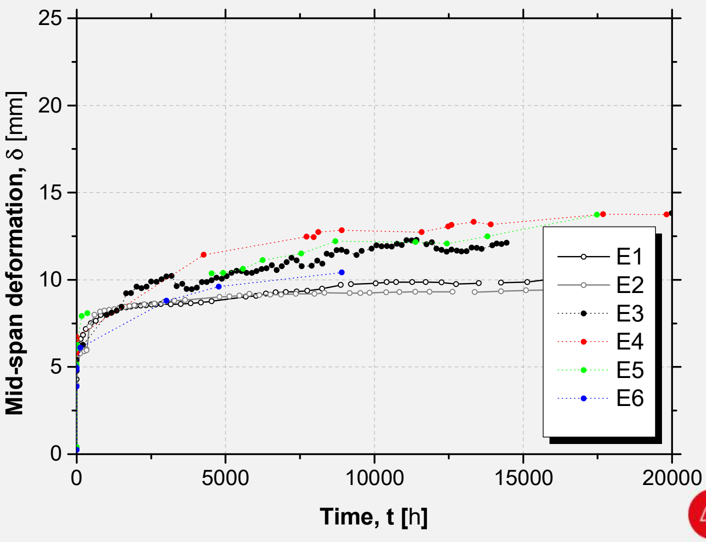
Long-term study > *Environment influence (Creep displacements)*

STRENGTHENING SOLUTION





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Long-term study > *Main Results*

	EBR				NSM				MA				GA			
	δ_{el}	δ_{10}	δ_{C10}	ϕ_{10}	δ_{el}	δ_{10}	δ_{C10}	ϕ_{10}	δ_{el}	δ_{10}	δ_{C10}	ϕ_{10}	δ_{el}	δ_{10}	δ_{C10}	ϕ_{10}
	[mm]	[mm]	[mm]	[-]	[mm]	[mm]	[mm]	[-]	[mm]	[mm]	[mm]	[-]	[mm]	[mm]	[mm]	[-]
E1	7.33	13.1	5.74	0.78	10.3	18.1	7.78	0.75	4.67	9.54	4.87	1.04	4.44	9.77	5.33	1.20
E2	8.32	12.8	4.51	0.54	11.3	18.0	6.67	0.60	4.78	10.0	5.25	1.10	5.09	9.20	4.11	0.81
E3	8.42	16.2	7.79	0.93	11.0	20.2	9.16	0.83	4.78	11.8	7.06	1.48	4.58	12.0	7.39	1.61
E4	8.54	16.0	7.44	0.87	12.1	20.7	8.55	0.71	5.11	12.7	7.06	1.49	5.33	12.8	4.46	1.40
E5	7.89	15.1	7.17	0.91	12.1	21.8	9.67	0.80	5.65	13.3	7.68	1.36	4.83	12.2	7.35	1.52
E6	8.50	14.6	6.08	0.72	10.4	18.4	8.01	0.77	5.13	11.3	6.17	1.26	3.41	10.4	7.01	2.06

Long-term study > *Main Results*

	EBR				NSM				MA				GA			
	δ_{el}	δ_{10}	δ_{C10}	ϕ_{10}	**δ_{el}**	δ_{10}	δ_{C10}	ϕ_{10}	**δ_{el}**	δ_{10}	δ_{C10}	ϕ_{10}	**δ_{el}**	δ_{10}	δ_{C10}	ϕ_{10}
	[mm]	[mm]	[mm]	[-]	[mm]	[mm]	[mm]	[-]	[mm]	[mm]	[mm]	[-]	[mm]	[mm]	[mm]	[-]
E1	**7.33**	13.1	5.74	0.78	**10.3**	18.1	7.78	0.75	**4.67**	9.54	4.87	1.04	**4.44**	9.77	5.33	1.20
E2	**8.32**	12.8	4.51	0.54	**11.3**	18.0	6.67	0.60	**4.78**	10.0	5.25	1.10	**5.09**	9.20	4.11	0.81
E3	**8.42**	16.2	7.79	0.93	**11.0**	20.2	9.16	0.83	**4.78**	11.8	7.06	1.48	**4.58**	12.0	7.39	1.61
E4	**8.54**	16.0	7.44	0.87	**12.1**	20.7	8.55	0.71	**5.11**	12.7	7.06	1.49	**5.33**	12.8	4.46	1.40
E5	**7.89**	15.1	7.17	0.91	**12.1**	21.8	9.67	0.80	**5.65**	13.3	7.68	1.36	**4.83**	12.2	7.35	1.52
E6	**8.50**	14.6	6.08	0.72	**10.4**	18.4	8.01	0.77	**5.13**	11.3	6.17	1.26	**3.41**	10.4	7.01	2.06

Long-term study > *Main Results*

	EBR				NSM				MA				GA			
	δ_{el}	δ_{10}	δ_{C10}	ϕ_{10}	δ_{el}	δ_{10}	δ_{C10}	ϕ_{10}	δ_{el}	δ_{10}	δ_{C10}	ϕ_{10}	δ_{el}	δ_{10}	δ_{C10}	ϕ_{10}
	[mm]	[mm]	[mm]	[-]	[mm]	[mm]	[mm]	[-]	[mm]	[mm]	[mm]	[-]	[mm]	[mm]	[mm]	[-]
E1	7.33	13.1	5.74	0.78	10.3	18.1	7.78	0.75	4.67	9.54	4.87	1.04	4.44	9.77	5.33	1.20
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E3	8.42	16.2	7.79	0.93	11.0	20.2	9.16	0.83	4.78	11.8	7.06	1.48	4.58	12.0	7.39	1.61
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E5	7.89	15.1	7.17	0.91	12.1	21.8	9.67	0.80	5.65	13.3	7.68	1.36	4.83	12.2	7.35	1.52
E6	8.50	14.6	6.08	0.72	10.4	18.4	8.01	0.77	5.13	11.3	6.17	1.26	3.41	10.4	7.01	2.06

Long-term study > *Main Results*

	EBR				NSM				MA				GA			
	δ_{el}	δ_{10}	δ_{C10}	ϕ_{10}	δ_{el}	δ_{10}	δ_{C10}	ϕ_{10}	δ_{el}	δ_{10}	δ_{C10}	ϕ_{10}	δ_{el}	δ_{10}	δ_{C10}	ϕ_{10}
	[mm]	[mm]	[mm]	[-]	[mm]	[mm]	[mm]	[-]	[mm]	[mm]	[mm]	[-]	[mm]	[mm]	[mm]	[-]
E1	7.33	13.1	5.74	0.78	10.3	18.1	7.78	0.75	4.67	9.54	4.87	1.04	4.44	9.77	5.33	1.20
E2	8.32	12.8	4.51	0.54	11.3	18.0	6.67	0.60	4.78	10.0	5.25	1.10	5.09	9.20	4.11	0.81
E3	8.42	16.2	7.79	0.93	11.0	20.2	9.16	0.83	4.78	11.8	7.06	1.48	4.58	12.0	7.39	1.61
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E6	8.50	14.6	6.08	0.72	10.4	18.4	8.01	0.77	5.13	11.3	6.17	1.26	3.41	10.4	7.01	2.06

Durability and long-term behaviour of slabs strengthened according to EBR and NSM techniques **L. Correia | 43**

Long-term study > *Main Results*

	EBR				NSM				MA				GA			
	δ_{el}	δ_{10}	δ_{C10}	ϕ_{10}	δ_{el}	δ_{10}	δ_{C10}	ϕ_{10}	δ_{el}	δ_{10}	δ_{C10}	ϕ_{10}	δ_{el}	δ_{10}	δ_{C10}	ϕ_{10}
	[mm]	[mm]	[mm]	[-]	[mm]	[mm]	[mm]	[-]	[mm]	[mm]	[mm]	[-]	[mm]	[mm]	[mm]	[-]
E1	7.33	13.1	**5.74**	0.78	10.3	18.1	**7.78**	0.75	4.67	9.54	**4.87**	1.04	4.44	9.77	**5.33**	1.20
E2	8.32	12.8	**4.51**	0.54	11.3	18.0	**6.67**	0.60	4.78	10.0	**5.25**	1.10	5.09	9.20	**4.11**	0.81
E3	8.42	16.2	**7.79**	0.93	11.0	20.2	**9.16**	0.83	4.78	11.8	**7.06**	1.48	4.58	12.0	**7.39**	1.61
E4	8.54	16.0	**7.44**	0.87	12.1	20.7	**8.55**	0.71	5.11	12.7	**7.06**	1.49	5.33	12.8	**4.46**	1.40
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E6	8.50	14.6	**6.08**	0.72	10.4	18.4	**8.01**	0.77	5.13	11.3	**6.17**	1.26	3.41	10.4	**7.01**	2.06

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Durability and long-term behaviour of slabs strengthened according to EBR and NSM techniques **L. Correia | 44**

Long-term study > *Main Results*

	EBR				NSM				MA				GA			
	δ_{el}	δ_{10}	δ_{C10}	ϕ_{10}	δ_{el}	δ_{10}	δ_{C10}	ϕ_{10}	δ_{el}	δ_{10}	δ_{C10}	ϕ_{10}	δ_{el}	δ_{10}	δ_{C10}	ϕ_{10}
	[mm]	[mm]	[mm]	[-]	[mm]	[mm]	[mm]	[-]	[mm]	[mm]	[mm]	[-]	[mm]	[mm]	[mm]	[-]
E1	7.33	13.1	**5.74**	0.78	10.3	18.1	**7.78**	0.75	4.67	9.54	**4.87**	1.04	4.44	9.77	**5.33**	1.20
E2	8.32	12.8	**4.51**	0.54	11.3	18.0	**6.67**	0.60	4.78	10.0	**5.25**	1.10	5.09	9.20	**4.11**	0.81
E3	8.42	16.2	**7.79**	0.93	11.0	20.2	**9.16**	0.83	4.78	11.8	**7.06**	1.48	4.58	12.0	**7.39**	1.61
E4	8.54	16.0	**7.44**	0.87	12.1	20.7	**8.55**	0.71	5.11	12.7	**7.06**	1.49	5.33	12.8	**4.46**	1.40
E5	7.89	15.1	**7.17**	0.91	12.1	21.8	**9.67**	0.80	5.65	13.3	**7.68**	1.36	4.83	12.2	**7.35**	1.52
E6	8.50	14.6	**6.08**	0.72	10.4	18.4	**8.01**	0.77	5.13	11.3	**6.17**	1.26	3.41	10.4	**7.01**	2.06

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Long-term study > *Main Results*

	EBR				NSM				MA				GA			
	δ_{el}	δ_{10}	δ_{C10}	ϕ_{10}	δ_{el}	δ_{10}	δ_{C10}	ϕ_{10}	δ_{el}	δ_{10}	δ_{C10}	ϕ_{10}	δ_{el}	δ_{10}	δ_{C10}	ϕ_{10}
	[mm]	[mm]	[mm]	[-]	[mm]	[mm]	[mm]	[-]	[mm]	[mm]	[mm]	[-]	[mm]	[mm]	[mm]	[-]
E1	7.33	13.1	5.74	**0.78**	10.3	18.1	7.78	**0.75**	4.67	9.54	4.87	**1.04**	4.44	9.77	5.33	**1.20**
E2	8.32	12.8	4.51	**0.54**	11.3	18.0	6.67	**0.60**	4.78	10.0	5.25	**1.10**	5.09	9.20	4.11	**0.81**
E3	8.42	16.2	7.79	**0.93**	11.0	20.2	9.16	**0.83**	4.78	11.8	7.06	**1.48**	4.58	12.0	7.39	**1.61**
E4	8.54	16.0	7.44	**0.87**	12.1	20.7	8.55	**0.71**	5.11	12.7	7.06	**1.49**	5.33	12.8	4.46	**1.40**
E5	7.89	15.1	7.17	**0.91**	12.1	21.8	9.67	**0.80**	5.65	13.3	7.68	**1.36**	4.83	12.2	7.35	**1.52**
E6	8.50	14.6	6.08	**0.72**	10.4	18.4	8.01	**0.77**	5.13	11.3	6.17	**1.26**	3.41	10.4	7.01	**2.06**

Long-term study > *Main Results*

	EBR				NSM				MA				GA			
	δ_{el}	δ_{10}	δ_{C10}	ϕ_{10}	δ_{el}	δ_{10}	δ_{C10}	ϕ_{10}	δ_{el}	δ_{10}	δ_{C10}	ϕ_{10}	δ_{el}	δ_{10}	δ_{C10}	ϕ_{10}
	[mm]	[mm]	[mm]	[-]	[mm]	[mm]	[mm]	[-]	[mm]	[mm]	[mm]	[-]	[mm]	[mm]	[mm]	[-]
E1	7.33	13.1	5.74	**0.78**	10.3	18.1	7.78	**0.75**	4.67	9.54	4.87	**1.04**	4.44	9.77	5.33	**1.20**
E2			**↓ -31%**	**0.54**			**↓ -20%**	**0.60**			**↑ 6%**	**1.10**			**↓ -33%**	**0.81**
E3			↑ 19%	**0.93**			↑ 11%	**0.83**			↑ 42%	**1.48**			↑ 34%	**1.61**
E4			↑ 12	**0.87**			↓ -5%	**0.71**			↑ 43%	**1.49**			↑ 17%	**1.40**
E5			↑ 17	**0.91**			↑ 7%	**0.80**			↑ 31%	**1.36**			↑ 27%	**1.52**
E6			↓ -8%	**0.72**			↑ 3%	**0.77**			↑ 21%	**1.26**			↑ 72%	**2.06**

Long-term study > *Main Results*

	EBR				NSM				MA				GA			
	δ_{el}	δ_{10}	δ_{C10}	ϕ_{10}	δ_{el}	δ_{10}	δ_{C10}	ϕ_{10}	δ_{el}	δ_{10}	δ_{C10}	ϕ_{10}	δ_{el}	δ_{10}	δ_{C10}	ϕ_{10}
	[mm]	[mm]	[mm]	[-]	[mm]	[mm]	[mm]	[-]	[mm]	[mm]	[mm]	[-]	[mm]	[mm]	[mm]	[-]
E1	7.33	13.1	5.74	0.78	10.3	18.1	7.78	0.75	4.67	9.54	4.87	1.04	4.44	9.77	5.33	1.20
E2	↓ -31%			0.54	↓ -20%			0.60	↑ 6%			1.10	↓ -33%			0.81
E3	↑ 19%			0.93	↑ 11%			0.83	↑ 42%			1.48	↑ 34%			1.61
E4	↑ 12			0.87	↓ -5%			0.71	↑ 43%			1.49	↑ 17%			1.40
E5	↑ 17			0.91	↑ 7%			0.80	↑ 31%			1.36	↑ 27%			1.52
E6	↓ -8%			0.72	↑ 3%			0.77	↑ 21%			1.26	↑ 72%			2.06

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Conclusions

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Conclusions

❑ **Short-term study**

- All the four strengthening solutions led to **higher ultimate load**.
- From the non-prestressed solutions, the **NSM technique** allowed the **strengthening goal** (double the ultimate load) with the **lowest amount of CFRP**.
- **Similar response** was observed in both **anchorage techniques**. Yet, the **metallic anchors** composing the MA system **prevented a premature failure**.
- Prestress allowed a more efficient use of the materials: (i) achied the strengthening goal with lower amount of CFRP; and (ii) higher CFRP strains at failure.

Conclusions

❑ **Long-term study**

- **Instantaneous mid-span displacement** after the **placement of the gravity load** is **similar to** values registered in the **short-term flexural tests** up to failure.
- **Good correlation** between the test results from the **FRPlondDur** project and previous results.
- **Laboratory environments** lead to the lowest creep developments, **regardless of the strengthening solution**.
- Specimens exposed to the **outdoor environments show higher creep developments**, and **higher creep coefficients:**

  Average creep coefficient in outdoor environments after 10 000h : **0.78, 0.86, 1.40, and 1.65** for **NSM, EBR, MA and GA**, respectively.

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