THE UNIVERSITY of EDINBURGH
School of Engineering

BRE CENTRE for FIRE SAFETY ENGINEERING

Damage assessment, residual cyclic behaviour and repair of fire-exposed reinforced concrete columns

Preliminary experimental results from fire resistance & residual cyclic loading tests

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Introduction

- Challenging RISK project:
  - *"It aims to produce new knowledge on the performance of* ***existing*** ***reinforced concrete structures*** *subjected to* ***earthquake*** *and* ***fire hazards*** *and to develop an integrated framework for performance-based assessment and structural mitigation."*

- Focus of this particular study:
  - Experimental assessment of the residual cyclic response of fire-damaged RC columns
  - Effectiveness of FRP confinement (wrapping) in repairing and retrofitting fire-damaged RC columns

CHALLENGING RISK

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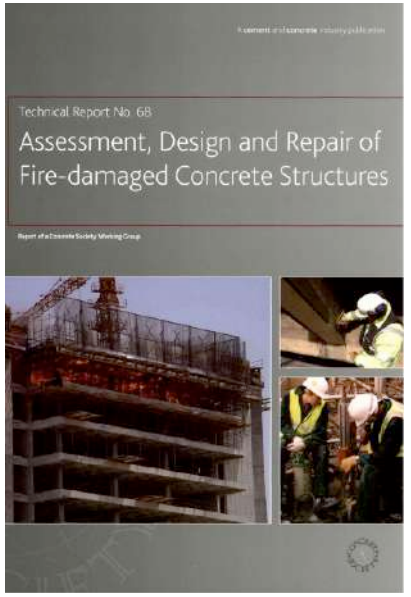
Motivation

- Property protection, performance-based requirements against multiple hazards, structural resilience…:
  - …are become increasingly important and popular for buildings and infrastructure
- RC structures historically considered to perform well in fires and in most cases can be repaired for reoccupation/reuse
- Relatively little information in literature regarding damage assessment, repair & strengthening of fire-exposed structures:
  - Typically it covers repairs with shotcrete/RC jackets
  - **Post-fire residual structural performance in seismic events and the repair effectiveness remain unknown**



Experimental Programme

Objectives:

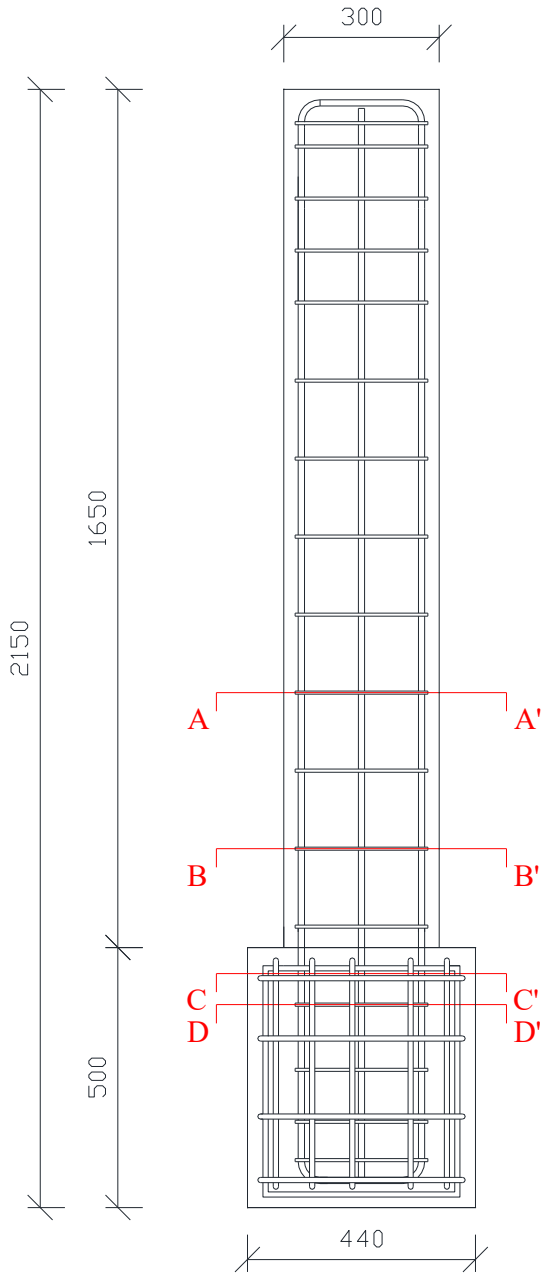
- Expose full-scale RC column specimens to quantifiable fire intensities in furnace tests
- Assess damage and residual structural behaviour under cyclic lateral loading
- Investigate effectiveness of FRP confinement as a retrofitting technique for fire-damaged concrete

Test Matrix:

#	Test ID	Fire exposure	Repair scheme before residual cyclic test
1	C	No	No repair
2	C-S	No	FRP wrapping
3	M30	30 mins ISO834	No repair
4	M30-S	30 mins ISO834	Repair mortar & FRP wrapping
5	L90	90 mins ISO834	No repair
6	L90-S	90 mins ISO834	Repair mortar & FRP wrapping
7	L90-2	90 mins ISO834	N/A

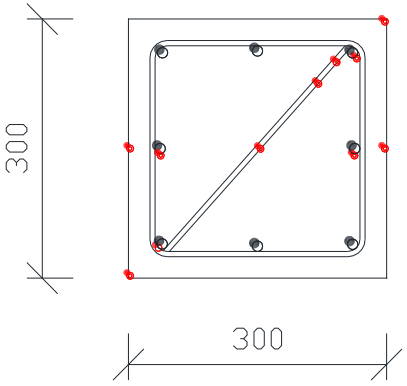
Test specimen details

- Flexure-dominate columns
- Axially loaded cantilevers; cyclic lateral load applied at the tip
- Designed according to pre-1970s Portuguese code (no seismic design provisions):
  - Representative of typical old RC columns that may require retrofit in seismic areas
  - Intentionally low strength concrete (C20/25)
  - 1% longitudinal reinforcement ratio (8 Ø12mm)
  - Low shear reinforcement ratio (Ø6mm at 150mm spacing)
- First heated ***unloaded*** **in the furnace**, then tested **under constant axial load and cyclic lateral load**
  - Load application and fixity ends protected with ceramic blanket insulation (50mm thick) to prevent premature failure during the structural test

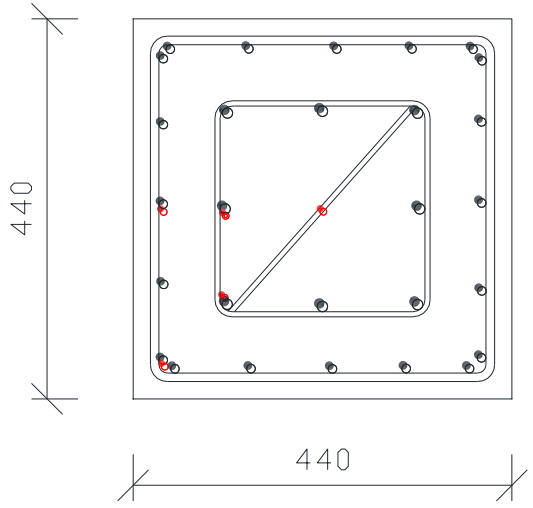


Thermocouple locations:

AA' & BB'

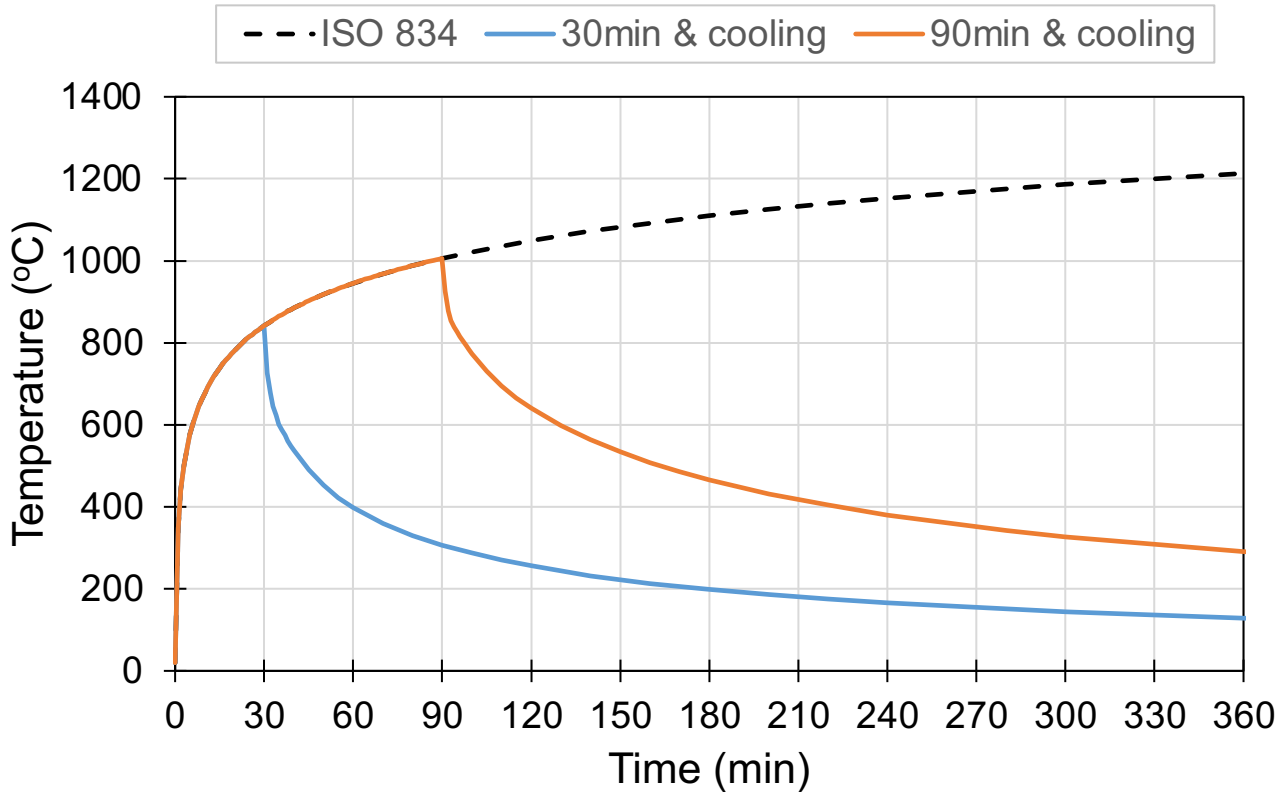


CC' & DD'

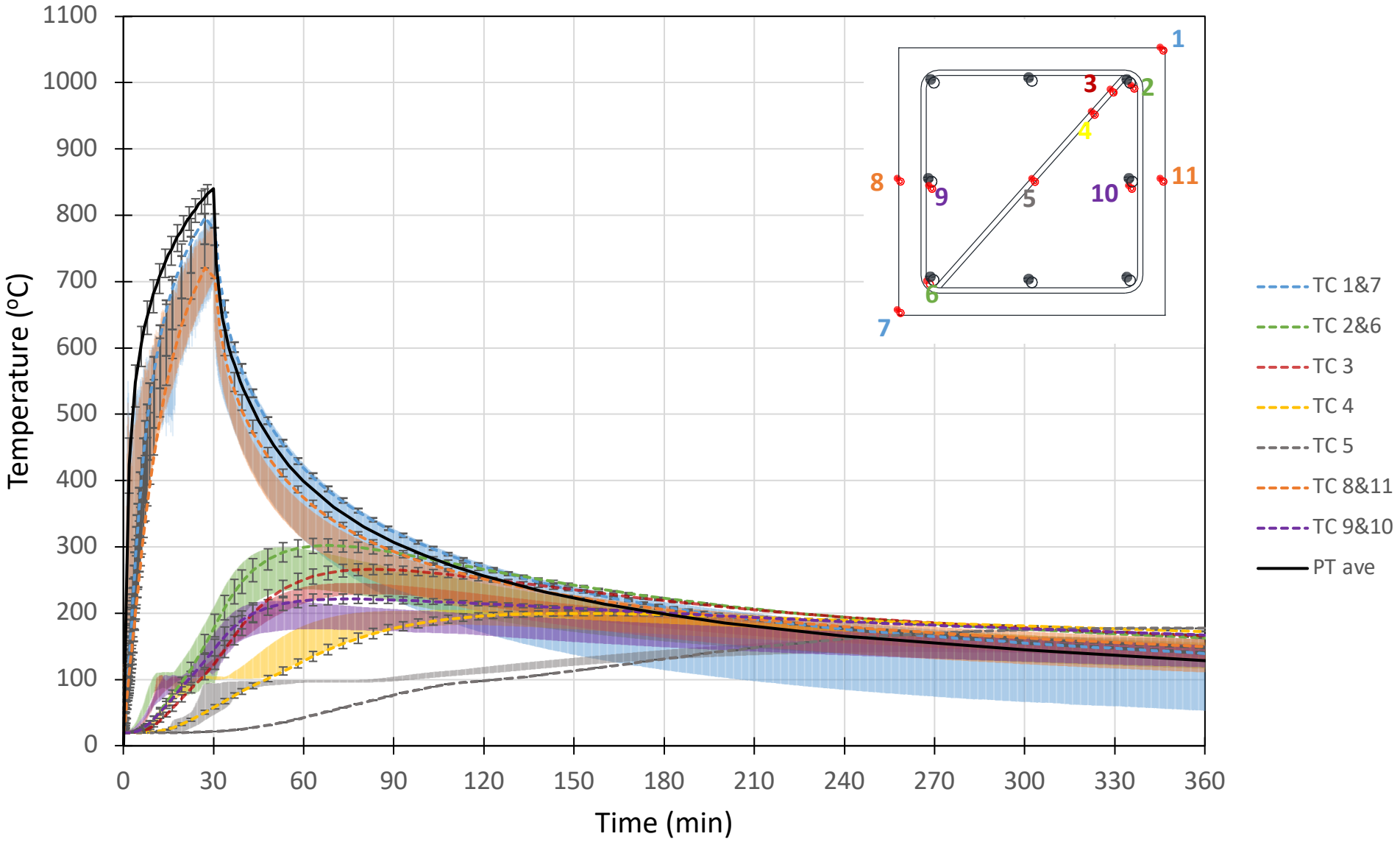


Furnace Testing

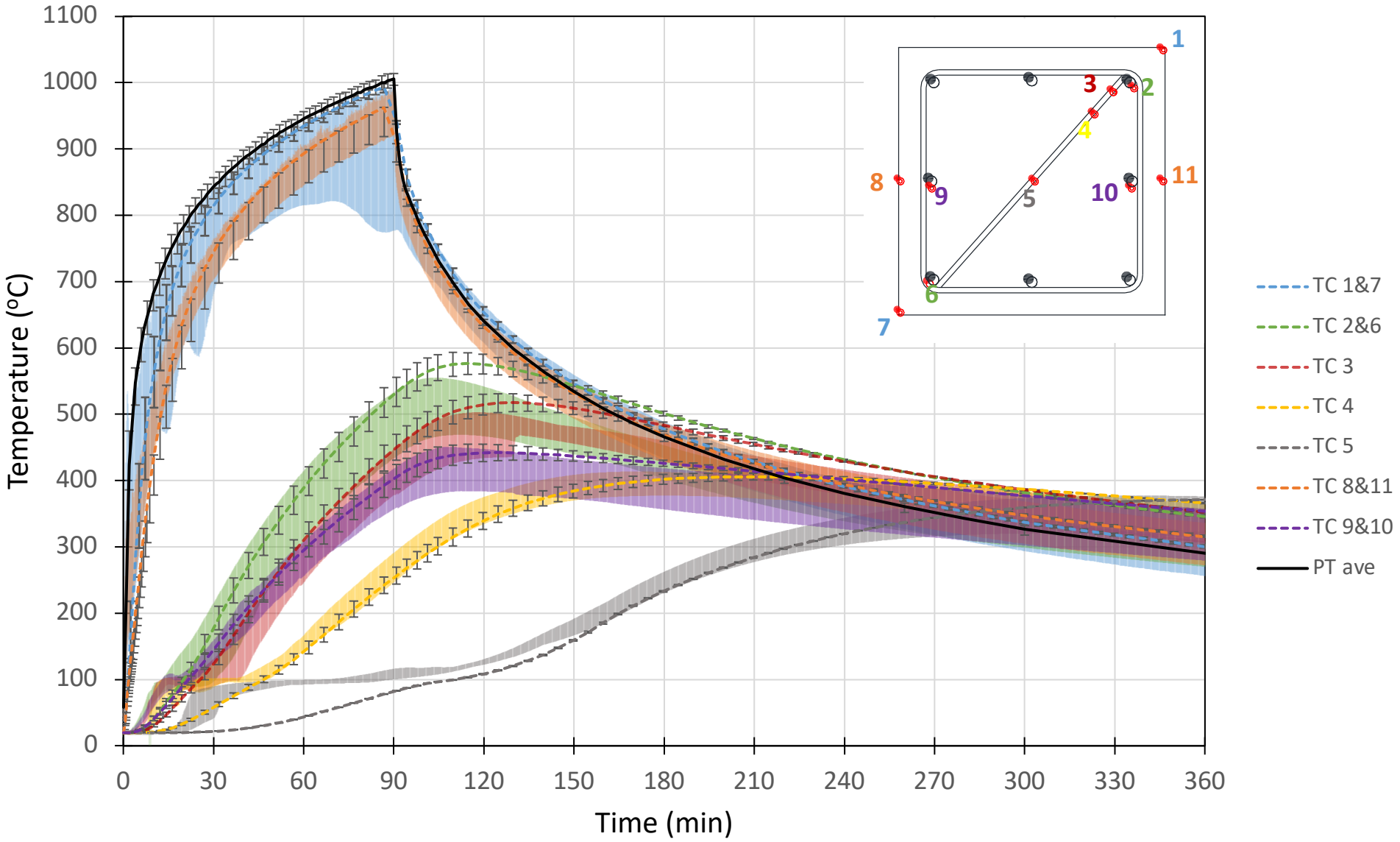
- Tests took place in a vertical furnace at the University of Aveiro in Portugal, then taken to University of Porto for structural testing
  - Test durations of either 30 or 90 mins to ISO 834, then left to cool down naturally
  - Temperatures were monitored until furnace was opened 24 hrs after the test



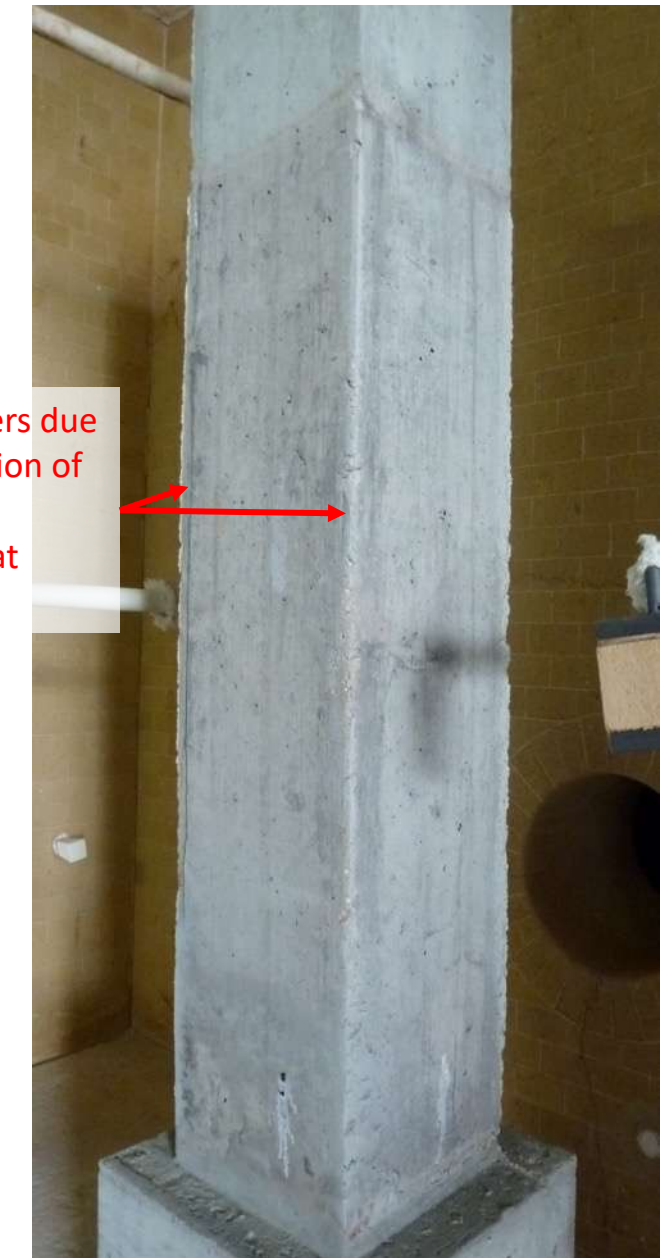
Temperature Evolution: 30min test; 2 specimens



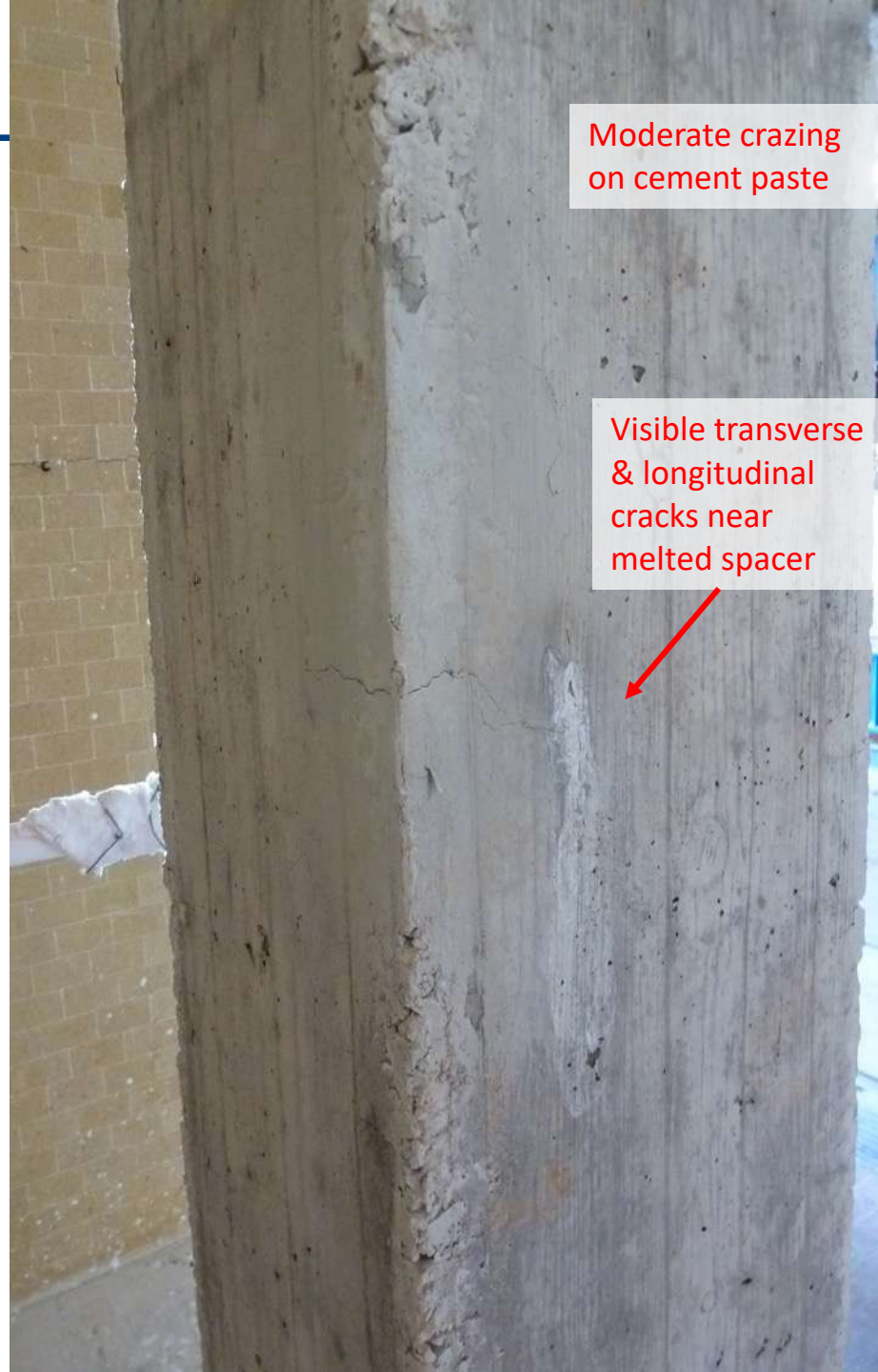
Temperature Evolution: 90min test; 3 specimens



Visual observations after 30 min fire test



Whitish corners due to disintegration of calcareous constituents at T>800^{o}C



Moderate crazing on cement paste

Visible transverse & longitudinal cracks near melted spacer

Visual observations after 90 min fire test

1 day after test:

- Extensive crazing
- Heavily cracked corners
- More extended whitish-grey concrete zones
- Very localised spalling at corners

Visual observations after 90 min fire test

4 days after test:

- ~1-2cm of outer concrete layer flaked and popped off:
  - limestone aggregates (and calcium carbonates in cement) turned into calcium oxide at ~825^{o}C
  - Upon rehydration after the fire test, the CaO aggregations react with water to form to $Ca(OH)_2$, they crumble/disintegrate and fall off

Generic assessment based on Concrete Society TR68 classes

Class of damage	Element	Surface appearance of concrete			Structural condition			
		Condition of plaster/finish	Colour	Crazing	Spalling	Exposure and condition of main reinforcement*	Cracks	Deflection/ distortion
0	Any	Unaffected or beyond extent of fire						
1	Column	Some peeling	Normal	Slight	Minor	None exposed	None	None
2	Column	Substantial loss	Pink/red**	Moderate	Localised to corners	Up to 25% exposed, none buckled	None	None
3	Column	Total loss	Pink/red** Whitish grey***	Extensive	Considerable to corners	Up to 50% exposed, not more than one bar buckled	Minor	None
4	Column	Destroyed	Whitish grey***	Surface lost	Almost all surface spalled	Over 50% exposed, more than one bar buckled	Major	Any distortion

30 min

90 min

Notes
* In the case of beams and columns the main reinforcement should be presumed to be in the corners unless other information exists
** Pink/red discolouration is due to oxidation of ferric salts in aggregates and is not always present and seldom in calcareous aggregate, see Section 2.2.2
*** White-grey discolouration due to calcination of calcareous components of cement matrix and (where present) calcareous or flint aggregate

Source: Concrete Society TR68 (2008)

Generic assessment based on Concrete Society TR68 classes

Table 8
Initial repair classification.

Class of damage	Repair classification	Repair requirements
0	Decoration	Redecoration if required
1	Superficial	Superficial repair of slight damage not needing fabric reinforcement
2	General repair	Non-structural or minor structural repair restoring cover to reinforcement where this has been partly lost.
3	Principal repair	Strengthening repair reinforced in accordance with the load carrying requirement of the member. Concrete and reinforcement strength may be significantly reduced requiring check by design procedure
4	Major repair	Major strengthening repair with original concrete and reinforcement written down to zero strength, or demolition and recasting

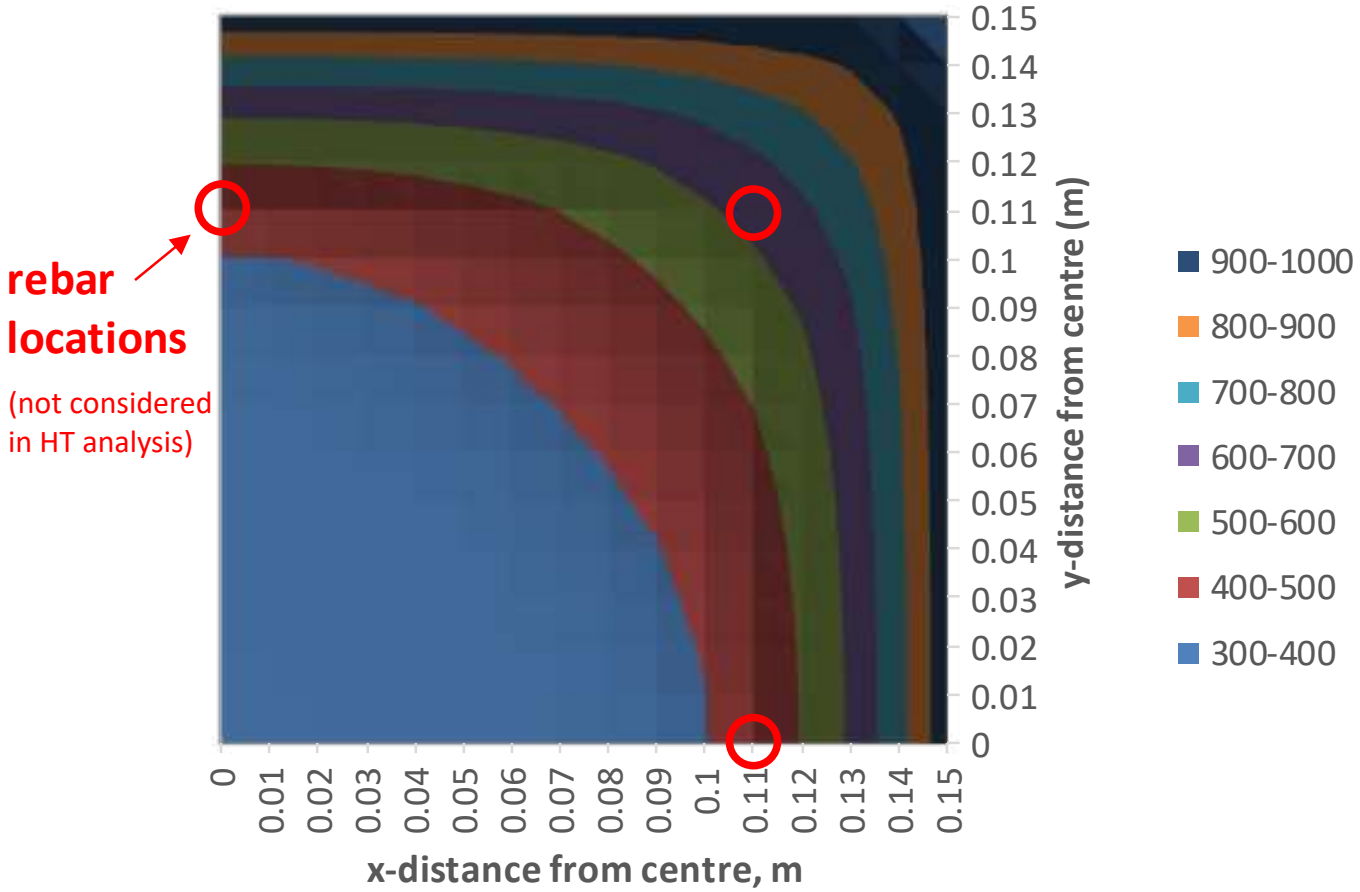
Source: Concrete Society TR68 (2008)

Temperature profile based on 2D FEA (90 min exposure)

*"Concrete not structurally useful after heating in temperatures in excess of **550°C-600°C**"*

(Concrete Society Technical Report No. 68)

Max temperature @Section A-A (¼-model FEM results)

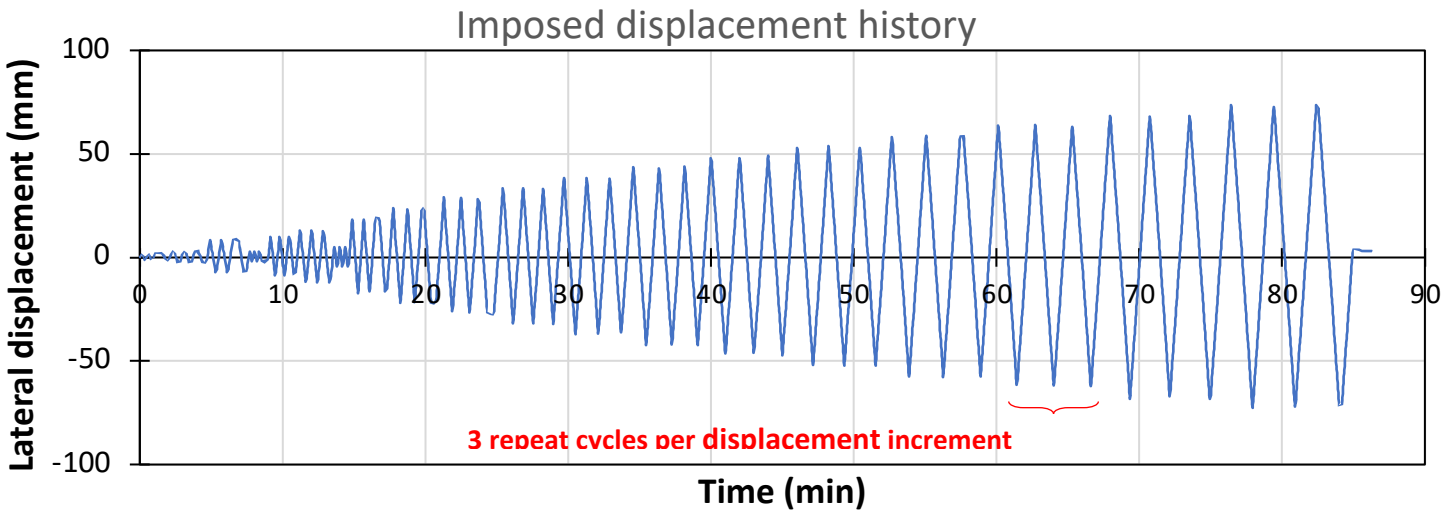


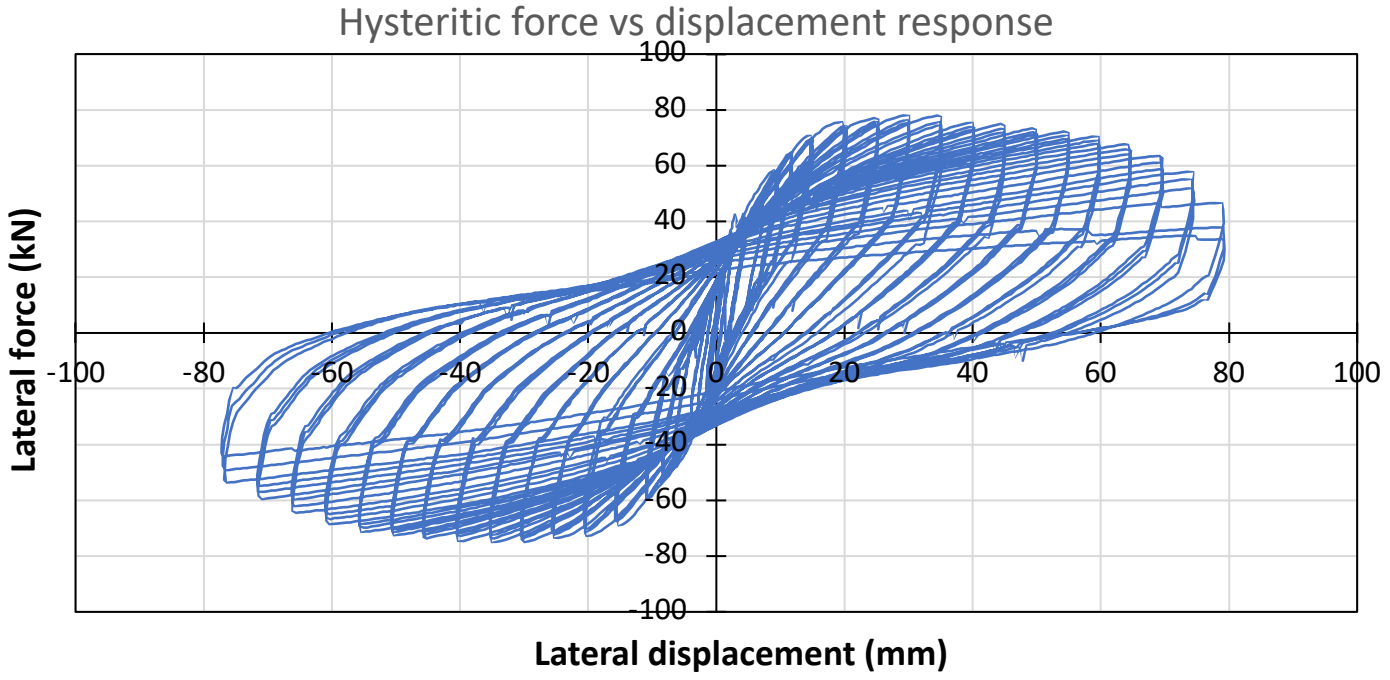
Weak concrete removed:

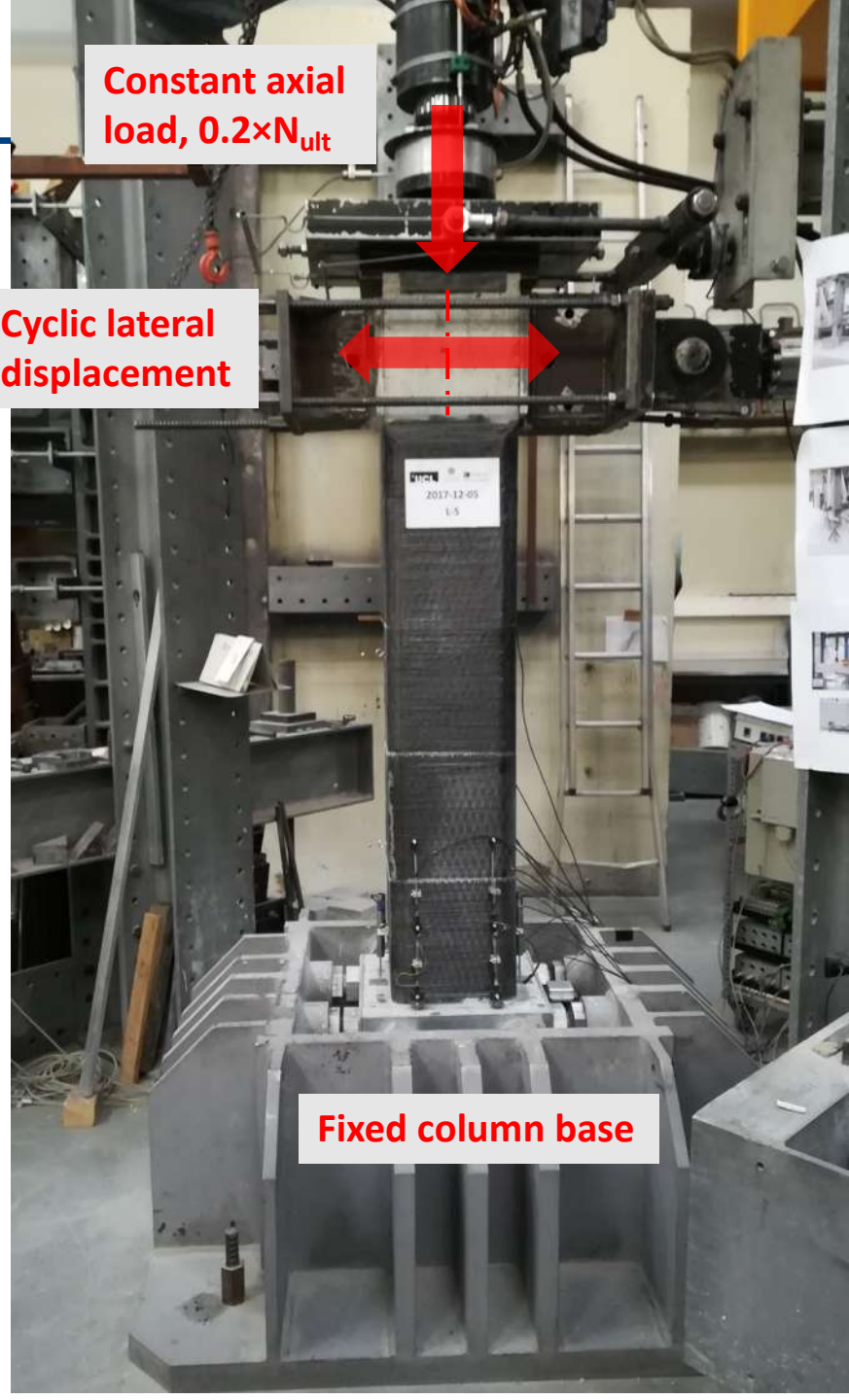
Repair & Strengthening by CFRP wrapping

- Damaged section reinstated with structural repair mortar
  - Only corners for 30-min
  - Whole cover for 90-min
- Wrapped with 3 layers of unidirectional CFRP
  - 300 g/m^2 fabric, high strength carbon fibres
  - **Over full column length**

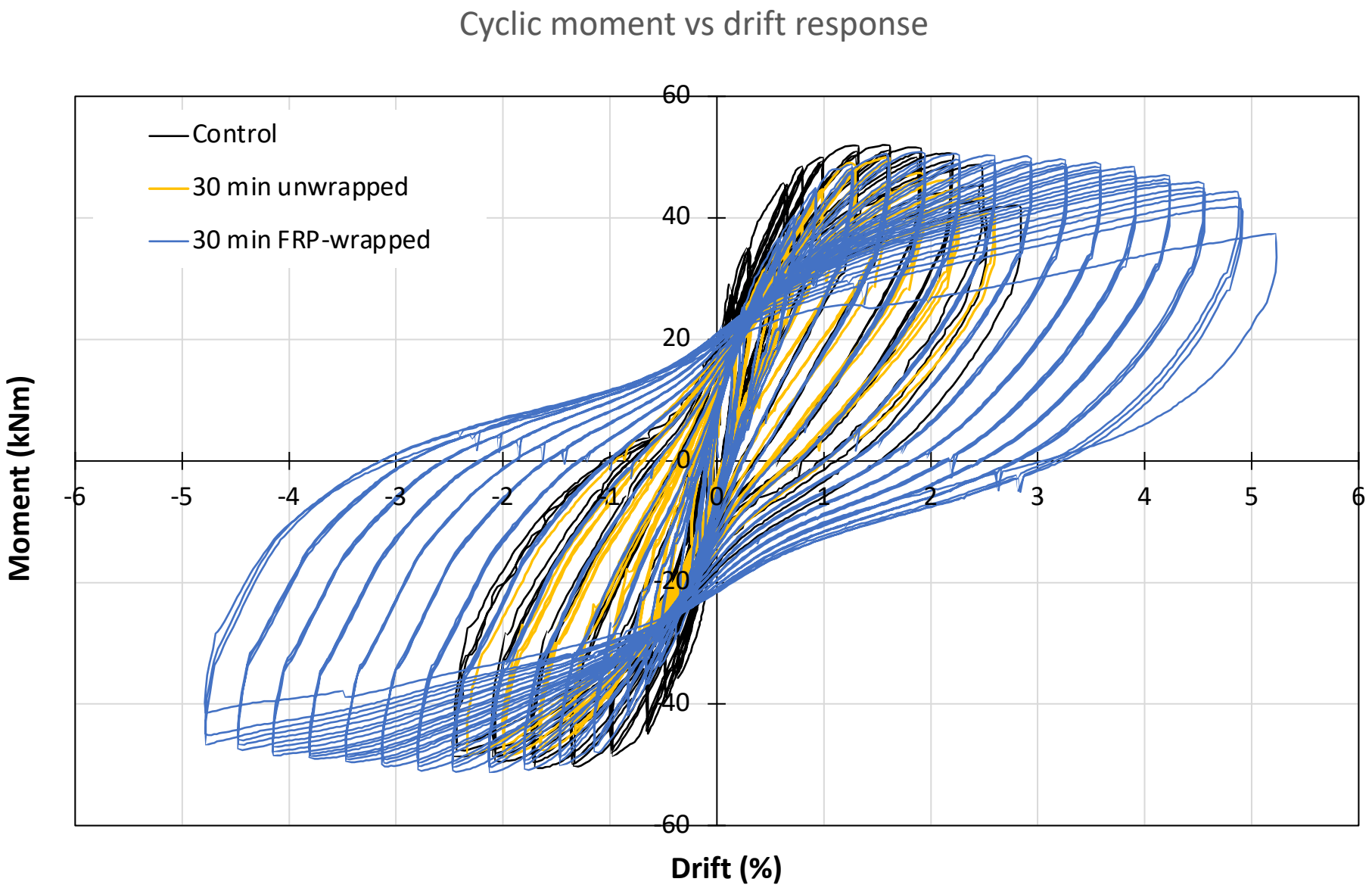
Cyclic test setup







Results – hysteretic responses



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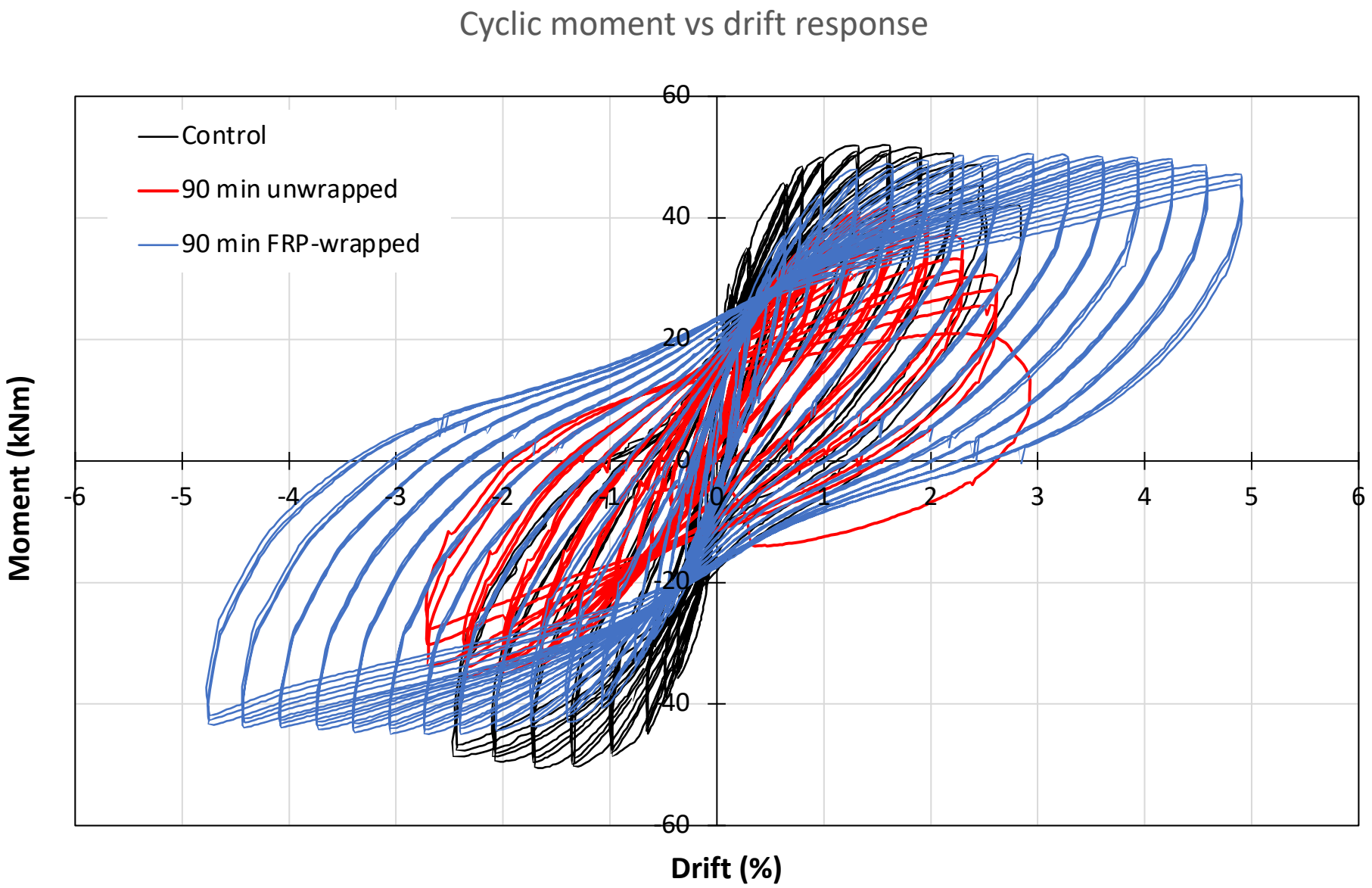
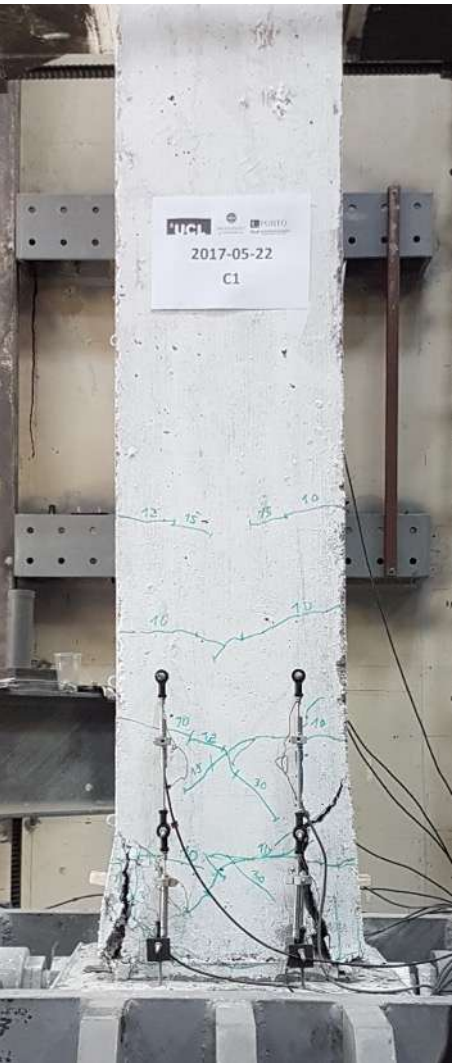
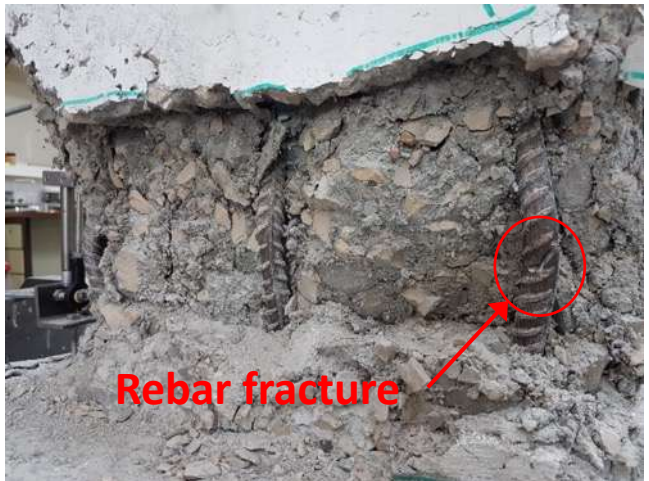


Failure modes: unwrapped specimens

Control column (no fire damage)





90min ISO834 column

- Plastic deformation spread over larger length;
- larger buckled length of rebars due to stirrup opening;
- concrete core completely damaged

Failure modes: FRP-wrapped specimens

The wrap confines concrete, allows it to reach larger compressive strains and delays rebar buckling by acting in hoop tension

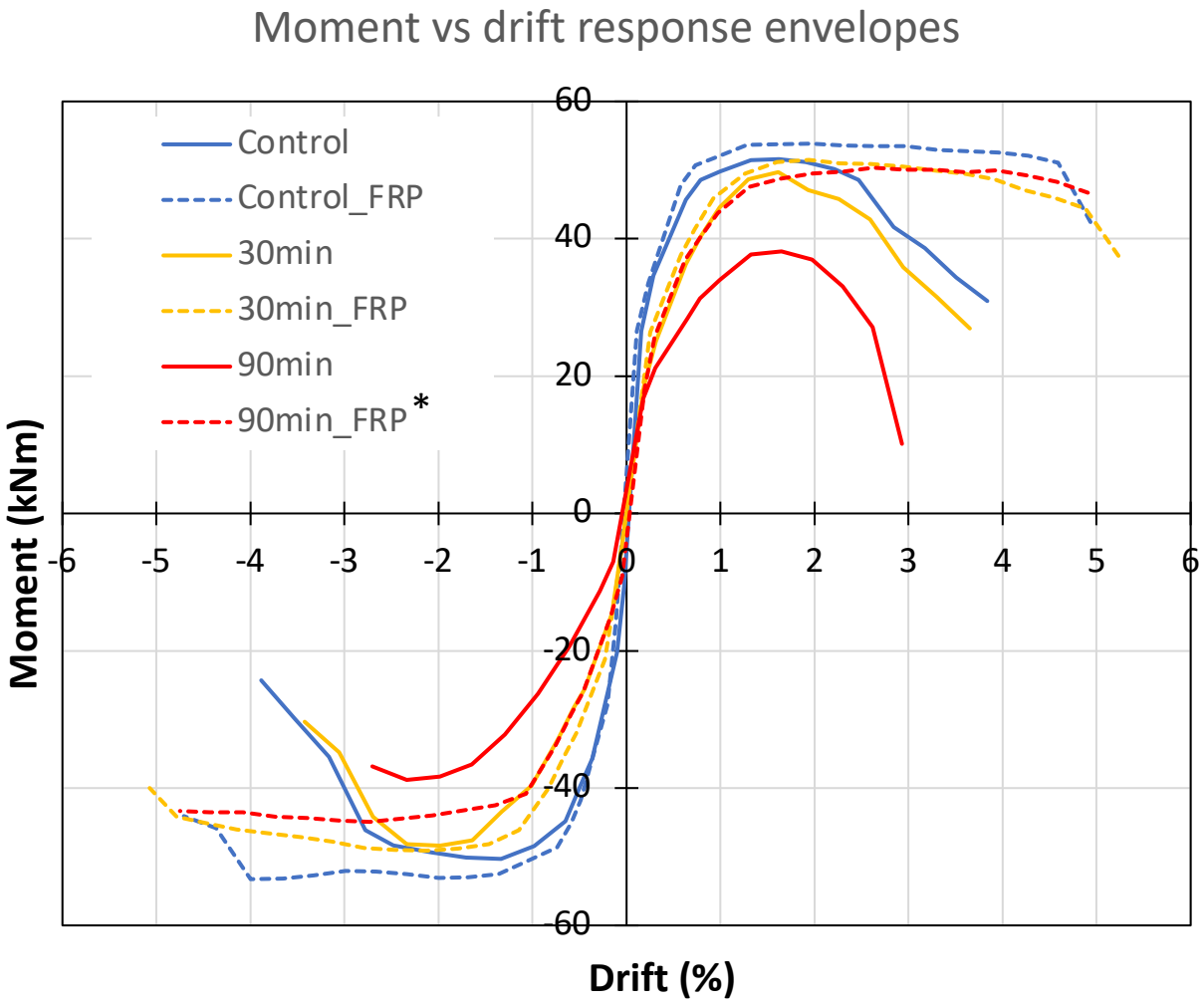
- hence: larger rotations of the plastic hinge ⇒ **enhanced ductility & energy absorption**

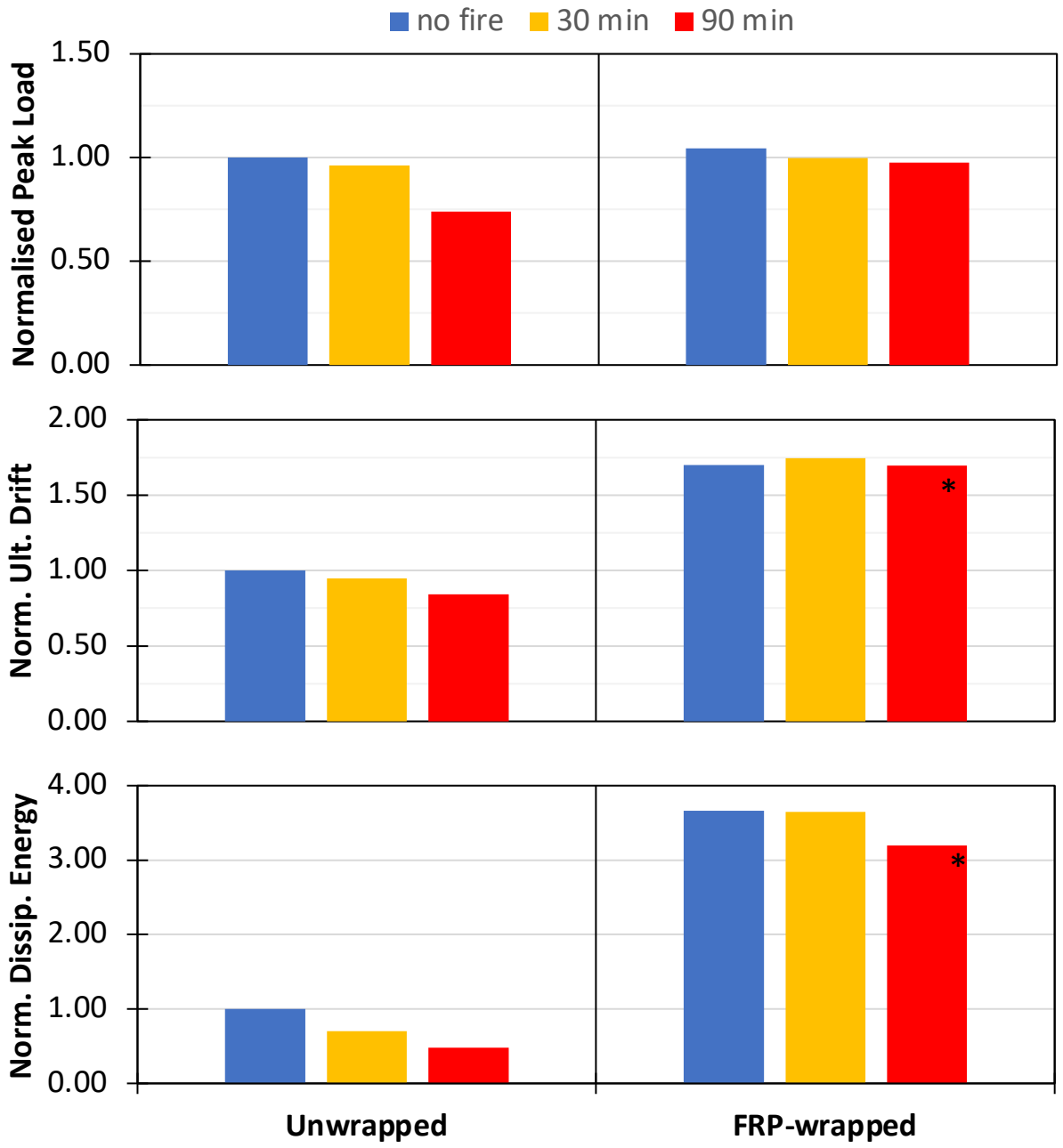
Flexural cracks between transverse unidirectional carbon fibres

Bulging due to middle rebar buckling

*Test stopped before the wrap reached its ultimate tensile (hoop) strain

Results summary and comparisons





* Note: 90min_FRP didn't reach ultimate drift (@ 80% F_{max}) because actuator stroke maxed out only at 7% load drop

Concluding remarks

- Just an overview of experimental programme presented, work still in progress...
- Tests showed that exposure to fire of increasing fire intensity results in greater reductions in load capacity, ultimate drift and dissipated energy (obviously… :D)
- The tested **FRP repair schemes** were effective in restoring the original load capacity before fire damage, and to **significantly improve ductility and energy dissipation**
- Detailed results, modelling work and project outputs will be presented hopefully in a future StiFF meeting!

Thank you!

Questions?

Acknowledgements:

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