FRP Strengthening of RC Beams - Research overview

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The University Of Sheffield.

The Institution of Structural Engineers

Sheffield Hallam University

FRP Strengthening of RC Beams

Research Overview

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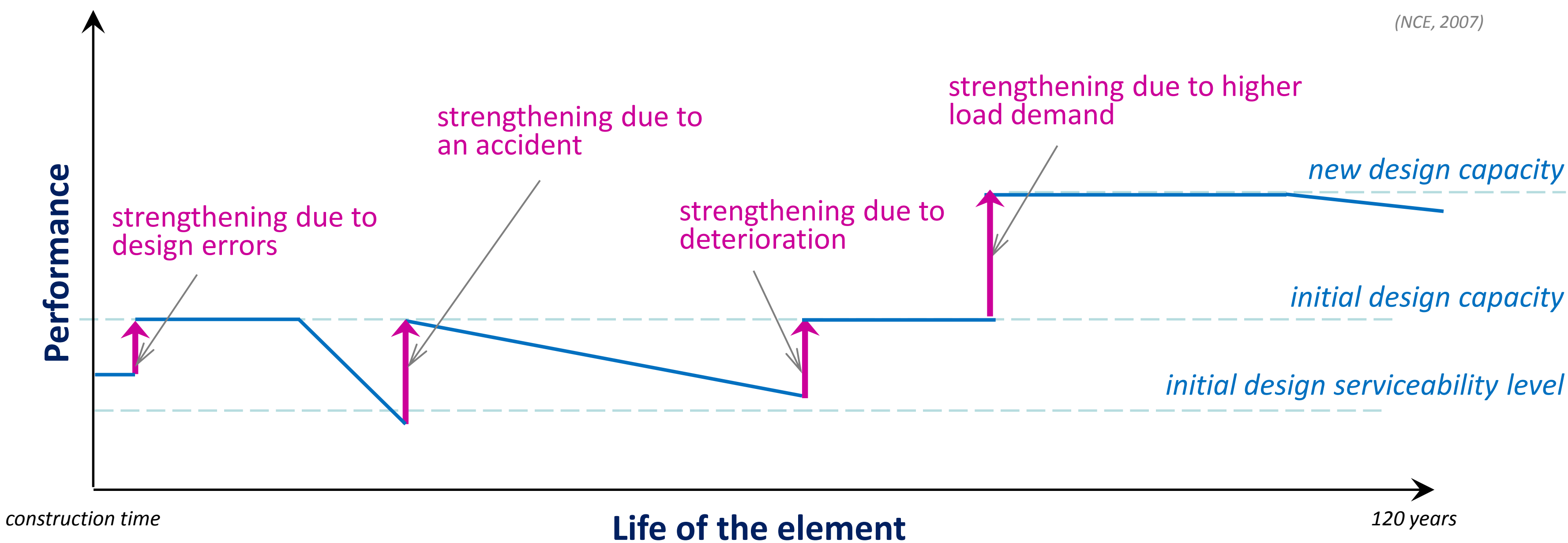
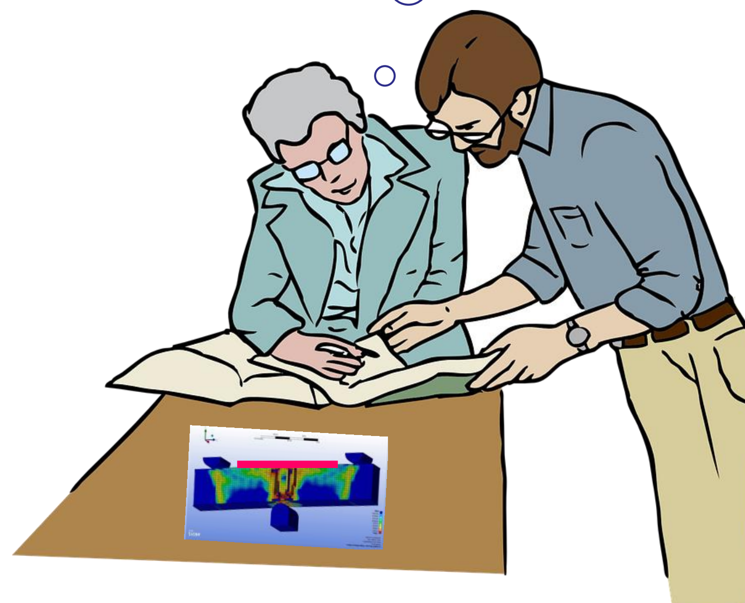
Need for strengthening

(NCE, 2007)



We need a STRONG and DURABLE as well as... ECONOMIC and FAST to install strengthening solution !

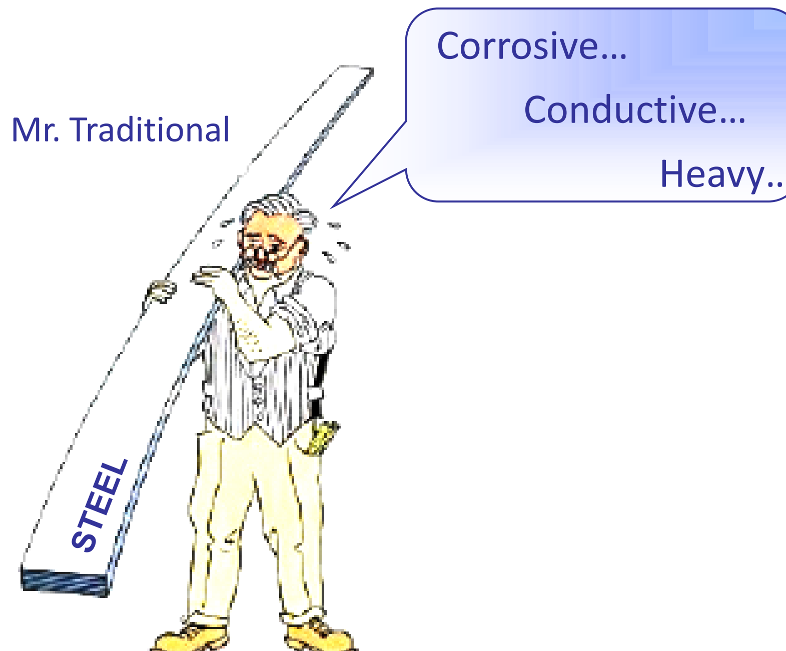
Externally Bonded Fibre Reinforced Polymer (FRP)?



Traditional strengthening

Steel plate bonding

Courtesy of G. Nichols



after U. Meier, EMPA

Modern strengthening

FRP plate bonding

buildera.com

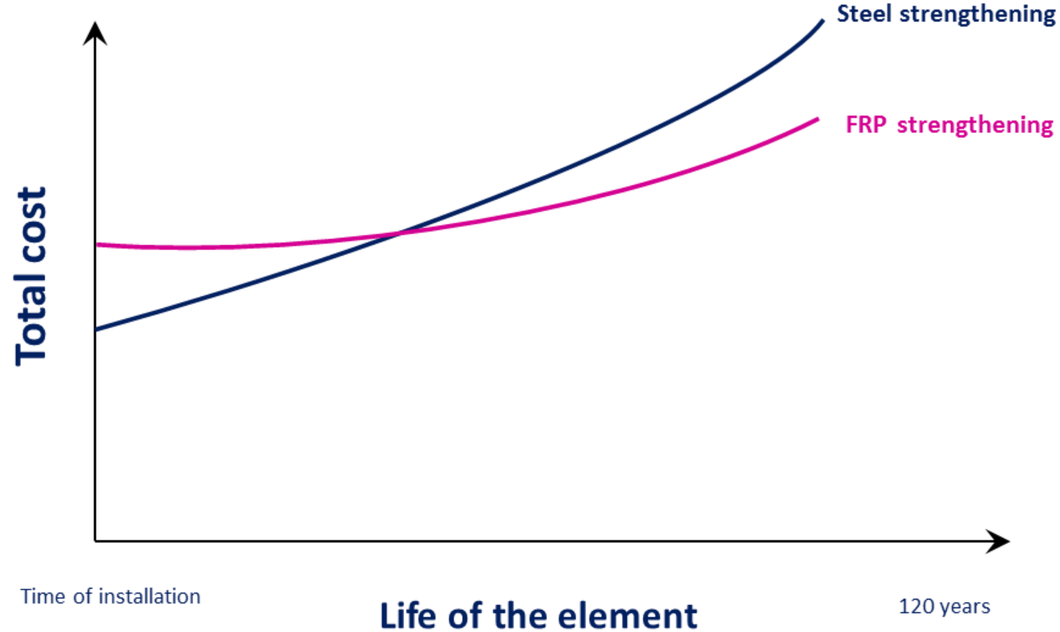
sika.com

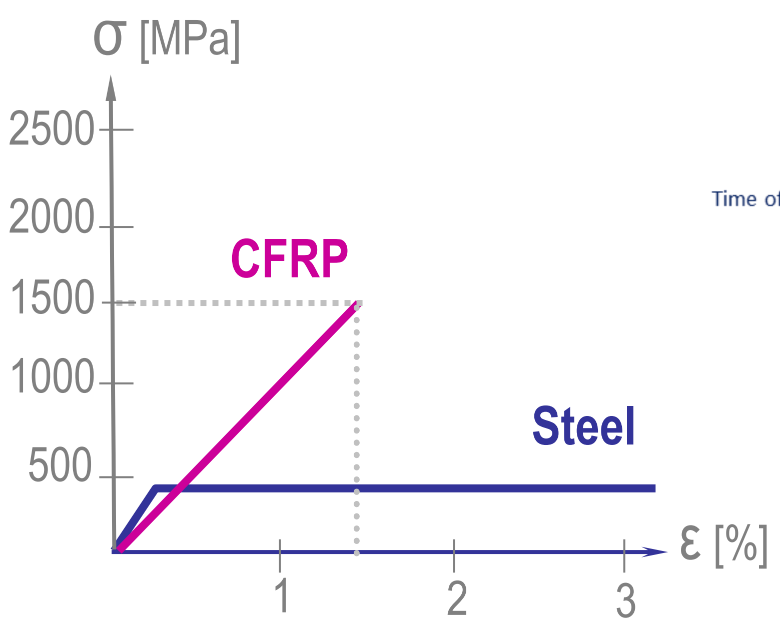
Miss Futura

Strong Light Versatile
Non-magnetic
Non-corrosive

after U. Meier, EMPA

FRP vs. Steel


Steel strengthening
FRP strengthening
Total cost
Time of installation
Life of the element
120 years


σ [MPa]
2500
2000
1500
1000
500
CFRP
Steel
ε [%]
1
2
3

FRP Systems - Issues

- Lack of Ductility
- Risk of Debonding
- Susceptibility to Damage
- Susceptibility to High Temperature
- Uncertain Long-Term Durability
- Lack of Easy-to-Follow Design Procedures

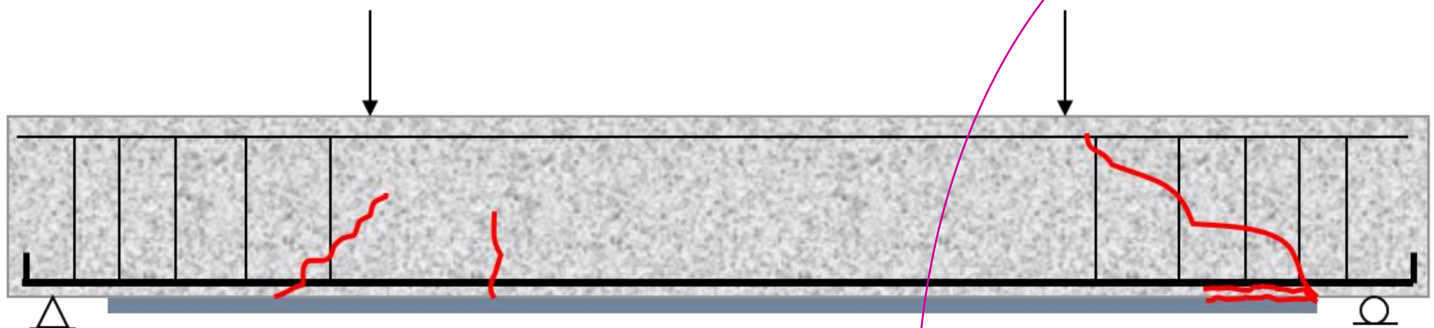
FRP Systems - Issues

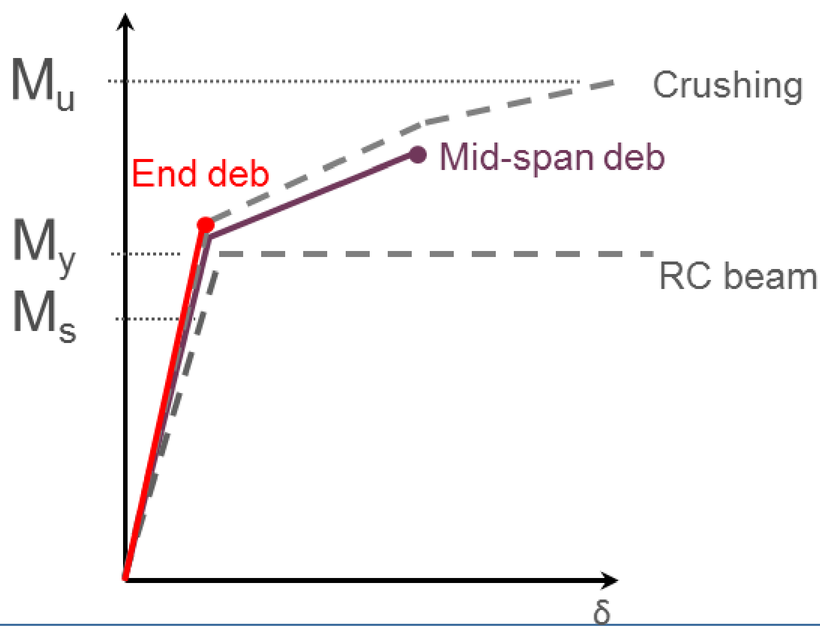
- Lack of Ductility
- 1 Risk of Debonding
- Susceptibility to Damage
- Susceptibility to High Temperature
- 2 Uncertain Long-Term Durability
- 3 Lack of Easy-to-Follow Design Procedures

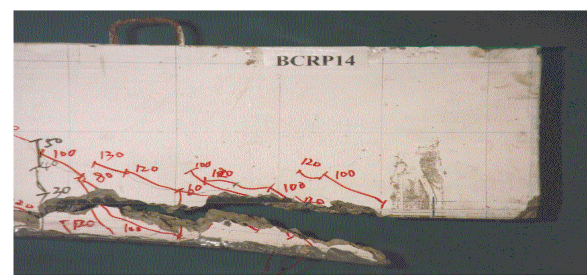
1. Risk of Debonding

Mid-span Debonding

End Debonding

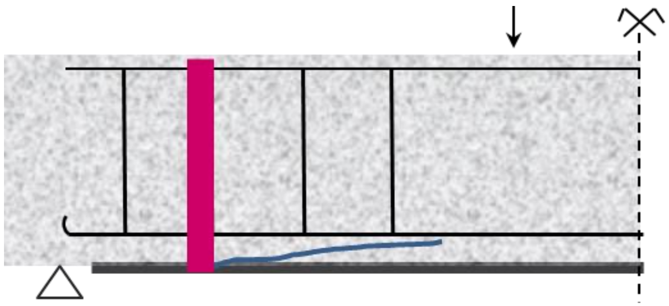






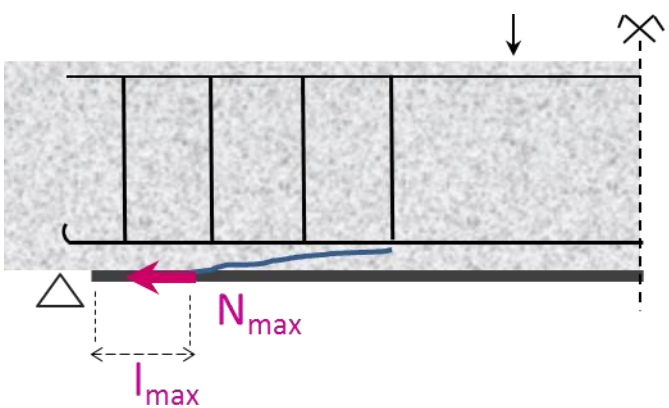
Control of End Debonding

- Provide mechanical anchorages



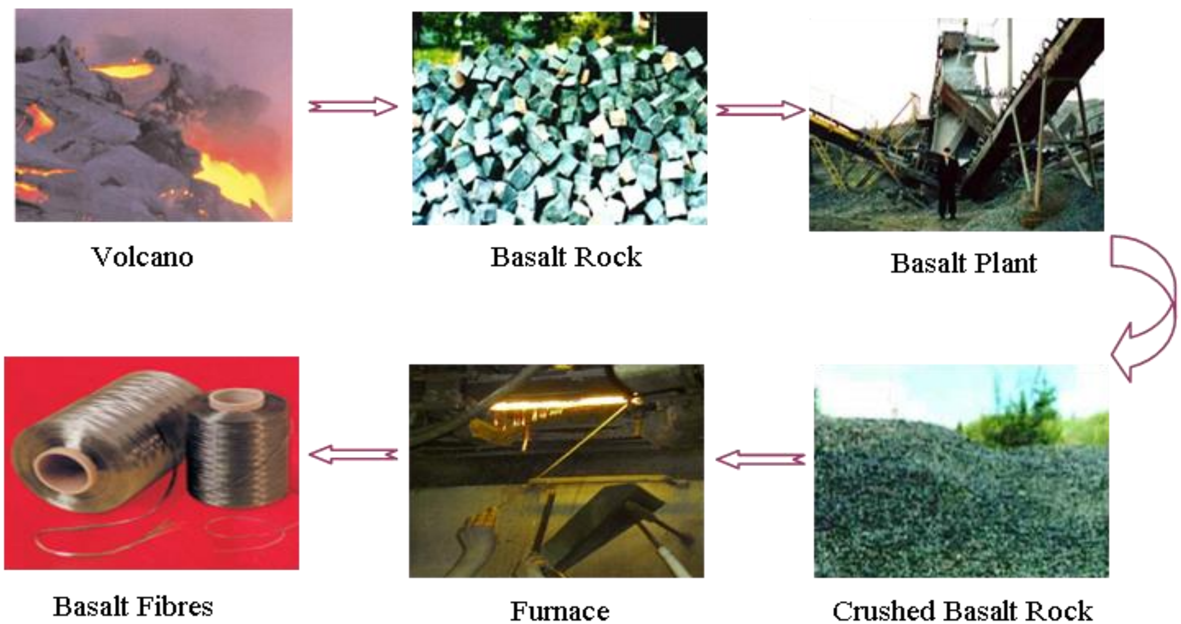
Issue	Solution?	Research
Additional cost	1.1 Use of Basalt FRP as anchorage	Beam tests/Analysis

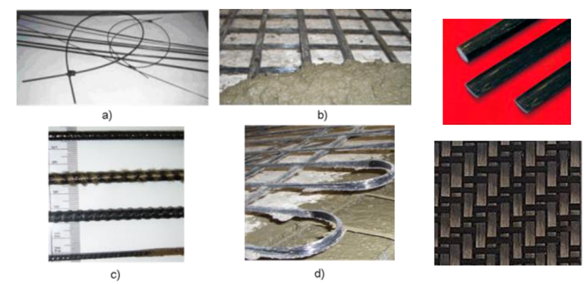
- Predict debonding loads



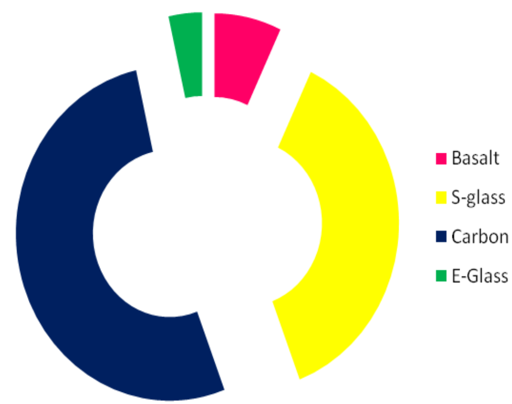
Issue	Solution?	Research
No reliable models	1.2 Standardised Bond Tests	Bond tests/Data mining

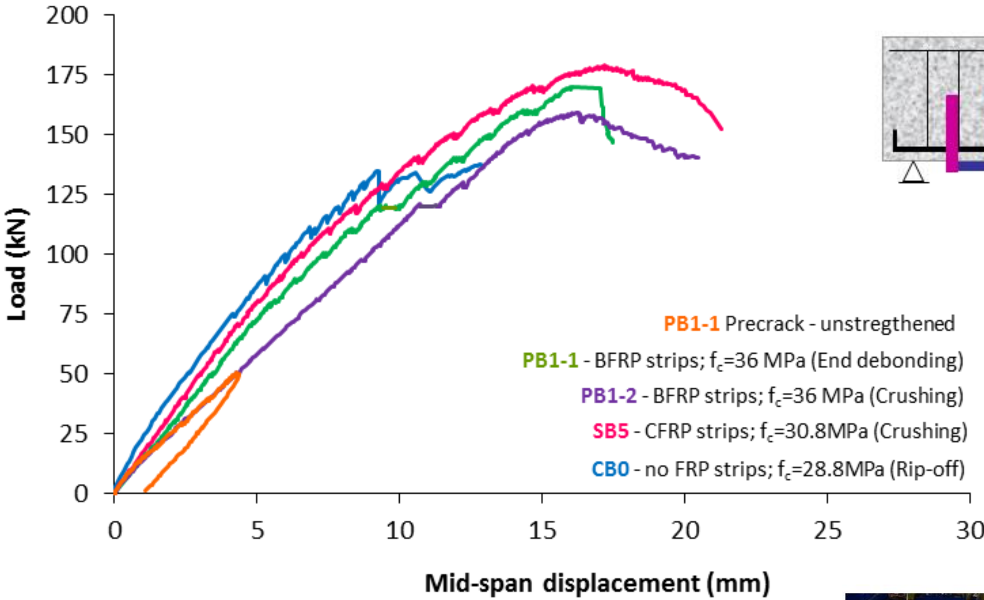
1.1. Use of Basalt FRP as anchorage

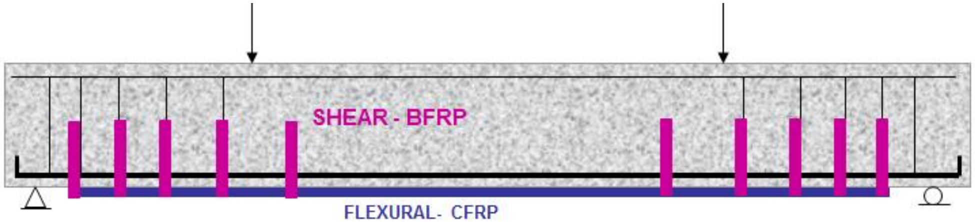


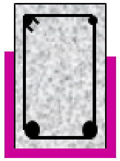


Characteristic of fibres	Basalt	E-Glass	S-Glass	Carbon
Tensile Strength (MPa)	3000~4840	3100~3800	4020~4650	3500~6000
Elongation at break (mm)	3.1	4.7	5.3	1.5~2.0
Elastic modulus (GPa)	79.3~93.1	72.5~75.5	83~86	230~600
Temperature of use (°C)	-260~+500	-50~+380	-50~+300	-50~+700

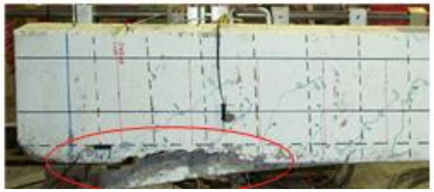


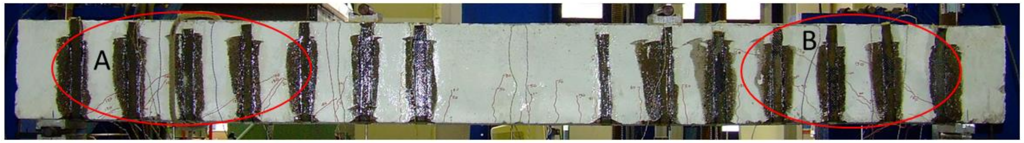




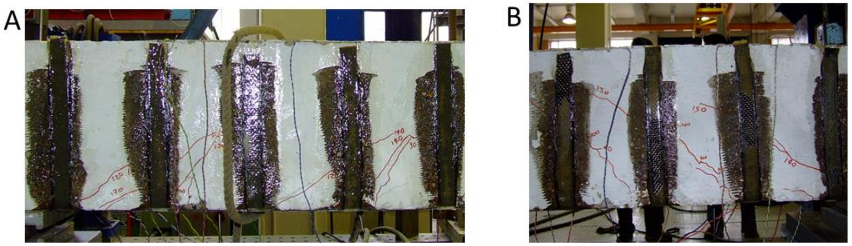


CB0





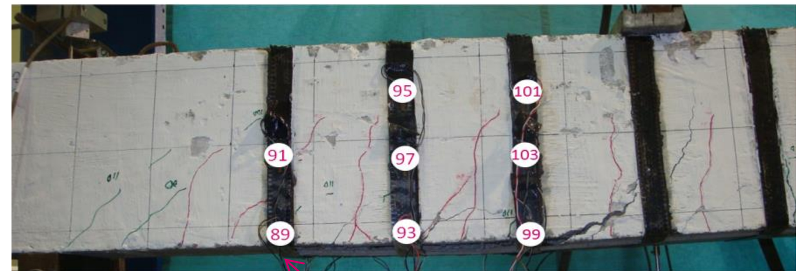
PB1-1

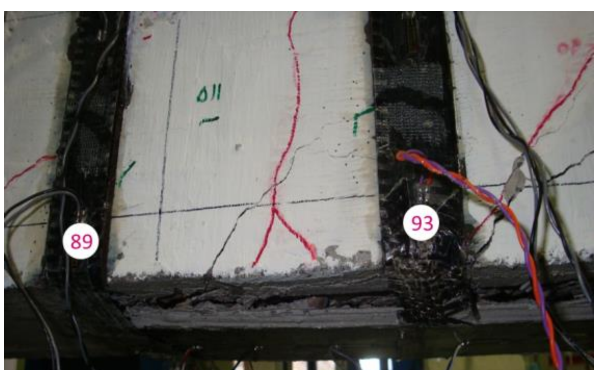


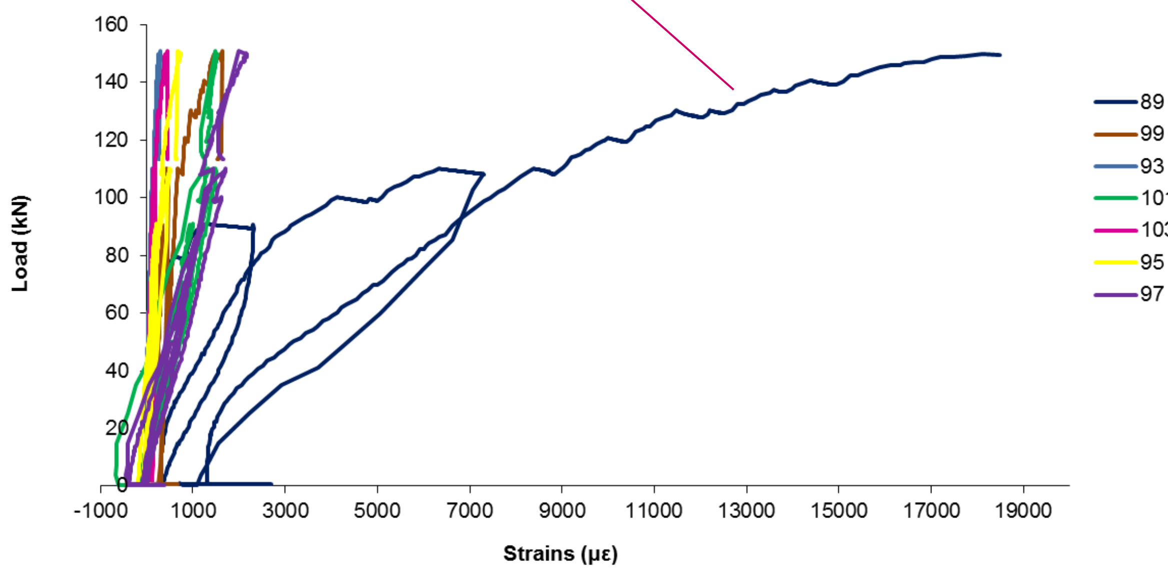
- Increase in debonding load (~27%)
- Pseudo-ductility
  CB0 beam (brittle)
  PB1-1 beam (distributed cracking)

- High strain in Basalt FRP strips

- No debonding of BFRP strips

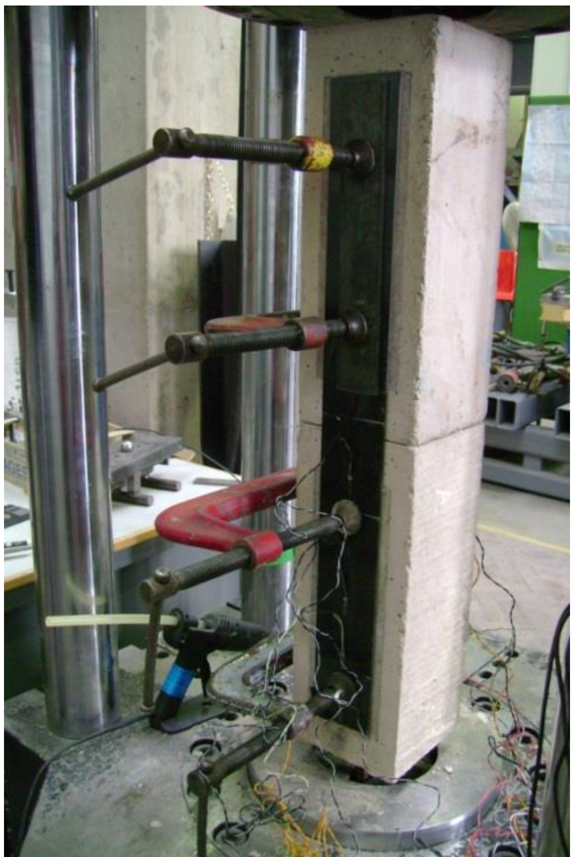






1.2. Standardized Bond Tests

Double-shear tests (20 specimens)



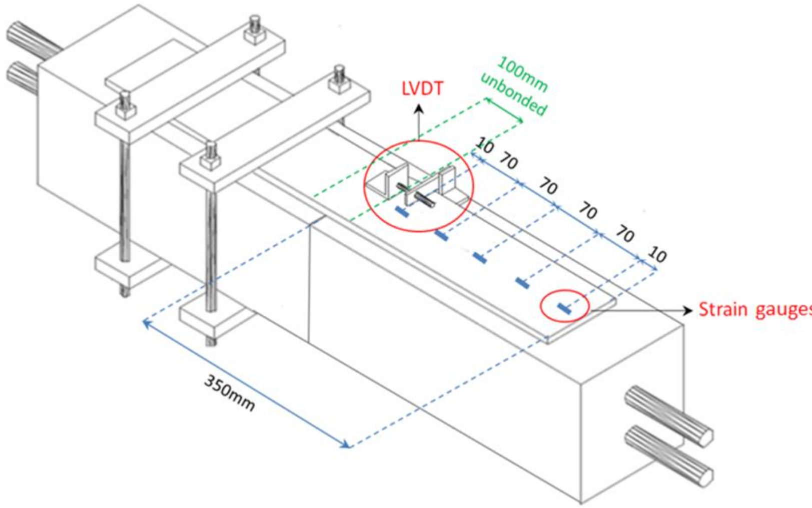
Parameters

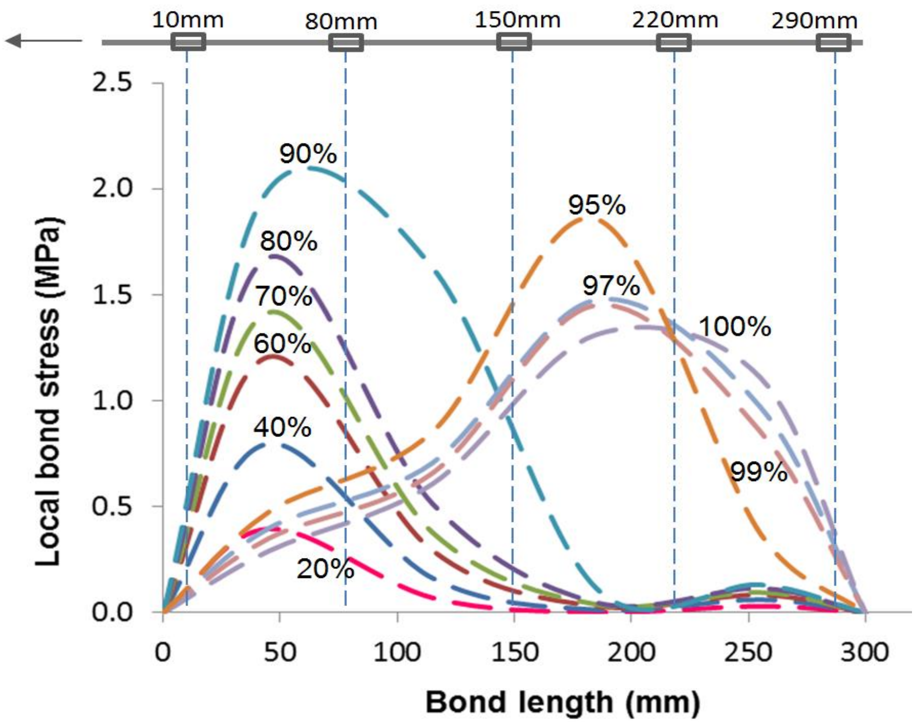
Name	Width b_f	Thickness t_f	Area A	Strength f_f	Elastic modulus E_f	Ultimate strain ε_u
	[mm]	[mm]	[mm^2]	[MPa]	[GPa]	[%]
C1A	100	1.2	120	3100	165	1.7
C1B	100	1.4	140	3100	210	1.3
C1C	60	1.3	78	3100	165	1.7
C3	100	1.2	120	2850	165	-
C4	100	1.4	140	3100	170	1.6
C5*	80	1.2	96	2590	200	-
C1C-R	60	1.3	78	3100	165	1.7

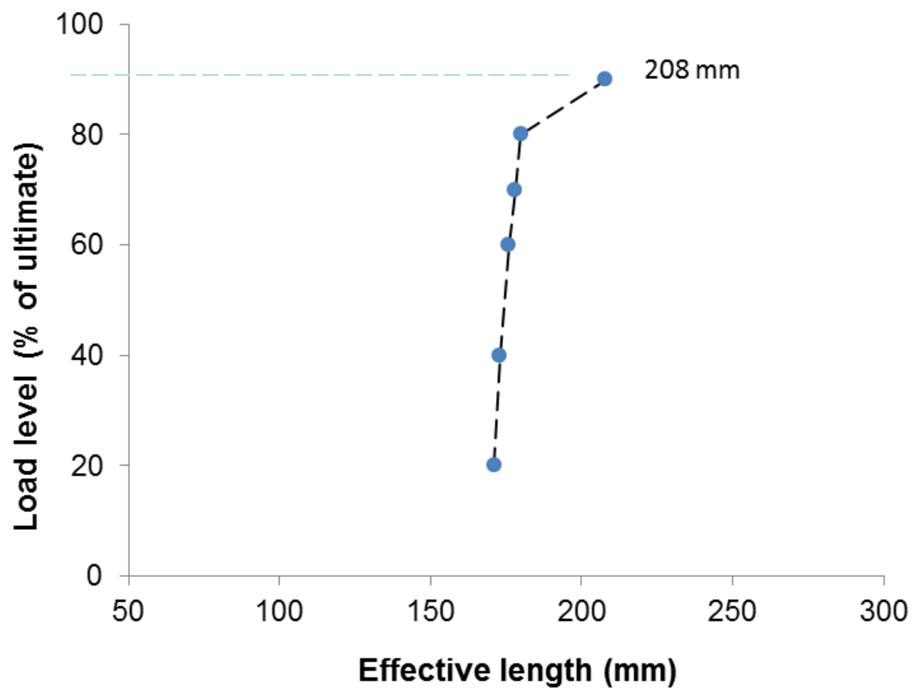
* - *tested at The University of Sheffield only*

Surface roughness

Local bond stress vs. bond length



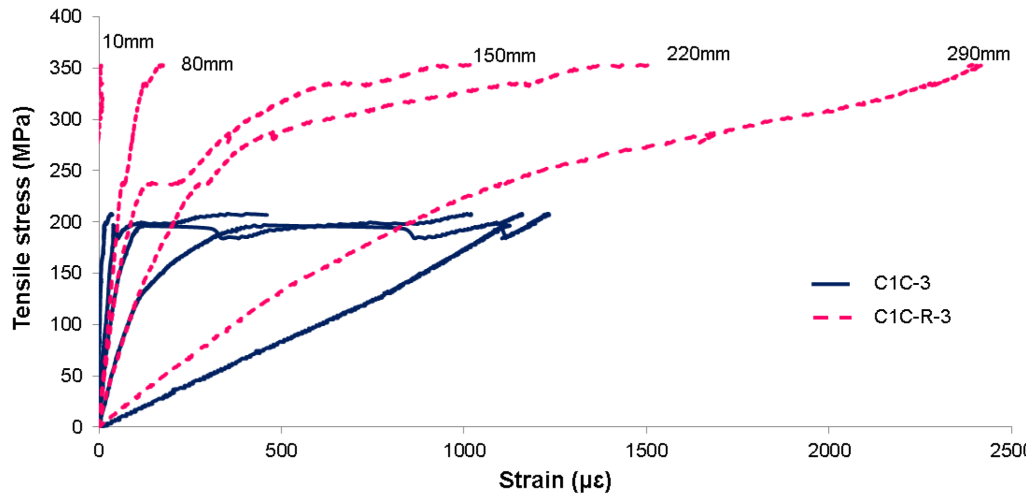


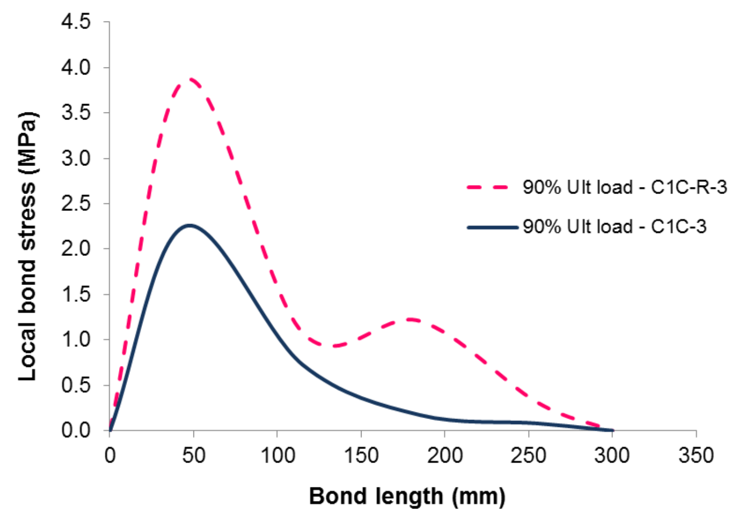


Effect of surface preparation

Rough surface

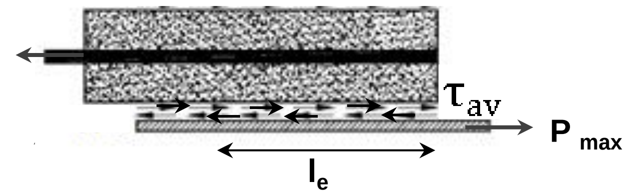
Smooth surface

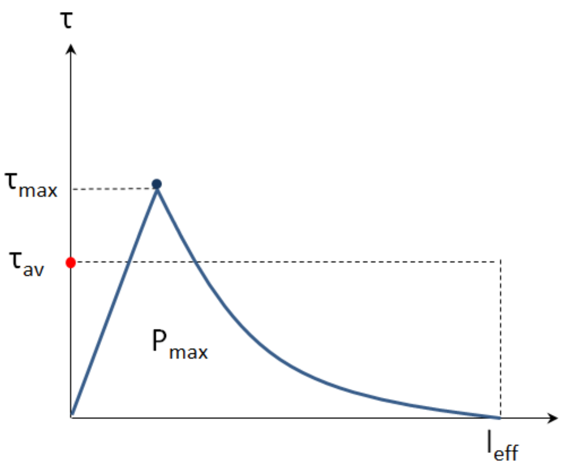




Proposed new model – Debonding force

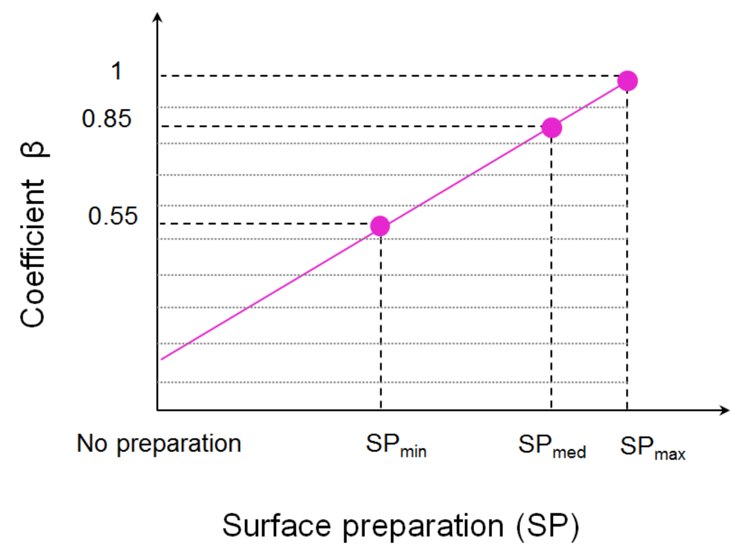
$$P_{max} = \beta \cdot k_{b_f} \cdot \frac{2}{3} \cdot (0.8 \cdot \sqrt{f_{cu}}) \cdot \left(\sqrt{\frac{E_f \cdot t_f}{2.8 \cdot f_{ctm}}}\right) \cdot b_f$$



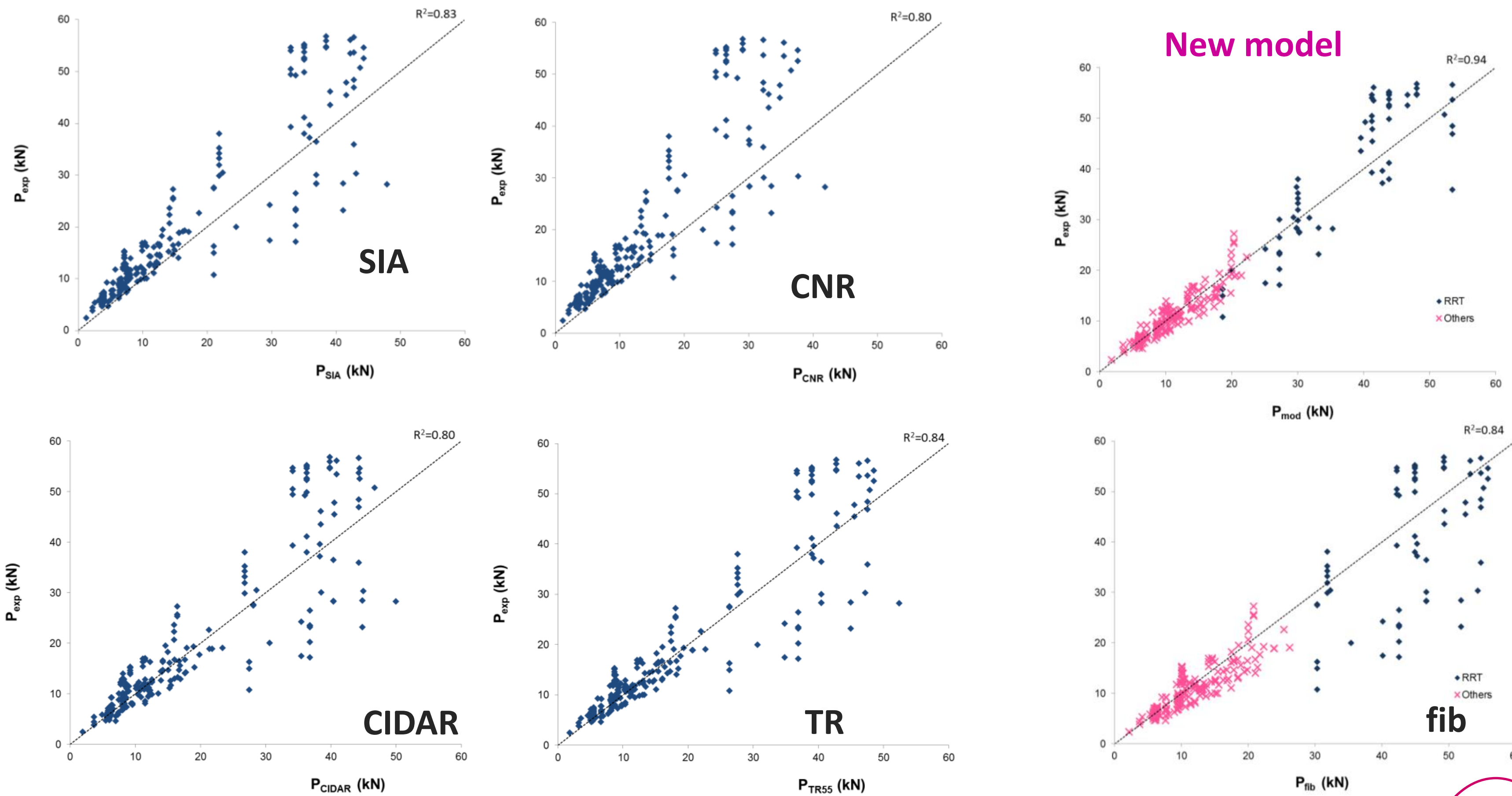


Surface preparation coefficient

$$\beta = \frac{\tau_{max}}{\sigma_s}$$



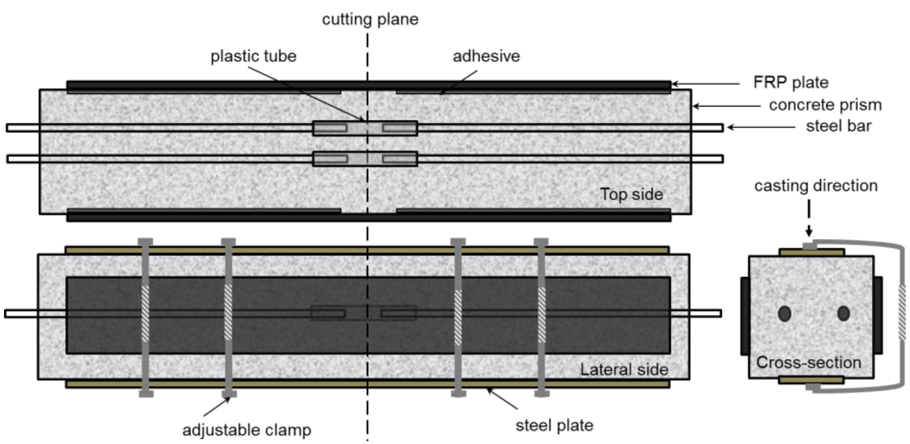
Model verification - database of 278 tests



Predictions		fib	SIA	CNR-DT	CIDAR	TR55	Proposed
P_{mod}/P_{exp}	AVG	1.12	0.78	0.70	0.99	0.98	1.01
	STDEV	0.30	0.24	0.21	0.27	0.26	0.17
	COV	0.27	0.31	0.29	0.28	0.27	0.17

Recommended Standard Test Protocol

Casting
Surface preparation
Loading rate
Transportation
Testing time
Bonding procedure



RRT - Check list

STAGE	ACTION	Done
Stage 1: Test parameters	- select FRP systems	√
	- determine experimentally the elastic modulus of FRPs and measure accurately their cross-sectional size	
	- estimate the effective length and choose a longer bond length	
	- select the strain gauge interval	
	- set the loading rate	
	- decide the targeted strength of concrete at 28 days	
Stage 2: Casting	- prepare moulds	
	- cast cubes and cylinders for compressive, tensile and E-modulus tests at 28 days	
	- cast each two specimens as a single prism	
	- prepare 3 specimens per FRP system	
	- tests fresh concrete properties (slump, density and flow)	
	- demould and cut each prism in half (~ 1 week of curing)	
	- test the properties of concrete at 28 days	
Stage 3: Bonding	- roughen the side surface of the prisms where the FRP systems will be bonded	
	- remove contaminants of the adherents and apply primer	
	- apply the adhesive using the template and let it cure for at least 24h	
	- prepare locally the FRP surface and mount the strain gauges	
Stage 4: Transportation	- place steel plates on the un-bonded sides of the prisms and hold the prisms together using G-clamps	
Stage 5: Testing	- test the compressive strength, tensile strength and flexural modulus of concrete at 28 days (testing time)	
	- mount the specimens in the testing machine and remove clamps from the test specimen	
	- connect the strain gauges	
	- mount the LVDTs	
	- apply tensile load force to failure at the specified rate	
Stage 6: Reporting	- describe the full testing methodology and report concrete mix-design and tested properties	
	- report failure modes	
	- present the raw data	
	- process the results (local bond stress and slip) and include relevant graphs	
	- include comments if any	

2. Durability tests

Set bar type	Tests		No. of bars per diameter	Nominal diameter (mm)	Actual area	Total no. of bars
1[1]	Tensile test (**TT1**)		5	3	9.6	20
			5	5	23.8	
			5	8	57.1	
			5	10	86.8	
2[1]	Tensile test (**TT2**)		5	3	9.4	5
	Durability test (**DT2**)	Water/20°C/1000h	5	3	9.5	20
		Water/60°C/1000h				
		pH13/20°C/1000h				
		pH 13/60°C/1000h				
		Water/60°C/200h	3	3	9.1	3
3[2]	Tensile tests (**TT3**)		9	6	33.3	24
			5	4	15.5	
			5	5	23.6	
			5	7	44.4	
	Durability test (**DT3**)	pH 9/20°C/100h	5	6	33.2	5
		pH 9/20°C/1000h	5	6	32.9	5
		pH 9/40°C/100h	5	6	33.2	5
		pH 9/40°C/1000h	5	6	30.1	5
		pH 9/60°C/100h	5	4	15.8	20
			5	5	22.9	
			5	6	32.6	
			5	7	44.4	
		pH 9/60°C/1000h	5	6	32.7	5
		pH 9/20°C/5000h	5	6	32.6	5
		pH 9/40°C/5000h	5	6	33.2	5
		pH 9/60°C/5000h	5	6	32.5	5

Note: the nominal diameters were verified and used for stress calculations for bars without strain

132 Basalt FRP bars

- Time:

100h, 200h, 1000h and 5000h

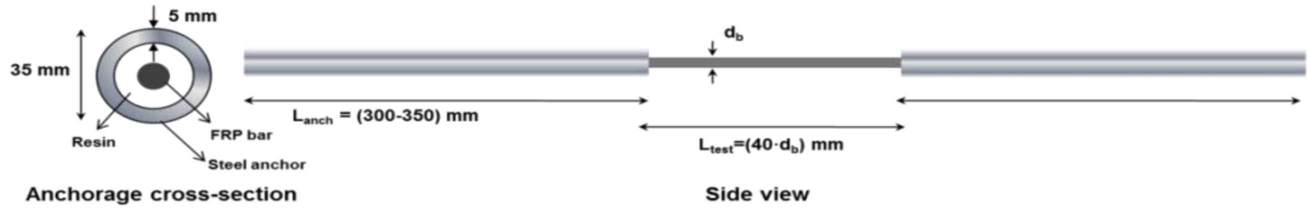
- Alkalinity:

pH7, pH9 and pH13

- Temperature:

20°C, 40°C and 60°C

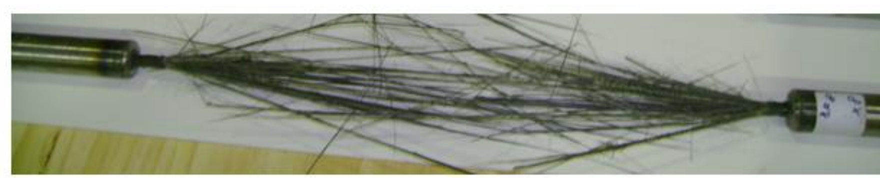
Basalt FRP bars



type 1 – 10 mm

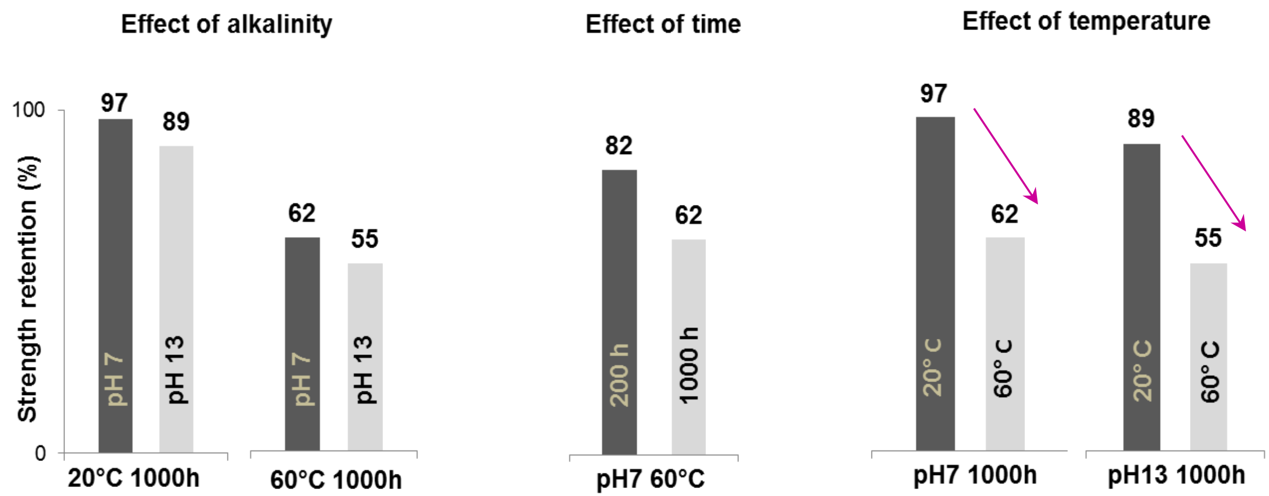
Conditioning

Tensile testing



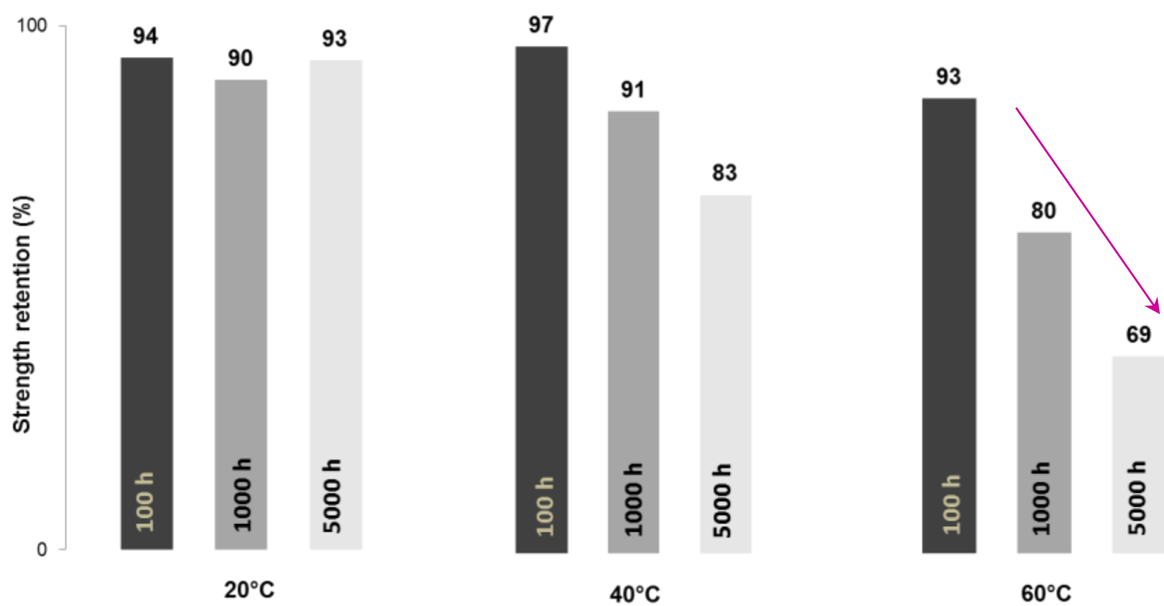
Conditioned specimens

type 1 bars



- pH – less effect
- Temp – high effect

type 2 bars in pH9



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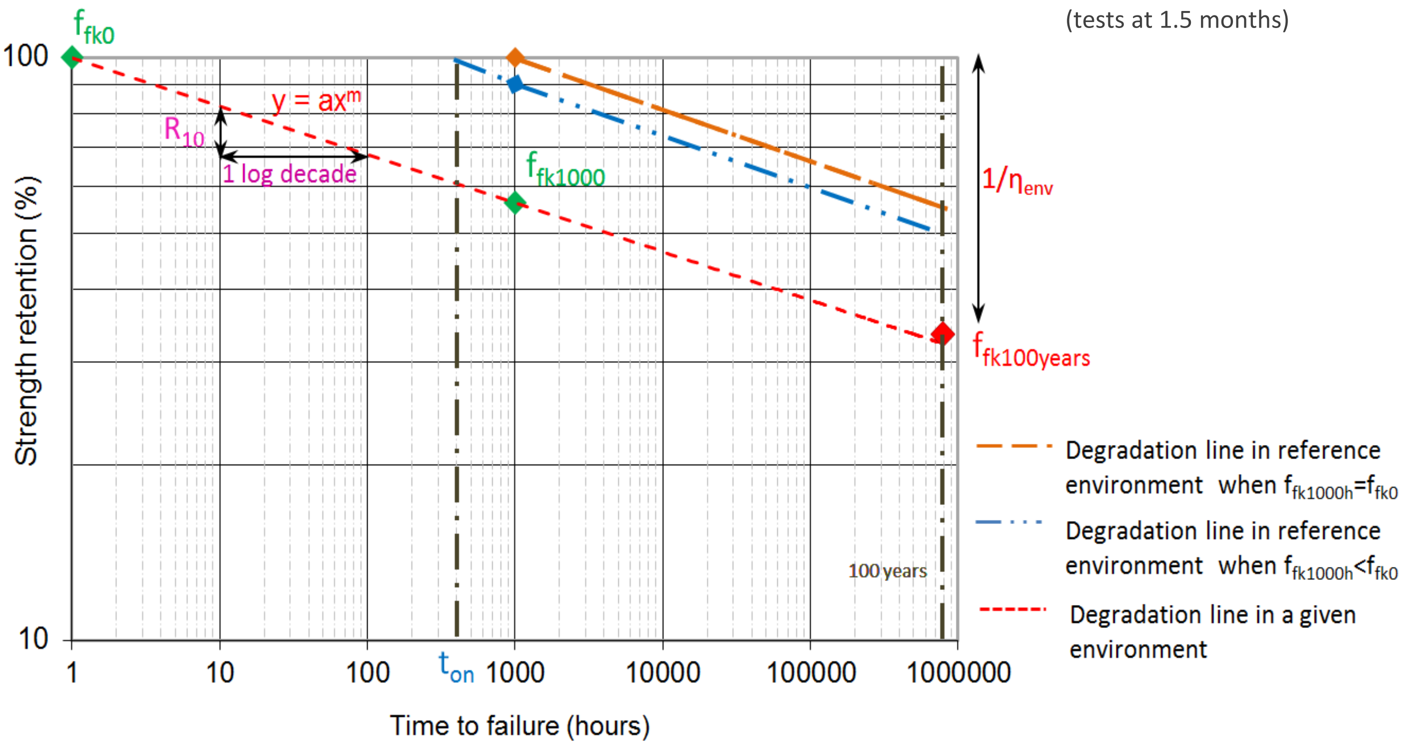
Long-term Strength Prediction

Short-term strength (tests at 1.5 months) - - - - - -> Long-term strength (100 years service life)



fib 40 (2007) $$n = n_{mo} + n_T + n_t + n_d + n_{pH} + n_{on}$$

Proposed

R_{10} - cst. n_{on} - changes

Proposed degradation parameters

Degradation	Range	Value
Moisture RH (n_{mo})	Dry (50%)	-1
	Moist (80%)	0
	Saturated (100%)	1
pH (n_{pH})	7	0
	10	0.5
	13	1
Time (n_t)	≤ 1000 h	0
	> 1000 h	log(hours/1000)
Diameter (n_d)	≥ tested	0
	~ 75% tested	0.5
	~ 50% tested	1
Temperature (n_T)	0°C	-0.5
	10°C	0
	20°C	0.5
	30°C	1
	40°C	1.5
	50°C	2
	60°C	2.5
Onset (n_{on})	$f_{fkref} = f_{k0}$	-1.5
	$f_{fkref} \neq f_{k0}$	$n_{on,opt}$

Proposed long-term strength prediction in any environment - Methodology

Step 1. Condition specimens — 1000h, 20°C, 40°C, 60°C, water, pH13

Step 2. Measure short term-strength — Tensile testing

Step 3. Establish degradation parameters — Use Table

Step 4. Determine the reference degradation curve — Find n_{on} and R_{10}

Step 5. Estimate the long-term strength

analytically

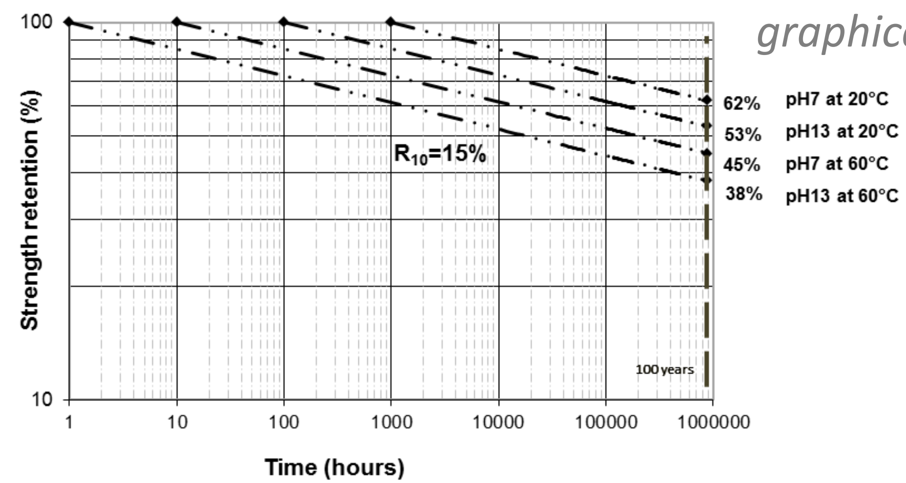
- environmental strength reduction factor

$$\eta_{env,t} = 1/((100 - R_{10})/100)^n$$

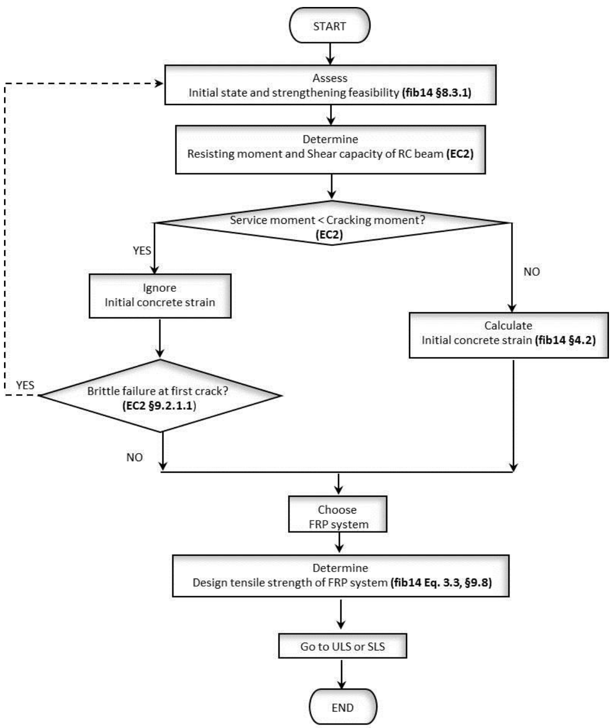
- percentage of the long-term strength retained

$$f_{fkt\%} = (1/\eta_{env,t}) \cdot 100$$

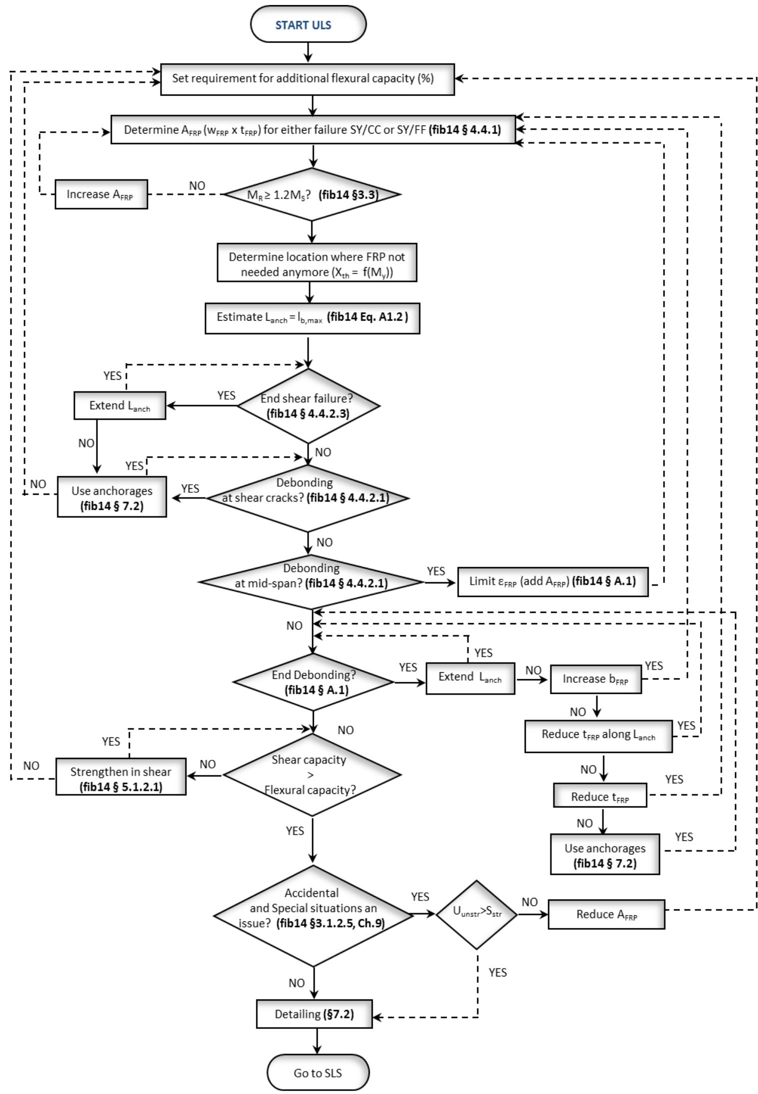
graphically



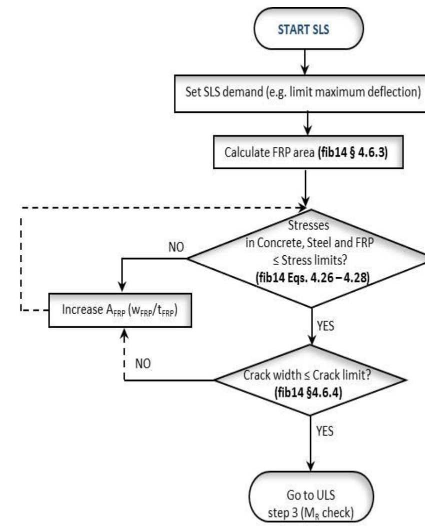
3. Proposed design flowcharts - designing with fib bulletin 14



Flowchart 1 – Initial state



Flowchart 2 – ULS



Flowchart 3 – SLS

Review

Issue addressed	Main Contributions
1. End debonding	▪ Bond tests improvements and methodology ▪ More accurate debonding model ▪ BFRP - effective U-anchorage
2. FRP durability	▪ Temp - high effect; pH - less effect ▪ Improved durability model and methodology
3. Design Procedure	▪ Design flowcharts

Contribute to providing engineers with more confidence in designing with FRPs!

Thank you!

Acknowledgments

- Encore RTN and Magmatech Ltd

FRP to Concrete Bond Tests

Published in American Society of Civil Engineers Journal

FRP Durability

Published in Journal of Composites Part B