Steel Structures Congress

16-18 November 2015

“CFRP Strengthening and Rehabilitation of Corroded Steel Pipelines Under Combined Bending and Bearing”

Dr Mohamed Elchalakani

Dubai Men’s College

UAE

- **Introduction**
  - **CFRP repair and strengthening of steel structures.**
  - **Types of Corrosion.**
  - **Traditional Methods of Repairs**
  - **Advantageous of using CFRP**
- **Laboratory Testing**
  - **Cutting CFRP Sheets**
  - **Cleaning**
  - **Mixing Part A+B**
  - **Application to pipe surface**
- **Test Results**
- **Conclusions**
- **Acknowledgment**
- **Video ??**

Why Do We Need Repair and/or Strengthening

We need to strengthen or rehabilitate steel structures because of:

1. Natural disasters (such as EQ.) or man-made disasters such as road crashes
2. Environmental effects such as Corrosion
3. Increase in traffic demands or upgrades of existing buildings.

Elchalakani, M. and Bambach M. (2007), Plastic Mechanism Analysis of CHS Stub Columns Strengthened using CFRP, Journal of Structural Engineering, Melbourne University Press., Vol 7, 1-57.

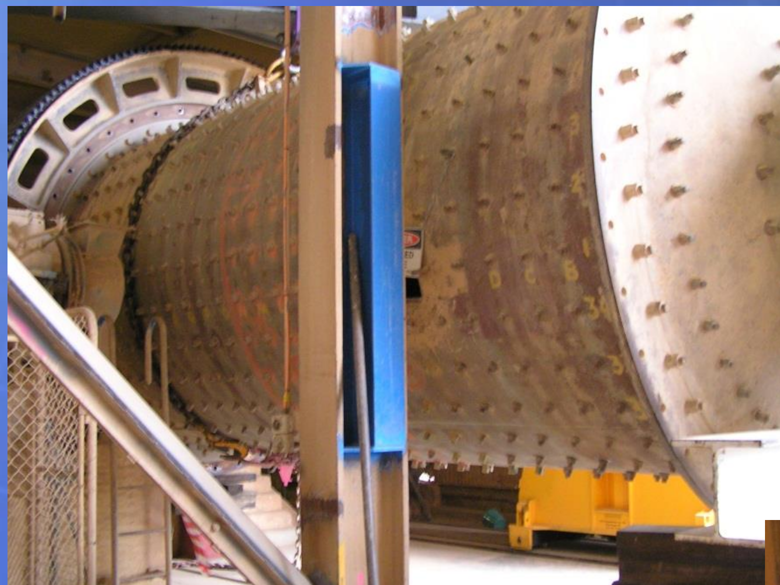
Traditional Strengthening of Steel Buildings, The Blue Circle Southern Cement-Geelong, Australia, $100M Project

Elchalakani, M. (2004), Design of Raw Mill Stack, New Preheater, New Raw Mill, Connell Wagner, Blue Circle Cement, Waurn Ponds, Geelong, Victoria, Australia

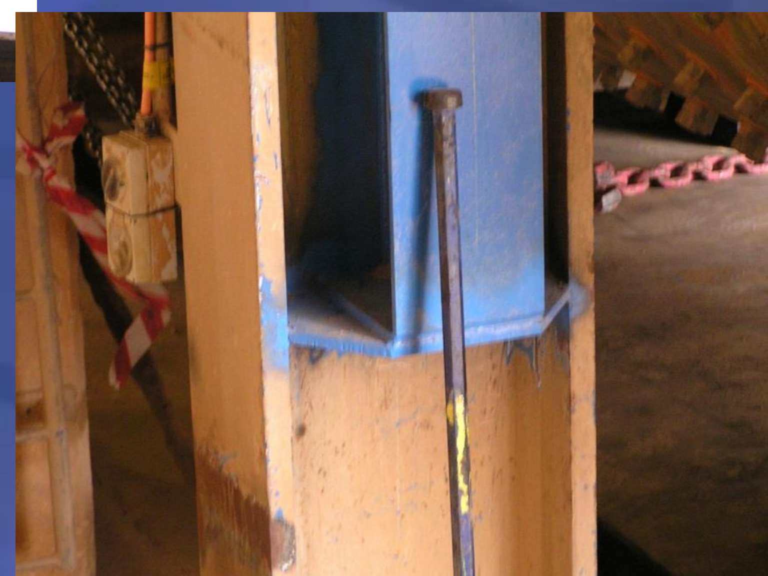
كلّيــات التقنيــة العليــا
HIGHER COLLEGES OF TECHNOLOGY

Traditional Steel buildings Strengthening

Columns Strengthening



Ball Mill Building



Welding Steel T-stubs at mid-height to increase the Critical buckling load

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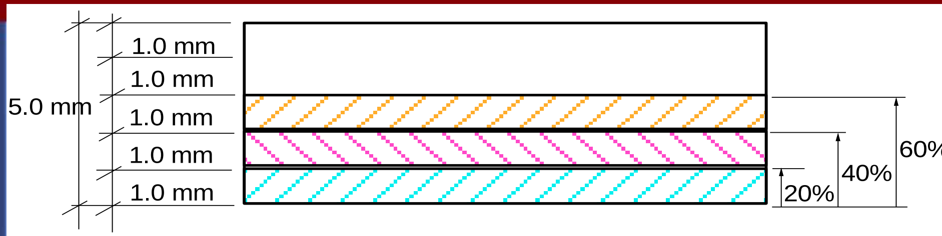
Traditional Strengthening Steel buildings

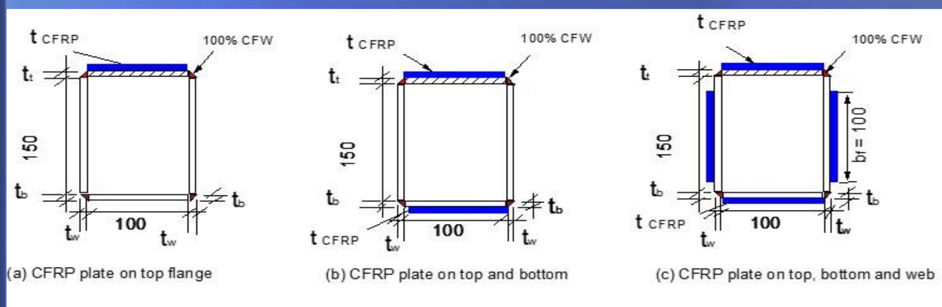
Floor and Walls Alterations - Beams and Braces

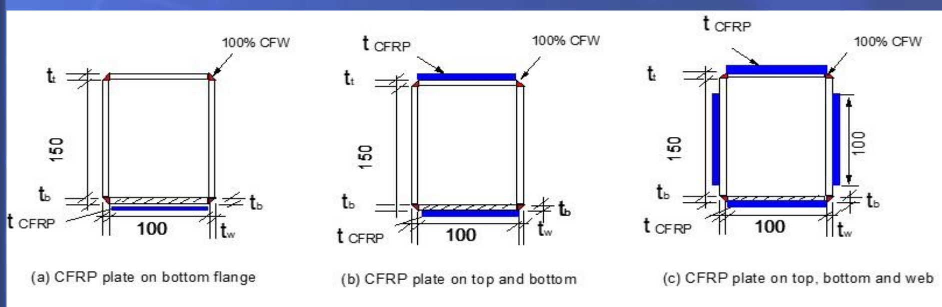
CFRP Strengthening of Steel Bridges

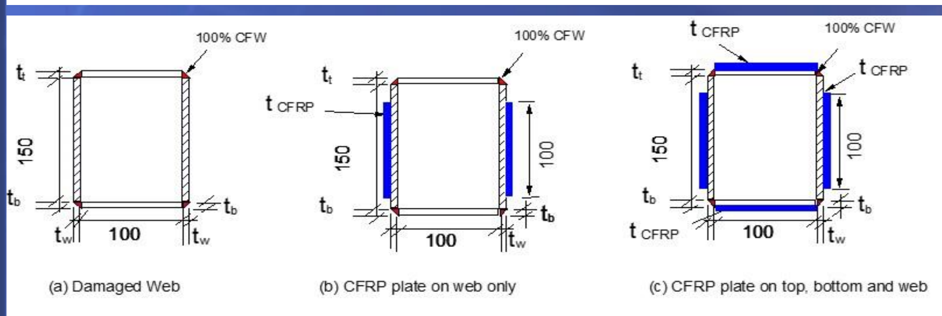
Modern Repair Work for Steel Structures

Rehabilitation of RHS using CFRP
Top, bottom and Web Surfaces-Rehabilitation





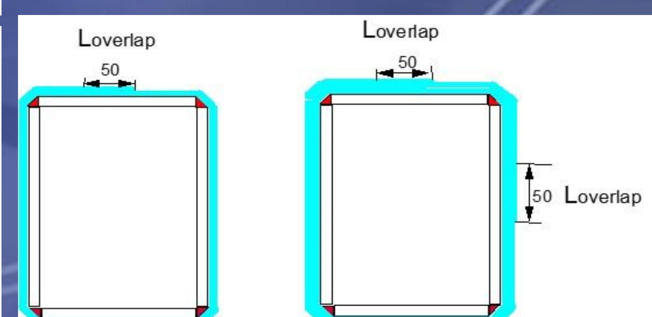




***Original Section 5.0mm thick.* CFRP plates location depends on the available access.**

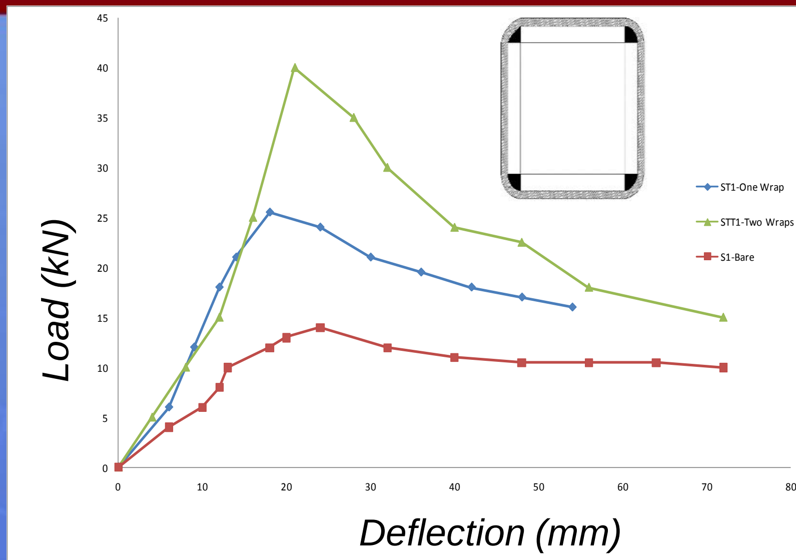
Three levels of corrosion at three different locations:

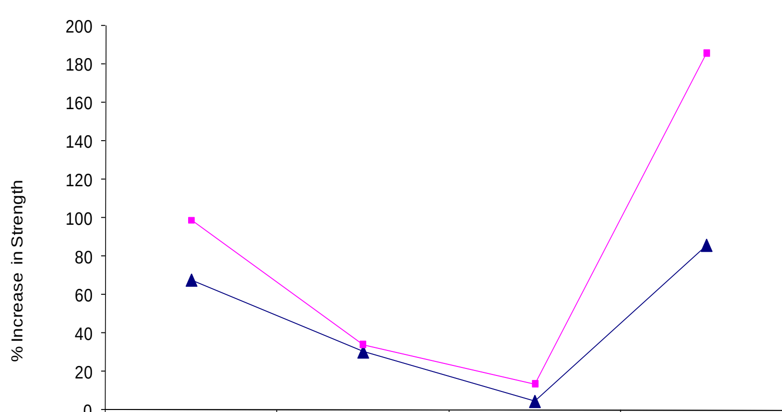
a) **20% on Top, bottom and web Plates**
b) **40% on Top, bottom and web Plates**
c) **60% on Top, bottom and web Plates**



Test Results

SME V-Wrap CFRP Strengthening of Box Girders





	Plastic	Compact	Semi-compact	Slender
1 Wrap	67.6	30.2	4.4	85.7
2 Wraps	98.6	34.0	13.3	185.7

Elchalakani, *M. and Fernando D. (2014), Repair and strengthening steel RHS beams strengthened with CFRP under 3-point bending, Journal of Thin-Walled Structures, Elsevier, UK, Vol. 57, No 1, 58-71.*

كليـــات التقنيـة العليـــا
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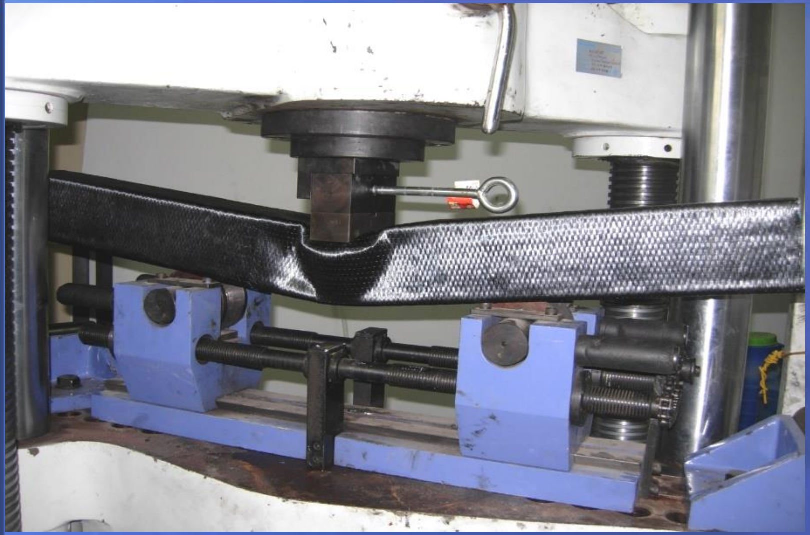
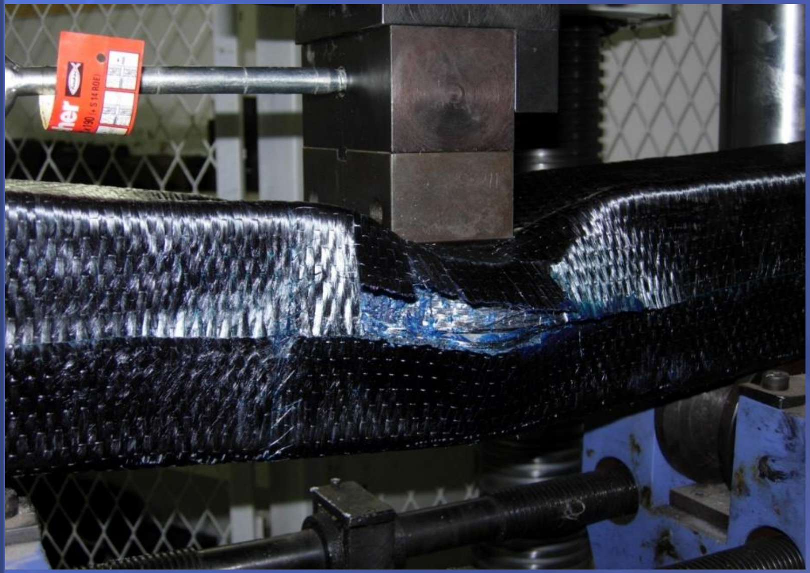
Strengthening Series-Failure Modes
Only the mid-span kink was observed





The failure modes observed includes;

a) *a ductile in-plane symmetric collapse mode under large bending deformation with the top flange forming a deep kink at mid-span associated with web crippling) was observed ;*

b) *The mixed mode where a LTB mode formed together with a deep mid-flange kink and web crippling was not observed*

c) *Pure LTB mode as Le/ry is small was not observed*

كليات التقنية العليا
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Rehabilitation Series-Failure Modes

Only the kink and mixed mode were observed

The failure modes observed includes:

a) ***a ductile in-plane symmetric collapse mode under large bending deformation with the top flange forming a deep kink at mid-span associated with web crippling); was observed***

b) ***The mixed mode where a LTB mode formed together with a deep mid-flange kink and web crippling for L=900 was observed***

c) ***Pure LTB mode as Le/ry is small was not observed***

__Elchalakani__, M. and Fernando D. (2014), Repair and strengthening steel RHS beams strengthened with CFRP under 3-point bending, Journal of Thin-Walled Structures, Elsevier, UK, Vol. 57, No 1, 58-71.

CFRP Strengthening of I-beam Failure Modes

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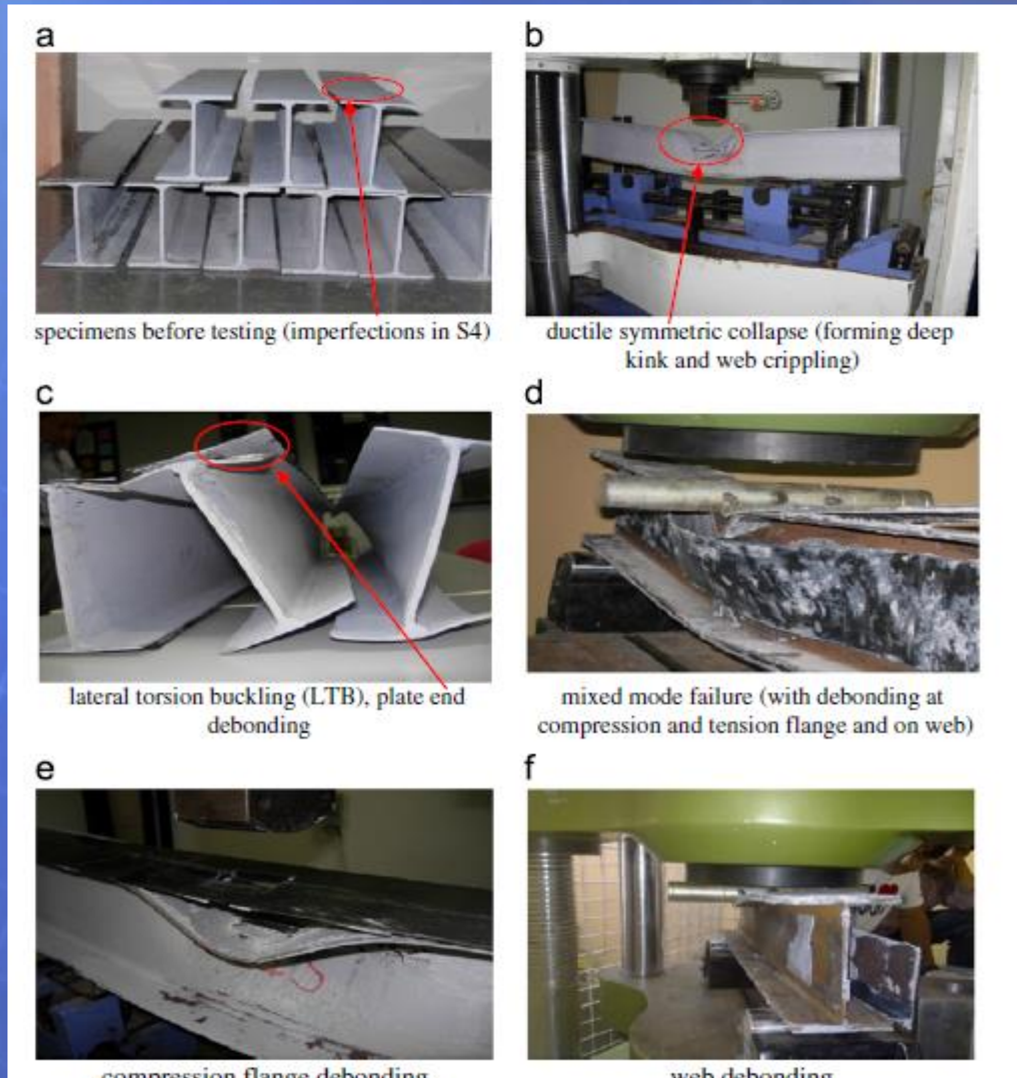

The failure modes observed includes;

(a) a ductile in-plane symmetric collapse mode under large bending deformation with the top flange forming a deep kink at mid-span associated with web crippling (S1, S2, S3, S6, SB1, SB2, SB3, STB1, STB2, STB3 and STBW6);

(b) a mixed mode where a LTB mode formed together with a mild mid-flange kink and web crippling (S5, STBW5). Unfortunately,

(c) a pure LTB out-of-plane lateral torsion buckling ((S4, SB4, STB4),

Elchalakani, *M. and Fernando D. (2012), Plastic Mechanism Analysis of unstiffened steel I-section beams strengthened with CFRP under 3-point bending, Journal of Thin-Walled Structures, Elsevier, UK, Vol. 57, No 1, 58-71.*

Corrosion Problem of Pipelines

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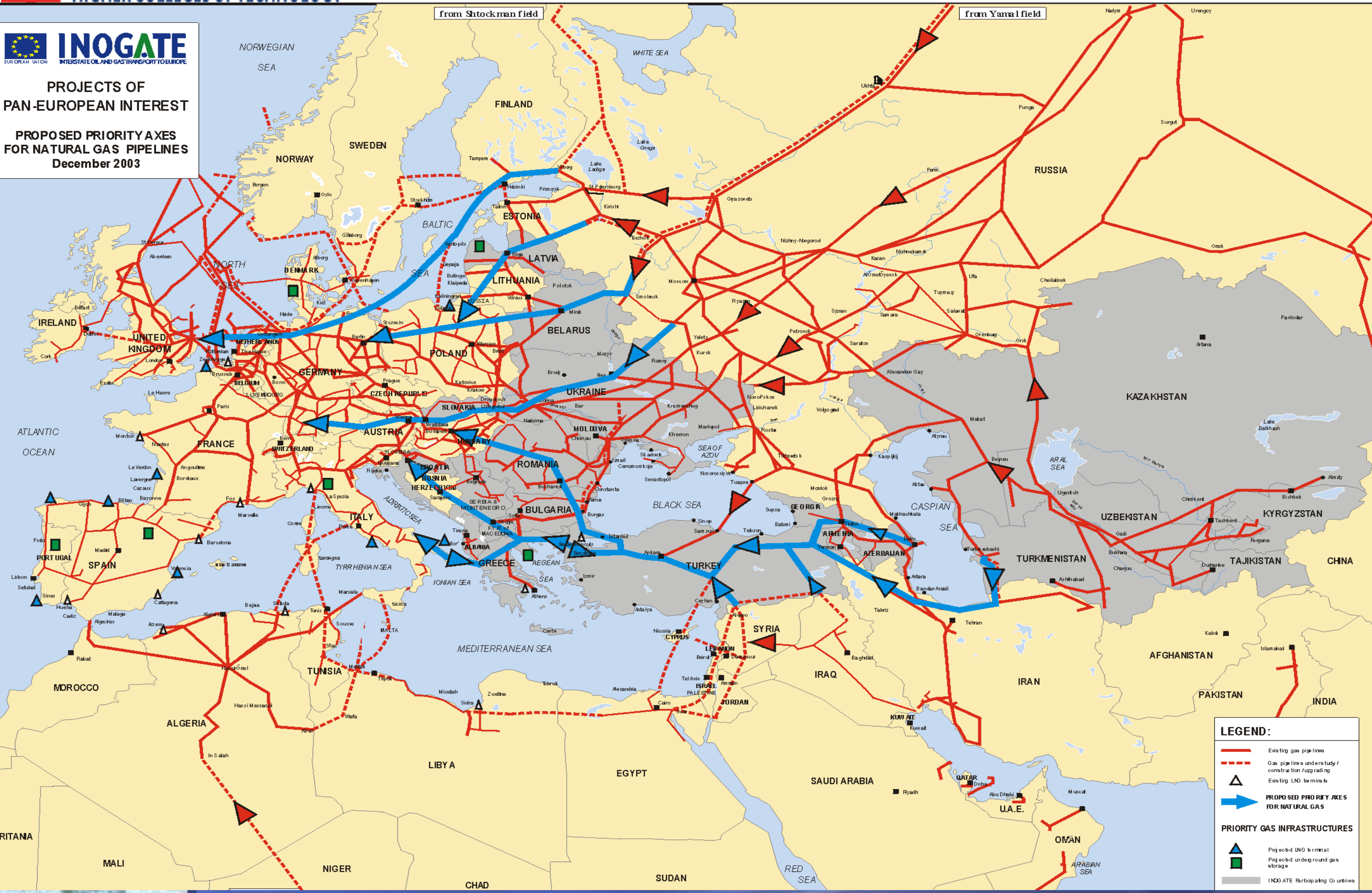
1.7 million km of Steel Pipelines

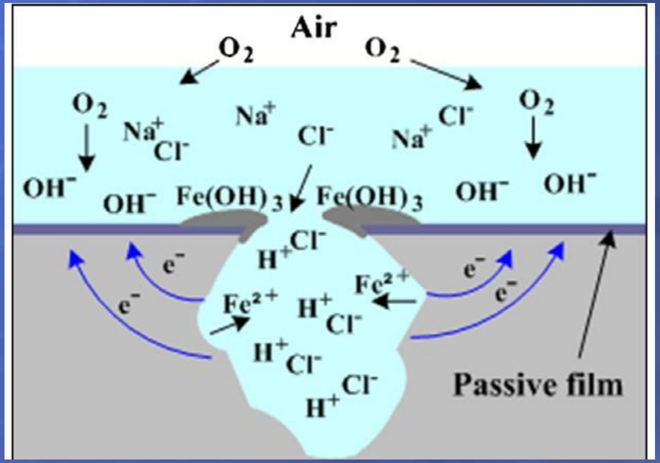


Economy loss due to corrosion

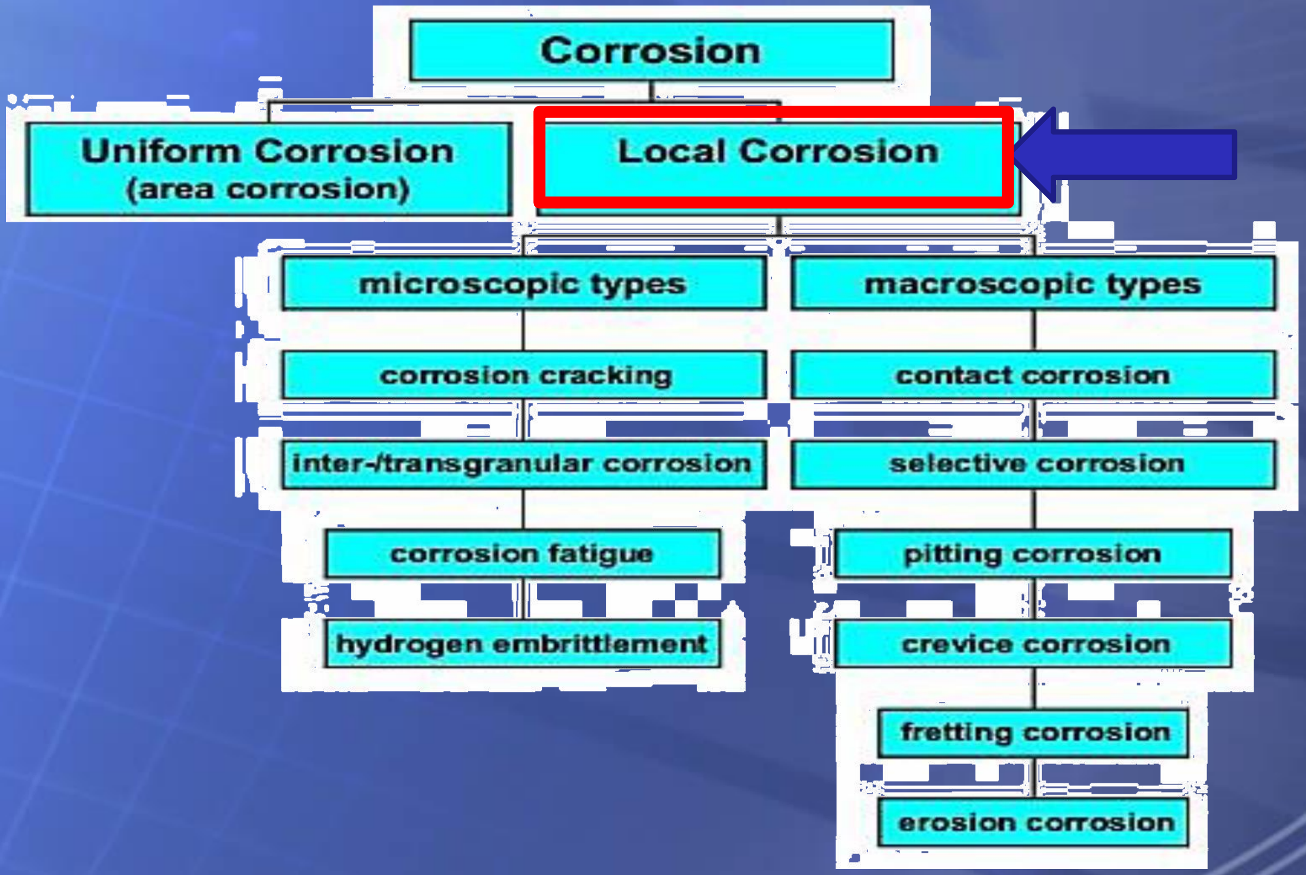
- Corrosion has a huge economic and environmental impact on virtually all facets of the world’s infrastructure, from highways, bridges, and buildings to oil and gas, chemical processing, and water and wastewater systems. In addition to causing severe damage and threats to public safety, corrosion disrupts operations and requires extensive repair and replacement of failed assets. The annual cost of corrosion worldwide is estimated to exceed $1.8 trillion, which translates to 3 to 4% of the Gross Domestic Product (GDP) of industrialized countries. In the US, the annual cost of corrosion is estimated as $276B. The annual cost of corrosion to the Australian economy is estimated to be between $36B and $60B, whereas for the New Zealand economy the cost lies between $5.5B and $9.2B. Yet, governments and industries pay little attention to corrosion except in high-risk areas like aviation and maritime industries.

Corrosion

- Result of interaction of the outer environment.
  - WATER
  - OXYGEN
- (Exothermic reaction)
- Formation of rust:
  - IRON OXIDE
  - The reaction between iron and oxygen in the presence of moisture or water.
- Strong acid and oxidizing agents.



Types of corrosion

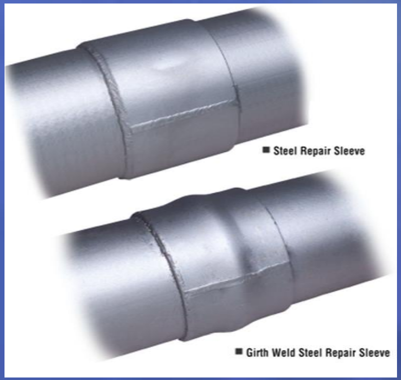


Local corrosion is the subject of this paper

Uniform corrosion

Traditional methods of repair

Welded sleeves



Bolted sleeves

External Patches

Advantages of using CFRP Repair

- 24% cheaper than welded steel sleeve repairs
- 73% cheaper than replacing the damaged section of the steel pipe
- Short amount of time.
- Undisrupted fluid transmission .
- No Explosion potential.

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Specimen Preparation

كليات التقنية العليا
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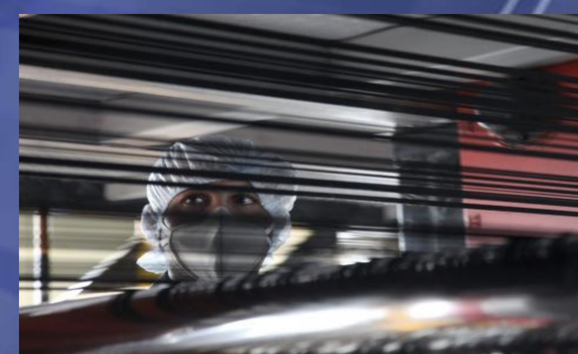
Carbon Fiber & Pipe Application

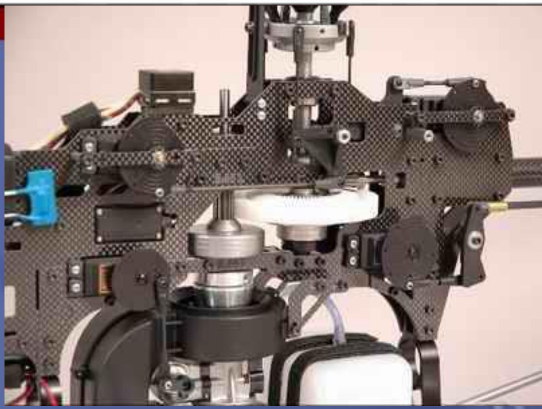
Carbon Fiber Sheet
V-Wrap™ C200

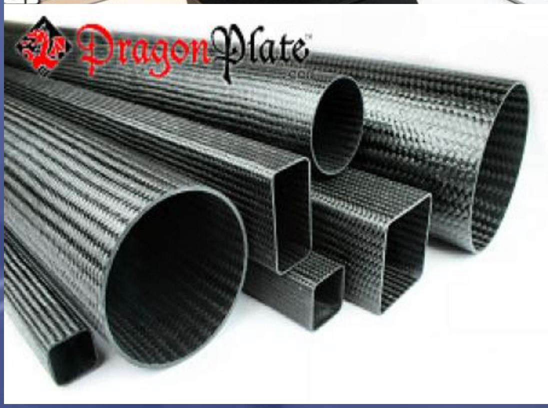
structural
TECHNOLOGIES



Uses Of Carbon Fiber

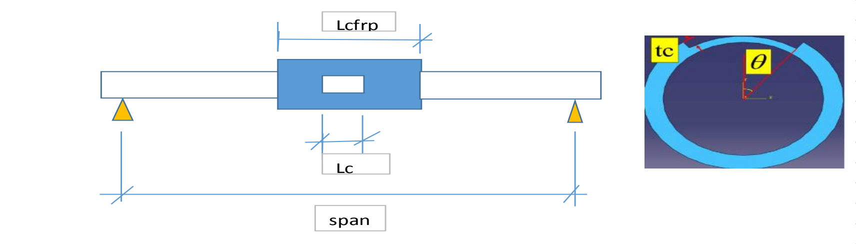
- Aircraft…
- Cars…
- Bicycle and Motorcycle…
- Buildings…
- Steel Beams…
- Steel Pipes…





Specimens Lc/D<3.0

Corrosion Level	New ID 21-Apr-14	thk mm	tc mm	Lc mm	Lcfrp mm	θ Deg.	CFRP	Span mm	Manufacturer	Transvere Sheet	Overlap	Long Sheet	Overlap
0%	T5L0C0-01	5	0	0	0	0	0	900	SME V-Wrap C200	0	0	0	0
	T5L0C0-02	5	0	0	0	0	0	900	SME V-Wrap C200	0	0	0	0
	T5L0C0-03	5	0	0	0	0	0	**600**	SME V-Wrap C200	0	0	0	0
Corrosion	Specimens ID	thk	tc	Lc	Lcfrp	θ	CFRP	Span	Manufacturer	Transverse Sheet	Overlap	Long Sheet	Overlap
20%	T4L1C0-0	4	1	100	0	360	0	900	SME V-Wrap C200	0	0	0	0
	T4L1C2-1T1L	4	1	100	300	360	1L1T	900	SME V-Wrap C200	450 x 300	150	450 x 300	150
	T4L1C2-2T2L	4	1	100	300	360	2L2T	900	SME V-Wrap C200	750 x 300	150	600 x 300	0
	T4L2C0-0	4	1	200	0	360	0	900	SME V-Wrap C200	0	0	0	0
	T4L2C4-1T1L	4	1	200	400	360	1L1T	900	SME V-Wrap C200	450 x 400	150	450 x 400	150
	T4L2C4-2T2L	4	1	200	400	360	2L2T	900	SME V-Wrap C200	750 x 400	150	600 x 400	0
	T4L3C0-0	4	1	300	0	360	0	900	0	0	0	0	0
Corrosion	Specimens ID	thk	tc	Lc	Lcfrp	θ	CFRP	Span	Manufacturer	Transverse Sheet	Overlap	Long Sheet	Overlap
40%	T3L1C0-0	3	2	100	0	360	0	900	SME V-Wrap C200	0	0	0	0
	T3L1C2-1T1L	3	2	100	300	360	1L1T	900	SME V-Wrap C200	450 x 300	150	450 x 300	150
	T3L1C2-1T1L-SIKA	3	2	100	300	360	1L1T	900	SIKA 300C Wrap	450 x 300	150	450 x 300	150
	T3L2C0-0	3	2	200	0	360	0	900	SME V-Wrap C200	0	0	0	0
	T3L2C4-1T1L	3	2	200	400	360	1L1T	900	SME V-Wrap C200	450 x 400	150	450 x 400	150
	T3L2C4-1T1L-SIKA	3	2	200	400	360	1L1T	900	SIKA 300C Wrap	450 x 400	150	450 x 400	150
	T3L3C0-0	3	2	300	0	360	0	900	0	0	0	0	0
Corrosion	Specimens ID	thk	tc	Lc	Lcfrp	θ	CFRP	Span	Manufacturer	Transverse Sheet	Overlap	Long Sheet	Overlap
60%	T2L1C0-0	2	3	100	0	360	0	900	SME V-Wrap C200	0	0	0	0
	T2L1C2-1T1L	2	3	100	300	360	1L1T	900	SME V-Wrap C200	450 x 300	150	450 x 300	150
	T2L1C2-1T1L-SIKA	2	3	100	300	360	1L1T	900	SIKA 300C Wrap	450 x 300	150	450 x 300	150
	T2L2C0-0	2	3	200	0	360	0	900	SME V-Wrap C200	0	0	0	0
	T2L2C4-1T1L	2	3	200	400	360	1L1T	900	SME V-Wrap C200	450 x 400	150	450 x 400	150
	T24L2C4-1T1L-SIKA	2	3	200	400	360	1T1L	900	SIKA 300C Wrap	450 x 400	150	450 x 400	150
	T2L3C0-0	2	3	300	0	360	0	900	SIKA 300C Wrap	0	0	0	0
Corrosion	Specimens ID	thk	tc	Lc	Lcfrp	θ	CFRP	Span	Manufacturer	Transverse Sheet	Overlap	Long Sheet	Overlap
80%	T1L1C0-0	1	4	100	0	360	0	900	SME V-Wrap C200	0	0	0	0
	T1L1C2-1T1L	1	4	100	300	360	1L1T	900	SME V-Wrap C200	450 x 300	150	450 x 300	150
	T1L1C2-2T2L	1	4	100	300	360	2L2T	900	SME V-Wrap C200	750 x 300	150	600 x 300	0
	T1L2C0-0	1	4	200	0	360	0	900	SME V-Wrap C200	0	0	0	0
	T1L2C4-1T1L	1	4	200	400	360	1L1T	900	SME V-Wrap C200	450 x 400	150	450 x 400	150
	T1L2C4-2T2L	1	4	200	400	360	2L2T	900	SME V-Wrap C200	750 x 400	150	600 x 400	0
	T1L3C0-0	1	4	300	0	360	0	900	0	0	0	0	0



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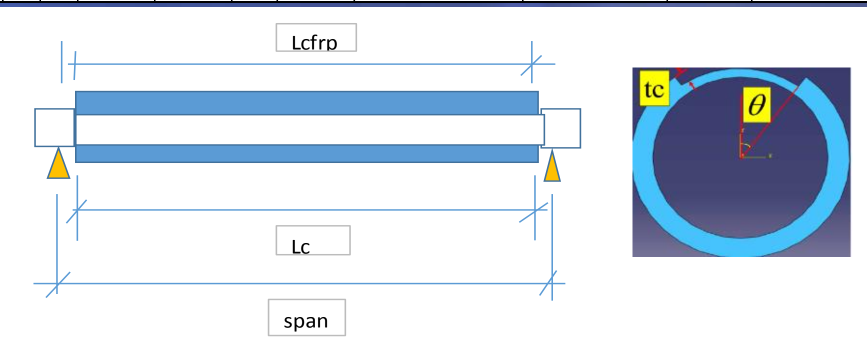
Specimens Lc/D=8.0

Corrosion	New ID	thk	tc	Lc	Lcfrp	θ	CFRP	Span	Manufacturer	Transvere Sheet	Overlap	Long Sheet	Overlap	Application
	21-Apr-14	mm	mm	mm	mm	Deg.		mm						
20%	ST4L8C8-0	4	1	800	0	360	0	900	SME V-Wrap C200	0	0	0	0	0
	ST4L8C8-2T2L	4	1	800	800	360	2L2T	900	SME V-Wrap C200	1 x 750 x 600 + 1 x 350 x 750	150	600 x 800	0	2L2T
	ST4L8C8-4T4L	4	1	800	800	360	4L4T	900	SME V-Wrap C200	2 x 750 x 600 + 2 x 350 x 750	150	2 x 600 x 800	0	2L2T2L2T
Corrosion	Specimens ID	thk	tc	Lc	Lcfrp	θ	CFRP	Span	Manufacturer	Transverse Sheet	Overlap	Long Sheet	Overlap	
40%	ST3L8C8-0	3	2	800	0	360	0	900	SME V-Wrap C200	0	0	0	0	0
	ST3L8C8-2T2L	3	2	800	800	360	2L2T	900	SME V-Wrap C200	1 x 750 x 600 + 1 x 350 x 750	150	600 x 800	0	2L2T
	ST3L8C8-4T4L	3	2	800	800	360	4L4T	900	SME V-Wrap C200	2 x 750 x 600 + 2 x 350 x 750	150	2 x 600 x 800	0	2L2T2L2T
Corrosion	Specimens ID	thk	tc	Lc	Lcfrp	θ	CFRP	Span	Manufacturer	Transverse Sheet	Overlap	Long Sheet	Overlap	Overlap
60%	ST2L8C8-0	2	3	800	0	360	0	900	SME V-Wrap C200	0	0	0	0	0
	ST2L8C8-2T2L	2	3	800	800	360	2L2T	900	SME V-Wrap C200	1 x 750 x 600 + 1 x 350 x 750	150	600 x 800	0	2L2T
	ST2L8C8-4T4L	2	3	800	800	360	4L4T	900	SME V-Wrap C200	2 x 750 x 600 + 2 x 350 x 750	150	2 x 600 x 800	0	2L2T2L2T
Corrosion	Specimens ID	thk	tc	Lc	Lcfrp	θ	CFRP	Span	Manufacturer	Transverse Sheet	Overlap	Long Sheet	Overlap	Overlap
80%	ST1L8C8-0	1	4	800	0	360	0	900	SME V-Wrap C200	0	0	0	0	0
	ST1L8C8-2T2L	1	4	800	800	360	2L2T	900	SME V-Wrap C200	1 x 750 x 600 + 1 x 350 x 750	150	600 x 800	0	2L2T
	ST1L8C8-4T4L	1	4	800	800	360	4L4T	900	SME V-Wrap C200	2 x 750 x 600 + 2 x 350 x 750	150	2 x 600 x 800	0	2L2T2L2T



كلّيـــات التقنيــة العليـــا
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The total number of specimens is 43

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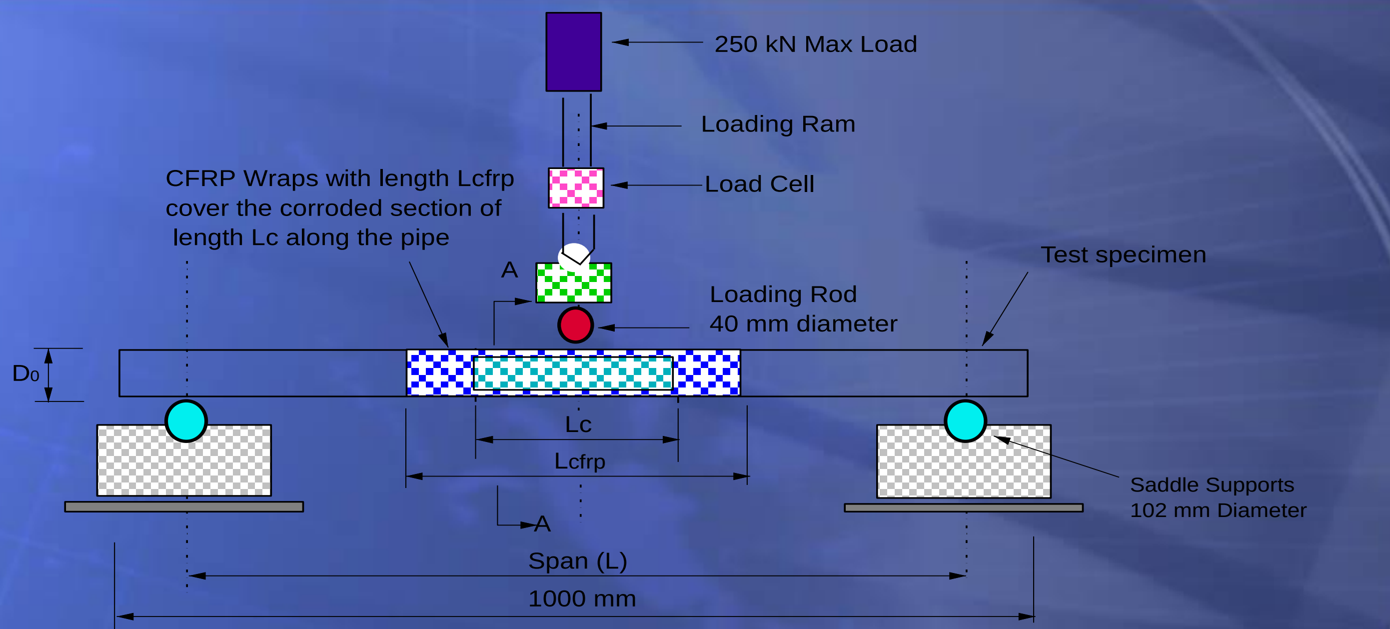
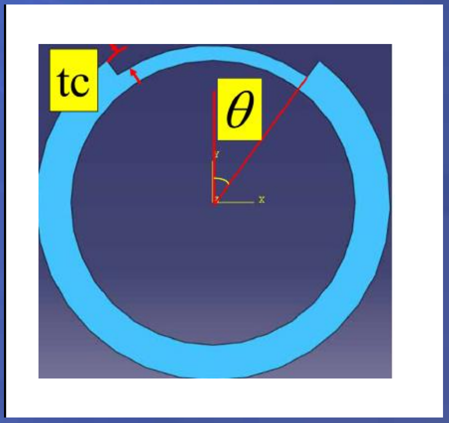
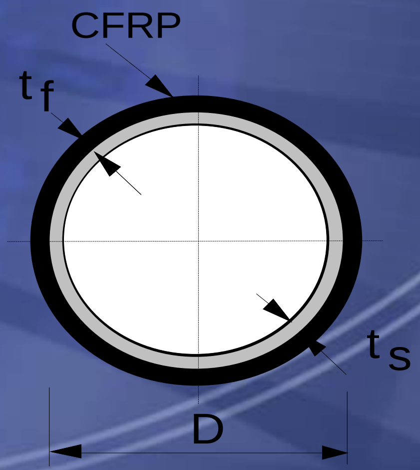




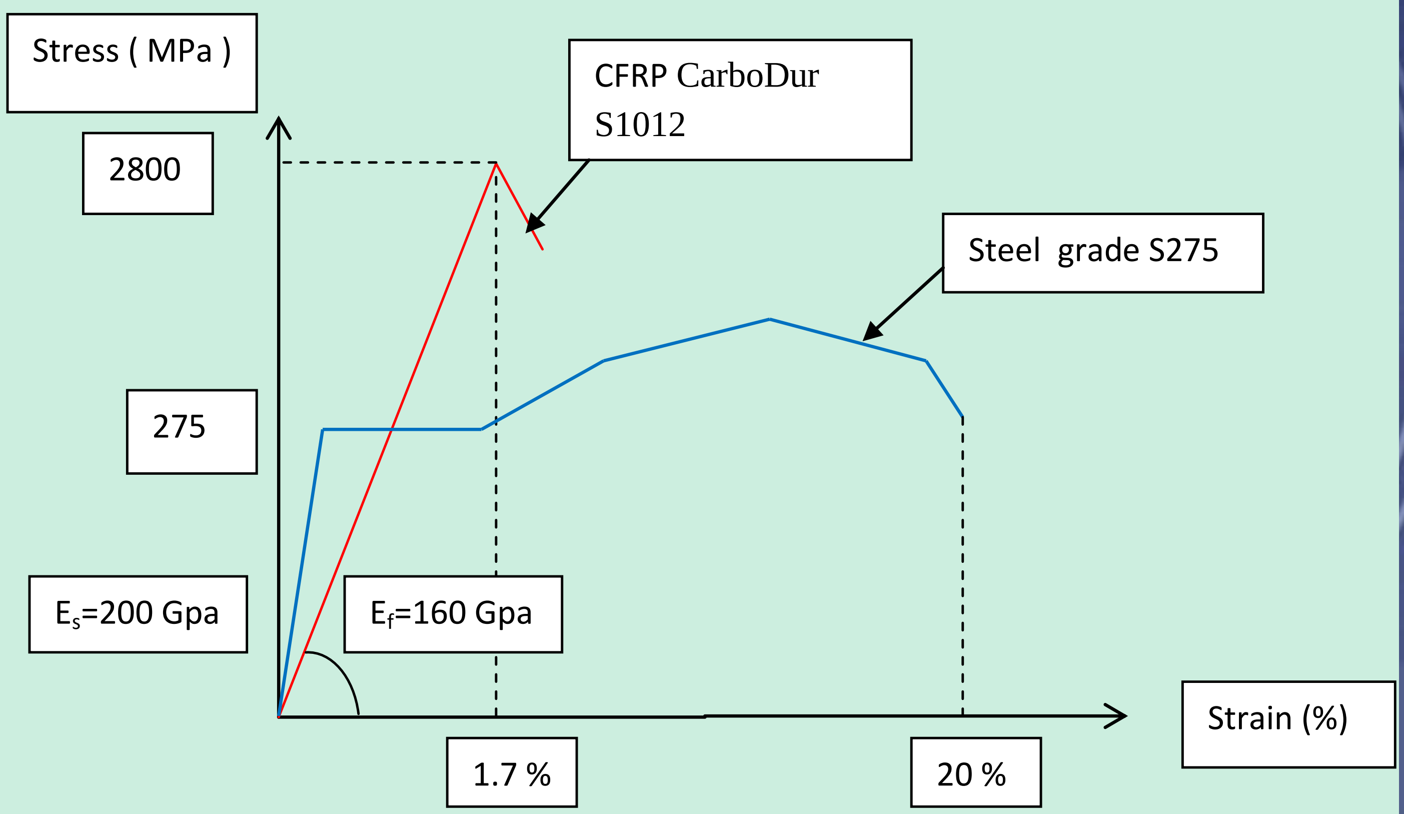


POST-TENSIONING INSTITUTE ®

Mechanical Properties of CFRP

Manufacturer		Sika Plates CarboDur S	Sika Sikadur 330 Sheets	Structural Tech C180 V-Wrap
E-Modulues	Mean Value	165,000 N/mm^2	230,000 N/mm^2	227,000 N/mm^2
	Min Value	> 160,000 N/mm^2	> 230,000 N/mm^2	> 227,000 N/mm^2
	5% Fractile Value	162,000 N/mm^2	230,000 N/mm^2	227,000 N/mm^2
	95% Fractile Value	180,000 N/mm^2	230,000 N/mm^2	227,000 N/mm^2
Tensile Strength	Mean Value	3,100 N/mm^2	3,500 N/mm^2	4,000 N/mm^2
	Min Value	> 2,800 N/mm^2	> 3,500 N/mm^2	4,000 N/mm^2
	5% Fractile Value	3,000 N/mm^2	3,500 N/mm^2	4,000 N/mm^2
	95% Fractile Value	3,600 N/mm^2	3,500 N/mm^2	4,000 N/mm^2
Stain at Break* (Min Value)		> 1.70%	> 1.5%	> 1.70%
Thickness (mm)		1.2	0.13	0.28

CFRP Plates and Mild Steel Tensile Properties



Prepare Carbon Fiber

Measurement

Cutting

كليات التقنية العليا
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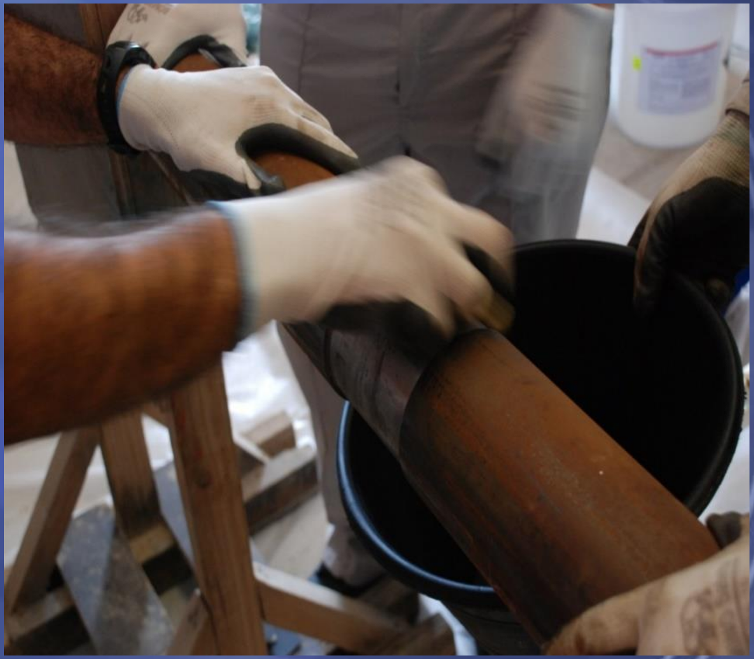
Pipe Application…

1	2	3
Cleaning	Adhesive Mixing	Carbon Saturated
• Sanding • Grinding	• Part A • Part B	• Saturated • Transverse& Longitudinal

Cleaning



Cleaning

Sanding

Cleaning

Grinding

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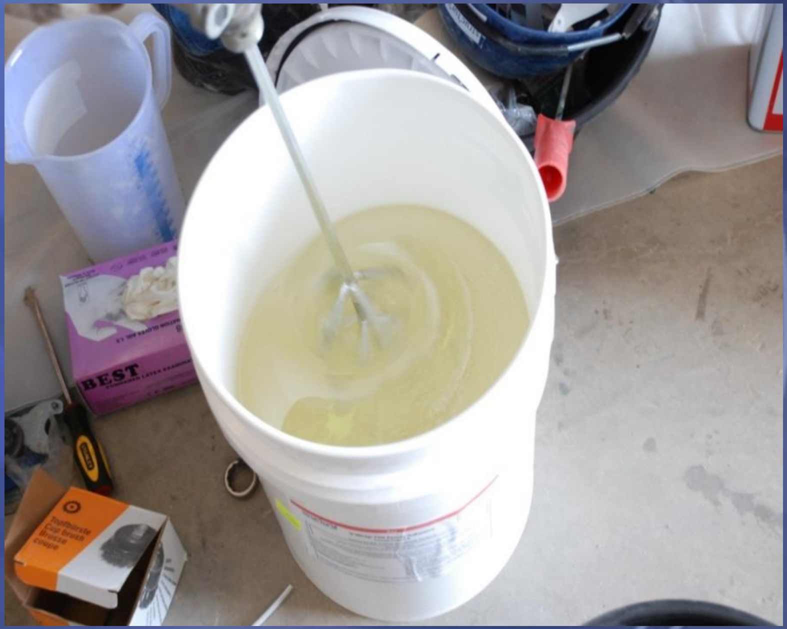
HIGHER COLLEGES OF TECHNOLOGY

Adhesive Mixing



Mixing Part A

Adhesive Mixing

Mixing Part B

Prepare The Surface Area

Preparing

Carbon Saturated

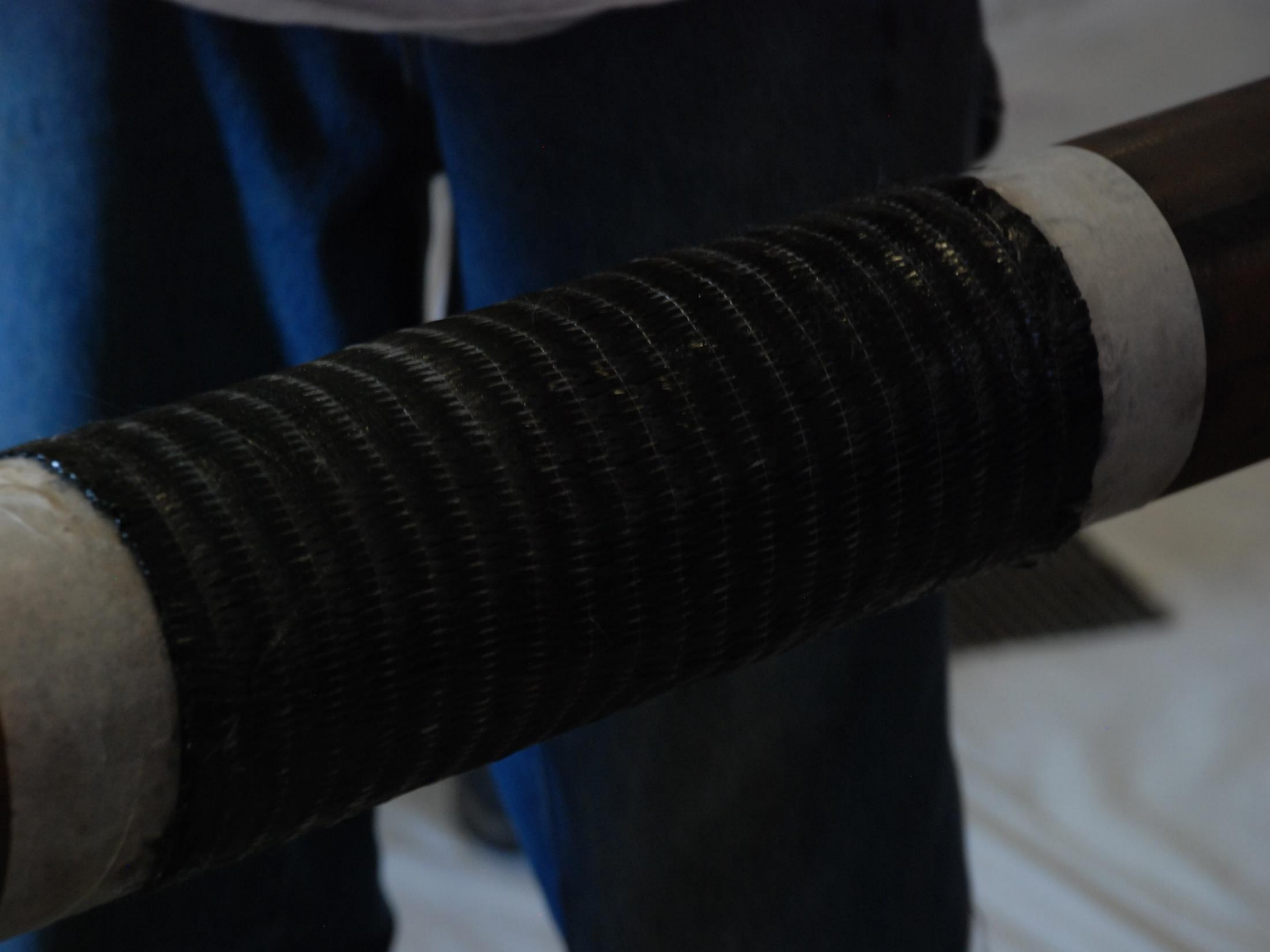
Saturated

Transverse

Carbon Saturated

Saturated

Longitudinal



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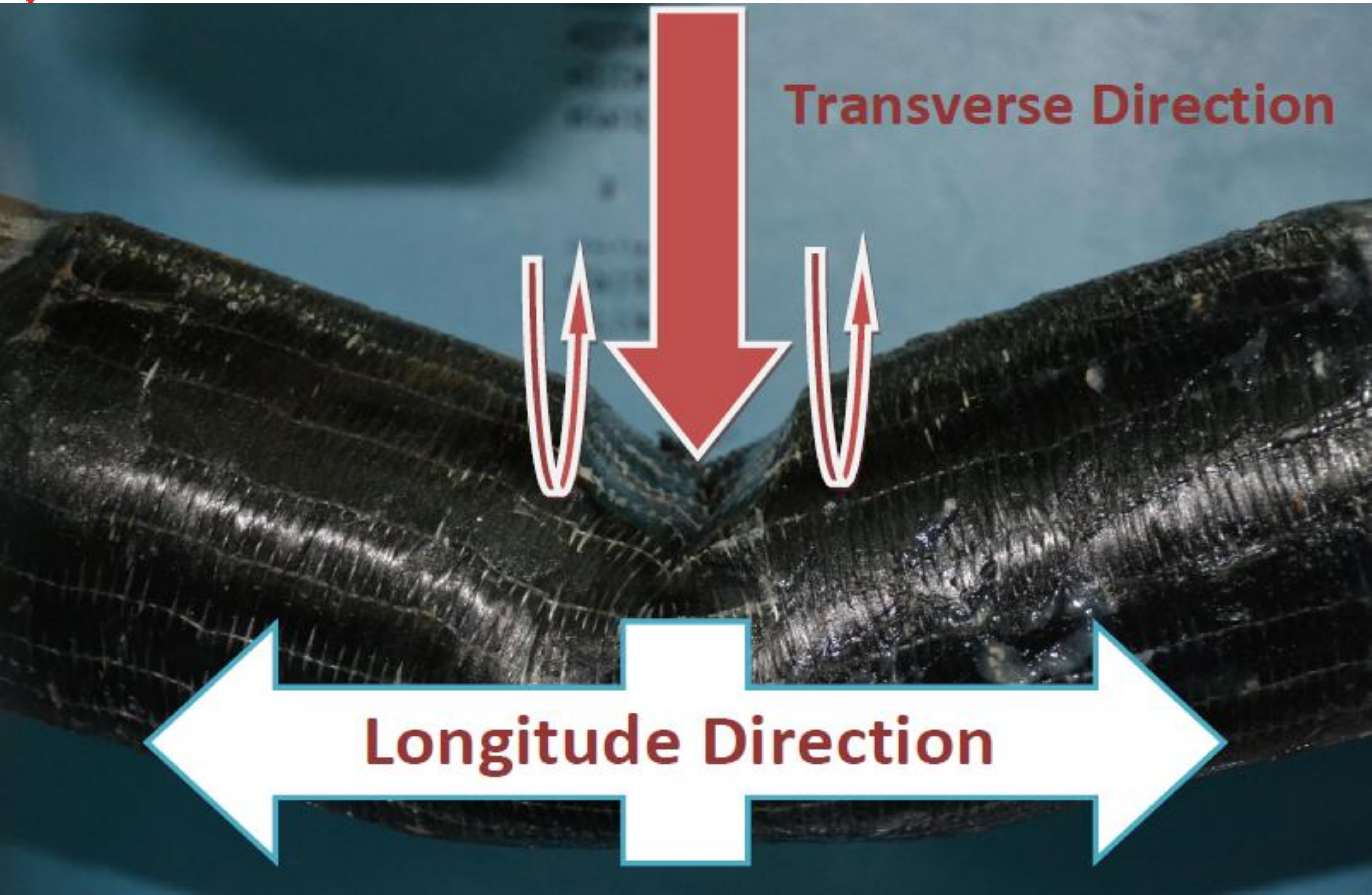
كلّيات التقنية العليا

Why Transverse & Longitude Direction?



2. Laboratory Testing

Test Set up

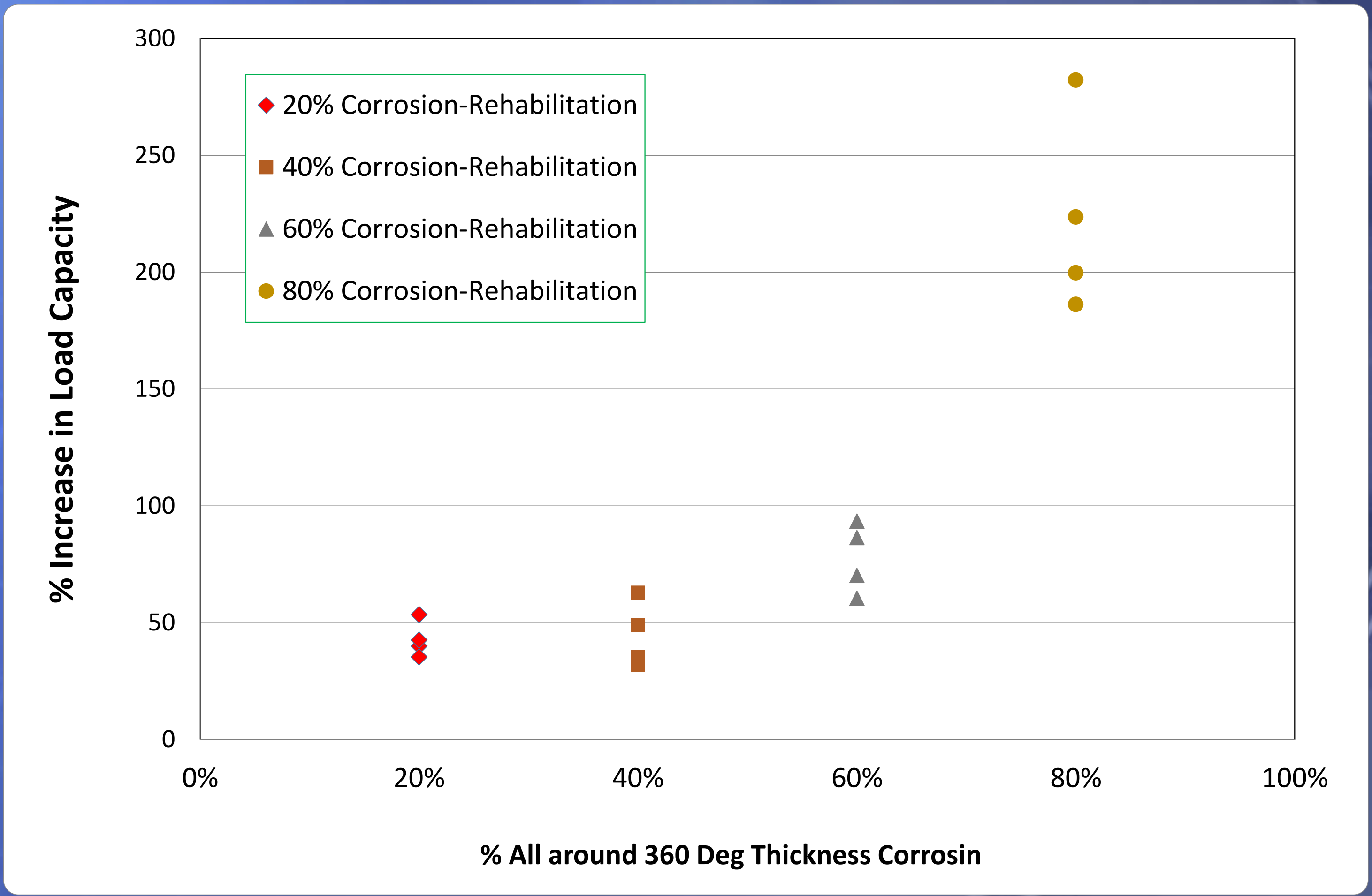
Failure Modes

- CFRP System
  - Fibre Fracture
  - Local Buckling
  - Intermediate Plate Debonding
- Steel Pipe
  - Steel Fracture
  - Local Buckling

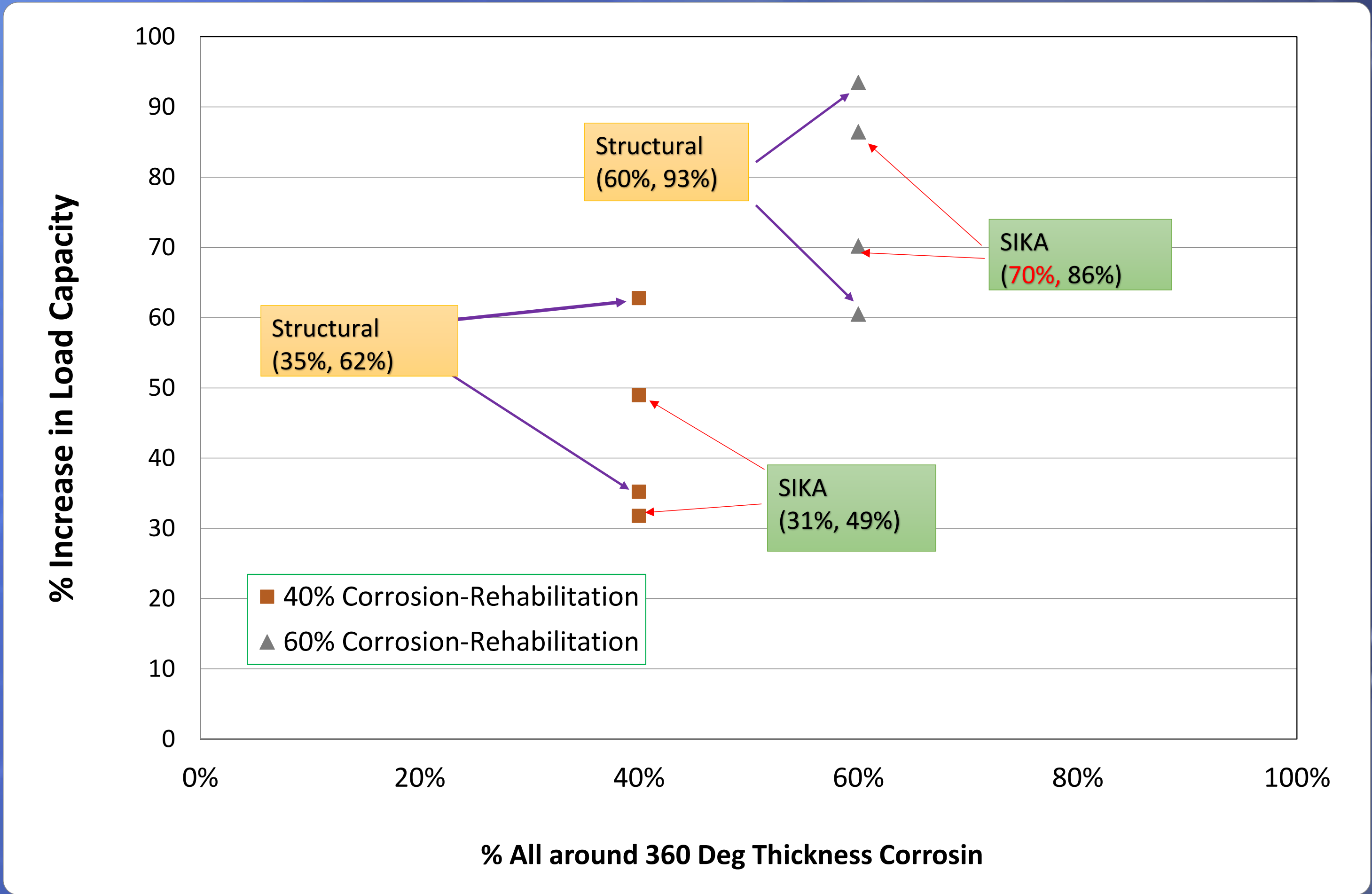
3. Test Results

Specimens after Testing

Gain in Strength due to CFRP



Structural Technology wrapping System Provided higher strength



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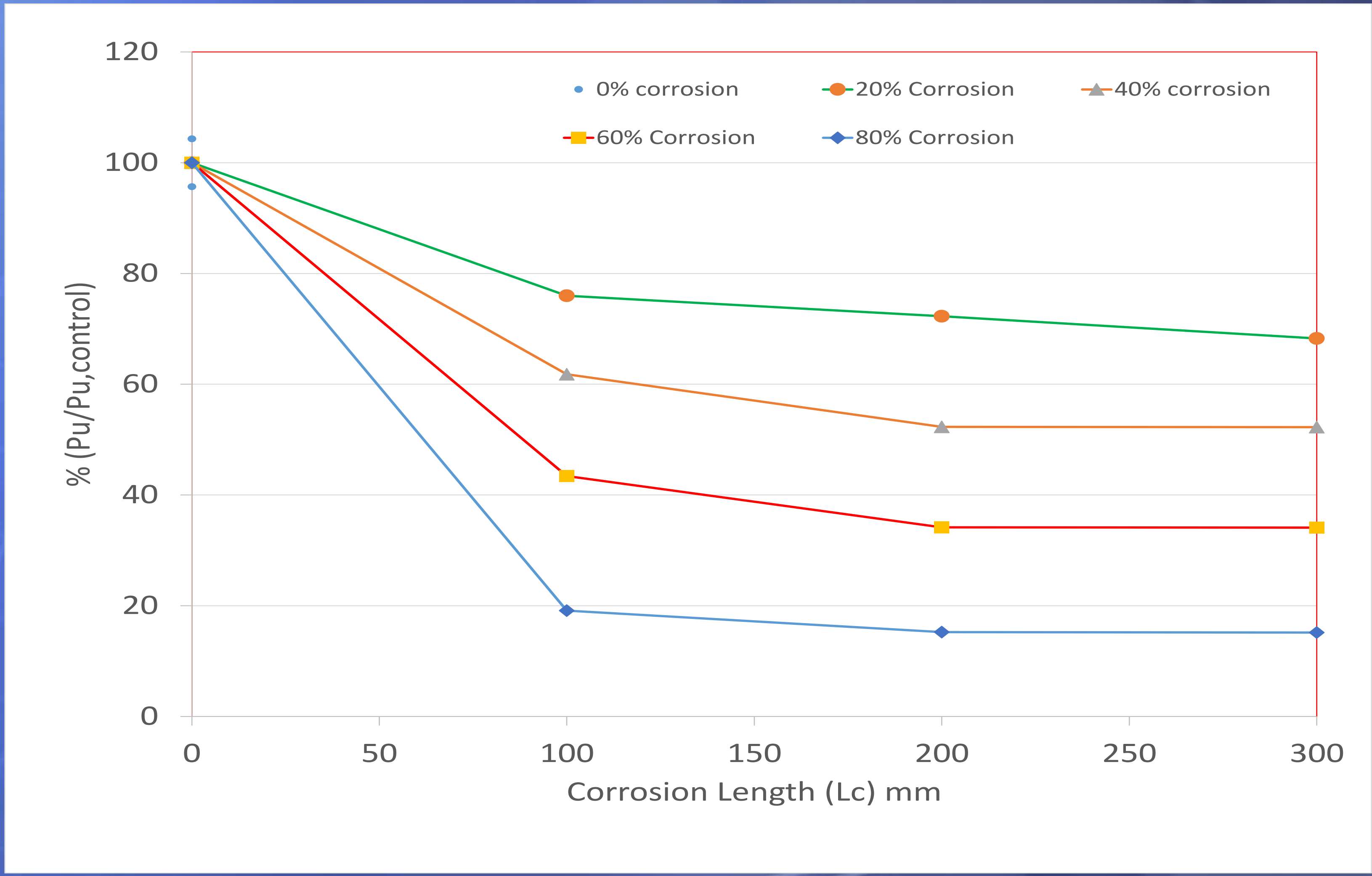
Effect of the corrosion length (L_c) on the normalised strength ($\%P_u/P_{u,control}$)



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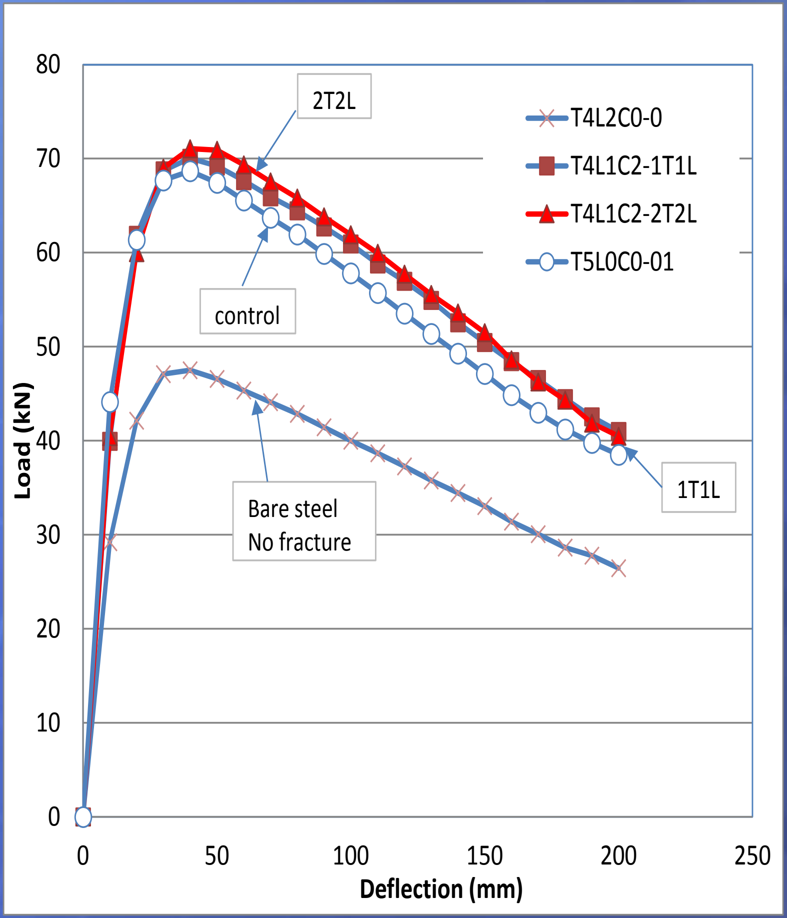
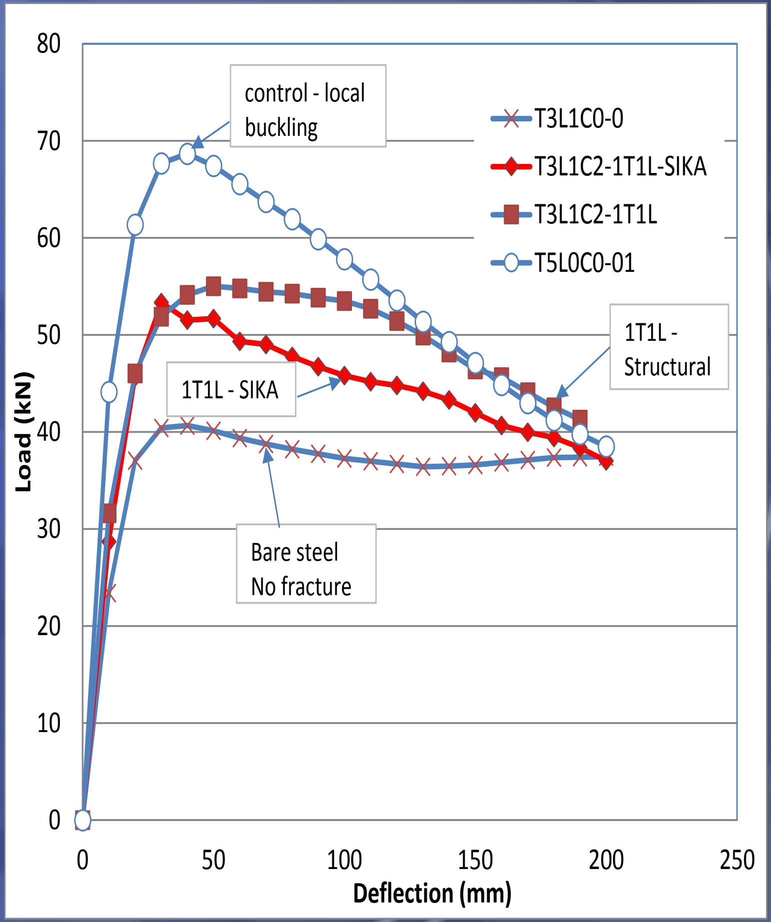
Load-deflection Curves



20% Corrosion



40% Corrosion

كليات التقنية العليا
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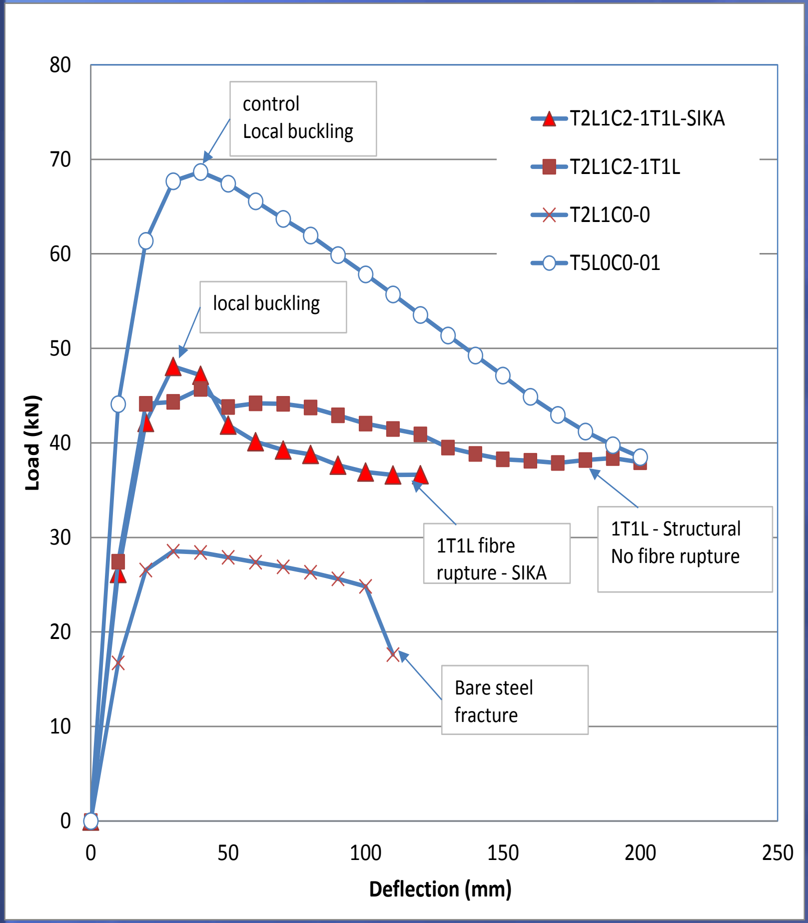
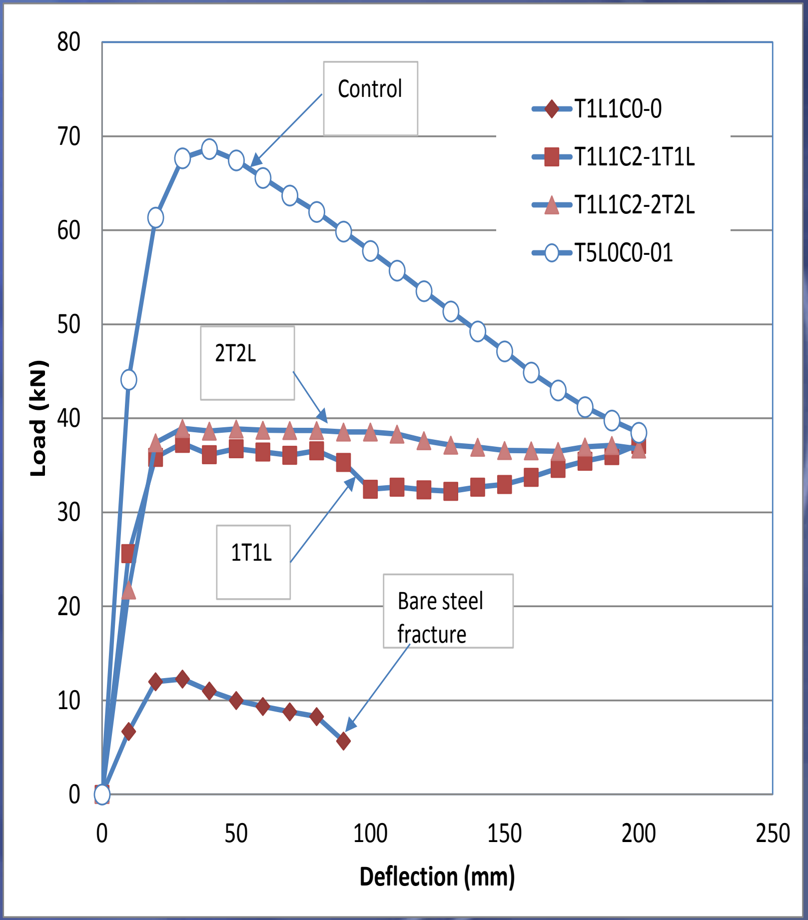
Load-deflection Curves





60% Corrosion

80% Corrosion

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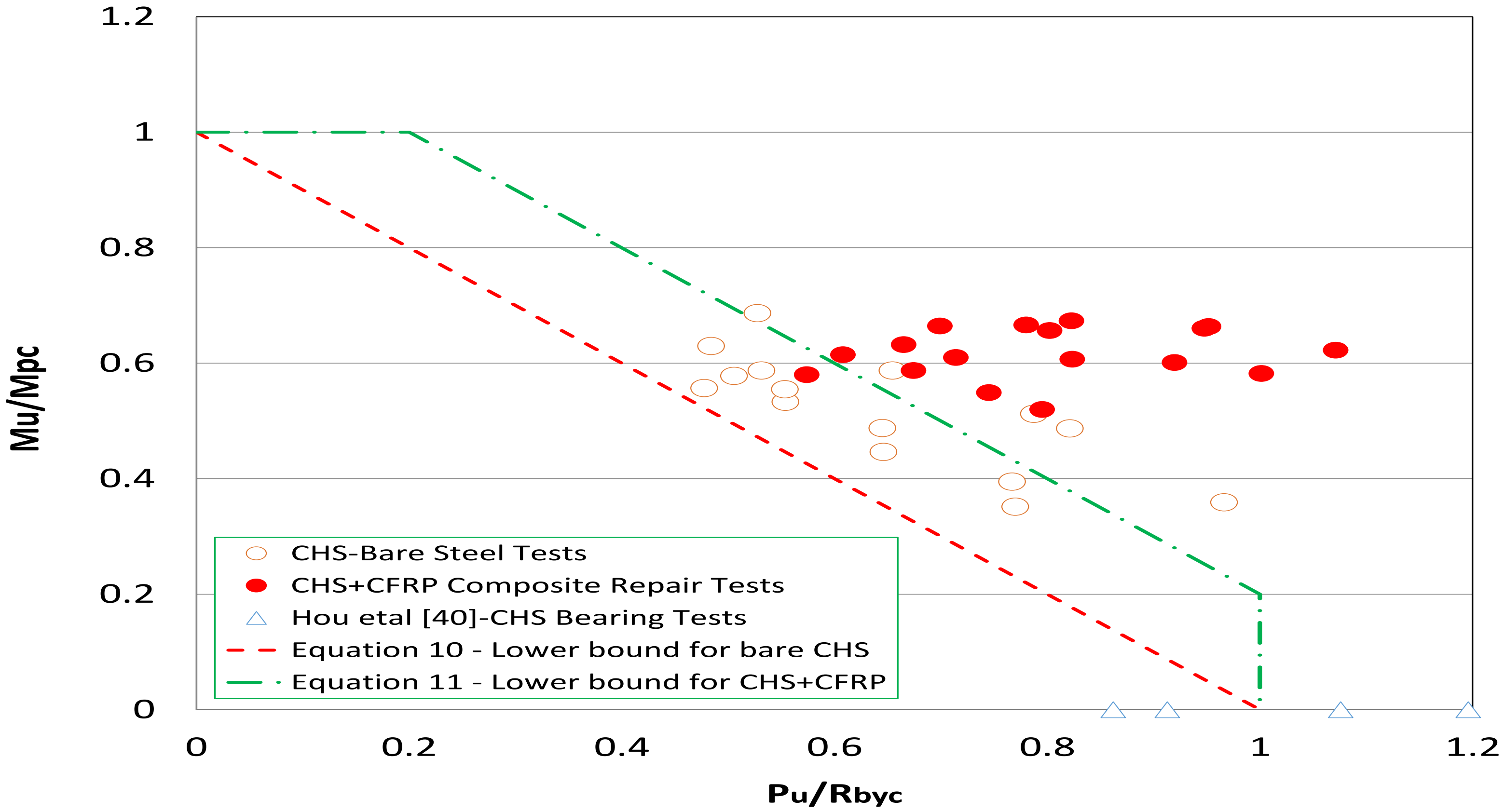
Design Method for Repair System Under Combined Bending and Bearing



$$\left(\frac{P_u}{R_{byc}}\right)+\left(\frac{M_u}{M_{pc}}\right)\leq 1.0 \text{ for bare CHS where } D_0/t_s = 164\varepsilon^2 \text{ and } L_c/D_0 = 3.0 \quad (10)$$

$$\left(\frac{P_u}{R_{byc}}\right)+\left(\frac{M_u}{M_{pc}}\right)\leq 1.2 \text{ for repaired CHS using CFRP where } D_0/t_s = 164\varepsilon^2 \text{ and } L_c/D_0 = 3.0 \quad (11)$$

Conclusions

The results showed that the combined flexural and bearing strength of the repaired steel pipelines can be significantly increased by adhesively bonding CFRP.

The percent increase in strength was mostly affected by the corrosion level where the maximum gain was 434% which was obtained for the most severe 80% corrosion in the wall thickness. The average increase in the load carrying capacity was 97% and 169% for the rehabilitation and strengthening series, respectively.

The stiffness and capacity of the un-corroded control specimen was fully restored for the repaired specimens with 20% corrosion in the wall. However, for higher levels of corrosion of 40% to 80% such stiffness and capacity were not fully restored. Thus adding more CFRP sheets in the circumferential and longitudinal directions may restore the un-corroded stiffness and capacity for 40% to 80% corrosion.

Design equations based on the bare and composite section properties were derived to predict the strength of bare and repaired CHS using CFRP under combined bending and bearing.

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