Mechanical behaviour of corroded reinforced concrete beams strengthened with NSM FRP technique

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NSM Repair in Bending

- Corrosion effect
- Repair technique in bending
- NSM effect on ductility, stiffness, ultimate capacity and failure modes

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NSM Repair in Shear

- Repair technique in shear
- Corrosion effect
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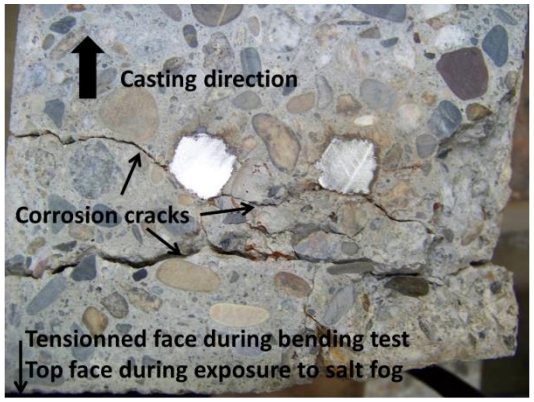
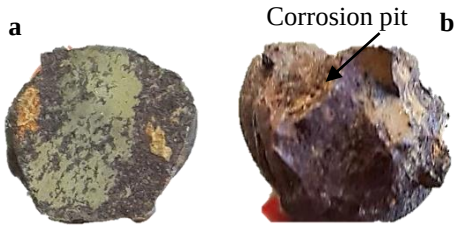
General Introduction

Corrosion Effect on RC structures

- A reduction in the cross-sectional area of the steel bars.
- Cracking and bonding problems.
- Bending stiffness and load capacity problems.





General Introduction

- ✓ Many studies focused on how to strengthen the RC elements using externally bonded fibre-reinforced polymer EBR (FRP) laminates
- ✓ Near Surface Mounted (NSM) FRP reinforcement has attracted much research and practical applications as a repair technique.

Advantages of NSM FRP technique

- The debonding in FRP was delayed compared to the EBR technique.
- FRP bars in NSM are protected by concrete cover and less time is required to install them

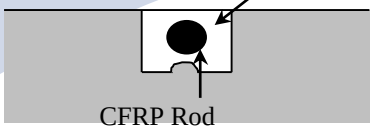
Research problem

- ✓ Very few researchers have studied the NSM effect on the corroded RC beams repaired only in bending.
- ✓ No studies were found of the NSM effect on the corroded RC beams repaired in shear.
- ✓ No work has been done on a significant scale to study the effect on the ductility, ultimate deflection & stiffness of repaired corroded RC beams.
- ✓ FEM model is needed to investigate the NSM effect on the mechanical behaviour of corroded RC beams.

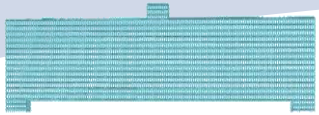
Research Objectives

The mechanical Properties of the corroded RC beams

NSM effect on RC beams repaired in bending & shear



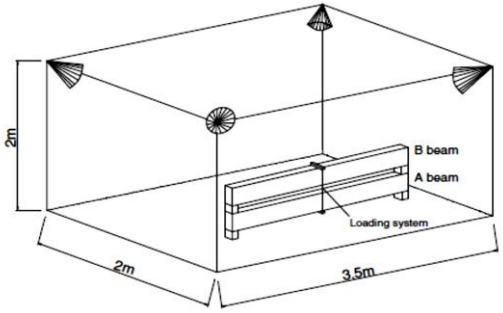
Create FEM model using ABAQUS



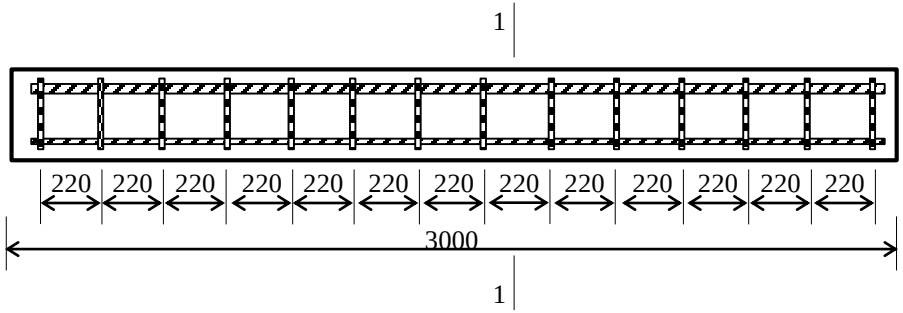
Experimental context

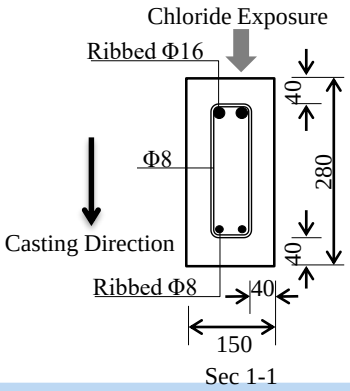
An experimental program was started at LMDC in 1984

- 72 RC beams were casted at the same time
- The geometrical shape (3,000 × 280 × 150 mm)
- 36 RC beams were kept in chloride environment



Many researches were conducted on those beams during the last years to study the corrosion effects on beams.



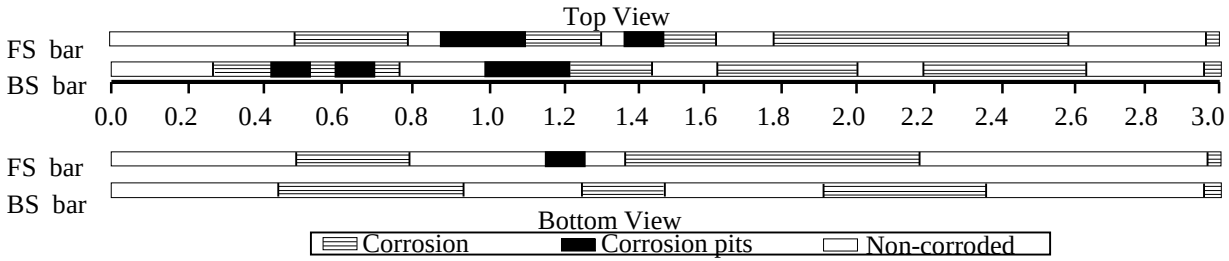


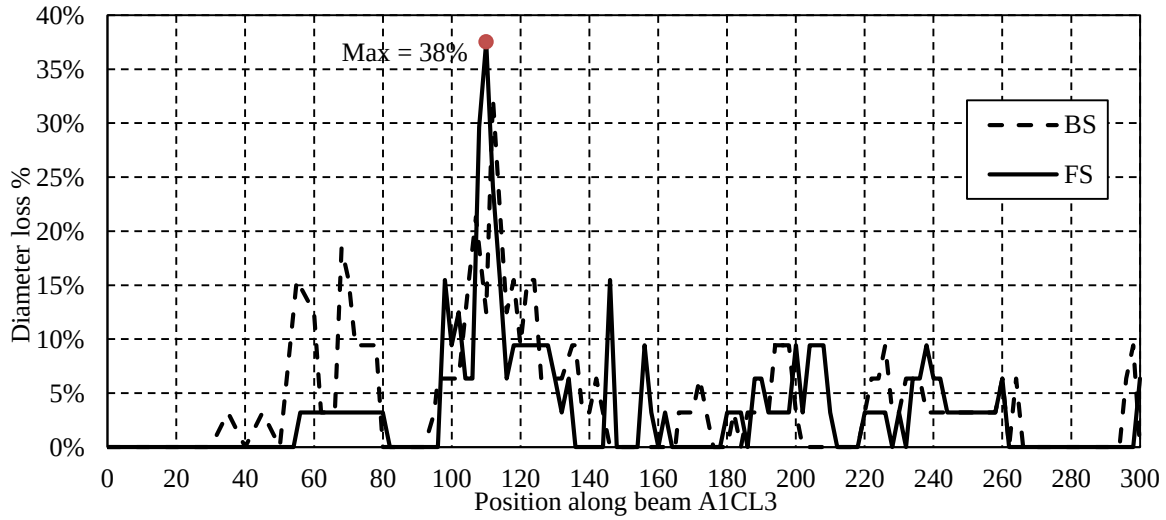
Experimental procedure

- Mechanical properties of corroded steel bars
- NSM repair in bending for one corroded beam (A1CL3-R) and one control beam (A1T-R)
- NSM repair in shear for one corroded short beam (A1CL3-SB) and one control beam (A1T-SB)

Corrosion Effect

- Corrosion found on the top and bottom of tensile steel bars





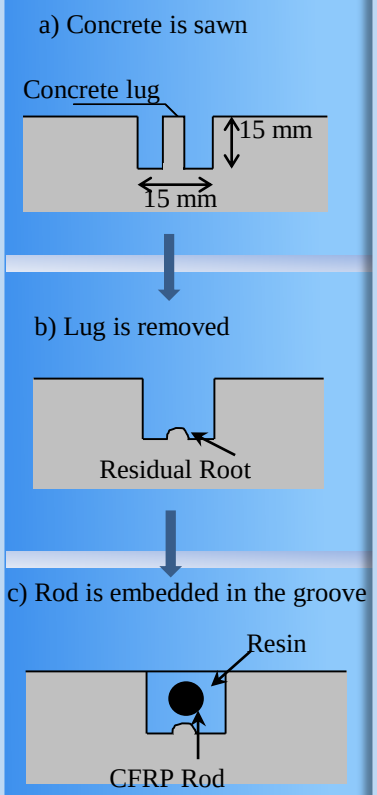
Corrosion Effect

- If there is 1% cross-section loss due to steel corrosion it will be reflected as a 1% loss in the yielding capacity value

Beam	Avg loss of cross section % at the middle (1)	Yielding capacity (kN.m)	Ultimate capacity (kN.m)	Loss of yielding capacity % (2)	Loss of ultimate capacity % (3)	(3)/(1) ratio	(2)/(1) ratio
A2T	0	45	50.9	0	0	0	0
A2CL3	21.5	32.5	40.9	27.8	19.6	0.7	1
A2CL1	30	31.3	35.6	30.4	34	1.1	1
A1T-R	0	53	65.5	0	0	0	0
A1CL3-R	20*	42.3	52.1	20.6	20.5	1	1

* Note: My = 42.3 kN.m meets 20% loss of cross section at the middle of the beam

Mechanical behavior of corroded RC beams strengthened with NSM FRP technique | NSM Repair in Bending



NSM Repair technique

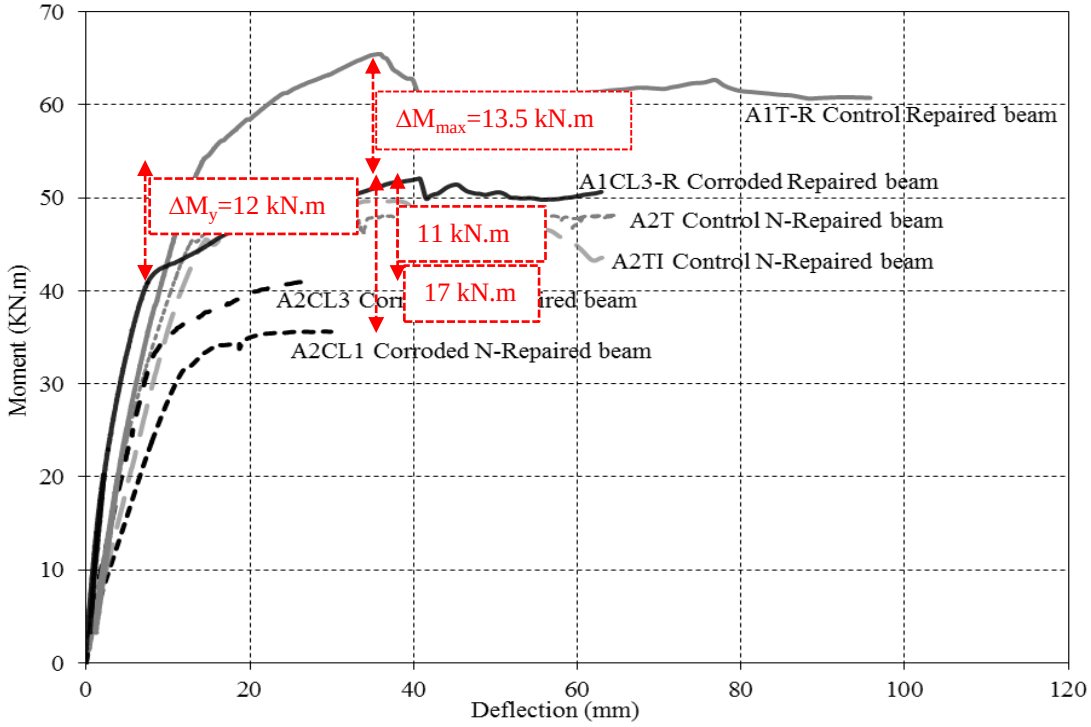
- The two beams were tested 1 week after installation of the CFRP rod
- The groove was 15 mm deep and 15 mm wide (around twice the rod diameter).

a) A1T –R Control Beam

b) A1CL3-R Corroded Beam

NSM Effect

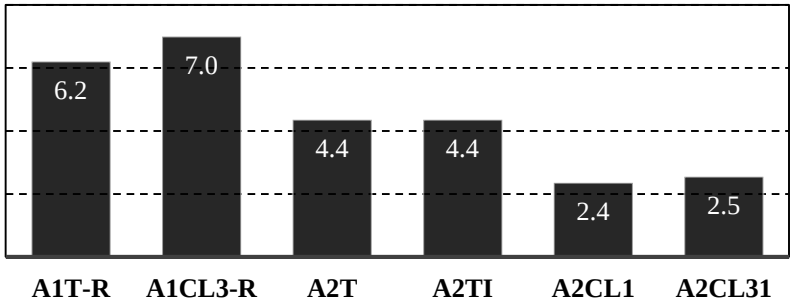
- Ultimate moment capacity increase



NSM Effect | Ductility & Yielding Capacity

- The NSM technique allows the initial ductility of the beam before corrosion to be recovered as shown in this figure

Ductility factor or index ($\Delta u/\Delta y$)

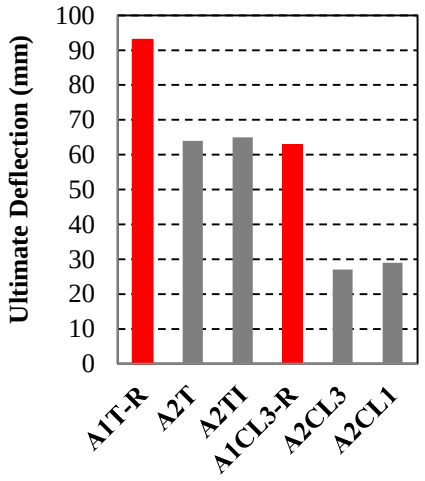


- An increase of 19 and 18 % was recorded In the yielding capacity of repaired beams

Beam	My, repaired (kN.m)	My, non-repaired (kN.m)	Increase percentage
A1CL3-R	43.5	36.5	19
A1T-R	51.7	43.7	18

NSM Effect | Ultimate Deflection

- Ultimate Deflection was significantly Increased by NSM

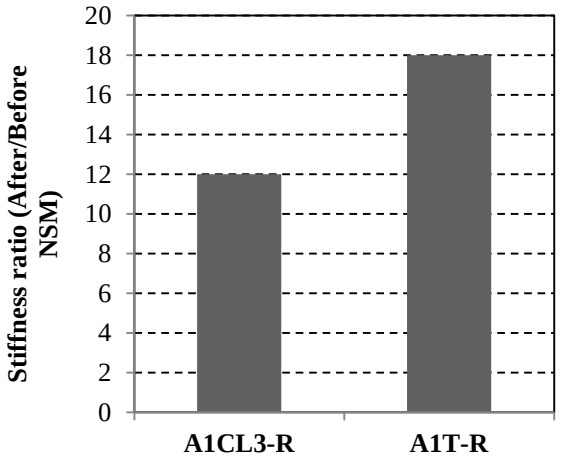


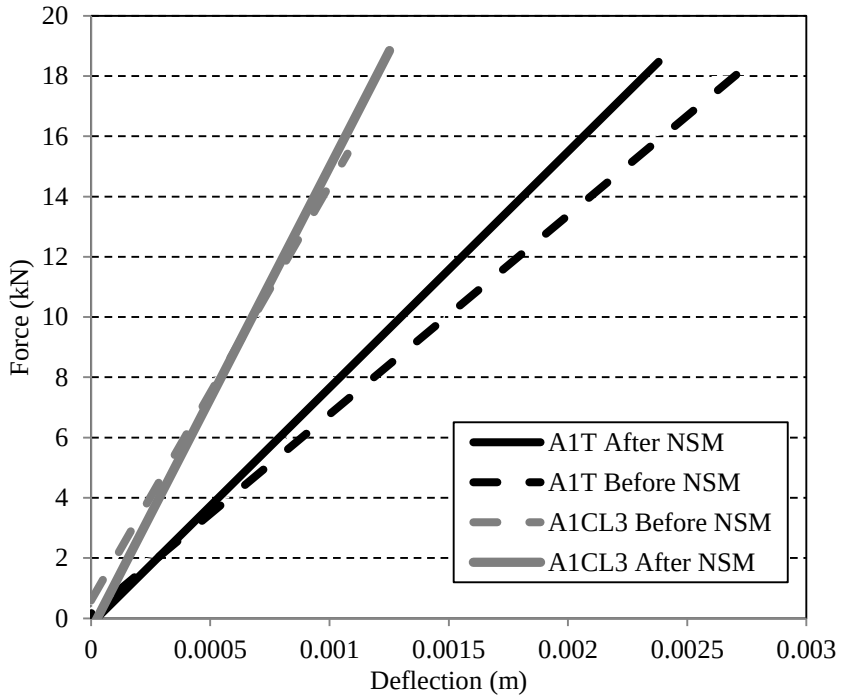
Beam	Description	Max diameter loss % (1)	Failure mode	Ultimate moment (kN.m)	Ultimate deflection (mm)	Ultimate Deflection loss % (2)	Ratio (2)/(1)
A1T-R	Repaired control beam	0	Concrete crushing	65.5	93	-	0
A1CL3-R	Repaired corroded beam	38	Separation of concrete cover	52.1	63	32*	0.84
A2T	Non-repaired control beam	0	Concrete crushing	50.9	64	-	0
A2TI	Non-repaired control beam	0	Concrete crushing	49.7	63.8	-	0
A2CL3	Non-repaired corroded beam	33	Failure of corroded steel bar	40.9	28	56**	1.7
A2CL1	Non-repaired corroded beam	44	Failure of corroded steel bar	35.6	29.9	53**	1.2

* Compared to control repaired beam A1T-R
** Compared to control non-repaired beam A2T

NSM Effect | Stiffness of beams

- NSM slightly increased the stiffness of RC beams





NSM Effect | Failure modes

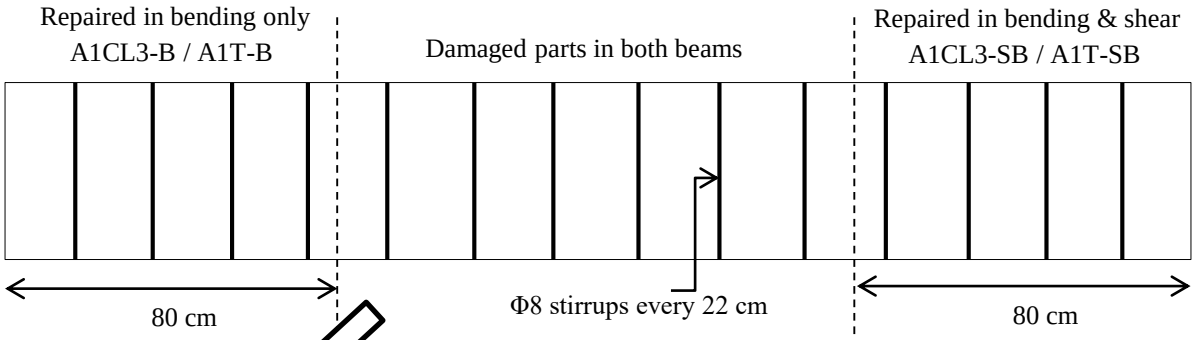
- Failure of A1CL3-R occurred by the Separation of concrete cover.
- Failure of A1T-R was classical: yielding of the steel bars was reached, followed by crushing of the compressive concrete.

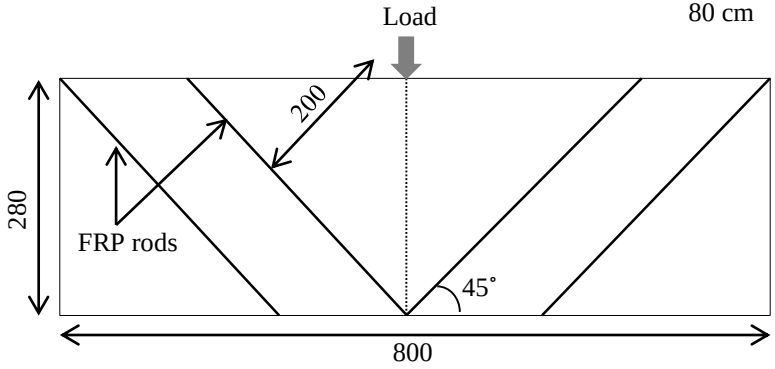
a) A1CL3-R Corroded Beam

b) A1T-R Control Beam

NSM Technique in shear

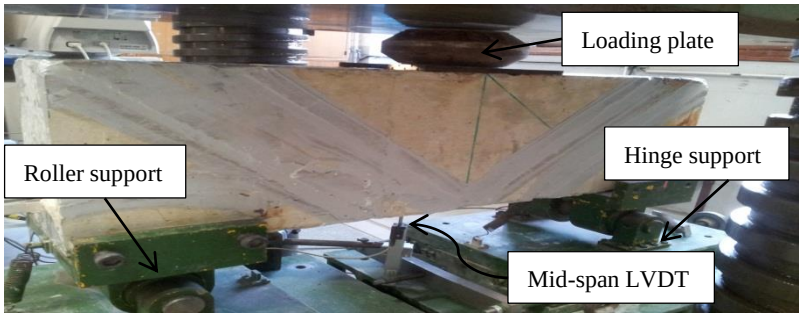
- 4 short beams were extracted



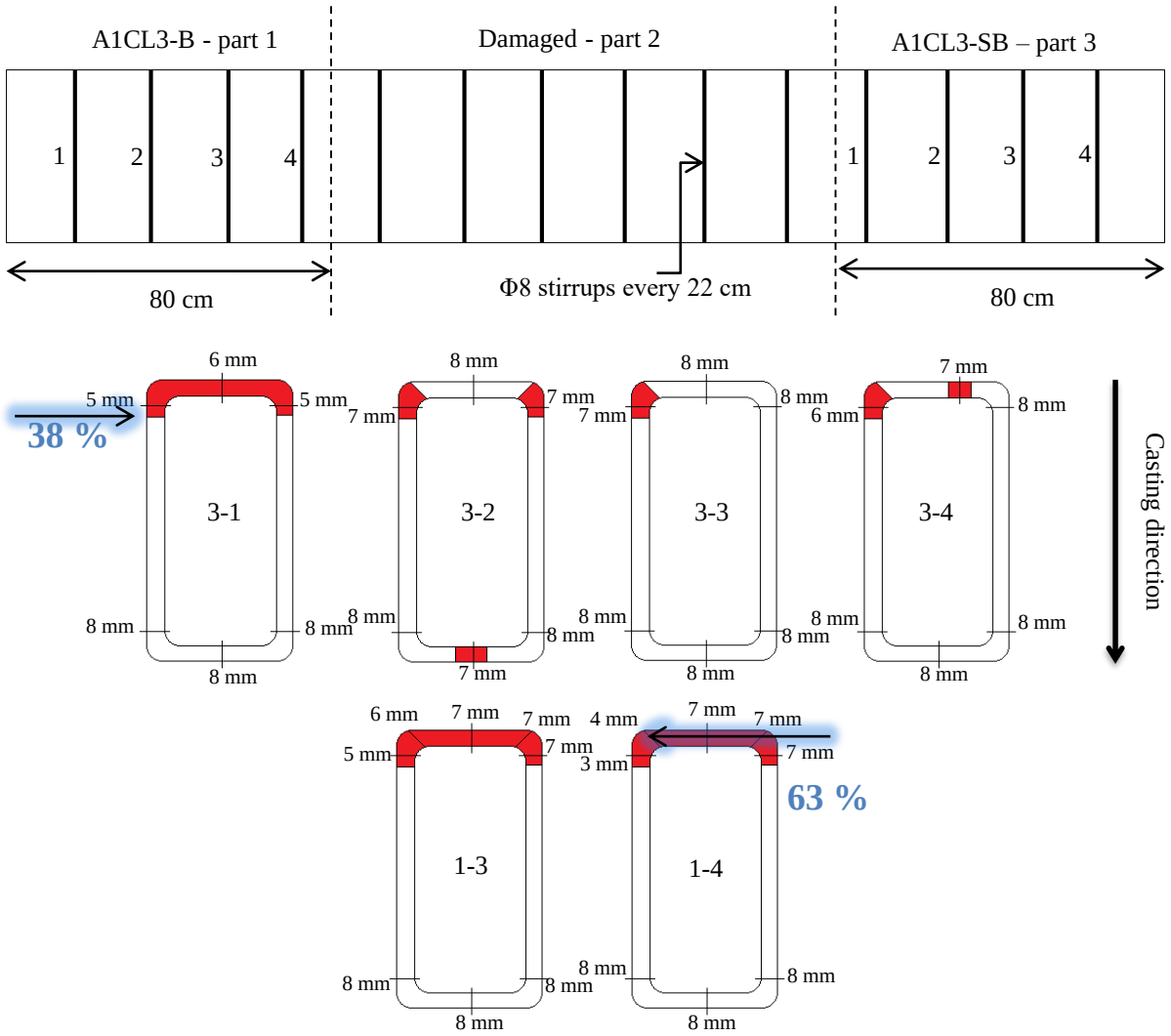


- 2 short beams were repaired in shear

- Beam Instrumentation

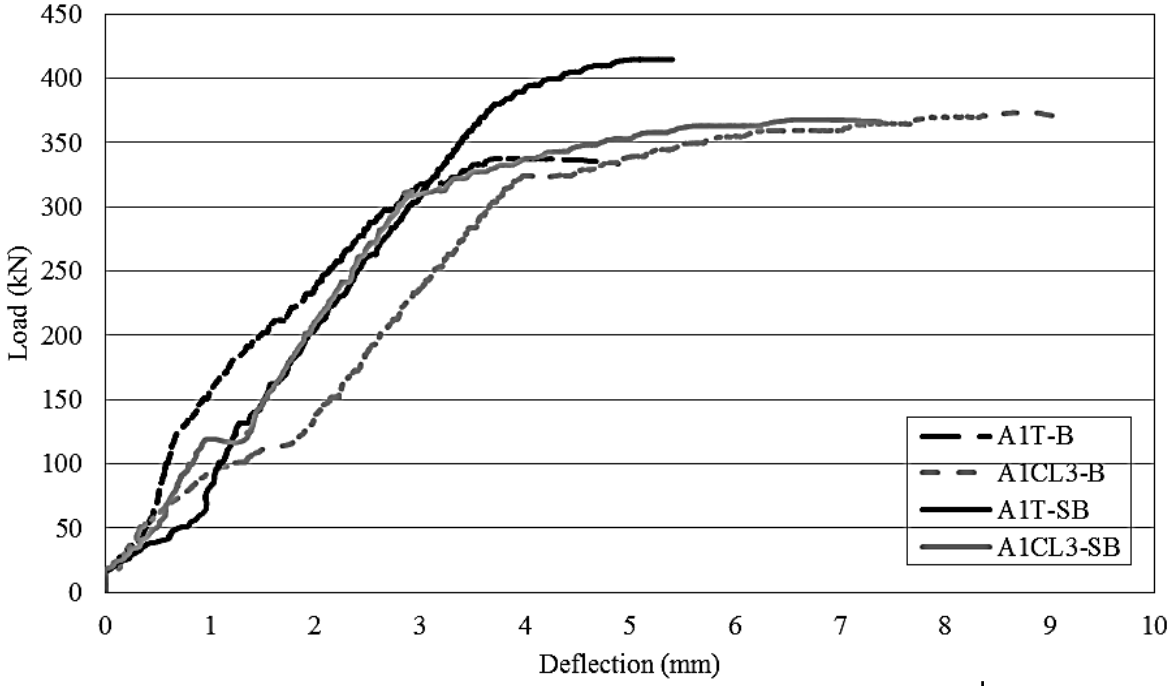


Corrosion in steel stirrups



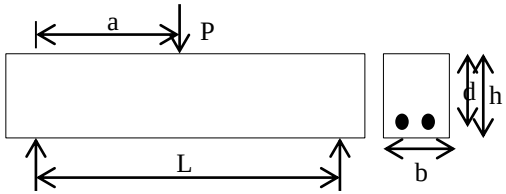
NSM effect on load capacity

- Increase in load capacity due to NSM in shear corresponding only to the control beam A1T-SB



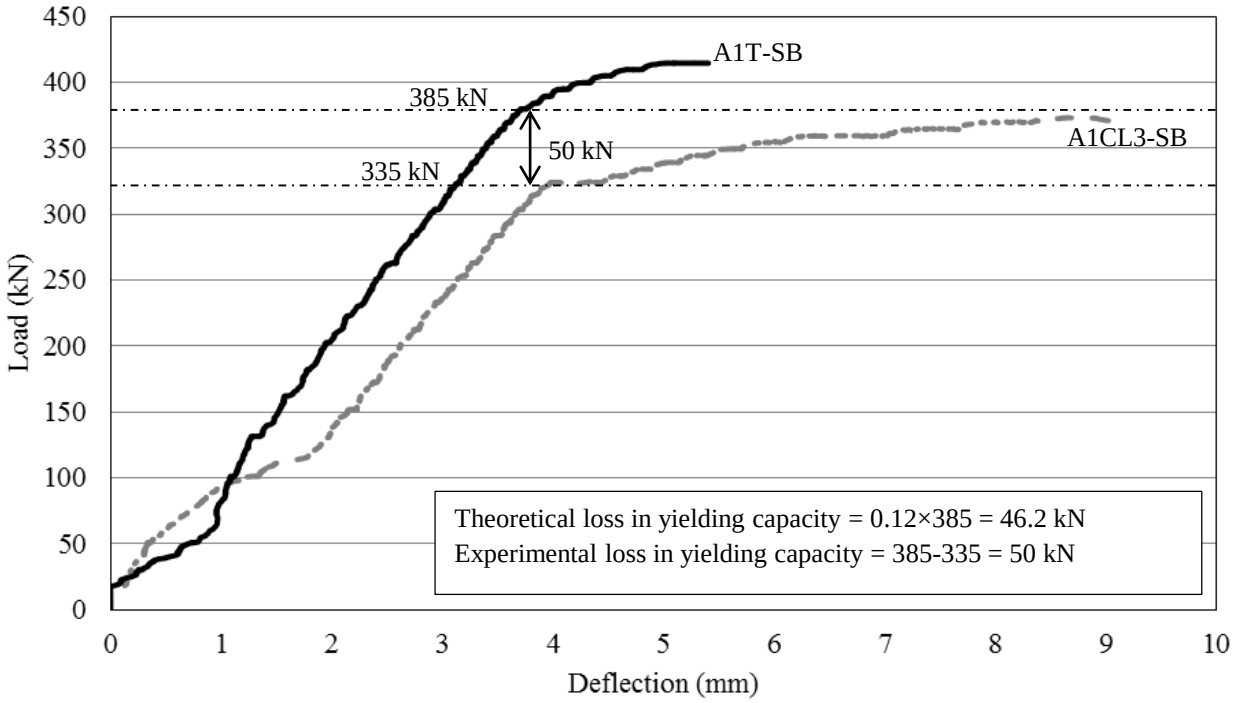
Beam	a/d	Ultimate Load (kN)	Load capacity ratio (1)	a/d ratio(2)	(1)/(2)
A1T-SB	1.4	415	-	-	-
A2T *	2	261	1.6	1.4	1.14

*Control non repaired in shear



Corrosion effect

- Slip occurred in the non-corroded side of the beams.
- The diameter loss of longitudinal steel bars at the middle of the beam A1CL3-SB 6% meets 46.2 kN loss in the yielding capacity compared to A1T-SB



NSM effect on Failure mode

- Failure mode was changed for those beams repaired with NSM repair in shear

a. A1CL3-B

b. A1T-B

Diagonal tension failure (Shear cracks failure with slip of tensile steel bars)

c. A1CL3-SB

d. A1T-SB

Compression crushing of the concrete (Large Flexural crack at the middle)

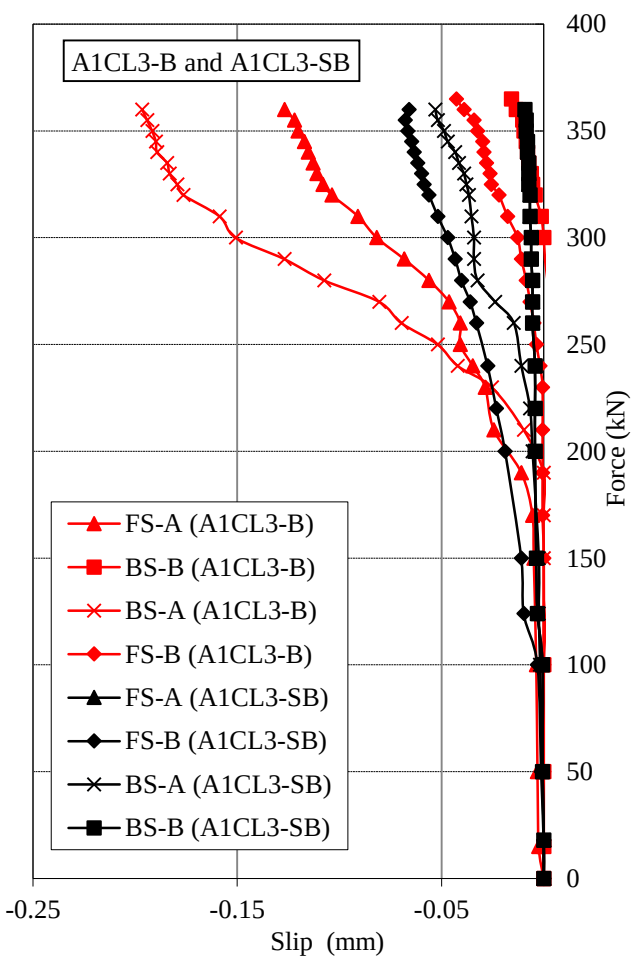
NSM effect on Failure mode

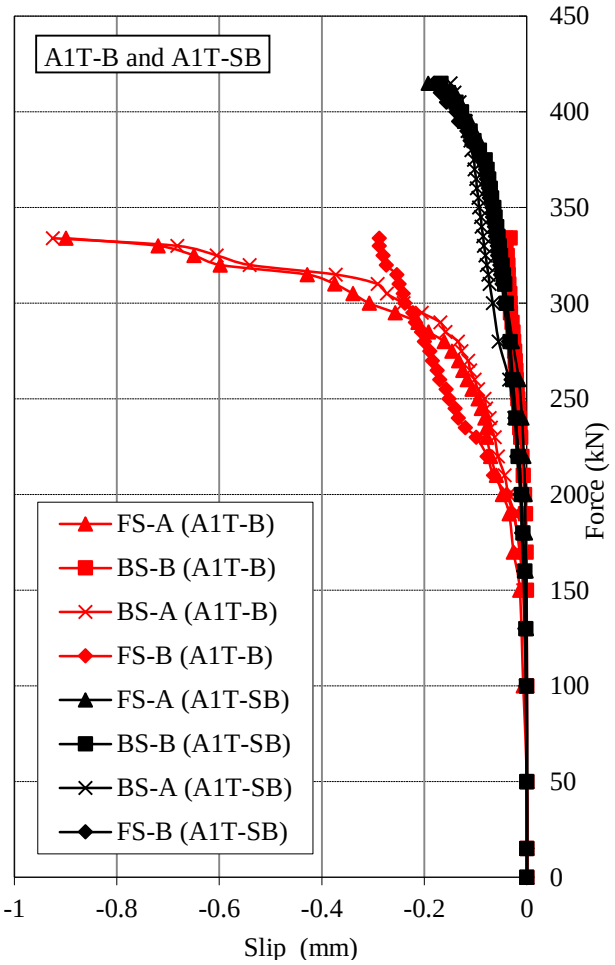
a. Diagonal Tension Failure

b. Concrete Crushing Failure

Slip measurements

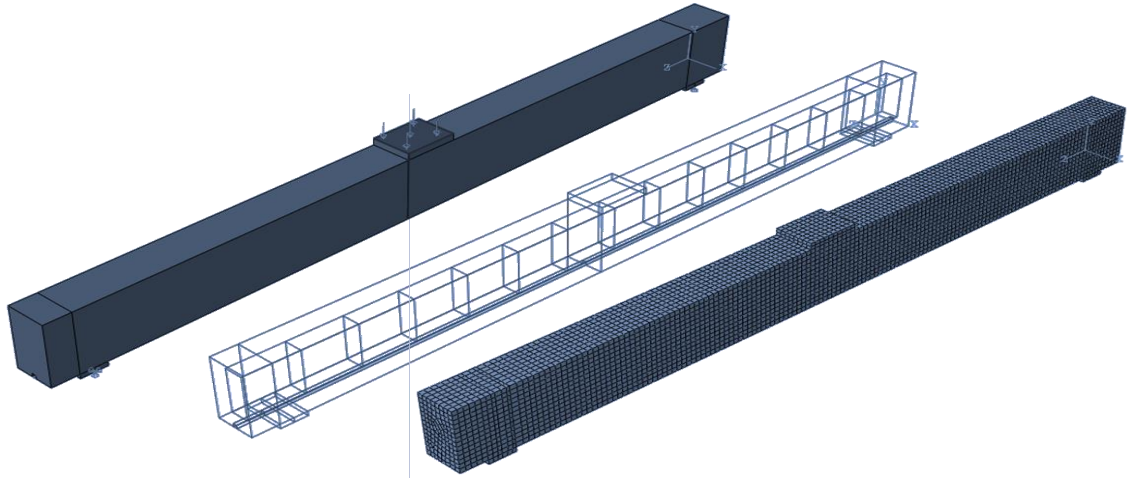
- The repairing in shear with NSM FRP rods decreased significantly the maximum slip values





Modelling Program

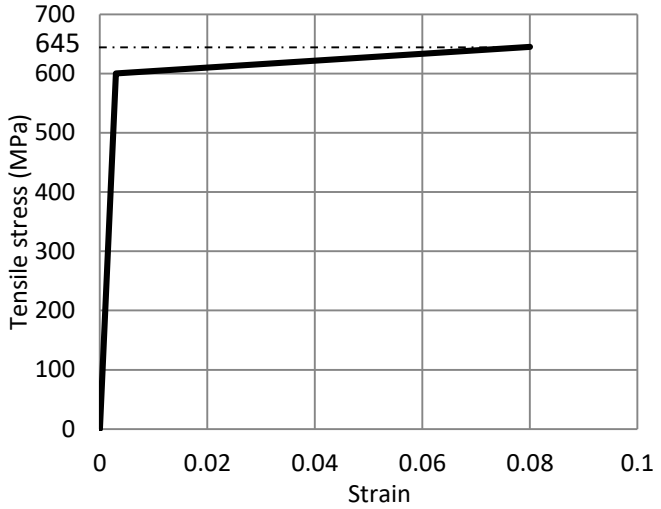
- 3-D deformable solid structural element in ABAQUS was used to simulate the concrete and Epoxy paste materials.
- 3-D wire truss element was used to simulate the steel bars and FRP rods.

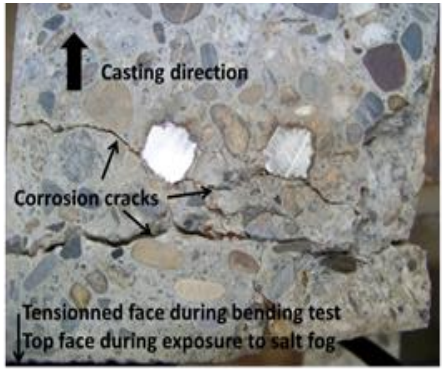


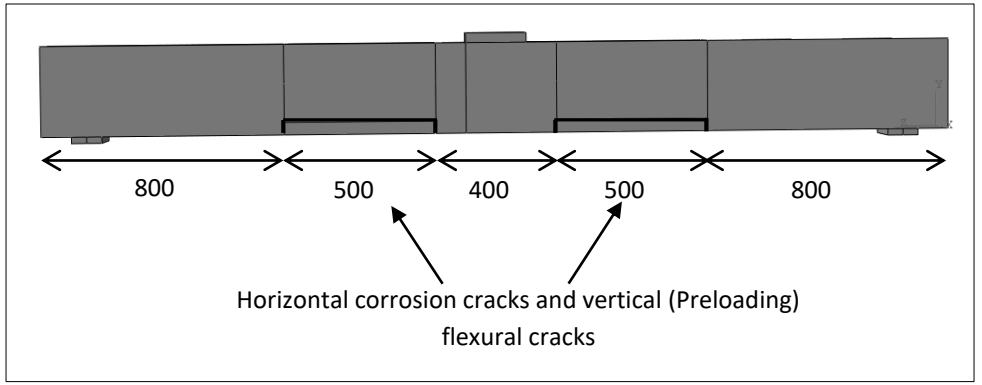
- Drucker-Prager was used to define the concrete behaviour in compression and tension.
- The mechanical properties of concrete were used in this model.

Modelling Program

- The nonlinear behavior of the steel reinforcement bars is considered to be linear elastic- plastic behavior.
- The corrosion and flexural cracks were simulated.
- The FRP rod is modeled with elastic stress-strain curve up to brittle failure in tension.

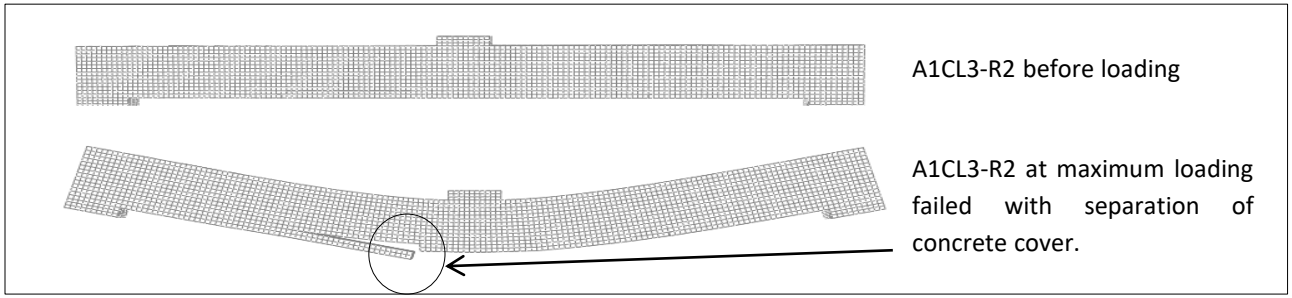




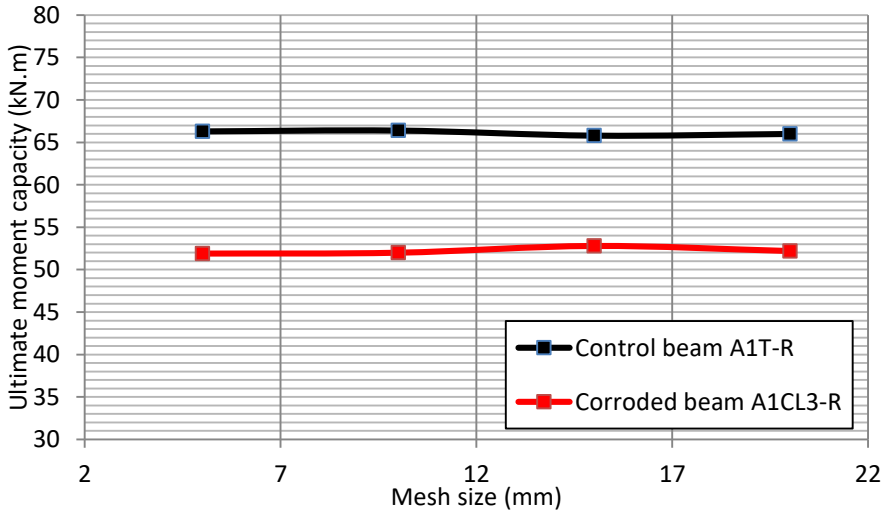


FEM Results

- The failure mode of the repaired corroded beam A1CL3-R was due to the separation of the concrete cover.

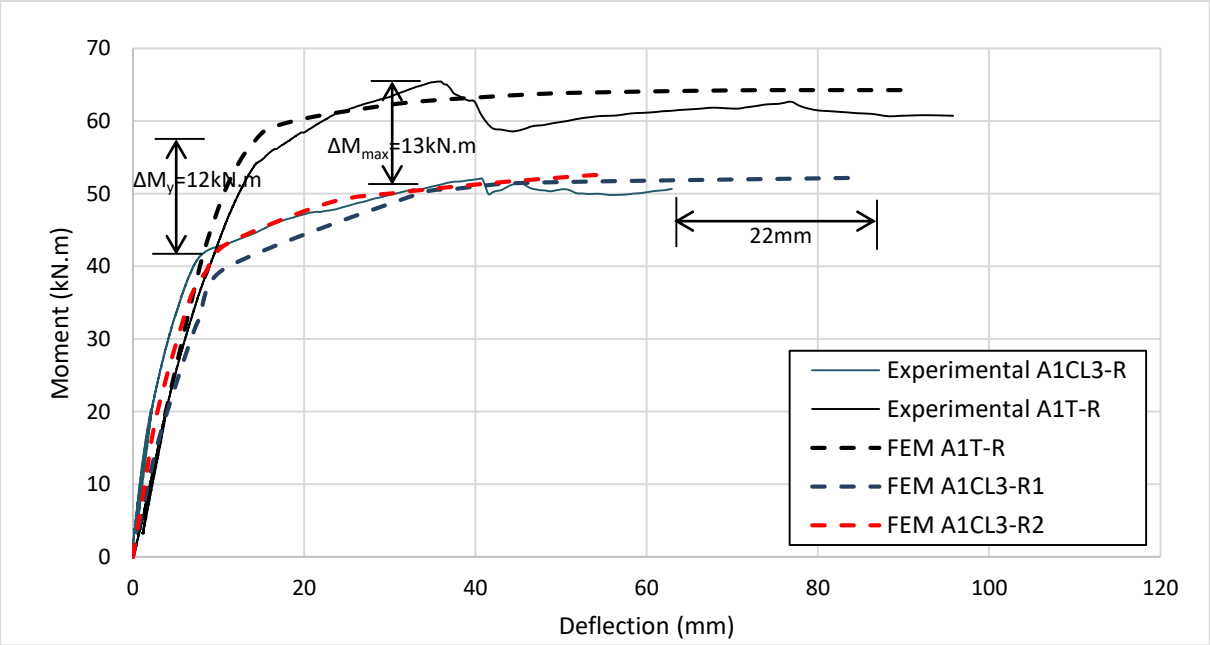


- There was no significant effect on the ultimate moment value for control beam A1T-R and corroded beam A1CL3-R if the mesh size is changed.



FEM Vs Experimental

- The repaired corroded beam without simulating the corrosion cracks (FEM A1CL3-R1) and repaired corroded beam with taking into account the corrosion cracks (FEM A1CL3-R2).



Conclusions

- The NSM technique is able to increase the ultimate load capacity of a corroded beam that has suffered considerable damage and can allow it to reach to the ultimate capacity of the control beam.
- The efficiency of the NSM technique in repairing corroded beams could be limited by the separation of concrete cover due to corrosion cracks.
- The NSM technique restores sufficient ductility (2.8 times that of the non-repaired corroded beams).
- The NSM technique slightly increases the stiffness of both repaired corroded and repaired control beams.
- The NSM technique increases the ultimate deflection value for repaired control and corroded beams.

Conclusions

- The repairing against shear using NSM FRP rods decreased significantly the maximum slip of the steel bars.
- The repairing against shear using NSM FRP rods could change the failure mode to concrete crushing for repaired beams.
- FEM analysis using ABAQUS is able to predict both load-bearing capacity and ultimate deflection reduction due to corrosion if crack plane induced by corrosion is taken into account in the model.

Publications

International Conference Proceedings

- ALMASSRI, B., KREIT, A., AL MAHMOUD, F., & FRANCOIS, R. (2013). Study on behavior of corroded RC beams repaired in shear with NSM CFRP rods. Chemistry and Materials Research, 5, 57-63. {Published}
- ALMASSRI, B., KREIT, A., AL MAHMOUD, F., & FRANCOIS, R. (2014). Study on behaviour of corroded RC beams repaired in shear with NSM CFRP rods – an experimental and finite element modeling study, 8-10th of July (2014), SFR London; 06/2014. {Published}

International Journal Papers

- ALMASSRI, B., KREIT, A., AL MAHMOUD, F., & FRANCOIS, R. (2014). Mechanical behavior of corroded RC beams strengthened by NSM CFRP rods. Composites Part B: Engineering, 64, 97-107. {Published}
- ALMASSRI, B., KREIT, A., AL MAHMOUD, F., & FRANCOIS, R. (2014). Study on behaviour of corroded RC beams repaired in shear with NSM CFRP rods. {Under Review in Composite Structures}

Future work

- Create FEM model can predict different modes of failure for previous beams repaired with NSM technique such as FRP pull-out.
- FEM model can predict the ultimate capacity of repaired beams using larger FRP diameters.
- More attention will be paid to the short beams repaired in shear and FEM model could be proposed.

Special Thanks

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Questions are never indiscreet, answers sometimes are.

Oscar Wilde

Belal Almassri

10/04/2014

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