-Technical Paper-

BEHAVIOR OF QUANTITATIVELY DAMAGED EPOXY INJECTED CONCRETE IN UNI-AXIAL TENSION

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ABSTRACT

The behavior of the epoxy injected concrete in tension has been investigated experimentally. The specimens preloaded to generate cracks of the predetermined magnitude, repaired and tested again for the response to the axial tensile loads. The crack width, effectiveness of resin, average stress-strain behavior of the repaired concrete and crack location were investigated. The injection of resin into the cracks makes that part of specimen stiffer and during the re-loading of the specimens, the cracks are likely to occur elsewhere.

Key Words: Resin injected concrete, uni-axial tension, average stress-strain relationship

1. INTRODUCTION

The application of the performance based design require the performance requirements to be met in terms of damage and reparability after the structure is subjected to the predefined ground motion levels defines by various design codes. Volume of cracks and its repair using the resin injection form a simple basis for the quantitative damage assessment, repair and response after repairing. Various studies [1,2] have reported an effectiveness of the resin injection into the concrete in restoring the mechanical behavior of the reinforced concrete members, beams and columns, but the uni-axial behavior in tension has not been investigated in particular. The assessment of response of the repaired structure need an analytical model for the application at the design stage. The non-linear finite element analysis methods for the response of the reinforced concrete are being used widely, the application of such techniques for the response of the repaired (resin injected) concrete require an appropriate constitutive models, which can be developed by proposing the modifications to the in use constitutive models like average stress-strain relationships for the response of reinforced concrete proposed by Prof. Maekawa [3]. Uni-axial behavior provides a key information to understand stress strain behavior. In the current research the behavior of the epoxy injected repaired concrete has been investigated in uni-axial tests, the specimens are subjected to uni-axial tension for the force deformation relationships.

2. SPECIMENS DETAILS

In order to investigate the behavior of repaired concrete in tension, two series of specimens were designed. Series 'TS' consisting of ten(10) specimens designed to control the damage with varying the residual crack widths, and series 'TL' consisting of two (2) specimens, designed as compatible specimens for which the average stress-strain relationships were originally proposed by Shima [4]. The size of the specimens, reinforcing bar and the desired residual crack width are given in Table 1, the specimens in 'TS' series are further divided based on the desired residual crack widths.

Table 1: Specimen Details

Series		Size Section (length)	Steel bar	Desired crack width
		(mm)		(mm)
TS	t_{1-1} & t_{1-2}	150x150 (600)	D22	0.3
	t_{2-1} & t_{2-2}	150x150 (600)	D22	1.0
	t_{3-1} & t_{3-2}	150x150 (600)	D22	2.0
	t_{4-1}, t_{4-2}	150x150 (600)	D22	3.0
	t_{5-1}, t_{5-2}	150x150 (600)	D22	0
TL	TL-1	150x150 (2050)	D22*	<0.3
	TL-2	150x150 (2050)	D22*	>1.0

* Screw type

The reinforcement bar for 'TS' series is D-22 deformed type yield strength of 384.1 N/mm^2, Modulus of elasticity (Es)= 193600 N/mm^2, where as for 'TL' series specimens it is D-22 screw type, yield strength of 396.3 N/mm^2 Modulus of elasticity (Es)= 196,000 N/mm^2. The gauges were mounted in pair at the center of the reinforcement and outside, 50 mm from edge, for 'TS' series where as for 'TL' series first pair inside at 200 mm and then @150 mm along the length of the bar as shown in the Fig. 1, carefully attached to the bar to avoid the disturbance of bond between steel bar and the concrete. The reinforcing bars were un-bonded at end up to 30 mm from face to avoid the occurrence of longitudinal cracks at ends. The specimens casted with normal strength concrete, cured for two weeks.

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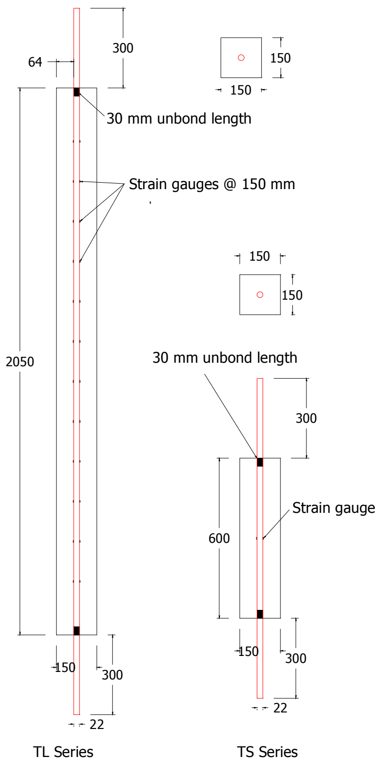

Fig. 1: Specimen dimensions and details

3. PRE-LOADING

3.1 TS Series:

The specimens for the 'TS' Series were tested in the universal testing machine as shown in the Fig. 2, the elongation was measured by measuring the displacement of the two end of the specimen with the help of transducers (LVDTs) .

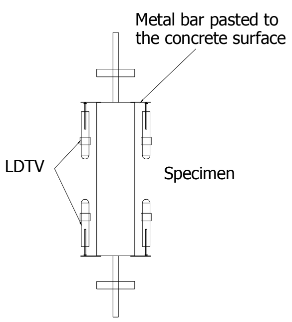

Fig. 2: Load Set up for TS series

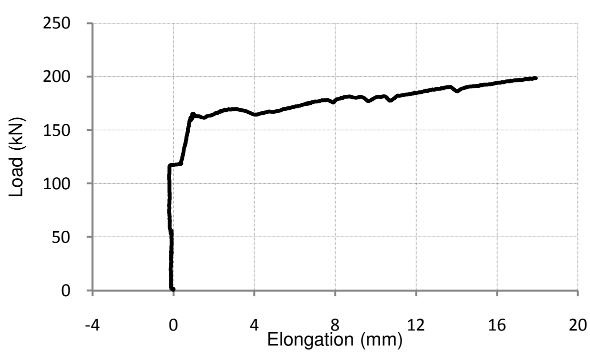

Fig. 3: Typical Load-Elongation Curve for TS

The strain of the reinforcement at the center of the specimen was measured using strain gauge mounted on it. The crack width under loading was measured and the test for each specimen was terminated when the crack width just match the desired residual crack width. Fig.3 shows the typical load-elongation curve of 'TS' series specimens in the monotonic loading.

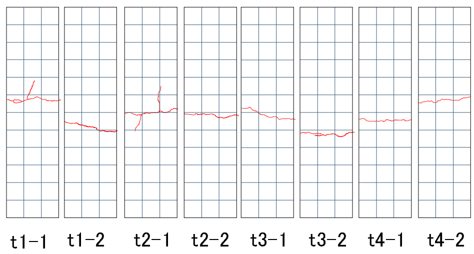

Fig. 4: Crack Diagram :TS series: Loading

For all specimens single major crack was observed at around mid span as shown in the Fig. 4, some fine cracks can also be observed in the longitudinal direction at higher load level for specimens t_{1-1} and t_{2-1}. At the onset of crack a small linear portion can be observed in the load-elongation curve indicating the occurrence of crack in the concrete.

The residual crack width is measured with the help of microscope at different points on the crack surface to calculate the average. The values for actual residual crack width are given in the Table 3.

3.2 TL Series

The test for 'TL' series, longer in length, was conducted on rigid steel frame laying the specimens in the horizontal position.

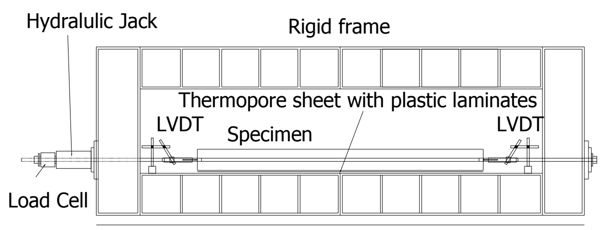

Fig. 5: Test set up for TL series

The specimen was placed on the bed plate and to minimize the friction between the specimen and the plate a layer of polythene along with the thermo-pore sheet was placed in between as shown in Fig.5. One end of the specimen was fixed using the high strength bar and screw where as the loading was applied with help of jack at the other end. The load was measured with the help of load cell and the displacement at two ends of the specimen was measured with the help of pair of transducers (LVDTs) placed at each end.

Fig. 6 is the plot of total force, average force in the steel and in the concrete against the average strain for the 'TL' series specimens TL-1 and TL-2 in the preloading. At the start, the share of the concrete in sharing the tension is much higher than the steel, after reaching to its maximum value just before cracking, the force in the concrete gradually decreases, and steel hold the major portion of the tensile force.

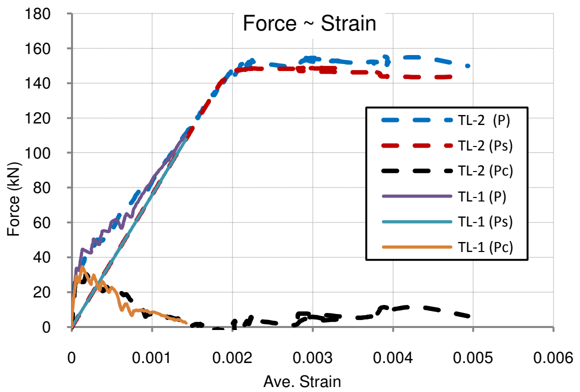

Fig. 6: Force-Strain curve for TL series

The force in the steel and concrete has been calculated from the equilibrium of the forces (Eq. 1) firstly by measuring the strain in the bar from strain gauges, then using stress strain relationship of the bare bar to calculate the stress at that point, and taking average of the measuring points along the bar.

$$P = P_s + P_c \qquad (1)$$

Where

P = total force

P_s = force in the steel

P_c= force in the concrete

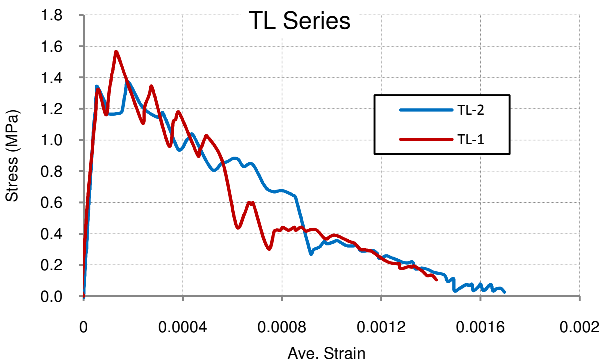

Fig. 7: Stress-Strain curve for RC : TL series

The stress-strain behavior of the concrete for 'TL' series specimens is shown in the Fig. 7, which is in line with the well known behavior of concrete in uni-axial tension with tension stiffening effect [3], in terms of the average stress strain within the length of the specimen. The stress in the concrete has been calculated by calculating the force in the concrete as explained above dividing it by the area of the concrete. The maximum stress in concrete for TL-1 is 1.57 N/mm^2 where as for TL-2 its value is 1.37 N/mm^2. The stress strain for the steel has been shown in the Fig.8. The stress-strain curve for the bare bar has also been plotted for reference indicated by dash line.

The specimen TL-1 was unloaded after reaching the maximum load of 110.2 kN, before the yielding point of the bar in the concrete, and therefore was able to recover the strain after the unloading.

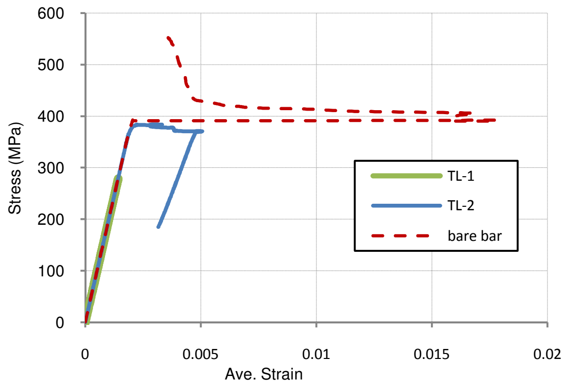

Fig. 8: Stress-strain Steel: TL series: Loading

The specimen TL-2 was loaded where the reinforcing bar has been yielded, and subjected to the maximum load of 155.5 kN. The yield stress of the bar in the concrete was 384.09 N/mm^2 just below the yield stress of the bare bar which is 396.3 N/mm^2.

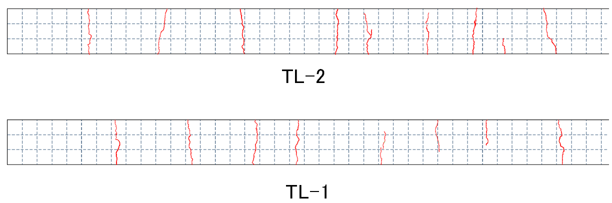

Fig.9: Crack diagram: TL Series: Loading

The crack diagram for 'TL' series specimens is given in Fig. 9. The cracks can be observed at regular intervals in specimens TL-1 and TL-2. The actual average values of the residual crack widths, measured with help of digital microscope are given in the Table 4.

4. REPAIR:

The specimens cracks were sealed at the surface leaving entry ports attached to it at regular intervals with the help of sealant and resin was injected into the cracks with help of pressurized syringes connecting to the ports. The specimens were left for 2 days under the pressurized syringes before the reloading started. The properties of resin used in this study are given in the Table 2.

Table 2: Resin Properties used

Density	Compressive strength	Tensile strength	Viscosity
(g/cm3)	(MPa)	(MPa)	mPa.s
1.15	45.0	10.0	1650

5. RELOADING

5.1 TS Series:

After repair the specimens were reloaded in uni-axial cyclic tension, Fig. 10 shows the plot of load-elongation curve for 'TS' series specimens in the reloading. Two distinct part of the reloading curve can

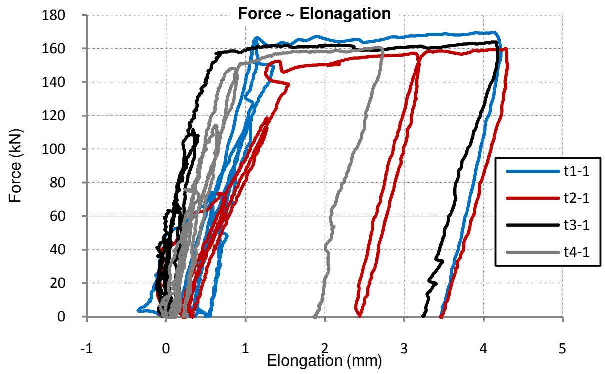

Fig. 10: Reloading: TS series

be observed, the point where the reinforcing bar starts yielding, and significant change in the stiffness occur, the value of load at that point are given in the Table 3 and plotted in the Fig. 12 against the residual crack width for 'TS' series specimens. After that point the inclination of the curve indicates the contribution of the concrete in sharing the tensile force.

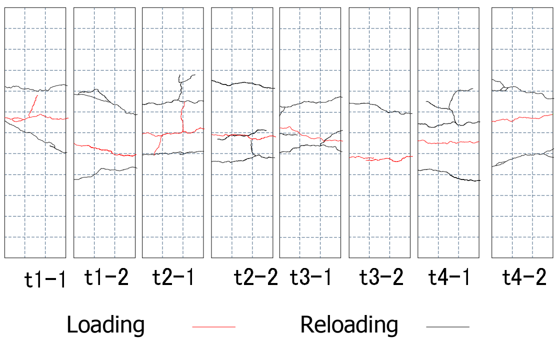

Fig. 11: Crack diagram: Loading & Reloading: TS

The cracks after the repair in reloading can be seen in the Fig. 11. These are observed to be relocated away from the loading cracks.

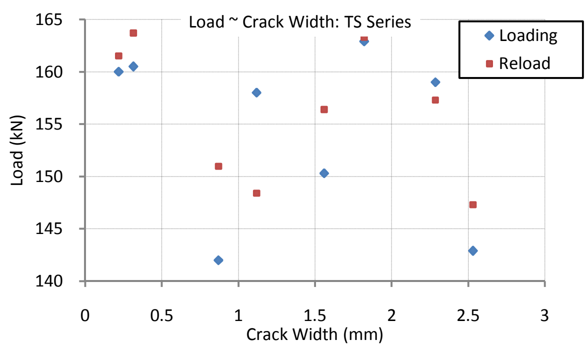

Fig. 12: Load ~ Residual crack width: TS Series

The injection of resin into the cracks made that part stiffer, there are two cracks, location of the cracks is changed dividing the specimen in the three parts except for $t_{3\text{-}2}$ for which the loading crack was near to the bottom side as shown in the Fig. 11.

All specimens of 'TS' series, there was no reopening of the cracks, and also there is not significant change in the mechanical behavior of repaired specimens of the varying residual crack width. Fig. 12 shows the plot of load carried by the specimen where stiffness starts changing, in loading and reloading, the value show that the load was recovered after repairing. The specimen $t_{1\text{-}1}$ and $t_{2\text{-}1}$ are observed to have a relatively lower value of the initial stiffness which can be attributed to the longitudinal cracks which appeared in the loading and resin was not able to fill that part.

Table 3: Yield Load and Crack width: TS Series

TS Series	Average Residual Crack Width (mm)	Max Load (*fc*'in MPa) (kN)	Max Re-Load (*fc*'in MPa) (kN)
$t_{1\text{-}1}$	0.219	161.03 (50.4)	161.52 (53.7)
$t_{1\text{-}2}$	0.315	163.12 (50.5)	163.7 (53.7)
$t_{2\text{-}1}$	0.870	149.55 (50.4)	150.97 (53.7)
$t_{2\text{-}2}$	1.119	151.97 (50.4)	148.4 (53.7)
$t_{3\text{-}1}$	1.560	150.31 (50.4)	156.4 (53.7)
$t_{3\text{-}2}$	1.821	162.99 (50.4)	163.3 (53.7)
$t_{4\text{-}1}$	2.286	154.90 (50.4)	157.3 (53.7)
$t_{4\text{-}2}$	2.531	149.28 (50.4)	147.3 (53.7)

fc' = compressive strength of concrete

5.2 TL Series:

The stress in the concrete has been calculated in the same way as for loading except the strain points on the reinforcing bar which were yielded, reloading stress was started from zero, keeping the loading strain as permanent.

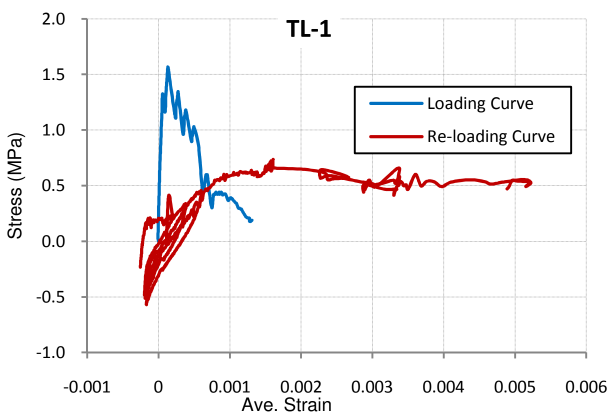

Fig. 13: Stress-Strain Curve for TL-1

From the stress-strain relationship of the repaired reinforced concrete it is observed that the starting point of curve depend on the loading history, TL-1 specimen was not loaded till the yielding of the bar and the reinforcing bar was able to recover the strains pushing the concrete into slight compression, all cracks in TL-1 were lesser than 0.1 mm, and in the reloading the stress in the concrete was able to reach to the value of 0.17 N/mm^2, the loading continues and specimen reaches gradually to the maximum value of 0.68 N/mm^2, and then gradually stays at 0.5 N/mm^2 as shown the Fig. 13.

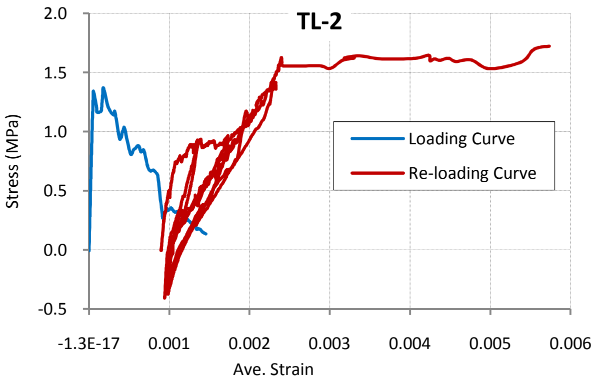

Fig. 14: Stress-strain: concrete: TL-2

The stress strain for the TL-2 specimen is shown in the Fig. 14, the response is similar, with different values of the peak in the non-repaired concrete and in the resin injected concrete. The TL-2 specimen was subjected to the yielding of the bar, strain measurements points along the bar show that at all points the bar was yielded, and at the unloading the permanent strain was there. The stress in the unloading path has been calculated by assuming the unloading stiffness equal to the loading stiffness of the bare bar.

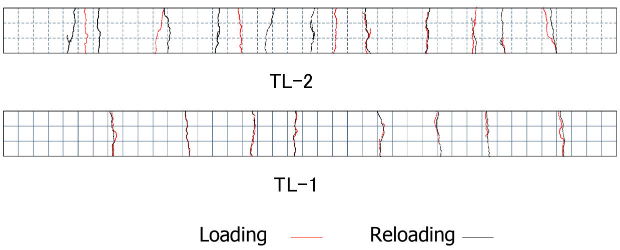

Fig. 15: Crack Diagram: TL series: Loading & reloading

The crack diagram for 'TL' series in given in the Fig. 15 , the location of loading cracks and reloading cracks are indicated on the diagram with different colors. The values of average residual crack widths, measured with the help of digital microscope are given in the table 4. Both of the specimens are observed to have eight (8) major cracks, TL-1, crack width ranging from 0.0443 mm to 0.0801mm, all the cracks reopened in the reloading. TL-2 with residual crack widths ranging from 0.08 mm to 1.168 mm, majority of cracks did not reopen upon reloading. One crack with average residual crack width of 0.08 reopened and two cracks with values of 0.177 & 0.151 occur very near to the cracks in the pre-loading.

Table 4: Residual crack widths: TL series

	Average Crack width TL-1 (mm)	Remarks	Average Crack width TL-2 (mm)	Remarks
1	0.0801	Re-opened	1.085	effective
2	0.0583	Re-opened	1.083	effective
3	0.0576	Re-opened	1.168	effective
4	0.0549	Re-opened	0.821	effective
5	0.0677	Re-opened	0.080	Reopened
6	0.0443	Re-opened	0.151	Near crack
7	0.0785	Re-opened	1.085	effective
8	0.0529	Re-opened	0.177	Near crack

Fig. 16 is the plot of residual crack width against the effectiveness of resin, fully effective crack means no reopening in the reloading has allotted a value of 1.0, where as the cracks which reopened has given the value of 0.0, and for the cracks for which the reloading cracks are really near to the loading cracks have given the value of 0.5.

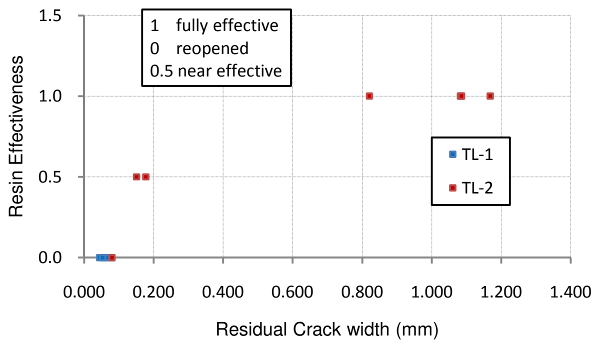

Fig. 16: Effectiveness of resin: TL Series

The stress-strain behavior of concrete in tension in 'TL' series has been investigated and in the loading of the specimen various crack appear in the concrete as explained by various authors [5,6,4]. After the concrete has cracked it can be seen in the forms of various segment connected to each other with the help of reinforcing bar, the resin can be injected in to the concrete and it can be assumed to be composed of segments of repaired and non-repaired concrete. In the reloading, the cracks will appear in the non-repaired concrete, leaving the resin injected portion without cracking , indicated by pink in the Fig. 17.

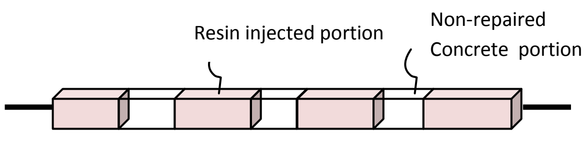

Fig. 17: Idealization of the resin injected concrete

In the stress strain curve of the repaired concrete in tension two distinct peaks can be observed , first peak in the non-repaired concrete second the peak in the resin injected concrete which is higher than the peak in the concrete and at a much larger value of the strain and after the peak has occurred its value does not come to zero gradually as oppose to the concrete but stays on a certain value . The resin injected portion, which is relatively stronger, continue to support the force in the steel because of its bond with the concrete which has even become stronger after the possible injection of the concrete in the interface between steel and concrete.

6. CONCLUSIONS:

From the investigations following conclusions can be drawn about the behavior of the repaired concrete in uni-axial tension.

1. The injection of resin greatly influence the location of cracks in the repaired concrete specimen, cracks are observed to occur leaving the portion repaired by resin injection.
2. The average stress-strain behavior of the repaired concrete is significantly changed, given the two peak values for concrete part and resin injected part, later being the higher, and a gradual increase in between.
3. The stresses in the repaired (resin injected) concrete are very much dependent on the pre-loading or damage history, repaired concrete specimen can also experience the pre-stressing.
4. The residual crack width, greater than a certain value (0.1 mm in this study), is found to be fully effective and negligible influence on the increase in the mechanical behavior of the repaired concrete in tension beyond that crack width. For the value of the crack width very near to the 0.1 mm, on the higher side, the re-loading cracks are very close to the pre-loading cracks.

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REFERENCES

[1] R. Felicetti, V.H. De Domennico : *Cracked concrete repair with epoxy-resin injection infiltration*. Concrete Repair, Rehabilitation and Retrofitting II, ISBN 978-0-415-46850-3.

[2] Camillee A. Issa, Pauls Debs: *Experimental study of epoxy repairing of cracks in concrete.* J. of Construction and Building materials 21(2007) 157-163.

[3] K. Maekawa, A. Pimanmas and H. Okmaura: *Nonlinear Mechanics of Reinforced Concrete* 2003, ISBN 0-415-27126-6

[4] Shima, H., Chou, L. and Okamura, H.: *Micro and Macro models for bond in reinforced concrete*, J. faculty of Engg. University of Tokyo, Vol. 39, No.2 pp. 133-194, 1987.

[5] M Ghalehnovi: *Response of reinforced concrete members under uniaxial tension*. 4th International conference on the conceptual approach to structural design, 28-29 June 2007, Venice , Italy

[6] David Z, Yankelevsky, Mahmood Jabareen, Amir d. Abutbul: *One-dimensional analysis of tension stiffening in reinforced concrete with discrete cracks*, J. Engineering Structures 30(2008) 206-217