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CYCLIC OVER LOADS ON LIFE OF BOND ANCHORAGES IN REINFORCED CONCRETE

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Abstract: Performance of anchorage reinforcement under dynamic loads is important to ensure adequate safety and structural integrity with adequate ductility. In the end regions, load transfer mechanism is influenced by cyclic loads under overloads. Since anchorage bond and its mechanics under cyclic over loading are absent, an experimental study to investigate the influence of type of loading and lateral confinement have been performed. Anchorage bond in concrete with different lateral confinement by spiral reinforcement has been studied under cyclic loading. The bond length was 80mm in the middle of 150mm depth of concrete. Bar diameter of 25mm was embedded in 25 MPa strength concrete with spirals of 8mm diameter with pitch of 25mm, 50mm and 75mm was adopted. It has been observed that the strength of concrete and the level of lateral confinement showed significant influence on the mode of failure and bond stress. Pullout failure was observed under monotonic and cyclic loading under overload in confined concrete. Different failure modes have been observed depending on the influencing parameters. The life of reinforced concrete due to deterioration of anchorage bond in rebars under cyclic loading is significantly reduced by the accidental overloads. The early application of overloads lowers the bond strength and service life of reinforced concrete.

1. INTRODUCTION

Bond strength of reinforcing bars in the surrounding concrete influences the behavior of reinforced concrete structures. The transfer of forces across the interface between concrete and steel through bond is important. Satisfactory bond performance is an important goal in the detailing of reinforcement in structural components. Pullout failures depend primarily on the concrete strength and the pattern and geometry of deformations. The second type is a splitting of concrete cover when cover or confinement is insufficient. Bond behavior under cyclic loading received comparatively little attention until design for seismic and wave loads became important. Investigations in these areas have clarified some of the important parameters influencing bond behavior under cyclic loads. The influence of many of these parameters is understood only qualitatively. However, the information on bond strength of RC under cyclic loads is scanty. Bond is necessary not only to ensure adequate level of safety allowing composite action of steel and concrete, but also to control structural behavior along with sufficient ductility. Bond is greatly affected by type of loads. Under monotonically increasing loads, the most important factors that affect the bond are concrete strength, construction quality, grade of steel, bar size, cover, transverse reinforcement, coating and bar spacing. Most parameters that are important

embedded in fiber reinforced cement based composites under monotonic, unidirectional cyclic loading, and 3) fully reversed cyclic loading. Frictional pull-out, and splitting failures were observed. Failure of all bars in SIFCON was by frictional pullout, while bars in plain concrete was by splitting of the concrete. Reinforcing bars in SIFCON showed much greater bond strength, higher energy absorption, and maintained substantially larger slips at high stresses, than bars embedded in plain concrete, confined concrete, or fiber reinforced concrete. Oh and Kim [5] reported the bond between reinforcing bars and concrete. The analysis of crack width in reinforced concrete flexural members requires an appropriate bond stress-slip relationship. It is, therefore, necessary to establish a realistic bond stress-slip model which takes into account the effect of repeated loadings. Hwan [6] analyzed crack widths of reinforced concrete flexural members influenced by under monotonic loading are also important under cyclic loading and overloads. The main objective is to understand the cyclic bond strength of reinforced concrete with overloads. The bond strength in reinforced concrete under cyclic loads depends on various factors such as bar size, anchorage length, cover, compressive strength of concrete, temperature, type and rate of loading and Surface condition (coating).

2. REVIEW OF LITERATURE

Popov [1] reviewed the importance to bond and anchorage for structures subjected to severe cyclic loading. The experimental effort was directed to study the behavior of bars in well-confined concrete. Pochanart and Harmon [2] presented a local bond-slip relationship in well-confined concrete for monotonic, cyclic, and fatigue-type loading, based on load and slip-controlled cyclic and fatigue tests of local bond. The model parameters are related to the bar's deformation and can be quantified directly from the dimensions of bar and concrete strength. A simple damage rule was developed based on the total slip excursion and amount of friction lost. David et al. [3] proposed models for bond-slip response of rebar in concrete under monotonic and cyclic loading. Results predicted by this model are compared with experimental results and show good correspondence.

Siva and Naaman [4] investigated the bond stress vs. slip response of reinforcing bars repetitive fatigue loadings. The bond stress after repeated loading approaches the ultimate bond stress under monotonic loading and increase of bond stress after repeated loading becomes sharper as the number of repeated loads increases. The bond stress-slip relation after repeated loading was derived as a function of residual slip, bond stress level, and the number of load cycles. The number of cycles to bond slip failure was derived on the basis of safe fatigue criterion.

Hawkins [7] described a computer model that predicts load-attack end deformations and development length requirements for reinforcing bars anchored and subjected to inelastic reversed cyclic loadings. Sain [8] proposed a fatigue crack propagation model for concrete based on fracture mechanics. This model takes into account the loading history, frequency of applied load, and size effect parameters. The fatigue crack propagation rate increases as the size of plain concrete beam increases indicating an increase in brittleness. In reinforced concrete (RC) beams, the fracture process becomes stable only when the beam is sufficiently reinforced. Filip [9] presented a simple and computationally efficient model of the hysteretic response of reinforcing bar anchorages under severe cyclic excitations. The bond stress value at these intermediate points is established by iteratively satisfying the equilibrium and compatibility equations of the bond problem. Krishnakumar [10] reported that all plain concrete failed prematurely under tensile loading due to concrete splitting. The load carrying capacity increases with increase in slip. After the peak load there has been a marginal drop in load, and some residual load resistance up to ultimate deformation. The concrete under cyclic tensile loading showed reduced residual tensile capacity than that of monotonic loading. However all the tested specimens under monotonic loading had residual capacity more than 160% of the maximum cyclic load which complies with ACI 355.4M-11. However, concrete under cyclic tensile loading along with constant shear force showed a marginal increase in the residual load carrying capacity when compared to concrete under cyclic loading only.

3. EXPERIMENTAL PROGRAM

3.1. Materials

53 grade Portland cement was used throughout the programme. 20mm and 12.5mm nominal maximum size aggregate were used as coarse aggregates at 60% and 40% of the total weight of aggregates respectively. Trial mixes were done to produce concretes of compressive strengths of 25 and 60 MPa. This was designed to study the effect of cyclic loading with overloads on bond strength of reinforced concrete with confined reinforcement of different pitches of spirals. The steel bars used were HYSD FE500**.** 16mm and 25mm diameter bars were used in Pull-out tests with 8mm diameter spiral reinforcement of spacing of 25,50 and 75 mm.

3.2 Preparation of test specimen

The pull-out cube moulds were cleaned and lubricated with oil on inner faces for easy demoulding.The bar bending of confinement in the form of lateral reinforcement was done as per the design. The batch mixing was done in batch mixer and the fresh concrete was filled in the mould manually so that no segregation occurs. Needle vibrator was used to compact concrete and finished top surface. After 24 hours the specimens were demoulded and cured with water for 28 days.

Figure 1: Reinforcement bars in Concrete

One set of pull-out specimens were tested under monotonic and cyclic loading with three LVDTs to measure the slip at free end and loaded end. Another set of pull-out specimens were tested under overloading with 03 LVDT to get the slip at free end and loaded end.

3.2 Anchorage bond specimens

The bond strength under monotonic, cyclic and over loads was studied with different lateral confinement. In all specimens, bond length in 150mm cube was only 80mm, with upper 50mm and lower 20 mm was unbonded by plastic strips. Two different bar diameters of 16mm and 25mm in using two concretes of M25 and M60 grades with varying confinement using 8mm diameter spirals with varying pitch of 25mm, 50mm and 75mm were considered.

3.3 Testing of anchorage specimens

The specimens were tested under monotonic, cyclic loading and Overload with pullout testing machine as shown in Figure 2 until ultimate failure. In monotonic loading, displacement was increased incrementally to prevent any dynamic effect. Cyclic test was done as specified in ACI. On the day of testing, three concrete cubes were tested to determine compressive strength.

Figure 2: Test set-up for Pull out Loading

3.4 Experimental set-up

The experimental set-up is prepared ras for testing of anchorage bond specimens under load control and the testing procedure is demonstrated in Figure 2. The test specimen were mounted in a suitable testing machine as shown in Figure 2 such that the bar is pulled out axially from the concrete to avoid any lateral movement. The end of the bar at which pull is applied should be projected from the top face of the concrete as cast. In assembling the specimen distance between the face of concrete and the point on the loaded end of reinforcing bar where the device for measuring slip is attached, was carefully maintained to estimate the elongation of the bar over this distance and deducted from the measured slip. Plaster of paris paste was applied at both ends of the specimen for proper contact with steel plates so that no lateral movement occurs during loading. The anchorage bond specimens were tested using Load control system and the slip was observed. Slip was measured at free and loaded ends of specimen by LVDTs. The loading was applied gradually and readings of movements were recorded till failure under monotonic loading. Under cyclic loading, the load range was 10% to 65% of ultimate load was continuously applied at the rate of 3 cycles/second till failure. The number of cycles was noted after failure of each anchorage specimen. In case of overloads, accidental loads (80% of ultimate load) was applied in three levels of fatigue life of three anchorage specimens. First overload was applied before designed cyclic load was applied, at initial 0 cycles, second overload was applied after 50000 cycles and third overload was applied at 100000 cycles.

3.5 Testing under different loading

To find the bond strength of concrete and to study the bond stress-slip response of concrete based on pull-out test under monotonic loading, cyclic loading and overload were applied. The test procedures were followed as per ACI for the loading conditions and other requirements. Under cyclic loading, the anchorage specimen was subjected to sinusoidal tension loads for number of cycles at the rate of 3 cycles/sec till failure occurred. The results are shown in Table 2. Fatigue load (minimum $0.10P_u$ and maximum $0.65P_u$) were applied continuously till failure of specimen and then number of cycles noted. For applying Overloading**,** the specimen was subjected to sinusoidal tension loads for number of cycles at the rate of 3 cycles/sec and then overload of 80% of P_u was applied on three anchorage specimens after different cycles of loading and after that continued till the specimen failed. The test results on life of anchorage specimens with overloading applied are shown in Table 3.

4. RESULTS AND DISCUSSION

The experimental results obtained from the testing of pull out specimens under monotonic and cyclic loading with overloads have been discussed. The failure modes of different pull-out specimens under different loading cases were found out to be similar in nature. Pull out failure was observed in all the anchorage specimens due to presence of lateral confinement as shown in Figure 3. But concrete under monotonic loading with 75mm pitch of confinement reinforcement was due to pull-out along with splitting of concrete. No splitting failure was observed during cyclic and overloads. Pull-out failure occurs when good confinement was provided to the bar by spiral reinforcement. The concrete immediately surrounding the bar failed due to shearing of concrete between rebar lugs. Pullout failure depends primarily on concrete strength and rebars surface pattern and geometry. Splitting failure occurs, as shown in Figure 4, primarily due to radial tensile stresses exerted by the bar lug bearing forces. In this case splitting cracks propagate up to the edges of the concrete member resulting in loss of cover and bond strength.

It was observed only where confinement was 75mm under monotonic loading.

Figure 3: Pullout failure of concrete.

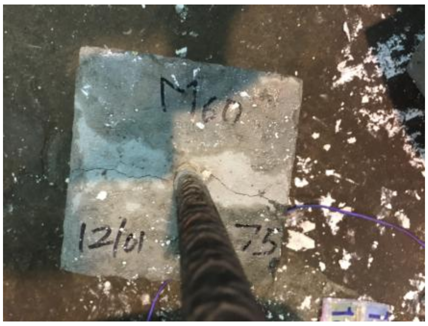

Figure 4. Splitting failure of concrete

4.1. Influence of confinement

Three different pitches of 8mm diameter HYSD bars spiral confinement of 25mm, 50mm and 75mm c/c spacing were used. The test results from monotonic loading indicated that the presence of confinement considerably enhanced the ultimate bond stress, which increased with decrease in pitch 9closer spacing of spirals). The variation of bond stress in anchorage pull-out specimens is shown in Figure 5. The test results under cyclic loading indicated that the presence of confinement considerably enhanced the fatigue life, which increases with decrease in pitch. Figure 6 shows the bar charts for various anchorage pull-out specimens with varying parameters under cyclic loading. Provision of confinement effectively prevented the concrete splitting failure and shifted the failure mode to pull-out mode.

4.2 Influence of strength of concrete

Two grade of concretes of M25 and M60 were adopted. The test results indicated that the bond strength increases with increase in strength of concrete. The ultimate bond stress under monotonic loading is high at failure in M60 grade concrete than the M25 grade concrete, which is shown in Figure 7. Similarly under cyclic loading number of cycles at failure is high in M60 grade concrete than that of M25 grade concrete, as shown in Figure 8.

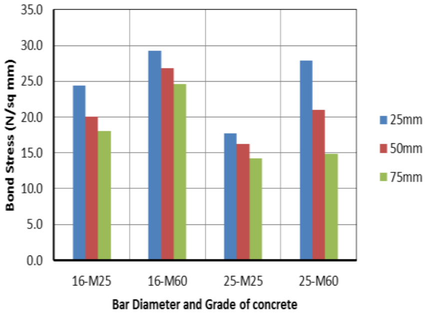

Figure 5: Bond Stress vs. Diameter in concrete by varying pitch of spiral under monotonic loading

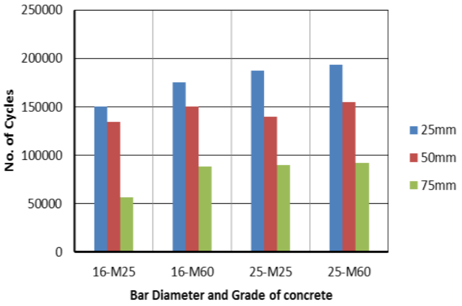

Figure 6: Number of cycles vs. Diameter of rebar in Concrete with different confinements

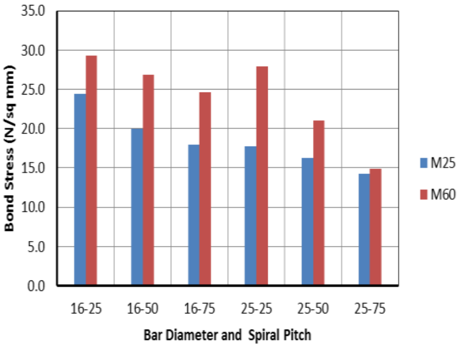

Figure 7: Bond Stress vs. Diameter of main bar and pitch in concrete under monotonic loading.

4.3 Influence of diameter of bar

Two different bars of diameters of 16mm and 25mm were adopted. The test results indicate the ultimate bond stress decreased with increase in diameter of reinforcement. The ultimate bond strength under monotonic loading is less at failure with 25mm diameter bar than that of 16mm diameter bar as shown in Figure 9. Similarly under cyclic loading number of cycles at failure are high with 25mm diameter bar than that of 16mm diameter bar as shown in Figure 10.

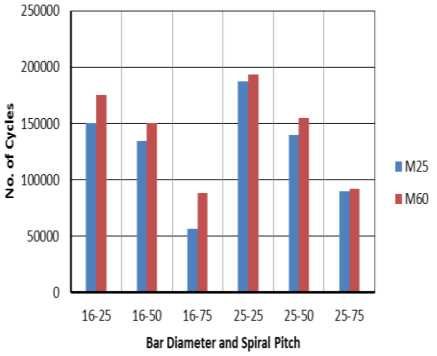

Figure 8: Number of cycles vs. Diameter of bar different pitch in concretes under cyclic loading

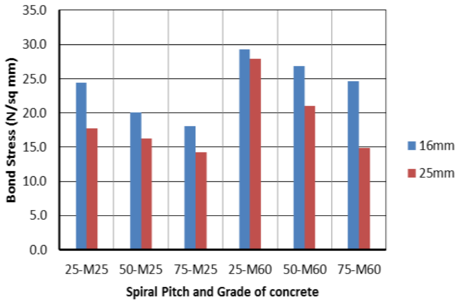

Figure 9: Bond Stress vs. Pitch and concrete grade with different bar diameter under monotonic loading

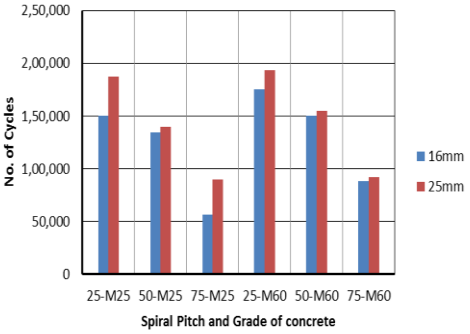

Figure 10: Number of cycles vs. Pitch and concrete grade and different bar diameter under Cyclic loading.

4.4 Influence of type of loading

Under monotonic loading, bond force and bond stress-slip curves are initially very steep due to adhesion. Due to concrete shrinkage, restrained by the reinforcing bar, small internal cracks exist immediately adjacent to the reinforcing bar. These cracks can act as stress raisers and points of crack initiation at the bar ribs at relatively low loads. Because cracks tend to form in front of the ribs, small splitting cracks may begin to propagate from the ribs, but due to strong confinement only pull out failure took place. Under Cyclic loading, slip increment depends on bond length and on parameters of the repeated load. The higher the load, the higher the slip. Slip increments decrease during the initial load cycles, and then slip increment was constant up to the slip at which the monotonic pull-out strength was reached. At higher values of slip, slip increases progressively up to pull-out failure. A pull-out bond failure occurred due to cyclic loads without applying the monotonic ultimate pull-out force. In pull-out specimen 16-M25-25, the effect of cyclic loading on slip in rebars is shown. As shown in Figure 11, slip increases with increasing number of cycles. After 1,20,000 load cycles the slip is 3.0mm, beyond this, the slip rapidly increases with further increase in the cycles. In pull-out specimen 16-M25-50, the effect of cyclic loading on slip in rebars is shown. As shown in Figure 12, slip increases with increasing number of cycles. After 1,20,000 load cycles the slip is 2.8mm, beyond this the slip rapidly increases with further increase in the cycles. The strain in rebar increases with increasing load. In pull-out specimen 16-M25-75, the effect of cyclic loading on slip is shown. As shown in Figure 13, slip increases with increasing number of cycles. After 50,000 load cycles the slip is 2.9mm, beyond this the slip rapidly increases with further increase in the cycles.

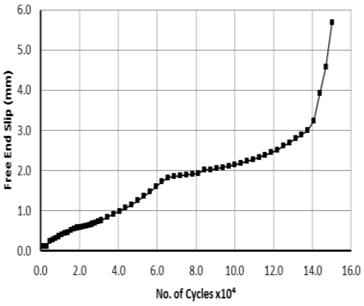

Figure 11. Slip at free end vs. No. of Cycles in 16-M25-25

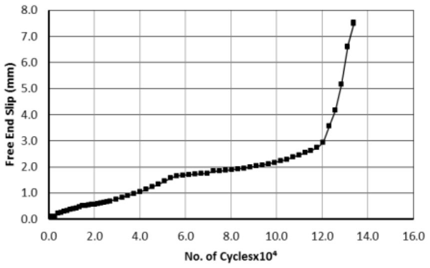

Figure 12. Slip vs. No. of Cycles in 16-M25-50.

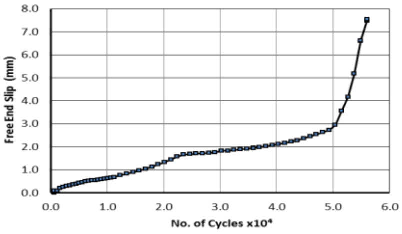

Figure13. Slip vs. No. of Cycles in 16-M25-75.

Bond Strength under Overloading in anchorage specimen 25-M25-50 is shown. Three anchorage specimens were tested under cyclic loading and also subjected to overloading after different load cycles. The overloading was 80% of the ultimate monotonic load, applied just before the designed cycles were applied. When the over loading was applied immediately after commissioning of the structural system without applying any load cycles, the slip increases to 2.7mm and subsequently it rapidly increase and the specimen failed at just 3000 cycles only as shown in Figure 14. The slip of rebar was not much increased up to 50000 cycles. Overloading of 80% of the ultimate monotonic load was applied after 50000 cycles, the rebar was pulled out of the concrete as shown in Figure 15. The slip was very negligible even up to 1,00,000 cycles. When the overloading of 80% of the ultimate monotonic load was applied after 1,00,000 cycles, the rebar was pulled out of the concrete with no time as shown in Figure 16.

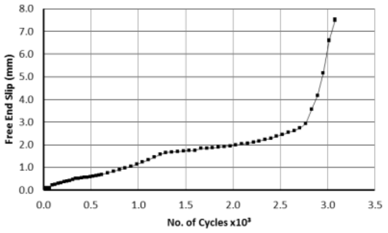

Figure 14: Slip vs. No. of Cycles under overloading in 25-M25-50.

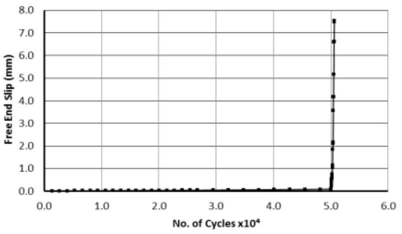

Figure 15: Slip at free end vs. No. of Cycles under overloading in 25-M25-50

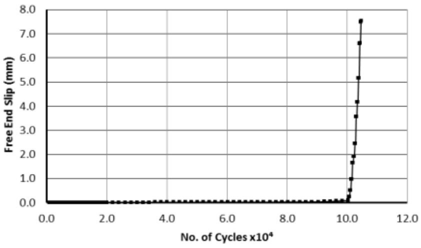

Figure 16: Slip at free end vs. No. of Cycles under overloading in 25-M25-50

Slip was very high when the overloads were applied in the initial stages itself. The life of RC in anchorage bond is only 3000 cycles. When the overloads were applied after 50,000 and 1,00,000 cycles, the sudden failures of RC members due to pulling out of rebars in concrete was observed. After overloading the life of RC structures is significantly reduced, leading to collapse.

5. CONCLUSION

The following conclusions can be drawn from the experimental studies.

1. The maximum bond stress τ_{max} for specimens confined with spirals was higher and exhibited significant ductility. The bond strength was efficiently improved by providing confinement in the form of spiral reinforcement, which is proved to be true in all types of loading.
2. The ultimate bond stress under monotonic loading is high at failure in M60 grade concrete than M25 grade concrete. The number of cycles at failure has been high in M60 grade concrete than in M25 grade concrete.
3. Under monotonic, and cyclic loading the presence of confinement considerably enhanced the ultimate bond stress, and the fatigue life of reinforced concrete, which increased with decrease in pitch of spiral

reinforcement. Provision of confinement effectively prevented the splitting of concrete and shifted the failure to pull-out type.

4. The ultimate bond stress under monotonic loading is less at failure and, the number of cycles at failure is more with 25mm diameter bar than 16mm diameter bar.
5. The slip suddenly increases after overloading of more than 80% of ultimate failure load applied, which leads to catastrophic failure. The life of reinforced concrete significantly decreases when the early overloads are acting.

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Table 1: Details of Anchorage Specimens and monotonic loading

S. No	Bar Diameter (mm)	Grade Concrete	Pitch (mm)	P_{max}(Ton)		Type of Failure
				Sp -1	Sp - 2	
01	16	M25	25	7.70	5.48	P
02			50	7.00	9.40	P
03			75	8.20	6.50	P
04		M60	25	10.00	10.56	P
05			50	12.00	10.00	P
06			75	10.40	9.76	P&S
07	25	M25	25	12.75	10.00	P
08			50	8.70	12.10	P
09			75	8.30	9.96	P&S
10		M60	25	17.90	17.86	P
11			50	10.67	16.20	P
12			75	5.70	13.38	P

Table 2: Details of anchorage specimens and cyclic loading results

S. No	Bar Diameter (mm)	Concrete Grade (N/mm^2)	Pitch of Spiral (mm)	P_u (Ton)	P_{min} (Ton)	P_{max} (Ton)	Frequency (Hz)	No of Cycles (N) at failure	Mode of Failure
01	16	M25	25	7.70	0.80	5.00	3	1,27,500	Pull out
02			50	9.40	1.00	5.00	3	1,34,000	Pull out
03			75	7.50	0.75	4.50	3	56,230	Pull out
04		M60	25	10.50	1.00	6.80	3	2,05,450	Pull out
05			50	10.00	1.00	6.00	3	1,20,280	Pull out
06			75	10.00	1.00	6.00	3	88,120	Pull out
07	25	M25	25	10.00	1.00	6.00	3	1,87,200	Pull out
08			50	10.00	1.00	6.50	3	1,15,000	Pull out
09			75	9.15	0.90	6.00	3	90,000	Pull out
10		M60	25	17.80	2.00	10.00	3	1,93,680	Pull out
11			50	13.38	1.50	8.70	3	1,45,000	Pull out
12			75	9.50	1.00	6.00	3	92,000	Pull out

Table 3: Details of experimental outcome of number of cycles under overloading

S. No	Bar Diameter (mm)	Concrete Grade (MPa)	Overload (cycles)	Spiral pitch (mm)	P_u (Ton)	P_{min} (Ton)	P_{max} (Ton)	No of Cycles (N) at failure	Type of Failure
01	25	M25	0	50	12.0	1.00 1.00	6.0 10.0	3080	Pullout
02			50,000	50	12.0	1.00 1.00	6.0 10.0	51000	Pullout
03			1,00,000	50	12.0	1.00 1.00	6.0 10.0	102000	Pullout
04		M60	0	50	16.0	1.50 1.50	8.5 12.0	69670	Pullout
05			50,000	50	16.0	1.50 1.50	8.5 12.0	53000	Pullout
06			1,00,000	50	16.0	1.50 1.50	8.5 12.0	105000	Pullout