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BEHAVIOR OF POST-INSTALLED ANCHORS UNDER TENSILE FATIGUE LOADING

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Abstract: Post-installed anchors are rigorously used in structures such as factory buildings, tunnels, and highway bridges to connect structural and non-structural elements, and are subjected to fatigue loading during service period. The investigation on fatigue behavior of post-installed anchors has been, however, limited up to now. In this paper, the fatigue behavior of post-installed mechanical expansion anchors has been investigated under cyclic tensile loading at dry and wet conditions. The results reveal that residual strength of mechanical anchor was enough comparing to the initial strength under both dry and wet conditions. However, pull-out displacement during fatigue tests under wet condition was larger than that of dry condition.

1 INTRODUCTION

The post-installed anchors (hereinafter called as anchors) are used to establish post-construction anchorage system, which is widely used in the construction industry to fasten the structural and non-structural components to existing reinforced concrete structures. Based on load transfer mechanism, anchors are classified into bonded and metal anchors. In the latter case, the load transfer take place by mechanical bond developed by forcing the sleeve to open while drive down along the conical base on the anchor body during anchor installation. While in bonded anchors, the load transfer take place by bond action of resin. Recent trends towards the realization of material-efficient and more fragile structures as well as the development of innovative machinery and production technologies led to increasing impact on the repeated and cyclic loading. Therefore, the fatigue performance of the post-installed anchor is becoming increasingly important. For example, the non-structural components and tunnel ceiling in tunnel construction are under repeated load due to high-speed vehicles passing through.

Extensive experimental work has been done on the performance of load and cracking behavior of post-installed anchors in concrete under monotonic load application considering different substrate concrete, anchor diameters with variable embedment depths [1]. Along with monotonic anchor capacities, special dynamic loading protocols were used, which include a specific finite number of load cycles with varying amplitude, to investigating the cyclic shear and tensile performance of cast in situ anchors [2]. The investigation on the fatigue performance of post-installed anchors has been, however, limited. In addition, less has been done to investigate the fatigue performance of post installed anchors under diverse conditions. In this study the fatigue resistance of post-installed mechanical expansion anchors has been investigated in both dry and wet conditions.

2 EXPERIMENTAL PROGRAM

2.1 Anchor with drilling details

For the metal anchors, sleeve driving type metal expansion anchors were used. Because the strength of the anchor bolt in ordinary products is low, high strength anchor bolt was replaced. It was made by screwing a 30mm high-strength steel conical shoe to the SNB7 steel anchor of M20 size with sleeve length of 75mm. Fig. 1 illustrates the ordinary low strength mechanical anchor. Fig. 2 illustrates the modified steel anchor. Before screwing the steel shoe, the bottom 30 mm portion of the steel bolt was glued with epoxy for making proper sleeve. The drilling bite diameter was 28mm and drilling depth of 88mm was used for installation of the anchor. A rotary hammer was used to drive the sleeve down the drilled hole along the anchor body.

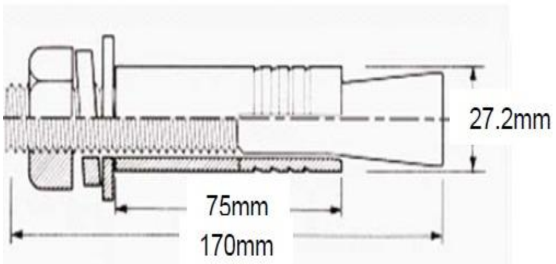


Figure 1: Details of used anchor.

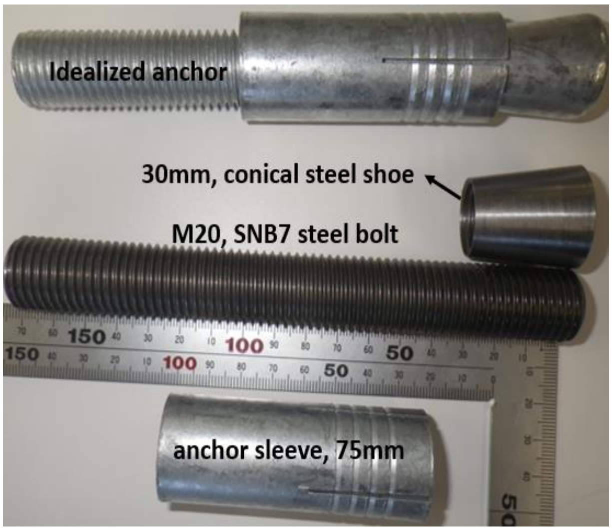


Figure 2: Modified anchor using high strength bolt.

Table 1 presents the details of metal expansion anchors used for investigation of fatigue resistance under dry and wet conditions. Moreover, the anchors were installed into the formed side (concrete floor with plastic cover) of the concrete substrate in the downward direction. This is because of having a more even surface for anchors depth measurement and having comparatively uniform concrete composition.

2.2 Substrate concrete

As substrate concrete for the anchor installation, a 4.5 mm thick steel pipe with external diameter of 216 mm was filled with concrete. The height of specimen was 150mm. Figure 3 illustrates the geometry of the substrate concrete with an installed anchor. Concrete with water to cement ratio of 58% with 25 mm maximum size of aggregates were used. The compressive strength of substrate concrete at the age of 28 days was 30.7 MPa with elastic modulus of 30.9 GPa.

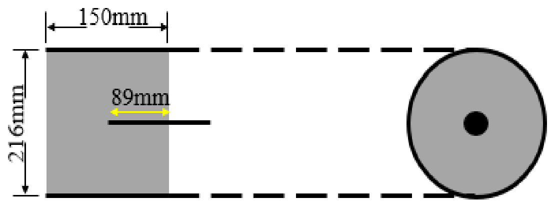


Figure 3: Substrate and anchor details.

The number of specimens and the applied test loads were determined in accordance with the specifications of ACI 355.2 and ASTM E488 [3, 4]. Five specimens for each case were casted and tested under fatigue load while exposing to a maximum of 2 million load cycles at 80%, 60% and 40% of the reference ultimate pull-out load capacity under dry and wet conditions. At the end of cyclic loading, a monotonic pull-out test was performed on each specimen to investigate the residual load capacity.

Table 1: Anchor and drilling conditions.

Substrate Thickness	Bolt dia. (mm)	Drill depth	Embedment length	Drill diameter
150mm	M20	89mm	75mm	28mm

2.3 Application of tensile fatigue load

The post-installed metal expansion anchors were subjected to tensile fatigue load after proper installation. All anchors were tested under tensile fatigue load at both dry and wet conditions. In case of wet condition, the specimens were submerged in water for more than 7 days. After the completion of water immersion period, a water pond of 190mm diameter and 20mm depth was introduced using steel ring and silicon sealing during the application of fatigue load as illustrated in Fig. 4. The applied pulsating tension load is conceptualized in Fig. 5. The cyclic loading protocol includes a maximum of 2 million tensile load cycles applied with a cyclic frequency of 4Hz at 80%, 60%, and 40% of the reference 95 percentile pull-out capacity. For the loading tests, a 200kN servo controlled

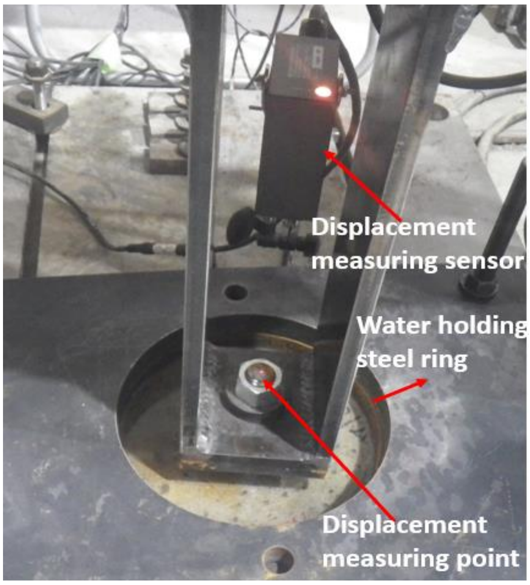


Figure 4: Fatigue test in wet condition.

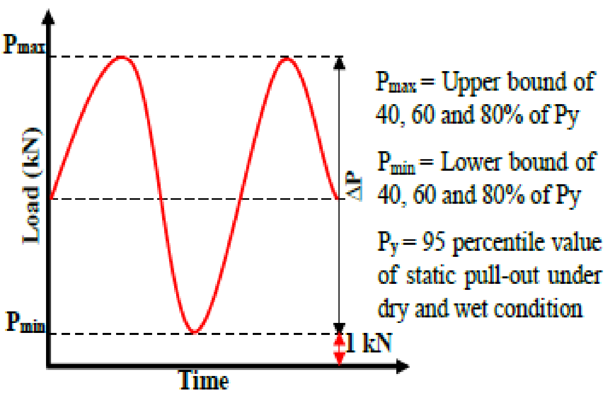


Figure 5: Conceptulized fatigue load (sine wave).

loading actuator was used. To measure the pull-out displacement during the loading tests, a highly sensitive laser displacement transducer, which was set at the top center of anchor body, was used. In terms of serviceability of the anchors, pull-out displacement of 5mm was defined as criteria, and the fatigue test was terminated. For the specimen after terminated, static pull-out test was conducted as follows.

2.4 Residual pull-out strength

After the fatigue load exposure includes reaching to both criteria (2 million cycles or pull-out displacement of 5mm), monotonic pull-out test was performed. The pull-out test assembly is shown in Fig. 6. A center hole jack of 200kN capacity was used, and two high sensitivity displacement transducers were attached to the opposite sides of the socket connecting the anchor body and steel rod. A load cell having 300kN capacity with sensitivity of 100N was used. For the pull-out test on wet samples, the water pond for fatigue tests was removed just before static tests.

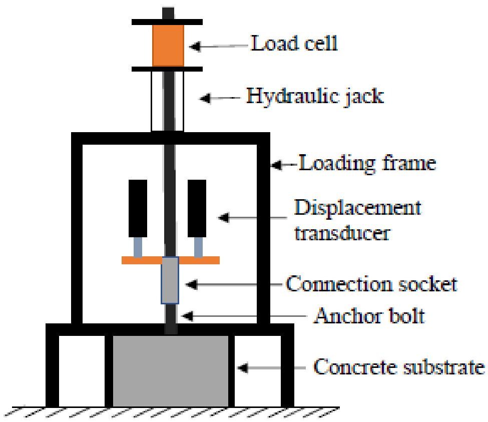


Figure 6: Pull-out test setup.

3 EXPERIMENTAL RESULTS AND DISCUSSION

3.1 Fatigue performance of the anchors

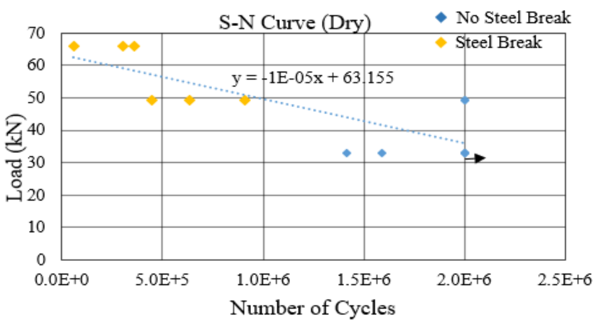
Table 2 illustrates the cyclic loading protocol based on static tests before fatigue Load exposure. Lower bound of 95% confidence interval of the mean static pull-out load under dry and wet condition was considered as reference for fatigue loading of

40, 60 and 80% was calculated and used for fatigue investigation of anchor specimens.

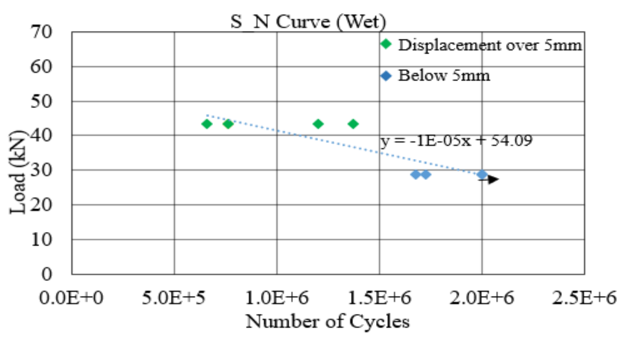
Table 2: Test load protocol.

Loading level	Loading conditions (kN)	
	Dry	Wet
100% P_u	101.8	96.7
Lower bound of 95% confidence interval P_y	82.3	72.3
80%	65.9	57.8
60%	49.4	43.4
40%	32.9	28.9

Figure 7 shows the load and number of cycles of each specimen tested under fatigue loading. The fatigue tests were stopped when either of the failure criteria that are pull-out displacement of 5mm under fatigue loading, breaking of anchor bolts or completed the 2 million cycles. Note that, A displacement of 5 mm corresponds to the displacement at about 50% of the maximum load in the load-displacement relationship of the static loading test.



(a) Dry condition



(b) Wet condition

Figure 7: Load vs number of cycles to failure under dry and wet conditions.

Anchor bolts breaking before completing 2 million cycles was observed in the case of 60 and 80% fatigue loading under dry condition. On the other hand, the pull-out displacement of the all the anchors in the case of 60% fatigue loading in wet condition reached to the criteria (5mm) before reaching to the 2million cycles.

Table 3 : Displacement under 40% fatigue.

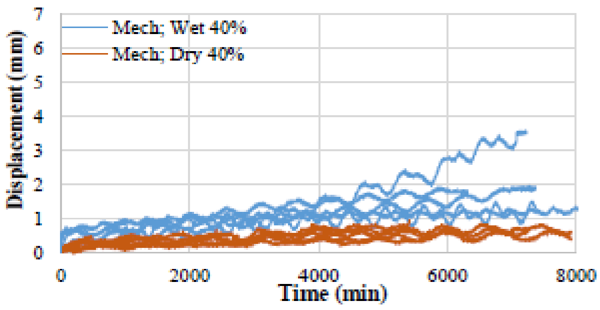
Loading Condition	No	Pull-out Disp. (mm)	Mean	COV %
40%-Dry	1	0.85	0.78	20.5
	2	0.69		
	3	0.51		
	4	0.96		
	5	0.88		
40%-Wet	1	1.97	2.08	37.9
	2	3.59		
	3	1.92		
	4	1.53		
	5	1.37		

Table 4: Displacement under 60% fatigue.

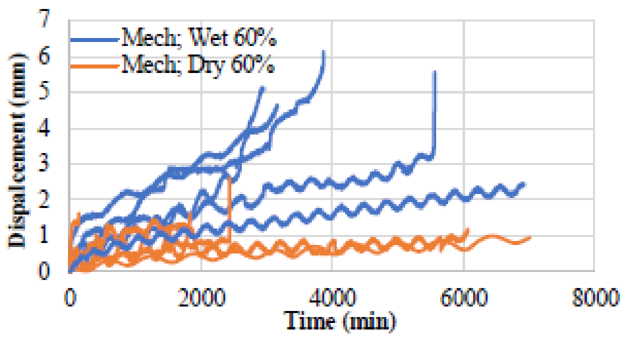
Loading Condition	No	Pull-out Disp.(mm)	Mean	COV %
60%-Dry	1	1.61	1.61	34.2
	2	1.63		
	3	1.21		
	4	2.6		
	5	1.00		
60%-Wet	1	4.65	4.79	26.3
	2	6.14		
	3	2.47		
	4	5.56		
	5	5.14		

Tables 3 and 4 show the pull-out displacement in the case of 40% and 60% loading cases, when the fatigue tests were terminated. The pull-out displacement of the 60% case was larger than that of 40% case. Also, the pull-out displacement of the specimen in wet condition was larger than that of dry conditions. In addition, the variation in the pull-out displacement during fatigue test under wet condition is higher than that of dry one.

The displacement and time relationship shows the damage process during the fatigue tests. The pull-out displacement was gradually increased during fatigue, and the increasing rate of pull-out displacement in the wet condition was larger than that in the dry condition. It seems that the concrete at fixed part of sleeve is locally crushed by the bearing force of the sleeve tip. Further investigations are needed in terms of microscopic observation. The displacement and time relationship during fatigue tests is presented in Fig. 8.



(a) 40% fatigue loading



(b) 60% fatigue loading

Figure 8: Pull-out displacement under 40% and 60% loading.

Figure 9: Concrete fatigue crack.

From visual observation, splitting crack was occurred in substrate concrete. The crack initiation and propagation in substrate concrete occur in the first 100 to 200 load cycles. However, the concrete cone fracture was not occurred in all series. The lateral steel confinement of anchored concrete does not allow the crack opening and keeps the resistance against fatigue loading. The crack in substrate concrete due to movement of the anchor furing fatigue load is represented in Fig. 9.

3.2 Post-fatigue residual strength

Figure 10 indicates the averaged residual pull-out strength of anchors tested under dry and wet conditions. The residual pull-out strength of the anchor after 40% fatigue test was slightly reduced by about 6.7% in the dry condition and 0.31% in the wet condition. Regarding the specimen after 60 and 80% fatigue tests, the residual pull-out strength was increased significantly. It seems that the higher fatigue loading makes the anchor move up, and fixation at a tip of sleeve increases in both dry and wet conditions.

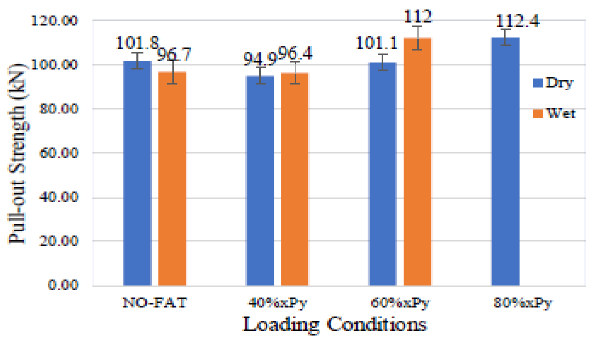
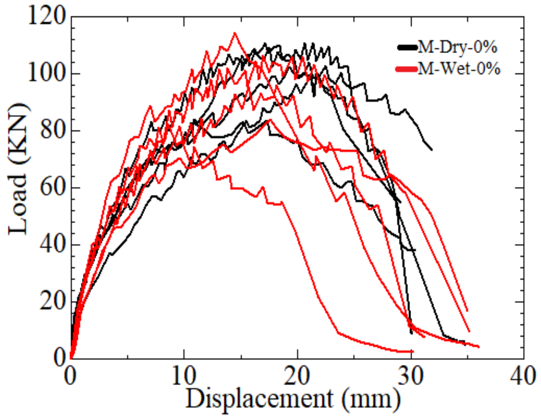


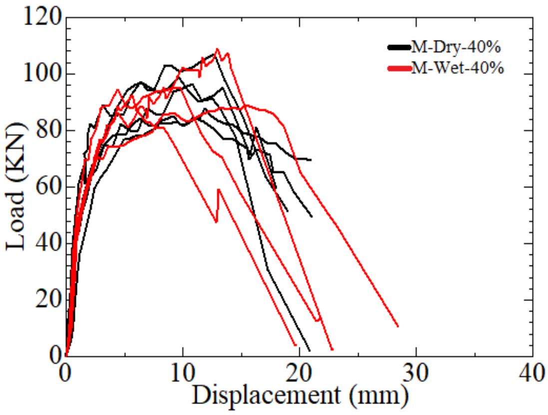
Figure 10: Residual pull-out strength.

Observations made based on the load and displacement relationship in pull-out, there is no significant difference in the shape of curve before and after the fatigue tests. Steeper increase in pull-out load until the peak was observed in the case after fatigue tests. Slightly lower ultimate displacement in post fatigue pull-out was observed in comparison to static pull-out. The reason seems that the center bolt of the anchor was pulled into the sleeve during the fatigue test, and shows the fracture progressed in the shallow part of substrate.

Figure 11 illustrates the relationship between load and displacement in the case of 40% loading case and table 5 presents the ultimate displacements observed during static and post fatigue pull-out.



(a) Static pull-out tests



(b) After 40% fatigue loading

Figure 11: Load vs displacement relationship.

Table 5: Displacement at ultimate load

Loading Condition	Displacement at ultimate load	COV %
Dry static	19.7	10.5
Wet static	15.2	23.1
Dry 40% Fatigue	11.2	9.1
Wet 40% Fatigue	10.9	33.9

Figure 12 shows the concrete cone fracture in static tests before and after the fatigue loading (40%). The length to the deepest part of the concrete cone was about 50 mm before the fatigue tests. The length to the deepest part of the concrete cone was about 40 mm after the fatigue tests at 40% fatigue load.

Figure 12: Concrete cone failure before and after fatigue loading.

4 CONCLUSIONS

Based on the experimental observations in this study, the following conclusions were obtained.

1. As the applied load in the fatigue test decreased, the number of cycles until the failure increased. However, there was a tendency for the number of cycles until the failure to be relatively small for the specimens under water conditions compared to those under dry conditions.
2. The specimen in wet condition exhibited larger pull-out displacement during fatigue loading. It seems that the concrete at the tip of the sleeve was damaged by fatigue and water actions.
3. Regarding the specimens after 2 million cycles loading or with pull-out displacement of 5mm, residual pull-out strength was measured. When the fatigue loading level was small, there was no significant effect, but when the fatigue loading level was high, the maximum load rather increased. The reason for this is considered to be that the anchor was pulled out by the fatigue loading and the anchoring strength improved.

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