Experimental study of post-installed anchor embedded in concrete under simulated seismic and wind loads

DOI : 10.36909/jer.16707

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ABSTRACT

In this study, experimental protocol to simulate wind-induced vibration of post-installed anchor embedded in concrete was developed. The proposed loading protocol was based on the ratio of deformation due to seismic load and dynamic wind load of anchors in the connection between the sign structure and the concrete building. Then, based on ACI 355.2 and the developed protocol, numerous experimental tests were conducted to evaluate the performance of anchor under simulated seismic and wind loads. In simulated seismic test, crack width of concrete did not affect the performance of anchor. Their maximum force as well as residual capacity showed practically the same value. Moreover, anchor used in this experiment satisfied the condition to be rated as full capacity for seismic performance. In simulated wind test, the crack width did not cause any difference in performance of the anchor in tension test. Though, in simulated wind shear test, there was a major difference for the anchor residual capacity. Additionally, the performance of anchor in simulated wind test did not satisfy the criteria to be rated as full capacity.

Keywords: Post-installed anchor; Simulated seismic test; Simulated wind test.

INTRODUCTION

As the complexity of concrete structures are increasing, connecting element systems of concrete-to-concrete or steel-to-concrete in various ways further contribute to this complexity (Kim et al., 2013) and (Belleri et al., 2017). Hence, the interests in the technique to connect those systems has been significantly on the rise. Along with all the available methods, the connecting system with the anchor was one of the methods of interest.

The use of a variety of post-installed anchors for strengthening purpose, rehabilitation or to support secondary components like equipment or sign structures is well-recognized. Many designs included provisions for safe design of the post-installed anchor systems (Gesoğlu & Güneyisi, 2007). A post-installed anchor system is connected or constructed in the anchorage zone of an existing primary structure (Jang & Suh, 2006), to hold-down lighter secondary systems like machinery or equipment, sign structures, and steel frames. It can also be used to attach new structure elements such as braces or infill walls used for strengthening or rehabilitating the existing primary structure (Brunesi et al., 2019). The behavior of these post-installed anchor systems has been extensively studied by researchers all over the world (Nascimbene & Bianco, 2021). ACI Committee proposed a design guideline and equation to determine the resistance capacity of an anchor system (ACI Committee, 2002), (ACI Committee, 2011) and (ACI Committee, 2014). Moreover, Concrete Capacity Design theory based on concrete fracture modes has also been used to evaluate the strength of these anchor systems (Fuchs et al., 1995).

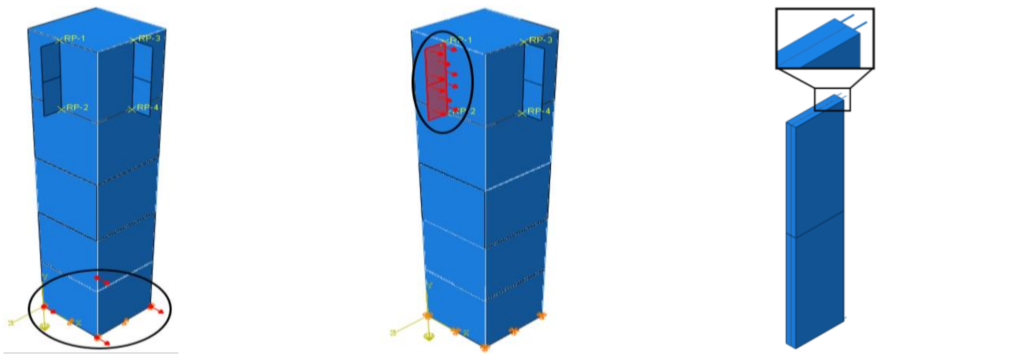
The experiments of anchor connection used in sign structure in the previous literature were mostly based on static loading which did not consider the degradation of sign structure throughout their service life due to the wind-induced vibration. Moreover, the guideline for evaluating the performance of post-installed mechanical anchors embedded in concrete in ACI 355.2 were mostly focused only on simulated seismic test (ACI Committee 2002). The vibration due to wind intensity was not clearly state in ACI 355.2 which only presented the general repeated load. Therefore, based on this guideline an experiment procedure to simulate wind vibration for anchor connection will be propose in this chapter.

PROPOSAL OF SIMULATED WIND EXPERIMENTAL METHOD

Modeling of a simplified and symmetrical 5-stories (20 m) concrete structures with two attached sign structures was developed for comparing the response of anchor when subjected to wind and seismic dynamic load. Since the loading protocol for simulating seismic load was clearly define in ACI 355.2 guideline, the loading protocol for simulating wind-induced vibration was defined based on the ratio of wind load to seismic load response.

Finite Element Models of Wind and Seismic Load

A simplified 5-stories (20 m) symmetrical concrete building model with two attached sign structures was shown in Figure 1 Sign structures were constraint as rigid bodies connecting top and bottom half of the sign panel to top and bottom anchors, respectively. The material properties used were shown in Table 1. The symmetry of model reduces the numbers of numerical analysis required, since the connection anchors for both sign structures were identical. Seismic loading only applied in x-axis as seen in Figure 1a and wind loading only applied on sign structure as seen in Figure 1b. For seismic loading, the tensile and shear responses obtained from both sign structures were compared to find the anchor with the maximum deformation. For wind loading, only the direction perpendicular to the sign structure (x-axis in Figure 1b) were loaded. The tensile force in anchor was generated due to the moment created by the sign structure (see Figure 1c). Like seismic loading, the anchor with the maximum tensile and shear deformation were determined.

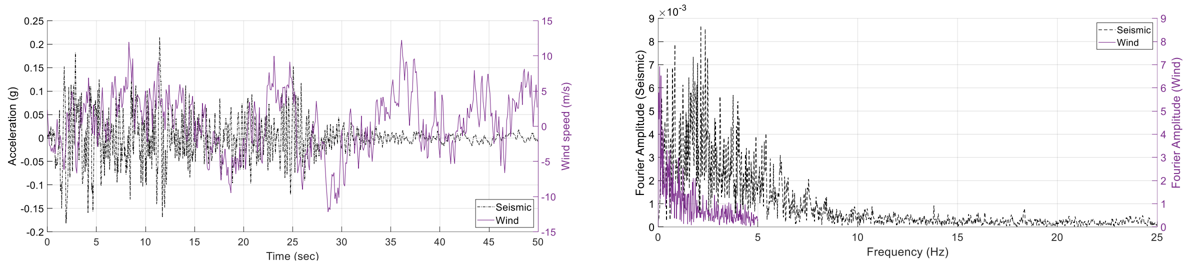


(a) Seismic load (b) Wind load (c) Sign panel with anchors

Figure 1. Failure mechanisms of post-installed anchor system

Table 1. Material properties of building model with attached sign structures

Material	Density (kg)	Young's Modulus (GPa)	Poisson's Ratio
Concrete	2400	31.259	0.18
Steel	7850	210	0.30
Sign	1000	150	0.30



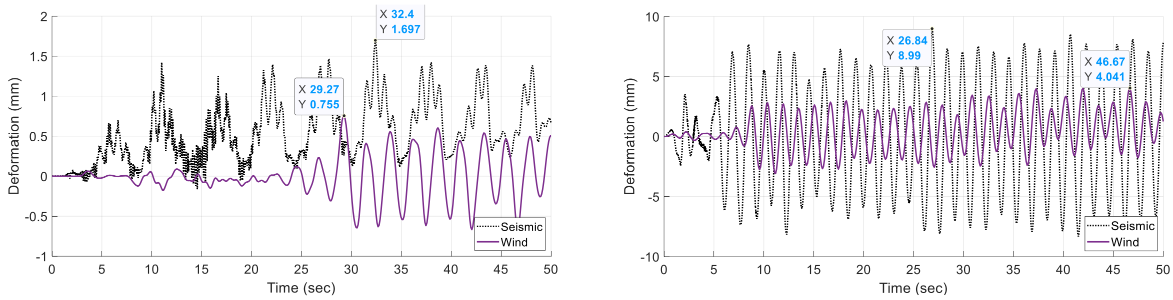
(a) Time domain (b) Frequency domain

Figure 2. Comparison between seismic ground acceleration and artificially generated wind

There was a total of 47 loads cases consisted of 11 historical seismic loads (micro, short and long wave) obtained from historical seismic data in U.S. Geological Survey (USGS) database (https://earthquake.usgs.gov/) and 36 artificially generated wind loads (exposure B, C and D, and wind speed 60, 120, 180 m/s) obtained from simulation application NOWS developed by NatHaz Modeling Laboratory at the University of Notre Dame (http://windsim.ce.nd.edu/). Figure 2 shows a comparison between one of the seismic ground acceleration historical records and artificially generated dynamic wind.

Analysis of Structural Response

The maximum anchor deformation due to tensile force generated by seismic and wind load were shown in Figure 3a for the most critical seismic and wind load case. As can be seen, seismic load produced larger deformation for the anchor (1.697 mm) compared to deformation due to wind load (0.755 mm). In this current study, the method to derive the loading intensity for simulated wind-induced vibration experiment was simply the ratio between anchor deformation due to wind load and anchor deformation due to seismic load. Since this is the first attempt for this task, the results of this choice will be further shown in the experiment conducted in the next section. The ratio of wind to seismic deformation for tensile load case was found to be 0.4448 (44.48%). Like tensile load case, the comparison between deformation of anchor due to seismic and wind load was shown in Figure 3b. The ratio of wind to seismic deformation for shear load case was 0.4495 (44.95%).

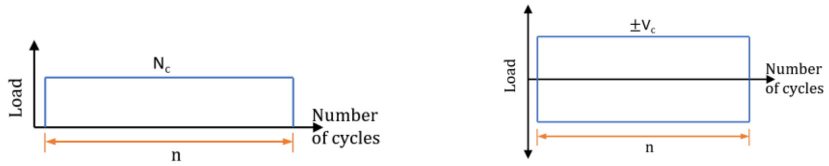


(a) Tension (b) Shear

Figure 3. Time history of anchor deformation due to tension and shear force

Proposed Simulated Wind Experiment Method

The loading pattern for simulated wind test shall be chosen as cyclic load test with the loading pattern shown in Figure 4, using a loading frequency between 0.1 and 2 Hz, where:



(a) Tension (b) Shear

Figure 4. Loading pattern for simulated wind tension and shear test

N_C = maximum simulated wind tension test load

V_C = maximum simulated wind shear test load

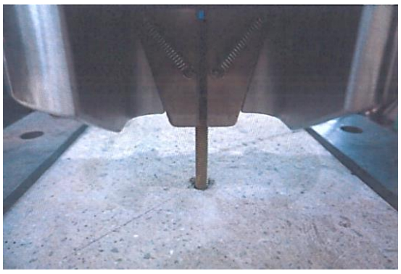
n = number of loading cycles

POST-INSTALLED ANCHOR SIMULATED SEISMIC AND WIND EXPERIMENTS

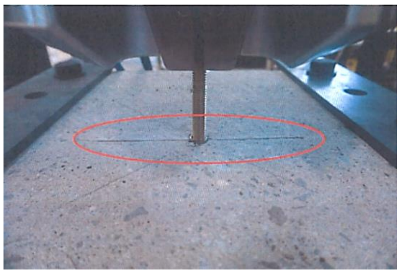
Experimental study for simulated seismic and wind load were conducted following the ACI 355.2 guidelines in conjunction with the proposed loading protocol. This experiment aims to collect basic data for the development of high-performance anchors for resisting seismic and wind loading. In order to evaluate the seismic and wind performance of anchor bolts, low cycle fatigue (LCF) and high cycle fatigue (HCF) shear and tension experiments were conducted.

Specimen Information

The post-installed anchor used in this experiment had a diameter of 12 mm. In order to compare the adhesion performance of the anchor, non-cracked and artificially cracked (0.3 mm crack and 0.5 mm crack) concrete block was fabricated for installing the anchor (see Figure 5). Table 2 and Table 3 show the anchor bolt and concrete block specification. The total number of specimens were 50 as classified in Table 4.



(a) Non-crack



(b) Cracked

Figure 5. Anchor bolt embedded in non-crack and cracked concrete

Table 2. Mechanical anchor specification

Type	Name	Diameter	Length	Sleeve	Embedded length
Post-installed anchor	M12	12mm	200mm	85.4mm	100mm

Table 3. Concrete block specification

Type	Width	Length	Height
Plain C20/25 concrete block	500mm	500mm	200mm

Table 4. Specimen quantities for each test

Case	Crack		Quantity (EA)			Type of test
	Condition	Width	Shear	Tension	Total	
Case I	non-crack	-	5	5	10	Monotonic and cyclic
Case II	crack	0.3mm	5	5	10	LCF test
Case III	crack	0.3mm	5	5	10	HCF test
Case IV	crack	0.5mm	5	5	10	LCF test
Case V	crack	0.5mm	5	5	10	HCF test

Test Program

Test Setup

In the pull-out experiment, a jig for fixing a concrete block to the reaction force floor of UTM was fastened using F10T M24 high tension bolts, and a concrete block was mounted on the jig and fixed with two steel plates and four F10T M24 high tension bolts. The experiment was performed after fixing the upper part of the anchor bolt using a hydraulic tension grip (see Figure 6a).

(a) Tension (b) Shear

Figure 6. Tension and shear test setup

In the shear test, a shear test jig was fastened to the UTM cylinder, and the reaction force floor as suggested in ACI 355.2, and the concrete block in which the anchor bolts were embedded was placed perpendicular to the ground and fixed to the shear test floor jig. The jig fastened to the cylinder and the anchor bolt were firmly connected, and the anchor bolt fixing plate was fastened. To prevent slipping of the floor jig for the shear test, eight F10T M24 high tension bolts were used to fix the jig to the floor (see Figure 6b).

Test Method

The tension and shear test were conducted according on ACI 355.2 guideline. During cyclic tension and shear loading, if the test specimen was damaged and the load was reduced to a certain level or the load resistance was lost due to severe damage, the test proceeding was stopped. If it was judged that the test specimen will not have any more load resistance due to severe structural damage, the monotonic loading was not performed.

In Case I, a monotonic test with the loading speed of 6.0 mm/min was performed for the first sample of tension and shear test specimens. These tension and shear capacities were the reference for loading in the subsequent tests. The cyclic tests were performed with the remaining 4 specimens. The cyclic tests were conducted with the load intensity 22% of the reference load obtained from the earlier monotonic test. According to ACI 355.2, the loading frequency can be up to 6 Hz. However, the test equipment performance cannot satisfy the 6 Hz load control speed, so the experiment was conducted by lowering it to 1 Hz. During the cyclic loading step, the measurement was not performed normally at the measured sample rate of 10 Hz, so it was adjusted upward to 20 Hz.

Table 5. Case II and Case IV loading method

Loading	**Reference load**	**50% load 10 cycles**	**37.5% load 30 cycles**	**25% load 100 cycles**
Tension	28.06 kN	–14.03 kN	–10.52 kN	–7.02 kN
Shear	24.07 kN	±12.04 kN	±9.03 kN	±6.02 kN

Table 6. Case I, Case III and Case V loading method

Loading	**Reference load**	**22% load n cycles***
Tension	28.06 kN	–6.17 kN
Shear	24.07 kN	±5.30 kN

*Case I cyclic test was repeated until structural damage occurred to the specimens
*Case III and Case V number of cycles for was 4600 cycles for shear loading and 5000 cycle for pull-out loading

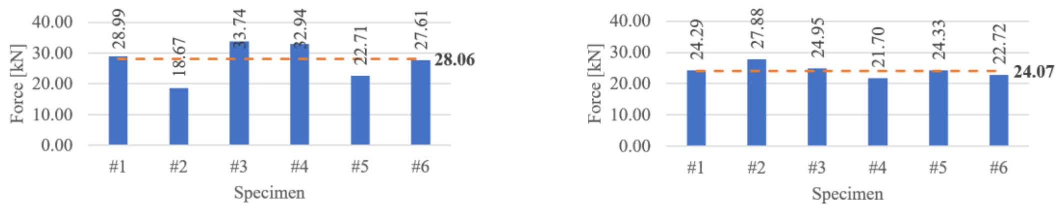
Case II and IV specimens were subjected to a Low Cycle Fatigue (LCF) test. The 3 loading steps suggested by ACI 355.2 were cyclically applied at 0.2 Hz. The applied load has 3 stages which were 50%, 37.5%, and 25% of the reference load from the monotonic test with 10 cycles, 30 cycles, and 100 cycles, respectively (see Table 5). After the cyclic loading was completed, monotonic loading was applied at a speed 6.0 mm/min to determine the residual capacity of the anchor.

Case III and V specimens were subjected to High Cycle Fatigue (HCF) test. Cyclic loading was applied at 22% of the reference load from the monotonic test with the loading speed of 1 Hz. The number of cycles was determined based on the cyclic loading results in Case I, 5000 cycles for tension test and 4600 cycles for shear test (see Figure 4 and Table 6). When the cyclic loading was completed or the load falls below 80% initial applied load, the cyclic loading step was terminated and monotonic loading with a speed of 6.0 mm/min was applied to determine the residual capacity of anchor.

EXPERIMENTAL RESULTS AND DISCUSSION

Monotonic Test

Monotonic test was used to determine the reference load for applying in the cyclic loading based on criteria in ACI 355.2. Six specimens maximum force were shown in Figure 7. The average of 4 samples, excluding the samples with maximum and minimum forces, were 28.06 kN and 24.07 kN for tension and shear test, respective. These values satisfied the criteria in ACI 355.2, which can be used as reference load for subsequent cyclic loading.



(a) Tension (b) Shear

Figure 7. Maximum forces of monotonic tension and shear test

Cyclic Test

As mentioned in the previous section, the cyclic loading test was performed to determine the appropriate number of cycles for HCF test. Figure 8 shows the number of cycles in cyclic tension and shear test. Due to data capture error, there were only 3 specimens for cyclic tension test. Therefore, the number of cycles for HCF test loading pattern (Figure 4) were chosen as 5000 cycles for tension test and 4600 cycles for shear test.

(a) Tension (b) Shear

Figure 8. Number of cycles in cyclic tension and shear test

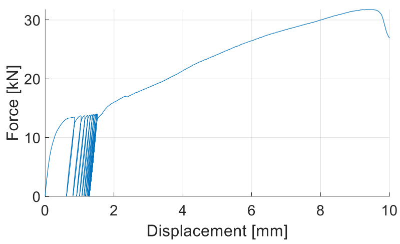
Simulated Seismic Test

Failure shape of specimens after monotonic loading in simulated seismic test can be seen in Figure 9. For tension loading, the concrete failure was shown to be dominant, whereas, for shear loading, the failure occurred on the anchor. Load-displacement curves of simulated seismic test were shown in Figure 10. The tail end of these load-displacement curves was the monotonic test for determining the residual capacity of anchor.

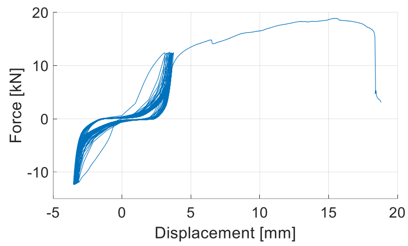
(a) Tension

(b) Shear

Figure 9. Simulated seismic tension and shear test failure shape



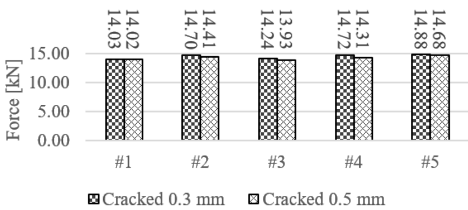
(a) Tension



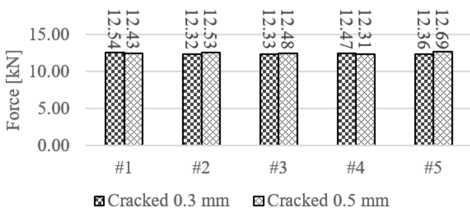
(b) Shear

Figure 10. Simulated seismic tension and shear test load-displacement curves

Maximum forces during cyclic tension and shear load step were shown in Figure 11. After cyclic loading, a monotonic loading was applied to determine the residual capacity of anchor bolt. These residual capacities were shown in Figure 12.



(a) Tension



(b) Shear

Figure 11. Maximum forces of simulated seismic tension and shear test

According to ACI 355.2, for the anchor to be rated the capacity equal to reference load, the residual capacity of anchor must remain above 80% of the reference load after simulated seismic test (ACI Committee, 2002), i.e., 28.06 kN × 0.8 = 22.45 kN for tension loading and 24.07 kN × 0.8 = 19.26 kN for shear loading.

(a) Tension (b) Shear

Figure 12. Anchor's residual capacity after simulated seismic test

For tension test, the difference of anchor maximum force during cyclic load step and their residual capacity was minor. The average maximum force was 14.51 kN and 14.27 kN for specimens with 0.3 mm and 0.5 mm cracked, respectively. The anchor residual force was average to 31.93 kN and 30.69 kN which were greater than the 80% of reference load.

Similarly, for shear test, the average anchor maximum force during cyclic load step was about 12.40 kN and 12.49 kN for specimens with 0.3 mm and 0.5 mm cracked, respectively. This result show that the cracked width simulated in concrete block in this experiment had minor effect on the anchor performance. This minor effect can also be observed in the anchor residual capacity. The residual force was average to 20.08 kN and 19.84 kN for specimens with 0.3 mm and 0.5 mm cracked, respectively. The performance of anchor in these experiments satisfied the criteria in ACI 355.2 to be rated at full capacity.

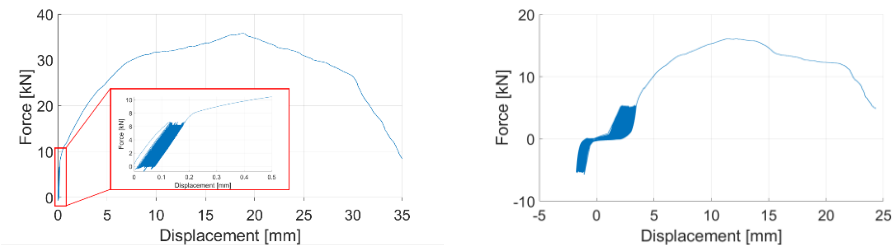
Simulated Wind Test

Failure shape of specimens after monotonic loading in simulated wind test can be seen in Figure 13. Like the failure shape in simulated seismic test, tension loading showed the failure occurred on the concrete block and for shear loading, the failure occurred on the anchor bolt. Load-displacement curves of simulated wind test were shown in Figure 14.

(a) Tension (b) Shear

Figure 13. Simulated wind tension and shear test failure shape

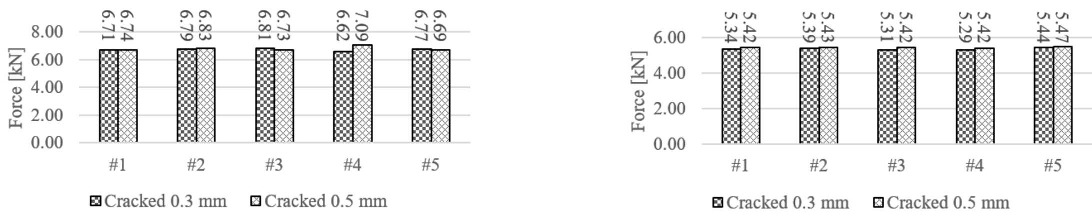
Maximum forces during cyclic tension and shear load step were shown in Figure 15. After cyclic loading, a monotonic loading was applied to determine the residual capacity of anchor bolt. These residual capacities were shown in Figure 16.



(a) Tension (b) Shear

Figure 14. Simulated wind tension and shear test load-displacement curves

For tension test, the difference of anchor maximum force during cyclic load step was minor. The average maximum force was 6.74 kN and 6.82 kN for specimens with 0.3 mm and 0.5 mm cracked, respectively. But there was some difference between their residual capacities which were average to 32.08 kN and 30.23 kN for specimens with 0.3 mm and 0.5 mm cracked, respectively. These residual capacities were greater than the 80% of reference load. Thus, the performance of anchor in tension loading can be rated as full capacity.



(a) Tension (b) Shear

Figure 15. Maximum forces of simulated wind tension and shear test

(a) Tension (b) Shear

Figure 16. Anchor's residual capacity after simulated wind test

For shear test, the average anchor maximum force during cyclic load step was about 5.35 kN and 5.43 kN for specimens with 0.3 mm and 0.5 mm cracked, respectively. This result shows that the cracked width simulated in concrete block in this experiment had minor effect on the anchor performance. However, the average residual capacity of anchors, as shown in Figure 16b, was significantly different for specimens with 0.3 mm and 0.5 mm cracked which were 5.56 kN and 8.92 kN, respectively. These residual capacities also lower than the 80% of reference load require to be rated as full capacity. Although no additional tests were done with reduced maximum simulated wind load (V_C), these results showed that anchor failure in simulated wind load test was more critical in shear loading condition.

SUMMARY AND CONCLUSION

This study proposed an experimental method to simulated wind-induced vibration. Additionally, an experimental program to verify the behavior of anchor system according to the existing guideline in conjunction with this proposed methodology was also conducted. Model of a simplified 5-stories concrete building was used to determine the ratio of deformation due to seismic load and dynamic wind load of the anchors in the connection between the sign structure and the concrete building. Comparing this ratio with the existing simulated seismic test guideline, a loading protocol which aimed to simulate the dynamic wind load was proposed. The loading pattern and intensity of this proposed method can be seen in Figure 4 and Table 6.

Through this proposed method and ACI 355.2, an experimental program was conducted to study the post-installed anchor system performances under dynamic loads when exposed to extreme loading events such as typhoon and earthquake. A total of 50 specimens was used to conducted four types of tests. Two preliminary tests (monotonic and cyclic test) were used to determine the required parameters for simulated seismic test and simulated wind test. Results of the experiment showed that:

- Crack width of concrete in simulated seismic test did not affect the performance of anchor. Their maximum force as well as residual capacity show practically the same value. Moreover, anchor used in this experiment satisfied the condition to be rated as full capacity for seismic performance.

- In case of simulated wind tension test, the crack width also did not cause the difference in performance of the anchor. Only a small difference for their residual capacity after the cyclic load regime. However, for shear test, there was a major difference for the anchor residual capacity. Moreover, the performance of anchor in simulated wind test does not satisfy the criteria to be rated as full capacity.

This study used a simplified model to determine the parameters for dynamic wind test. Additional field data for calibration was recommended to improve the reliability and accuracy of the proposed protocol. Numerical model should be developed to characterize the performance of anchor embedded in concrete under dynamic wind.

ACKNOWLEDGMENTS

This research was supported by Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education (2021R1A6A1A03044326).

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