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Review Article

Performance Evaluation of Precast Pretensioned Hollow Core Slab Units by Loading Test

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Abstract

Strength evaluation of building components by analysis and in-place load testing is recommended in cases where the degree of suspected deficiencies in design, materials or construction cannot be readily determined. In the study, the purpose of the tests was to evaluate the performance of prestressed concrete hollow core slab (HCS) units carrying dead and live loads as composite members with topping concrete. The first test was conducted on HCS-300 panels, some of which were already installed in the buildings. A monotonic loading test on the ground at the construction site was performed on a non-composite panel to evaluate the actual composite panel's performance. In accordance with the project's quality procedures, to verify the performance of the HCS-400 panels, the second test was decided to be performed on HCS-400 composite panels in the precast plant prior to starting the mass production. The paper describes the application of monotonic loading test procedures and acceptance of test results according to the American ACI 318 standard.

Keywords: Loading Test, Precast Prestressed Hollow Core Units, Performance Evaluation.

1. INTRODUCTION

Prestressed hollow core precast products are designed to withstand the specified design loads in accordance with applicable industry design standards ACI 318 [1], PCI MNL-120 [2], and PCI MNL-126 [3].

This paper presents the application and interpretation of the evaluation criteria adopted for the assessment of in-situ load tests performed on two prestressed hollow core slab panels, namely HCS-300 and HCS-400, manufactured for use in reinforced concrete building floor slabs. The reason for the first performance test was that some of the floor panels had been stored on site for over a year and the quality of the panels was questionable on visual inspection. It was decided that the second test would be carried out to verify the performance of the panels in accordance with the project's quality procedures.

The American ACI 318 [1], and ACI 562 [4], standards are applicable to the evaluation of an existing structure prior to repair. While ACI 318 was developed to provide minimum design requirements for new concrete structures, ACI 562 was specifically created as a performance-based code for the evaluation of existing structures prior to repair. However, because ACI 562 refers extensively to ACI 318 for design procedures for structural repairs, the documents are complementary and both can be used to evaluate an existing structure prior to repair.

The American Concrete Institute (ACI) addresses in-situ load testing in two standards: a) ACI 318 "Building Code Requirements for Structural Concrete", which adopts a monotonic (24 hour) load test, and b) ACI 437 "Code Requirements for Load Testing of Existing Concrete Structures", which adopts both the cyclic load test (CLT) and a modified version of the monotonic (24 hour) load test. However, there are notable differences in load magnitudes and acceptance criteria between ACI 318-14 [1], and ACI 437.2-13 [5]. These differences were removed in ACI 318-19 [6], by incorporating all of ACI 437.2 into ACI 318-19. The test load magnitude is unified, the monotonic acceptance criteria are unified and cyclic testing is included by reference to ACI 437.2. More detailed information can be found in El Batanouny *et al.*, [7, 8].

The first test was performed on HCS-300 panels that were partially installed in the buildings. However, most of the remaining ones had been stored at the construction site and in direct sunlight for over a year. A field loading test on non-composite panels was decided to evaluate the performance of the panels. In addition, it was decided to conduct a second test on HCS-400 panels at the precast plant to verify the panels' performance according to the project's quality procedures prior to starting mass production. The test unit was composed of three HCS-400 panels made of composite with topping concrete.

Both tests were performed under the supervision of a third-party testing company according to an approved method statement. The test protocol was chosen based on a 24-hour-duration uniformly distributed static load, at a magnitude determined as a ratio of the design load, as defined in the ACI 318M-14 Building Code. Application of the load testing procedure and acceptance of test results were carried out according to the ACI 318M-14 standard.

2. Description of Non-composite (Isolated) HCS-300 Panel Test

Design and testing of the 300 mm thick hollow core slab (HCS) panel with cross section shown in Figure 1 were performed in accordance with References [1-9]. The HCS panel was placed on concrete supports to provide a 9.90 m clear span. Neoprene pads at both ends of the slab were placed simulating the actual support conditions. The test slab unit was supported by solid concrete blocks previously prepared for tower crane stability at the site. Deflection readings were taken at three locations but with six dial gauges which were positioned closer to each end and in the middle of the slab unit. Prior to the test, readings were taken at each end of the slab and in the center and the test unit was visually inspected by third party test company engineer.

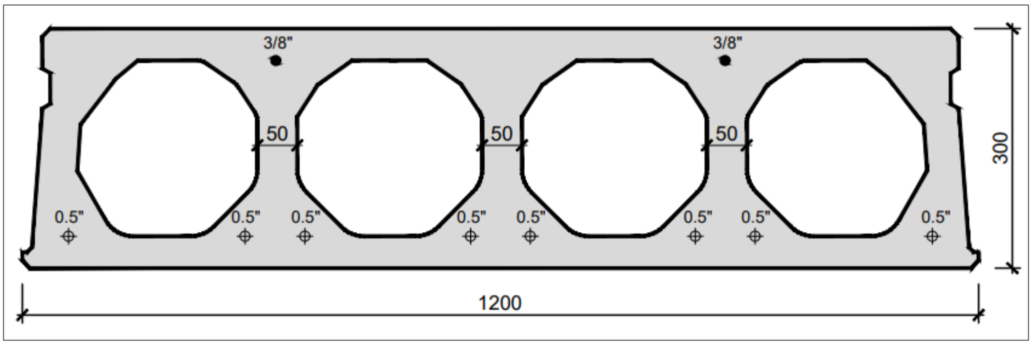

Figure 1: Non-composite (Isolated) HCS-300Panel Cross Section

3. Description of Composite HCS-400 Panel Test

Design and testing of the 400 mm thick hollow core slab (HCS) with cross section shown in Figure 2 were performed in accordance with References [1-9]. For testing purposes, three HCS panels were placed on concrete supports to provide a 10.16 m clear span. Neoprene pads at both ends of the panels were placed simulating the actual support conditions. The test slab unit was supported by solid concrete blocks available at precast manufacturing plant. For the composite panel test, the precast manufacturer preferred to execute testing on three composite panels integrated to each other to better simulate the actual condition. Three HCS units were monolithically integrated with 60mm topping concrete including single layer of rebar cage. Deflection readings were taken at three locations but with six dial gauges which were positioned closer to each end and in the middle of the slab unit. Prior to the test, readings were taken at each end of the slab and in the center and the test unit was visually inspected by third party test company engineer.

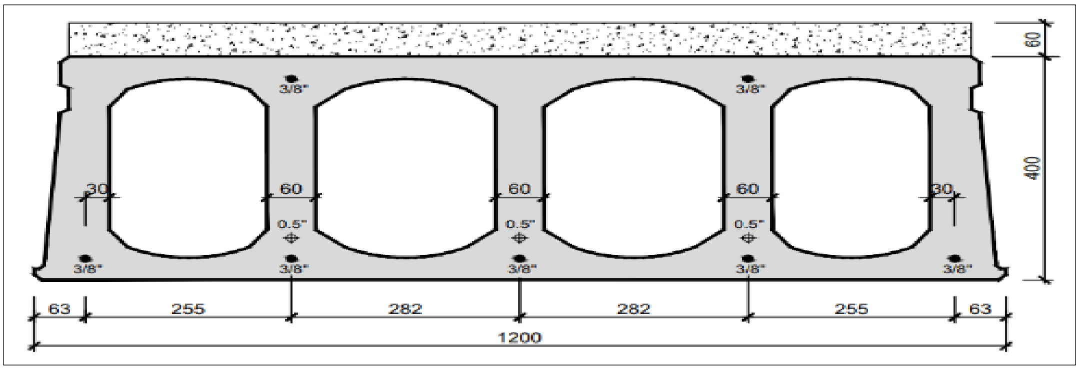

Figure 2: Composite HCS-400 Panel Cross Section

4. Test Loads (ACI 318-14)

The minimum total test load magnitude as defined in the ACI 318-14 Chapter 27.4.2.2. The total test load, T_t, including dead load already in place, shall be at least the greatest of Equations (4a), (4b), and (4c):

$Tt = 1.15D + 1.5L + 0.4\ (L_r \text{ or } S \text{ or } R)$ (Eq. 4a)
$T_t = 1.15D + 0.9L + 1.5\ (L_r \text{ or } S \text{ or } R)$ (Eq. 4b)
$T_t = 1.3D$ (Eq. 4c)

Where, *D* and *L* are the design dead and live loads, respectively. (L_r=roof live load, S=snow load, R=rain load)

Before commencing the test, the slab design trials corresponding to each load stage and both non-composite and composite slabs were conducted. These trials were executed using a commercial software [9].

The load level was determined based on ACI 318-14 Clause 27.4.1.4 in which the test requirements are as follows:

A precast member to be made composite with cast-in-place concrete shall be permitted to be tested in flexure as a precast member alone in accordance with (a) and (b)

a) Test loads shall be applied only when calculations indicate the isolated precast member will not fail by compression or buckling.
b) The test load, when applied to the precast member alone, shall induce the same total force in the tensile reinforcement as would be produced by loading the composite member with the test load in accordance with ACI 318-14 Section 27.4.2.

4.1. 24-hour-Uniformly-Distributed Load Test (Isolated HCS-300 Panel)

As per approved design of the building structural calculation, the HCS is subject to total D=9.34kN/m and L= 6.0kN/m dead and live loads, respectively. Self-weight of the HCS panel is 4.50kN/m and therefore the most unfavorable total test load is determined to be:

T_t = (1.15x9.34 – 4.50) + 1.5x6.0= 15.24kN/m

Taking into consideration of the requirement (b) above, the test load to be applied to the precast member alone was determined to be around 90 % of the load considered in design of composite panel. Finally, total test load was determined to be 0.90x15.24= 13.72kN/m. The ratio of the isolated precast panel area to the composite panel area and the ratio of the bottom section modulus are both around 0.78.

It was decided to load the slab uniformly using precast hollow concrete blocks available on the site. The blocks have dimensions of 1200x1000x150mm. The weight of each block was 269 kg (2.74kN). The test slab was marked off with 9 equal spaces. Since the slab was nominally 1200 mm wide, each of the 9 rectangles represented 1.32 m^2. The total number of concrete blocks was decided to be 48 and the final load stage in six layers (rows) is shown in Figure 3. One layer of block placed on the slab within these rectangles would represent 2.49kN per linear meter.

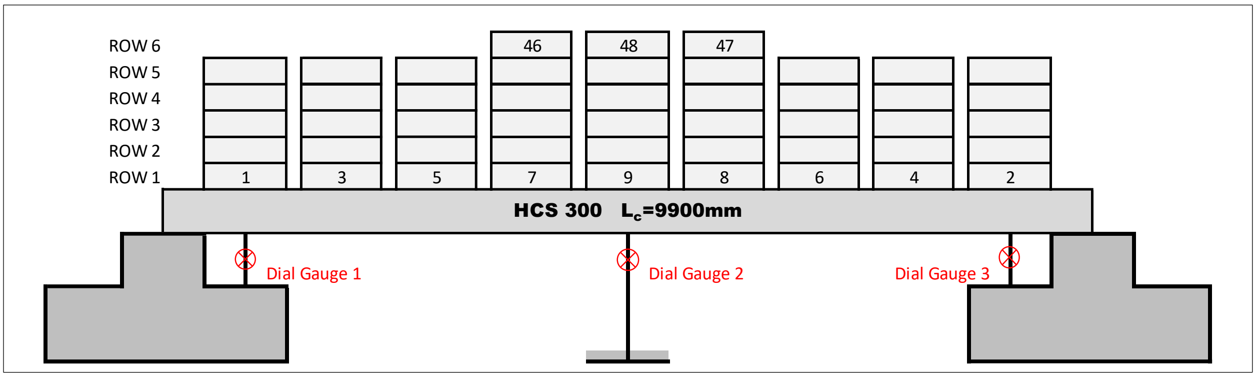

Figure 3: Final Load Stage and Dial Gauge Locations

4.2. 24-hour-Uniformly-Distributed Load Test (Composite HCS-400 Panel)

As per approved design of the building structural calculation, the HCS is subject to total D=13.86kN/m and L=2.40kN/m dead and live loads, respectively. Self-weight of the HCS panel is 5.34kN/m, topping concrete is 1.80kN/m and therefore the maximum total test load is determined to be:

T_t = (1.15 x13.86 – 5.34 – 1.80) +1.5x 2.4= 12.40kN/m.

It was decided to load the slab uniformly using precast hollow concrete blocks available on precast manufacturing plant. The blocks have dimensions of 1200x1000x150mm. The weight of each block was 269kg (2.74kN). 1200x2000x150mm double-sized blocks were also available, each weighing 538kg. The test slab (composed of adjacent three HCS panels) was marked off with 10 equal spaces. Since the single slab was nominally 1200mm wide, each of the 10 rectangles represented 1.22 m^2. The total number of concrete blocks for the one slab was decided to be 48 and the final load stage in five layers (rows) is shown in Figure 4. One layer of block placed on the slab within these rectangles would represent 2.70kN per linear meter.

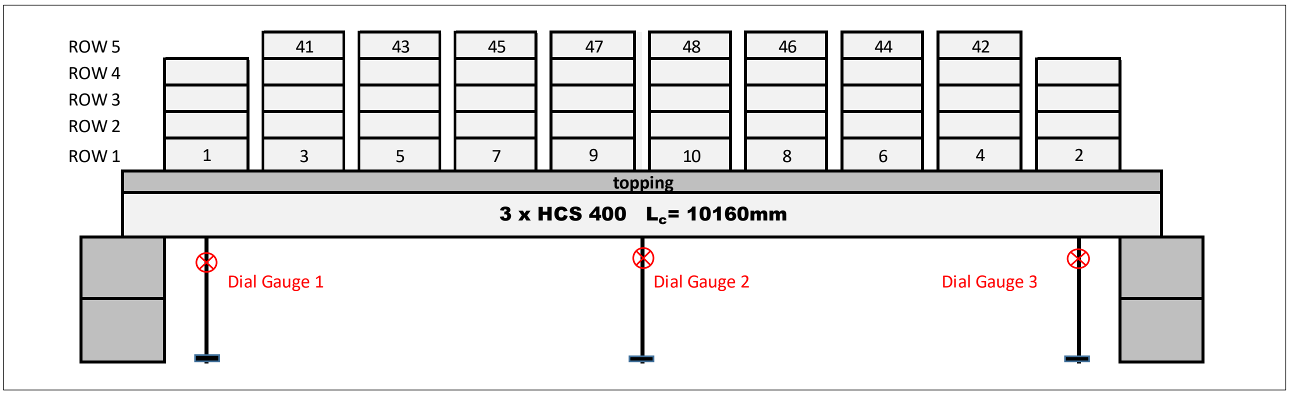

Figure 4: Final Load Stage and Dial Gauge Locations

5. Load Test Protocol (24-Hour-Uniformly-Distributed Load Test)

The 24-hour load test consists in the monotonic loading of the structure up to the designed load level followed by a phase in which the load is sustained for a time period of at least 24 hours. Chapter 27 of the ACI 318-14 Building Code prescribes that the load must be arranged to maximize the deflections and stresses in the critical regions of the structural elements under investigation.

Once the structure is conveniently instrumented (where maximum response is expected), initial values of each instrument are to be recorded not more than 1 hour before the application of the first load increment. After the test is started, the load must be applied in not less than four approximately equal increments. If the measurements are not recorded continuously, a set of response readings should be registered at each of the four load increments until the total test load has been reached, and after the test load has been applied on the structure for at least 24 hours. Once the aforementioned readings have been taken, the test load must be removed and a set of final readings must be made 24 hours after the test load is removed.

6. Acceptance Criteria (ACI 318M-14)

Two different set of acceptance criteria are described in order to establish whether the tested member has passed or not the load test. The first one is based on a set of visual parameters: no spalling or crushing of compressed concrete or evidence of excessive deflections that would not meet the safety requirements of the structure are allowed. The second one is based on the measurement of the maximum deflections.

One of the following two equations, (Eq. 6a) or (Eq. 6b), shall be satisfied:

$$\Delta_1 \leq \frac{\ell_t^2}{20,000h} \quad \text{....(Eq. 6a)}$$

$$\Delta_r \leq \frac{\Delta_1}{4} \quad \text{....(Eq. 6b)}$$

Where, h and l_t are the height and the span of the tested member in mm, respectively.

Δ_1= maximum deflection, during first load test, measured 24 hours after application of the full test load, mm

Δ_r = residual deflection measured 24 hours after removal the test load. For the first load test, residual deflection is measured relative to the position of the structure at the beginning of the first load test. For the second load test, residual deflection is measured relative to the position of the structure at the beginning of the second load test, mm.

If Eq. (6a) or (6b) above is not satisfied, it is permitted to repeat the load test but not earlier than 72 hours after the removal of the first test load. Portions of the tested structure in the repeat (second) test shall be considered acceptable if deflection recovery satisfies the following condition.

$$\Delta_r \leq \frac{\Delta_2}{5} \quad \text{....(Eq. 6c)}$$

Δ_2 = maximum deflection, during second load test, measured 24 hours after application of the full test load. Deflection is measured relative to the position of the structure at the beginning of the second load test, mm.

7. Performance of Precast HCS Panels

The test blocks started to be placed from one end of the test HCS unit towards the middle of the unit. After each layer of block was placed on the slab, deflection readings were taken. The slab unit was inspected visually for any cracking during each block placement.

The isolated HCS panel test was stopped under 45 blocks since cracking initiated at several locations in mid region of the test panel and deflection measured was much more than the calculated.

The composite HCS panel test was performed as per the approved method statement under full loading.

8. Loading Test Results

As the ACI 318-14 code specifies the final load was decided to be left on the structure for 24 hours.

8.1. Isolated HCS-300 Panel Test

Table 1 shows deflections both measured in the load test and obtained from the commercial software [9], for prestressed concrete design. Once the cracking was started under 45 blocks the test was stopped and final deflection readings were taken. At this stage the load was 12.10kN per linear meter and mid deflection was measured to be 36.79mm. As shown in Figure 5, it is interesting to note that the measured deflections were in very good agreement with the calculated deflections based on composite section properties till load level of 9.68kN/m (4 layer =36 blocks). However, sudden change due to crack initiation occurred between 4-5 layer loading and the deflection was measured around estimated deflection for non-composite section under 5-layer load which corresponds to 12.10kN/m. Table 2 shows the ACI 318 element classification according to the tension at bottom fiber of isolated HCS panel.

Table 1: Design and Measured Deflections

DEFLECTION (mm)			
LOAD (kN/m)	NON-COMPOSITE	COMPOSITE	TEST
2.42	-5.90	-3.60	-3.95
4.84	-14.40	-8.80	-8.80
7.26	-22.80	-14.00	-13.62
9.68	-31.30	-18.10	-18.69
12.10	-39.80	-24.30	-36.79
14.50	-49.40	-29.50	-
16.94	-87.00	-34.70	-

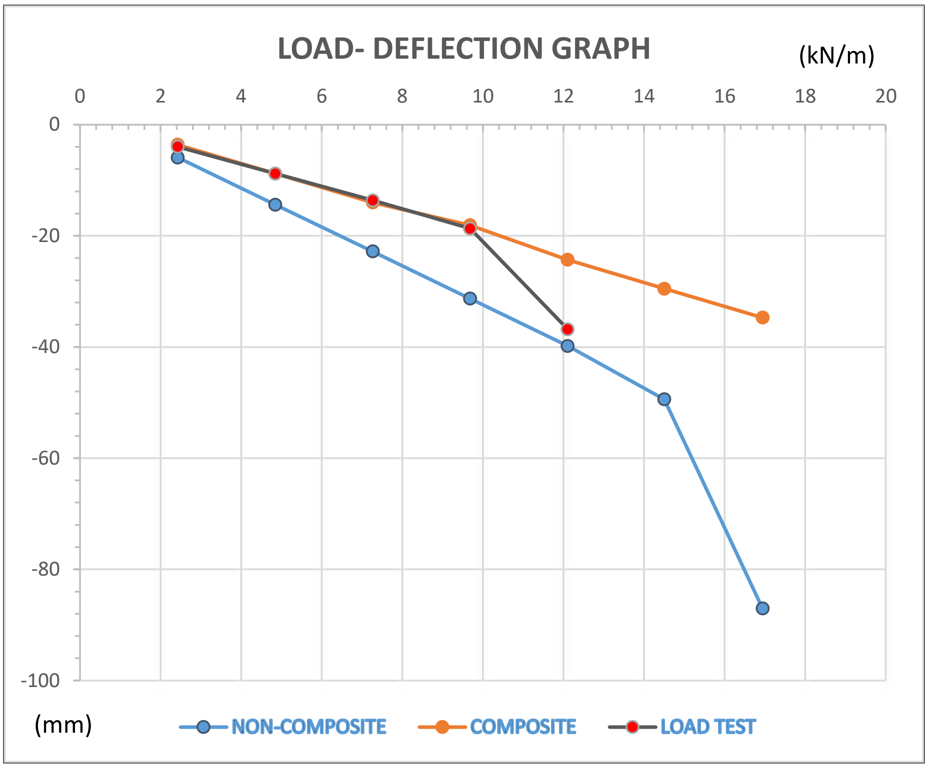

Figure 5: Load–deflection Curves for Non-composite Design, Composite Design and Test Load

Table 2: Tension at Bottom of Isolated HCS Panel

LOAD (kN/m)	NON-COMPOSITE	COMPOSITE
2.42	-	-
4.84	-	-
7.26	-	-
9.68	-0.30*	-
12.10	-2.25*	-
14.50	-4.20*	-1.50*
16.94	-6.20**	-4.50*

* Class U member - not cracked
** Class T member - cracking controlled

As ACI 318-14 specifies the final load was decided to be left on the structure for 24 hours. The measured mid deflection was increased to 43.47mm under full load for 24 hours and more cracks were appeared in the test panel. The crack widths were more than 0.5mm. Following, the blocks were removed to determine the recovery. In this case, the measured mid deflection was reduced to 7.56mm. After 24-hour unloading the mid deflection was measured as 3.74mm.

According to the ACI 318, the maximum permissible deflection, (Eq. 6a), was calculated to be 16.34mm. The total deflection under 45 blocks, Δ_1 = 43.47mm was found unsatisfactory as it was more than 2.5 times greater than the reference criteria. The residual deflection, Δ_r = 3.74 mm is within the limit Δ_1 / 4 = 43.47 / 4 = 10.87mm. Therefore, it satisfies the deflection criteria of (Eq. 6b).

Based on the ACI 318 evaluation criteria the test can be concluded as satisfactory because one of the criteria was found to be satisfactory. However, isolated HCS unit was deemed unacceptable for the following reasons: almost full depth cracking occurred in the test unit at several locations near the mid-span, the number of crack locations further increased, the cracks propagated during the 24-hour test and, the test was stopped at an incomplete load level (F45 units). The mid-span cracks occurred under final stage of loading is shown in Figure 6.

Figure 6: Mid-span Cracks under 45 Block Loading

8.2. Composite HCS-400 Panel Test

The measured mid deflection was 8.81mm maximum and increased to 9.15mm under full load for 24 hours. No crack was appeared in the test panel. Following, the blocks were removed to determine the recovery. In this case, the measured mid deflection was reduced to 1.84mm. After 24 hours the mid deflection was measured to be 0.58mm.

According to the ACI 318-14, the maximum permissible deflection, (Eq. 6a), is calculated to be 11.22mm. Total deflection under full loading, Δ_1, was measured less than the criteria and therefore it was found satisfactory. The residual deflection, Δ_r = 0.58mm is rather smaller than the limit Δ_1 / 4 = 9.15 / 4 = 2.29mm. Therefore, it also satisfies the deflection criteria (Eq. 6b).

Figure 7 shows the experimentally measured deflection values and calculated values from commercial software [9]. The experimentally obtained deflection is about half of the calculated value. Calculated long-term prestress losses (creep, shrinkage, relaxation, etc.) were thought to contribute to the differences.

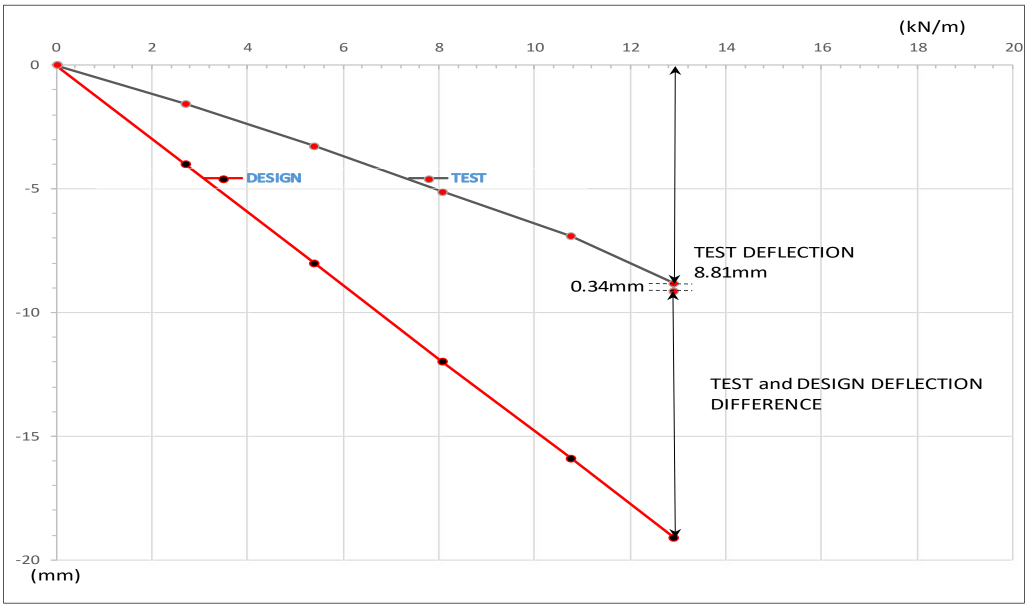

Figure 7: Load–deflection Curves for Composite Design and Test Load

9. Test Loads and Acceptance Criteria (ACI 318M-19)

The ACI 318M-19 had not yet been published at the time of conducting the field tests and finalizing the evaluations. The requirements of the recent ACI 318M-19 code are briefly given below to provide a better understanding of implications and applicability of each test method.

9.1. Test Loads (ACI 318M-19)

The total test load, T_t, including dead load already in place, shall be at least the greatest of Equations (9a), (9b), and (9c):

$T_t = 1.0D_w + 1.1D_s + 1.6L + 0.5\ (L_r\ or\ S\ or\ R)$ (Eq. 9a)
$T_t = 1.0D_w + 1.1D_s + + 1.0L + 1.6\ (L_r\ or\ S\ or\ R)$ (Eq. 9b)
$T_t = 1.3(D_w + D_s)$ (Eq. 9c)

Where, D_w is the load due to self-weight of the concrete structural system and D_s is the superimposed dead load. ACI 318-19 treats dead loads from self-weight and superimposed dead load separately. The live load, L, may be reduced by the general building code governing safety considerations for the structure.

Taking into consideration of self-weights of the HCS panels the most unfavorable total test loads are determined from Eq. 9a as the following:

For isolated HCS 300 test, T_t = 14.92 kN/m (2% less than ACI 318-14 test load level)

For composite HCS 400 test, T_t = 11.23 kN/m (9% less than ACI 318-14 test load level)

9.2. Acceptance Criteria (ACI 318M-19)

The first acceptance criteria based on a set of visual parameters in ACI 318-19 are the same as for ACI 318-14: the portion of the structure tested shall show no spalling or crushing of concrete, or other evidence of failure.

The second acceptance criteria for the test in ACI 318-19 are different than that of ACI 318-14. For the structure to pass the load test, the residual deflections shall satisfy the limit in (Eq. 9d). In other words, if the structure shows no evidence of failure, recovery of deflection after removal of the test load is used to determine whether the strength of the structure is satisfactory.

If the maximum deflection measured during the test, Δ_l, does not exceed (Eq. 9e) the residual deflection requirement shall be permitted to be waived.

$$\Delta_r \leq \frac{\Delta_1}{4} \quad \text{(Eq. 9d)}$$

the larger of 1.3mm or l_t /2000 (Eq. 9e)

If either Equation (9d) or Equation (9e) is not satisfied, it shall be permitted to repeat the load test. Portions of the structure passes the repeated test if the residual deflection of this test, Δ_r, is less than one-fifth of the maximum deflection, Δ_2, as shown in Equation 9f.

$$\Delta_r \leq \frac{\Delta_2}{5} \quad \text{(Eq. 9f)}$$

For both the HCS 300 and HCS 400 tests, as shown in the above sections, the residual deflections are smaller than the requirement in Eq. 9d. Based on the ACI 318-19 evaluation criteria the tests can be concluded as satisfactory. However, isolated HCS 300 unit was deemed unacceptable due to the poor performance of almost full depth cracking occurred in the test unit at several locations near the mid-span.

CONCLUSIONS

The ACI 318 code clearly states that the evaluation criteria are valid if the structure shows no evidence of failure in the test. In this respect, the performance of the HCS-300 panel was considered unsatisfactory, mainly due to excessive deflection and the occurrence of several cracks in the mid-span of the panel.

It was recommended that the precast producer take the following actions:

1) Rather than using the ACI 318 code equations based on the compressive strength of the concrete, perform beam load tests and concrete splitting tests to determine the actual modulus of rupture (tensile strength) of the concrete.
2) Limit the tensile stresses in the design of the member away from the allowable limits of the code.
3) Verify the performance of the HCS panels by performing load tests at specified intervals and take the necessary measures to improve performance.

The composite HCS-400 panel test was concluded to be satisfactory since both criteria (set of visual parameters and the test results) were found satisfactory and there was no evidence of cracking at all.

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