# In-Situ Load Testing: A Theoretical Procedure to Design a Diagnostic Cyclic Load Test on a Reinforced Concrete Two-Way Slab Floor System

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**Abstract.** The objective of this paper is to showcase to an engineer who is considering performing a diagnostic cyclic load test a theoretical procedure for determining the patch load, which when applied to a two-way reinforced concrete (RC) slab floor system would generate internal forces at critical locations equal to those resulting from the uniformly distributed load. This procedure should also help the practitioner to define a representative model of the structure and to update the magnitude of the target load at the end of each loading and unloading cycle by means of a real-time evaluation of boundary conditions and slab stiffness. The routine to design a cyclic load test is described theoretically first and then validated with the results of a load test on a concrete two-way RC slab floor system.

## Introduction

The current role of testing within structural engineering has gained increasing importance, as it can now be applied to every phase of the structure's life because of innovative materials and new design approaches. By focusing on either the preliminary testing of a new structure or the necessary control checks prior to assessing the strength of an existing one, in-situ load testing can determine the real behavior of the structure under the existing loading conditions. Accordingly, researchers can have an overall, accurate understanding of the mechanical properties of the structural members. In the United States of America, the current American Concrete Institute (ACI) 318 Building Code [1] provides requirements for load testing of concrete structures. ACI Committee 437 [2] proposes a diagnostic cyclic load (DCL) testing procedure consisting of the application of patch loads in a quasi-static way to the structural member according to loading and unloading cycles. Patch load magnitude and distribution shall simulate the uniformly distributed load defined in the ACI 318 Building Code. The DCL protocol [3,4] defines three acceptance criteria that can be easily computed, in real time, for any structural member by simply checking its behavior under the test load (see Fig. 1 for necessary notation).

*Repeatability* and *Permanency* represent the behavior of the structure during two identical load cycles; *Deviation from linearity* represents the measure of the nonlinear behavior of a member being tested.

$$\text{Repeatability} = \frac{\Delta^{B}_{max} - \Delta^{B}_{r}}{\Delta^{A}_{max} - \Delta^{B}_{r}} \times 100\% \geq 95\% ; \qquad (1)$$

$$\text{Permanency} = \frac{\Delta^{B}_{r}}{\Delta^{B}_{max}} \times 100\% \leq 10\% ; \qquad (2)$$

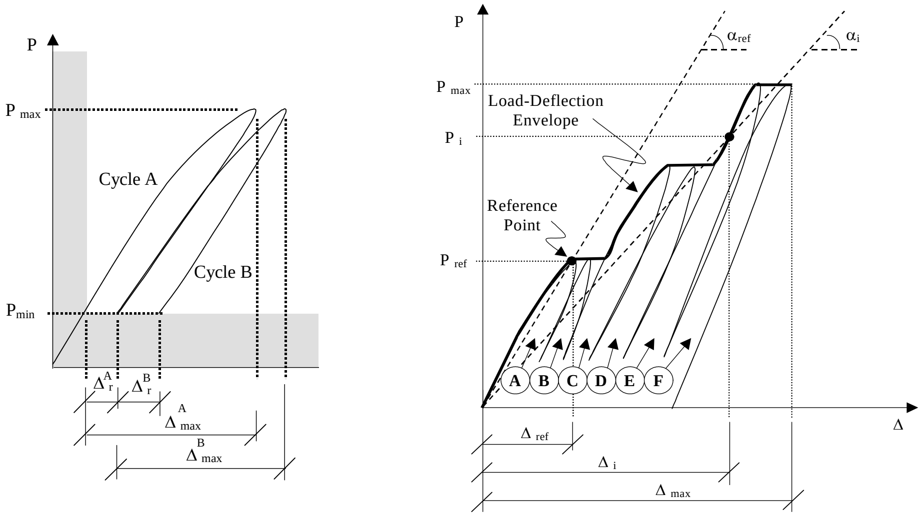

Fig. 1 – Schematic Load vs. Deflection plot for computing the acceptance criteria

$$\text{Deviation from Linearity}_{\,i} = 100\% - \frac{tan(\alpha_i)}{tan(\alpha_{ref})} \times 100\% \leq 25\% . \qquad (3)$$

The limit value indicated in all three criteria, have been set by experience [4] and have been calibrated for test loads with magnitude close to ultimate condition.

## Load Test Procedure

The intellectual and practical procedure the practitioner performing a cyclic load test should follow has been split into six fundamental phases by Masetti [5]. They can be slightly changed if the load test is performed on a two-way reinforced concrete (RC) slab floor system. The six phases are outlined in the following lines.

**Phase 1: Geometry and Material Characterization.** Prior to carrying out a load test on any type of structure, one must have a detailed understanding of the structure in terms of materials, geometries, and the loading history throughout its entire “service life”.

**Phase 2: Selection of the Type of Load Test.** Once the preliminary investigation has been carried out, the choice of the type of load test should be made. One needs to determine the method for the load application to select the type of patch load that could simulate the effect of a uniformly distributed load, to determine the type of the instrumentation to be used, and to select the location in which the structural response has to be monitored.

**Deflections and Rotations Measurement.** Choosing the position where the instrumentation is to be installed is a critical issue. The deflected shape of the structure will be defined by measuring deflections and rotations in a reasonable and helpful number of locations; the more diligent the choice of those locations, the more accurate the approximation of deflected shape. Measurements of rotations near the columns and deflections where the load is applied should be very accurate. The practitioner could take advantage of symmetry wherever possible.

**Phase 3: Independent Assessment by the Load-Test Engineer.** The practitioner should perform a structural analysis, following the current code, to have a realistic and up-to-date evaluation of the ultimate capacity of the investigated structure. One needs to define the magnitude of the uniformly distributed test load. Typically, the owner requests the target distributed load to rate the structure. In any case, after selecting the type of internal forces that mostly affect the selected member, the section capacities should be determined according to ACI 318, and the ultimate distributed load should be evaluated for the governing section capacity.

**Punching Shear Checks**. Since the load is applied by a hydraulic jack to reproduce a concentrated force, the load is applied to the RC slab by means of a steel plate and a plywood board to avoid any localized damage. Punching shear shall be checked in the area where the load is applied. The shape of the footprint shall be similar to that of the tested structure; if we say *l*, the minimum dimension of the tested slab, and *a*, the side of the footprint, the ratio *a/l* could be equal to about 1/10.

**Phase 4: Determination of the Magnitude of the Equivalent Patch Load.** Once the practitioner has gathered all the information from the previous phases, he or she should define the magnitude of the equivalent patch load after the boundary conditions and the stiffness of the structure have been evaluated. The idea is to define a patch load magnitude that generates internal forces at critical locations equal to those resulting from the uniformly distributed load. Generally, the distribution of internal forces in the two types of load test (uniformly distributed load vs. patch loads) is different, so maximizing both bending moments and shear forces at the same time is not possible.

**Phase 5: Load Test Performance.** A load test has to be performed adopting safety procedures that have to take into account the consequences of a partial or complete collapse of the tested structure. During the data recording phase, a real-time evaluation of the structural response is possible and allows researchers to constantly monitor the overall site safety, to continuously adjourn the required test load, and to estimate the acceptance criteria parameters after each twin cycle.

**Phase 6: Interpretation of the Data.** Once all the data are gathered, the load test practitioner has to analyze them and make a “diagnosis” for the tested structure. He or she has to specify not only whether the load test failed or not, but also the reasons for an eventual test failure.

## Determination of the Magnitude of the Equivalent Patch Load

**Preliminary Analysis.** The tested slab is modeled by the Finite Difference Method (FDM): it is isolated from the continuous floor system and it is thought to be connected to the rest of the structure by means of translational and rotational springs distributed along the edges. Springs are supposed to have a linear elastic behavior. Stiffness of each spring is defined in each single node along the edges (see **Error! Reference source not found.**).

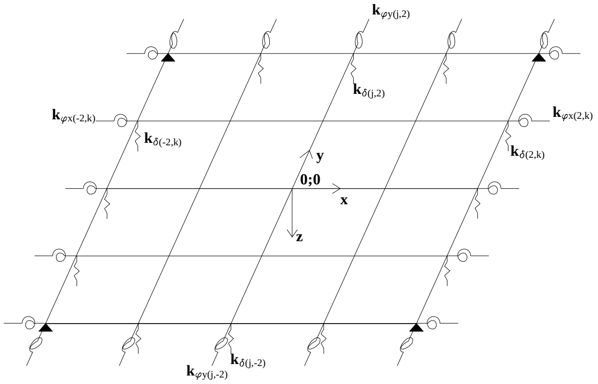

Fig. 2 – FDM tested slab model with a distribution of translational and rotational springs along the edges.

Slab stiffness along the edges can be computed in the field by running a small load cycle up to a predetermined load, which shall be decided by the engineer to assure safety without compromising the structural integrity. By interpolating measured deflections and rotations in selected nodes, we know deflections in all inner nodes so that we can evaluate the distribution of bending moments and shear forces along the edges. After defining deflections, rotations, bending moments and shear forces along the edges, we can evaluate spring stiffness for each node.

**First estimation of the patch load magnitude.** Since springs stiffness along the edges of tested slab are known the target patch load for the first twin loading/unloading cycles can be estimated. Two different load conditions have to be considered:
1) a uniformly distributed load $q_{TL} = 0.85(1.4DeadLoad + 1.7LiveLoad)$;
2) a uniformly distributed load q = DeadLoad and a patch load $F_{PL}$ applied in the middle of the slab. Patch load magnitude is unknown. By solving the slab (modeled as in **Error! Reference source not found.**) under the two different load conditions by FDM, we can evaluate the entity of the internal forces *S* that mostly affect the selected member for both load cases. For cases 1 and 2 we have, respectively, $S_{UL} = \alpha(K_{\varphi}, K_{\delta}, l_x, l_y, E_c, s)\cdot q$ , and $S_{PL} = \beta(K_{\varphi}, K_{\delta}, l_x, l_y, E_c, s)\cdot F_{PL}$ . FDM allows us to solve the problem of deflection of slab even if the magnitude of the patch load is unknown.
Since we are looking for a magnitude of patch load that generates internal forces at critical locations similar to the ones generated by the uniformly distributed load in the initial design of the member, we can say that $S_{UL} = S_{PL} \Rightarrow \quad F_{PL} = \alpha(K_{\varphi}, K_{\delta}, l_x, l_y, E_c, s)\, q \,/\, \beta(K_{\varphi}, K_{\delta}, l_x, l_y, E_c, s)$.

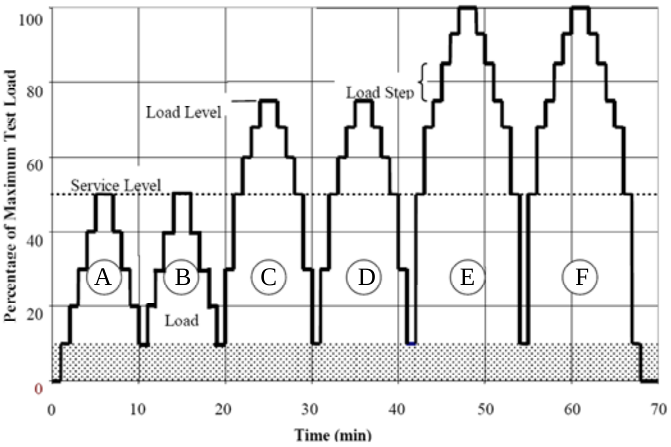

Fig. 3 - Load steps and cycles for a cyclic load test

Once the maximum load $F_{PL}$ is determined, then the load test was performed according to the protocol indicated by ACI 437R-03 [2]. Six increasing loading and unloading cycles are determined: the first two at approximately 50% of $F_{PL}$, the third and fourth at 75% of $F_{PL}$, and finally the fifth and sixth cycles reaching $F_{PL}$ (see Fig. 3).
**Execution of the first twin cycles.** During the first two loading/unloading cycles, the slab is loaded up to $0.50F_{PL}$. When the structure is unloaded, deflections and rotations have to be measured in chosen locations. Deflections and rotations for all inner nodes and the distribution of bending moments and shear forces along the edges have to be evaluated by means of interpolation.
**Updating of slab stiffness.** Values of translational and rotational springs stiffness along the edges can be updated at the end of the first twin cycles. A new evaluation can take in account possible non-linear behavior of slab near the column.
**Second estimation of the patch load magnitude.** New current values for slab stiffness along the edges allow us to define a new target patch load, $F_{PL}^{II}$. The same procedure used for defining $F_{PL}^{I}$ in the first two cycles has to be followed.

**Execution of the second twin cycles.** Cycles 3 and 4 will be leaded up to 0.75 $F_{PL}^{II}$. When the structure is unloaded, deflections and rotations have to be measured again in chosen locations. Deflections and rotations for all inner nodes and the distribution of bending moments and shear forces along the edges have to be evaluated by means of interpolation.

**New updating of slab stiffness.** Slab stiffness has to be updated again at the end of the second twin cycles.

**Third estimation of the patch load magnitude.** New current values for slab stiffness along the edges allow us to define the final target patch load, $F_{PL}^{III}$ following the same procedure described for $F_{PL}^{II}$.

**Execution of the third twin cycles.** Cycles 5 and 6 will finally be leaded up to 1.00 $F_{PL}^{III}$.

## Validation of the Procedure

Here to follow the in-situ structural evaluation of a two-way RC slab at the National Institute of Health building (Bethesda, MD) was presented. The load test was performed on December 8 and 9, 2006. Its data were used to validate the load test procedure described above. The aim of the load test is to assess the structural performance of the floor system to positive and negative moments in correspondence of selected areas as highlighted in Fig. 4 and Fig. 5.

**Preliminary Investigation.** The structural geometry including column locations and member sizes were determined from the engineering drawings. The structural floor is a two-way slab supported by rectangular columns. The concrete slab is mostly 10.5 in (265 mm) thick.

**Material Characteristics.** The specifications indicate a nominal concrete strength of 3000 psi (20.7 kN/mm$^2$) and minimum yield strength for the steel mild reinforcement of 40 ksi (276 kN/mm$^2$).

**Structural Capacity.** The loading conditions are derived from information given by the owner. In particular:

- Factored uniform load for lower levels: 1.4 Dead Load+1.7 Live Load.
- Dead Load: self-weight of the structure (130 psf (6.2 kN/m$^2$)) and additional 25 psf (1.2 kN/m$^2$) of super imposed dead load.
- Live Load: 125 psf (6 kN/m$^2$).

Using the loading layout given in Fig. 4 and Fig. 5, a maximum load of 14.5 kips (64.5 kN) should be applied in each loading point to reach the ultimate moment of the slab in correspondence of the columns H-12 for Area 1 (Positive Moment); and a maximum load of 29.5 kips (131.3 kN) should be applied in each loading point to reach the ultimate moment of the slab in correspondence of the line between columns H and G for Area 2 (Negative Moment).

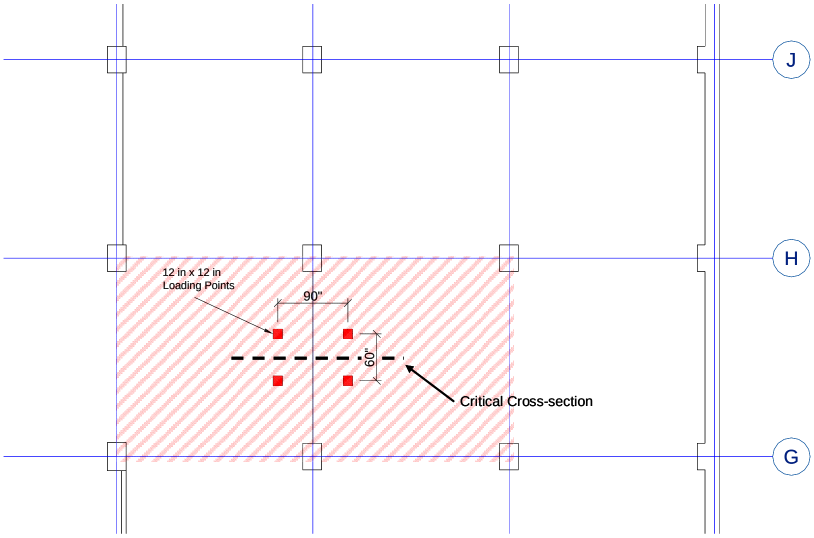

Fig. 4 – Load Test Area 1: Positive Moments Column Line 12 between H and G

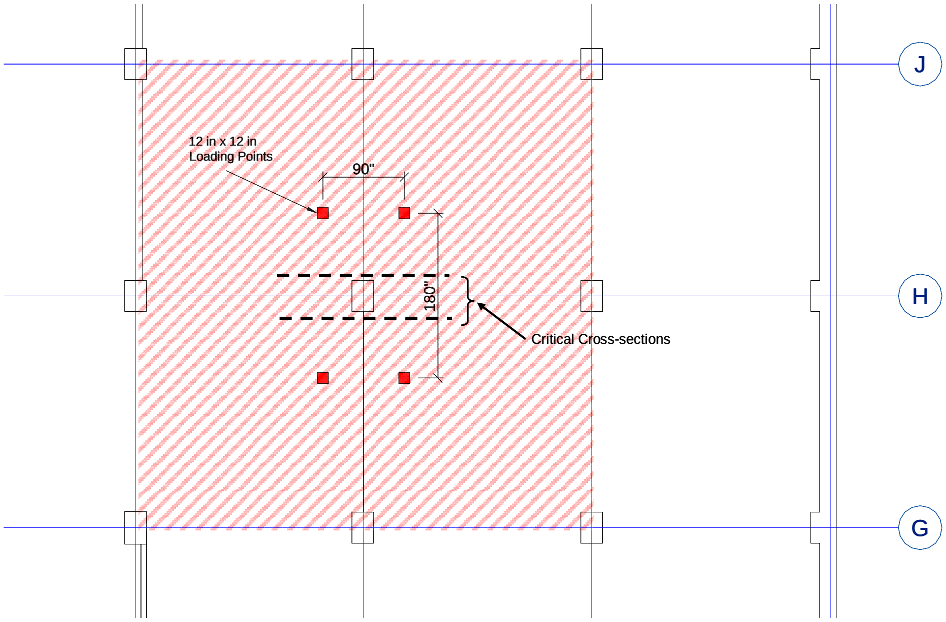

Fig. 5 – Load Test Area 2: Negative Moments Column H-12

The value for the point load $P_{LL}$ chosen for the load test was determined in order to produce the same maximum moment at the column line of interest as the uniform load applied on the portion of structure under investigation.

Table 1 summarizes the findings in terms of point load $P_{LL}$ determined prior testing using the actual loading configuration for all the tests.

Table 1– Planned Point Load $P_{LL}$ Values

| **Test Label** | **$P_{LL}$ [kip] ([kN])** | **Slab Strip Width, b [ft] ([mm])** | **Mu Uniform [k-ft] ([kN-m])** | **Mu Concentrated [k-ft] ([kN-m])** |
|---|---|---|---|---|
| Area 1 | 14.5 (64.5) | 21 (6400) | 155.5 (210.9) | 154.8 (210.0) |
| Area 2 | 29.5 (131.3) | 21 (6400) | 254.1 (344.6) | 255.3 (346.3) |

**Finite Difference Model of the Structure and Target Load Evaluation.** 5in by 5in (125mm by 125mm) square elements were used in the discretization of the mesh for both load test area 1 and load test area 2. Following the procedure outlined in this paper, deflections after each loading cycles were used to evaluate the target load to be applied according to the FDM model of the tested structure. Table 2 and Table 3 summarize the predetermined target load valued by the FDM Model compared to the target load applied to the structure.

Table 2 – Comparison between the predetermined target load and the ideal target load (test area 1)

| **Cycle** | **Predetermined Target Load [lb] ([kN])** | **Ideal Target Load [lb] ([kN])** | **Percentage difference [%]** |
|---|---|---|---|
| Preload | 800 (0.32)<br>1500 (0.6) | N/A | N/A |
| 1 and 2 | 8200 (3.28) | 7872 (3.15) | 4.1 |
| 3 and 4 | 10200 (4.08) | 9588 (3.84) | 6.2 |
| 5 and 6 | 12200 ( 4.88) | 11346 (4.54) | 7.3 |
| 7 and 8 | 14100 (5.64) | 12972 (5.19) | 8.2 |
| Unload | 800 (0.32) | 776 (0.31) | 3.6 |

Table 3 – Comparison between the predetermined target load and the ideal target load (test area 2)

| **Cycle** | **Predetermined Target Load [lb] ([kN])** | **Ideal Target Load [lb] ([kN])** | **Percentage difference [%]** |
|---|---|---|---|
| Preload | 800 (0.32)<br>3000 (1.2) | N/A | N/A |
| 1 and 2 | 17000 (6,8) | 16150 (6.46) | 4.9 |
| 3 and 4 | 21400 (8.56) | 19902 (7.96) | 6.8 |
| 5 and 6 | 25300 (10.12) | 24541 (9.82) | 3.1 |
| 7 and 8 | 28200 (11.26) | 25944 (10.4) | 7.9 |
| Unload | 800 (0.32) | 744 (0.30) | 6.7 |

## Summary

The discussed FDM procedure can become a helpful and useful tool in the practitioner’s hands. To be that tool, it needs to be translated in a computer language and validated by means of several in situ applications. A careful choice of the locations where displacements are measured is really fundamental. The accuracy of the procedure goes through the accuracy of the deformed shape we can obtain by fitting measured data. The FDM model wants to be as accurate as the finite element method (FEM) model. The definition of a good mesh is a crucial step for the procedure. In a wide point of view, the idea is to develop an algorithm able to increase the number of nodes till the variation between the new solution and the previous one is less than 5 percent. The explained procedure gives the engineer a real-time evaluation of slab stiffness, a real-time updating of target load, and an in-situ evaluation of possible boundary non-linear structural behavior. On the other hand, the FD method allows to consider only a variability of thickness over the structure but no variation of Young’s Modulus. In the future, the procedure discussed in this chapter could be translated into a computer language, routinely developing a software to upload on a data acquisition system and to use in the field.

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