Abstract: The primary objective of in-situ load testing is to evaluate the safety and serviceability of an existing structural system with respect to a particular load condition and effect. In light of technological advances in construction methods, analytical tools and monitoring instrumentation, new different evaluation criteria are being proposed in addition to different in-situ load test methods. Some criteria may be more appropriate than others based on the expected damage and failure mechanisms of the structure being considered. The companion paper describes the rationale and application of both a consolidated and an alternative approach to the determination of load level, loading procedure and instrumentation requirements for two case studies. This paper discusses in detail the evaluation criteria and outcomes of these two field projects consisting of a posttensioned concrete slab with structural deficiencies due to tendon and mild reinforcement misplacement and a floor bay of a two-way reinforced concrete slab showing cracking at the positive and negative moment regions. After discussing the relative merits of the evaluation methodologies and the significance of their respective acceptance thresholds, concepts for the development of a new global criterion are discussed.


CE Database subject headings: Concrete structures; Field tests; Instrumentation; Load tests; In situ tests; Concrete slabs; Serviceability; Safety.

Introduction

There is a clear need for the in-situ strength evaluation of reinforced, prestressed, and posttensioned concrete (RC, PC, and PT, respectively) structures. In-situ load test evaluation may be the only tool available to the structural engineer in many instances including the assessment of the effects of construction and design deficiencies, the efficiency of strengthening or retrofit methods, and the capabilities of an existing structure to carry loads not considered during its design.

This paper presents the application and interpretation of the evaluation criteria adopted for the assessment of in-situ load tests performed on two structures (a parking garage and a building) described in the companion paper (Galati et al. 2008). For each case study, the evaluation criteria of interest were those associated with the recently proposed cyclic load test (CLT) method and acoustic emission (AE) criteria. The results obtained in the two projects are described and the relative merits of the evaluation methodologies are compared. Finally, a new global criterion is proposed and its significance demonstrated.

Research Significance

Evaluation criteria based on principles of structural behavior such as repeatability, linearity, and permanency as recently introduced with the development of the cyclic load test method as well as evaluation criteria based on principles of acoustic emission appear of significant relevance in the assessment of concrete structures. These criteria are similar in the sense that they focus on changes in behavior of the structural system due to a pattern of loading and unloading. The primary difference between the CLT and AE evaluation criteria are in the nature of the data collected. Whereas the CLT evaluation criteria typically relate to load and associated displacements or strains, AE evaluation criteria are based on the energy released as the result of crack growth (from loading and load holds) or crack closure during unloading. CLT and AE evaluation criteria have the potential to be used in a complimentary fashion. This paper presents the results obtained for two field projects. Such results from load tests performed on actual structures are vital for calibration and understanding of the evaluation criteria.

Background Research

The requirements of Chapter 20 of the ACI 318 Building Code ACI 318 (2005) include provisions for load testing of RC and PC...
structures. The general procedure required by ACI 318-05 (2005) involves gradually applying the test load until a maximum load is reached and maintaining such load level for 24 h. Measurements are recorded before any load is applied, after each load increment, when the maximum load is achieved, after 24 h of sustained loading, and 24 hours subsequent to the removal of the test load. It should be noted that the recovery deflection measurements are only needed if the limit on maximum deflection is exceeded. No commentary, however, is offered regarding the purpose of the intermediate deflection readings. These measurements could allow verification of the linear response of the structure and provide an opportunity to terminate loading if a large increase in deflection is observed after a loading increment. This concept of “deviation from linearity,” could provide an explicit guideline for interpretation of deflection readings taken during the sequence of load application steps (ACI 2007). Evaluation of the structure is based on the maximum recorded deflection and the amount of deflection recovery. No acceptance criteria for establishing satisfactory behavior at service load level are given.

Alternative methods of analyzing displacement data to establish new evaluation criteria have been introduced recently to accompany the cyclic load test method (ACI 2007). Deflection evaluation criteria should be based on the following principles of engineering mechanics (ACI 2007):

- Maximum deflection under full test load compared with calculated theoretical maximum deflection at that load level,
- Recovery of deflection upon full removal of load, and
- Linearity of deflection response during loading and unloading.

A recent literature search conducted by ACI Committee 437 (ACI 2007) has shown that historical load test practice suggests that deflection recovery can be properly used as an evaluation criterion for load testing of concrete structures. Arnan et al. (1950) showed that deflection recovery can be monitored with the application of the test load in cycles of loading and unloading with increasing peaks until the full test load is in place. ACI 318-05 (2005) suggests that the deflection recovery after 24 h in a static load test, without incremental loading and unloading of the structure, should be at least 75% of the maximum recorded. Arnan et al. (1950) and more recently ACI 437.1R-07 (2007) suggest that the deflection recovery requirement should be significantly higher, on the order of 90%, when using the cyclic load test method or when retesting a structure using the static load test method.

Evaluation of RC components and structures with AE has been in existence for over 20 years with notable advances in Japan in terms of its acceptance and standardization [NDIS 2421 (2000)]. Notable investigations include that of Hearn and Shield (1997), wherein a pattern was recognized that is consistent with other studies for the “Felicity Ratio” (see the Appendix) to decrease as loading is increased. Acoustic emission during unloading was included in evaluation criteria in the form of a plot of “calm ratio” versus “load ratio” as described in Ohitsu et al. (2002). Colombo et al. (2005), also focused on AE during unloading. A study by Ridge and Ziehl (2006), proposed an evaluation criterion that is based on a ratio of energy released during the hold portion of load and reload cycles. Other published AE investigations of RC structures include Yuyama et al. (1999, 2001). Evaluation of deteriorated RC bridges with AE is described in Golaski et al. (2002).

### Evaluation Criteria

#### ACI 318-05

Section 20.5 of ACI 318-05 (2005) defines the evaluation criteria for interpreting the results of the 24 h monotonic load test based on two different sets of values. The measured maximum or residual deflections must satisfy one of the following two equations:

\[
\Delta_{\text{max}} \leq \frac{f^2}{20,000 \text{ h}} \quad (1)
\]

\[
\Delta_{\text{max}} \leq \frac{\Delta_{\text{max}} - \Delta_{\text{r}}}{4} \quad (2)
\]

If the measured maximum and residual deflections do not satisfy these equations, the load test may be repeated, but not earlier than 72 h after the removal of the first test load. It should be noted that if Eq. (1) is met then Eq. (2) need not to be met.

#### ACI 437-07

### Service Load Level

Irrespective of the loading procedure (monotonic or cyclic load) and type of load [uniformly distributed load over the entire tributary area, strip load, or patch load(s)], measurements of flexural deflection and crack spacing and width under the test load equivalent to the service condition should be recorded and checked against limiting values given in Table 9.5(b) of ACI 318-05 Chap. 9 (2005). These limits are only applicable if the load distribution pattern reflects the one used for design. The maximum width of new flexural cracks formed during the course of the load test or the change in width of existing flexural cracks is limited to the suggested tolerable crack widths as reported by ACI Committee 224 (2001) for an aggressive environment.

### All Load Levels

The three parameters that have been established to analyze the behavior of a tested structure when loading is performed according to the CLT method are repeatability, permanency (related to deflection recovery), and deviation from linearity. The three criteria may be related to any response (e.g., deflection, rotation, and strain); however, deflection appears to be the most convenient and for this reason, deflection is used herein.

1. **Repeatability** represents the behavior of the structure during two identical loading cycles. Repeatability is calculated according to Eq. (3) referring to Fig. 1

\[
I_p = \text{repeatability index} = \frac{\Delta_{\text{max}} - \Delta_{\text{r}}}{\Delta_{\text{max}} - \Delta_{\text{r}}} \times 100\% \quad (3)
\]

Mettemeyer (1999) has shown that a repeatability index in the range 95–105% can be considered as satisfactory.

2. **Permanency** represents the amount of permanent change displayed by any structural response parameter during the second of two identical load cycles. The permanency index should be less than 10% (Mettemeyer 1999) and is computed by the following equation referring to Fig. 1 (e.g., during Cycle B)

\[
I_p = \text{permanency index} = \frac{\Delta_{\text{y}}}{\Delta_{\text{max}}} \times 100\% \quad (4)
\]
3. **Deviation from Linearity** represents the measure of the nonlinear behavior of a member being tested. As the member becomes increasingly more damaged, its behavior may become more nonlinear, and its deviation from linearity may increase.

To define deviation from linearity, linearity itself must first be defined. Linearity is the ratio of the slopes of two secant lines intersecting the load-deflection envelope. The load deflection envelope is the curve constructed by connecting the points corresponding to only those loads greater than or equal to any previously applied loads, as shown in Fig. 1. The linearity of any point \( i \) on the load-deflection envelope is the percent ratio of the slope of that point’s secant line \( (\tan \alpha_i) \) to the slope of the reference secant line \( (\tan \alpha_{ref}) \), as expressed by

\[
\text{linearity} = \frac{\tan \alpha_i}{\tan \alpha_{ref}} \times 100\% \quad (5)
\]

The deviation from linearity index of any point on the load-deflection envelope is the compliment of the linearity of that point, as given in the following:

\[
I_{DL} = \text{deviation from linearity index} = 100\% - \text{linearity} \quad (6)
\]

Once the level of load corresponding to the reference load has been achieved, deviation from linearity should be continuously monitored. Experience (Mettemeyer 1999) has shown that acceptable values of deviation from linearity, as defined earlier, are less than 25%. Deviation from linearity may not be useful when testing a member that is expected to behave in a nonlinear elastic manner; for such a member, its repeatability and permanency may be better indicators of damage.

**Acoustic Emission**

Terminology related to AE evaluation is given in the Appendix. Two evaluation criteria based on AE measurements are described in the following.

**Calm Ratio versus Load Ratio**

One method that has been suggested for quantifying AE data due to loading and unloading cycles is referred to as calm ratio versus load ratio (Ohtsu et al. 2002). With this approach the data are plotted and then separated into four quadrants identified as minor, intermediate, and heavy damage. For the investigations described, the load ratio is defined as

\[
\text{load ratio} = \frac{\text{Load at onset of significant AE activity}}{\text{previous maximum load}} \quad (7)
\]

The onset of significant AE activity was determined from the change in slope of the cumulative signal strength curve. Load ratio is similar to the Felicity ratio (ASTM 2006).

The calm ratio compares the AE activity during loading to that during unloading. Cumulative signal strength (CSS) was used to quantify the amount of AE activity and calm ratio was defined as

\[
\text{calm ratio} = \frac{\text{CSS during unloading of the reload cycle}}{\text{CSS during loading of the previous load cycle}} \quad (8)
\]

Although the calm ratio versus load ratio criterion has usually been applied on a qualitative basis, for purposes of developing a more quantitative evaluation the distance from the point of no damage (load ratio = 1.0, calm ratio = 0) is proposed as an additional evaluation criterion. To give equal weight to the calm and load ratio the calm ratio is first normalized to the load ratio and then the distance from the point of no damage to the load set under consideration is calculated. This method does not fully agree with the qualitative assessment plot; however, it is believed to provide a reasonable interpretation of the damage state and is necessary for the development of the global performance index described later in the paper. Similar to the indices for the CLT method, and index is proposed for plots of calm ratio (CR) versus load ratio (LR) as follows:

\[
I_{CRvLR} = \sqrt{\text{normalized CR}}^2 + (1 - \text{LR})^2 \quad (9)
\]

**Cumulative Signal Strength Ratio**

Recent studies indicate that the amount of AE activity (defined by cumulative signal strength) generated during reloading when compared to that generated during initial loading may be a useful indicator of damage. An index is proposed for CSS ratio as follows:

\[
I_{CSSR} = \frac{\text{CSS during initial loading}}{\text{CSS during reloading}} \times 100\% \quad (10)
\]

Limited previous studies (Ridge and Ziehl 2006) indicated that CSS ratios in excess of 40% were indicative of a significant level of damage.
Table 1. Experimental Results—Two-Way PT Slab (Parking Garage) CLT No. 1: Simulated Shear Collar

<table>
<thead>
<tr>
<th>Load set number</th>
<th>Load combination</th>
<th>Load level [kN (kip)]</th>
<th>Repeatability [%]</th>
<th>Permanency (% ≤10%)</th>
<th>Performance according to ACI 437-07</th>
<th>Calm versus load ratio (% ≤30%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.5(1.0D + 1.6L)</td>
<td>27.1 (6.1)</td>
<td>103.9</td>
<td>2.1</td>
<td>Satisfactory</td>
<td>NA</td>
</tr>
<tr>
<td>2</td>
<td>0.75(1.0D + 1.6L)</td>
<td>39.1 (8.8)</td>
<td>102.1</td>
<td>3.3</td>
<td>Satisfactory</td>
<td>NA</td>
</tr>
<tr>
<td>3</td>
<td>1.0D + 1.6L</td>
<td>51.2 (11.5)</td>
<td>101.7</td>
<td>4.0</td>
<td>Satisfactory</td>
<td>0.15</td>
</tr>
<tr>
<td>4</td>
<td>1.15D + 1.5L</td>
<td>57.8 (13.0)</td>
<td>101.2</td>
<td>7.2</td>
<td>Satisfactory</td>
<td>0.11</td>
</tr>
</tbody>
</table>

Results of Case Studies and Discussion

Two-Way PT Concrete Slab (Parking Garage)

CLT Evaluation Criteria

In this section the results of the three tests introduced in the companion paper (Galati et al. 2008) (i.e., CLT No. 1 and 24 h No. 1 for the simulated shear collar, and CLT No. 2 with CFRP strengthening applied to increase negative moment and punching shear capacity) are described. Only the measurements from the sensors at the most demanding locations are reported here.

CLT No. 1 (simulated shear collar). The structure was loaded using the procedure shown in Fig. 8(a) of the companion paper (Galati et al. 2008). Fig. 2 shows the measured deflections at DS10 (see Fig. 6 in the companion paper) during the eight cycles depicting an elastic behavior with no residual deflection. The structure passed the test as repeatability, permanency, and deviation from linearity were within the limits prescribed by ACI 437 (see Table 1).

No new cracks formed when performing the cyclic load test: the effect of the applied load was mostly to increase the size of the existing cracks (Fig. 3). The maximum change in width of existing flexural cracks at the service load condition (1.0 D + 1.0 L) was 0.14 mm (0.0045 in.), and did not exceed the suggested tolerable crack width of 0.18 mm (0.007 in) (ACI 2001) for this type of structure and environmental condition.

24-h No. 1 (simulated shear collar). After concluding the cyclic load test, the maximum load was kept on the structure for 24 h, as shown in Fig. 8(b) of the companion paper. Fig. 4 shows the corresponding time–deflection diagram. The plot shows that deflection increases 20% from the instant value at maximum load.

This significant increase in deflection is explained as the result of cracks opening as demonstrated by AE activity during the entire duration of the test. The crack growth could not be confirmed by the horizontal direct current variable transformer (DCVT) measurements because the increments in crack size were comparable to the resolution of the sensor type.

The structure met the acceptance criteria of Chap. 20 of ACI 318-05 (2005), as at the completion of the 24 h sustained loading and upon unloading, the two criteria listed in the following were verified:

\[
\Delta_{max} = \Delta_{max, 24 h} + \Delta_{r, cyclic} = 4.57 \text{ mm (0.18 in.)} \\
+ 0.25 \text{ mm (0.01 in.)} = 4.82 \text{ mm (0.19 in.)} \\
\leq \frac{L^2}{20,000 \text{ h}} = 20.1 \text{ mm (0.79 in.)}
\]

and

\[
\Delta_{max} = \Delta_{max, 24 h} + \Delta_{r, cyclic} = 0.48 \text{ mm (0.019 in.)} \\
+ 0.25 \text{ mm (0.01 in.)} = 0.7 \text{ mm (0.029 in.)} \\
\leq \frac{\Delta_{max}}{4} = 1.1 \text{ mm (0.045 in.)}
\]

where \(\Delta_{r, cyclic}\) residual deflection after the CLT and \(\Delta_{max, 24 h}\) and \(\Delta_{r, cyclic, 24 h}\) represent the maximum and the residual deflections after the 24 h load test, respectively. Eqs. (11) and (12) account for the fact that the 24 h test was conducted following the CLT and, therefore, both maximum and residual deflections included the values recorded during the cyclic load test.

CLT No. 2 (after CFRP strengthening). The load levels for CLT No. 2 were higher than those for CLT No. 1 (see Table 2) because the simulated shear collar shifts the location at which the moment capacity is to be evaluated. This results in lower concentrated loads for CLT No. 1 when compared to CLT No. 2. Fig. 5
The AE activity is present and in this case should not be applied. The results of the AE evaluation are shown in Figs. 8. The AE results are plotted in terms of CSS ratio in Figs. 9(a and b) (CLT No. 1 and CLT No. 2). Evaluation may be misleading when little AE activity is present and in this case should not be applied. The minimum value for AE evaluation was set to 4 × 10^6 pV s (based on cumulative signal strength recorded during the initial loading cycle). In Fig. 8(a), the results for Load Sets 3 and 4 fall within the range of minor and intermediate damage. Load Sets 1 and 2 were not evaluated due to an insufficient amount of AE activity. In Fig. 8(b), the results fall within the quadrants related to minor (Load Set 1) and intermediate (Load Sets 2, 3, and 4) damage with the exception of Load Set 5. This load set falls well within the quadrant related to heavy damage and is notable for its significant increase in the calm ratio value.

The distance from the point of no damage to Load Set 5 in Fig. 8(b) is calculated as 0.90. To establish a quantitative measure of damage a threshold value must be determined. Based on the data from CLT No. 1 and CLT No. 2 a threshold value of 0.45 for the distance from the point of no damage was chosen.

The AE results are plotted in terms of CSS ratio in Figs. 9(a and b) (CLT No. 1 and CLT No. 2). The numerical value of cumulative signal strength is plotted for each load cycle. The important aspect of the results is the value of the reloading cycle of each load set (e.g., Load Cycle 8 in Load Set 4) when compared to the initial load cycle of that same load set (Load Cycle 7 in Load Set 4). In Fig. 9, the results for the CSS ratio are shown numerically as a percentage value above the reloading cycle of each load set. In Fig. 9(a), all values are well below the 40% threshold reported in the literature (Ridge and Ziehl 2006). In Fig. 9(b), the value for Load Set 5 does approach 40%. Given the information from the plot of calm ratio versus load ratio it is clear that Load Set 5 of CLT No. 2 plots in the quadrant indicative of heavy damage, a threshold equal to 30% may be more appropriate and is adopted for purposes of the evaluations described here. The value of 40% as reported in the literature refers to passively reinforced beam specimens as opposed to the post-

Table 2. Experimental Results—Two-Way PT Slab (Parking Garage) CLT No. 2: after CFRP Strengthening

<table>
<thead>
<tr>
<th>Load set number</th>
<th>Load combination</th>
<th>Load level [kN (kip)]</th>
<th>Repeatability [95–105%] (%)</th>
<th>Permanency (≤10%) (%)</th>
<th>Deviation from linearity (≤25%) (%)</th>
<th>Performance according to ACI 437-07</th>
<th>Calm ratio versus load ratio (≤0.45) (%)</th>
<th>CSS ratio (≤30%) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.5(1.0D+1.6L)</td>
<td>34.7 (7.8)</td>
<td>104.7</td>
<td>9.6</td>
<td>3.5</td>
<td>Satisfactory</td>
<td>0.00</td>
<td>2</td>
</tr>
<tr>
<td>2</td>
<td>0.75(1.0D+1.6L)</td>
<td>46.7 (10.5)</td>
<td>104.4</td>
<td>11.9</td>
<td>10.4</td>
<td>Unsatisfactory</td>
<td>0.13</td>
<td>8</td>
</tr>
<tr>
<td>3</td>
<td>1.0D+1.6L</td>
<td>62.3 (14.0)</td>
<td>103.3</td>
<td>16.4</td>
<td>15.6</td>
<td>Unsatisfactory</td>
<td>0.24</td>
<td>25</td>
</tr>
<tr>
<td>4</td>
<td>1.15D+1.5L</td>
<td>73.8 (16.6)</td>
<td>103.2</td>
<td>17.5</td>
<td>21.5</td>
<td>Unsatisfactory</td>
<td>0.33</td>
<td>18</td>
</tr>
<tr>
<td>5</td>
<td>1.2D+1.6L</td>
<td>82.3 (18.5)</td>
<td>98.6</td>
<td>17.5</td>
<td>26.7</td>
<td>Unsatisfactory</td>
<td>0.90</td>
<td>39</td>
</tr>
</tbody>
</table>
tensioned slab system described and therefore some variation from the literature seems justified. The results of the AE evaluation for calm ratio versus load ratio and CSS ratio are shown along with the CLT evaluation results in Tables 1 and 2.

AE activity was monitored continuously during the 24 h load test and it was present throughout the load test period as shown for one 4 h period [Fig. 10(a)]. Source location was determined based on time of arrival and triangulation. A plot of AE activity showing active cracking (determined by located AE events) during the same 4 h period is shown in Fig. 10(b). Much of the emission shown in Fig. 10(a) was not located. This is because the
activity was generally of low amplitude and therefore in many cases only one or two sensors detected a given hit. For two-dimensional source location a hit must be detected by a minimum of three sensors.

### Two-Way RC Slab (Library)

#### CLT Evaluation Criteria

The structure was loaded using the protocol described in Fig. 15 of the companion paper (Galani et al. 2008). Fig. 11 shows the load–deflection diagram with deflections measured at DS12 (see Fig. 12 in the companion paper). As seen in Fig. 11, the structure had a non-linear behavior with a change in slope at a load of approximately 45 kN (10 kip). This is attributed to the formation of new cracks at the first load set. In the first two load sets repeatability, permanency, and deviation from linearity were within the limits prescribed by ACI 437 (2007) (Table 3). The structure exceeded the maximum permanency at Load Set 3 with deviation from linearity also very close to the threshold. In the last load set, both deviation from linearity and permanency exceeded acceptance thresholds.

#### AE Evaluation Criteria

The calm ratio versus load ratio plot is shown in Fig. 12(a) and the CSS ratio plot is shown in Fig. 12(b). Load Sets 1 and 2 were not meaningful for evaluation due to the low amount of AE activity recorded. Load Set 3 falls within the range of intermediate damage, whereas Load Set 4 falls on the boundary of minor and intermediate damage. In terms of the quantitative approach described previously, both Load Sets 3 and 4 had a distance of less that 0.45 from the point of no damage.

In regard to the CSS ratio criterion, Load Set 4 had a CSS ratio of 34% and exceeded the 30% threshold proposed in this paper. The results of the AE evaluation are shown in Table 3 along with the CLT evaluation results.

#### New Concept for Acceptance Criteria: Global Performance Indices

For both structures, the AE activity indicated a significant increase in damage when both the permanency and deviation from linearity criteria were failed at the same time. Repeatability had very small variations during the loading and unloading cycles, indicating that the limits posed on repeatability for statically indeterminate structures may not be appropriate due to load redistribution. This behavior was not observed in statically determinate

### Table 3. Experimental Results—Two-Way RC Slab (Building) CLT: Negative Moment

<table>
<thead>
<tr>
<th>Load set number</th>
<th>Load combination</th>
<th>Load level [kN (kip)]</th>
<th>Repeatability (95–105%) (%)</th>
<th>Permanency (&lt;10%) (%)</th>
<th>Deviation from linearity (&lt;25%) (%)</th>
<th>Performance according to ACI 437-07</th>
<th>Calm versus load ratio (&lt;0.45) (%)</th>
<th>CSS ratio (&lt;30%) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>(D + D_x + L)</td>
<td>75.6 (17.0)</td>
<td>104.3</td>
<td>3.9</td>
<td>2.8</td>
<td>Satisfactory</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>2</td>
<td>(0.75(1.0D + 1.1D_x + 1.6L))</td>
<td>95.2 (21.4)</td>
<td>103.9</td>
<td>3.3</td>
<td>12.3</td>
<td>Satisfactory</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>3</td>
<td>(1.0D + 1.1D_x + 1.6L)</td>
<td>112.5 (25.3)</td>
<td>101.7</td>
<td>10.5</td>
<td>24.6</td>
<td>Unsatisfactory</td>
<td>0.30</td>
<td>21</td>
</tr>
<tr>
<td>4</td>
<td>(0.85(1.4(D + D_x) + 1.7L))</td>
<td>125.4 (28.2)</td>
<td>104.1</td>
<td>13.5</td>
<td>26.5</td>
<td>Unsatisfactory</td>
<td>0.18</td>
<td>34</td>
</tr>
</tbody>
</table>
structures for which the failure of only one of the three CLT criteria indicates significant damage in the structure (Galati et al. 2004).

The two load tests described show that, for statically indeterminate structures, overall performance should not be evaluated based on the load level at which one acceptance criterion is failed. Rather, it should be based on a combination of all acceptance criteria (i.e., permanency, repeatability, and deviation from linearity) and on how far the computed value falls from the global limit. An equation that reflects such an approach is described in the following equation:

\[ I_G = \frac{1}{3} \left( \frac{\alpha R_g + \alpha R_p}{10} + \alpha DL \right) + \alpha DL \]  

(13)

For an even more robust structural evaluation, the CLT and AE criteria could be combined in the proposed global limit given in

\[ I_G = \frac{1}{5} \left( \frac{\alpha R_g + \alpha R_p}{10} + \alpha DL \right) + \alpha CR vs LR \]  

(14)

where \( i_R \) = index of repeatability defined as

\[ i_R = \begin{cases} 2 - \frac{I_R}{95} & \text{if } I_R \leq 95 \\ \frac{1}{5}(I_R - 100) & \text{if } 95 < I_R \leq 95 \\ \frac{I_R}{105} & \text{if } I_R > 105 \end{cases} \]

The coefficients \( \alpha R_g, \alpha R_p, \alpha DL, \alpha CR vs LR, \) and \( \alpha CSSR \) in Eqs. (13) and (14) are variables to account for the importance of each individual index given the type of structure under investigation. The denominators in the equation are chosen such that the global index threshold corresponds to unity. The multiplier \( \kappa_G \) takes into account the knowledge of the structure by the load test team and the number of load tested members with respect to the total number of similar members in the building structure. For instance, a lower \( \kappa_G \) factor can be used in Eqs. (13) and (14) if the as-built conditions (i.e., depth of reinforcement, thickness of slab, concrete compressive strength, etc.) are known. Conversely, if the only information available is that shown on the original structural drawings, then a higher \( \kappa_G \) should be used.

For the two structures described (both continuous two-way slabs and therefore statically indeterminate), the repeatability may not be critical and therefore the coefficient \( \alpha R_p \) could be taken as less than 1.0, whereas permanency and deviation from linearity could have coefficients \( \alpha R_p \) and \( \alpha DL \) greater than 1.0. Additionally, for the parking garage, the tested area was selected by the engineer of record after conducting a comprehensive investigation of the entire structure, which included computation of structural capacities based on as-built conditions and selection of the most critical bay. For the building, the test area was selected at random based on original drawings and space available for load testing. The coefficient \( \kappa_G \) is intended to capture the level of knowledge of the structure by the load testing team, resulting in lower values for the parking garage and in a higher, statistically dependent value for the building.

Due to the scarcity of research data on load testing, both in the laboratory and in the field, numerical values for the coefficients \( \alpha R_g, \alpha R_p, \alpha DL, \alpha CR vs LR, \alpha CSSR, \) and \( \kappa_G \) cannot be proposed at this time. The calibration of these coefficients should be based on reliability analysis after conducting a statistically significant number of tests to failure for various classes of structural members.

Table 4 reports the corresponding values of the proposed global performance index according to Eq. (14) assuming coefficients \( \alpha R_g, \alpha R_p, \alpha DL, \alpha CR vs LR, \alpha CSSR, \) and \( \kappa_G \) to be equal to 1.0 for CLT No. 2 of the parking garage and the CLT for the building. For both load tests, the increase in AE activity in the structure is accompanied by a jump in the global performance index. The results for CLT No. 1 (simulated shear collars) as well as 24 h No. 1 of the parking garage are not shown as the structure passed those tests.

### Ultimate Capacity Margin

Because the load tests were conducted on structures in use, local or global failure had to be avoided; therefore, the true ultimate capacity of the slabs could not be determined. However, an expected ultimate capacity margin (UCM) can be calculated based on the finite element method analysis performed on the tested...
component. This UCM index when experimentally validated and available would allow engineers to know how much reserve is left in the structure once it fails the load test. The availability of UCM would transform a “proof” test into a “prognostic” test.

The expected UCM may be expressed in terms of the load (or moment) at which any of the individual or global evaluation criteria reaches a threshold level as given in the following:

\[
\text{UCM}_{\%} = \left(1 - \frac{M_{cf}}{M_{ult}}\right) \times 100\% \quad (15)
\]

where \(\text{UCM}_{\%}\) = ultimate capacity margin expressed (\%) \(M_{cf}\) = load or moment at which an evaluation criterion reaches the threshold value (cf = criterion failure); and \(M_{ult}\) = theoretical ultimate load or moment capacity.

UCM values for CLT No. 2 of the parking garage and for the building are shown in Table 4. The comparison of the various UCM’s based on individual CLT and AE indices shows that the AE method corresponds to the lowest UCMs and such values generally agree with those corresponding to the global performance indices. For the parking garage, the UCM was 54% as the permanency did not meet the ACI 437 criteria at the second Loadset. This ultimate capacity margin appears to be overly conservative and this is attributed to the fact that the acceptance criteria defined in ACI 437 are based on limited experience (Chap. 3 of ACI 437) and do not account for structural redundancies.

The proposed global performance indices led to lower ultimate capacity margins than the ACI 437 approach. The results of applying the global performance indices are shown in Fig. 13 for CLT No. 1 and CLT No. 2 of the parking garage and the CLT of the building. In Fig. 13, it is clear that Load Set 5 for CLT No. 2 is well beyond the threshold value of 1.0. All other load sets are below 1.0 and, as expected, they tend to increase with increasing load set number. It should be noted that Load Set 4 of the CLT for the building practically reaches unity. Further calibration is required to establish more appropriate values for the coefficients \(\alpha_{cr}, \alpha_{cf}, \alpha_{DL}, \alpha_{CRDLR}, \alpha_{CSSR}, \) and \(\kappa_{c}\) even though the proposed approach appears promising.

Summary and Conclusions

This paper presents the evaluation of two two-way concrete slabs (PT and RC). For each case the structural assessment based on CLT and AE evaluation criteria is critically discussed.

For both structures redundancies resulted in very conservative ACI 437 criteria values when compared with the AE evaluation. In fact, significant AE activity was recorded when two of the ACI 437 criteria failed at the same time. This observation allowed defining, for statically indeterminate structures, a global performance index accounting of permanency, repeatability, deviation from linearity, and the AE evaluation criteria of load ratio versus calm ratio and CSS ratio. An equation was also defined for use when AE data is not available.

The proposed global performance index was used to evaluate the ultimate capacity margins for the load tests performed on both structures. The general approach appears very promising, however, further extensive experimental and analytical work is needed for the calibration of the parameters utilized.

Acknowledgments

The ACI Concrete Research Council, the NSF Industry/University Cooperative Research Center on Repair of Buildings and Bridges with Composites and the UMR–University Transportation Center on Advanced Materials are gratefully acknowledged for their financial support to the research. Yizhuo Chen assisted with the load tests and data reduction and his assistance is greatly appreciated.

Appendix. Terminology Related to Acoustic Emission

Acoustic emission (AE) = class of phenomena whereby transient elastic waves are generated by the rapid release of energy from localized sources within a material, or the transient waves so generated (ASTM 2006).

Amplitude = largest voltage peak in the AE signal wave form; customarily expressed in decibels relative to 1 \(\mu\)V at the preamplifier input (\(\text{dB}_{\text{ae}}\)) assuming a 40 dB preamp (Physical 2001).

Calm ratio = AE activity during unloading/AE activity during previous maximum loading (as described in Ohtsu et al. 2002).

\(\text{dB}\) = unit of measurement for AE signal amplitude A, defined by \(A (\text{dB}) = 20 \log V_p,\) where \(V_p\) is the peak signal voltage in microvolts referred to the preamplifier input (Physical 2001).
Felicity effect = presence of acoustic emission, detectable at a fixed predetermined sensitivity level at stress levels below those previously applied (ASTM 2006).

Felicity ratio = ratio of the stress at which the Felicity effect occurs to the previously applied maximum stress (ASTM 2006); because stress varies with location and direction, load is used in place of stress for the evaluation described.

Kaiser effect. The Kaiser effect represents the irreversibility of AE events that are not generated in a material until it is stressed beyond its prior stress state (Ohatsu et al. 2002); it is defined in ASTM (2006) as “the absence of detectable emission at a fixed sensitivity level, until previously applied stress levels are exceeded.”

Signal strength = measured area of the rectified AE signal with units proportional to volt-seconds (ASTM 2006) (the proportionality constant is specified by the AE instrument manufacturer).

Notation

The following symbols are used in this paper:

- \( CR \) = numerical value of calm ratio;
- \( D \) = dead load; units depend on structural member considered;
- \( D_s \) = superimposed dead load; units depend on structural member considered;
- \( h \) = overall thickness of member (mm (in.));
- \( I_{CRsLR} \) = calm ratio versus load ratio index (dimensionless);
- \( I_{CSSR} \) = cumulative signal strength index (dimensionless);
- \( I_{DL} \) = deviation from linearity index (dimensionless);
- \( I_G \) = global performance factor (dimensionless);
- \( I_P \) = permanency index (dimensionless);
- \( I_R \) = repeatability index (dimensionless);
- \( L \) = live load; units depend on structural member considered;
- \( LR \) = numerical value of load ratio;
- \( I_i \) = span of member under load test; units depend on structural member considered (ACI 318);
- \( M_{ef} \) = load or moment at which an evaluation criterion reaches the threshold value (\( cf = \) criterion failure);
- \( M_{ult} \) = theoretical ultimate load or moment capacity;
- normalized \( CR \) = numerical value of calm ratio normalized to load ratio;
- \( P \) = applied load during load test;
- \( P_i \) = load of point \( i \) in load–deflection envelope for computation of IDL acceptance criterion;
- \( P_{min} \) = minimum load to be maintained during load test (typically 10% of total test load);
- \( P_{ref} \) = reference load for computation of IDL acceptance criterion;
- \( TLM \) = test load magnitude (including dead load already in place); units depend on structural member considered;
- \( UCM \) = ultimate capacity margin expressed as percent;
- \( \alpha \) = strength-reduction factor as per ACI 318;
- \( \alpha_{DL} \) = importance coefficient applied to the deviation from linearity;
- \( \alpha_i \) = slope of secant line of point \( i \) in load–deflection envelope (deg);
- \( \alpha_{CRsLR} \) = coefficient to be applied to calm ratio versus load ratio criterion;
- \( \alpha_{CSSR} \) = coefficient to be applied to CSS Ratio criterion;
- \( \alpha_p \) = importance coefficient applied to the permanency;
- \( \alpha_R \) = importance coefficient applied to the repeatability;
- \( \alpha_{ref} \) = slope of reference secant line in load-deflection envelope, degrees;
- \( \kappa_G \) = global coefficient accounting for the level of knowledge of the structure by the load testing team;
- \( \Delta_{Amax} \) = maximum deflection in Cycle A under maximum test load [mm (in.)];
- \( \Delta_{Ar} \) = residual deflection after Cycle A under minimum test load [mm (in.)];
- \( \Delta_{Bmax} \) = maximum deflection in Cycle B under maximum load [mm (in.)];
- \( \Delta_{Br} \) = residual deflection after Cycle B under minimum test load [mm (in.)];
- \( \Delta_i \) = deflection of point \( i \) in load-deflection envelope for computation of \( I_{DL} \) acceptance criterion;
- \( \Delta_{max} \) = measured maximum deflection [mm (in.)];
- \( \Delta_{ref} \) = reference deflection for computation of \( I_{DL} \) acceptance criterion; and
- \( \Delta_{max} \) = measured residual maximum deflection [mm (in.)].

References


226 / JOURNAL OF PERFORMANCE OF CONSTRUCTED FACILITIES © ASCE / JULY/AUGUST 2008
