Core Testing Requirements for Seismic Evaluation of Existing Structures

Evaluation practices for nonseismic structures can be adapted

by Halil Sezen, Chuck Hookham, Kenneth J. Elwood, F. Michael Bartlett, and Mark A. Moore

Determining in-place concrete strengths is particularly important for the seismic evaluation of existing buildings and their components, as in-place strengths can be quite different from original concrete cylinder data, if available. Although core testing is the most widely accepted method for determining in-place concrete compressive strengths, procedures for planning the scope of the investigation and interpreting the test results are not standardized.

For nonseismic rehabilitation projects, conventional practice is to adopt a lower-bound estimate of the in-place concrete strength when evaluating capacity of a component or element to resist load. For example, ACI 214.4R-10 recommends procedures for converting core test results to “equivalent-to-specified” strengths for use in conventional resistance equations with customary resistance factors. The converted results are lower-bound (10%) fractiles of the in-place strengths (90% probability of being exceeded).

Underestimating the concrete strength in a seismic rehabilitation design, however, can undervalue component resistances, potentially triggering inappropriate rehabilitation solutions. For instance, underestimating the concrete strength of a shear wall may lead to strengthening of the wall. This would, in turn, subject other elements in the system, such as the diaphragm-to-wall connection, to higher forces. Also, because mean values of the modulus of elasticity should be used in a dynamic structural model to ensure an appropriate estimate of the natural period and seismic demands on the structure, it would be inappropriate to base modulus values on lower-bound strengths.

ASCE/SEI 41 was developed based on FEMA 356 and includes condition assessment and materials testing requirements for the seismic rehabilitation of existing buildings. Eurocode 8 provides guidance and provisions for materials inspection and testing for seismic assessment of existing structures. There is concern, however, that the core testing requirements specified in these documents may be too onerous. Various ACI guidelines and standards indicate little consensus on the location and number of cores needed to determine the concrete strength in existing structures.

The objective of this article, therefore, is to review assessment requirements and guidelines and identify ways of setting core sampling requirements appropriate for seismic evaluation. Recommendations are based on a review of statistical methods to select sample size for an acceptable error level and assessment of outlier data.

Strength Data for Seismic Evaluation

ASCE/SEI 41 and ACI 369R

ASCE/SEI 41 requires both expected and lower-bound values for concrete strength, depending on the action or attribute being considered. For concrete components, most actions are classified as deformation-controlled. So, with the exception of brittle failure modes with high consequences of failure (such as punching shear failure of slab-column connections without continuity reinforcement and a high gravity-shear ratio), expected strengths should be used.

ACI 369R-11 is based on ASCE/SEI 41 and its supplement. The first edition includes recommendations...
Table 1: Minimum number of concrete cores required per selected industry standards and guidelines

<table>
<thead>
<tr>
<th>Document</th>
<th>Method</th>
<th>Minimum number of cores/tests</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACI 369R-11&lt;sup&gt;5&lt;/sup&gt;</td>
<td>Minimum, use specified default material properties</td>
<td>None</td>
</tr>
<tr>
<td></td>
<td>Usual (specified design strength known)</td>
<td>One per concrete class</td>
</tr>
<tr>
<td></td>
<td>Usual (specified design strength not known)</td>
<td>Three per floor level</td>
</tr>
<tr>
<td></td>
<td>Comprehensive (specified design strength known)</td>
<td>Six per building</td>
</tr>
<tr>
<td></td>
<td>Comprehensive (specified design strength not known)</td>
<td>Three per floor level</td>
</tr>
<tr>
<td>Eurocode 8&lt;sup&gt;4&lt;/sup&gt;</td>
<td>Limited level of inspection and testing</td>
<td>One per component per floor</td>
</tr>
<tr>
<td></td>
<td>Extended level of inspection and testing</td>
<td>Two per component per floor</td>
</tr>
<tr>
<td></td>
<td>Comprehensive level of inspection and testing</td>
<td>Three per component per floor</td>
</tr>
<tr>
<td>ACI 214.4R-10&lt;sup&gt;11&lt;/sup&gt;</td>
<td>Engineer should select core locations (per ASTM C823)</td>
<td>Cites ASTM C823 recommendation of five per concrete class</td>
</tr>
<tr>
<td>ASTM C823/C823M-07&lt;sup&gt;9&lt;/sup&gt;</td>
<td>Establish reliability-based sampling plan or use minimum of five</td>
<td>Five per concrete class</td>
</tr>
<tr>
<td>ACI 364.1R-07&lt;sup&gt;11&lt;/sup&gt;</td>
<td>More samples may be required in different parts of structure</td>
<td>Three per location in structure</td>
</tr>
<tr>
<td>ACI 437R-03&lt;sup&gt;12&lt;/sup&gt;</td>
<td>Number of tests are related to degree of confidence</td>
<td>No minimum specified</td>
</tr>
</tbody>
</table>

for material testing and data collection that are very similar to the requirements in ASCE/SEI 41.<sup>3,8</sup> Three knowledge levels (minimum, usual, and comprehensive) are used to determine material properties and core test minimums (Table 1).

For the “minimum” knowledge level, no testing is required. Specified default lower-bound concrete compressive strengths can be used in linear analysis procedures defined in ASCE/SEI 41. A “knowledge factor” of 0.75 is applied to all calculated capacities to reflect the low confidence in the actual material properties and structural condition.

For the “usual” knowledge level, if the originally specified concrete strength is known, at least one core is recommended for each concrete grade in the building, and at least three cores should be taken for the entire building. If the specified strength is unknown, at least one core should be taken from each type of component, and at least six cores should be taken for the entire building. As the average strength of the original concrete often considerably exceeds the specified strength, cylinder data from the time of construction, adjusted for age, may provide a better measure of the in-place concrete strength. The confidence in the strength determined from core tests increases if such cylinder test data, nondestructive test results, or other complementary information are available; however, this information is not currently used in concrete strength determination recommendations in ACI 369R-11.

For the “comprehensive” knowledge level, at least three cores should be taken for each type of element, and at least six cores should be taken for the entire building. If the building contains different concrete classes (strengths or grades), at least three cores should be taken for each. If the originally specified strength is known but original cylinder test data are not available, at least three cores should be taken for each floor level, 400 yd<sup>3</sup> (about 300 m<sup>3</sup>) of concrete, or 10,000 ft<sup>2</sup> (about 1000 m<sup>2</sup>) of surface area; if the specified strength is unknown, this minimum increases to six. If the coefficient of variation (COV) exceeds 14%, ACI 369R-11 recommends that additional tests are taken until the COV is equal to or less than 14%. Because the typical COV of cast-in-place concrete averages 13%, however, this recommendation may be impossible to meet.

**Eurocode 8**

Eurocode 8<sup>4</sup> includes in-place inspection and testing requirements for confirming the concrete strength as determined from standards at the time of construction, original design specifications, or original test reports. For each type of primary element (beam, column, or wall), one core is required from each floor level. If test values are lower than default values specified in construction standards in effect when the project was constructed, “extended” in-place testing (two cores per component type per floor) is required. “Comprehensive” in-place testing (three cores per component type per floor) is required when a higher level of knowledge is necessary. “Extended” or “comprehensive” level tests are required when the original design specification and original test reports are unavailable.
The required minimum number of tests can be excessive if Eurocode 8 or the comprehensive method in ACI 369R-11 is applied to a typical building. For example, Eurocode 8 requires, for a 10-story building comprising beam, column (or wall), and slab elements, 30, 60, and 90 core tests for “limited,” “extended,” and “comprehensive” test levels, respectively. For the same building, the ACI 369R-11 comprehensive method requires 30 cores if the originally specified design strength is known and 60 if it is unknown. The need for this onerous level of testing will be explored after a review of general evaluation recommendations in other documents.

**Strength Data for General Evaluation**

**ACI 214.4R-10**

ACI 214.4R-10 recommends the procedures in ASTM C823 and ASTM E122 for determining a core sampling program and number of cores. It cites the ASTM C823 requirement that a minimum of five core test specimens be obtained for each category of concrete with a unique condition or specified quality, specified mixture proportion, or specified material property and presents a methodology to determine a sample size to achieve a predetermined maximum error. It also recommends that “the investigator should select locations from which the cores will be extracted based on the overall objective of the investigation, not the ease of obtaining samples. To characterize the overall in-place strength of an existing structure for general evaluation purposes, cores should be drilled from randomly selected locations throughout the structure using a written sampling plan.” Finally, ACI 214.4R-10 recommends two procedures to determine an “equivalent-to-specified strength” value from the test data that can be used in conventional resistance equations with customary resistance factors.

**ACI 364.1R-07**

ACI 364.1R-07 emphasizes that a large structure with little or no distress or deterioration may warrant few, if any, cores—especially where design documents are available and no change of use is planned. Alternatively, a structure exhibiting considerable distress or deterioration may require many cores to adequately diagnose the conditions. It states, “Where cores are taken to determine a strength property, at least three cores should be removed at each location in the structure. The strength value should be taken as the average of the three cores. A single core should not be used to evaluate or diagnose a particular strength problem.”

**ACI 437R-03**

ACI 437R-03 uses an approach similar to that in ACI 214.4R-10; it also refers to ASTM C823 and ASTM E122. It does not specify a minimum number of samples but stresses that the number of samples should depend on the acceptable risk and on the degree of confidence desired in the average values obtained from the core tests.

**Variability and Sample Size**

ASTM E122 provides guidance for determining the sample size to achieve a target accuracy that the sample mean value will lie within a percentage error of the population mean. As the sample size increases, e reduces. Assuming the concrete strengths are normally distributed, the sample size can be determined as

\[ n = \left( \frac{2 \cdot \text{COV}}{e} \right)^2 \]  

where COV is the estimated coefficient of variation (the ratio of the standard deviation to the mean) of the in-place strengths. The multiplier 2 corresponds to a 4.5% risk that the target e will be exceeded. The risk reduces to 0.3% if the multiplier is increased to 3.

Reference 8 quantifies the typical overall variability of concrete strength throughout a structure using COV values. As shown in Table 2, the COV can be taken as 0.130 (or 13%) for most cast-in-place reinforced concrete structures. The COV reduces if the structure is precast or cast from a single batch of concrete. The COV value of 0.25 represents a reasonable upper limit, attributable perhaps to poor concrete production control, erratic field curing practices, and possible deterioration of the concrete due to exposure.

Using Eq. (1) and three of the COV values from Table 2, the number of cores necessary to have a 95.5% likelihood of achieving the target e is shown in Fig. 1. For example, to be 95.5% sure of limiting e to 10%, at least seven cores are needed for a cast-in-place concrete building cast using many batches of concrete (13% COV), and at least three cores are needed for an element cast using a single batch of concrete (8% COV). For the upper limiting case, more than 20 samples are needed.

**Table 2:**

Typical coefficient of variation (COV) of in-place concrete strengths

<table>
<thead>
<tr>
<th>Structure description</th>
<th>COV</th>
</tr>
</thead>
<tbody>
<tr>
<td>One batch of concrete</td>
<td>0.084</td>
</tr>
<tr>
<td>Cast-in-place—many batches</td>
<td>0.130</td>
</tr>
<tr>
<td>Precast—many batches</td>
<td>0.103</td>
</tr>
<tr>
<td>Approximate upper limit</td>
<td>0.250</td>
</tr>
</tbody>
</table>

Table 2:

Typical coefficient of variation (COV) of in-place concrete strengths
Removal, inspection, and testing of cores may reveal damage in the concrete structure, attributable to original placement problems, in-service loading (including past seismic events), or environmental exposure. This should not automatically result in increasing the number of cores, but should trigger further evaluation of damage through both physical and nondestructive testing. Means to evaluate the extent of damage are available (refer to, for example, References 11 and 13) and should be carried out independent of the determination of concrete strength.

Identification of Outliers

An outlier (an unusually low or unusually high test result) should not be indiscriminately discarded. A test result can be ignored only if justified by a physical explanation or a statistical test. ACI 214.4R-10\(^1\) provides guidance on extraction and testing of cores and the physical factors that can contribute to extreme strength results. ASTM E178\(^{14}\) presents statistical tests and criteria to determine whether an extreme test value should be rejected as an outlier. The ASTM E178 test requires the selection of a “significance level,” or the probability that a test result may be improperly rejected as an outlier. A (one-sided) significance level of 1% is commonly used for regular buildings, whereas a significance level of 0.1% may be more appropriate for important structures.

Figure 2 illustrates the ASTM E178 test for outliers for a significance level of 1%. The test statistic is \((\mu - x_{\text{min}})/\sigma\), where \(\mu\) and \(x_{\text{min}}\) are the mean and minimum values in the data set; and \(\sigma\) is the standard deviation computed for the sample including \(x_{\text{min}}\). If the test statistic falls below the dashed blue line, the questionable test result should be accepted, but if it falls within the shaded region, the test result should be rejected. This test statistic can never exceed the solid black line, defined as \((n - 1)/\sqrt{n}\), where \(n\) is the number of cores.\(^{15}\) It is clear from the convergence of the black and blue lines that the ASTM E178 test is not useful for distinguishing outliers unless six or more cores are collected.

Nondestructive Testing

The number of samples and removal of cores to determine concrete properties may potentially be reduced using nondestructive testing (NDT). In particular, the rebound number (ASTM C805\(^{16}\)), penetration resistance (ASTM C803/C803M\(^{17}\)), and ultrasonic pulse velocity (ASTM C597\(^{18}\)) may have the most applicability to existing structures. None of these methods directly measures strength, however, and each has shortcomings related to surface roughness, access to and quality of cover concrete, and presence of reinforcing steel. All are most effective when NDT results are effectively calibrated by direct correlation to strengths of cores obtained from locations evaluated using the NDT method. Further guidance is provided in ACI 228.1R and 228.2R.\(^{19,20}\)

Basis of Proposed Core Requirements for Seismic Evaluation

Equation (1) provides a basis for selecting numbers of cores considering both the desired level of data collection (“usual” or “comprehensive” per ACI 369R and ASCE/SEI 41) and knowledge about the existing structure. For “usual” data collection, the recommendation of six cores from each grade of concrete from Reference 8 is appropriate for a typical cast-in-place building in the absence of original cylinder tests or NDT data. For \(n = 6\) and \(\text{COV} = 13\%\) (Table 2), Eq. (1) indicates that this corresponds to \(e = 10.6\%\). Additional knowledge about the existing structure from original cylinder tests or NDT data allows a larger acceptable \(e\) so fewer cores will be required. For
example, $e$ of about 12% could be selected if cylinders or NDT are available and $e$ of about 14% could be selected if cylinders and NDT are available. However, reductions in the number of cores should only be allowed if the results from the cylinders or NDT confirm the core results. If there is a contradiction, the additional data do not provide further confidence in the core results and therefore cannot justify a reduction of the number of cores required.

These recommendations are illustrated in Fig. 3. For example, if one were considering a cast-in-place building with more-than-typical strength variation (COV = 18%) and with NDT results available, Fig. 3(a) indicates that nine cores would be required from each grade of concrete for “usual” data collection. For “comprehensive” data collection (for an important structure), a decrease in the acceptable $e$ values selected previously for “usual” data collection is appropriate. Figure 3(b) illustrates the recommended number of cores for comprehensive data collection based on Eq. (1) and assumed maximum errors.

References
1. ACI Committee 214, “Guide for Obtaining Cores and Interpreting Compressive Strength Results (ACI 214.4R-10),” American Concrete Institute, Farmington Hills, MI, 2010, 17 pp.
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