These tests may be considered necessary to determine the distribution of forces within the structure, the stress-strain levels and stress ranges at design or at actual service levels, and the deflections and other displacements or rotation when analytical methods alone cannot accurately reflect the true structural response. The nature of the loading systems used in the tests must reflect the nature and magnitudes of the loads superimposed on the structure. In any case, a structural analysis should both precede and follow any load tests. Load test to failure can be performed to determine failure modes and capacity, although load tests to failure are seldom conducted on existing structures, as the structure will be further damaged or destroyed. Load tests to a percentage of capacity (with capacity often defined as the code-specified load requirement) can be conducted but may require that the structure or adjacent area be vacated during the test. Depending on the situation, this may result in considerable hardship (and cost) for people or companies not directly involved with the investigation.

4.6.2 Laboratory Testing

Laboratory testing conducted on samples or components from the element or condition under investigation is a common type of testing. Testing materials or systems in the laboratory enables a wide range of operations to be conducted with much greater efficiency and accuracy than if they were performed in the field. Samples of materials are collected in the field and tested using the controlled conditions of a laboratory. Material, strength, or chemical characteristics are often the goal of this testing. Timber, concrete, metals, plastics, and synthetic materials all have specific testing requirements to determine the relevant characteristics for use in the investigators evaluation and/or analysis. Sampling protocols outlined herein should be evaluated with respect to statistical relevance and the need for a representative sample.

4.6.3 Mock-ups

Mock-up tests can be used to simulate an entire structure or significant portion in a scaled-down size, such that

- The actual structure is not subjected to a test load which may render it useless or un-repairable after testing.
- The model may be caused to fail in various failure modes.
- The entire model can fit in test facilities, such as wind tunnels.
- Scaled-down loads are within ranges available at test facilities.

The test loading system must reflect the nature of the actual loads superimposed on the structure. For example, ultimate static load tests cannot represent failure due to fatigue. A uniform load may not satisfactorily represent a series of concentrated loads.

Examples of mock-ups are scale models subjected to wind tunnel testing, a recreated beam-column connection subjected to cyclic loading, or materials exposed to various conditions in environmental chambers. If the mock-ups are constructed/fabricated at a scale that is different (generally smaller) than the actual structure, or portion of the structure being recreated, the principles of similitude should be considered (in this case, the mock-up should be representative of the true structure with as-built conditions and loading must be appropriately scaled).

4.7 SAMPLE COLLECTION

4.7.1 Determining Sample Size and Distribution

Several ASTM standards exist to guide an investigator in determining sample size if a statistically significant sample is desired. Often a statistically significant sample is not available or economically viable. In this case, it is desired to select a sample without bias. This sample could also be a random sample, but not necessarily, as purely random samples in a failure investigation are often not practical given the constraints of the existing structure. As sample size and distribution is determined, care should be exercised to obtain samples from damaged and undamaged and questionable and non-questionable portions of the structure if applicable.

ASTM E122, *Standard Practice for Calculating Sample Size to Estimate, With a Specified Tolerable Error, the Average for a Characteristic of a Lot or Process*, can be followed to determine the number of samples required for a desired level of accuracy.[1] The number of samples will depend on

- The error, E, that can be tolerated in the estimate of the measured value;
- The preferred probability, or confidence level, that the measured value is within the limit of error; and
- An estimate of the variation, σ, of the measured value from one unit to another within the population.

Assuming that the measured result is normally distributed and that the population is large, the following equation, based on an assumed 95% confidence interval, can be used to calculate the number of samples, n, for testing:

$$n = \left(\frac{1.96\sigma}{E}\right)^2$$

where n equals the number of samples, σ equals the standard deviation of measured results, and E equals the allowable error in the measured result.

The factor 1.96, based on a desired 95% confidence level, gives a 0.050 (5%) probability that the actual value is not within plus or minus the allowable error, E, of the measured property.

The statistical significance of an evaluation should only be reported with the results if the sampling procedure followed appropriately applied statistical principles.

Deterministic sampling describes a situation when a set number of samples are available or sampling is constrained by any of the factors discussed herein and only a set number of samples can be taken (access, effects on the element under consideration, budget, etc.). This sampling protocol requires engineering judgment to ensure that a representative estimate of the characteristic under consideration is obtained.

4.7.2 Methods of Sample Selection

Sample locations should be selected to ensure that a representative estimate of the measured value is determined with the results. Several methods are available to select sample locations. These include, but are not limited to, stratified sampling, random sampling, and systematic sampling. There are advantages and disadvantages to each of the sampling methods depending on the element or condition being investigated. Limitations, such as access, need to be considered when identifying the sampling protocol.

Stratified sampling may be appropriate if subpopulations within the overall population exist. Stratification is the process of dividing the population into homogeneous subgroups (or subpopulations) before sampling. The strata should be mutually exclusive, meaning that every element in the population is contained in only one stratum, and all inclusive, meaning that all samples must be contained in one of the stratum. Once the strata have been identified and divided, random or systematic sampling can be applied within each stratum independently.

With random sampling each sample location is chosen randomly, such that each location has the same probability of being chosen at any stage during the sampling process. One method to achieve random sampling is to generate random numbers to determine which locations are sampled.

With systematic sampling, sample locations are selected at evenly spaced intervals throughout the structure, beginning at a randomly selected starting point. Care should be taken to ensure that the sampling interval is selected so as to not hide a pattern. Systematic sampling is typically easier to execute than random sampling because it may reduce the amount of time spent in the field locating samples.

4.7.3 Budgetary Considerations

The investigator should consider budget during the development of the testing protocol. A larger number of samples will logically result in higher costs. ASTM E 122 addresses this issue by providing a procedure for balancing cost with allowable error, confidence level, and number of samples. In cases where a smaller error and/or higher confidence level is required, the number of samples will increase. The opposite is then true, such that when a larger error and/or lower confidence level is acceptable, the number of samples will decrease. This consideration of budgetary factors should be conducted on a case-by-case basis bearing in mind the objectives for the investigation.

4.7.4 Methods of Sampling by Material Type for Conducting Laboratory Tests

The purpose of testing is to gather information that can help explain the cause of a failure, or factors that led to the failure. If laboratory tests are to be conducted, there are typical samples that are taken, depending on the goal of the testing. The examples below should not be considered all-inclusive but are presented to give investigators a sense of the samples that have been used in other investigations by material type.

Metal samples are often obtained by coring, torch cutting, or sawing with a diamond wheel. Cores or coupons from metal components may be used to assess the strength and metallurgical composition of the material.

Concrete saws may be used to remove large samples. These samples may be used to examine the representative condition of the concrete. Concrete cores can be used to assess chemical properties, strength of concrete, splitting tensile strength, the presence of delaminations, and as a sample source for petrographic studies. Core diameters usually vary in size from approximately 2 in. to 8 in. (5 cm to 20 cm) or more.

Samples from structural timber members may be taken by collecting cores of small clear specimens. Cores can be used to determine wood species and are used to examine for the presence of biological organisms that can reduce strength. Small clear wood specimens of sizes dictated by ASTM D143 can also be used to evaluate wood strength.(2) Occasionally, full-size members are removed for destructive testing (typically, dimension lumber rather than structural timbers).

Masonry samples taken from the structure might include individual masonry materials or masonry assemblages. It might also be necessary to obtain new specimens of the cement or sand that was commonly used in the mortar at time of construction to assist in analysis of hardened mortar taken from the building to determine the proportions of cement, lime, and sand used. Reliable compositional analyses can usually be done on extracted mortar samples; however, trying to replicate the mortar with new materials is difficult and may not be necessary.

4.7.5 Example of a Generic Sample Collection Protocol

The following sample protocol based on examination and testing of masonry is intended to give a sense of the various tasks that might go into a well-defined protocol. A written protocol allows for others involved with the investigation to review and comment on the proposed procedures. Once agreed upon, the written protocol should be kept in the project file and made available during discovery, if requested. Locations for sample removal and specific testing standards to be followed would be defined as the protocol is further developed.

I. Purpose

The purpose of this protocol is for the collection of samples at the subject location in order to evaluate the cause of delamination of brick from the concrete foundation. The samples will be analyzed for compatibility with recognized and generally accepted standards (appropriate standards would be defined) that outline requirements for materials and construction of thin brick veneer. This analysis proposes to determine:

- Buildup of the materials used and thickness
- Location of adhesion loss
- Evidence of surface preparation techniques used
- Potential presence of contaminants at the bond interface, such as concrete form release agent, dust/debris, chemicals, etc.

II. Equipment

- Concrete saw for removal of samples
- Hammer and chisel
- Aluminum SEM sample stubs with carbon tape

III. Laboratory Equipment

- Stereo-microscope
- Scanning Electron Microscope (SEM)
- Energy Dispersive Spectroscopy (EDS/EDX)
- Fourier Transform Infrared Spectroscopy (FTIR)

IV. Field Data Collection

Select four areas of brick attached to the concrete foundation wall.

- Two samples in a delaminated area detected by light tapping with a hammer to determine an area that has become detached from the concrete.
- One sample in an area not delaminated as determined by light tapping.
- One sample in an area that borders the delaminated area.

Sample removal

- A concrete saw shall be used along joints in the brick to the desired depth, but not more than 2 in. (5 cm).
- In the delaminated area, the brick shall be removed by sawing.
- A chisel and hammer shall be used to remove samples from the concrete surface.
- All samples shall be labeled with location and date. They will be depicted on a wall elevation from the architectural plans. Samples shall be enclosed in a sealable plastic bag.
- In the delaminated areas, surface lift-off samples will be obtained using aluminum SEM stubs coated with carbon tape applied to them. A protective film will be removed from the carbon tape surface immediately prior to sampling. Surface lift off samples will be taken on both delamination surfaces.

- Photographs will be taken of the areas before, during and after removal of the samples.

V. Laboratory Analysis

- After general documentation, the samples may require further sectioning to facilitate more detailed observation. Sample cross-sections may be cut to perform microscopy/petrography.
- Stereo-microscopic examination of the sample surfaces will document surface texture and materials on the surfaces, such as efflorescence or debris. Digital images will be taken.
- Depending on the observations in the above investigations, further examination using a scanning electron microscope (SEM) will allow for greater magnification. Semi-quantitative elemental analysis of materials present can be obtained in the SEM using Energy Dispersive Spectroscopy (EDS/EDX). Digital images will be taken.
- Fourier Transform Infrared Spectroscopy (FTIR) may be used to assist in identification of any residues or organic compounds.

Based on findings revealed in the course of the data collection, changes to the protocol may be made. Changes will be permitted only with agreement by participating parties at the site.

While this sample protocol has the tasks necessary for the stated purpose, other protocols may have quite different tasks but will likely conform to this general format.

4.8 REPORTING THE RESULTS FOR USE IN THE INVESTIGATION

Results should be presented in an unbiased and factual manner. The selection of the testing method, sampling protocol, collection methods, reference standards used, and sampling and testing dates and conditions should be identified in the report along with the results. Any deviation from standard test procedures should be identified and the reason for deviation discussed. For example, testing of an element that had smaller dimensions than those dictated in the test standard should be stated, along with any implications of the deviation from the test protocol.

Personnel that conducted the testing should be identified, and their credentials provided when applicable. Interpretation or opinion as to the use or consequence of test results should be presented where appropriate. In some cases, the results will stand for themselves without interpretation. Test reports for standardized tests should be completed and appended to the full report of the investigator, which would outline the interpretation and/or opinions. Any variations from standard test methods should be identified and the justification for these variations presented.

References

[1] ASTM. 2017a. *Standard practice for calculating sample size to estimate, with specified precision, the average for a characteristic of a lot or process*. ASTM E122-17. West Conshohocken, PA: ASTM.

[2] ASTM. 2017b. *Standard test methods for small clear specimens of timber*. ASTM D143-14. West Conshohocken, PA: ASTM.

This page intentionally left blank

CHAPTER 5

Data Analysis and Interpretation

5.1 INTRODUCTION

At this point in the investigation, the data should have been collected from several sources. As indicated in Chapter 3, these sources may include the historical documents from the original design, construction, maintenance, and repair of the facility, data collected in the field regarding the actual physical conditions before and after the failure, and the observed deterioration or damage of the item, structure, or facility being investigated. As part of the investigation, materials or assemblies may have been tested in the field or laboratory to determine material or assembly behavior using parameters intended to replicate conditions at the time of the failure. The next step is data analysis and interpretation. Data analysis and interpretation may be the culmination of, possibly, months or years of investigative effort. Have the questions asked of the investigator been answered with a defined level of certainty? Was the cause (or causes) of failure identified? Were the culpable parties, if any, determined?

To answer those questions, all the data collected needs to be reviewed, synthesized, and analyzed in accordance with the scientific method. The scientific method is a method of research in which a problem is identified, relevant data are gathered, a hypothesis is formulated from the data, and the hypothesis is empirically tested. When a hypothesis is confirmed to an acceptable level of certainty, it may be presented as a conclusion or the most likely conclusion.

The steps in developing the potential failure hypotheses and preliminary conclusions include

1. Analyzing the data collected from the field, field or laboratory tests, photographs, and the collected documents.
2. Developing and investigating alternative hypotheses of the cause of failure.
3. Using computational modeling and analysis, experimental testing, or cognitive reasoning to validate or exclude potential hypotheses.
4. Comparing the accumulation of evidence for each hypothesis and developing preliminary opinions and conclusions.

5.2 DATA ANALYSIS

After data has been collected from the field and document review, the data needs to be analyzed and hypotheses developed using inductive reasoning. With a robust and properly managed data collection process, the investigator may use their experience and knowledge in combination with specific observations to develop general hypotheses. Data obtained during the investigation should be retained and applied to the hypotheses. If there is data or other forms of evidence that appear to invalidate or oppose the considered hypotheses, such conditions should be investigated further to determine the feasibility of the various hypotheses.

ASTM E678, *Standard Practice for Evaluation of Scientific or Technical Data*, is a good resource document for discussion of this evaluation process.[(1)] As indicated in this standard, the evaluation includes identification of the source of the data, determination of the validity of the source of the data, and determination of the relevance of the data. Proper cataloging of the data with the source information is helpful in the evaluation. ASTM E860, *Standard Practice for Examining and Preparing Items that are or May Become Involved in Criminal or Civil Litigation*, is another useful document regarding handling of data and determining its validity.[(2)] It is important to note that not all collected data may be pertinent to the focus of the investigation. The source validity can be compared to data that has been documented in peer-reviewed professional journals or to other standard practices applicable to the testing of data. Alternatively, professional judgment may be required to evaluate the relevance of data as indicated in Section 5.1.4 of ASTM E678.

Examples of collected data include original construction drawings and specifications, topographic survey data, measurements of structural elements or appurtenances, photographs of the site and structure, reports, laser-scanned images, field tests, material samples, and interviews.

Construction drawings may be compared to actual measurements and photographs for validation to identify discrepancies that could impact behavior and may have contributed to the failure. As-built drawings and shop drawings are helpful in assessing the accuracy of construction drawings. As-built drawings are drawings that were marked by the engineer or contractor with changes that were made during the construction process. They are generally more accurate than bid documents, but many times do not have all construction changes included. Requests for information (RFIs) and reports generated during construction often provide a good record of changes made during construction that are not on as-built drawings. Shop drawings of components are helpful to show the fabricated dimensions, materials specifications and connections. They can be compared to as-built construction drawings and field dimensions for validation.

Topographic or laser-scanned survey data and in-place component measurements can be validated by cross-checking measurements using different methods while keeping in mind the precision, make, model, calibration and accuracy of the measuring instruments.