Structural Failure Investigations

The skills required of a forensic engineer differ from those of a design engineer, but the analysis of a structural failure can provide much benefit in the design and construction of new projects.

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Investigations of structural failures are conducted for a variety of purposes. Most commonly, when a structure collapses there is litigation involved, and the forensic engineer may be retained by a party who represents a plaintiff's or defendant's interest in order to determine what went wrong and who is responsible. A particular challenge for the forensic engineer in this role is not to succumb to pressure to compromise objectivity and impartiality when answering to a client with a particular bias. For failures less catastrophic than a collapse, the forensic engineer may be retained by the owner or manager of a building, or insurance company, to diagnose structural malperformance and prescribe a remedy — litigation may not be anticipated at all. Occasionally, an investigation may be commissioned simply to tell the general public or a government agency what went wrong. The National Bureau of Standards (NBS), now the National Institute of Science and Technology (NIST), has been called upon by government groups to perform in this role. For example, the U.S. Senate and the Mayor of Kansas City asked the NBS to investigate the 1981 walkways collapse at the Hyatt Regency in Kansas City so that the public would have an explanation for this disaster.[1] In addition, the Occupational Safety and Health Administration (OSHA) retained the NBS to determine the cause of the failure of a cooling tower at Willow Island, West Virginia, in 1977[2] and the collapse of the L'Ambiance Plaza in Bridgeport, Connecticut in 1987.[3] The purpose of these investigations was to assist OSHA in assessing fines.

Generally, while the structural engineering profession has no direct means of authorizing investigations to determine what lessons may be learned from failures, many individuals and groups have been active in gleaning what has been learned from investigations conducted for other purposes and disseminating those lessons to the profession. With a breadth of purposes comes a breadth of client types. Some of the types of individuals and organizations that make use of structural investigations are:

- Owners;
- Developers;
- Public and government agencies;
- Plaintiffs in litigation (injured parties);

- Defendants in litigation (parties involved with design, construction, maintenance or operation);
- Tenants;
- Attorneys;
- Insurance companies;
- Materials manufacturers;
- Designers; and,
- Contractors.

Forensic engineers may be called upon to determine two types of causes of failure: *technical causes* and *procedural causes*.

Technical causes are the actual physical proximate causes of failure. For example, the hanger-rod-box-beam connection at Line U2 ruptured. Or, the roof collapsed due to a 150 percent overload from drifting snow. Or, the timber truss failed by buckling of the fourth compression diagonal. Often compounding problems lead to failure, and determining the relative contributions from various structural defects is challenging. Sometimes compound defects are so debilitating that the challenge is not to determine why the structure fell down but rather why it stood for as long as it did.

Procedural causes are the human error, communication problems or shortcomings in design, construction or maintenance that were responsible for the flaws that led to the technical cause. For example, the welding of the hanger-rod-box-beam connections did not meet the design requirements. Or, the structural engineer neglected the effects of drifting snow in the design. Or, the carpenters omitted critical bracing for the truss diagonals.

Often, determining the procedural causes is the more difficult but important aspect of an investigation, particularly for determining the lessons to be learned. Neal FitzSimons has estimated that 90 percent of failures are due not to a lack of technical information, but to procedural errors.[4]

Several available guides for conducting investigations describe particular techniques.[5-12] Similarly, there are available guidelines and standards for material-specific or test-specific methods.

The term *forensic* is often misunderstood since it has two meanings in engineering. In the most literal sense, it relates to court or other public disputes. More generally, and as used by the American Society of Civil Engineers Technical Council on Forensic Engineering (ASCE/TCFE), it means all of the activities involved with investigating the causes of failure or malperformance. Indeed, it is typically the case that only a small fraction of the forensic engineer's work is involved in litigation activities. The latter, broader definition is the focus herein.

Project Initiation

Project Objective & Scope. As with any consulting assignment, the project usually begins with a meeting or phone call during which the potential client describes his or her needs and objectives for the investigation. A few special recommendations for the initial contact in a forensic investigation follow:

- Always check to ensure that there are no conflicts of interest in undertaking the assignment. Until such a check has been made, caution the potential client not to reveal confidential information that could jeopardize the client's position (such as a theory for attacking the litigation) should the engagement have to be declined due to a conflict. Otherwise, the potential client could have grounds to completely disqualify the engineer from the case. (See *Recommended Practice for Design Professionals Engaged as Experts in the Resolution of Construction Disputes).*[13]
- Beware of "takeout moves," wherein the client agrees to engage work, forwards an executed contract, possibly with a small retainer, but then does not extend any work. The purpose is to inexpensively exclude an engineer from working on the behalf of others. It happens.
- Inquire as to the client's motives and the degree to which the engineer will be free to perform an objective investigation in order to form opinions with a reasonable degree of engineering certainty (see Recommendation 12 in Ref. 13). Resolve any scope issues now or refuse the engagement.
- Carefully examine the potential client's objectives. If the client intends to use the

investigation to support a certain point of view in trial, and it is unlikely that the investigation and analysis will be able to support that point of view, inform the client at the beginning. It is always better to be honest up front, even if it means refusing the assignment.

Conflicts of Interest. The guide *Recommended Practice* states:[13]

> Regardless of the expert's objectivity, the expert's opinion may be discounted if it is found that the expert has or had a relationship with another party which consciously or even subconsciously could have biased the expert's services or opinions. To avoid this situation, experts should identify the organizations and individuals involved in the matter at issue, and determine if they or any of their associates have or ever had a relationship with any of the organizations or individuals involved. Experts should reveal any such relationships to their clients and/or client's attorneys to permit them to determine whether or not the relationships could be construed as creating or giving the appearance of creating conflicts or interest.

Conflict avoidance in large organizations is difficult. A computer database of current and past projects can be used by a firm to try to identify potential conflicts.

Establishing the Investigative Plan. To determine the technical causes of failure, the goal of the investigation is to establish:

- The mode and sequence of the failure;
- The demands (loads) acting on the structure at the time of the failure; and,
- The capacity of the structure at the time of the failure.

The process usually involves developing hypotheses regarding the causes of failure and then analyzing and testing those hypotheses. With effort, certain failure theories are eliminated and, it is hoped, in the end, the facts will support one theory. Sometimes the investigation reveals that the demand on a certain part of the structure exceeded its capacity for one and only one failure mechanism and that mechanism is consistent with the evidence of the mode and sequence of the failure. Sometimes the results are not so straightforward.

From the outset, the forensic engineer creates an investigative plan, a common general flow chart for which is given in Figure 1. However, not all investigations entail using every step, and the investigative plan is continuously revised to account for evolving theories and information. Some investigators have developed elaborate flow charts for the investigative process (such as those shown in Blockley[12] and Kaminetzky[14]).

Establishing the Investigative Team

Qualifications of the Investigator. By education, structural engineers are trained generally for the design and construction of new works. To the author's knowledge, no universities offer degree programs in forensic engineering, although a few offer courses in failure causes.

Structural design and structural investigations require very different approaches. The first is a process of synthesis; the second, one of analysis. Design requires, among other things, an ability to create a cost-efficient load-bearing scheme in accordance with a set of "rules" prescribed by building codes for minimal design cost. Simplicity and optimization are paramount. However, investigation requires a structured approach of data collection, and the development and scrutiny of failure hypotheses. Advanced analyses, precision, attention to detail and patience are key. For these reasons, good structural designers do not necessarily make good investigators and vice versa.

The key to proficiency in either discipline is experience, and any individual with interest in structural failure investigations should make a thorough review of available literature. A review of this literature not only provides insight into investigative processes and techniques, but it also demonstrates the common ways that structures fail. A veteran investigator of thousands of failures, Jack Janney, once remarked, "structures nearly always fail by buckling or where loads must turn a corner" (see Figures 2 and 3 on pages 67 and 68, respectively). While quite a generalization, this statement is not far off the mark. It is this type of real-world understanding of why build-

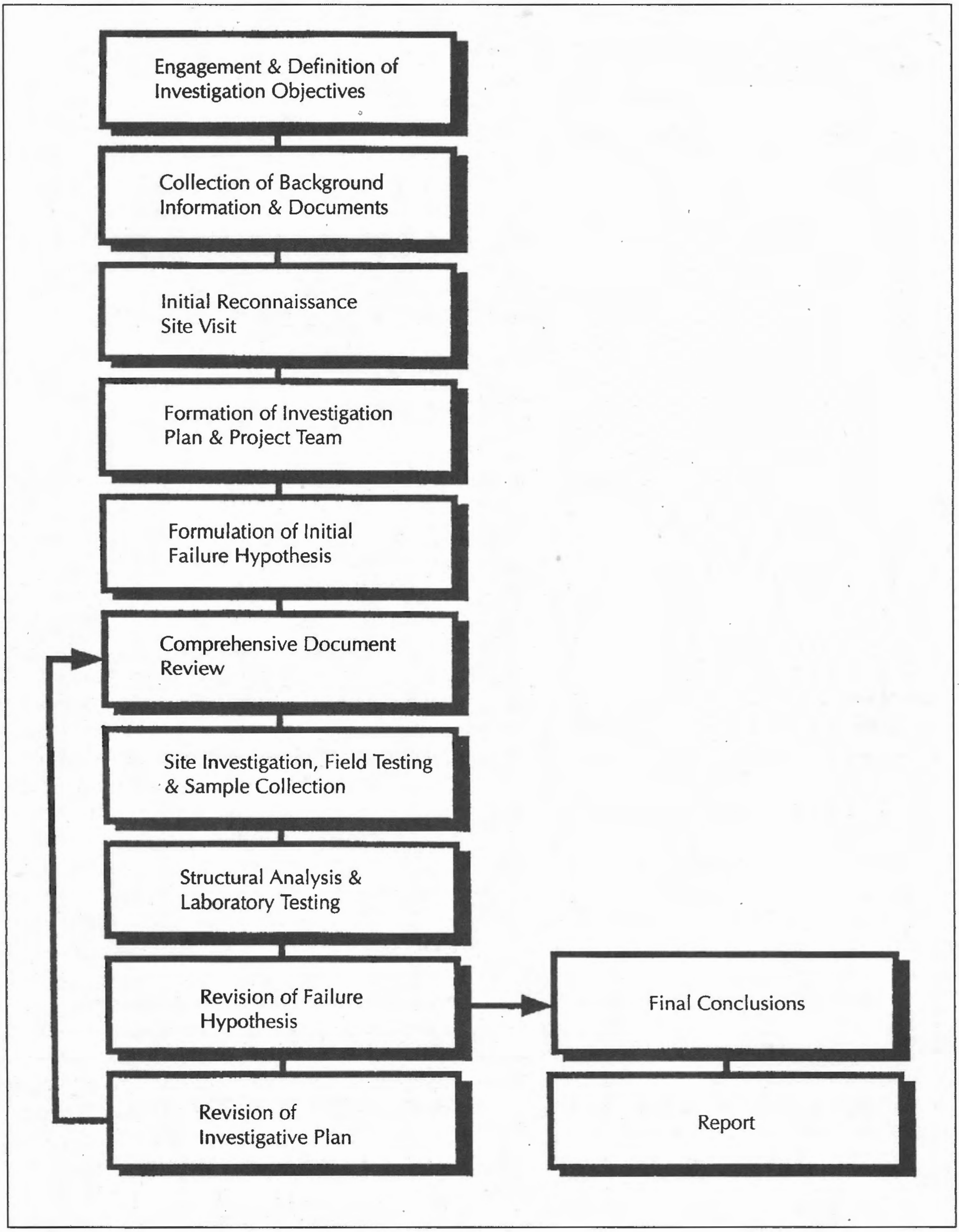

FIGURE 1. The investigative process.

ings stand and why they actually fail that, in part, differentiates a good investigator from a good designer.

In addition to technical skills, the forensic engineer requires outstanding characteristics in the following areas:

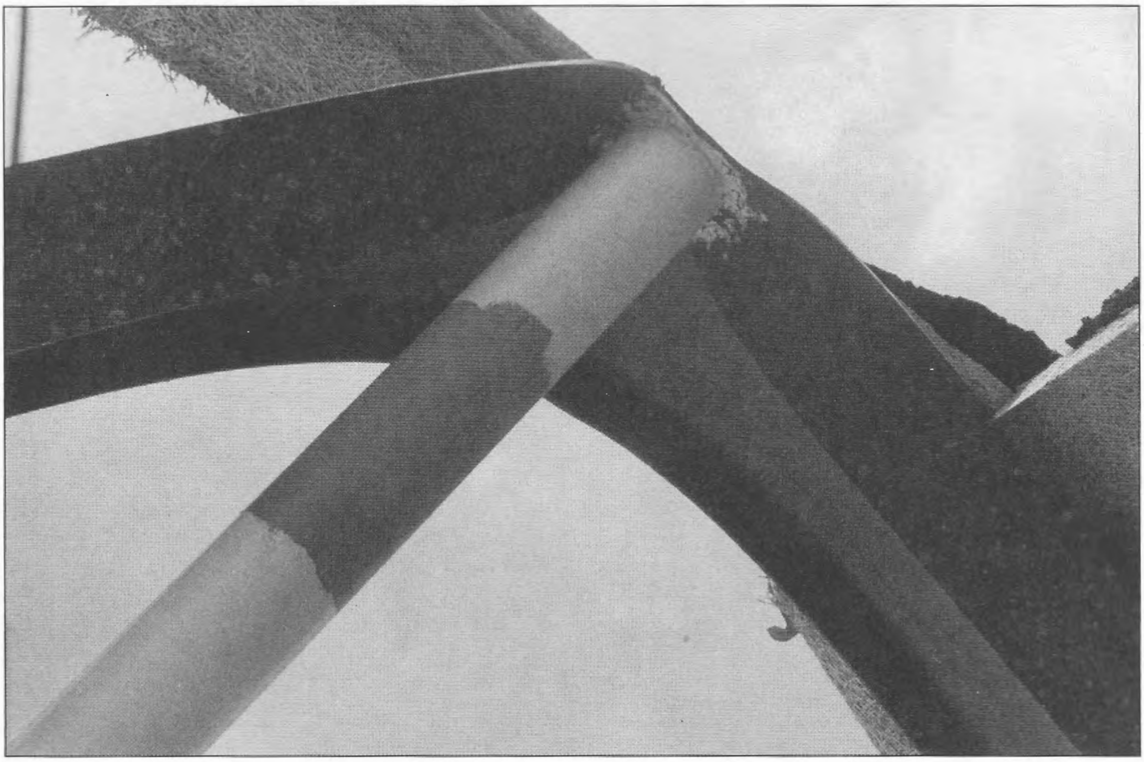

FIGURE 2. Roof failure by buckling of the beam/column joint.

- Credentials that grant credibility to the individual's opinions;
- The ability to convey often complex issues simply and convincingly to lay people;
- Absolute honesty and the ability to work impartially under pressure from individuals with partial interests;
- Stamina and constitution to sustain the stress of litigation proceedings;
- The ability to remain composed under sometimes hostile examination; and,
- When called upon to convey opinions regarding procedural causes of failures, knowledge of the standard of care of practitioners in the industry.

Available Guides. The process of investigating failures will never follow standard procedures. Each investigation is different and requires a tailored approach. Nevertheless, there are some useful guidelines for conducting investigations. The most noteworthy are:

- *Guidelines for Failure Investigation,* by the ASCE/TCFE Task Committee on Guidelines for Failure Investigation;[5]
- *Guide to Investigation of Structural Failures,* by the ASCE Research Council on Performance of Structures;[6]
- *Building Failures – A Guide to Diagnosis, Remedy and Prevention,* by Lyall Addleson;[7] and,
- *Building Pathology, A State-of-the-Art Report,* CIB Report Publication 155.[15]

In addition, there are a number of useful articles on the subject.[9-12,14]

Sources of Failure Information. For anyone interested in the study of failure investigations, the ASCE *Journal of Performance of Constructed Facilities* is highly instructive. Published quarterly, that journal contains case studies of individual failure investigations as well as articles on particular failure issues. In addition, failure books and articles are often published in other industry literature.[16-30]

Some of the most thorough and well documented reports of failure investigations are

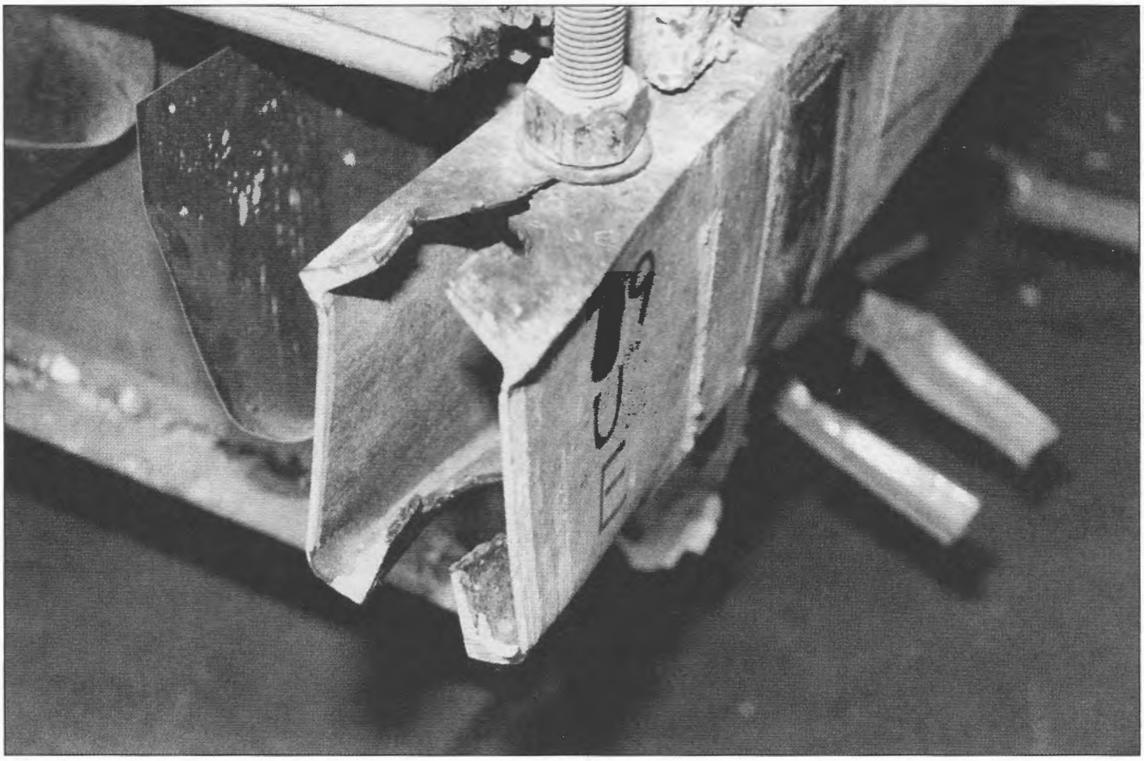

FIGURE 3. Failure by connection tear-out.

those of the NBS/NIST. Among others, the NBS/NIST has investigated the 1981 Hyatt Regency, Kansas City walkways failure,[1] the 1981 collapse of the Harbour Cay Condominium in Cocoa Beach, Florida,[31] and the 1988 collapse of L'Ambiance Plaza in Bridgeport, Connecticut.[3]

Team Organization. In large, complex investigations it is rare for the Principal Investigator (PI) to possess all of the requisite technical skills. Therefore, the PI may rely on specialty subconsultants in such areas as:

- Materials behavior;
- Testing and instrumentation;
- Special loads effects (*e.g.*, wind); and,
- Special analysis techniques.

A comprehensive list of the specialists on which the PI may rely is given in Table 1. The qualities required of these specialists are generally the same as those that are required of the forensic investigator. The forensic engineer should have pre-established relationships with such specialty consultants, so that they may be summoned on short notice when a structure fails.

When working on large, complex cases, strong project management involving the establishment of clear lines of communication and responsibility is essential. Periodic updates of the investigative plan must be conveyed to the entire team. Continuous quality control/assurance over in-house staff and external subconsultants must be exercised.

Cooperative Efforts With Other Investigators. Investigations can be expensive, and available debris for testing and examination limited. For these reasons, investigators answering to parties of different interests sometimes cooperate in the data collection and testing phases of an investigation, which was the case, for example, in the Hyatt Regency walkways collapse, where there were numerous experts representing a number of parties. Critical structural components from the debris needed to be tested destructively. The interested parties assembled and agreed that the NBS would perform the necessary laboratory analysis and testing, using procedures agreed to by all experts. All ex-

TABLE 1.
Specialist Consultants

Aerodynamics	Field testing	Photoelasticity
Aluminum	Fracture	Photogrammetry
Architecture	Geology	Pile driving
Blasting vibrations	Geotechnical engineering/ foundations	Pipelines
Climatology	Glass	Pipes
Cold weather construction	Ground water	Plasticity
Composite materials	Hydraulics	Plastic materials
Computer design	Hydrodynamics	Prestressed concrete
Concrete materials	Impact	Probability theory
Construction equipment & methods	Masonry	Protective coatings
Corrosion	Mathematics	Railroads
Cost estimating	Measurement technology	Shoring
Data systems	Meterology	Stability
Dynamics & vibration	Nondestructive testing	Statistical analysis
Elasticity	Ocean engineering	Steel
Electronics	Offshore construction	Surveying
Engineering mechanics	Painting	Waterproofing
Environmental engineering	Parking engineering	Welding
Fabrication	Pavements	Wind
Fatigue	Petrography	Wood

perts were allowed to witness the testing, and data were shared.

The Investigative Process

Analysis Versus Synthesis. When investigating a structural failure, a forensic engineer cannot think like a designer. Whereas in the design process the designer has the freedom to arrange the structure to behave the way he or she wants, after a structural failure there is no such control — the structure has already behaved the way it wanted.

Building code methods that designers use are assumed to be conservative, but they do not always describe structural behavior well. For example, just because a structural steel beam may be loaded to its theoretical yield point (allowable stress times factor of safety), it cannot be assumed that the beam will collapse. The beam has post-yield capacity; it can strain harden; there may be redundancy and alternate load paths; and, the yield strength is likely to be higher than the minimum specified. The more redundant and ductile the structure, the more likely it will yield, redistribute load and continue to maintain load-bearing ability. The investigator must take all of these factors into account.

Simple and conservative techniques — the hallmark of good design — are not appropriate for investigations. In an investigation, greater precision is required, advanced analysis is often called for, all facts must be verified and any unconfirmed assumptions can lead to costly errors.

Development & Analysis of Failure Hypotheses. A mistake sometimes made by novice and experienced investigators alike is to fail to consider all possible failure hypotheses. All probable hypotheses must be developed and systematically analyzed until they either can be proven or disproved. Key in developing failure hypotheses is to study carefully the configuration of the debris after the failure, and then try to imagine all of the different failure sequences the structure could have undergone to arrive at its final configuration. The structure tells a story that should be listened to carefully.

Establishing the Actions on the Structure. Dead loads are verified by cataloging observations from field investigations. Sometimes it is necessary to weigh existing components, material samples or assemblies. Often dead loads are less than the allowances made during design, but they may be greater. Long-term maintenance and modification can lead to increased dead loads in the form of additional roofing membranes, ceilings or mechanical equipment. Leaky roofs and walls saturate components. In cast-in-place concrete construction, structural deflections due to the "ponding" of wet concrete have led to slabs thicker than required by design.

Live loads, of course, take many forms and often are difficult to verify. Snow, ponded water, furniture and equipment, and human occupancy are the common forms of live load. Cataloging, sampling and weighing, and eyewitness accounts are all available forms of data collection for determining live loads. The increasing use of video security surveillance cameras often affords an invaluable source of information regarding loads and sequences of failures. Load effects other than those caused by gravity also cannot be overlooked. They may include temperature, shrinkage and creep, wind and seismic, vehicular impact, vibrations from equipment and foundation settlements — to name a few. Live load behavior may vary from simplified assumptions. For example, some materials will tend to arch over relatively flexible structural components.

Establishing the Capacity of the Structure. Usually the first step in determining the capacity of the structure is to review the structural drawings for the project. While drawings can be a great time-saver in establishing the overall structural configuration, they can lead an investigator down an erroneous path if they are relied on without critical verification. Dimensions and member sizes often must be confirmed. Material strengths may require certification. The amount of verification required to reach conclusions with a reasonable degree of engineering certainty may be enormous; occasionally it is practically impossible.

Structures may deteriorate from the as-built condition from a number of effects such as:

- Water intrusion and other corrosive effects;
- Fatigue;
- Damage from nearby blasting, traffic vibrations or adjacent construction; and,
- In concrete, material degradation from chloride attack, alkali-silica reaction or delayed ettringite reaction.

Following documentation of the as-built condition, the determination of strength may come from load testing, from calculations, or both. It should be noted that non-structural elements, most notably exterior walls and interior partitions, may play an unintentional role in the behavior of the structure by interacting with the structural frame.

Advancement of Failure Hypotheses. Over the course of an investigation, failure hypotheses are continuously tested by the facts and the results of testing and analysis. Some hypotheses may be disproved and dropped, while new ones may be advanced. It is generally advisable to assemble the investigative team shortly after the initial site investigation for a brainstorming session on failure hypotheses.

Document Review

Sources of Project Documents. Project documents are key to understanding not only how the structure was built but also how it was maintained and modified over time. Without such documents the job is difficult for a project of any complexity. Whenever possible, the investigator should obtain and review at least the most fundamental design documents prior to initial site investigation. Project documents are also key when the forensic engineer is called on to opine on the procedural causes of the failure in that they provide insight into the actions of those responsible for the design, construction and operation of the facility.

Common sources of project documents are from:

- Architects and engineers involved in the original design, modification or repair of the facility;
- Past and present owners;
- Past and present building managers;
- General contractor and/or construction manager for the original construction, modification or repair of the facility;
- Subcontractors involved in the original construction, modification or repair of the facility;

TABLE 2.
Project-Specific Documents Used in Investigations*

Contract drawings (including all revision issues thereof)
- Structural (including progress prints)
- Architectural (including progress prints)
- Mechanical (HVAC)**
- Electrical**
- Plumbing**
- Lighting**

Contract specifications
- Technical sections of interest
- General conditions
- Supplementary general conditions
- Special conditions

Contracts
- Owner/architect
- Architect/structural engineer
- Contract revisions
- Addenda
- Bulletins
- Field directives
- Change orders
- Any correspondence authorizing change to the structure from the contract requirements

Shop drawings & other submissions
- Structural steel (detail drawings & erection drawings)
- Bar joists & prefabricated trusses
- Metal decking
- Reinforcing bar
- Product data

As-built drawings

Field & shop reports (including construction photos)
- Structural steel inspection laboratory (including weld & bolt inspection)
- Concrete inspection laboratory (reinforcing steel, formwork, concrete)
- Concrete mix designs
- Clerk of the works
- Structural engineer
- Architect
- Construction supervisor's daily log
- Local building inspector
- Owner's or developer's field inspectors

Materials strength reports or certification
- Concrete compressive strength
- Masonry prism strength
- Steel mill certificates
- Welding procedures (*e.g.*, type of electrodes, required preheat)
- Fastener certification
- Results of special load tests

Project correspondence
- Owner/consultant
- Intraconsultant
- Owner/contractor
- Consultant/contractor
- Transmittal/records
- In-house memoranda
- Records of meeting notes
- Records of telephone conversations

Consultant reports
- Feasibility studies
- Progress reports
- Soils consultant reports (including boring logs)

Calculations
- Primary structural engineer
- Reviewing structural engineer
- Specific subcontractor's engineers (where required by contract)

Maintenance & modification records

Notes: *The scope will vary depending on the investigator's assignment.
**Assist principally in establishing dead loads.

- Developer of the facility;
- Construction mortgagee of the facility;
- Materials or systems suppliers for the original construction, modification or repair of the facility;
- Previous or other current investigators;
- City, town or state building departments; and,
- Testing agency involved in the original construction, modification or repair of the facility.

Types of Available Documents. Table 2 contains a comprehensive list of documents that may be useful for failure investigations. Documents of the non-structural trades — architectural, mechanical/electrical, etc. — are often useful for determining dead loads on the structure. In addition, non-structural elements may play an unintentional role — positive or negative — in the structure's loadbearing capacity.

The importance of materials produced subsequent to the issuance of the design documents — addenda, shop drawings, bulletins, and field inspection reports — should not be underestimated since they often provide critical information about the departure of the structure from the structural drawings. In addition, as-built drawings are rarely accurate.

Field Investigation

Access to & Control of the Site. Particularly following a large, catastrophic failure, the PI must verify his or her rights and limitations regarding access to the site and activities there. (Often disaster sites are controlled by local or state police or national guard.) Who has authority over site access and who is authorized to admit investigators to the site? Are there limitations on where the investigator may go and may do? Does the investigator have authority to alter evidence by moving debris or collecting samples?

Site Safety. Collapse scenes can be dangerous places (see Figure 4). Once, during an investigation of the collapse of an earth-covered garage, a second section of the garage collapsed.[32] Thus, the leading concern of every team member must be the safety of the team as well as others at the site. There are other hazards in addition to direct falling hazards that are of concern. Sometimes failures lead to the release of environmental hazards. Also, investigators may be entrapped in confined spaces. Many OSHA regulations define procedures for construction site safety, training and certification that are relevant to field investigations.

Where rescue operations are ongoing during field investigations, such operations must take precedence over the investigator's interest in data collection. If the investigator arrives on site shortly after the failure while rescue operations are underway, it may be necessary to suspend investigative efforts to lend special expertise to the rescue effort.

Sample Removal. The PI establishes the overall project protocol for identifying, cataloging, removing, shipping and storing samples. It is recommended to mark each sample with a permanent marker and then photograph it before it is removed (see Figure 5). Note any existing damage or distinguishing characteristics before removing the artifact from the structure. Samples that may deteriorate quickly after removal may have to be environmentally protected. Fracture surfaces may be sprayed with a clear acrylic coating, for example. Moisture-sensitive materials may be placed in sealed bags or other containers, sometimes with desiccants. It is important to maintain a traceable chain of custody of samples so that the sample's origin and handling can be verified without question.

Required Scope of Observations & Sampling. The sampling program should be based, in scope and content, on the presumed failure hypotheses. The number and location of the samples should be carefully planned and will depend on a number of factors such as:

- The variation from sample to sample;
- The degree of reliability required in the results;
- Whether or not there are any explainable trends in the test results (*e.g.*, differing batches of concrete); and,
- The size of structure.

In straightforward cases, the number of samples may be established from statistical principles such as set forth in Ang and Tang[33] or ASTM E105[34] and ASTM E141.[35] Material-specific recommendations are also available in ASTM and other standards.

Observations & Documentation. The PI establishes the overall grid/identification system for the structure. The PI also determines the procedures for sample cataloging, photograph identification, observations openings, etc.

The PI should visit the site early in the process (during the initial site visit if possible) to gain general familiarity with the site. It is important to establish to the extent possible the degree to which the debris may have been modified by others. Subsequent members of the team should similarly obtain a general overview of the site before detailed examination. Each investigator should have his or her own kit of basic tools as well as standard safety

FIGURE 4. Failure sites can be dangerous places.

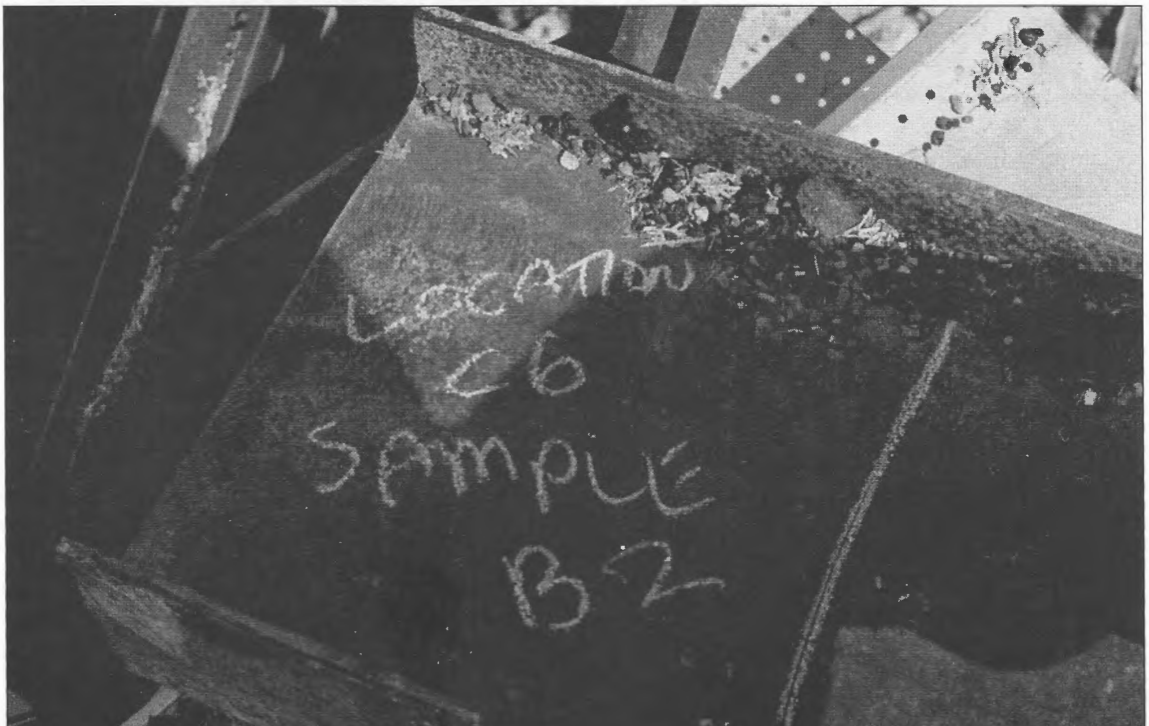

FIGURE 5. Label and photograph each sample before removing it.

TABLE 3.
Small Tools & Equipment Used in Field Investigation

Measurement	10-inch dial caliper; 12-inch steel ruler; 20-foot tape; 100-foot tape; Optical comparator; Tape-on crack monitors
Tools	Hammer; Screwdrivers; Prybar; Pocket knife; Flashlight
Photographic	Film; Camera; Lenses; Flash; Batteries; Lens papers
Clothing	Hardhat; Coveralls; Steel-toed workboots; Gloves
Stationery	White-lined paper; Calculation pad; Architect scale; Pencil & leads; Eraser; Field notebooks; Triangles; Felt markers; Clipboard; Lumber crayons
Books	AISC manual; ACI code; Other applicable failure guides
Other	Calculator; Stick-on labels; Wire-on labels; Plastic sample bags; Duct tape; Job file; Spray paint; Dictation recorder & tapes

gear (*e.g.*, hardhats and steel-toed shoes). A suggested equipment list is given in Table 3. Field support specialists usually included on a site investigation are:

- Surveyors;
- Concrete coring or sawing technicians (for sample removal);
- Welders (for sample removal);
- Photographers;
- Crane operators;
- Shoring specialists;
- Field and laboratory testing technicians;
- Measurement technicians; and,
- Witness interviewers.

Investigators use a number of techniques for recording field observations and activities. Some keep separate logs of samples, sketches, discussions and general observations. It is preferable that each team member keep a running diary of all field activities, for example in a spiral bound notebook. That way there can be no question as to who was responsible for what observation and at what point in time the observation was made. It is often important to know at what stage or in what context various activities took place. Also, it is much less likely that notes will be misplaced. Common field activities that require recording are

- Sketches of the overall failed configuration;
- Observation of the behavior of adjacent construction during and subsequent to the failure;
- Detailed sketches of critical members and connections;
- Inventory of construction materials to establish dead loads;
- Observation of deterioration;
- Information regarding detailed as-built conditions, including plan and detail dimensions;

- Description of fracture surfaces;
- Notes of samples removed;
- Procedures and results of field tests;
- Indications of environmental conditions acting on the facility at the time of failure;
- Log of photographs; and,
- Notes of conversations with others.

The individual logs or summaries of observations of activities of many investigators can be compiled at a later time from these individual diaries. Sketches and photographs are better than lengthy verbal descriptions (either in writing or tape recording) since they can record more information in a shorter space and are less likely to be misinterpreted.

The speed of observation and data collection may be important in an ever-changing site where rescue operations are ongoing and evidence is being destroyed. The experienced investigator quickly assesses the probable failure hypotheses and targets the field work accordingly.

Field observations are made and recorded on three scales:

- *Overall Configuration:* How did the structure fail? Note movements from initial position and relative positions of components. What is the relationship of damaged and undamaged components? Examine the interfaces of damaged to undamaged components.
- *Member & Connection Configuration:* How are members bent and fractured? Examine fracture surfaces.
- *Materials:* Is there degradation (corrosion, spalling, cracking, rot)? Are there signs of distress (*e.g.*, flaking paint)?

Photography is an essential recording medium, and, while some investigators prefer to use professional photographers, others prefer to take their own shots. The investment in good 35 mm camera equipment and in the time to develop photographic skills may be worth it. Videos are useful to convey action, but video cameras can be more cumbersome to use.

Early in the investigation, good overall aerial shots are invaluable to establish the overall failed configuration and conditions at the site. Such shots may be obtained from an adjacent building, from an aerial lift or from aircraft.

Field Tests. Field testing generally falls into two types: load tests and materials tests. Load tests are useful when an undamaged portion of the structure remains that is representative of the failed section (see Figure 6). They are particularly useful when the structure is severely deteriorated. However, they can be expensive, particularly when several tests are required to obtain statistical significance. Some things to bear in mind regarding full-scale load testing are:

- A number of loading methods are available, including hydraulic jacks, mechanical jacks, water or other weights, and air bags.
- Redundancy in instrumentation is helpful to ensure reliability in results.
- If possible, calibrate equipment before and after testing.
- Safety is critical. Have a safeguard (such as shoring or immediate load relief) in place in the event that the structure begins to fail catastrophically.
- In cases involving many parties in a litigation, it is often appropriate or even required to afford other parties the opportunity to witness tests.
- The portion of the structure being tested must be isolated from structural and nonstructural elements that are not part of the test.
- Some form of back-up or verification of the test results are advisable, either corroborating calculations or another form of test.

ASTM Publication STP 702, *Full-Scale Load Testing of Structures,*[36] provides additional information on this subject. There are also a number of ASTM standards on material or assembly-specific tests.[37-43]

In-field materials tests are numerous and are set forth in many documents. Two comprehensive guides are ANSI/ASCE 11-90, *Guideline for Structural Condition Assessment of Existing Buildings,*[44] and the Institution of Structural Engineers, *Appraisal of Existing Structures.*[45]

Eyewitness Accounts. Eyewitness accounts may not be fully reliable. This unreliablity is not because people are intentionally dishonest, but because most lay observers are not trained

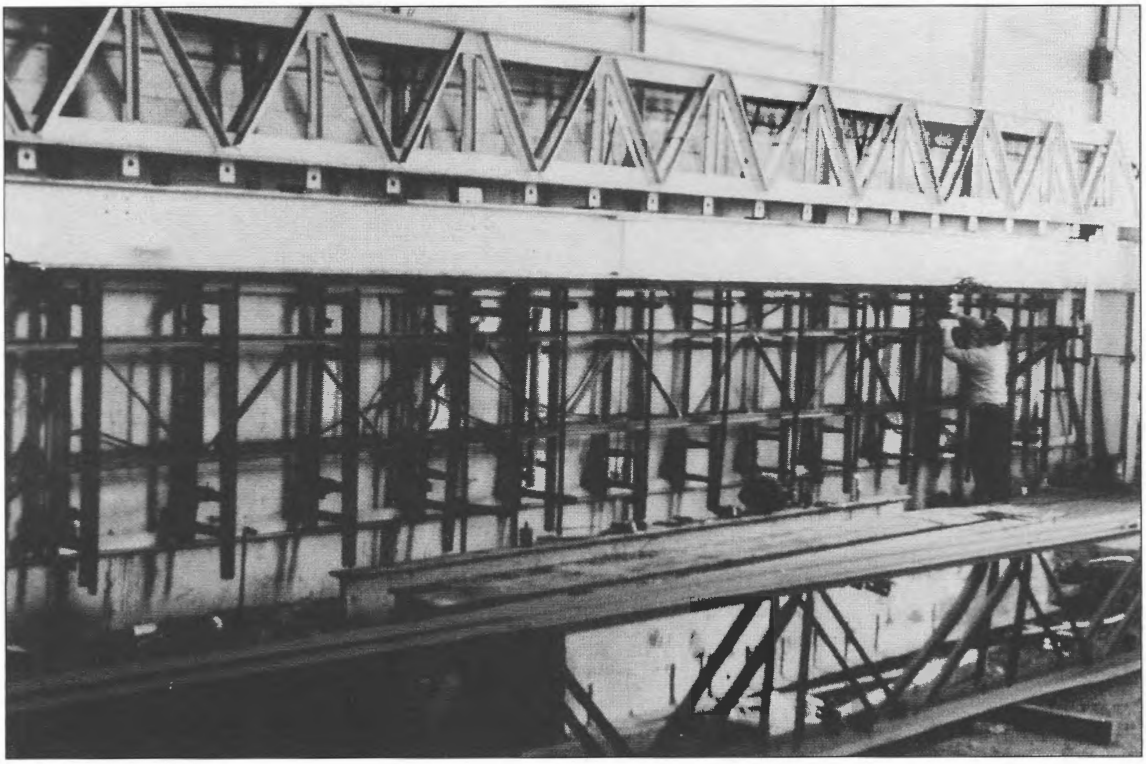

FIGURE 6. Full-scale load testing of a bar joist.

in structural engineering, and the experience of witnessing a traumatic collapse can leave memories distorted. Nevertheless, eyewitness accounts can be useful for obtaining clues and for corroborating other evidence. Janney provides useful guidelines for gathering and evaluating eyewitness accounts.[6]

Laboratory Analysis

Materials Testing. The testing of materials samples that have been removed from the structure may take many forms.

Some of the more common laboratory techniques for the testing of metals are:

- *Basic Mechanical Properties:* yield and tensile strength, elongation, reduction of area, modulus of elasticity, fatigue properties.
- *Fractography:* failure analysis of fracture surface, usually with an optical or scanning electron microscope (see Figure 7).
- *Fracture Toughness:* Charpy V-Notch, fracture toughness, nil-ductility transition temperature.
- *Welding:* radiography, visual, dye penetrant, ultrasonic, magnetic particle, eddy current, metalograph.
- *Hardness:* Brinell, Rockwell, Vickers, and Knoop.
- *Metallurgy & Quantitative Analysis:* Chemical composition, grain analysis, phase type, flaw detection.

Some of the more common laboratory techniques for the testing of concrete and other cementitious materials are:

- *Basic Mechanical Properties:* compressive strength, tensile strength, shear strength, modulus of elasticity, density, bond strength, fatigue strength, abrasion resistance.
- *Dimensional Stability:* creep and shrinkage, coefficient of thermal expansion.
- *Petrographic Analysis:* quantitative analysis, air content, degree of hydration and carbonation, alkali-carbonate reaction, alkali-silica reaction, cement aggregate reaction, cement content, soundness, water/cement ratio, sulfate attack.

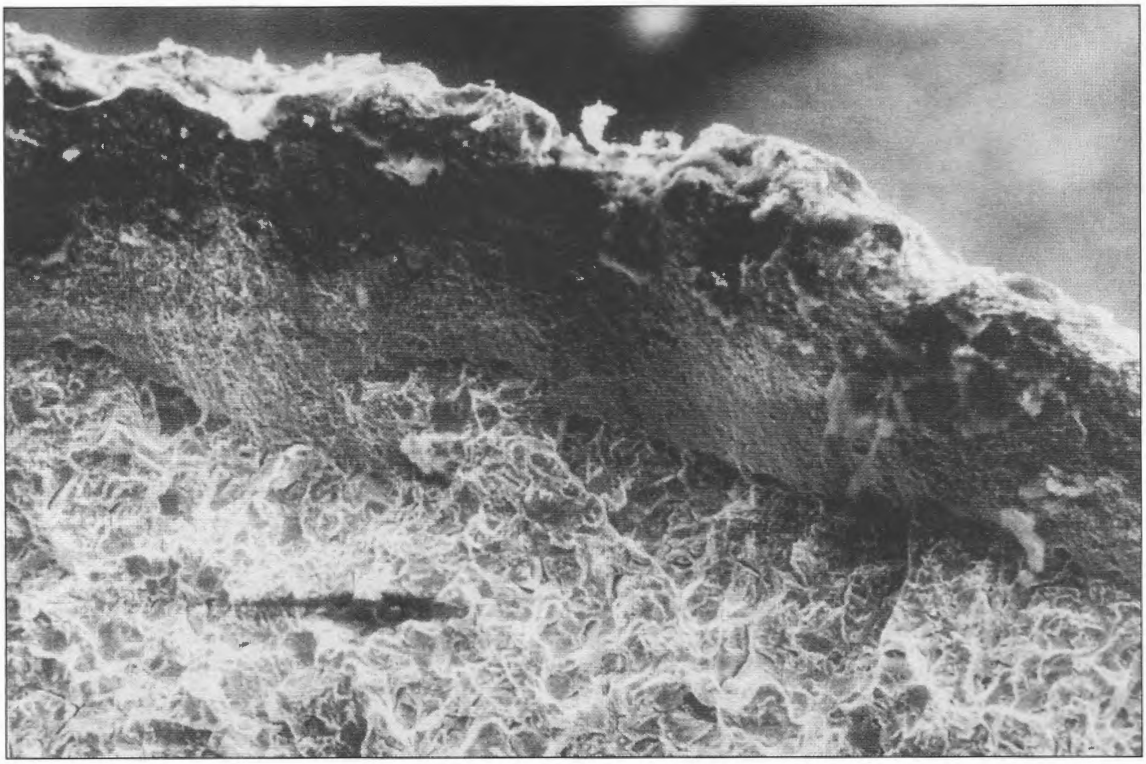

FIGURE 7. A scanning electron micrograph of a fracture surface.

- *Corrosion & Durability:* Permeability, half-cell potential.

Some of the more common laboratory techniques for the testing of wood are:

- *Basic Mechanical Properties:* tensile, shear, compressive, and bearing strength; modulus of elasticity, density.
- *Dimensional Stability:* creep and shrinkage, moisture content.
- *Presence of Decay:* microscopic inspection.

Component Testing. Load testing may be performed on components removed from the field or on mock-ups made in a laboratory. A few recommendations follow:

- Component testing is subject to many sources of error just as are calculations. In particular, the modeling of the test boundary conditions is critical to obtain realistic results.
- Follow established procedures (such as ASTM standards) wherever possible. If there must be any deviation from accepted standards, do so understanding fully the consequences, and be prepared to defend the reasons.
- An individual who is prepared to testify as to the authenticity of the test procedures and results must witness the tests.
- Maintain all test equipment in good working order and make sure it is properly calibrated.
- Use redundant checks on the test results by corroborating calculations or conducting alternative tests.
- The number of tests must be consistent with the investigative objectives for a high level of confidence.

Structural Analysis

Methods. Calculations are almost always required to determine the loads acting on the structure and its resistance. In many cases, simple hand calculations suffice and may be used instead of complex computer analyses . Often, however, it is necessary to resort to computer methods, such as finite-element or finitedifference methods. Structural failures, of course, often result in material and geometrically non-linear behavior, which can be handled directly or indirectly by many finite-element techniques. In many cases, however, non-linear behavior can be sufficiently described by hand methods. A few general recommendations regarding calculations follow:

- Great care is required in complex computer analysis. Programs should be prequalified and their limitations understood. Models must capture all important structural actions and their input must be verified. The mathematical "goodness" of the solution should be verified and the results scrutinized. Computer analysis should be approximately checked by hand techniques.
- Secondary effects of temperature, creep, foundation settlement, stresses induced by construction sequence and eccentricities are often neglected but may be quite significant.
- In reviewing structural designs, do not get hung up in exhaustive documentation of simple code violations that have no causal relationship to the failure.[46]
- Scrutinize all of the parameters in the resistance relationships to see whether the values being used accurately represent the state of the structure at the time of failure.

Precision & Sensitivity Analysis. Sometimes one or more structural parameters affecting strength are not known with precision. In such cases, it is common to perform sensitivity tests, wherein multiple analyses are performed with uncertain parameters input with their probable high and low extremes.

Determining the Cause of Failure

Analysis of Competing Failure Theories. Failure theories are often developed based on prior experience with similar failures, although the team members should always be open-minded as to the causes or combinations of causes that have never before been experienced. As the investigation advances, facts are collected and failure hypotheses are either substantiated or disproved and dropped. New hypotheses may emerge. In a straightforward investigation, all hypotheses will be eliminated but one (*i.e.*, in only one circumstance do the actions on the structure meet or exceed its predicted capacity). Often, however, the results are not so straightforward and the investigation concludes that different causes are more or less probable. If the estimated loads acting on the structure at the time of failure greatly exceed the predicted capacity, there may be something wrong with the analysis.

Closing the Loop. After the potential failure causes are narrowed to one or a few, re-examine all the evidence to determine if it does or does not support the presumed cause(s). In particular, the evidence regarding the initiation and sequence of the failure should agree with the load-and-resistance analysis.

Reports

The final report is usually the culmination of all of the investigative efforts. It may be the final and only work product the client sees. If it is used as part of a litigation process, it is the basis for the expert's testimony. Well prepared, it may help a client avoid litigation altogether by setting forth the client's engineering case so convincingly that the opposition is compelled to settle. Poorly written, it is a source of unending difficulty for the expert witness and client.

A properly structured report will set forth the factual bases for the analysis as well as a presentation of the facts on which the conclusions will be based. In this respect, the process of writing the report serves as a type of quality check of the investigation, because all facts and opinions must be supported and argued in the text.

For these reasons, it is advisable to devote a significant fraction of the investigative effort to the report. Examples of excellently prepared reports are those of the NBS.[1-3, 31]

Organization. Reports should be organized so that proven facts from a variety of sources are first laid out. Hearsay normally should not be relied on in forming opinions. Where it is necessary to do so through lack of factual information or other reason, such qualification should be clearly stated.

Table 4 provides a general outline for reporting structural investigations. A few suggestions in drafting a report follow:

- The introduction and description of the project should contain information useful for orienting the reader, describing the scope and objective of the investigation, and setting forth the sources of information relied on.
- Field investigation, laboratory tests and calculation results sections set forth factual information obtained from the field program, from laboratory testing, and from calculations. In the testing and calculations sections, the standards employed must be stated clearly.
- All facts collected are reviewed in the discussion section, including statements of what failure hypotheses were explored and an analysis of which hypotheses were proven and disproved and why. The discussion is the first point at which non-factual information is presented. All discussion must be supported by the facts presented in the previous sections.
- Conclusions and recommendations should flow logically from, and be supported entirely by, the discussion.

TABLE 4.
General Report Outline

Letter of Transmittal
Abstract
Table of Contents
- Introduction
- Objective
- Scope
- Background
- Responsible Design & Construction Agencies
- Construction Documents

Description of the Structure (or Project)
Field Investigation
Laboratory Tests
Results of Calculations
Discussion of Field Investigation, Laboratory Tests & Results of Calculations
Conclusions
Recommendations

The entire report must present a convincing and logical argument from the facts to the discussion to the conclusion. The causal relationship between identified deficiencies in design, construction and maintenance must be shown.

Conclusions

Forensic engineering is a specialty distinct from design engineering. The following summarizes the author's experience:

- The investigations of structural failures serve many purposes, most notably to help settle disputes between parties, to diagnose problems so building owners may make repairs, and to help design and construction professionals learn from the failures.
- The activities of the forensic engineer offer, on the one hand, enormous professional challenges. There are few things more difficult than sorting through the wreckage of a structural collapse and pinpointing the cause of the failure. On the other hand, the forensic engineer's work can be disheartening and stressful. No one likes to witness failures of major constructed works, especially when human casualties occur, and the legal process can be fatiguing and hostile.
- Forensic engineers are not prepared for their trade by academic training, and must learn from their own experience and that of others. The synthesis required in structural design is very different from the analysis of structural investigations. Few engineers are both good designers and good investigators.
- A thorough review of case studies of structural failures is invaluable to develop the forensic engineer's expertise and ability to readily form failure hypotheses.
- Structural investigations cannot be reduced to prescribed standards. Each investigation must be tailored to the task at hand. However, there are certain logical processes common to all investigations that help to guide the process.

- Failure investigations involve an iterative process of data collection, formation of failure hypotheses, testing and analyses, and the testing of hypotheses. The goal is to establish the loads and other environmental factors acting on the structure at the time of failure, to establish the resistances of the various critical structural components and, through a process of confirmation or elimination, find the failure cause(s) consistent with evidence regarding the collapse sequence.
- Communication, both verbal and written, of the findings of the investigation are the ultimate product of the work and should receive a substantial fraction of the effort of the investigation.

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REFERENCES

1. National Bureau of Standards (NBS), *Investigation of the Kansas City Hyatt Regency Walkways Collapse*, NBS-BSS 143, Washington, D.C., U.S. Department of Commerce, May 1982.

2. National Bureau of Standards (NBS), *Investigation of Construction Failure of Reinforced Concrete Cooling Tower at Willow Island, WV*, NBS-BSS 148, Washington, D.C., U.S. Department of Commerce, September 1982.

3. National Bureau of Standards (NBS), *Investigation of L'Ambiance Plaza Building Collapse in Bridgeport, Connecticut*, NBSIR 87-3640, Washington, D.C., U.S. Department of Commerce, September 1987.

4. Gatje, S.P., *The Role of the Federal Government in the Investigation of Structural Failures*, WISE Internship Report to ASCE, 1984.

5. Task Committee on Guidelines for Failure Investigation of the Technical Council on Forensic Engineering, *Guidelines for Failure Investigation*, New York, ASCE, 1989.

6. Janney, J.R., *Guide to Investigation of Structural Failures*, New York, ASCE, 1986.

7. Addleson, L., *Building Failures – A Guide to Diagnosis, Remedy and Prevention*, London, Architectural Press, 1982.

8. American Society of Civil Engineers (ASCE), *Guideline for Structural Condition Assessment of Existing Buildings*, ASCE 11-90, New York, 1991.

9. Crist, R., & Stockbridge, J., "Investigating Building Failures," *Consulting Engineer*, June 1985.

10. Roberts, R., & Pense, A., "Basics in Failure Analysis of Large Structures," *Civil Engineering*, Vol. 50, No. 5, May 1980.

11. Sowers, G.F., "Investigating Failure," *Civil Engineering*, Vol. 57, No. 5, May 1987.

12. Blockley, D.I., "Logical Analysis of Structural Failure," *Journal of the Engineering Mechanics Division (ASCE)*, Vol. 107, No. EM2, April 1981.

13. *Recommended Practices: For Design Professionals Engaged as Experts in the Resolution of Construction Industry Disputes*, 1988.

14. Kaminetzky, D., "Failure Investigations, Who? Why? When? What? and How?" *Proceedings – Construction Failures: Legal and Engineering Perspectives*, American Bar Association, October 1983.

15. *Building Pathology: A State-of-the-Art Report*, Publication 155, CIB Report, Delft, The Netherlands, June 1993.

16. American Society of Civil Engineers (ASCE), Research Council on Performance of Structures, *Structural Failures: Modes, Causes, Responsibilities*, New York, 1973.

17. Bell, G.R., & Parker, J.C., "Roof Collapse, Magic Mart Store, Bolivar, Tennessee," *Journal of Performance of Constructed Facilities (ASCE)*, Vol. 1, No. 2 May 1987.

18. Fairweather, V., "Bailey's Crossroads: A/E Liability Test," *Civil Engineering*, Vol. 45, No. 11, November 1975.

19. Feld, J., & Carper, K.L., *Construction Failure*, 2nd ed., New York, John Wiley & Sons, 1997.

20. LePatner, B.B., & Johnson, S.M., *Structural and Foundation Failures: A Casebook for Architects, Engineers, and Lawyers*, New York, McGraw-Hill, 1982.

21. Loomis, R.S., Loomis, R.H., Loomis, R.W., & Loomis, R.W., "Torsional Buckling Study of Hartford Coliseum," *Journal of the Structural Division (Proceedings of ASCE*, Vol. 106, No. STI, Proc. Paper 15124, January 1980.

22. Loss, J., & Kennett, E., *Identification of Performance Failures in Large Scale Structures and Buildings*, NSF Project No. ECE 8608145, College Park, University of Maryland, 1987.

23. Pfrang, E.O., & Marshall, R., "Collapse of the Kansas City Hyatt Regency Walkways," *Civil Engineering*, Vol. 52, No. 7, July 1982.

24. Ropke, J.C., *Concrete Problems: Causes and Cures*, New York, McGraw-Hill, 1982.

25. Ross, S.S., *Construction Disasters: Design Failures, Causes, and Prevention*, New York, McGraw-Hill, 1984.

26. Schousboe, I., "Bailey's Crossroads Collapse Reviewed," *Journal of Construction Division, Proceedings of ASCE*, Vol. 102, No. C02, Proc. Paper 12186, June 1976.

27. Smith, E.A., & Epstein, H.I., "Hartford Coliseum Roof Collapse: Structural Collapse Sequence and Lessons Learned," *Civil Engineering*, Vol. 50, No. 4 April 1980.

28. Stockbridge, J.G., "Cladding Failures – Lack of a Professional Interface," *Journal of the Technical Councils, Proceedings of ASCE*, Vol. 43, No. 1, Proc. Paper 15085, January 1973.

29. Thornton, C.H., *Lessons Learned from Recent Long Span Roof Failures. Notes from ACI Seminar on Lessons from Failures of Concrete Buildings*, Boston, American Concrete Institute, April 1982.

30. Vannoy, D.W., "20/20 Hindsight – Overview of Failures," *Proceedings – Construction Failures: Legal and Engineering Perspectives*, American Bar Association, October 1983.

31. National Bureau of Standards (NBS), *Investigation of Construction Failure of Harbour Cay Condominium in Cocoa Beach, Florida*, NBS-BSS 145, Washington, D.C., U.S. Department of Commerce, August 1982.

32. Kaminetzky, D., "Structural Failures and How to Prevent Them," *Civil Engineering*, Vol. 46, No. 8. August 1976.

33. Ang, A.H.S., & Tang, W.H., *Probability Concepts in Engineering Planning and Design*, New York, John Wiley & Sons, 1975.

34. "Standard Practice for Probability Sampling of Materials (E 105-58)," *1996 Annual Book of ASTM Standards: General Test Methods, Nonmetal; Laboratory Apparatus; Statistical Methods; Forensic Sciences*, Vol. 14.02, Pennsylvania, 1996.

35. "Standard Practice for Acceptance of Evidence Based on the Results of Probability Sampling (E 141-91)," *1996 Annual Book of ASTM Standards: General Test Methods, Nonmetal; Laboratory Apparatus; Statistical Methods; Forensic Sciences*, Vol. 14.02, Pennsylvania, 1996.

36. Schreiver, W.R., *Full-Scale Load Testing of Structures, ASTM STP 702*, Philadelphia, American Society for Testing and Materials, 1980.

37. "Standard Practice for Static Load Testing of Truss Assemblies (E 73-83)," *1996 Annual Book of ASTM Standards: Building Seals and Sealants; Fire Standards; Building Constructions; Dimension Stone*, Vol. 04.07, Pennsylvania, 1996.

38. "Standard Practice for Gravity Load Testing of Floors and Flat Roofs (E 196-95)," *1996 Annual Book of ASTM Standards: Building Seals and Sealants; Fire Standards; Building Constructions; Dimension Stone*, Vol. 04.07, Pennsylvania, 1996.

39. "Standard Guide for Conducting Flexural Tests on Beams and Girders for Building Construction (E 529-94)," *1996 Annual Book of ASTM Standards: Building Seals and Sealants; Fire Standards; Building Constructions; Dimension Stone*, Vol. 04.07, Pennsylvania, 1996.

40. "Standard Practice for Reporting Data from Structural Tests of Building Constructions, Elements, Connections, and Assemblies (E 575-83)," *1996 Annual Book of ASTM Standards: Building Seals and Sealants; Fire Standards; Building Constructions; Dimension Stone*, Vol. 04.07, Pennsylvania, 1996.

41. "Standard Method of Measuring Relative Resistance of Wall, Floor, and Roof Construction to Impact Loading (E 695-79)," *1996 Annual Book of ASTM Standards: Building Seals and Sealants; Fire Standards; Building Constructions; Dimension Stone*, Vol. 04.07, Pennsylvania, 1996.

42. "Standard Test Method for Structural Performance of Glass in Exterior Windows, Curtain Walls, and Doors Under the Influence of Uniform Static Loads by Destructive Methods (E 997-84)," *1996 Annual Book of ASTM Standards: Building Seals and Sealants; Fire Standards; Building Constructions; Dimension Stone*, Vol. 04.07, Pennsylvania, 1996.

43. "Standard Test Method for Structural Performance of Glass in Windows, Curtain Walls, and Doors Under the Influence of Uniform Static Loads by Nondestructive Method (E 998-84)," *1996 Annual*

Book of ASTM Standards: Building Seals and Sealants; Fire Standards; Building Constructions; Dimension Stone, Vol. 04.07, Pennsylvania, 1996.

44. American Society of Civil Engineers, *Guideline for Structural Condition Assessment of Existing Buildings*, ANSI/ASCE Standard 11-90, 1991.

45. The Institution of Civil Engineers, *Appraisal of Existing Structures*, July 1980.

46. Janney, J.R., "Fixing a Failure," *Proceedings – Construction Failures: Legal and Engineering Perspectives*, American Bar Association, October 1983.

RECOMMENDED READING

American Society of Civil Engineers (ASCE), *Research Council on Performance of Structures*, ASCE Official Register 1997, New York, 1997.

Bendat, J.S., & Piersol, A.G., *Random Data: Analysis and Measurement Proceedings*, New York, John Wiley and Sons, 1971.

Colloms, M., *Computer Controlled Testing and Instrumentation*, New York, John Wiley and Sons, 1983.

Ellingwood, B., "Design and Construction Error Effects on Structural Reliability," *Journal of Structural Engineering (ASCE)*, Vol. 113, No. 2, February 1987.

Gibble, K., ed., *Management Lessons from Engineering Failures*, New York, ASCE, October 1986.

Jones, L., & Chin, A.F., *Electronic Instruments and Measurements*, New York, John Wiley and Sons, 1983.

Smith, D.L., *Test and Measurement Techniques Using Personal Computers*, Madison, New Jersey, American Institute for Professional Education, 1985.

Whitehurst, E.A., *Evaluation of Concrete Properties from Sonic Tests*, Detroit, American Concrete Institute, 1966.