Documenting and Analyzing Construction Failures

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Abstract: A research project was conducted to explore construction failure investigation techniques and processes to determine whether they were adequate and to develop failure investigation guidelines. Data was collected on failures and failure investigation techniques from surveying 115 members of the engineering and construction industry. Construction failure case studies were created using documentation provided by the federal Occupational Safety and Health Administration, state offices of safety and health, and forensic engineers. The construction failure case studies were analyzed to determine how these organizations conduct their investigations and to develop guidelines that can be used for construction failure investigations. This article provides: (1) description of the methods used for the research; (2) results obtained from the industry survey; (3) summary of the results of an investigation into case studies on construction failures; (4) analysis of the results; (5) discussion on construction failure investigative techniques; (6) guidelines developed during the research project for investigating and documenting failures; and (7) recommended format for reporting the findings of failure investigations.

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Introduction

Efforts to reduce construction failures by studying their causes has led to a meaningful reduction in occurrence. Trying to reduce the incidence of construction failures is a continuous process, and organizations such as the Occupational Safety and Health Administration (OSHA) and others are dedicated to this goal. OSHA collects detailed information after a construction accident or failure, but this data is not analyzed nor compared to other OSHA cases. OSHA enters the results it obtains from investigating an accident into a database that contains only the facts discovered during the failure investigation. The construction failure investigation techniques research gathered additional information through a survey of members of the engineering and construction industries to explore the processes used for construction failure investigations to determine whether the methods being used for documenting construction failures were adequate. The construction failure research investigation was performed to examine failure investigation techniques and processes and to provide standard guidelines to help improve the documentation of construction failures.

This article provides background information on construction failures and investigation techniques. It describes the results obtained from a survey of 115 engineering and construction (E&C) industry professionals, and the results of an investigation into the OSHA case studies on construction failures. It provides an analysis of the results and discusses construction failure investigative techniques being used in the engineering and construction (E&C) industry and discusses a new procedure for investigating, documenting, and reporting construction failures.

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Background Information

Murray Hohns defines failure as: ''1) the act of falling short, being deficient, or lacking; 2) nonattainment or nonsuccess; 3) nonperformance, neglect, omission; 4) bankruptcy; and 5) loss of vigor or strength'' (Hohns 1985, p. 75).

There usually are multiple causes that contribute to structural failures. Bell (1985) discussed the types and levels of failure information that are required and how the data should be disseminated. Bell mentioned that information on the sources of failures is required before attorneys and forensic engineers can adequately address causes of failures. Bell divides failures into two major categories—technical and procedural.

Technical causes are actual physical proximate causes. For example, improper compaction of soil could lead to excessive settlement of a foundation. Procedural causes are related to human errors and include things such as communication problems, or shortcomings, in the design and construction process that cause physical failures to occur. One example of this would be when a contractor places the top reinforcing steel too low in a slab. Another example of a procedural error would be when a testing laboratory fails to check the compaction of the soil (Bell, 1985 p. 46).

Thornton (1985) claims that failures can be classified into three categories—safety, functional, and ancillary—and causes of failures fall into five general areas (Thornton 1985 p. 14):

- Design deficiencies
- Construction deficiencies
- Material deficiencies
- Administrative deficiencies
- Maintenance deficiencies.

Several previous studies indicated that many structural failures can be attributed to various types of human errors. According to Levy and Salvadori, these types of failures are due to (Levy and Salvadori 1992, p. 264):

- Knowledge not currently available and thus unavoidable
- Delayed communication of acquired knowledge
- Ignorance of recently acquired knowledge
- Misunderstanding of accepted knowledge
- Outright ignorance
- Incorrect procedures.

When investigating structural failures, after trying to determine what happened and why, an additional important task is to suggest methods for preventing similar failures. It is impossible to totally eliminate structural failures, but the safety record of the construction industry can be improved by reducing the overall number of structural failures.

Dr. Henry Petroski, a civil engineering professor at Duke University, reported that in 1982 a subcommittee of the U.S. House of Representative's Committee on Science and Technology held hearings to examine the problems of structural failures in the United States. The findings of the committee included six factors that were suggested to help prevent structural accidents from happening (Petroski 1985b, p. 209):

- Good communications and organization in the construction industry
- Inspection of construction by structural engineers
- Increasing the general quality of design
- Improving the structural connection design details and shop drawings
- Proper selection of architects and engineers
- Timely dissemination of technical data.

Careful inspection during construction might be the most important factor in preventing structural failures. Jacob Feld stated, ''Inspection, or lack of it, has never caused a failure. It can only serve, by warning or even halting the work, to prevent the failure caused by some error omission for which others are responsible. Competent control, on every level of responsibility, is the best insurance against mishaps'' (Feld 1968, p. 374).

Guidelines for failure investigation have been suggested by the American Society of Civil Engineers (ASCE) that describe methodologies for investigation procedures. Jack Janney provides a list of steps that can be used for failure investigations. Janney gives a brief outline of each step and refers to specific sections and appendices for a general description of the steps (Janney 1986, pp. 4–6). In addition, Janney provides suggestions for managing failure investigations.

The ASCE (1989) published *Guidelines for Failure Investigation*, which includes methodologies for conducting failure investigations. Prepared by the Task Committee on Guidelines for Failure Investigation, Technical Council on Forensic Engineering, these guidelines expand on Jack Janney's *Guide to Investigation of Structural Failures* (Janney 1986). A methodology for investigative procedures is provided and includes a description of the different types of reports that may be needed during an investigation. Guidelines are also included for preparing an investigation relating to geotechnical and structural failures. One chapter provides an overview of the legal considerations accompanying a failure investigation and describes the duties and responsibilities of expert witnesses. These guidelines do not provide a sample investigation.

George E. Sowers in his article, ''Failure Investigation for Forensic Engineering,'' states that a failure study consists of the following steps (Sowers 1986, p. 12):

- Protect the evidence
- Obtain physical evidence
- Interview witnesses
- Conduct on-site and laboratory tests
- Compile data
- Review project construction records
- Develop an hypothesis of failure
- Analyze the data
- Report findings and conclusions.

James M. Fisher in his article, ''What to Do When a Failure Occurs,'' provides the following 11 steps for investigating failures (Fisher 1986, pp. 23–24):

1. Assemble an investigation team
2. Perform visual and photographic observations
3. Establish a coordinated scheme for detailing the location of various debris
4. Develop failure hypotheses
5. Test each failure hypothesis
6. Remove and identify samples for laboratory testing
7. Conduct eyewitness interviews
8. Undertake a review of the contract documents
9. Review original structural design and conduct an independent structural analysis
10. Examine all data and develop final conclusions
11. Prepare a written report and present findings and recommendations

There are many resources that discuss construction failures; however, there are only limited materials on construction failure investigation techniques (Carper 1986, 1987; FitzSimmons and Vannoy 1984, 1985; Godfrey 1984a; 1984b; Hadipriono 1985; Hinkley 1986; Kaminetzky 1976; Kocsis 1982; Leonards 1982; McKaig 1962; Petroski 1985a; 1985b; Ross 1984; Ward 1986).

Definitions

The following definitions of the terms that are used in this article.

Failure

Dov Kaminetzky defines failure as '' . . . a human act; omission of occurrence or performance; lack of success; nonperformance; insufficiency; loss of strength; and cessation of proper functioning or performance'' (Kaminetzky 1991, p. 20).

Structural Failure

Jack Janney defines structural failure as, ''The reduction of the capability of a structural system or component to such a degree that it cannot safely serve its intended purpose'' (Janney 1986, p. 1).

Construction Failure

''A construction failure is a failure that occurs during construction and they are considered to be either a collapse, or distress, of a structural system to such a degree that it cannot safely serve its intended purpose'' (Janney 1986, p. 1).

Forensic Engineering

Forensic engineering is defined as ''the application of the art and science of engineering in matters which are in, or possibly related to, the jurisprudence system, inclusive of alternative dispute resolution'' (Specter 1993, p. 1).

Objectives

The objective of this research project was to study construction failure investigation techniques to: 1) review construction failures investigation processes; and 2) develop a modified and concise technique that would provide a more effective documentation process for construction failures. In order to achieve this objective the study:

- Examined the failure analysis processes being used by forensic engineers for conducting failure investigations and developed recommendations for improving investigative techniques.
- Investigated construction failure case studies documented by the OSHA, state safety and health agencies, and forensic engineering firms to determine how these organizations conduct their investigations and how they document accidents and failures.

The purpose of this research project was to: 1) provide engineers, architects, and contractors with an overview of current literature related to construction failures; 2) review the records provided by OSHA on construction failures that they have investigated to determine if there were any important trends in the causes of accidents and failures over a 10-year period; 3) investigate the methods used for documenting construction failures; and 4) provide members of the construction industry with information and guidance on construction failure investigations to improve the investigation process.

Methodology

The data were collected from different organizations that are directly related to the engineering and construction industry using a questionnaire that was sent to federal and state safety and health administrators, architects, engineers, construction managers, and contractors.

This project included the following seven phases:

1. Conduct a literature review of construction failure investigation processes.
2. Develop a construction failure investigation questionnaire.
3. Select participants for the study.
4. Collection data through a survey of engineering and construction industry professionals and from OSHA for the case studies.
5. Conduct an analysis of the survey results and the case studies.
6. Develop a modified construction failure investigation process.

A pilot questionnaire on investigating construction failures was developed and tested by 13 members of the National Academy of Forensic Engineers, and their suggestions were incorporated into a revised questionnaire. This questionnaire contained 51 detailed questions that were designed to elicit ''yes'' or ''no'' responses from the survey participants.

Selection of Participants for the Study

After the questionnaire was developed and tested, the survey participants were selected from regional administrators of OSHA, area directors of OSHA, state administrators of OSHA, approved occupational safety and health programs, and members of the National Academy of Forensic Engineers. The survey participants included civil engineers, architects, architectural engineers, construction managers, construction superintendents, architectural and civil engineering professors, and architecture and construction managers.

To provide an adequate representation of participants in the study, many different types of organizations were included. A total of 446 questionnaires were distributed, and 115 were completed and returned. The response rate was 26%, which is reasonable for this type of research. (A goal of 27% is the normal requirement for surveys.)

Case Study Process

Case studies on construction failures were created from data collected from various agencies. The Office of Management Data Systems of the United States Department of Labor (OSHA) provided information on accidents that occurred after 1984 and were investigated by OSHA and state occupational and safety health offices. The Office of Management Data Systems (OMDS) sent over 3,000 pages of computer printout listing approximately 6,000 accidents that were examined and used to compile a list of inspections specifically related to construction failures.

After establishing relevance, the reports were summarized and analyzed (due to the length of the case studies, only a sample of the summary format is included in this article). A more thorough analysis of the case studies is provided in other publications (Lockley 1998; Yates and Lockley 1999). The OSHA report provided the following information:

- Establishment inspected
- Address of establishment
- Date and time of occurrence
- Inspection number
- Ownership (private sector, local government, state government, or federal agency)
- Type of violation (serious, willful, or other)
- OSHA Standard or Regulation violated
- Proposed penalty
- Description of the failure
- Abatement methods to prevent recurrence.

Included with several case study reports was the following information:

- Names of injured/deceased
- Minutes of conferences held between the employer and the safety officer
- Informal settlement agreements between OSHA and the employer
- Decisions of administrative law judges representing the OSHA appeals board
- Photographs and sketches
- Interview statements
- Police reports
- Investigation reports prepared by consulting engineers
- Investigation reports prepared by state and local public works agencies
- Laboratory reports
- Newspaper articles.

Results

This section describes the results obtained for this research investigation. OSHA cases were reviewed and analyzed, and the data obtained was used to determine the three most prevalent causes of construction failures that are discussed later in this article. Due to the excessive length of the questionnaire, it is not included (51 questions), but the questions are paraphrased in the section on ''Results of the Questionnaires.''

Types of Survey Participants

A large percentage of the survey respondents were civil engineers who supervise building construction and work for either small firms with less than 11 employees or large firms with over 200 employees. The respondents were from the following professions (Question 1):

- Safety specialists, 8%
- Engineers, 56%
- Architects, 9%
- Professors, 4%
- Construction managers, 18%
- Construction superintendents, 1%
- Construction engineers, 4%.

The type of work performed by the respondents was (Question 2):

- Residential construction, 13%
- Building construction, 51%
- Highways and airfields, 7%
- Heavy construction, 5%
- Utilities, 4%
- Industrial construction, 3%
- Safety and health administrators, 4%
- No supervisory role, 5%
- Failure investigations, 4%
- All of those listed, 4%.

The type of firms where the respondents worked were (Question 4):

- Public agencies, 12%
- Private owners, 3%
- Consulting engineering firms, 36%
- Architectural firms, 3%
- Architectural/engineering firms, 20%
- Constructors, 10%
- Construction management firms, 11%
- Academia, 5%

The companies varied in size from 1 employee to over 200 employees: under 10 employees, 21%; 11–20 employees, 9%; 21–50 employees, 14%; 51–100 employees, 12%; 101–200 employees, 11%; over 200 employees 30%; and blank responses, 3% (Question 5).

Results from the Questionnaires

This section provides results that were obtained from the failure investigation techniques questionnaire. The question numbers are included with the results, and the content of each question is included in the discussions.

Methods for Reducing the Incidence of Construction Failures

The survey respondents were provided with a list of methods that could be used to reduce construction failures, and they ranked these methods in the following manner (Question 6)—1 received the most responses.

1. Design and detailing of critical connections by the engineer of record.
2. Design and supervision of construction of temporary structures by a professional engineer.
3. Clear definition of responsibility among the engineer, fabricator, and contractor.
4. Constructability reviews during the design stage.
5. Full-time inspection of construction by structural engineers.
6. Education and training of construction teams.
7. Comprehensive quality assurance/quality control plan.
8. Structural redundancy in the design to avoid progressive collapse.
9. Peer review of the structural design and details by an independent professional.

Other methods that might reduce the incidence of construction failures were listed (Question 7):

- Design engineers should review all shop drawings, shoring, and formwork design.
- Construction personnel should be certified for temporary structure design/construction.
- Realistic construction schedules (requires education and enlightenment of clients/owners) should be provided.
- Structural engineers should review temporary bracing and shoring designs, details, and construction and submit forms to public agencies indicating such review.
- Contractor's superintendents should be educated about temporary bracing and stability.
- Part-time visitation should be provided by all design principles, not just the structural ones.
- Full-time inspection should be furnished by an independent construction professional.
- All construction activities should be reviewed prior to the performance of the work by professional engineers with construction experience. This includes the selection and positioning of cranes, concrete pumps, and truck movements.
- Site-specific safety plans, which address specific issues that are approved by the engineer, should be furnished. Include any dead loads during construction.
- Contractors and subcontractors should be hired based on a prequalification system for quality, safety, and liability.
- In-depth inspection should be provided by local authorities rather than cursory walk-throughs.
- Stronger supervision should be provided on the part of the contractor to avoid ''short cuts'' by workers.

The survey respondents were asked several questions that required them to state whether they thought certain processes would help reduce errors and construction failures. Of the respondents, 57% expressed approval for the innovative design and construction practices suggested in the survey (Questions 8–11).

In Europe, the design engineer of a concrete structure prepares the placement, or shop, drawings that include bar lists and bending details. Of the respondents, 60% thought this practice would reduce the type of errors that enter into drawings prepared by bar fabricators and overlooked by the design engineer in the checking of these drawings (Question 8).

Of the respondents, 85% thought a system where the owner of a project has one firm design the project, another firm review the shop drawings, and a third firm provide contractor quality control contributes to construction failures (Question 9). Of the respondents, 58% felt that a legal requirement for periodic inspections of old buildings would help to reduce the incidence of construction failures due to alterations (Question 10).

Of the respondents, 57% stated that the engineer of record should indicate in the contract documents the methods to be used for shores and reshores for which the structure was safely designed. Of the respondents, 37% thought that design/construct contracts increase the incidence of construction failures, because they eliminate the separate review process that is normally performed by both engineering and the construction firms (Question 12).

Of the respondents, 95% indicated that contractors should be responsible for developing a safety program and 81% thought that if construction management is used on a project, the construction manager should be held liable for directing and coordinating safety programs (Questions 13, 14). Of the respondents, 66% indicated that they did not think that construction superintendents should obtain a license through a licensing process that would be similar to the type of process that professional engineers and architects must pass to obtain their licenses (Question 15). Of the respondents, 86% indicated that field inspectors should check installed construction against the original design and the approved shop drawings, because implementing this practice is one way to minimize construction failures due to human error (Question 16).

Of the respondents, 59% or only a slight majority, expressed support for requiring soil borings to determine subsoil conditions regardless of the size of the project (Question 17). A few respondents remarked that a test pit might also work, and another respondent stated that the need for borings is a function of the size of the project.

Of the respondents, 53% thought that the engineer of record should not be held responsible for the design of precast elements and their connections to other elements. designed by a specialist retained by the contractor (Question 18). Of the respondents, 44% indicated that the engineer of record should review and approve the design of these elements and connections as this is one way of employing peer review to help minimize construction failures.

Of the respondents, 61% thought that design engineers should not include temporary bracing systems in contracts (Question 19). Of the respondents, 36% indicated that there are three main causes of construction failures: 1) formwork failures and collapses; 2) inadequate temporary bracing; and 3) overloading and/or impact during construction. In question, 21 of the survey participants provided other causes of construction failures (Question 21):

- Failure to have a qualified person in charge
- Designs do not reflect the actual construction loads and field conditions
- Construction sequences not consistent with design considerations
- Improper definition of responsibility
- Financial pressures to complete the project early
- Incomplete connections—installing a few bolts and intending to complete the bolting process later
- Failure to use the materials specified or prefabricated elements being damaged during their handling and erection
- Unauthorized modifications to the construction specified in the contract document
- Supporting members damaged by other prime contractors as they are installing their work (i.e., duct work/plumbing)
- Poor communication, failure to follow design plans, failure to follow recommended industry practice, and carelessness
- Inadequacy of the system during erection
- Lack of common sense, including intoxicated, drug impaired workers, or improper safety equipment
- Poor communication between the designer and constructor
- No consideration for soil conditions
- Incorrect crane operations
- Not thinking fast enough
- Working too fast
- Incompetent supervisors
- Nature, gross design error, terrorism, or contractor negligence
- Inadequate original design, which is unknown to the contractor
- Insufficient or improper checking of the shop drawings
- Decisions from those with insufficient knowledge or education
- Lack of proper inspection
- Unreasonable schedule
- Inadequate training and education
- Unknown or erroneous geotechnical information.

Of the respondents, 57% indicated that safety inspections by insurance companies would help to reduce accidents and that contractors should strip forms after the strength of the in-place concrete had been verified by field cured cylinders (Questions 22, 23). For Question 24, 62% thought that there is no need for contractors to make and test a companion set of concrete cylinders and only 37% thought that new materials should be used on projects (Question 25).

Results of Questions on Architecture and Engineering Performance Center

Unfortunately, 79% of the respondents indicated that they were not familiar with the efforts of the Architecture and Engineering Performance Information Center (AEPIC). This unfamiliarity suggests that the AEPIC should try to increase their profile by disseminating more information on construction failures to the E&C construction industry. The extremely low number of responses to all of the questions concerning the AEPIC were related to the respondents unfamiliarity with the AEPIC (Questions 27, 28). The majority of ''yes'' responses, 94% and 83%, to questions Q-29 and Q-30, respectively, showed that the use of construction failure case studies should be included in both undergraduate and graduate programs.

Results to Questions Related to the OSHA

The high percentage of ''no'' responses to question Question 32, 68%, indicated that the records produced by the OSHA on construction failures should contain additional information.

Only 29% of the respondents thought that having OSHA require the engineer, or architect, of record to conduct safety visits and enforce safety standards would significantly reduce construction failures. Of the respondents, 57% agreed that the OSHA regulations have had a significant impact in reducing accidents and failures and that OSHA should require contractors to hire professional engineers to be construction safety specialists (Questions 33–35). Of those responding to Question 36, 64% thought that the OSHA reports often lack technical expertise.

Most of the respondents (between 70% and 95%) thought that OSHA should include the following in their reports (Question 37):

- Synopsis of the highlights of the accident
- Summary of eyewitness accounts of the failure
- Description of the construction activities leading up to the failure
- Compilation of graphic records
- List of position and orientation of debris
- Conclusions relating to the probable cause, or causes, of the failure.

One respondent suggested that in a structural failure, the size of the structural members, modes of connections at the time of failure, and specific information on loads should be included in failure reports.

Suggestions were provided on other types of information that could be included in an OSHA report, such as:

- Analysis of the effectiveness of the job site safety plan and health program. Key elements should be part of the report. This would include engineering design and prejob planning, as

well as the procedure followed at the actual site of the mishap. Engineering design analysis would be reviewed and reported, as well.
- For structural failures, the size of the members needs to be indicated, along with the mode of connection at the time of the failure, and specific information on loads.
- Expanding eyewitness accounts of construction failures.

The most preferred kind of information that the respondents would like to see included in an OSHA report is a description of the construction activities leading up to the failure (Question 38).

Results to Questions on Construction Failure Investigations

The responses were divided equally on whether a list of engineering firms capable of conducting a failure investigation should be provided by organizations such as the National Academy of Forensic Engineers and funded by a fee from those desiring an investigation (Question 39). Of the respondents, 37% indicated that they were in favor of the registration of consultants who conduct construction failure investigations (Question 40).

Most of the respondents thought that an independent panel composed of designers, researchers, and consultants would be the best team to investigate failures (Question 41), and a majority of respondents (56%) thought that the present process of failure investigation techniques do work satisfactorily (Question 42).

The survey participants were asked to specify any change(s) to be made to the investigation process and their suggestions included (Question 43):

- All information and circumstances surrounding a failure should be communicated to the investigative team through *one* coordinator representing the owner. Casual remarks to the press by unqualified personnel can do irreparable harm to the owner's reputation.
- In a complex failure, an independent forensic firm should be retained. OSHA is interested in assessing responsibility and not in finding solutions to the cause of the problem.
- A licensed engineer should be retained to assist in the initial investigation and report preparation.
- Dissemination of findings to the engineering and construction industry should be mandated
- Make it illegal to disturb debris after searching for the dead, injured, and survivors. As soon after the collapse as is possible, obtain low altitude aerial photos of the site.
- There is a need for better training of the OSHA investigators.
- Provide more knowledgeable, thorough, and careful investigators.
- Provide more funding for OSHA for more inspections.
- Provide more funding for OSHA to investigate smaller accidents. This suggestion is very important for preserving evidence before it is lost.
- Provide rapid deployment of a certified forensic specialist before the scene is altered.
- Eliminate lawyer imposed constraints.
- Provide more sophisticated, motivated, and knowledgeable inspectors
- Use intelligently taken photos.

Of the respondents, 52% replied that both a joint investigation and a simultaneous forensic investigation are acceptable methods, however, only one-third of the respondents approve of the ''diagnosis of exclusion'' technique (determining probable causes by identifying the negative factors that preclude other causes). Over 50% of the respondents failed to indicate acceptance or rejection of this procedure which may mean that they are unfamiliar with this process. One respondent suggested that ''investigations should be by an independent panel not representing the owner, contractor, or engineer (Question 44).

Of those that participated in the survey, 70% indicated that they were unfamiliar with the *Guidelines for Failure Investigation* adopted by the American Society of Civil Engineers (Question 45). Because so many of the respondents were unfamiliar with the guidelines only 22% were able to indicate whether they felt the Guidelines were inadequate or adequate (Question 46). Of the respondents, 55% thought that construction failures are not adequately documented at the job site (Question 44), and 70% felt that a standard format should be used to investigate failures (Question 49).

The acceptable methods for documenting construction failures at job sites that were recommended were:

- Record all violations of safety procedures that result in construction failures.
- Record failures due to instability of structures that are partially completed to determine if there was a need for temporary bracing and guy wires on similar sections.
- Record functional failures, such as leaky and sagging walls.
- Maintain records of field data on failures in the form of sketches, photographs, video recordings, and eyewitness reports.
- Record preliminary hypotheses on the possible cause, or causes, of failures.
- Record the position and orientation of debris after the collapse.
- Prepare a written report detailing the salient components of the investigation, including recommendations for remedial actions and how the findings may be used to prevent future failures in this, or similar, facilities.

Space was provided on the last page of the questionnaire for any comments on construction failures or forensic investigations. The following comments were included in this section:

- Peer reviews of designs, construction methods, and temporary construction devices along with adequate *hazard analyses* are the best techniques in reducing ''failures'' and ''accidents''at job sites.
- Most failures of a masonry wall under construction result from inadequate, or missing, temporary bracing. Insurance companies should not provide coverage for failures attributed to improper or inadequate bracing.
- Continue to have contractors responsible for safety at the job site, but allow engineers to comment on safety violations observed without fear of liability repercussions.
- Regulations must have a favorable cost/benefit ratio. This must be carefully considered in any proposed OSHA or registration regulations. The Truss Plate Institute (TPI) is a good example of an organization using education to reduce failures. Construction collapses of light wood trusses, caused by inadequate top chord bracing were common. The TPI developed detailed bracing instructions and a distribution system to assure that instructions are sent and received with every order.
- Construction inspection should be done by degree structural engineers and not technicians.
- Photos are extremely important. It may help to develop preprinted forms for different types of investigations. Forms should be used as a reminder to get complete information. They would not be used as a rating device. Using check marks to fill out this form would be nonproductive unless you are just checking off an activity that is more thoroughly documented either in the same form or elsewhere

- Develop seminars and educational programs on technical report preparation.
- The agenda of most investigative reporting and analysis seems to be focused less on cause and conditions and more on fixing blame for legal purposes. Most parties are involved in an incident look for ‘‘damage control’’ to direct attention away from themselves.
- Better train contractors in engineering principles.

Analysis of the Questionnaire Results

From the results obtained during this research investigation, the following factors were determined to be the most important related to investigating construction failures.

Construction Failures

There is no one preferred method for reducing the incidence of construction failures, but several important issues need to be considered such as:

- It is important for contractors to develop a safety program for each of their projects.
- Construction managers should be held liable for directing and coordinating safety programs in construction management contracts.
- It is not necessary for contractors to obtain a license similar to that of a professional engineer.
- It is necessary for field inspectors to check installed construction against the original design drawings and the approved shop drawings.
- There is a need for the AEPIC to distribute additional information to members of the E&C industry.
- Case histories on design and construction failures should be included in architecture and undergraduate engineering curriculums.
- Graduate programs in structural and/or construction engineering should include a course in forensic engineering.
- The regulations enforced by OSHA have significantly contributed to a reduction in accidents and failures; however, members of the E&C industry would like to see additional information provided in the failure investigation reports maintained by OSHA.
- OSHA should require the engineer, or architect, of record to conduct safety inspection visits and enforce safety standards construction failures might be significantly reduced.

Construction Failure Investigations

Construction failure investigation techniques and processes could be improved by the implementation of several different strategies. Members of the E&C industry would like to see additional improvements to current investigation processes. Other important issues include:

- There was no strong preference for just one type of information to be included in an OSHA inspection report that would be the most beneficial to failure investigations.
- Most of those surveyed believed that an OSHA report should include a description of the construction activities leading up to the failure.
- There is a lack of familiarity among E&C industry professionals on the *Guidelines for Failure Investigation* developed by the ASCE (1989) and Janney (1986).
- Construction failures should be documented using a standardized format at job sites.
- There was strong agreement that if construction failures were documented more effectively at the job site, their incidence could be reduced.

Results and Analysis of the Case Study Investigations

Table 1 is a sample summary used to document the results obtained from investigating OSHA and other case studies. Several hypotheses were statistically tested as part of this research project, but the results were too extensive to include in this article (Lockley 1998). For the detailed case studies summarized in Table 1, the most prevalent types of construction failures were: 1) inadequate temporary bracing; 2) overloading during construction; and 3) formwork failures. Inadequate temporary bracing caused the most monetary penalties assessed by OSHA, the most fatalities, and the gravest accidents; but formwork failures caused more injuries. Building failures had lower incidences of injuries, and trusses had higher levels of injuries from their failure. Structural steel failures were assessed the most penalties, and failures due to concrete formwork were assessed the lowest penalties.

Investigative Techniques and Documentation Methods

To be able to complete a successful construction failure investigation an investigator should select steps and procedures that will accomplish two objectives: 1) determine what happened and why; and 2) provide suggestion on how to try to prevent it from happening again. The following recommendations provide guidelines that were developed during the construction failure research investigation project, which should be used by investigators to help them achieve the objectives with maximum results. The ASCE publishes a *Guide to Investigation of Structural Failures*, and *Guidelines for Failure Investigation* (1989). (Janney 1986). Both booklets provide an introduction to construction failure investigation processes for the beginning engineer and supply the experienced forensic engineer with general guidance on how to carry out a specific failure investigation. The booklets also describe methodologies for investigative procedures that may be used to identify the cause, or causes, of construction failures. However, neither booklet provides a concise format to remind investigators of specific steps to follow during a failure investigation. Therefore, the following suggestions are intended to augment existing publications by providing a quick reference for investigators.

The investigating engineer has a goal to observe and record all available information about a construction failure. The effectiveness of the investigator will be measured on how skillful he/she is in obtaining answers to who, where, what, when, and why?

The answer to ‘‘who’’ should: (1) identify the case study, (2) describe the type of project, such as whether it is a bridge or another type of structure; (3) describe the type of substructure such as trusses; and (4) describe the type of materials, connection, and foundation.

Where did the failure take place? In what city and state did the failure occur and where was the exact location of the failure?

The answer to the ‘‘what’’ question should contain more information than a simple statement such as ‘‘structural distress,’’ ‘‘structural collapse,’’ or the all encompassing expression ‘‘struc-

Table 1. Sample, Summary of Results of Construction Failures Case Study Investigation

Case number	Type of failures	Materials involved	Injuries (I); fatalities (F)	Penalties proposed	Penalties paid	Gravity of failure[d]	Most probable cause of failure
1	Building	Structural steel	1 I, 1 F	$23,560	Unknown	10	ITB[a]
2	Building	Concrete	0 I, 1 F	$2,000	Unknown	4	ITB[a]
3	Building	Steel/concrete	1 I, 0 F	Unknown	Unknown	3	Overloading/Concrete
4	Building	Structural steel	0 I, 1 F	$7,000	Unknown	8	ITB[a]
5	Building	Concrete/soils	3 I, 1 F	$1,440	Waived	4	ITB[a]
6	Building	Structural steel	1 I, 1 F	$1,074	Unknown	4	ITB[a]
7	Bridge	Concrete/Form	7 I, 1 F	$6,000	Unknown	8	Formwork failure
8	Bridge	Structural steel	1 I, 2 F	$24,000	Unknown	10	ITB[a]
9	Tower	Structural steel	0 I, 3 F	$16,920	Unknown	10	ITB[a]
10	Truss	Wood	7 I, 0 F	$510	Unknown	2	ITB[a]
11	Truss	Wood	5 I, 0 F	$2,000	Unknown	4	ITB[a]
12	Truss	Wood	3 I, 0 F	$200	$200	1	ITB[a]
13	Truss	Wood	None reported	NA[b]	NA[b]	3[c]	ITB[a]
14	Steel	Joists/Deck	01, 2F	$960	Unknown	3	ITB[a]
15	Steel	Structural Steel	1 I, 1 F	$13,500	$9,500	10	ITB[a]
16	Steel	Structural Steel	0 I, 1 F	$1,600	$800	4	ITB[a]
17	Concrete	Concrete	1 I, 1 F	$7,500	$2,800	8	Overloading/Concrete
18	Concrete	Concrete	3 I, 0 F	$1,000	$1,000	4	ITB[a]
19	Connection	Wood	1 I, 1 F	$4,375	Waived	7	ITB[a]
20	Connection	Wood	None reported	NA[b]	NA[b]	1[c]	ITB[a]
21	Formwork	Concrete/Form	2 I, 0 F	$200	Unknown	1	ITB[a]
22	Formwork	Concrete/Form	4 I, 0 F	$380	Unknown	2	Formwork failure
23	Formwork	Concrete/Form	01, 1F	Unknown	Unknown	3	Formwork failure
24	Formwork	Wood	3 I, 0 F	$740	Unknown	3	Formwork failure
25	Formwork	Scaffolding	4 I, 0 F	$635	$635	3	Formwork failure
26	Formwork	Concrete/Form	5 I, 0 F	$200	Waived	1	Formwork failure
27	Falsework	Concrete/Form	5 I, 0 F	$3,000	$1,500	4	Formwork failure
28	Falsework	Concrete/Form	8 I, 1 F	$350	$250	2	Formwork failure
29	Foundation	Concrete/Soils	None reported	NA[b]	NA[b]	2[c]	ITB[a]

[a]Inadequate temporary bracing.

[b]Inspection conducted by a consulting forensic engineer. No penalty was assessed.

[c]Value established subjectively.

[d]Gravity of failure: Gravity is a number from 1 to 10 representing the gravity or severity of the violation. Values are regarded as: 1 to 10, high; 4 to 7, moderate; and 1 to 3, low. Values are from monetary penalties assessed by OSHA or state OSHA. Gravity 1, penalty assessed: from $0 to $200; Gravity 2, penalty assessed: from $201 to $500; Gravity 3, penalty assessed: from $501 to $1,000; Gravity 4, penalty assessed: from $1,001 to $2,000; Gravity 5, penalty assessed: from $2,001 to $3,000; Gravity 6, penalty assessed: from $3,001 to $4,000; Gravity 7, penalty assessed: from $4,001 to $5,000; Gravity 8, penalty assessed: from $5,001 to $7,500; Gravity 9, penalty assessed: from $7,501 to $10,000; Gravity 10, penalty assessed: from $10,000 and up.

tural failure.'' The investigator should describe what happened that prompted an investigation—an incident that caused serious or fatal injuries, damaged materials, or a total collapse of the structure.

The answers to the ''when'' question should not only be related to the time, day, and year but also provide information and relationships between pairs of activities or events that were examined. Weathear conditions before, and at the time of the accident, may be important factors in determining the possible cause of the failure.

Answers to the ''why'' question will probably be the most difficult to obtain. Determining the cause, or causes, of a failure is one of the goals of an investigation, but often the most difficult one to obtain. However, once this question is answered, suggestions for preventing a similar failure may evolve.

As the investigator seeks answers to these five questions, he/she must remember that the main objective of the investigation is not to apportion blame but to gather data that will serve as a basis for preventing future failures, therefore, impartiality is essential. Determining who is to blame for a failure may be the objective of insurance agents, or safety and health organizations such as the OSHA, but it has no place in an ''unprejudiced'' investigation.

The following list provides several important steps to be followed during a forensic investigation:

1. Select a principal investigator who may act independently in the investigation, or as the manager of a staff of engineers and technicians.
2. Assemble (if needed) a staff of in-house engineers and technicians and/or outside specialists.
3. Investigate the scene of the failure as quickly as possible.
4. Conduct an overall visual examination of the failure site.
5. Generate as many hypotheses of causes of failure as possible.
6. Record visual information using photographs, video cameras, sketches, or drawings.
7. Collect samples for field and laboratory testing.
8. Conduct field tests or arrange for laboratory testing.
9. Conduct eyewitness interviews.
10. Review documents relating to the design and construction of the facility.
11. Review the structural design and perform an analysis of the structure.
12. Analyze the data collected and draw conclusions.
13. Prepare and submit a written report to the sponsor of the investigation.

Recommended Format for Reporting the Findings and Conclusions of a Construction Failure Investigation

The following information should be collected to properly document a failure investigation:

- Name of the case study.
- Location (city, state).
- Date of failure (month, day, year).
- Time of day.
- Type of project.
- Materials or equipment involved.
- Injuries or fatalities.
- Weather.
- Ownership of the facility (private, local, state, or federal government).
- Name of person, or persons, conducting the investigation.
- Description of the failure. An abstract should be prepared that answers the following two questions: (1) What happened? Describe the construction activities leading up to the failure and the failure itself including damage; (2) Why did it happen? Present the most probable cause of the failure, secondary causes, and the relevant factors affecting the cause.
- Lessons learned. Prepare a practical summary of ''lessons,'' that may be used to prevent a similar failure should be prepared.

Recommended Checklist for Investigating and Documenting Structural Failures

The following checklist may be used by construction failure investigators, it contains comprehensive steps and procedures to follow during an investigation. The checklist provides guidelines for helping to plan, prepare, and execute a successful investigation.

- Has a principal investigator been selected to conduct and manage the investigation?
- Are there in-house personnel available to assist in the investigation?
- Should outside specialists be retained as consultants?
- Have you assembled an inspection kit needed to probe, measure, sample, and record the wreckage?
- Did you make an overall site examination to evaluate the scope and nature of the failure?
- Have you generated as many hypotheses of causes of failure as can be developed based on past records of similar failures?
- Have you established a coordinate system for defining the location of fallen debris?
- Have you recorded the position and orientation of the debris after the collapse?
- Have you protected the evidence so that it can be properly documented?
- Have you completed documenting the site of the failure using photographs, video tapes, sketches, or drawings?
- Are you using a pocket recorder to record your thoughts and impressions as they occur?
- Have you conducted written or taped records of eyewitness accounts to the failure?
- Are samples collected and tagged for field and laboratory testing?
- Are all field tests completed and results documented?
- Have you arranged for all necessary laboratory testing?
- Have you reviewed the contract documents, inspection reports, project schedules, project correspondence, weather records, and any other related documents which reflect the history and life of the structure?
- Have you examined all violations of safety procedures that may have caused the failure?
- Have you reviewed the structural design and either performed or arranged for an independent structural analysis to determine what behavior would have to be anticipated for the structure?
- Have you examined and recorded deviations from the design?
- Was there unconventional use of materials or unusual construction erection techniques?
- Was there a curtailment, even partial, of on-site construction by the design professionals?
- Have you reviewed U.S. Weather Bureau records to log the weather during the period to be investigated?
- Have you made a final analysis of the data and arrived at any conclusions?
- Have you prepared a written report summarizing your findings and recommendations?

The previous checklist is provided to aid investigators in planning construction failure investigations, collecting and recording field and test data, generating a failure theory, and analyzing and drawing conclusions related to failures. It is only a guide and should be used as a supplement to the more detailed ASCE publications, previously mentioned.

Conclusions and Recommendations

The construction failure investigation study did not focus on the causes of construction failures or on the methods for preventing failures, as several books on construction failures have been written that discuss these topics. The research was conducted to determine: 1) the most frequent causes of failures in construction; 2) what can be done to improve the methods of investigating and documenting failures; and 3) what can be learned from a study of failure investigations conducted by OSHA, state OSHA agencies, and forensic engineers. This article provides information that should be used by members of the engineering and construction industry to facilitate standardized reporting of construction failures.

The following are recommendations that could be incorporated into construction failures investigations efforts:

- A special effort could be undertaken by one specific government agency to assist contractors in providing proper education and training opportunities for construction personnel.
- The first recommendation could be addressed through seminars, workshops, or through efforts of professional societies.
- An effort could be made to prescribe a review process for formwork design and construction by qualified professional engineers.
- OSHA could provide additional training to their personnel on the need to provide complete and accurate failure inspection reports.
- Special effort could be undertaken by the AEPIC to advertise what it can do to help engineers, architects, and contractors in preventing failures.
- Case studies could be developed and provided to educators to incorporate lessons from failures in undergraduate and graduate course in construction, structural engineering, and architecture.
- ASCE could aggressively disseminate information to its membership on the availability of booklets published by the ASCE that provide guidelines for failure investigation.

If members of the engineering and construction professions do not continue to exert efforts to reduce failures, public safety is jeopardized and confidence in the ability of members of the engineering and construction industry to monitor their own industry is weakened which could lead to increased government regulations. This research project discussed several different issues related to construction failures that members of the construction industry need to examine if they wish to continue to provide a safe environment for construction workers and the public. This research has focused on those issues that have an impact on the performance of constructed facilities.

Construction failures can never be completely eliminated, but the construction environment could always be improved. Lessons learned from case studies of failures can obviate their recurrence, thus reducing some of the risks of injury and delay claims. Improving the failure investigation process would produce results to provide insight into the behavior of structures under construction. Knowing more about the cause of failures, or performance problems in constructed facilities, would enhance the safety of structures and help to minimize construction failures.

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