Y_i = dependent variable of the ith observation;
$\mathbf{Y}$ = matrix of dependent variables;
α = confidence level;
β_o = Y intercept;
β_P = slope of Y with X_P, holding constant $X_P, \ldots, X_{P-1}$;
$\hat{\beta}$ = estimate of β;
$\boldsymbol{\beta}$ = β matrix;
$\hat{\boldsymbol{\beta}}$ = $\hat{\beta}$ matrix; and
ϵ_i = random error in Y for observation i.

ANALYSIS OF RECENT U.S. STRUCTURAL AND CONSTRUCTION FAILURES

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ABSTRACT: Structures are used for a wide variety of purposes, some being residential, commercial, industrial, environmental, or transportational in nature. The construction process involves a number of procedures that follow together from the first stage of the building process to the end of the life cycle of the structure. The building process of any structure, regardless of its type, location, price, or any other factor, basically includes planning, design, construction, utilization, demolition, and alteration phases. The concepts of structural and construction safety are still issues of concern for engineering practitioners. The relative importance of structural and construction safety is associated with the adverse consequences that may result from a structural and/or construction failure. A recent study of 604 structural and construction failures in the United States during the period 1975–1986 is presented. The analysis aims to demonstrate the practical dimensions and causes of structural and construction safety problems, to evaluate the social and economic consequences of failures, and to assist in providing guidelines to control and improve the safety of facilities during and after construction. In addition, an attempt has been made to estimate safety-risk measures for the U.S. construction industry.

INTRODUCTION

A total of 604 structural and construction failures in the United States during the period of 1975–1986 were analyzed. In this study, failure cases that were mainly caused by variation within and departure from common engineering practices were considered. Failures caused by purely natural disasters such as earthquakes, floods, landslides, hurricanes, tornadoes, and brush fires were excluded.

The case literature survey was based on information gathered from the *Engineering News-Record* (*ENR*) from 1976 to 1986. (All issues of *ENR* for this period were used in the study.) *ENR* reported on only selected major failure cases. Several independent investigations supportive to the cases reported by *ENR* were also considered to enhance and present a review of the various dimensions of the structural and construction failure problem (Hadipriono and Diaz 1988; Hadipriono and Wang 1986; Lew et al. 1981; Leyendecker and Fattal 1973; Ross 1984). *ENR* reporting procedures depended on the severity of the case and randomness of the selection, and were not restricted by the type of construction, the time of failure, the stage of failure, the type of failure, or the failure causes or consequences.

All failure cases reported by *ENR* for the period of 1975–1986 were analyzed in this study without exception. Therefore, it is valid to argue that the cases covered by *ENR* represent an approximately representative sample of major failure cases. The cases covered by *ENR* represent a large sample of

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failure cases during the construction process or the service life of the project. The strategy followed by *ENR* to report a major failure case involves the study of the physical structural and construction failures, economic and social impacts, and investigation results by the Occupational Safety and Health Administration (OSHA). The information provided by *ENR* was supplemented, in certain cases, with the writers' judgment regarding failure causes, factors, etc.

DATA-BASE SYSTEM FOR ANALYSIS OF FAILURES

In this study, the strategy followed for reporting and analyzing failure cases was based on a certain conceptual framework established to evaluate the problem of structural and construction safety. The framework was divided into four major components: (1) Information on the occurrences of failure; (2) details on the causes of failure; (3) information on the consequences of failure; and (4) information on the various areas for improvement and controls to minimize the effects of failure.

The occurrences component of the framework included information about the sources reporting the failure, type of failure, type of project, source of errors in the building process, type of failed elements, manner of failure, and time of failure.

The causes component reported on the uncertainties associated with the structural and construction performance. Uncertainties in the building process were divided into natural and man-made hazards, variations within common practices, and departure from common practices (Eldukair and Ayyub 1988a; Nowak and Carr 1985). The most important types of uncertainty affecting the various stages of the building process were natural hazards and departure from common practices, which was defined as human errors.

The consequences component gave information about project damages associated with economic and social effects, as well as the amount of time required to recover the damage.

Finally, the control component was defined as a feedback element for the framework structure to reduce or enhance the recovery of future failures. The control component was used to get the necessary information for establishing restrictions on the acceptable risks of design and construction procedures and for planning and improving work strategies to detect and avoid human errors with respect to technical, management, and human behavior functions. The control component also focused on establishing correction, checking, and warning procedures for owners, contractors, construction managers, and structure users.

The analysis of the occurrences, causes, consequences, and controls of the studied failure cases is discussed here.

Occurrences of Failure

The building process of a structure includes planning, design, construction, utilization, demolition, and alteration phases. The types of failed structures observed in this study included commercial and residential buildings, industrial projects, transport projects (mainly roadway networks), dams, tunnels, underground construction, bridges, and stadium and hospital projects. The types of failure were divided into three categories: collapse, loss of safety or distress, and loss of serviceability. Collapse was defined as a permanent mode of failure where all or some elements of the structure need replacement. Loss of safety and serviceability are both important because they represented a transition mode and, therefore, could lead to a collapse if adequate levels of remedial work were not met (Eldukair and Ayyub 1988a; Hadipriono 1985). In general, the study indicated that collapse failures were more frequent than other types of failures. Fig. 1 indicates that 56.4% of the failure cases were associated with collapse, while 4.1% and 39.4% were associated with loss of safety, and loss of serviceability, respectively.

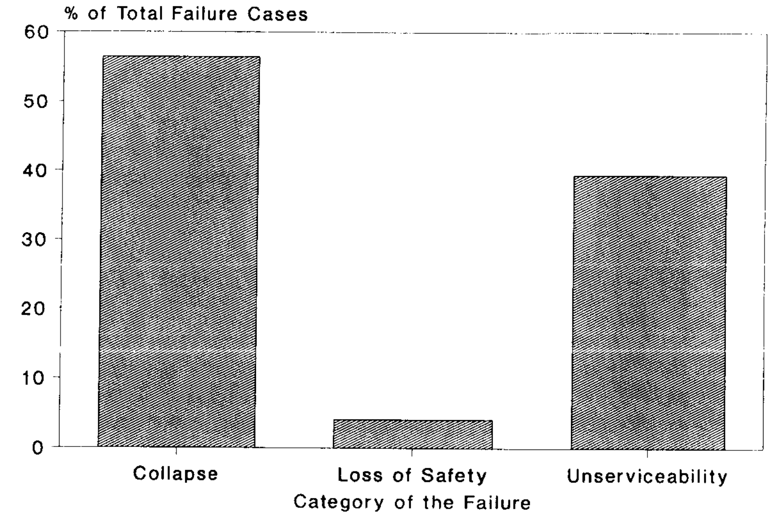

FIG. 1. Types of Failure

Collapse and loss of safety were isolated, progressive, or due to load shedding (Walker 1980). Isolated failures were defined as the independent failure of structural members and elements without causing the failure of the structural system. They were dominant for both collapse and distress cases. As shown in Fig. 2, only 37% of the total failure cases were isolated collapse and 3.1% of the total cases were isolated distress. In addition, 18.5% of the failure cases were progressive collapse, and 1% of the cases were progressive distress.

Fig. 3 shows a classification of failures according to the different modes of failure. Most collapse and loss-of-safety types of failure did not show warnings for their occurrence. The analysis of the failure cases indicated that 58.8% of the cases failed without sign or warning of impending collapse or loss of safety and they were caused by the instability and rupture of a critical structural element.

Similarly, the study showed that the loss-of-serviceability type of failures was also common in the United States. As shown in Table 1, the major symptoms of loss-of-serviceability failures were local damage and cracking of structural elements. Only 29.1% and 11.1% of total failure cases showed loss-of-serviceability failures with local damage and cracking symptoms, respectively.

Most of the loss-of-serviceability types of failures were associated with

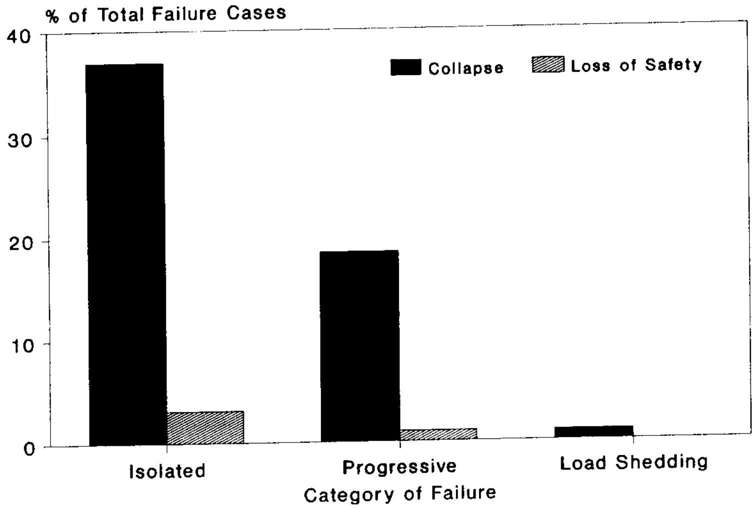

FIG. 2. Types of Collapse and Loss of Safety

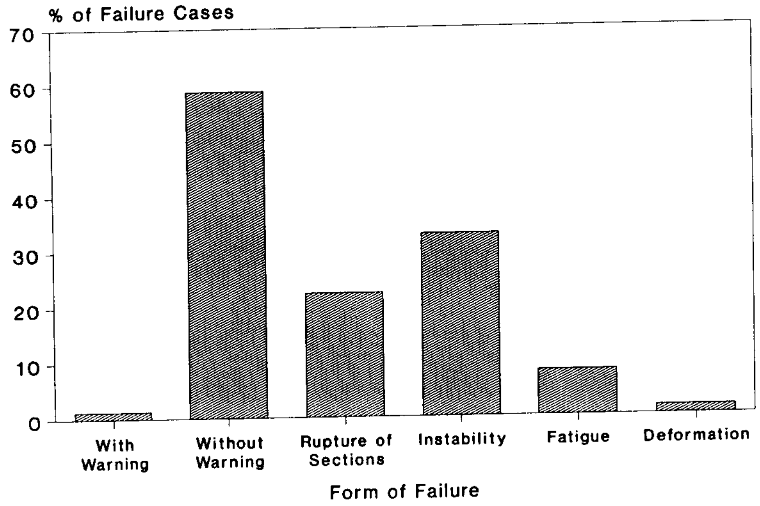

FIG. 3. Modes of Failure

delamination of structural composites, water penetration, and corrosion. Only 26.3% of total failure cases indicated that delamination of composites was the main reason for loss-of-serviceability failures.

Structural failures occur in a wide variety of construction projects. In this study, most of the failure cases were related to commercial, bridge, and residential projects. They constituted 48.2%, 21.2%, and 18.2% of the total failures, respectively.

TABLE 1. Loss of Serviceability Symptoms

Type of symptom (1)	Failure cases (%) (2)
Deformation	1.0
Cracking	11.1
Local damage	29.1
Displacement	2.1
Vibration	0.17
Others	0.17

The frequency of structural failures occurring during the construction and utilization phases of the building process accounted for 43.7% and 56.3% of the reported cases in this period, respectively. However, the population of existing structures is larger than the population of projects under construction. Therefore, the number of failures during construction is considered to be more critical than the number of failures of existing structures. Most of the failures occurred in the period of 1979–1980 as shown in Table 2. In addition, most of these failure cases involved commercial and residential projects. This high number of failure cases is attributed to severe weather conditions experienced during this period in the northeast United States, combined with the failure of local and state codes of practice to require safety measures to deal with the contingency of excessive snow loads. The dramatic increase in commercial and industrial construction, as a result of economic growth, also contributed to the structural and construction failure problem.

The building process is an interactive sequential process consisting of a series of activities and events. The performance of work activities usually involves a variety of resources, i.e., manpower, materials, equipment, time, and money. Any limitations on integration, interaction and control of resources can increase the chance of errors in the building process, and there-

TABLE 2. Number of Failures with Respect to Type of Structure and Time of Occurrence

Year (1)	Type of Project							
	Commercial (2)	Industrial (3)	Transport (4)	Tunnel (5)	Dam (6)	Bridge (7)	Residential (8)	Others[a] (9)
1975	6	0	1	2	2	4	0	1
1976	5	0	0	0	2	40	0	1
1977	6	2	1	1	2	7	0	1
1978	91	4	1	0	2	4	0	0
1979	53	4	1	0	1	25	91	2
1980	103	3	0	0	2	7	0	0
1981	3	0	0	0	0	5	4	1
1982	3	2	5	2	1	3	0	0
1983	8	1	5	2	2	17	4	3
1984	7	2	0	0	0	8	6	0
1985	2	1	2	0	0	5	1	2
1986	4	2	4	0	1	3	4	1

[a] Others include underground, stadium, and hospital projects.

TABLE 3. Sources of Technical Error

Type of technical error (1)	Failure cases (%) (2)
Planning	4.0
Design	51.2
Construction	56.6
Operation	30.5

fore, bring about a project environment system in which it is quite complicated to execute all work tasks effectively and safely (Eldukair and Ayyub 1988b; Matousek 1977; Nowak and Carr 1985).

Sources of error in the building process were mainly associated with technical problems, management problems, effect of construction accidents, and environmental effects. In general, 77.9% of structural failure cases indicated that technical errors were the dominant source of error in the building process. On the other hand, 39.6%, 3.6%, and 56.1% of the failures involved management problems, effect of construction accidents, and environmental effects, respectively.

Errors in the technical process involved a variety of deficiencies in carrying out technical matters during the performance of the various phases of the project. Technical errors were classified as errors in the planning, design, construction, or operation and utilization processes. The study of the structural failures indicated that construction errors were the most unfavorable events in performing the technical stage of the building process. Table 3 shows that 56.6% of total failure cases recorded deficiencies in construction procedures.

Errors in management practices have a tremendous effect on the performance of project activities, the schedule, and safety. They included deficiencies in work responsibilities, deficiencies in the communication process, and lack of work cooperation. Errors in defining work responsibilities were dominant for the deficiencies in management practices type of failure cases. Table 4 indicates that 30.3% of the total failure cases were associated with this type of error.

In addition, management errors represented by the deficiency of work supervision and control were also responsible for some failures that were influenced by the effect of construction accidents. Only 2.2% of the failure cases experienced errors in work supervision and control.

The sources of environmental errors involved political, financial, or economic pressures and the effect of weather conditions. Table 5 shows that 49.9% of failure cases were associated with poor weather conditions.

TABLE 4. Sources of Management Error

Type of management error (1)	Failure cases (%) (2)
Work responsibilities	30.3
Work communication	17.2
Work cooperation	4.8

TABLE 5. Sources of Environmental Effect

Type of effect (1)	Failure cases (%) (2)
Political pressures	10.4
Financial pressures	11.6
Weather conditions	40.9

The most common types of failed structural elements included foundations, vertical elements, beams and trusses, plates and slabs, connections, and temporary structures, i.e., falsework and formwork. Table 6 indicates that 4.1%, 10.8%, and 10.6% of failure cases experienced problems with slab elements, beams and trusses, and vertical elements, respectively.

Structural elements can involve a wide variety of material deficiencies. Most of the failure cases indicated that reinforced concrete elements were predominant. Table 7 shows that 86.4% of failures recorded deficiencies in reinforced concrete elements. Current common construction practice in the United States involves reinforced and prestressed concrete technologies more than steel construction technology (Wang and Salmon 1979). Concrete is a nonhomogeneous material that behaves differently under common circumstances of various loading systems, methods of casting, handling, and curing, as well as temperature and weather conditions. Concrete construction

TABLE 6. Types of Failed Elements

Classification of the elements (1)	Failure cases (%) (2)
Foundation (soil, raft, footings)	6.1
Vertical (columns, piles, walls)	10.6
Beams and trusses	10.8
Slabs and plates	34.1
Connections (cables, formwork, falsework)	8.8
No information	33.8

TABLE 7. Classification of Material of Failed Elements

Type of materials (1)	Failure cases (%) (2)
Masonry and mass concrete	0.33
Timber elements	2.8
Reinforced concrete	86.4
Prestressed concrete	1.3
Precast concrete	0.83
Steel structures	9.0
Aluminum elements	0.5
Plastic elements	0.5
Glass cladding	1.8
Rock and earth materials	5.8
No information	0.34

TABLE 8. Distribution of Failure Cases with Respect to Sources of Error by Participant

Description of the participant (1)	Failure cases (%) (2)
Project architect	3.0
Structural designer	48.2
Resident engineer	31.1
Inspector	27.6
Contractor (head office)	3.8
Contractor (site staff)	59.6
Contractor (workmen)	17.4
Operator (crane, vehicle, ship)	2.8

needs more consistent and continuous attention from engineers to maintain the safety and durability of the structural components. This provided a justification for the relatively large number of construction failures due to deficiencies in concrete structural elements.

Human errors were major causes of several deficiencies in preparing, executing, and controlling work activities along the planning, design, construction, and utilization phases of the building process. Contractors at job sites were common participants in generating human errors. In addition, structural designers, and resident engineers who control work tasks were also a major source of errors in structural failures. Table 8 shows that 59.6%, 48.2%, and 31.1% of failures involved mistakes made by contractors, structural designers, and resident engineers.

Human errors were caused by different deficiencies in human behavior toward proper performance of the phases of the building process. Table 9 indicates that ignorance, negligence, and carelessness were among the major factors of human behavior deficiency, as evidenced in 82% of failures. In addition, the effect of underestimation of certain planning, design, and construction requirements was also considered a critical factor that might contribute to structural and construction failures. Similarly, insufficient knowledge and lack of education and work training programs were considered critical factors, as evidenced in 66.7% and 57.3% of the failures, respectively.

TABLE 9. Distribution of Failure Cases Relative to Human Behavior

Description of human behavior (1)	Failure cases (%) (2)
Insufficient knowledge	66.7
Lack of education/training	57.3
Lack of foresight/imagination	33.0
Lack of authority in decisions	45.4
Reliance of other parties	29.0
Underestimation of influence	72.2
Ignorance, negligence, and carelessness	82.0
Objectively unknown situation	33.3
Lack of ability to communicate	37.1

TABLE 10. Primary Causes of Failure

Description of the primary causes (1)	Failure cases (%) (2)
Inadequate load behavior	45.2
Inadequate connection elements	47.0
Reliance on construction accuracy	1.8
Errors in design calculations	2.5
Unclear contracts information	23.5
Contravention of instructions	21.8
Complexity of project system	1.2
Poor erection procedures	54.3
Unforeseeable events	7.1
No information	15.5

Causes of Failure

The causes of failure involved primary and secondary factors. The primary factors may have caused failure if they occurred independently, while secondary factors may have caused failures if two or more factors occurred at the same time and interacted. The primary causes of the studied failure cases are presented in Table 10, while the secondary factors are shown in Table 11.

Inadequate, poor execution and erection procedures were the major primary cause of failures with 54.3% of such cases indicating their involvement. Poor execution and erection procedures were evidenced in the inadequacy level of load behavior and connection elements with 45.2% and 47% of failure cases indicating their involvement, respectively.

On the other hand, the major secondary factors that caused failures involved negligence of environmental effects and lack of supervision and control. These factors were experienced in 49% and 36.6% of the cases, respectively. The study indicated that most of the failures involved com-

TABLE 11. Secondary Causes of Failure

Description of secondary causes (1)	Failure cases (%) (2)
Lack of engineering responsibilities	8.1
Environmental effects*	49.0
Poor material and equipment usage	23.5
Lack of engineering specialization	0.9
Improper workmanship	7.0
Lack of safety training and orientation	1.7
Lack of work coordination	7.1
Lack of supervision and control	36.6
Improper communication procedures	33.3
Application of new technology	1.2
Foreseeable deterioration	28.3
No information	34.0

*Environmental effects include weather effects, political pressures, financial constraints, and industrial pressures.

mercial-building and bridge projects. One hundred twenty-eight bridge failures occurred during the 12-year period of the study. In addition, 291 commercial-building failures were recorded over the 12-year period of the study.

The 1986 number of bridges added every year to the bridge population according to the Department of Transportation ranges between 1,500 and 2,000 units. On the other hand, the number of commercial buildings added every year to the commercial-building population ranges between 50,000 and 55,000 units (*Construction* 1986).

The most frequent primary causes of bridge failure were attributed to financial constraints in exercising maintenance and inspection programs, fatigue loading due to excessive traffic volume and axial loads, and excessive wind loads. In general, 52.3% of bridge failures involved financial pressures, while 44.5% and 43% of bridge cases involved fatigue and wind loading effects, respectively. On the other hand, the primary causes for commercial building failures involved inadequacy in load behavior, inadequacy in connections design, and poor erection procedures.

In addition to the determination of primary and secondary causes of failures, the study aims to determine the stages where failures originate. The stages included planning procedures, design procedures, design analysis and detailing, contract information, construction procedures, and operation procedures. The studied failures showed that 25.7% of the cases involved deficiencies in the planning stage associated with improper evaluation and assessment of project tasks and activities. In addition, improper design concepts and inadequate consideration of loading and environmental effects also contributed to the initiation of the failures. These factors were involved in 42.9% and 47.3% of the failure cases, respectively.

On the other hand, the interaction of inadequate design calculations, poor structural detailing, and ineffective preparation of specification documents seems slightly responsible for the number of reported failure cases, since such an interaction is seen in only 10.1% of the failure cases. Finally, deficiencies in construction and operation (or utilization) procedures were responsible for many failure cases. Some of the deficiencies in the construction procedures involved inadequate construction methods, ineffective evaluation of laws; safety regulations; standards and recommendations for project activities; improper verification of calculation procedures for design detailing; and inadequate definition of planning, control and supervision measures of project activities. In addition, the deficiencies in the operation (or utilization) procedures mainly involved improper use of operational safety standards, ineffective inspection and maintenance programs, and the effect of poor weather conditions. Lack of proper and effective construction methods, and improper weather conditions were predominant factors, as reflected in 33.6% and 46.2% of the failures, respectively.

Consequences of Failure

Construction failures have many consequences. They include human deaths and injuries, economic losses, time delays in work schedules, discredit to responsible parties, and impact on the industry. The analysis of the failure cases indicated that the studied failures caused 416 total deaths and 2,515 total injuries. The frequency of deaths and injuries depends primarily on the severity of the failures rather than the number of occurrences. Table 12 indicates that dam, bridge, and residential building projects were the riskiest because they involved the highest numbers of death and injury. The large number of recorded injuries associated with the dam projects stems from the failure of the Teton Dam in Idaho (Ross 1984).

TABLE 12. Potential Casualties with Respect to Type of Construction

Type of construction (1)	Deaths (%) (2)	Injuries (%) (3)
Commercial buildings	1.0	1.5
Industrial projects	3.0	2.8
Transport projects	1.0	1.5
Tunnel projects	0.2	0.2
Dam projects	3.0	57.0
Bridge projects	5.5	1.2
Residential buildings	0.5	6.0
Stadium projects	0.2	0.5

The total direct costs of damage of the studied structural and construction failures were estimated at $3.5 billion in 1986. The economic losses involved only estimated direct structural and construction damage as well as equipment and material costs. Several hidden or indirect costs were not included because it was very difficult to determine such information for the studied cases. Table 13 depicts that industrial, dam, and bridge failures had the highest damage costs at $1 billion.

Another important fact about structural and construction failures in the United States is the time required to recover the damage. Table 14 shows the time needed to overcome the damage for the studied failures. The period of seven to nine months was the most frequent time period to overcome damages as it involved 44.2% of the failure cases.

Controls of Failure

Most of the studied failures were caused by various errors in the different phases of the building process. Based on the studied failures, errors can be discovered with additional inspection procedures along the planning, design, construction, and utilization phases of the building process. The construction

TABLE 13. Economic Consequences of Damage with Respect to Type of Construction

Type of construction (1)	Damage cost (millions of dollars) (2)
Commercial buildings	204.04
Industrial projects	1,043.66
Transport projects	232.66
Tunnel projects	5.71
Dam projects	1,102.70
Underground projects	0.50
Bridge projects	959.10
Residential buildings	38.55
Stadium projects	8.14
Hospital projects	0.25

TABLE 14. Time Required to Overcome Existing Damage

Time required in months (1)	Failure cases (%) (2)
0	5.0
1–3	31.6
4–6	6.6
7–9	44.2
10–12	4.6
13–24	0.8
25–36	1.2
37–48	0.0
49–60	0.17
>60	0.17
No information	5.6

and utilization procedurbs were the most critical because 64.4% and 66.1% of failures occurred during these phases, respectively. Results indicated that errors might have been discovered if proper checking procedures were maintained during the construction and operation of the structure.

The writers express their own judgment in recommending certain control measures that should be established to minimize the recurrence of structural and construction failures. Personnel recruitment, checking and inspection procedures, work procedures, codes of practice, and research and technology are among the major areas where control measures should be considered. The four major areas that can be used to control the recurrence of failures include appointment of experienced and qualified site staff, implementation of quality assurance and quality control procedures, enforcement of penalties on contractors, and implementing systematic procedures, i.e., planning, scheduling, supervision and control. About 58% of the failures cases indicated the positive impact that such major areas can have on the safety of construction operations. In addition, 91.7% of the failure cases indicated the benefit of implementing systematic procedures to minimize the effect and recurrence of the failures.

ESTIMATION OF RISKS FOR U.S. BUILDING INDUSTRY

As mentioned earlier in this paper, the procedure followed to select the failure cases depended totally on the actual detection of a failure criteria in either the structural and construction systems. Therefore, it was a random selection that depended on the severity nature of the case without any restrictions to the type of construction and type, stage, mode, time, causes, and consequences of failure. Thus, the information gathered from the sample cases can be mapped to draw conclusions on the entire population of failures in the United States. This represents a simple approach to determine and evaluate risk measures for the building industry.

Construction risks may be estimated based on the results and analyses generated from studying the sample of 604 cases of structural and construction failures. To calculate risk measures, it is important to determine information concerning the U.S. construction industry with respect to:

1. The average annual dollar volume of the industry.
2. The average annual work force employed in the industry.
3. The average number of construction projects created every year.

The average annual volume of the construction industry was estimated at approximately $300 billion in 1986. The 1986 average annual work force was estimated to be 6 million. The 1986 annual construction employment constituted 6% of the total work force (*Construction* 1986; *Construction* 1985). The 1986 average annual number of jobs created every year in the United States was estimated to be 1.5 million. This estimate includes the different structural facilities as defined by the U.S. Bureau of Census (*Construction* 1986). These average values were based on the reported statistics for the years 1975–1986.

It is possible to estimate some risk measures based on the analysis of the structural and construction failures. Some of the measures include the risk of casualties in the construction industry, the financial risks resulting from failures, and the risk of structural and construction failures.

The estimates of risk are determined based on the following procedure and assumptions (Eldukair and Ayyub 1988a):

1. Since *ENR* reports on major failure cases, and does not report on all cases, the studied cases were assumed to be an approximate, valid statistical sample for the U.S. building industry. The failure consequences based on this sample were assumed to be approximately equal to the corresponding annual values.
2. The cost of damages for the studied cases reflected only direct costs. Therefore, to incorporate the impact of the indirect costs into the total cost function of failures, it was assumed that the ratio of indirect to direct costs is equal to four. This assumption was based on hypothetical analysis and studies conducted by Levitt and Samelson (1987) on the costs of construction safety.
3. The average annual number of deaths and injuries is equal to the total number of casualties for the studied cases.
4. The average annual number of construction failures is equal to the total number of the studied 604 failure cases.
5. The annual risk of casualties in the United States was obtained by calculating the ratios of deaths and injuries with respect to the total population of the work force in the U.S. building industry. Table 15 presents the annual risk of fatalities and injuries in the U.S. building industry.
6. The annual financial risk of failures was determined by calculating the ratios of the cost of damage resulting from failures with respect to the total dollar volume of the U.S. construction industry. The annual financial risk of construction failures is depicted in Table 16.
7. Finally, the annual risk of structural failures was determined by calculating the ratios of the number of project failures with respect to the average number of construction projects created every year. Table 17 shows the estimates of the annual risk of failures according to the type of construction. For example, the annual risk measure for commercial buildings was determined as $(291/406) \times (406/1{,}500{,}000) = 0.000194$.

The risk measures in the building industry are very difficult to determine because they are based on variables that are very difficult to evaluate. The estimation of such risk measures further demonstrates the significance of the

TABLE 15. Estimates of Annual Risk of Construction Casualties

Description (1)	Values (2)
Annual number of deaths (failures)	456
Annual number of deaths (accidents)[a]	1,569
Annual number of injuries (failures)	2,515
Annual number of injuries (accidents)[a]	968
Total annual number of deaths	1,985
Total annual number of injuries	3,483
Size of construction work force in the U.S.	6,000,000
Risk of fatalities in construction	3.31×10^{-4}
Risk of injuries in construction	5.81×10^{-4}
Risk of fatalities and injuries in construction	9.11×10^{-4}

[a] The analysis of construction accident cases is not presented in this paper. A detailed evaluation of such cases in the United States is provided by Eldukair and Ayyub (1988a).

TABLE 16. Estimates of Annual Financial Risk of Failures

Description (1)	Values (2)
Annual cost of failure in dollars[a]	1.44×10^{10}
Annual U.S. construction volume in dollars	3.00×10^{11}
Annual financial risk of structural failures	4.80×10^{-2}

[a] Direct and indirect costs were considered in the annual cost function of structural failures.

building failure problem. In addition, the evaluation of the risk measures indicated that engineering practitioners should study and closely review the various construction methods and sequences in order to reduce the potential of failure occurrences.

COMPARISON BETWEEN U.S. AND EUROPEAN BUILDING FAILURES

In 1976, a study of European failures was conducted by Matousek and Schneider (1976). The study considered 800 failure cases occurring in the period of 1960–1976. The methods of reporting the European and U.S. failures involved the analysis of the facts, causes, consequences, conclusions, and controls. The volume of the European failures roughly showed the same distribution to the various types of construction (Matousek 1977). The European study showed that a great part of the financial losses, injuries, and fatalities came from traffic-related construction failures, i.e., bridges, highways, and tunnels. However, the analysis of the U.S. failure cases showed that a relatively great part of financial losses and fatalities came from the failure of dams, bridges, and industrial facilities. Most of the injuries were due to dam and residential building failures, and involved most the reported incidents.

TABLE 17. Estimates of Annual Risk of Failures for Type of Construction

Type of construction (1)	Frequency of failure (2)	Annual risk of failure (3)
Commercial buildings	291	1.94×10^{-4}
Industrial projects	21	1.40×10^{-5}
Transport projects	20	1.33×10^{-5}
Tunnel projects	7	4.67×10^{-5}
Dam projects	15	1.00×10^{-5}
Underground/excavation	1	6.67×10^{-7}
Bridge projects	128	8.53×10^{-5}
Residential buildings	110	7.30×10^{-5}
Stadium projects	10	6.70×10^{-6}
Hospital projects	1	6.67×10^{-7}

The European failure cases were collected from data-base centers and various reports. However, the U.S. failure cases were mainly collected from *ENR* and several independent studies supportive to the cases reported in *ENR*. The studies analyzed a large number of structural and construction failures. The samples in both cases can be considered representative of the respective failure populations of the building industry since both studies analyzed the reported cases that occurred within the respective reporting periods without exception. The analysis of the cases was objectively related to present the dimension of the building safety problem, which should be very useful in defining effective safety strategies.

The analysis of the European and U.S. failures agreed in reporting that most damage happened during the construction of the structures. This is due to the fact that the operation stage is considered and investigated during the design phase of the structure, while the construction stage is often considered to a lesser extent in the design phase.

The analysis of the European failures depicted that most of the damage during the utilization phase of the building process involved industrial projects. However, the damage resulting from traffic and residential building construction had been detected mainly during the erection stage of the construction phase of the building process. Regarding the U.S. failures, the number of failures occurring during the service life of the structure was slightly higher than during construction. However, the population of the existing structures is larger than the population of the projects under construction. Most of the cases involved commercial and residential projects.

In most of the European cases, errors by engineering and contractor teams were responsible for most of the failure incidents. Similarly, the analysis of the U.S. failures verified that errors by structural designers, resident engineers and contractors were the main contributors to the failures. In addition, ignorance, carelessness, and negligence during planning, design, construction, and operation phases of the project cycle were reported in both studies as being among the major areas to cause human unreliability.

Finally, European and U.S. failure studies indicated that most errors could have been detected in time by further proper checking and inspection control. Only a small portion of the cases would have escaped in spite of safety strategies.

CONCLUSIONS

Construction safety is still an issue of concern to engineering practitioners.

The importance of structural and construction reliability is associated with the adverse consequences that may result from structural and construction failures and construction accidents.

The performance of work activities usually involves a wide variety of resources including manpower, materials, equipment, time, and money. The limitations on integration and control of the resource parameters can bring about a project environment in which it is very difficult to execute work activities effectively, efficiently, and safely. The study revealed that the main sources of errors in the building process were technical procedures, management practices, and environmental effects.

The critical problem of structural and construction safety is associated with technical and management errors committed during the construction stage of the building process. These errors were mainly attributed to inadequate coordination and communication procedures between engineers, designers, and contractors. Therefore, the problem of failures is mainly related to deficiencies in checking and inspection procedures and not to the lack of refinement of codes of practice or quality control of materials and work procedures.

Finally, the frequency of structural and construction failures can be reduced by developing consistent techniques for safety assessment and evaluation of construction operations. The techniques should account for quantifying the subjectivity and uncertainty associated with the factors that affect safety of construction operations.

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