Study of Recent Building Failures in the United States

Kumalasari Wardhana[1] and Fabian C. Hadipriono, P.E., F.ASCE[2]

Abstract: A total of 225 building failures in the United States from 1989 to 2000 were recorded in this study. The result shows that failures of low-rise buildings constitute about 63% of all cases, followed by multistory buildings as a distant second. In terms of their functions, apartments are the most frequent to fail. External events and construction and maintenance deficiencies have been identified as the most frequent principal causes. External events include rain, wind, snow, vehicular impact, and collision. Construction deficiencies encompass improper renovation, unplanned demolition, poor workmanship, and unsafe excavation operations. Maintenance deficiencies are associated with building deterioration that was overlooked and improperly maintained. A comparative analysis conducted between this study and two previous studies indicates an inclined trend of relative failure occurrences of low-rise and multistory buildings. The study also suggests that, despite the recent enhancement of information technology, current sources of information are still incomplete. The creation of new complete databases, further improvement of information sources, and their dissemination through the Internet are deemed essential to prevent building failures from recurring.

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Introduction

The number of new buildings being constructed each year continues to grow. New facilities are continuously being added each year to meet public demands. Approximately 1.5 million new houses were built annually from 1996 to 2000; in the commercial section, about 70,000 buildings were built each year from 1990 to 1995 (U.S. Census Bureau 2001).

Engineers have realized the importance of collecting information regarding failures of constructed facilities. Our study shows that many people are still reluctant to share failure information due to legal reasons and fear of ruining their reputation. Hence, except for those published, not too many repositories of failed buildings can be readily found. A failure center named AEPIC (Architecture and Engineering Performance Center) was established in 1984 to gather failure cases of constructed facilities. Despite such an exemplary effort, due to funding problems and lack of support, this center was closed after only a few years of service (Kaminetzky 1991).

Reports on individual cases of failures of constructed facilities can be found in engineering journals, magazines, and books. The American Society of Civil Engineers (ASCE) Technical Council on Forensic Engineering has sponsored a pair of meetings (Rens 1997; Rens et al. 2000) discussing issues in forensic engineering. One paper presents a study of implementing a failure report system as one of the strategies in preventing construction failures (Ortega 2000). Detailed explanation of failures can also be found in recently published forensic-engineering-related books (Feld and Carper 1997; Ratay 2000). Still, only few studies on the collection and analysis of building failures have been carried out in the last decade.

Examples of studies on integrated topics of failures are the analysis of 800 construction failures by Matousek and Schneider (1976) and the survey of structural and construction failures in the United States between 1975 and 1986 by Eldukair and Ayyub (1991). Furthermore, two studies were conducted at the Ohio State University for failures that took place between 1977 and 1981 (Hadipriono 1985) and between 1982 and 1988 (Hadipriono and Diaz 1988). In addition, the writers of this paper performed a parallel study of recent bridge failures in the United States (Wardhana and Hadipriono 2003).

The purpose of this paper is to continue earlier studies conducted by the writers to examine failure of buildings in the United States between 1989 and 2000. For this purpose, a database containing general information about building failures was created in this study (Wardhana 2002). The information in the database is collected mainly from the online newspaper collection database Academic Universe LexisNexis (LexisNexis 2001), from engineering journals and magazines such as *Engineering News Record* and *Civil Engineering*, from Internet resources, and from the writers' own experience.

By collecting data regarding building failures and then analyzing that data, this study is intended to serve as an informational basis that may be needed by engineering and construction professionals, especially, to achieve a better understanding about the recent facts and trends of building failures.

Failure Defined

The first study by the writers, cited in the previous section, which became the foundation for this paper, discovered 65 cases of building failures that occurred between 1977 and 1981, while the second study retrieved 46 cases of building failures that took place between 1982 and 1988. These figures represent the number

[1]Graduate Student, Ohio State Univ., Columbus, OH 43210.

[2]Professor, Civil Engineering, Ohio State Univ., Columbus, OH 43210.

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of much publicized and well-known failure cases that were collected rigorously yet manually, without the advantage of current information technology, such as database availability and the Internet. In this paper, the writers have collected 225 cases of building failures that occurred from 1989 to 2000. To present sufficiently accurate figures of failed buildings in the United States, classifying building types and defining the term ''failure'' is essential.

Buildings come in various types and shapes, frequently determined by their functions. While there are multitudinous ways to classify buildings, for the purpose of this study, buildings are categorized based on their shapes and functions. In this analysis, buildings having four or less stories are considered as low-rise; otherwise, they are regarded as multistory buildings. Each group of these buildings is further classified based on their functions; examples include apartments, warehouses, and office buildings. The next category is buildings having a distinctive slender and tall shape, such as broadcast towers; these are classified as towers. Buildings with unique characteristics covering unusually wide areas, such as stadia and auditoria, are categorized as long-span buildings. Next, buildings with specific functions and shapes serving as a plant or a factory were grouped separately as plant-industrial buildings.

Throughout this paper, the term failure refers to two conditions, collapse and distress. Failure is defined as the incapacity of a constructed facility (in this case, a building) or its components to perform as specified in the design and construction requirements. A building collapse occurs when the entire or a substantial part of a structure comes down, in which the structure loses the ability to perform its function. Depending on the extent of the collapse, this term may be further classified into two categories, total collapse and partial collapse. A total collapse implies that several primary structural members have fallen down, practically eliminating occupancy underneath it. Generally, a total collapse requires full replacement of the building. A partial collapse suggests a condition where some of the primary structural members have fallen down—hence, endangering the lives of those inside or nearby the structure. A partial replacement may be needed in the case of a partial collapse. The term distress refers to the unserviceability of a structure or its component(s) that may or may not result in a collapse. Moreover, distress is a particular condition of the structure, which has undergone some deformations without losing its entire structural integration. In this study, both collapse and distress are assumed to be the subsets of failure.

Causes of Failures Defined

The following terms are used in concert with those presented in earlier studies (Hadipriono 1985; Hadipriono and Diaz 1988). The principal causes of building failures are categorized as deficiencies in design, detailing, construction, maintenance, use of materials, and inadequate consideration of external events. The first four deficiencies represent integral roles in the construction of a building. Deficiency in design constitutes errors, mistakes, oversight, omission, or conceptual flaw that could have taken place during the design process of the building. Detailing is a ''transition'' process between design and construction periods, in which the details of the structural design are prepared for their implementation through shop drawings. Design detailing is commonly performed by the contractors and approved by the engineers. Changes are often made emphasizing on workability and constructibility of the facility. Previous studies cited herein revealed that this process is vulnerable to discontinuity or loss of the original design concepts. Therefore, deficiency in design detailing may be considered as a class by itself. It includes errors, mistakes, omissions, and discontinuity/loss of design concept. Construction deficiency occurs as problems with workmanship and deviation of results from the specifications. Examples of such deficiencies are improper installation and inadequate temporary structure to support the permanent structure. Examples of maintenance deficiencies are corrosive and damaged components that take place during postconstruction or the service life of the buildings.

When construction components are precast or prefabricated, material deficiency originated by the manufacturer may contribute to building failures. Examples of such deficiencies are the use of defective and substandard materials. The first five deficiencies are those associated with problems having internal effects on the structure or its components. On the other hand, a building or its components may also suffer from external effects, such as vehicle impact or corrosive environment. The external causes included are limited only to the events that are usually encountered in design codes. Failures due to natural disasters (e.g., excessive impacts from earthquakes, storms, floods), fires, war, and terrorism are excluded in this study. In so doing, the writers intend to isolate causes that are related primarily to unintentional human-induced problems during the building process. Note that all these deficiencies may be correlated but such correlation may not be readily apparent; hence, in this study, only the most probable principal cause was considered in each case.

With respect to the effects on the building or its components, these deficiencies may be categorized as enabling, triggering, and procedural causes. The enabling causes are those related to the internal condition or performance of buildings or its components. Hence, the first five principal causes (design, detailing, construction, maintenance, and material-related problems) discussed previously fall into the category of enabling causes. The triggering causes are external events that could initiate failure of a structure. The procedural causes include management problems, legal issues, contractual matters, and problems concerning the interrelationship between parties involved in a project. The latter causes are generally difficult to prove, because they are usually hidden and unpublished; however, their occurrence could promote the enabling and triggering causes.

Results of Study

An important result of the study is the discussion of failure occurrences, which incorporates the categories, the types, and the stages at which the buildings failed. In addition, the study reveals 16 states where failures occurred most frequently. The next discussions are associated with the principal causes and the more specific causes of these failures. Based on these results, a comparative analysis involving two previous studies is presented.

Failure Occurrences

The 225 recorded building failures within the 1989–2000 time span in the United States are shown in Fig. 1, in which the number of failures are distributed with respect to the year the failures occurred. The overall pattern of the graph depicted in Fig. 1 reveals a trend of increasing number of failures despite the relatively stable growth of building population in the last five years (U.S. Census Bureau Housing Inventory). The age of the failed buildings ranges from one year (during construction) to 142

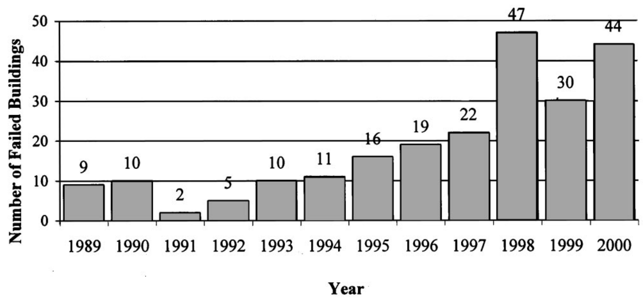

Fig. 1. Number of failed buildings distributed by year

years, with a mean value of 32 years, a median of six years and mode of one year. Not all observed cases came with age information; these central measures were obtained from 104 failure cases (46%) where information on year built and failed was recorded. Out of the 104 cases, 48 occurrences (46%) took place during construction, which explains why the median value is much lower than the mean value. For buildings that failed during their service life, these measures are somewhat different: the average age is 60 years, with a median of 71 years and a mode of 30 years.

The highest number of failures took place in 1998 (21% of total failures), where most of the buildings that failed were low-rise buildings. In addition, about 20% of failures happened in year 2000. Note that failures in the last three years of the observed period (1988–2000) represent an overwhelming 54% of the total number of failures. Further analysis on the 1998 failure cases reveals that about 42% of these failures took place in the state of New York, approximately 70% of the buildings were low-rise, and several of them were old (58% of cases with age information were older than 50 years). Fig. 2 shows failure distribution in the state of New York, which peaks in 1998. Almost 30% of these accidents started with the failure of a wall element and 21% began with the collapse of the roof component. One half of these failures occurred during the spring season (February–May). Almost 21% of the failures at that year were attributed to rain.

Table 1 shows the number of failures based on the building types and functions described earlier. Note that buildings that are not in use at the time of failure are identified as vacant buildings. About 10% of the buildings cannot be identified as to which group they should belong; thus, they are classified as "other."

Notable among these failures are low-rise (63%) and multistory buildings (14%). In its Current Housing Reports, the U.S. Census Bureau indicates 120.5 million total buildings, which consists of 115.9 million housing units and 4.6 million commercial buildings. Based on the number of stories, these buildings consist

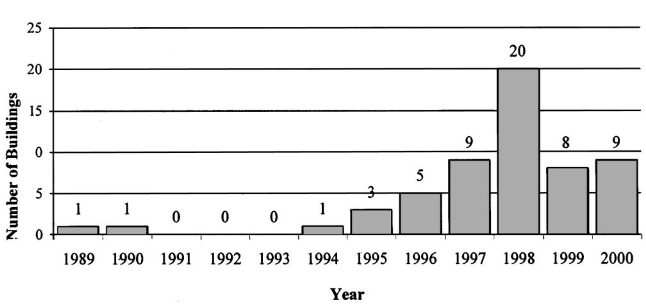

Fig. 2. Number of failed buildings in the state of New York distributed by year

Table 1. Type and Number of Building Failures

Building type	Function	Number of failures	Percentage
Low-rise		**141**	**63**
	Apartment	22	
	Vacant building	20	
	Warehouse	18	
	Store	14	
	Office	11	
	Commercial	8	
	House	6	
	School	6	
	Garage	5	
	Church	4	
	Hotel/motel	4	
	Restaurant	4	
	Other/unknown	19	
Multistory		31	14
	Apartment	9	
	Office	5	
	Vacant building	4	
	Hotel	3	
	Garage	1	
	Other/unknown	9	
Tower		7	3
	Broadcast tower	2	
	Other	5	
Long-span		9	4
	Stadium	5	
	Auditorium	2	
	Pool roof	2	
Plant-industrial		7	3
	Plant	4	
	Oil/water tank	2	
	Chimney	1	
Other		30	13
Total		225	100

of 98.9 million low-rise and 7.9 million multistory structures. The bureau further reports a total of 78.3 million single-family dwelling units. Despite the fact that these one- and two-story houses (single-family dwellings) represent the major population of buildings in the United States, the highest failure occurrences seemed to plague low-rise buildings other than single-family dwellings.

From this category, failures of apartment buildings (multiple-family dwellings) are paramount (22 occurrences, or 10% of total failures), followed by those of vacant buildings (20 occurrences, or 9% of total). Under the category of multistory buildings, the number of apartment failures is also the highest (nine occurrences, or 4% of total). In terms of their functions, total apartment failures represent 31 occurrences or 14% of all observed failures. Failures of all vacant buildings represent 11% of total observed failures.

Failure occurrences in the categories of plant-industrial buildings, long-span structures, and towers are less significant as compared with the low-rise and multistory buildings. Of particular interest are collapses of stadia. For example, the five failure occurrences experienced by stadia represent 2% of the total failures. However, due to the higher risk factor in occupancy, this figure should not be ignored. Fortunately, most of these failures are partial collapses during construction (four partial roof collapses and one beam collapse).

Table 2. Number of Failures with Respect to Stage of Failure Occurrences

Types of failures	Construction	Service	Unknown
Distresses	1	16	—
Partial collapses	35	126	—
Total collapses	11	35	—
Unknown	—	—	1
Total	47	177	1

Table 2 indicates the number of failure occurrences with respect to the type of failures (distress, partial collapse, or total collapse) by considering the time or stages at which failures took place, during construction or service life. The number of buildings that failed during service life is almost four times that during construction. This is expected, because with any constructed facilities, at any point in time, the number of existing buildings during service life is generally far greater than that during construction. Also, the duration of the buildings' service life is much longer than that of the construction of buildings. Furthermore experience shows that, with time, additional loads are often added to buildings without strengthening them, and in some cases, the building's function was altered without considering its capacity to perform the new function.

Table 2 also shows an overwhelming number of partial collapses (161 occurrences, or 72% of total) as compared with total collapses (46, or 20% of total) and distresses (17, 8% of total). This is expected, especially since, in order to reach a point where a total collapse occurs, a building must be flawed in both design and construction. Also, a partial collapse usually takes place prior to a total collapse; when partial collapse occurs, stresses are redistributed to other components that may arrest the partial collapse from progressing into a total collapse. One possible explanation for the small number of distresses is that, when a structure experienced a distressed condition, it quickly underwent a repair and escaped from being reported. Thus, only notable and well-documented distresses are found in this study.

The number of failures varies from state to state. The distribution of building failures for the 16 states where the most failures took place is given in Table 3 (ranked from 1 to 10). The failures that took place in these 16 states represents 83% of the total number of recorded failures. The rankings presented in this table are based on the percentage of the total number of failures. The figures in the table reveal New York as the state with the highest number of failures (57 occurrences, or 25% of total) with California trailing at a distant second (29 occurrences, or 13% of total). A possible reason for the significant number of failures in the state of New York is that it is one of the oldest states established in this country, where old buildings currently exist in a large number.

Out of the 57 failures in New York, only 19 have age information (four failed during construction, four before reaching 50 years, and 11 over 50 years old) with a mean of 67 years and a range between 1 year (failed during construction) and 101 years old. Hence, deterioration of these buildings may have contributed to these failures. This suggestion is consistent with the specific causes of failures delineated in a later section. In California, several of the failed buildings are due mostly to external events (nine events due to rain, impact force, and overload), construction (seven occurrences) and maintenance deficiencies (five occurrences). A possible explanation for the high number of failures is the fact that California has been building a large number of low-rise commercial buildings and dwelling units in the past decade. This growth is parallel to the explosive development of information technology facilities in the Silicon Valley. For example, according to the U.S. Census Bureau (2001), with more than 12 million housing units, California has the largest number of housing as compared with any other states in this country. Thus, while number of failures in California is second in rank, its failure rate is, presumably, low.

Table 3. States, Ranked by Building Failure Frequency

Rank	Name of states	Number of failures	Percentage of total failures
1	New York	57	25
2	California	29	13
3	Pennsylvania	16	7
4	New Jersey	10	4
4	Wisconsin	10	4
5	Illinois	9	4
5	Ohio	9	4
6	Georgia	8	4
7	Texas	7	3
8	North Carolina	6	3
9	Florida	5	2
9	Missouri	5	2
10	Louisiana	4	2
10	Massachusetts	4	2
10	Tennessee	4	2
10	Virginia	4	2

Principal Causes

Causes of building failures are classified into six principal causes, which include both enabling (design, detailing, construction, maintenance, and material-related problems) and triggering (external-related events) causes, as shown in Table 4.

Table 4 also presents principal causes, which are distributed into the types of buildings. About 27% of the total failures are attributable to external causes. These principal causes triggered the failures of 40 (18% of total failures) low-rise buildings. The remaining principal causes (design, detailing, construction, maintenance, and material deficiencies) constitute 45% of all causes. While the external events are considered the triggering causes, these latter deficiencies enable the building to fail; hence, they are termed the enabling causes. Among these causes, construction and maintenance deficiencies took place most frequently (63 and 23 occurrences, or 14 and 10% of total failures, respectively).

Table 4. Number of Principal Causes of Failure with Respect to Types of Buildings

Principal causes	Low-rise	Multistory	Plant-industrial	Long-span	Towers	Others
Design	4	1	—	2	1	—
Detailing	2	—	—	—	—	—
Construction	34	18	2	1	2	6
Maintenance	21	1	—	—	—	1
Material	2	—	—	1	—	—
External	40	2	3	3	1	12
Others	38	9	2	2	3	11
Total	141	31	7	9	7	30

Table 5. Number of Principal Causes of Failure with Respect to Phase of Occurrences[a]

Principal causes	Partial collapses	Collapses	Distresses
Design	7	—	1
Detailing	2	—	—
Construction	41	11	11
Maintenance	18	4	1
Material	3	—	—
External	48	12	1
Others (NA)	42	19	3
Total	161	46	17

[a]One case is unknown.

The relationships between principal causes and failure types are presented in Table 5. Data given in Table 5 are consistent with information presented in Tables 2 and 4. Here, too, partial collapses are observed to be the most frequent type of failures, with external events as the primary cause. Furthermore, Table 5 depicted the principal causes under each type of failures.

Numerous partial collapses are attributable to external events, construction deficiencies, and maintenance problems (48, 41, and 18 out of 161 occurrences, respectively). In the group representing total collapses, the same principal causes are noticeable (12, 11, and four out of 46 occurrences, respectively), while in the distresses group, construction deficiencies are significant (11 out of 17 occurrences).

Specific Causes

Although the general category of deficiencies is described by principal causes, more specific attributes are required to understand the reasons behind these failures so as to prevent the recurrence of similar cases. Therefore, specific causes are presented in Table 6 for each building category.

The subtotal of these causes is furnished in column 8 of Table 6. The figures disclose that deterioration, the most frequent specific cause, accounts for over 10% of all failures during the observed period. This cause is associated with several recorded old low-rise buildings that failed, especially in the eastern part of the country, which is populated by a relatively large number of old buildings. Observation shows that deterioration was precipitated by many factors, such as insects, leaking water, and improper maintenance or repair procedures. Several deteriorated structures were built in the late nineteenth or early twentieth century and failed when weather conditions changed.

Many collapses commenced with the failure of roof elements. Sometimes the reason behind a collapse is not readily apparent, especially when the latest inspection showed the structure was in good condition. In 1994, for instance, no one suspected that the roof of one particular building would collapse. The insulation material on the underside of the wood panel inside the roof entrapped moisture which, through time, developed wood decay and metal corrosion. Such deteriorated roof components were not visible and collapse of the roof building was considered, deceptively, as without warning.

Although the term deterioration connotes a process that reduces a building's performance capacity, such a process could have been arrested had proper maintenance been instituted. Thus, failures due to deterioration are related to maintenance inadequacy, one of the principal causes presented in Table 4. Table 6 also shows that the contribution of rain, wind, and snow accounts for 80% of all external events. A relationship can also be drawn between the high frequency of these latter causes and failures due to deterioration of the buildings. In addition to the above, human-induced external events, such as collision impact on buildings, contributed to the failures of eight buildings (4% of total failures).

Other significant causes identified in Table 6 are demolition and renovation, which caused 13 and 14 failures, respectively. Note that, while the purpose of demolition is to properly fail a building as planned, cases reported in this study are associated with demolition that deviated from the intended plan and resulted in accidental collapses. Examples of demolition problems are accidental impact of a dozer on a beam and inadequate shoring that resulted in accidental collapse of the building. Renovation problems are exemplified by improper shoring, incorrect sequence of load-bearing wall removal, and inappropriately stacked old roof on unsupported area. Other significant causes found during the observed period are the inadequate construction-related activities that precipitated 35 failures. These issues are classified as improper construction procedures (13 cases), activities or excavation work on an adjacent building (nine cases), underground excavation (nine cases), and falsework-related problems (five cases).

Improper construction procedures include poor workmanship such as bolt overload, improper installation of walls, and inadequate girder connections. Other than poor workmanship, construction accidents took place mainly in conjunction with the failure of rope-supporting trusses, collapse of wall when braces were removed, slippage of crane cable carrying concrete slab, and collapse of concrete components during pouring. During the construction of building foundations, excavation, and the impact of other activities (e.g., excavation of an adjacent structure without shoring and vibration of a faulty transformer) were to blame for the collapse of an adjacent building. Underground excavations causing buildings to fail are exemplified by inappropriate deep tunnel digging. Examples of falsework-related problems are inadequate shoring causing a floor deck to collapse, failure of scaffold, and improperly installed shoring system. These construction-related deficiencies account for 16% of all observed failures. Including demolition and renovation, construction-related issues represent 28% of the total failures. Table 6 also illustrates the overwhelming number of specific causes that fall under the category of low-rise and multistory buildings.

Comparison of Three Surveyed Periods

To discern potential trends in the causes of recent failures, the writers compared the results of this study with those obtained from two previous analyses (Hadipriono 1985; Hadipriono and Diaz 1988). Note that this comparative study should be viewed in light of its relative occurrences. This is especially true because the number of years investigated varies among the three studies and, while the format and methods conducted for all studies are similar, the study presented in this paper (the third study) capitalizes on the use of the Internet and databases that were not previously available. For these reasons, the total number of failures in the third study is found to be relatively much greater than those of the previous two (as can be seen in Table 7).

Among the three studies, low-rise buildings are consistently the most frequent structures that failed; however, causes of these events vary. In the first study, causes of failures were associated with design deficiencies of structural components of several school buildings. The prestressed concrete components experienced long-term creep and shrinkage that had been overlooked in the design process. In addition, construction deficiencies, such as inadequate inspection of bracing, connection, and members of

Table 6. Specific Causes of Failure

Principal cause	Failure causes and events	Low-rise	Multistory	Plant-industrial	Long-span	Towers	Other	Subtotal	Percentage
Design	Design errors	4	1	—	2	1	—	8	4
Detailing	Detailing mistakes	2	—	—	—	—	—	2	1
Construction		34	18	2	1	2	6	63	28
	Renovation	12	2	—	—	—	—	14	6
	Demolition	6	3	1	—	1	2	13	6
	Construction procedure	7	2	—	—	1	3	13	6
	Excavation work on adjacent building	4	4	—	—	—	1	9	4
	Underground excavation	2	6	—	1	—	—	9	4
	Falsework problems	3	1	1	—	—	—	5	2
Maintenance	Deteriorate	21	1	—	—	—	1	23	10
Material	Material problem	2	—	—	1	—	—	3	1
External		38	2	3	3	1	12	61	27
	Rain	13	1	—	1	1	5	21	9
	Wind	11	—	1	—	—	4	16	7
	Snow	7	—	2	2	—	1	12	5
	Collision/hit by others	5	1	—	—	—	2	8	4
	Overload	4	—	—	—	—	—	4	2
Other		38	9	2	2	3	11	65	29
	Foundation settlement, collapse	2	—	1	—	—	—	3	1
	Soil	1	—	—	—	—	1	2	1
	Other/unknown	35	9	1	2	3	10	60	27
Total		141	31	7	9	7	30	225	100

scaffolding, were identified as another frequent reason causing these buildings to fail. In the second study, construction deficiencies such as falsework problems were to blame for several collapses of low-rise buildings. In the third study (also see Table 6), the principal causes of failures of low-rise buildings were external (e.g., rain, wind, and snow), construction (e.g., renovation, demolition, excavation, and falsework problems), and maintenance-related deficiencies (e.g., deterioration).

The next most frequently failed buildings vary among the studies; they are plant-industrial, long-span, and multistory buildings for the first, second, and third study, respectively. In the first study, failures of plant-industrial facilities were associated with explosions of coal-fired power plants and grain silos. In the second study, long-span buildings failed due to external events (e.g., snow loads) and construction and maintenance deficiencies. In the third study, multistory buildings failed primarily due to various construction deficiencies, such as excavation impacts on adjacent buildings and underground excavation.

A comparison of failure occurrences of the three studies is presented in Table 8. Failure types are divided into collapses (total and partial collapses) and distresses, and each type is further identified by the phase it occurred (during construction and service). For reasons elaborated in the previous section, collapses and distresses of all structures had invariably taken place during their service life. For service life collapses, the first and second studies show 40 and 52% occurrences of their respective total failures. In the third study, however, service life collapses reaches a pronounced 72% (of total failures) as compared with 20% construction collapses. Table 8 also shows distresses in all three studies that are relatively insignificant as compared to collapses. Many distressed buildings were neither published nor reported; and in some cases they remained unnoticed until collapse took place.

A comparison was also made with regard to the relation between the principal causes and collapses or distresses among the three study periods. Table 9 shows that, in the first two studies, construction deficiencies were the most frequent cause of collapses (37 and 32% of respective total failures), while external events contributed to a great number of collapses in the third study (29% of total). Note that external events also triggered numerous collapses in the first two studies (27 and 30%, respectively). In the first study, distresses due to design deficiencies are dominant (40%), followed by construction (20%) and detailing problems (17%). In the second study, 44% of maintenance defi-

Table 7. Comparison of Failure Distribution with Respect to Type of Building Failures

Types of buildings	1977–1981 number (%)	1982–1988 number (%)	1989–2000 number (%)
Low-rise	**57 (54)**	**20 (43)**	**141 (63)**
Multistory	13 (13)	4 (9)	31 (14)
Plant-industrial	21 (20)	4 (9)	7 (3)
Long-span	14 (13)	11 (24)	9 (4)
Towers	—	7 (15)	7 (3)
Other	—	—	30 (13)
Total	105 (100)	46 (100)	225 (100)

Table 8. Comparison of Failure Distribution with Respect to Stage of Occurrence

Type/stage of failures	1977–1981 number (%)	1982–1988 number (%)	1989–2000 number (%)
Collapses during construction	9 (14)	13 (28)	46 (20)
Collapses during service	26 (40)	24 (52)	161 (72)
Distresses during construction	9 (14)	—	1
Distresses during service	21 (32)	9 (20)	16 (7)
Unknown	—	—	1
Total	65 (100)	46 (100)	225 (100)

Table 9. Comparison of Principal Causes of Building Failures[a]

Principal causes	Collapse 1977–1981 number(%)	Collapse 1982–1988 number(%)	Collapse 1989–2000 number(%)	Distress 1977–1981 number(%)	Distress 1982–1988 number(%)	Distress 1989–2000 number(%)
Design	14 (23)	5 (14)	7 (3)	**12 (40)**	1 (11)	1 (6)
Detailing	6 (10)	5 (14)	2 (1)	5 (17)	1 (11)	—
Construction	**22 (37)**	**12 (32)**	**52 (25)**	6 (20)	2 (22)	**11 (65)**
Maintenance	1 (2)	—	22 (11)	1 (3)	**4 (44)**	1 (6)
Material	1 (2)	—	3 (1)	2 (7)	—	—
External	**16 (27)**	**11 (30)**	**60 (29)**	4 (13)	—	1 (6)
Others (NA)	—	4 (11)	61 (29)	—	1 (11)	3 (18)
Total	60 (100)	37 (100)	207 (100)	30 (100)	9 (100)	17 (100)

[a]One case is unknown.

ciencies contributed to distresses. In the third study, the majority of distresses were the consequence of construction-related deficiencies (65%).

In sum, based on relative number of failure occurrences, the comparative study displays a seemingly increasing trend of failures of low-rise and multistory buildings. Conversely, other types of buildings exhibit a decreasing trend in their relative failure occurrences. A similar pattern of increasing trend seems to take shape for relative occurrences of service life collapses, being most pronounced in the latest study. With respect to the relative occurrences of principal causes, external events form a strong upward inclination while other principal causes declined considerably.

Summary and Conclusions

Buildings do fail. Several toppled due to natural forces, many others collapsed on account of our negligence, and numerous more failed due to combinations of both. Some fell down because of old age, others broke down prematurely. Numerous published papers and detailed investigative reports have elaborated root causes of these accidents and thus contributed to a better way of perceiving the mechanism of building failures. While these efforts should resume, studies incorporating trends and patterns of occurrences and causes of failures complement investigative cases and are thus essential for design and construction professionals to minimize the recurrence of failures. This paper presents the results of such studies.

The findings of 225 failure cases of various buildings investigated in this paper disclose an overall pattern of an increasing number of failures. An average of 32 years of service life was found when failures during construction are included; however, by isolating service life failures, the study reveals a more sanguine average of 60 years of service life, almost twice as long as the former. This pattern suggests that construction failures play a dominant role in changing failure trends. Of primary interest is the increasing trend in the last years of the study period which culminates in the year 1998, when a large number of low-rise buildings failed. Failures in the last 3 years of the observed period constitute over half of the total number of failures, attributable to the numerous deteriorated buildings, especially in the eastern part of the country where old buildings are commonplace. In terms of their functions, failure of apartment buildings took the highest toll.

Consistent with the phase at which failures occurred, the study reveals construction deficiencies and external events as the two most frequent principal causes, followed by maintenance deficiencies as a distant third. These causes contributed to the failures of low-rise and multistory buildings. Under the category of construction deficiencies, more specific causes, such as improper renovation, unplanned demolition, poor workmanship, and unsafe excavation operations were identified. External events include rain, wind, and snow that precipitated building collapses. While nature was often blamed for these accidents, weather-related loads are covered in numerous building codes; nevertheless, failures still occurred even when the magnitude of natural forces were below the allowables. Human-induced vehicular impacts and collisions were also found under the category of external events.

The next most frequent problem deserving mention is the process of deterioration that plagued several buildings but was overlooked and, eventually, caused structures to fail. The study reveals that problems associated with building envelopes, such as roofs, walls, and facades, occurred because of lack of maintenance. Moreover, various collapses commenced with certain distress conditions such as cracks and other visible deformations that were noticeable by the building occupants. Although in the long run buildings deteriorate, by proper maintenance, the process of deterioration can be arrested. Unfortunately, as was the case with several buildings investigated in this study, efforts made to remedy these conditions were not done properly and resulted in much worse conditions beyond repair.

Another pernicious impact of building failures is the harm they can bring to the occupants. The 225 failures investigated in this study killed 97 people and injured 460 others. The highest number of casualties took place when a disaster struck during a public gathering. This is exemplified by cases involving the grandstand of a circus that failed, injuring 44 people, and the balcony on which a party was held that collapsed, afflicting another 30.

A comparative study performed among three survey periods substantiates the rise of relative occurrences of failures of low-rise and multistory buildings. Notice that, at this stage, findings are limited to the delineation of relative failure occurrences. Obtaining the rate of failures of the various types of buildings in the United States is still impracticable. Despite the enhancement in information technology in the past decade, still very limited databases currently exist. During the course of this study, the writers observed that, for many of those in existence, the databases and other sources of information were sketchy and incomplete. For instance, several cases investigated in this study lack information as fundamental as the type and age of the failed buildings, rendering such information nugatory.

Consequently, this study also suggests the creation and maintenance of new databases and the improvement of current ones. These sources of information are rendered useful if they are open to public and disseminated through the Internet. In addition, a concerted effort to build a Web-based repository may serve as a means to reduce the recurrence of future failures. Finally, this research leads to the need to uncover the procedural causes from which the enabling and triggering causes often originate. These procedural causes can be obtained from legal records and insurance claims. Efforts associated with finding these causes may become an extension of this study.

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