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NBSIR 73-221

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Norman F. Somes

Center for Building Technology
Institute for Applied Technology
National Bureau of Standards
Washington, D. C. 20234

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Interim Report
Covering period November 1971 – August 1972

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U. S. DEPARTMENT OF COMMERCE, Frederick B. Dent, Secretary

NATIONAL BUREAU OF STANDARDS, Richard W. Roberts, Director

SI Conversion Units

In view of present accepted practice in this country in building technology, common U.S. units of measurement have been used throughout this paper. In recognition of the position of the United States as a signatory to the General Conference on Weights and Measurements which gave official status to the metric SI system of units in 1960, we assist readers interested in making use of the coherent system of SI units by giving conversion factors applicable to U.S. units used in this paper.

Length

1 in = 0.0254 meter (exactly)

1 ft = 0.3048 meter (exactly)

Force

1 lb (lbf) = 4.448 Newton (N)

Pressure

1 psi = 6895 N/m^2

Abstract

The document is an interim report of ongoing studies at the National Bureau of Standards. It defines the several aspects of abnormal loading on buildings and the problem of progressive collapse. It documents the extent to which present U.S. Codes and Standards address the problem.

Abnormal loadings are identified, classified and discussed with regard to their characteristics and frequencies of occurrence. The report reviews the state of international knowledge of the characteristics of abnormal loadings and the response of buildings and building elements to these loadings. The latter includes discussion of several incidents in which multistory buildings have collapsed progressively.

Using currently available statistics an estimate is made of the combined frequency of abnormal loadings on residential buildings in the U.S. For buildings susceptible to progressive collapse, the corresponding risk of fatality is compared with the levels of risk that society will generally accept. The risk is further compared with the risk of mortality associated with fire in residential buildings, an area of considerable public concern and expenditure.

It is concluded that U.S. standards-writing bodies should adopt appropriate rational criteria as soon as possible to reduce the risks of progressive collapse. There are several areas in which criteria might be introduced to reduce the risk of progressive collapse. These are discussed; particular attention is given to the philosophies behind the structural criteria implemented in the USA and other countries.

Key Words: Abnormal loading, buildings, codes, design criteria, multistory, progressive collapse, risk, stability, standards, strength, United States.

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Author's Note

This document is one of 15 state-of-the-art reports that provided source material for a National Workshop on Building Practices for Disaster Mitigation held at the National Bureau of Standards, Boulder, Colorado, August 28 - September 1, 1972.

With other reports and findings of the Workshop, this document was published in full in National Bureau of Standards Building Science Series 46, February 1973 to which reference may be made.

At the request of the project sponsor, the document is now printed separately as an NBS Report.

ABNORMAL LOADING ON BUILDINGS AND PROGRESSIVE COLLAPSE

By

Norman F. Somes

1. Introduction

Since 1968, there has been growing international concern that multistory buildings are frequently designed without explicit consideration for abnormal loading conditions. On May 16 of that year, there occurred the much-publicized collapse of a portion of the Ronan Point apartment building in London. The building has 22 stories of precast concrete panel construction above a cast-in-place concrete podium. A typical floor layout is shown in Figure 1 in which the structural walls are shown solid. The collapse was triggered by an accidental explosion of gas that leaked from the connection of a gas range located in an apartment on the 18th floor. The Report of the Inquiry into the Collapse [1] states:

> "The explosion blew out the non-load-bearing face walls of the kitchen and living room, and also, unfortunately, the external load-bearing flank [end] wall of the living room and bedroom of the flat, thus removing the support for the floor slabs on that corner of the nineteenth floor, which collapsed. The flank walls and floors above this collapsed in turn, and the weight and impact of the wall and floor slabs, falling on the floors below, caused a progressive collapse of the floor and wall panels in this corner of the block [building] right down to the

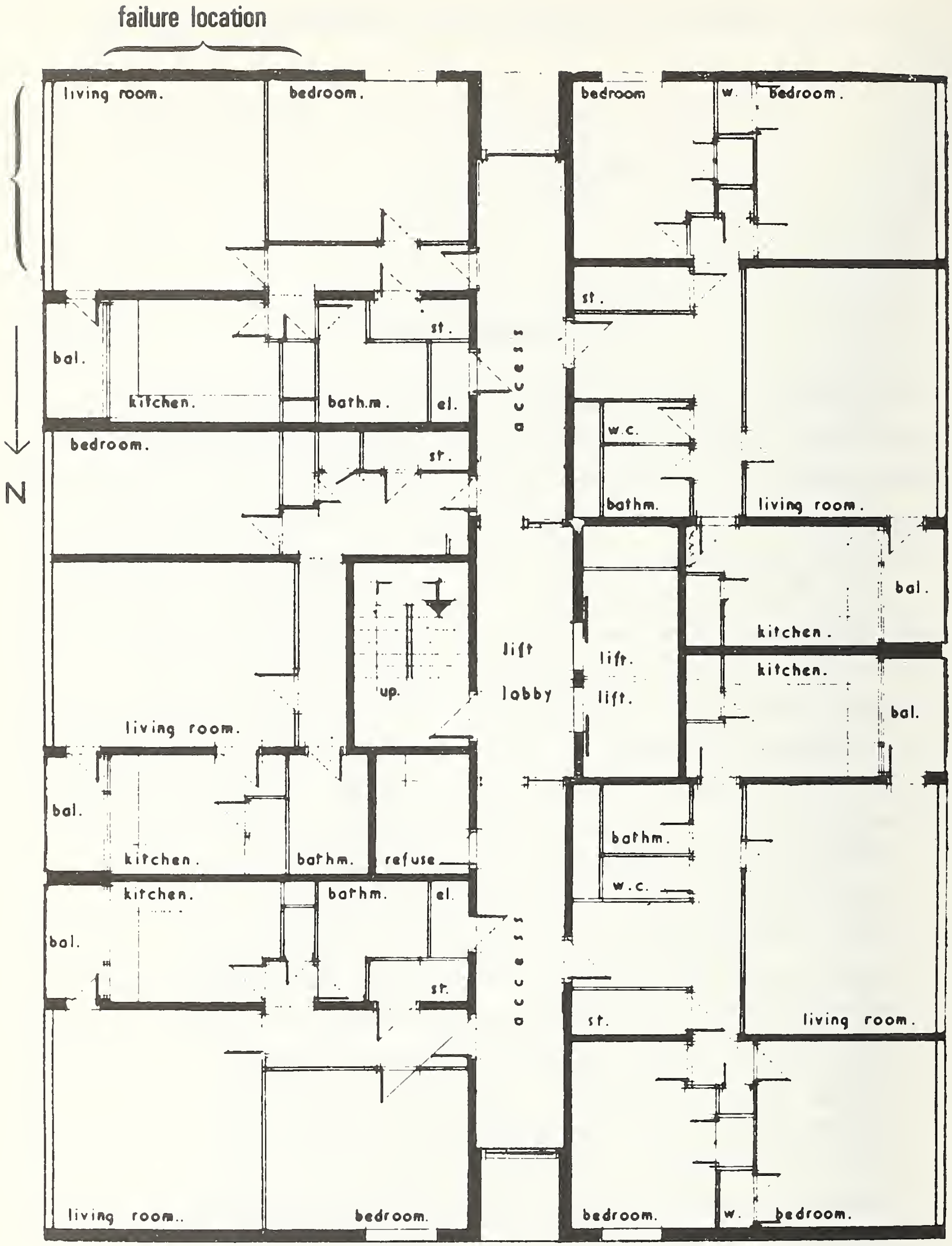

Figure 1 Typical floor layout of Ronan Point apartment building (explosion occurred in a SE-corner apartment). Reproduced from [1].

level of the podium."

The extent of the collapse is shown in Figure 2; an adjacent building of identical construction shows the appearance of the building prior to the collapse. From Figures 1 and 3 it may be seen that collapse affected both the living room and bedroom above the 16th floor, while below this level, the collapse was limited to the living room. Four people were killed in the collapse and seventeen people were injured.

> "The loss of life and injury might well have been very much worse. At 5:45 a.m., mercifully, most tenants were in their bedrooms . . ."

The Report also documents that, by a fortunate chance, of the four apartments directly above the one in which the explosion took place, only one was occupied at that time.

The Report of the Inquiry drew international attention to several deficiencies in existing codes and standards, particularly as they applied to multistory buildings. Interim additional criteria [2], having regard to the appraisal and strengthening of existing buildings and the design of new structures, were quickly implemented in the United Kingdom. Several other countries in Europe introduced additional design criteria to deal explicitly with the risks exposed by the Ronan Point incident.

To date, with one exception, the U.S. codes- and standards-writing bodies have not published criteria to provide protection against abnormal loads and possible progressive collapse. The exception is the 1972 American National Standards Institute A58, Minimum Design Loads in Buildings and Other Structures [3] which provides a short statement drawing attention of the designer to the problem. Several standards-writing bodies have established technical committees to consider the problem, however.

The prime mover in the matter of progressive collapse in the USA has, to date, been the Department of Housing and Urban

Figure 2 Ronan Point apartment building after the collapse, with a second identical building in the background. Reproduced from [1].

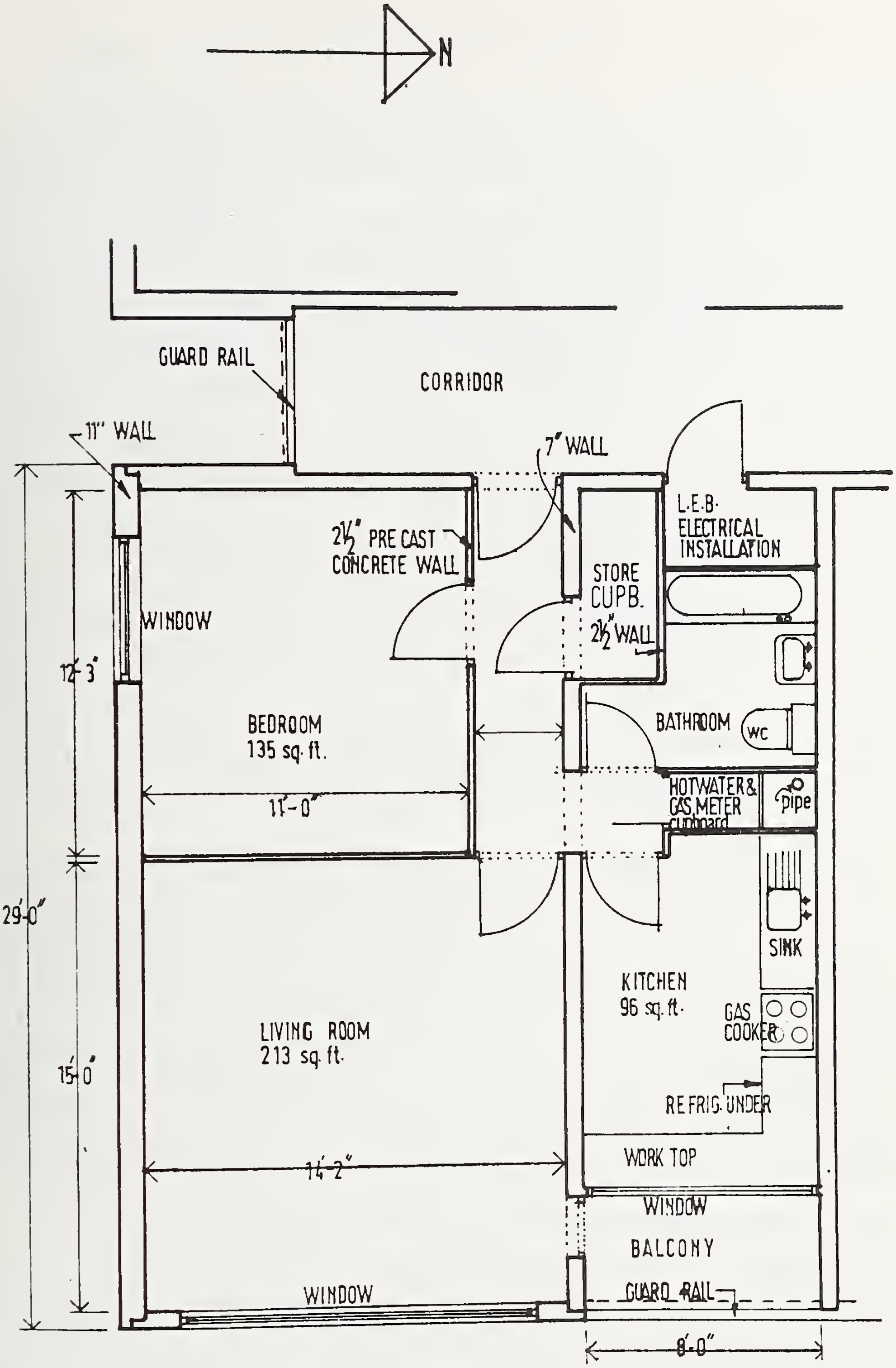

Figure 3 Layout of the SE-corner apartment on the 18th floor where the explosion originated. Reproduced from [1].

Development (HUD). In August 1969, provisions against progressive collapse were included for the first time in a Structural Bulletin [4] issued to the producer of a precast concrete housing system by HUD's Federal Housing Administration (FHA). Criteria against progressive collapse were included in HUD's Guide Criteria documents [5] prepared by the National Bureau of Standards (NBS) early in 1970 and implemented in HUD's experimental housing program Operation Breakthrough. In October of 1971, the FHA circulated its draft document "Provisions to Prevent Progressive Collapse" [6] for review by certain trade associations, standards-writing bodies and members of the design profession. This document expressed criteria intended for application by FHA in evaluating multistory buildings for which Federal mortgage assurance is required. The document has not been circulated in final form but the draft has served as a starting point for much discussion. In each of these preceding instances, the criteria reflected the United Kingdom requirements at that time.

In November 1971, the National Bureau of Standards, at the request of HUD, began a detailed study of abnormal loading on buildings in the USA and the problem of progressive collapse. The result to date provide the basis for this interim progress report, which firstly attempts to define the parameters of the problem, to classify and discuss the various sources of abnormal loading and to quantify their frequency insofar as the currently available U.S. data permits. The implication of these findings for the USA are then discussed. The response of buildings and building elements to abnormal loading is then reviewed, including cases of progressive collapse. Several alternative approaches for the introduction of criteria are presented and, finally, conclusions are given with respect to the problem posed in the USA.

2. Problem Definition

Progressive collapse may be defined as a chain reaction of failures following damage to only a relatively small portion of a structure.

An abnormal loading may be defined as a condition of loading which a designer, following established practice, does not include in the normal analysis and design of a particular structure. It is a loading condition of sufficient severity and probability of occurrence to be a cause for concern, but still of such a relatively rare nature as to be outside of normal design-life expectancy. This definition goes beyond that of static and dynamic forces and includes such conditions as the dislodgement of a bearing wall panel, and the development of a weld failure in a steel connection.

Recent reports [7, 8] confirm the growing view that studies of the problem of progressive collapse should deal with multistory construction of all types and not be limited to high-rise construction or simply to that using precast concrete panels. However, the view is also widely held that framed buildings are more tolerant of local damage and have more resistance to progressive collapse than load-bearing structures. It is reasoned that this is due to the fact that continuity between members is more easily accomplished in framed buildings than in load-bearing structures, and that the former have greater ability for developing alternate paths for forces in the event of the loss of a critical member. This viewpoint is supported in part by the documented experience of engineers during World War II bombings [9].

Occupants of multistory buildings, whatever type of construction is used, have a right to expect adequate and consistent levels of safety. The user requirement may be expressed as adequate protection from extreme loads.

Expressed as a performance requirement, this corresponds to adequate strength, namely compliance with a specified load capacity. Present U.S. design standards specify load capacity in terms of combinations of severe dead, live, snow, wind, or earthquake loads. They do not specify load capacity with respect to abnormal loading conditions as defined herein.

In a general sense, adequate safety is achieved by insuring that, at loads less than the specified load capacity, there is no loss of static equilibrium resulting in:

Local Collapse, or
Extensive Collapse.

The Ronan Point incident was clearly due to an abnormal loading condition and the collapse was extensive. Had the damage been confined to the apartment in which the explosion originated, it is doubtful whether the accident would have received more than local newspaper coverage. Such explosions occur somewhere every day and arouse little reaction from society at large. It is only when they produce extensive collapse that they generate international attention.

The foregoing discussion serves to delineate the NBS study which is concerned with abnormal loadings on multistory buildings of any type of construction, and the need to prevent progressive collapse, as a result of such loadings.

3. Public Acceptance of Risk

Risk is a function of the probability of occurrence and the consequence of a particular event. Zero risk in the face of all possible conditions and hazards can never be achieved. By assessing the statistics of all foreseeable hazards and evaluating their consequence, an acceptable level of safety can be achieved, acceptable safety at an acceptable cost. The acceptable risk to life and property is probably best decided by representatives of the community at large.

Otway et al [10] have provided one basis for considering the risks with which society is prepared to live. For this purpose, they use the U.S. accidental death statistics for 1966. The probability of death per person per year is given for a series of types of accidents in the following table:

Table 3.1

Motor Vehicle	2.7×10^{-4}
Falling	1.0×10^{-4}
Fire	4.0×10^{-5}
Drowning	2.8×10^{-5}
Firearms	1.3×10^{-5}
Poisoning	1.1×10^{-5}
Earthquake	8.0×10^{-7}
Lightning	5.5×10^{-7}

The paper points out that situations providing hazards on the order of 10^{-3} deaths per person per year are uncommon. When a risk approaches this level immediate action is taken to reduce the hazard. This level of risk is unacceptable to everyone in society. At an accident level of 10^{-4} deaths per person per year, people spend money, especially public money, to control the cause. Risks at the level of 10^{-5} deaths per year are still significant to society. Accidents with a probability about 10^{-6} deaths per person per year are not of great concern to the average person. He may be aware of them but he feels that will never happen to him. There is a general lack of concern about accidents having a mortality risk of less than 10^{-6} per person per year.

Some qualification should be made with respect to this last point and the statistic for earthquakes. In fact, a considerable amount of money is spent on earthquake protection and this would appear to conflict with Otway's last general comment. However, Otway divided incidents by the total U.S. population whereas the earthquake risk is geographically concentrated. If, for example, the population living within seismic Zone 3 were used, the probability of death per person would be increased by a factor of approximately 5, to 4.0×10^{-6}, thereby appearing to remove the above conflict. Another factor contributes to the considerable U.S. expenditure on earthquake protection; in addition to deaths and injuries, serious earthquakes are accompanied by large property losses.

Public expenditure to provide protection against fire in buildings is very considerable and this is in response to a probability of 4×10^{-5} deaths per person per year together with heavy property damage. It would be useful to assess the frequency of abnormal loading incidents that, for people living in buildings susceptible to progressive collapse, would constitute a risk of death from that cause equal to that from fire. It is important to differentiate between buildings that are and are not susceptible to progressive collapse. Figure 4 shows a speculative plot of the total number of U.S. housing units, increasing with time, and having a value of Y units at a particular point in time. There is a reason to believe that, in the absence of new criteria to minimize the risk of progressive collapse, the number of buildings that are susceptible, will otherwise increase. A second plot shows the number of susceptible units increasing with time from a relatively insignificant level to a very significant fraction of the total number of housing units. Of course, it is with the objective of stopping any such growth, that the NBS study and related studies are underway.

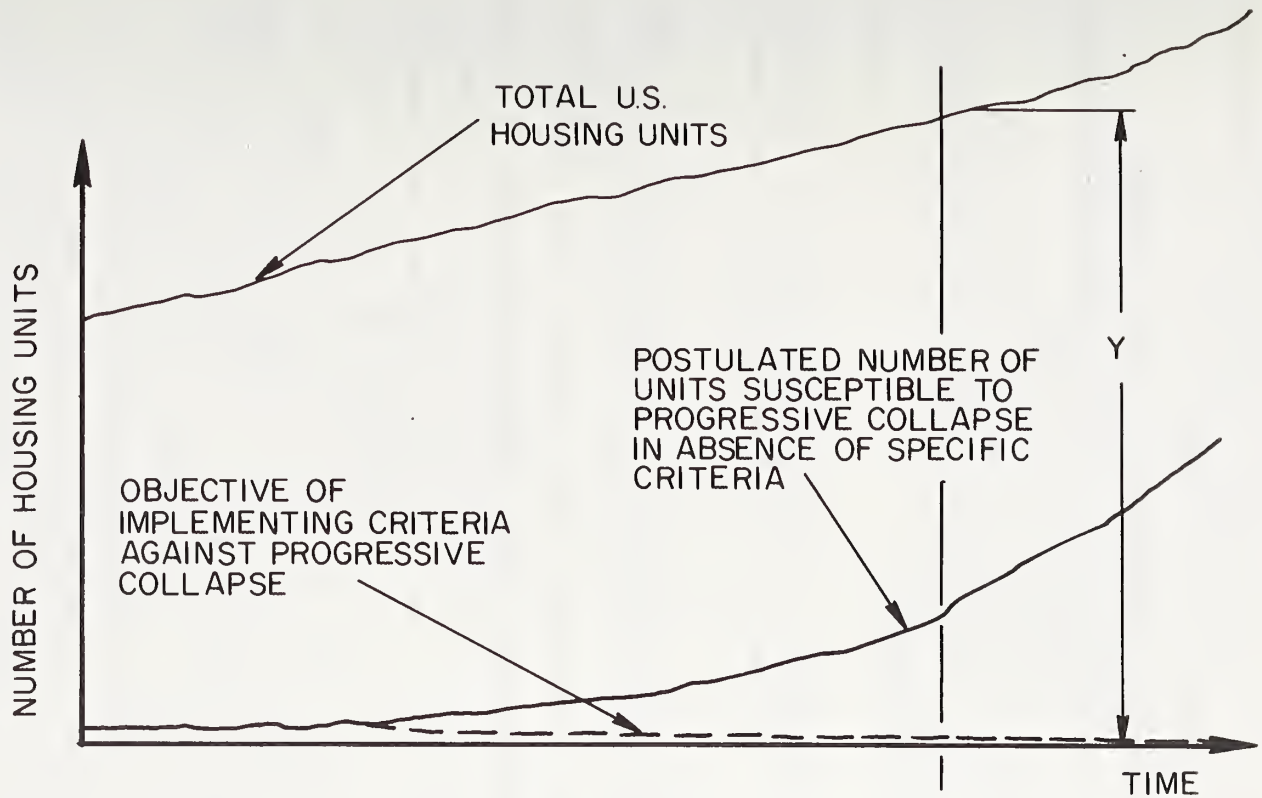

Figure 4 Postulated growth of number of housing units susceptible to progressive collapse in the absence of additional criteria.

The following assumptions will be made in order to carry out a comparison of the respective risks due to progressive collapse and fire:

1. The total number of abnormal loading incidents affecting U.S. housing units in a year corresponding to the selected point in time is N.
2. The probability of occurrence of an abnormal loading on a housing unit is the same irrespective of the type or location of the unit.
3. The abnormal loadings in question are of such severity that progressive collapse of susceptible buildings could occur.

On the basis of assumption 2, the probability of an abnormal loading per year in a housing unit susceptible to progressive collapse is N/Y.

In what follows, the result will be seen to depend upon the size and architectural arrangement of the multistory building considered. Consider a 100 housing unit building with a central service core, four housing units per story and an average occupancy rate of 4 persons per unit. If, as in the Ronan Point building, the collapse affected one quarter of the building in plan, then an estimate of loss of life would have to be based upon some fraction of the number of occupants of that quarter. For part of each 24 hours, people will be absent from the building e.g., at work or school or in recreational activity. Furthermore, it is doubtful if more than one-half of the casualties would result in death. There would be a number of severely injured, less injured, etc. When both factors are considered, a reasonable estimate of the number of deaths would appear to be 25, namely 1/16 of the total number of building occupants.

The following discussion will be confined to units susceptible to progressive collapse.

The probability of an abnormal loading in a 100 unit building per year is

$$\frac{N}{Y} \times 100$$

The risk of death due to progressive collapse per person per year in that 100 unit building is

$$\frac{N}{Y} \times 100 \times \frac{1}{16}$$

Equating this risk of fatality to that due to fire

$$\frac{N}{Y} \times 100 \times \frac{1}{16} = 4 \times 10^{-5}$$

If Y is taken to correspond to the U.S. housing unit total as given by the 1970 U.S. Housing Census [11], namely 67.7 million

$$N = \frac{4 \times 10^{-5} \times 16 \times 67.7 \times 10^{6}}{100}$$

$$= 433 \text{ incidents}$$

This result states that, for the conditions considered, an annual U.S. total of 433 abnormal loadings on housing units would result in a risk of fatality that would correspond to the general risk of fatality in fire. Clearly the result is a function of the architectural layout of the building considered and hence the estimation of the ratio of possible deaths to the total number of occupants of the building.

It is shown that the risk of fatality due to progressive collapse per year could be written

$$\frac{N}{Y} \times \text{No. of units} \times \frac{1}{16}$$

For a given architectural layout, and given values of N and Y, the risk appears to be directly proportional to the number of units, namely the number of stories.

The use of the figure of 433 incidents should be qualified to account for the assumptions made and for its dependence upon architectural layout and size of building. Nonetheless, the figure of 433 incidents establishes an order of magnitude that is useful in assessing the significance of the statistics for abnormal loadings that are discussed in Chapter 5 and summarized in Chapter 6. In Chapter 6 it will be shown that a lower bound estimate of the number of abnormal loadings per year on housing units is 702.

4. Classifications of Abnormal Loadings

Publications such as the Engineering News Record regularly describe engineering failures as well as successes. The authoritative work of Feld [12] has described many building failures. Allen and Schriever [7] have summarized reported failures of recent years in North America. Two conclusions are drawn from works such as these: Only a small minority of building failures occur due to a loading of a type explicitly considered in the design. The great majority of failures result from loading conditions for which current codes and standards give little or no guidance and which, as a consequence, are not considered in design. Such loading conditions are termed abnormal loadings in this report. The second conclusion is that there is a large variety of abnormal loadings and no classification of them could reasonably be expected to be complete. One important contributing factor is that, with ever-advancing technology, new sources of abnormal loadings can be expected to be generated. With these several thoughts in mind, the following classifications are deliberately limited to abnormal loadings for which the probability of occurrence seems significant. The first classification is an overall generic one:

Violent change in air pressure
Accidental impact
Faulty practice
Foundation failure

These classifications will now be discussed in more detail.

A. <u>Violent Change in Air Pressure</u>

This includes:

Sabotage bombings
Service system explosions
Other explosions within the building
Explosions external to the building

Sabotage, using explosives, is a very serious form of abnormal loading. The motive for sabotage might concern only one person, a family, or an organization resident in the building, yet the bombing could affect many or all of the occupants. Service system explosions can originate in heating, cooling, and cooking systems, in high-pressure steam pipes and in boilers. Sources of other internal explosions include containers of liquified gases such as propane or butane or containers of gasoline. There are a number of sources of accidental explosion external to the building such as the shipment of hazardous materials through urban areas by truck, railroad, and waterway or by the rupture of gas transmission and distribution systems.

B. <u>Accidental Impact</u>

This includes:

Highway Vehicles
Construction Equipment
Aircraft

Trucks and automobiles leaving the highway out of control are included in the first category. Accidents involving cranes and lifting devices of all kinds are included in the second category. In urban areas, construction frequently takes place on congested sites that have relatively small clearances from existing occupied buildings.

C. Faulty Practice

Past experience would indicate that when failures do occur, they are frequently the result of faulty practice. Whether or not local or extensive collapse results is largely a function of the type of construction involved, i.e. whether it can tolerate local damage without extensive collapse.

Design Error
Construction Error
Misuse or Abuse by the Occupant

Misuse or abuse by the occupant can include ill-considered architectural changes or cutting of the structure.

D. Foundation Failure

The ASCE Research Council on Expansive Soils has documented [13] that building foundation failures and distress account for average annual property damage in the USA valued at $740 million. While this figure is not broken down into specific categories of failure, it is nonetheless indicative that present codes and standards may not provide adequate requirements for foundation design. Feld [12] has documented a number of instances in which foundation failure has produced severe building distress and even total collapse. It is apparent that foundation failures, including the following specific cases, can pose severe abnormal loadings:

Unforeseen Settlement
Foundation Wall Failure

Scouring Action of Floods on Foundations
Adjacent Excavation

An important factor affecting the probability of foundation failure is the growing scarcity of land in urban areas which is causing more and more buildings to be located on sites previously considered to be of marginal quality for construction purposes.

5. Studies of Abnormal Loadings

The NBS studies to date have revealed that statistics have been or are being compiled by appropriate authorities with respect to sabotage bombings, gas explosions, explosions of hazardous materials in transit, highway vehicle accidents and aircraft accidents. Efforts to locate data regarding other abnormal loadings will continue; however, it is recognized that, for certain incidents, statistics either may not be available or they may be collected in such a fragmented manner as to make them of little value.

A. Sabotage Bombings

Sabotage bombings are generally classified as explosive or incendiary, but it is the former that are of particular relevance to progressive collapse.

A.1 Characteristics of Loading

There is no shortage of published technical information relating to the pressures, rise time, and distribution relationships for explosive charges. Organizations such as the U.S. Department of the Army have developed and distributed materials that serves as a guide in the use of explosives in the destruction of military obstacles and in certain construction projects. The Army Field Manual [14] provides information

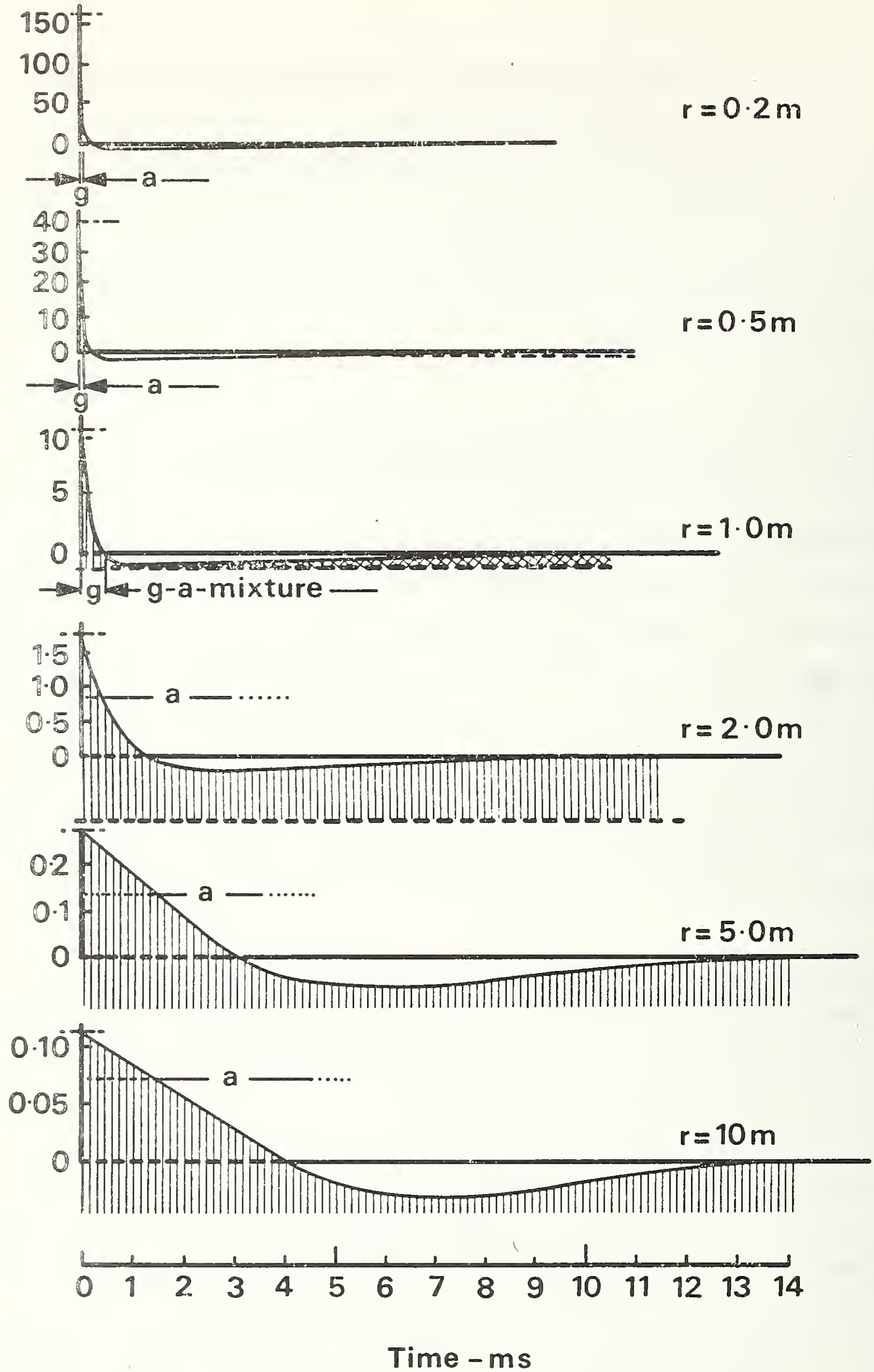

Figure 5 Pressure-time curves at selected distances (r) from a 2.2 lb (1 kg) charge of TNT. The ordinates give the pressures in atmospheres above atmospheric pressure. The horizontal dashed lines correspond to a total vacuum. g = gas, a = air. (Due to Granstrom, reference 1.5, reproduced from [70]).

including type, characteristics, and uses of explosives and auxiliary equipment, preparation, placement and firing of charges, and charge calculation formulas.

Figure 5 due to Granstrom [15] expresses pressure-time curves at selected distances from a 1 kg (2.2 lb) charge of TNT. The ordinates express the static peak pressure in atmospheres. As an illustration, at a distance of 1 meter (39.4 in) from the detonating charge the peak static pressure would be approximately 11 atmospheres corresponding to approximately 160 psi. This positive pressure pulse would have a duration significantly less than 1 millisecond. A pressure of 160 psi is so large in comparison with the normal resistance of walls and floors as to make their destruction a certainty. At a distance of 10 meters (32.8 ft) from the charge the peak static pressure would be approximately 1.5 psi while the positive pressure pulse would last approximately 4 milliseconds. Pulses of these durations are so short, in comparison to the natural period of building elements such as walls and floors (20-40 milliseconds) as to require any structural analysis of the element in question to be a dynamic one.

The characteristics of explosive charges differ considerably from those of flammable gases. According to Rasbash [16]:

> "As a rule, gas and vapor explosions take place substantially more slowly than explosions involving high explosives such as TNT. The most explosive mixture of a fuel vapor and air in a volume of $30 m^3$ ($1050 ft^3$) will contain about 2.5 kg (5.5 lb) of fuel. The energy potential of this will be equivalent to that of 20 kg (44 lb) of TNT, but the pressure pulse with the gas explosion would last several hundred milliseconds and with TNT only about 1 millisecond."

For comparison, Figure 6 is included to show the pressure-time curves for typical vented gas explosions.

A.2 Probability of Explosive Bombings

Two organizations have gathered nationwide statistics for sabotage bombing in the USA, namely the Federal Bureau of Investigation and the International Association of Chiefs of Police (IACP).

The Federal Bureau of Investigation (FBI) commenced its program to collect and classify bombing incidents at the start of 1972. The Bureau issues monthly bulletins [17] summarizing the data reported by its Field Agency; it is understood that the first annual report, containing statistics for 1972, will be issued in the spring of 1973. Figures for the 10 month period, January through October 1972, are given in Table 5.1. The term "actual" is used to denote that detonation of an explosive or ignition of an incendiary material actually occurred, whereas "attempted" denotes that detonation or ignition of the bomb did not take place.

Because reports continue to trickle in long after the reporting period has passed, the FBI cautions the user of the data that the figures are subject to revision (in an overall upward sense). The figures for the most recent months are likely to change most. The monthly totals should therefore not be used in an attempt to define trends.

Referring firstly to Lines 1 through 5 of Table 5.1, it is seen that, during the 10-month period, there was a total of 608 actual explosive bombings out of a total of 1689 incidents of all categories. The ratio of actual explosive bombings to actual and attempted explosive and incendiary incidents is 608/1689, namely 0.36.

The FBI uses a number of categories with which to describe the target. For brevity, only four main categories

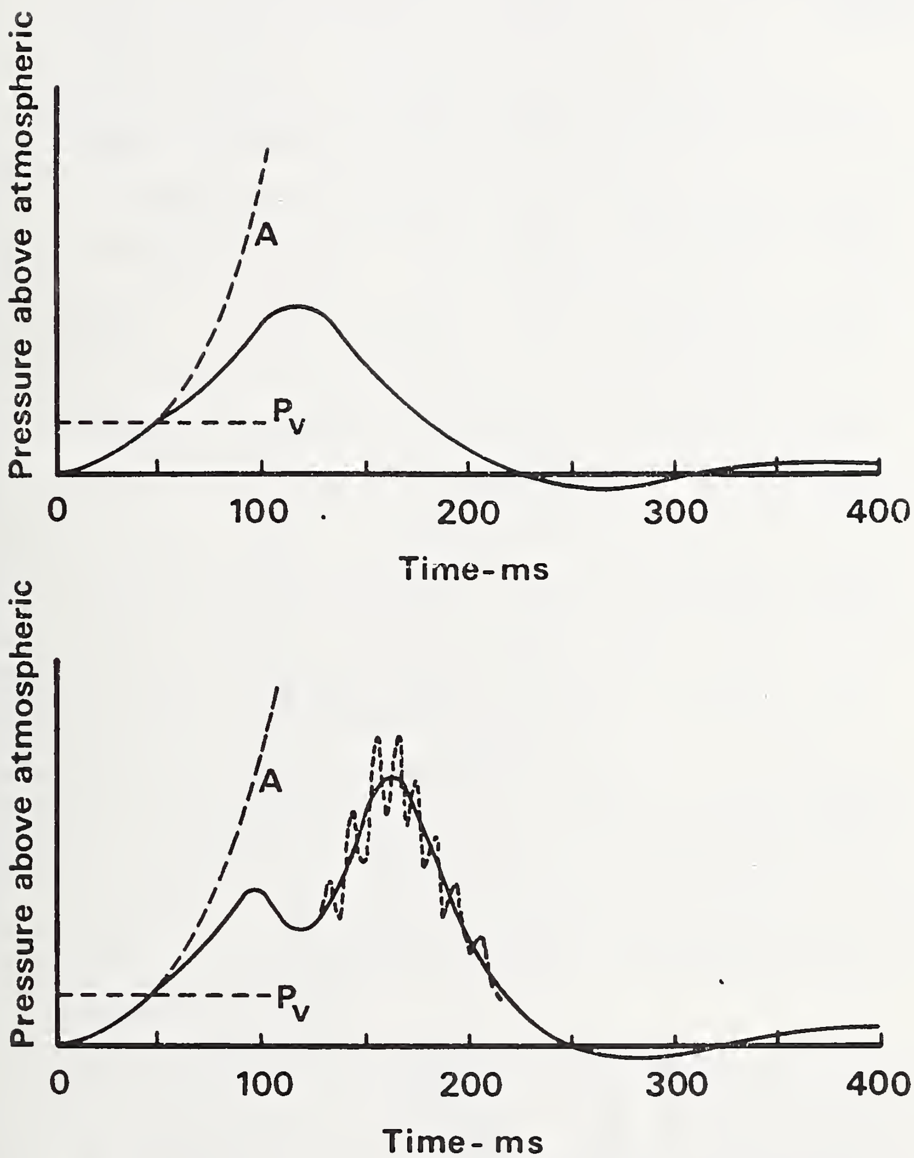

Figure 6 Pressure-time curves for typical vented gas explosions. P_v = pressure at which vents fail. Broken line A denotes the subsequent pressure rise in the absence of vents. Upper curve shows the effect of smaller vents. Time scale is only approximate. (Due to Mainstone, reference 70).

Table 5.1 Sabotage Bombing Statistics Provided by the Federal Bureau of Investigation

Line	Category of Reported Incident	1972 Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	FBI Totals for 10 Month Period	Authors Extrapolat Totals For 1 Yea
1	Actual Explosive	78	63	59	62	52	72	54	59	59	50	608	703
2	Actual Incendiary	81	50	62	80	83	79	99	83	50	41	708	805
3	Attempted Explosive	28	28	8	24	18	14	24	12	27	18	201	241
4	Attempted Incendiary	12	20	16	19	27	13	20	14	20	11	172	206
5	Actual & Attempted, Explosive and Incendiary	199	161	145	185	180	178	197	168	156	120	1,689	2,027
	Various Targets												
6	Commercial Buildings	40	29	34	41	27	35	40	47	27	24	344	413
7	Office Buildings	4	5	8	7	1	7	3	6	1	3	45	54
8	Automobiles	20	18	15	13	10	13	19	23	11	15	157	188
9	Residences*	55	53	41	49	45	55	58	47	52	26	471	566
	Sub-Categories of Residences												
10	Private Residence	50	52	36	47	38	52	48	43	39	21	426	512
11	Apartment House	5	1	5	2	7	3	10	4	3	5	45	54

*The FBI include sheds, garages, and other private property in their figure under this heading. In this case, it is simply the sum of lines 10 and 11.

NOTE: Lines 6 through 11 cover all incidents whether they be actual or attempted, explosive or incendiary.

are given; those having the most bearing on the subject in hand. Lines 6 through 9 show figures respectively for the main categories: commercial buildings, office buildings, automobiles and residences. It is important to note that the listed category of target is that in which the incident took place. Thus, if an office unit within a residential building were the target of an incident, the occurrence would be listed under category "Office Building" not "Residences." If the unit had been a store rather than an office, the entry would be under "Commercial Building." Similarly, if an automobile parked in a basement garage to the residential building was the object of an attack, the incident would be listed under "Automobiles." This suggests that inasmuch as they could constitute abnormal loadings for the building as a whole, certain incidents listed on Lines 6 through 8 might contribute to the figures defining the probability of explosive loading on residences i.e., line 9 might constitute a lower bound to the frequency of abnormal loadings on residences. At this time however, the readily available FBI data do not permit these incidents to be identified, and for this reason, only the figures on line 9 will be used further.

The FBI uses the term "Residences" to cover private residences, apartment houses and other private property such as sheds, and garages adjoining the residential building or in its vicinity. The figures for other private property are not included in the table; however the 10-month total for this subcategory is 26.

At the present time, the FBI makes no attempt to report the number of stories in the building that was subjected to the attack, or the severity of the attack in terms of structural damage to the building. Such information would add greatly to the value of the statistics, at least as far as building safety is concerned. It would also be valuable to have a clear definition of the difference between a private residence and an apartment house with respect to the FBI's classification of incidents.

Probably the most useful figure to use, in order to assess the frequency of abnormal loadings due to sabotage bombing, is the 10-month total for residences, 471. To arrive at an estimate of the number that were actual explosive incidents this number is multiplied by 0.36 giving 170. If this is converted to a yearly estimate, the result is 204. It appears therefore, that at the present time, 566 sabotage bombing incidents per year occur where the direct target is a housing unit. Of these, an estimated 204 can be expected to involve explosives with detonation taking place. For reasons discussed earlier, this figure may be a lower bound; it is also conceivable that not all incidents were recorded by the FBI during this initial 10-month period of their data collection.

Corroborating evidence to support the FBI data is provided by the ICAP [18] and, on a State basis, by the California Department of Justice [19]. In the period July 1971 through February 1972, the IACP operated the National Bomb Data Center under the auspices of the U.S. Department of Justice. Since that time, the functions of the Center have been transferred to the FBI. The monthly summary reports of the Center, during the period July 1971 through February 1972, provide a brief description of each incident in addition to a statistical treatment of all bombings for the month in question. One description, taken from the January 1972 report [20], serves to illustrate the possible scale of the risk:

> "January 5, Las Vegas, Nevada. An explosive device, consisting of 40 sticks of dynamite, was placed in the laundry room of an apartment building. The blasting cap detonated, but improper assembly of the device, and the age of the dynamite combined

to produce only partial detonation. No damage resulted."

Had the explosion occurred and had the building been of a design similar to that used at Ronan Point, the United States may have had its first "Ronan Point" incident, with comparable political and professional repercussions.

B. Gas Explosions

This subsection deals with loadings arising from explosions occurring accidentally as a result of the distribution and use of gas. Because of Ronan Point, the dynamics of gas explosions and their interaction with building construction of various forms have received considerable study in the United Kingdom. The greater part of U.K. gas is still manufactured, yet a rapidly increasing percentage is of natural origin from North Sea sources. In contrast to the U.K., the U.S. production of manufactured gas amounts to only a few percent of the total, natural gas providing almost all the needs.

B.1 Time-Magnitude-Distribution of Load

Rasbash documented [16] the maximum fundamental burning velocities of some gas-air mixtures under atmospheric conditions. Table 5.2 shows manufactured gas to burn approximately three times as rapidly as natural gas. Such data has caused certain members of the engineering profession to make some distinction between the two types of gas when considering the risk of progressive collapse.

Alexander and Hambly [21] discussed various means of reducing the consequences of gas explosions in buildings; such as, complete removal of the explosive source, forced ventilation, and control of the maximum flow of gas from the supply. They provided a qualitative description of the nature of a gas explosion in terms of gas/air mixture, presence of

Table 5.2 Fundamental Burning Velocities (Maximum) of Some Gas-Air Mixtures Under Atmospheric Conditions Due to Rasbash [16]

Gas or Vapor	Burning Velocity	
	ft/s	m/s
Methane (natural gas)	1.2	0.37
Butane	1.3	0.40
Hexane*	1.3	0.40
Propane	1.5	0.46
Ethylene	2.3	0.70
Manufactured Gas**	4.0	1.2
Acetylene	5.8	1.8
Hydrogen	11.0	3.4

* Similar to gasoline.

**Approximate value for manufactured gas - depends on composition.

venting, pressure rise, turbulence, and other related paramenters. They also provided a method of analysis of structures subjected to these dynamic loads.

In another paper, Alexander and Hamley [22] developed a method for design of structures to withstand dynamic loading from gaseous explosions similar to that which caused the collapse at Ronan Point. The loading pressure pulse was described only qualitatively; a precise description could not be given at that time due to the absence of relevant experimental data. The response of the structure to such dynamic loads was discussed and a method of design presented, with examples for floor, slabs, and load-bearing walls. Proposals were given for research that should be carried out to determine the design pressure pulse and to check the validity of the assumptions made.

Stretch [23] examined how explosions, caused by vapor-phase reactions between common inflammable solvents or sources of energy and air are controlled by particular features of domestic buildings, and consequently strain or damage the structure during their passage. He concluded that the general use of materials such as gas is a safe and convenient element in contemporary society, so that, today, homes are considered fit for human occupancy only if they are designed to withstand and contain, within tolerable limits, the risks incumbent on a high standard of living. He showed how inherent features of established structural systems have obscured the necessity of special precautions in more recent systems. Stretch gave simplified forms of the pressure waves and used these to analyze the behavior of buildings of traditional brick design, framed construction, and concrete panel construction, respectively.

Rasbash [16], in a paper accompanying that presented by Stretch [23], discussed the influence of potential relief of explosion pressures provided by external windows and doors during gas and vapor explosions. He provided a quantitative approach for estimating these pressures.

To define experimentally those data needed in the mathematical modeling of gas explosions in buildings, Rasbash, Ralmer, Rogowski and Ames [24] carried out experiments in which they exploded mixtures of air and manufactured gas or natural gas, respectively. These explosions took place in a strong chamber with partitions simulating the division of a building into rooms.

Further experiments were carried out by Astbury, West, and Hodgkinson [25] to investigate the effect of different gas layering conditions in a pair of rooms. During the tests, different layers of both gas and a gas/air mixture were used. In two of these experiments, the most explosive (stoichiometric) mixtures of manufactured gas and air were obtained and the resulting explosion caused, in one case, minor, and in the other case, major damage to the 3 1/2-story building which was of load-bearing brick. These experiments were a repeat of earlier tests in which an attempt was made to demonstrate the effects of turbulence. Turbulence has the effect of increasing the pressures developed when an explosion proceeds from one room to another filled with gas namely, the "cascade" effect. The test demonstrated the effectiveness of venting in limiting the maximum pressure developed in an explosion. Despite suffering the extensive damage, the brick building could be safely propped and no progressive collapse occurred.

West [26] carried out tests involving the effect of gas explosions on windows of various details in order to study their effectiveness in providing venting. Specimens included single-glazed windows of 32 oz glass and double-glazed units of the same thickness of glass. Because of their higher strength, the double-glazed windows provided ineffective venting. Further, the resistance of glass to short-term loads (defined as lasting 3 seconds) is more than twice that under sustained loadings. Repeated explosions that do not break the glass may be the cause of eventual failure at a lower pressure. The strength of glass decreases with time. For example, glass 18 months old failed at loads some 20 percent less than those obtained with newly-manufactured glass. Finally, while the failure of glass may give an indication of the pressure developed in a real incident, care is necessary in interpreting test results since a distortion of the frame can cause the glass to break at a pressure less than its actual breaking strength.

Mainstone [27] reviewed the existing experimental data on the strength of glass under loads of very short duration. He provided the basis for a graphic presentation of likely breaking pressures, under gas-explosion loading, for particular sizes and thicknesses of window panes. An earlier review by Rasbash of data on the venting of gas explosions was then used as a basis for extending the graphic presentation to cover also the possible rise in pressure after the glass is broken by an explosion. The graphic presentations can be used directly for estimating the pressure reached in actual explosions from observations on the damage to glass windows; and they were prepared primarily to be used in the design of glazing as an explosion vent.

On the basis of a review of the above studies, it is concluded that there is sufficient data available to allow satisfactory prediction of the characteristics of gas explosions in buildings, providing the gas mixtures can be defined.

B.2 Probability and Consequence of Load

The probability of gas explosions has been studied both in the United States and the United Kingdom. Whereas the Ronan Point incident did not occur unit 1968, the American

Gas Association, which represents approximately 85 percent of the U.S. gas industry, had compiled statistics of gas incidents some years earlier. Before reviewing the results of the AGA studies, it will be useful to consider the studies in the U.K. to gain perspective.

In the Report of the Inquiry into the collapse at Ronan Point, Griffiths, Pugsley and Saunders [1] assembled the data available at that time dealing with the probability of gas explosions in the U.K. Table 5.3 is taken from the report of Griffiths et al and contains an analysis of explosions in housing for each of the years 1957 through 1966.

Structural damage is defined as damage to the structure over and above the mere blowing out of windows and window frames. It will be seen from Tables 5.3 and 5.4 that, of the known causes of explosions, manufactured gas is the principal hazard. In the year 1966, there were approximately 18 million housing units (apartments and houses) in the United Kingdom and, of these, approximately 12,260,000 were supplied with manufactured gas. The 1966 figures show that the frequency of explosions involving manufactured gas in premises supplied with gas is approximately 8 per million dwellings, of which 3.5 per million will be of sufficient violence to cause structural damage. Griffiths et al assessed the chance of a gas explosion in a high-rise apartment building. In a building the size of Ronan Point, with 110 apartments and a life of 60 years, there is slightly more than a 2 percent risk that a gas explosion causing structural damage will occur in one of the apartments during the lifetime of the building, i.e., $3.5 \times 10^{-6} \times 110 \times 60 \times 100 = 2.31$ percent. In other words, the chances are that of every 50 such buildings, one will experience structural damage as a result of a gas explosion in its lifetime. They pointed out that, whereas it may be argued that it is cheaper to prohibit the use of gas in tall apartment buildings than to make the

Table 5.3

Frequencies of Explosions in Housing Units Estimated from Samples of Fire Department Reports in the United Kingdom - Damage and Explosive Material Reproduced from [1]

Year	Sampling factor	Total explosive	Manufactured Gas			Liquefied Petroleum Gases			Liquids			Other and unknown
			Total	Superficial	Structural	Total	Superficial	Structural	Total	Superficial	Structural	
1965	1/1	213	97	55	42	14	8	6	33	25	8	69
65	1/1	181	76	40	36	14	8	6	29	20	9	62
64	1/2	168	80	28	52	8	—	8	18	16	2	62
63	1/6	216	84	54	30	6	—	6	18	12	6	108
62	1/2	234	70	20	50	8	2	6	34	28	6	122
61	1/2	198	46	28	18	10	4	6	38	30	8	104
60	1/4	144	72	36	36	16	—	16	12	8	4	44
59	1/4	148	88	24	64	—	—	—	24	20	4	36
58	1/4	192	64	28	36	12	—	12	48	32	16	68
57	1/1	195	70	41	29	8	3	5	44	35	9	73
Total	—	1,889	747	354	393	96	25	71	298	226	72	748

Table 5.4

Explosions in Domestic Premises in the United Kingdom

Reproduced from [1]

Total Explosions	Explosive Material		Damage		Fault	
213	Manufactured gas	97	Superficial	55	Installation	35
					User	20
					Unknown	0
			Structural	42	Installation	26
					User	9
					Unknown	7
	L.P.G. (Liquefied petroleum gases)	14	Superficial	8	Installation	3
					User	4
					Unknown	1
			Structural	6	Installation	5
					User	0
					Unknown	1
	Liquids	33	Superficial	25	Installation	6
					User	17
					Unknown	2
			Structural	8	Installation	0
					User	7
					Unknown	1
	Other and Unknown	69	---		---	

structures free from the risk of progressive collapse, they did not accept this argument. They reasoned that gas is justifiably regarded as a safe and acceptable fuel in domestic premises generally [28]. Furthermore, the banning of gas would not completely eliminate the risk of damage to the structure of a tall apartment building, resulting in progressive collapse, although admittedly it would remove the most likely cause. There would remain the possibility of explosions caused by substances other than manufactured gas, for example, gasoline or other volatile inflammable liquids, butane gas cylinders, electrical apparatus, and so on; as well as other forms of accidental damage.

Prompted by the Ronan Point incident, the U.K. Construction Industry Research and Information Association (CIRIA) established a pilot survey [29] to establish the procedures for future and wider surveys on the frequency of gas explosions and the structural damage they can cause. Newspapers were used to obtain reports of explosions in residences and, where appropriate, visits were made to damaged properties and comprehensive investigation of the circumstances carried out. Findings showed that gaseous explosions in U.K. housing causing significant structural damage occur at the rate of less than one per week.

Fry [30] examined U.K. fire incidents involving explosions of manufactured gas in dwellings during the 13 years, 1957 to 1969. The average annual incidence was shown to be approximately 90 but appeared to be increasing as the consumption of gas increases. The average rate of incidents is about 5.0 per 10^8 therms of gas sold. Approximately 48 percent of the incidents cause some structural damage and in 40 percent of these it was considered "severe." From reports involving manufactured gas and natural gas in 1969, it appeared that natural gas was more likely to cause explosions but that the explosions were of similar violence for the two types of gas.

A later report [31] of the field survey of damage, caused by gaseous explosions in the U.K. contained the conclusion that roughly one severe or very severe explosion occurs every two weeks. Furthermore, there is some evidence that the frequency is increasing.

It is now useful to discuss the probability of gas explosions within the Continental USA. The two principal sources of information on the gas industry are the American Gas Association and the Office of Pipeline Safety (OPS) of the U.S. Department of Transportation. The following is an attempt to evaluate information from each of these sources.

Within the Continental USA there are 915,000 miles of gas pipeline [32]. This total is composed of 288,000 miles of pipeline in gathering and transmission systems and 627,000 miles of pipeline involved in subsequent distribution of gas [33]. Since the former are located largely in rural areas, it is with gas distribution systems that this study is primarily concerned. It is significant that, within the gas distribution system, gas leaks are reported to occur at an annual rate of 1 per 1.1 mile of gas line; e.g., a total of more than 560,000 leaks in 1972. More than 300,000 of these leaks occurred as a consequence of normal wear and tear; i.e., corrosion, fatigue, material failure, etc. Leaks are reported [33] to occur with comparable frequency in both the mains and service lines and about two-thirds of all leaks were associated with the pipe itself, the remainder being associated with the fittings and other attachments.

Including both single and multiple dwelling units, almost 34.7×10^6 housing units in the USA used gas for house heating in 1970 [32]. It is also estimated [5] that natural gas serves about 55 percent of all housing units as a fuel for residential space heating, and it is significant that, of all new customers for house heating in 1970, 37 percent were conversions to a gas service system. Because a single customer or meter or furnace may involve more than one dwelling unit, these figures may not be fully representative of the total number of dwelling units to which gas is supplied. The AGA estimates that, including appliance usage, natural gas is supplied to upwards of 60 percent of the total residential market.

A prime source of information on gas leak incidents is the summary to the research report "Public Safety and Gas Distribution" [34] prepared for the American Gas Association by Arthur D. Little, Inc., and dated December 1967. This was a survey of the gas distribution industry in which 140 companies and systems participated, representing 83.3 percent of all gas distribution meters. The yearly averages for gas-related incidents are based on the 10-year period 1957-66. As far as incidents involving payment of compensation are concerned, the yearly averages are representative of the 7-year period 1957-1963. Both in terms of the time periods and the number of companies involved, this survey constitutes the most comprehensive, if not the only, study of the overall safety of the gas distribution system within the continental U.S.

With reference to Table 5.5, assembled from information contained in the A. D. Little, Inc., summary, it is evident that 1,508 gas explosions can be expected in an average year and, of these, 329 will require monetary compensation. A total of 151 (60 percent of 253) explosions will involve payments of more than $1,000. It is recognized that only a portion of these explosions could have been severe enough to cause structural damage, but unfortunately, there is no record of:

1. the relative proportion of personal and property damage,
2. whether or not one or more buildings were involved

Table 5.5

Gas Related Incidents. Their Nature, Annual Incidence and Consequence (Taken from A. D. Little Summary Report to American Gas Association [34]

	10 YEAR AVERAGE		7 YEAR AVERAGE - 1957-63 INCLUSIVE				
NATURE OF INCIDENT	INCIDENT REPORTED		INCIDENTS INVOLVING PAYMENT*		SIZE OF PAYMENT		
					>$1,000	<$1,000 >$ 25.	< $25.
	NUMBER	%	NUMBER	%	%	%	%
EXPLOSION	1508	12.8	329	13.3	60	10	4
FIRE	1835	15.6	274	11.1	36	9	7
PRODUCTS OF COMBUSTION	1228	10.4	109	4.4	7	5	3
UNIGNITED GAS	3118	26.5	1498	60.7	12	66	69
FLASHBACK	4122	35.1	217	8.8	6	9	11
OTHER	344	2.9	167	6.8	3	7	8
		103.3+		105.1+	124+	106+	102+
TOTAL NUMBER OF INCIDENTS	11753		2466		253 / 10.3%	1607 / 65.1%	606 / 24.6%

* Total Payments by Gas Company exclusive of Company repair costs.

+ Some incidents may involve more than one of the listed phenomena.

and, if so, the type of building, and

3. the relative severity of each of the incidents involving payment greater than $1,000.

It may be presumed that of the explosions incurring payment of less than $1,000, very few, if any, were likely to have involved significant structural damage. In order to evaluate a probability based upon the AGA statistics, it will be assumed that only one building was involved in each of the 151 incidents and that each suffered significant structural damage. This assumption can be seriously questioned as the following illustration from an OPS report [35] would indicate but, in the absence of more specific data, it at least provides the basis of a conservative estimate:

"Mobile Oil Corporation High Pressure Natural
Gas Pipeline
Houston, Texas, September 9, 1969 - Synopsis

At 3:40 p.m. on September 9, 1969, the 14-in pipeline carrying natural gas at a pressure of more than 780 psig ruptured in a newly constructed residential subdivision 3 1/4 miles north of Houston, Texas. The escaping gas created a dust storm like condition and sounded like a jet engine. Electrical and telephone utility servicemen working in the area, with the help of local residents, immediately commenced to evacuate all residents in the vicinity of the rupture. About 8 or 10 minutes later, the escaping gas exploded violently. Thirteen houses, ranging from twenty-four ft to 250 ft from the rupture were destroyed by the blast. The leaking gas caught fire and continued to burn to a height of 125 ft for 1-1/2 hours until valves on the other side of the leak were closed by Mobile workmen dispatched to the valve locations. The fire abated at that time, but some gas burned for another five hours. In all, 106 houses were damaged and property damage was estimated at $500,000. Miraculously, there were no deaths but nine people were injured, two seriously."

Office of Pipeline Safety figures for 1971 [35] indicate that, of the total number of reported explosions, 50 percent occurred in residential buildings and 7 percent in commercial buildings. The remainder occurred in manholes, regulator pits, etc., and it is unlikely that these involved compensation in excess of $1,000 since, in most instances, these incidents occurred on or within gas company property and it is unlikely that they involved the gas company in claims for payment. Accordingly, it is presumed that 50/57, namely, 87.5 percent of the 151 incidents, namely 131, were likely to have involved residential buildings.

The period over which the AGA statistics were gathered centers approximately on 1960. According to the 1960 Census of Housing [36], the occupied housing in the U.S. totaled 58,314,784 units. Accordingly, a crude estimate of the annual probability of occurrence of a structurally significant gas-related explosion in a residential unit is of the order of 131/58,314,784 x 100 = .00022 percent or 2.2 structurally significant explosions per million dwelling units per year.

During the period 1957-1963, the average annual natural gas sales to residential customers totaled 300 x 10^8 therms. In terms of energy, the annual rate of structurally significant gas-related explosions is 0.44 for every 10^8 therms of gas supplied. If all gas-related explosions and the total amount of natural gas sales are considered, the probability of explosion is 1.67 explosions per 10^8 therms per year.

In accordance with the provisions of the National Gas Pipeline Safety Act of 1968 [33], a nationwide reporting system for gas-related incidents was initiated in 1970 by the Office of Pipeline Safety (OPS). Detailed reports are required of individual incidents that involved one or more of the following criteria:

1. Caused a death or a personal injury requiring hospitalization;
2. Required any segment of transmission pipeline to be taken out of service;
3. Resulted in gas igniting;
4. Caused estimated damage to the property of the operator, or others, or both, of a total of $5,000 or more;
5. Required immediate repair and other emergency action such as evacuation of a building, blocking off an area, rerouting of traffic to protect the public; and
6. Were deemed significant but did not meet the criteria of 2, 3 or 4.

All gas companies with more than 100,000 customers (over 85% of the total number of gas customers) are required to submit reports within 30 days of the incident. Records for 11 months of 1970 and all of 1971 are publicly available [33].

In an NBS Technical Note entitled "Residential Buildings and Gas-Related Explosions" [37] the AGA and OPS statistics are fully discussed. It is shown that at this point in time the AGA and OPS statistics are in conflict and of the two, the AGA statistics would appear to be the more representative since:

1. They attempt to cover all incidents, both upstream and downstream of the meter in distribution systems

(see Table 5.6),

2. They represent a 10-year average, whereas the first complete year of OPS statistics is 1971.

In that report, it is concluded that, though due regard has to be taken for the limitations inherent in the available statistics, the probabilities of the occurrence:

1. of a gas explosion capable of causing significant structural damage is 2.2 per million housing units per year.
2. of a gas explosion capable of causing significant structural damage in a hundred-unit apartment building during a 50-year service life is 0.011 or 1.1 percent.

C. Explosions of Hazardous Materials

The National Bureau of Standards is now gathering statistics of explosive incidents arising from the normal transportation of hazardous materials in urban areas by road, rail, and waterway. Such materials include petroleum and its products, chemicals, explosives, and liquified gases. Approximately 20 percent of all hazardous materials transported in the USA are moved on waterway [38]. Waterway explosions of such a nature that buildings are damaged in the course of the incident are rare, yet the potential for such an incident is not only present but increasing, particularly as the tonnage of petroleum and petrochemicals shipped by water increases. Another source of potentially abnormal loading exists where fuel transportation terminals are located. Such terminals provide a storage facility for large volumes of petroleum which have been transported on waterways. Storage tanks are now located in many densely populated areas including Providence, Boston, Staten Island, and Philadelphia; more are planned.

Table 5.6

Relative Location of the Basic Cause of the Various Gas-Related Incidents in a Typical Year (Taken from A. D. Little Summary Report to American Gas Association [34])

	10 YEAR AVERAGE		7 YEAR AVERAGE	
LOCATION OF BASIC CAUSE OF INCIDENT	TOTAL NUMBER OF INCIDENTS		TOTAL NUMBER OF INCIDENTS INVOLVING PAYMENT	
	NUMBER	%	NUMBER	%
BEFORE OR AT THE METER I.E., UPSTREAM	3,122	26.5	1,780	72.1
AFTER THE METER I.E., DOWNSTREAM	8,296	70.6	639	25.9
OTHER	335	2.9	47	2.0
TOTAL NUMBER OF INCIDENTS PER YEAR	11,753	100%	2,466	100%.

It would appear that the shipment of hazardous materials, by road and rail, poses a problem that is not negligible. Strehlow [39] contends that the explosion of unconfined vapor clouds, produced by the dispersion of flammable liquid or vapor spills, is becoming a serious problem. He points out that this is mainly because of the increased size of the spills in recent years. Illustrating this point is the accident that occurred in East St. Louis, Missouri on January 22, 1972. Since the National Transportation Safety Board is currently investigating the incident, and the report is not yet released, the following information was obtained from a file of newspaper clippings maintained by the Safety Board; it should not be considered official:

> The accident occurred in an East St. Louis railroad yard where a process known as "humping" was taking place. In this process, a railroad car is allowed to roll freely toward other coupled cars with sufficient momentum to allow the couplers to fasten. This is a process regularly used to make up trains. Alledgedly, in this instance not 1 but 4 already coupled cars were being humped. The lead car, filled with 500,000 lb (30,000 gallon) of propylene, a derivative of liquid petroleum gas (LPG), was travelling at approximately 15 mph, instead of the recommended 6-7 mph, when it bumped a hopper car at the end of the partly-assembled train. The total momentum of the impact was such that the hopper car coupler jumped over the coupler of the lead rail car and punctured its propylene tank. The cars continued to move for several hundred feet. The released propylene formed an unconfined vapor cloud which exploded 500 ft. from the location of the leaking car.
>
> The explosion shook a 4 square mile area and shattered windows 8 miles away; the concussion was felt up to 20 miles from the scene of the accident. The explosion caused roofs and walls to collapse as much as 6 blocks away. At least 3 separate fires followed the explosion and involved 30 additional railroad cars. Apparently none of these additional cars contained hazardous materials, for no further explosions were reported.

> Early reports estimated that 1,000 buildings had been damaged including 650 homes and 350 business buildings. Later information indicated that 868 buildings had been reported as damaged. One hundred families were left homeless. In all 176 people were injured and total non-railroad property damage was estimated to be 6.5 million dollars.

It is estimated by the National Transportation Safety Board that the report will be completed by January 1973. Strehlow cites a 1962 accident in the State of New York that involved a truck:

> July 26, 1962, New Berlin, New York [40]. 7,000 gallon tank truck in a single truck accident. Tank ruptured catastrophically in town. Vapor cloud covered 200,000 square feet and was 80 ft deep before ignition. Explosion and following fire killed 10, caused $200,000 damage.

Strehlow states that the characteristics of the initial fire or explosion, which follows the ignition of a spill, depend on four things:

1. The nature of the fuel.
2. The rapidity of the spill coupled with the wind conditions, terrain and/or location of nearby buildings.
3. The delay before an ignition source is found.
4. The nature of the ignition source.

He concludes that current theoretical results are unable to predict the observed pressure-time behaviors.

Strehlow [39] has tabulated 108 accidental unconfined vapor cloud explosions that have been documented over the past 42 years. The list is not complete because it is limited almost entirely to explosions that have occurred in the USA and Germany, because the documentation of individual explosions has often been fragmentary, and because information about many on-site plant explosions are not accessible to the general public. Using Strehlow's data, Figure 7 has been plotted showing the average number of explosions per year over periods of 2, 5 or 10 years. It is seen that the number per year is increasing rapidly. In approximately two years, 1970 through January 1972, a total of 15 incidents occurred, causing damage estimated at 23-27 million dollars. It appears from Strehlow's paper that, with one exception, these occurred in the United States.

How many housing units were subjected to severe blast loading is not known with any certainty, but it is clear from the incident at East St. Louis, January 22, 1972, described earlier, that the number would be significant. The reports of the incident, which has been previously discussed, estimated that 650 homes were damaged and 100 families were left homeless. It would appear that a lower bound to the number of housing units subjected to abnormal loading due to this explosion was 100. The non-railroad loss in this incident was 6.5 million dollars, out of an estimated total of 23-27 million dollars for the last two year period shown in Figure 7. If it is assumed that the number of housing units affected in two years can be arrived at by prorating the figures for St. Louis then this number would be approximately

$$100 \times \frac{23}{6.5} = 354 \text{ housing units}$$

On this basis, albeit a crude one, it could be expected that 354/2, namely 177 incidents occur per year unless some change in the incidence of accidental unconfined vapor clouds were to take place.

C.1 Highway Vehicle Impact

Sanders [41] has developed relationships to aid the structural designer in estimating the probability of a

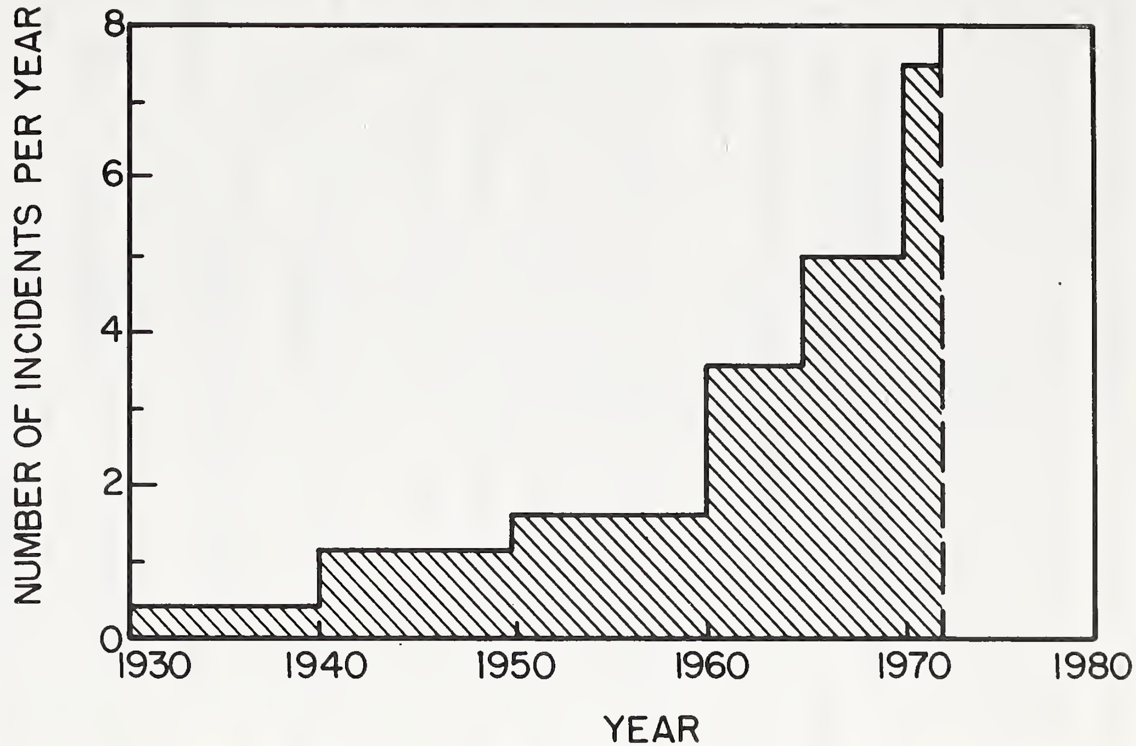

Figure 7 Histogram of unconfined vapor cloud explosions, 1930 through January 1972, based on data compiled by Strehlow [39] and principally based on incidents occurring in the United States and Germany.

structural component being struck by an errant motor vehicle. An example of this type of incident would be a motor vehicle straying from its normal path and hitting a building column. The probability of failure of the column is derived from combining the probabilities: (a) of a vehicle striking the column and (b) of the vehicle having the mass, velocity, and stiffness to cause failure of the column. The probability of a motor vehicle striking an object located near a traffic path is derived as a function of (a) the distance of the object from the traffic path and (b) the volume of traffic flow.

For the USA in 1970, the total number of motor vehicle accidents of all types was approximately 16 million [71]. Highway accident statistics are compiled by each State and the categories of information on the reporting forms frequently total as many as 60 items. In spite of this, incidents in which vehicles collide with buildings receive scant coverage. Indeed, it is the exception for the report to identify the object struck when a vehicle leaves the highway. The U.S. Department of Transportation has assisted NBS in identifying two states in which building strikes were considered in the data collection. These States are Oklahoma and Illinois, the former having relatively little urban area while the second has large urban concentrations. In each case the data analyzed were those of 1970.

Throughout the year 1970, there were 65,183 motor vehicle accidents in Oklahoma. In 50 of these, a vehicle was reported to have collided with a building. In Illinois in 1970, there were 409,174 motor vehicle accidents and, of these, the number in which a vehicle was reported to have collided with a building is 1229.

If the following assumptions are made: 1) the Oklahoma data, added to the Illinois data, is representative of the USA as a whole; 2) the number of vehicle collisions with buildings (C) is propertional to the population (P), then, based on 1970 data:

$$\frac{C_{US}}{P_{US}} = \frac{C_{ILL} + C_{OKLA}}{P_{ILL} + P_{OKLA}}$$

$$C_{US} = \frac{1279}{13,674,000} \times 203,212,000$$

$$C_{US} = 19,000 \text{ (approximately)}$$

This estimate is for the number of vehicle collisions with buildings for the USA as a whole in 1970, based upon combined Oklahoma and Illinois data.

It is interesting to differentiate between urban and rural situations, where urban is used to denote an incorporated area having a population of 2500 or more.

URBAN: $$C_{US} = \frac{1171}{10,970,000} \times 149,325,000$$

$$= 16,000 \text{ (approximately)}$$

RURAL: $$C_{US} = \frac{108}{2,704,000} \times 53,887,000$$

$$C_{US} = 3,000 \text{ (approximately)}$$

On this basis, it is estimated that, nationally, the 1970 figure for vehicle building collisions is 16,000 in urban areas and 3,000 in rural areas.

So far the discussion has dealt with reported collisions of vehicles with buildings, with no consideration for what is meant by 1) vehicle collision, and 2) building. Vehicles vary widely in mass, and collisions can range from a gentle nudge to an impact capable of removing a structural element. The term building covers a range of structures from barns to multistory apartment houses. As far as this study is concerned, all standard reporting forms are unsatisfactory in these respects. Efforts to break out the particularly-relevant data are continuing; however, it seems unlikely that the probability of abnormal loading of housing units due to highway vehicle impact will be defined with any clarity unless: 1) existing data recording procedures used by the States are slightly modified, or 2) a separate detailed study is made (this could be based on statistical sampling and involve relatively small areas of the country).

However, with due regard to the uncertainties inherent in the data available, a lower bound estimate can be made of the number of abnormal loads per year on residential structures subjected to highway vehicle impact. From a study of what detailed information is available, it is assumed that at the national level at least one tenth of the incidents will involve residences and, of these, one tenth will involve sufficiently large to be considered an abnormal loading.

On this basis a conservative estimate of the number of abnormal loadings on residential buildings per year due to highway vehicle impact is believed to be 190 or, on the average, four per State.

C.2 Aircraft Collisions With Buildings

In comparison with other forms of abnormal loading the probability of such incidents is trivial. Using data furnished by the U.S. Federal Aviation Authority, the NBS study was shown that for buildings located further than 3 miles from the end of an airport runway the probability of collision with buildings per year is approximately 10^{-8} per building.

6. Summary of the Probabilities of Abnormal Loadings And Their Implications for the USA

Chapter 5 discussed the available statistics from which preliminary estimates have been made of the annual incidence of five sources of abnormal loading on residential buildings. Chapter 4 reveals several abnormal loadings for which data has not been presented. Efforts to quantify the probability of occurrence of these other loadings will continue; however, it should be recognized that for several reasons this quantification may never be satisfactorily accomplished.

In arriving at estimates in Chapter 5, it has been the author's intention to err on the low side in cases of doubt about the available data. For this reason, and because not all sources of loading are included, it is believed that the following summation provides a lower bound result.

Source	Number of Abnormal Loadings Per Year
Explosive Bombing	204
Gas Explosion	131
Explosion of Hazardous Materials	177
Highway Vehicle Impact	190
Summation	702

Chapter 4 discussed the national risk due to fire as a basis for assessing the incidence of abnormal loadings in housing units. It was shown that architectural layout and building size affected the number of abnormal loadings on housing units per year that, in buildings susceptible to progressive collapse, would pose the same risk as fire. For a 100-unit building, with 4 apartments per story, an average of 4 persons per apartment, and a central service core, this number was 433, while for a 50-unit building of similar arrangement the corresponding number would be 866.

Comparing these figures with the lower bound estimate of 702 abnormal loadings a year, it appears that, for buildings susceptible to progressive collapse, abnormal loadings do pose a risk comparable to that of fire. In the case of the fire risk, specific design criteria are currently implemented.

The United Kingdom Authorities introduced criteria to minimize the risk of progressive collapse upon concluding that the frequency of explosions, involving gas in housing units supplied with gas, was approximately 8 per million housing units per year, of which, 3.5 million were of sufficient violence to cause structural damage. It should be noted that this figure relates to only one source of abnormal loading.

In the USA, the frequency of abnormal loadings on housing units per year appears to be in excess of $702/(67.7 \times 10^6)$, approximately 10 per million. These data appear to provide adequate justification and need for standards-writing bodies to adopt criteria to deal explicitly with abnormal loadings and progressive collapse.

7. Alternative Approaches for Criteria

Each of the following approaches, or some combination, may be used in the preparation of criteria to reduce the level of risk from abnormal loadings:

Eliminate Source
Reduce Magnitude
Limit Extent of Structural Damage
Resist Local Structural Damage

The banning of gas from buildings would illustrate an attempt to partially implement the first of these approaches. The second is illustrated by regulations that might call for buildings to be sited at distances from a highway and with such barriers that impact from vehicles become unlikely. The provision of alternate paths for loads in the event of the loss of a critical member illustrates the third approach. The fourth approach is the basis of the U.K. criterion, in which the element is designed to resist 5 psi pressure in any direction, applied to the element and to those elements attached to it.

For the most part, the first two approaches are non-structural.

A. Non-Structural Design Criteria

It could also be feasible to consider introducing criteria in non-structural areas including the following:

Zoning, Siting, Planning
Regulations for Service Systems
Transportation Regulations

A.1 Zoning, Siting, and Planning Criteria

The following are examples of areas in which criteria could be considered for development or modification:

1. The location of gas mains in urban areas.
2. The location of multistory buildings with respect to highways, railroads, and waterways.
3. The location of multistory buildings with respect to similar buildings.
4. The zoning of land for residential use, taking into account the possibility of local external explosions.

A.2 Regulations for Service Systems

The following are features of service systems that might be studied with a view to reducing risk:

1. The location of high pressure gas riser mains in multistory buildings.
2. The location of boiler rooms and furnaces and HVAC plant in general.
3. Ventilation provisions for gas mains, boilers, and furnaces.
4. Specifications for pipe work and fittings.
5. Maintenance and inspection procedures for plumbing installations.

As an illustration, French regulations [42] prohibit the use of gas in buildings higher than 50 meters (164 feet), and this law was enforced before the Ronan Point collapse. Furthermore, when gas is installed in buildings, French codes have requirements for ventilation that are more stringent than most codes; e.g., the gas supply pipes are enclosed in a ventilated duct space.

A.3 Transportation Regulations

Considerable volumes of hazardous materials are transported through urban areas in the U.S. by means of truck, railcar, and waterway traffic. Minimization of the risk incurred might come about from new or improved regulations following a study of:

1. The type and volume of hazardous materials transported as one cargo.
2. The engineering specifications used in the regulation of the design and maintenance of vehicles used in this transportation, the standard procedures for the operation of these vehicles, and the procedures for the supervision of operatives.
3. The routes over which this transportation is permitted to take place and, in particular, the

proximity to urban areas.

4. The statistics for explosions of hazardous cargoes in shipment.

8. Philosophies for Structural Criteria

Criteria to minimize progressive collapse are being implemented in several countries including the Nordic Countries, Countries of Eastern Europe, France, Italy, United Kingdom, the United States and Canada. A detailed review of the contents of these various criteria is beyond the scope of this paper. It is sufficient and more appropriate to identify the various philosophies that have been used in the preparation of these criteria:

1. The Cautionary Note: The attention of the structural engineer is drawn to the risk of progressive collapse and he is urged to take precautionary measures to deal with it, as in the National Building Code of Canada, 1970 Edition [43] which states that: "Buildings and structural systems shall provide such structural integrity that the hazards associated with progressive collapse, due to local failure caused by severe overloads or abnormal loads, not specifically covered in the section, are reduced to a level commensurate with good engineering practice." The 1972 American National Standards Institute A58, Minimum Design Loads in Buildings and Other Structures [3], also gives a cautionary note as follows: "Progressive Collapse - Buildings and structural systems shall provide such structural integrity that the hazards associated with progressive collapse such as that due to local failure caused by severe overloads or abnormal loads not

specifically covered herein are reduced to a level consistent with good engineering practice."

2. <u>The Alternate Path Approach</u>: Criteria of this form call upon the designer to consider successively the removal of structural elements or combinations thereof from the building in a systematic manner, and insure thereby through analysis and design, that the building remains capable of withstanding a specified combination of loads albeit with a small overload factor.

3. <u>Specified Abnormal Loadings</u>: In this approach, an equivalent static loading consisting of a uniform pressure is assumed to envelope the loading states that might be produced by the various abnormal loadings on buildings. A structural element or combination of such elements, that may not be removed in accordance with the previous approach, is required to withstand the application of this pressure to its surface and those surfaces of elements attached to it (subject to the strength of their connections). An example of this approach is provided by the United Kingdom Regulations [44].

4. <u>Specifications for Reinforcement and Reinforced Connections</u>: This approach removes from the structural designer the responsibility for considering successively the application of abnormal loadings to various portions of the structure. It does so by specifying reinforcement for elements and for their connection in such a way as to insure an adequate strength and ductility in the event of abnormal loadings. An example of this is provided by the CEB Regulations [45] used in France and in the soon-to-be ratified Uniform Code in the United Kingdom [46].

5. Deemed to Satisfy Clauses: Finally, there have emerged a number of documents in which it is stated that design in accordance with certain national standards is deemed to satisfy the intent of other standards dealing explicitly with the risk of progressive collapse. Examples of this include BS 449, Design for Steel Structures, in the United Kingdom [47].

In the United States, there have been two cases where criteria have been developed explicitly to deal with progressive collapse, albeit applied in a limited manner. One of these involved the preparation of the Guide Criteria [5] for use in the evaluation of the housing systems demonstrated as a part of the Operation BREAKTHROUGH program. These criteria were prepared by the National Bureau of Standards on behalf of the Department of Housing and Urban Development. Expressed in performance language, they were an adaptation of the Fifth Amendment to the U.K. Building Regulations 1970 [48], and expressed both the alternate path approach and the use (where absolutely necessary) of the specified abnormal loading approach (5 psi). These criteria were used in the evaluation of multistory systems in the BREAKTHROUGH program.

The second set of criteria [6] was prepared by the Federal Housing Administration of the Department of Housing and Urban Development for use in the preparation of Structural Engineering Bulletins for those industrialized systems being designed and built with a FHA mortgage guarantees. Essentially, FHA based these criteria on the British Standard Code of Practice 116, Addendum No. 1 for the Design of Large Concrete Panels [44].

There is no shortage of literature discussing the reaction of the building community to the introduction of criteria against progressive collapse in high-rise buildings. The reader is referred to Collins [49], Short and Miles [50], Rodin [51, 52], Creasy [53], Ferahian [54, 55], Lewicki [56, 57], and a collection of the discussions of structural engineers at a special meeting on the subject [58, 59]. It is a subject which has generated a great deal of interest among structural engineers.

9. Building Response to Abnormal Loadings

This section will deal with the response of buildings to abnormal loadings from three standpoints: cases of progressive collapse, experimental studies, and analyses.

A. Cases of Progressive Collapse

A number of people including Griffiths [1], Rodin [52], and Ferahian [54] have provided considerable insight into the behavior of the Ronan Point building. Slack [60], has discussed two other instances of explosions in reinforced concrete buildings, albeit factory buildings. The first case study is concerned with an explosion in a 4-story cast-in-place framed structure, while the second illustrates the nature of blast damage within a single-story precast concrete framed building. In the cast-in-place structure the progression of the explosion pressure wave is traced and the resulting damage to the external cladding as well as fire damage are described. The precast concrete frame building suffered column damage due to the confinement of the primary explosion. In both of the buildings, large areas of cladding, or their connections, were weaker than the main structural frame, resulting in limited overall damage to the buildings. From the first case, it appears that the framed cast-in-place structure had a greater inherent resistance to damage than would be indicated by a straight-forward analysis taking account of structural continuity. In the precast frame structure, it was found that a precast frame can have a greater resistance to collapse than would seem apparent from a basic reinforced concrete design analysis. However, it is Slack's recommendation that full or partial continuity at the cast-in-place joint be provided to give individual members greater resistance to damage.

A short report [61] was given on the bombing of an Army Officer's building in Aldershot near London in February 1972. The Irish Republican Army claimed to have carried out the bombing using 280 pounds of gelignite. The building did not collapse. The walls of one-half of the building were blow away completely, but the structural frame of reinforced concrete remained intact.

A gas explosion destroyed a row of 22 single-story shops in Clarkston, Glasgow, Scotland. Below the shops, were a series of basement voids into which gas seeped from a nearby broken main, and concentrated until it was ignited. The explosive pressure has been estimated to be at least 7.3 psi (and possibly as high as 14.6 psi). The maximum damage occurred about half way along the row. At the location of the explosion, floor slabs were lifted and the collapse of the front row of columns was attributed to the failure of 12 in by 18 in reinforced concrete beams at ground level.

On the night of March 6, 1972, an explosion occurred in an 11-story apartment building in Barcelona, Spain, resulting in the collapse of a portion of the building (See Figure 8) and the deaths of 18 people and many injuries. It was concluded [8] that the collapse was the result of a conventional explosive. Basically, the building is a load-bearing brick structure. From evidence available, it would appear that the explosion occurred in an apartment on the fourth floor, destruction of this unit then leading to the progressive collapse of all stories above. Falling debris caused destruction of the rooms directly below the apartment. The

Figure 8 Apartment building at Calle Santa Amelia, Barcelona, Spain following a progressive collapse on March 6, 1972.

opinions given in the report [8] are based upon evidence available at the time of its preparation in July 1972, and may not be the final word as to the cause. If it is assumed that the apartments in question were occupied at the rate of 4 persons per apartment, then the death toll represents 18 out of 44 affected by the incident, 41 percent.

It was reported [62] that a car crashed into a five-story tenament building in New York dislodging a column and sending tenants and portions of the structure crashing into the street.

A considerable discussion of cases of progressive collapse in Canada and the U.S. in the years 1968 to 1972 has been given by Allen and Schriever [7].

B. Experimental Studies

It is appropriate to discuss these studies from the standpoint of the materials concerned.

B.1 Reinforced Concrete Panels

Ronan Point provided considerable impetus for construction companies in the United Kingdom to expand their already large experimental efforts and to develop improved procedures for design. Accordingly, the large construction companies marketing concrete panelized systems carried out evaluations of their systems to determine whether they met the new criteria [2].

Much of the testing has been carried out in the U.K., by the Building Research Establishment and Imperial College, concerning the ability of concrete panel structures to bridge over the loss of structural elements.

Outside the United Kingdom, considerable experimental work has been carried out by Hanson and Olesen [63] in Denmark. Tests were made to determine the strength and stiffness of vertical-keyed shear joints between wall elements of prefabricated concrete. It is known that Olesen is continuing with a series of laboratory tests, in which two stories and two bays of a building of precast concrete panel construction are simulated. In these tests, wall and floor panels will be removed successively to determine the distress in the remaining structure.

Granstrom [64], in Sweden, has reported model tests, to scale of 1:20, involving studies of joint forces and framework deformations of buildings that have sustained local damage. The tests relate mainly to domestic and office buildings of precast concrete. The results show that providing joint connections, even of moderate strength, can reduce dramatically the probability of collapse of buildings. The shear resistance of vertical joints in large concrete panel construction, and the ability of the joints to transmit horizontal in-plane tensile forces, has been studied extensively and the various contributions are too numerous to list in this report. The same is true of horizontal connections between floor panels and the top of wall panels. The reader is referred to the considerable volume of information presented in March 1970, at a Symposium on joints in Precast Concrete Components held in the United Kingdom [65].

B.2 Load-Bearing Masonry

Wilton, Gabrielsen, Edmunds, and Bechtel [66] reported the early progress on a long range program with the objective of developing improved methods of predicting the structural response, failure modes, and debris characteristics of masonry wall panels. This information is required by the Office of Civil Defense in order to develop improved shelter systems. The study combines both analytical and experimental work and, in the period reported, the authors have developed a statistical failure theory for brick structures, a failure theory for wall panels, and the development of an analytical program whereby wall panel failure predictions may be used in the design of an experimental test program. Their research included testing of brick wall panels, interior gypsum board wall panels, concrete wall panels and a small number of tests to investigate the effect of air blast on shelter ventilating equipment. A later report by Wilton, Gabrielsen, and Morris [67] describes the results of the continued investigation of the response to blast loading of full-scale wall panels of relatively brittle materials, notably non-reinforced brick. Information such as element-failure times, energy transmitted to a building frame, and the influence of support conditions and other geometric factors were obtained from the tests. Loading tests were carried out on walls which completely closed a test tunnel, on walls with 17.5 percent doorway openings, and on walls with 16.7 and 27 percent window openings.

In the United Kingdom, it is now a requirement under the Building Regulations [48], that structures of five stories and more shall remain stable after the removal of a specified length of load bearing wall, although at a substantially reduced safety factor. Sinaj and Hendry [68] describe three experiments that had the objective of confirming that this could be achieved in a simple five-story brick cross-wall structure. In each experiment, a section of the main load bearing wall was removed at ground level to test the stability of the structure in a damage condition, as might occur following an internal explosion. Measurements were made of the applied loads, deflections and strains. The theoretical conclusion that the structure would remain stable under these conditions was confirmed and some information was obtained concerning the strength of 114 mm. (4.5 inches) thick wall panels subjected to lateral loadings.

C. Analysis

The most extensive work in the area of analysis of building response to overpressure loading is that of Newmark [69] who prepared a state-of-the-art report presented at the August 1972 Conference on the Planning and Design of Tall Buildings. In this paper, he discussed the effects on buildings of external loadings of a transient or impulsive nature where these loadings can arise from the detonation of explosives, including gas or other sources, from sonic boom from aircraft, or from accidental impact. Fundamental relations for developing blast resistance design procedures are also presented based upon the work of Newmark and others over a period of many years.

Other analytical procedures have been reviewed earlier in this paper in the context of their application.

10. Conclusions

This report is in the nature of a progress document, coming at the end of the first year of a study of abnormal loadings and progressive collapse. This study is being carried out by the National Bureau of Standards on behalf of the Department of Housing and Urban Development.

The report has discussed the state of knowledge with respect to abnormal loadings on buildings, the response of buildings and building elements to these loadings, and criteria by which the risk of progressive collapse might be minimized.

Probably very few buildings of the types constructed in the past would be susceptible to progressive collapse in the event of an abnormal loading. To date, few incidents of progressive collapse have occurred in the USA, and none approach the magnitude of the Ronan Point incident in the

United Kingdom.

The patterns of siting, design, and construction of buildings are changing, however, and the frequency of occurrence of certain abnormal loadings on buildings is increasing. The NBS study is concerned not so much with U.S. buildings of the types constructed in the past, but with those types constructed now, and in the future. There is reason to believe that, in the absence of new criteria to minimize the risk of progressive collapse, the number of buildings that are susceptible will increase.

It should not be assumed that conventional systems are free from the risk of progressive collapse. Rather, studies should be made to determine the general degree of susceptibility to progressive collapse of multistory buildings of all construction types. There is also need to study certain abnormal loadings on buildings for which little knowledge is available at present, such as unconfined vapor cloud explosions and vehicular impact.

Several other countries have implemented criteria to minimize the risk of progressive collapse. The data presented and discussed in Chapters 5 and 6 of this report are believed to express a lower bound to the probability of abnormal loadings in the USA. Yet these data indicate that, for buildings susceptible to progressive collapse in the USA, the risk substantially exceeds that which prompted other countries to implement criteria. Furthermore, the risk of fatality appears to be on a par with that for fire.

It is concluded, therefore, that U.S. standards-writing bodies should adopt appropriate rational criteria as soon as possible.

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16. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)

The document is an interim report of ongoing studies at the National Bureau of Standards. It defines the several aspects of abnormal loading on buildings and the problem of progressive collapse. It documents the extent to which present U. S. Codes and Standards address the problem.

Abnormal loadings are identified, classified and discussed with regard to their characteristics and frequencies of occurrence. The report reviews the state of international knowledge of the characteristics of abnormal loadings and the response of buildings and building elements to these loadings. The latter includes discussion of several incidents in which multistory buildings have collapsed progressively.

Using currently available statistics an estimate is made of the combined frequency of abnormal loadings on residential buildings in the U. S. For buildings susceptible to progressive collapse, the corresponding risk of fatality is compared with the levels of risk that society will generally accept. The risk is further compared with the risk of mortality associated with fire in residential buildings, an area of considerable public concern and expenditure.

It is concluded that U. S. standards-writing bodies should adopt appropriate rational criteria as soon as possible to reduce the risks of progressive collapse. There are several areas in which criteria might be introduced to reduce the risk of progressive collapse. These are discussed; particular attention is given to the philosophies behind the structural criteria implemented in the USA and other countries.

17. KEY WORDS (Alphabetical order, separated by semicolons) Abnormal loading; building; codes; design criteria; multistory; progressive collapse; risk; stability; standards; strength; United States

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