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Economics of Protection Against Progressive Collapse

Robert E. Chapman and Peter F. Colwell

Building Economics Section
Technical Evaluation and Application Division
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National Bureau of Standards
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Final Report

U.S. DEPARTMENT OF COMMERCE
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NATIONAL BUREAU OF STANDARDS, Richard W. Roberts, Director

PREFACE

This study was conducted by the Building Economics Section to demonstrate how economic analysis can be applied to the evaluation of standards for protection against progressive collapse. Dr. Harold E. Marshall and Mr. Phillip T. Chen provided reviews of the economic and engineering aspects of this paper.

ABSTRACT

Public and government concern about the progressive collapse of buildings caused by abnormal loading has resulted in the development of draft standards to provide protection against progressive collapse. From society's viewpoint, standards for protection against progressive collapse should result in a level of protection which is more efficient (i.e., the net social benefits from protection should be increased). An economic model utilizing the principles of benefit-cost analysis is developed which establishes a methodology for determining the efficiency of various levels of protection against progressive collapse. An application of the model to a partial evaluation of a specific standard demonstrates some of the capabilities of the model. Recommendations are made for a complete evaluation of this standard and for the further refinement of the model.

EXECUTIVE SUMMARY

In the United States the potential exists for an incident of progressive collapse as severe as England's Ronan Point disaster. Interest in standards intended to protect against progressive collapse will grow as the number of buildings susceptible to progressive collapse grows. A model for determining the efficiency of standards is needed to ensure that the standards which are developed will increase the efficiency of resource allocation.

This study develops an economic model for the evaluation of levels of protection against progressive collapse. An increase in efficiency is indicated if the additional social benefits of increased protection exceed the additional social costs of the increased protection. The consideration of more levels of protection and smaller intervals between levels increases the liklihood of finding the most efficient level (i.e., the most efficient standard).

Sensitivity diagrams are discussed as a guide for the public decision maker to aid in the evaluation of standards which are intended to provide protection against progressive collapse. A sensitivity diagram may be used to determine the extent to which the efficiency of a change in the level of protection is sensitive to changes in the estimates of cost and benefit components.

A comprehensive evaluation of the efficiency of a mandatory progressive collapse standard is shown to require a broader view than a concern with effects of the standard on a single building. A more efficient standard may result in less efficient levels of protection for some buildings producing more than offsetting increases in efficiency for other buildings. Thus, the whole range of effects must be considered when evaluating a progressive collapse standard.

A hypothetical case study is presented which partially evaluates the potential impact of draft Department of Housing and Urban Development (HUD) progressive collapse standards. First, the evaluation is limited by only considering the impact on a single building. Second, the case study does not indicate whether the incorporation of the standard in the design of the specific building considered would increase efficiency. This is because only the benefits of incorporating the standard are estimated. However, the case study may be considered a first step toward quantifying the magnitudes called for in the model,

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LIST OF SYMBOLS

AD_k^b = the annual building damage with design k.

AD_k^p = the annual personal property damage with design k.

AI_{jk} = the expected annual number of injuries of type j due to progressive collapse with design k.

$B(q)$ = the benefits of protection against progressive collapse as a function of the level of protection, q.

$C(q)$ = the costs of protection against progressive collapse as a function of the level of protection.

D_k^b = the value of the building per housing unit including demolition and removal with design k.

D_k^p = the value of the personal property damaged and destroyed in a unit affected by progressive collapse with design k.

E_e = the expense of training another individual to take the place of the deceased.

E_m = premature mortuary expenses.

F = the probability that a resident is an occupant.

h = long-term daily hospital expenses.

H_k = the expected number of housing units affected per collapse with design K.

i_j = the expected number of injuries of type j per housing unit experiencing progressive collapse.

k = a subscript used to indicate whether a design incorporates a standard or not: $k = 1$ without a standard and $k = 2$ with a standard.

K_k = capital costs for design k.

L = building life in years.

MAB = the marginal annual benefits of additional protection against progressive collapse.

MAC = the marginal annual costs of additional protection against progressive collapse.

MC = the marginal costs of additional protection against progressive collapse (i.e., implementing a standard).

MAD = the marginal annual building and personal property damage averted.

MAD^b = the marginal annual building damage averted.

MAD^P = the marginal annual personal property damage averted.

MAI = the marginal annual number of composite injuries.

MAI_j = the marginal annual number of injuries of type j.

MAV = the marginal annual value of all injuries averted.

MAV_j = the marginal annual value of injuries averted of type j.

N = the number of housing units in a building.

OM_k = the present value of operation and maintenance costs for design k.

P_j = the probability an occupant suffers a j type injury in a progressive collapse.

r = the annual discount rate expressed as a decimal.

R = the average number of residents per unit.

S = short-term daily hospital expenses.

T = the average number of years remaining in the individual's life.

Θ = the expected annual rate of inflation.

U_k = the expected annual probability of a unit being affected by progressive collapse.

V = the value of averting a composite injury.

v_j = the social value of averting an injury of type j.

w_j = the relative value of averting an injury of type j.

Y = annual per capita income

z = the expected annual number of collapses.

Z = the number of units susceptible to progressive collapse.

1. INTRODUCTION

International concern about the problem of progressive collapse has been brought about by the tragic collapse of a precast panel apartment building at Ronan Point, England, in May of 1968. As a result of this collapse several reports have been written on problem definition and on the development of suitable progressive collapse standards.[1] In this study the economic implications of standards for protection against progressive collapse are examined. The evaluation of levels of protection against progressive collapse and of techniques for achieving such protection is accomplished by means of a benefit-cost model. This model provides a method for computing the marginal social benefits and marginal social costs of a structure with and without progressive collapse standards. The economic model is then applied to a specific hypothetical case study where a given standard is evaluated on the basis of its marginal social benefits.

As buildings grow in height, the seriousness of a potential progressive collapse grows. Progressive collapse is a chain reaction of building failures following damage to a relatively small portion of the structure.[2]

Previous studies conducted in Europe and in this country have found that certain structural systems are more susceptible to progressive collapse than others.[3] As a result of these studies, the author determined that two structural systems, precast panel bearing wall and masonry bearing wall structures, are potentially susceptible to progressive collapse. These structural systems generally have little continuity if a load bearing member should be removed. Conceivably, buildings utilizing these two types of structural systems could collapse progressively upon the removal of a bearing member.

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[1] Department of the Environment, Partial Stability, 17597 BRS, London, England, August, 1971; Ferahian, R. H., Design Against Progressive Collapse, National Research Council of Canada, BRD, Technical Paper 332 (NRCC 11769), April, 1971; and Somes, N. F., "Abnormal Loading on Buildings and Progressive Collapse," Building Practices for Disaster Mitigation, NBS-BSS-46, February, 1973.

[2] Somes, N. F., "Abnormal Loading on Buildings and Progressive Collapse," p. 431.

[3] Ferahian, R. H., Design Against Progressive Collapse.

2. BENEFIT-COST ANALYSIS[1]

Benefit-cost analysis, by the systematic study and weighing of available alternatives, provides a guide for increasing the efficiency of resource allocation. In some situations it may be possible for benefit-cost analysis to identify the most efficient level of providing safety (e.g., the most efficient level of protection against progressive collapse). More generally however, benefit-cost analysis is useful for determining the more efficient of two levels of safety such as the levels of building safety with and without the incorporation of a specific safety standard.

The term efficiency, as it is used in this study, does not refer to the welfare of single individuals. Rather, it refers to the potential welfare of society generally. Thus, a project which results in increased efficiency generates sufficient welfare gains so that the potential exists for everyone affected by the project to have a gain in welfare. While this potential must exist in order that efficiency may be said to be increased, the potential need not be realized. Benefit-cost analysis, which evaluates the efficiency of a project, requires that all costs (i.e., social costs) and all benefits (i.e., social benefits) which are produced by the project be considered regardless of whether or not they flow through the marketplace and regardless of to whom they accrue.[2] Social costs include noise, pollution, and hazards in addition to the more commonly thought of costs which flow through the marketplace. A reduction in social costs can be considered a social benefit. Thus a reduction in some building hazard is a social benefit.

For efficiency to be maximized, two considerations must be satisfied.[3] First, the project techniques (e.g., the modification of building systems necessary to satisfy progressive collapse standards) selected to accomplish a given purpose should be less costly than any other available means of achieving that specific level of protection. Second, the level of progressive collapse protection for the project must be the level that maximizes net social benefits (i.e., social benefits minus social costs).

An increase in efficiency is indicated if the additional costs of increased protection are exceeded by the additional benefits generated by the increased protection. When evaluating the efficiency of a progressive collapse standard, it is important that the amount used to represent the costs be the least possible costs which allow the requirements of the standard to be met. A standard is efficient (i.e., increases efficiency) if it results in greater benefits than costs.

2.1 Maximum Efficiency In Protection Against Progressive Collapse

In order to determine the most efficient level of protection against progressive collapse, all social benefits must be included in the benefit-cost analysis. Benefits should be included regardless of who the recipients are (e.g., tennants, owners, neighbors, passers-by). Therefore, the social benefits of protection consist of averting human injury as well as averting real and personal property damage.

The costs which are relevant for determining the most efficient level of protection within the framework of benefit-cost analysis are the least-costs for producing any level of safety. For simplicity, we assume that there are only two techniques, A and B (e.g.,

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[1] Benefit-cost analysis is sometimes called the benefit-risk analysis in the context of safety.

[2] Subcommittee on Evaluation Standards, Proposed Practices for Economic Analysis of River Basin Projects. Report to the Inter-Agency Committee on Water Resources, May, 1958, p. 6; and Sewell, W.; Davis, J.; Scott, A.; Ross, D.; Guide to Benefit-Cost Analysis, Queen's Printer and Controller of Stationery, Ottawa, 1965, p. 9.

[3] Throughout, it is assumed that projects (i.e., standards) are technically feasible.

two types of structural modifications), which produce protection against progressive collapse.[1] The levels of these two techniques are variable and are measured along the axes of Figure 1. The curves in Figure 1 which are labeled q_1, q_2, and q_3 are equal-protection curves. Each equal-protection curve indicates all those combinations of techniques A and B which will produce an equal amount of protection against progressive collapse. In Figure 1, higher equal-protection curves indicate higher levels of protection. The straight lines, in Figure 1, labeled C_1, C_1^*, C_2, C_3, and C_3^*, are equal-cost lines based on the assumption that unit prices for techniques A and B are constant. Each equal-cost line shows all the combinations of Techniques A and B which cost the same. In Figure 1, higher equal cost lines indicate greater costs. Thus the least-cost combination of techniques for producing a certain level of safety is the one where the lowest possible equal-cost line touches (i.e., is tangent to) the specific equal-protection curve in question. Points α, β, and γ are the least-cost combinations which produce q_1, q_2, and q_3, respectively. By allowing the level of only one of the two techniques to vary, the resulting combinations of techniques are not necessarily least-cost combinations. Thus, if one were to hold technique B constant at level B_1 and just vary the level of technique A, q_1 would be produced at C_1^* which is higher than C_1, q_2 would be produced at C_2, and q_3 would be produced at C_3^* which is higher than C_3.

Figure 2 further illustrates this point by showing costs as a function of the level of protection being produced. The C* function shows the costs of producing various levels of protection while holding technique B constant. The C function shows the lowest costs (i.e., it implies using the most cost-effective methods) of producing various levels of protection. Any cost curve which is not derived from the path of tangency points between the equal-protection curves and the equal-cost lines cannot be below the C function. Therefore, the C function is the lower envelope of all other cost curves derived from the same equal-cost and equal protection curves. It is the C function which is relevant for determining the most efficient level of safety with benefit-cost analysis.

The point of maximum efficiency is determined uniquely by the social benefit and cost functions when the following assumptions are made:

(1) Project benefits and costs, denoted by $B(q)$ and $C(q)$ respectively, are continuous monotonically increasing functions of the level of progressive collapse protection in the region under study. Although we would not expect to find such well-behaved functions in the real world, the major analytical points derived with these functions are valid for the discontinuous functions to be found in the real world.

(2) The first $[B'(q), C'(q)]$ and second $[B''(q)], C''(q)]$ order derivatives of both functions exist in the region under study;

(3) $B''(q) < 0$ and $C''(q) > 0$; (i.e., as the level of progressive collapse protection (q) increases, the benefit function is increasing at a decreasing rate whereas the cost function is increasing at an increasing rate).

Figures 3 and 4 demonstrate how the most efficient level of protection is identified. To arrive at the most efficient level of protection (q_e in Figures 3 and 4), the level of protection should be such that net benefits, the excess of social benefits over costs $[B(q) - C(q)]$, are maximized (Figure 3). This corresponds to the point where marginal social benefits and costs are equal (i.e., where MB = MC in Figure 4). Any level of protection against progressive collapse below q_e (e.g., q_1 in Figure 4) will cause society to forego potential net benefits, whereas any level above this point (e.g., q_2 in Figure 4) will cause real net benefits to be foregone. These benefits foregone (potential and real) are illustrated in Figure 4 by the shaded areas between the MB and MC functions.

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[1] An example of a variable level technique would be reducing the probability and perhaps the velocity of vehicular impact by ringing the building with different numbers of bumper guards.

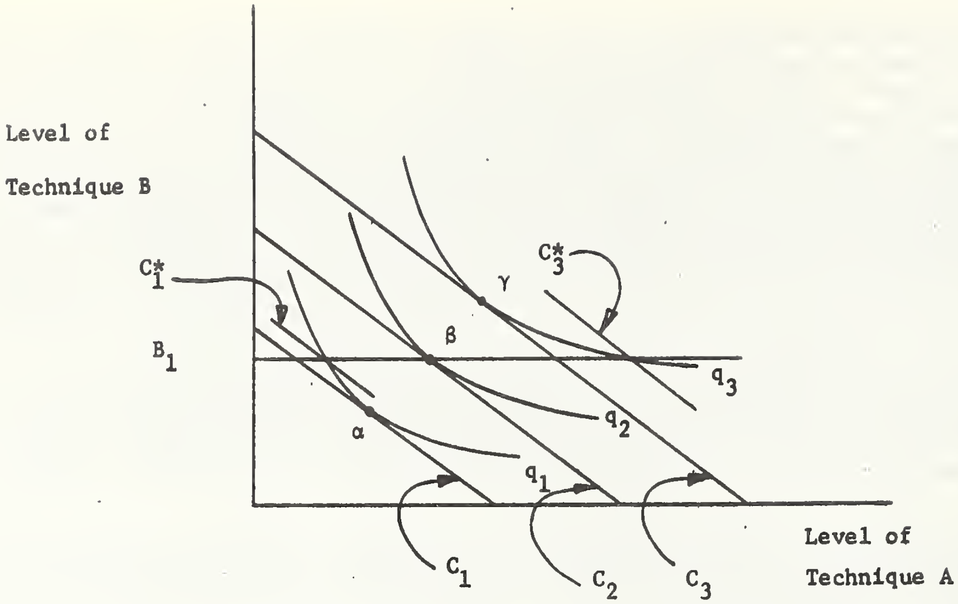

Figure 1. EQUAL-COST LINES AND EQUAL PROTECTION CURVES

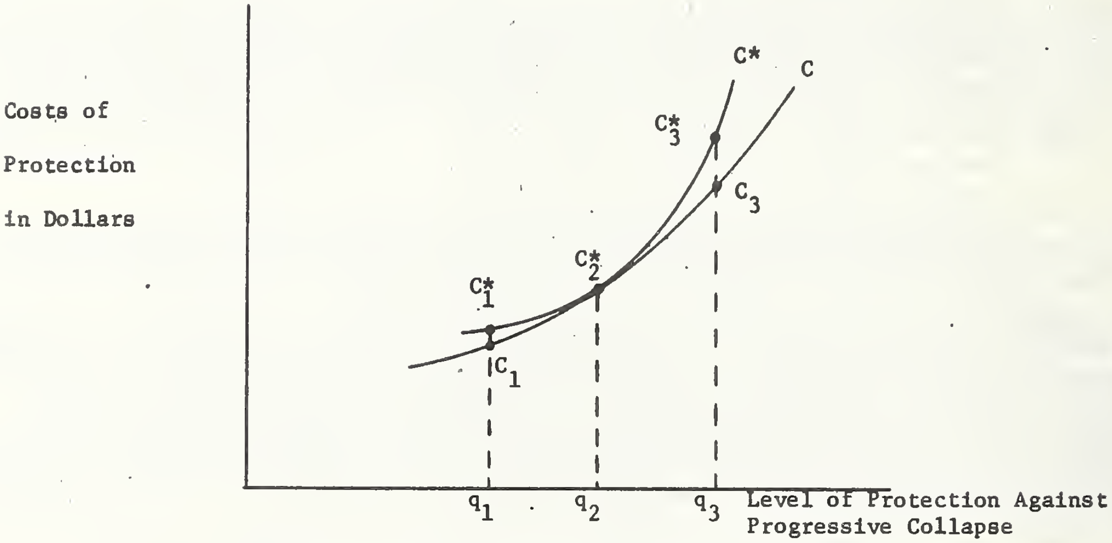

Figure 2. COSTS OF PROTECTION AGAINST PROGRESSIVE COLLAPSE VERSUS THE LEVEL OF PROTECTION

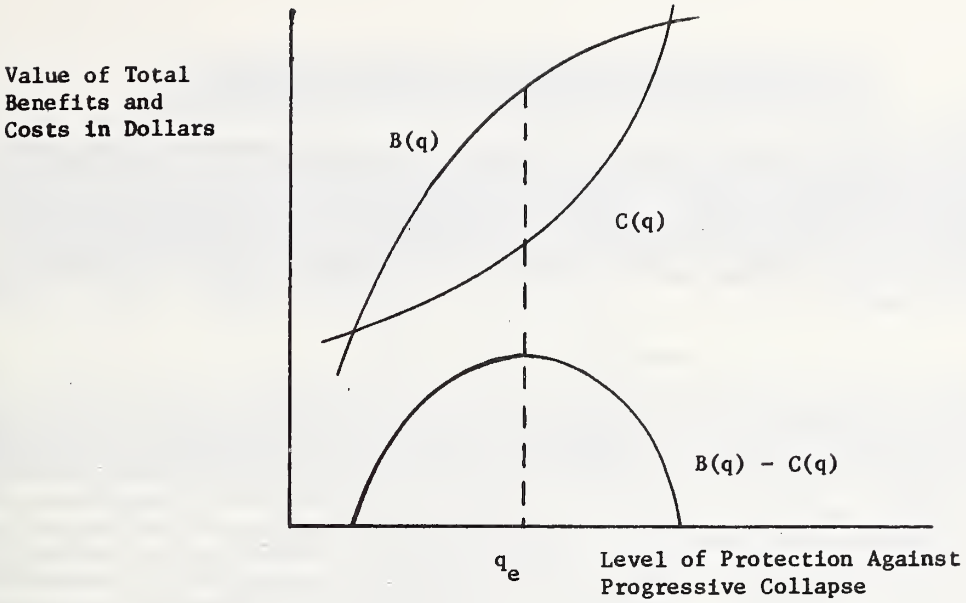

Figure 3. VALUE OF TOTAL BENEFITS AND COSTS IN DOLLARS VERSUS THE LEVEL OF PROTECTION AGAINST PROGRESSIVE COLLAPSE

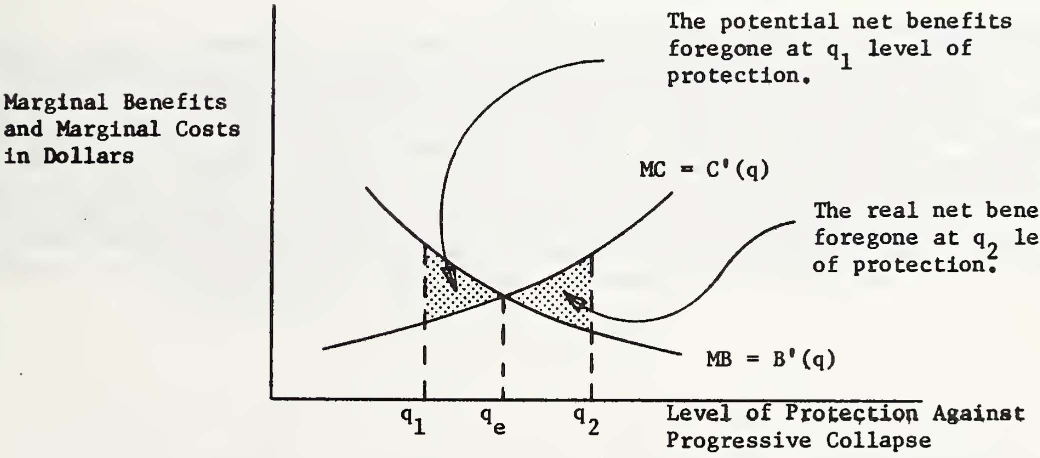

Figure 4. MARGINAL BENEFITS AND MARGINAL COSTS IN DOLLARS VERSUS THE LEVEL OF PROTECTION AGAINST PROGRESSIVE COLLAPSE

2.2 A Model for Determining the Efficiency Impact of Progressive Collapse Standards on a Single Building[1]

The benefits which accrue from the incorporation of a progressive collapse standard in the design of a building include the value of injuries, including injuries resulting in death, and property damages averted. Annual magnitudes are used in the model in order to obtain comparability among benefit components. The marginal annual benefits (MAB) are defined as the sum of the marginal annual building damage averted (MAD^b), the marginal annual personal property damage averted (MAD^p), and the marginal annual value of injuries averted (MAV). That is,

$$MAB = MAD^b + MAD^p + MAV. \qquad (2.1)$$

The costs of protection against progressive collapse depend, of course, on the methods used to reduce the probability of a progressive collapse. The probability of a building undergoing progressive collapse is a function of its probability of undergoing a condition of abnormal loading.[2] Hence, one method of reducing the probability of progressive collapse is to treat the problem of abnormal loading. This may be accomplished by studying a building's systems and their attributes, establishing which systems could potentially cause a condition of abnormal loading to occur, and by reducing the probability of abnormal loading through codes or standards.[3] A second method of reducing the probability of progressive collapse, and the one used in this study, is to assume that the abnormal loading condition cannot be prevented from occuring, but that its effects can be limited to some acceptable level should it occur. This method approaches progressive collapse alternatives by modification of the structures system enabling this system to resist a specified abnormal loading condition. A third method combines the two previous approaches.

The costs which are incurred as a result of the incorporation of a progressive collapse standard in the design of a building are also expressed in annual magnitudes for the purpose of comparability. The marginal annual benefits will exceed the marginal annual costs (MAC) if the standard is efficient. That is,

$$MAB > MAC \qquad (2.2)$$

indicates that the standard increases efficiency.

The consideration of more levels of protection and smaller intervals between levels increases the likelihood of finding the most efficient level (i.e., the most efficient standard). Smaller intervals between the levels of protection considered will reduce the potential for misallocating resources arising from accepting a standard which is excessively stringent or not stringent enough. For the purposes of developing the model, however, it is sufficient to compare two levels of protection. To actually compare more than two levels simply requires applying the model to each successive pair. That is, each level of protection should be compared with the next higher level using the benefit-cost model. In this way, the levels considered can be ranked according to their efficiency as the most efficient level is approached (i.e., there is transitivity in efficiency).

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[1] Although the model relates specifically to progressive collapse standards, it may be applied to other types of building safety standards.

[2] Ferahian, R. H., Design Against Progressive Collapse, p. 9. A condition of abnormal loading is one which would no be considered in the normal analysis and design of a particular structure. Somes, N. F., "Abnormal Loading on Buildings and Progressive Collapse," p. 431.

[3] For example, gas supply pipes in France must be enclosed in a ventilated duct space. Ferahian, R. H., Design Against Progressive Collapse, p. 17.

2.2.1 Marginal Costs of a Progressive Collapse Standard

The marginal cost of incorporating a given standard for protection against progressive collapse (MC) is defined as the difference between the capital costs plus operation and maintenance costs with the standard incorporated ($K_2 + OM_2$) and the capital costs plus operation and maintenance costs of a building with identical attributes but without the standard for protection against progressive collapse ($K_1 + OM_1$). That is, MC is defined as follows:

$$MC = (K_2 + OM_2) - (K_1 + OM_1). \qquad (2.3)$$

Marginal annual costs of implementing the standard (MAC) are equal to the product of the marginal costs and the capital recovery factor. The capital recovery factor is the level periodic payment which will pay interest and full amortization on an investment of one dollar.

$$MAC = MC \, \frac{r(1 + r)^L}{(1 + r)^L - 1} \qquad (2.4)$$

where r = annual discount rate expressed as a decimal, and L = building life in years.

2.2.2 Marginal Benefits of a Progressive Collapse Standard

In this section the components of marginal annual benefits shown in equation 2.1 are derived. First, it is necessary to develop a statement of the annual probability of a unit being affected by progressive collapse (U_k). This probability is the ratio of the product of the expected annual number of collapses (z) and the expected number of housing units affected per collapse (H_k) to the number of housing units susceptible to progressive collapse (Z), or

$$U_k = \frac{z \cdot H_k}{Z} \tag{2.5}$$

for k equal to 1 or 2 and where k = 1 refers to a design without the incorporation of a standard and k = 2 refers to a design with the incorporation of a standard.

The marginal annual property damages averted are found by first determining the annual property damages with and without the standard incorporated. The annual building damage (AD_k^b) is given as follows:

$$AD_k^b = U_k \cdot D_k^b \cdot N \tag{2.6}$$

for k equal to 1 or 2 and where D_k^b = the value of the building per housing unit including demolition and removal with design k.

The marginal annual building damage averted (MAD^b) (i.e., the building damage averted by incorporating the standard) is given by

$$MAD^b = AD_1^b - AD_2^b \quad . \tag{2.7}$$

Similarly, the annual personal property damage (AD_k^p) is as follows:

$$AD_k^p = U_k \cdot D_k^p \cdot N \tag{2.8}$$

for k equal to 1 or 2 and where D_k^p = the value of personal property damaged and destroyed in a unit affected by progressive collapse.

Thus, the marginal annual personal property damage averted (MAD^p) (i.e., the personal property damage averted by incorporating the standard) is given by

$$MAD^p = AD_1^p - AD_2^p \quad . \tag{2.9}$$

In order to determine the marginal annual value (MAV) of all injuries averted by the incorporation of a standard, the annual number of injuries averted of various types must be estimated. The expected number of injuries of type j per housing unit (i_j), given the unit experiences progressive collapse, is expressed by the following equation:

$$i_j = P_j \cdot F \cdot R \tag{2.10}$$

where P_j = the probability an occupant suffers a j type injury in a progressive collapse.

F = the probability that a resident is an occupant. This is called the occupancy factor. It is the ratio of the total person occupancy of the building in hours per year to the product of the number of hours in a year and the person capacity of the building in normal use.

R = the average number of residents per unit.

The expected annual number of injuries of type j with design k due to progressive collapse is given as follows:

$$AI_{jk} = U_k \cdot i_j \cdot N \qquad (2.11)$$

for k equal to 1 or 2 and where N = the number of housing units in a building. The marginal expected annual number of injuries averted of type j is

$$MAI_j = AI_{j1} - AI_{j2} \quad . \qquad (2.12)$$

Therefore the marginal annual value of injuries averted of type j is

$$MAv_j = MAI_j \cdot v_j \qquad (2.13)$$

where v_j = the social value of averting an injury of type j. The marginal annual value of all injuries averted (MAV) is as follows:

$$MAV = \sum_{j=1}^{n} MAv_j \quad . \qquad (2.14)$$

By expanding equation 2.1, the marginal annual benefits of incorporating a standard to provide additional protection against progressive collapse can be expressed as follows:

$$MAB = \frac{Nz}{Z} \left[H_1 (D_1^p + D_1^b) - H_2(D_2^p + D_2^b) + (H_1 - H_2) \sum_{j=1}^{n} i_j v_j \right] .$$

2.2.3 Sensitivity Analysis

Sensitivity diagrams (see Figure 5) provide the public decision maker with a guide to aid in the evaluation of standards intended to protect against progressive collapse. In Figure 5, a linear function called an indifference line establishes a rule for deciding whether efficiency would be improved by building with the progressive collapse standard under consideration.

The concept of a composite injury must be introduced in order to deal with more than one type of injury and limit the sensitivity diagram to two dimensions. A composite injury consists of one of each type of injury the investigator includes. The value of averting a composite injury (V) is the sum of the values of averting each type of injury which makes up

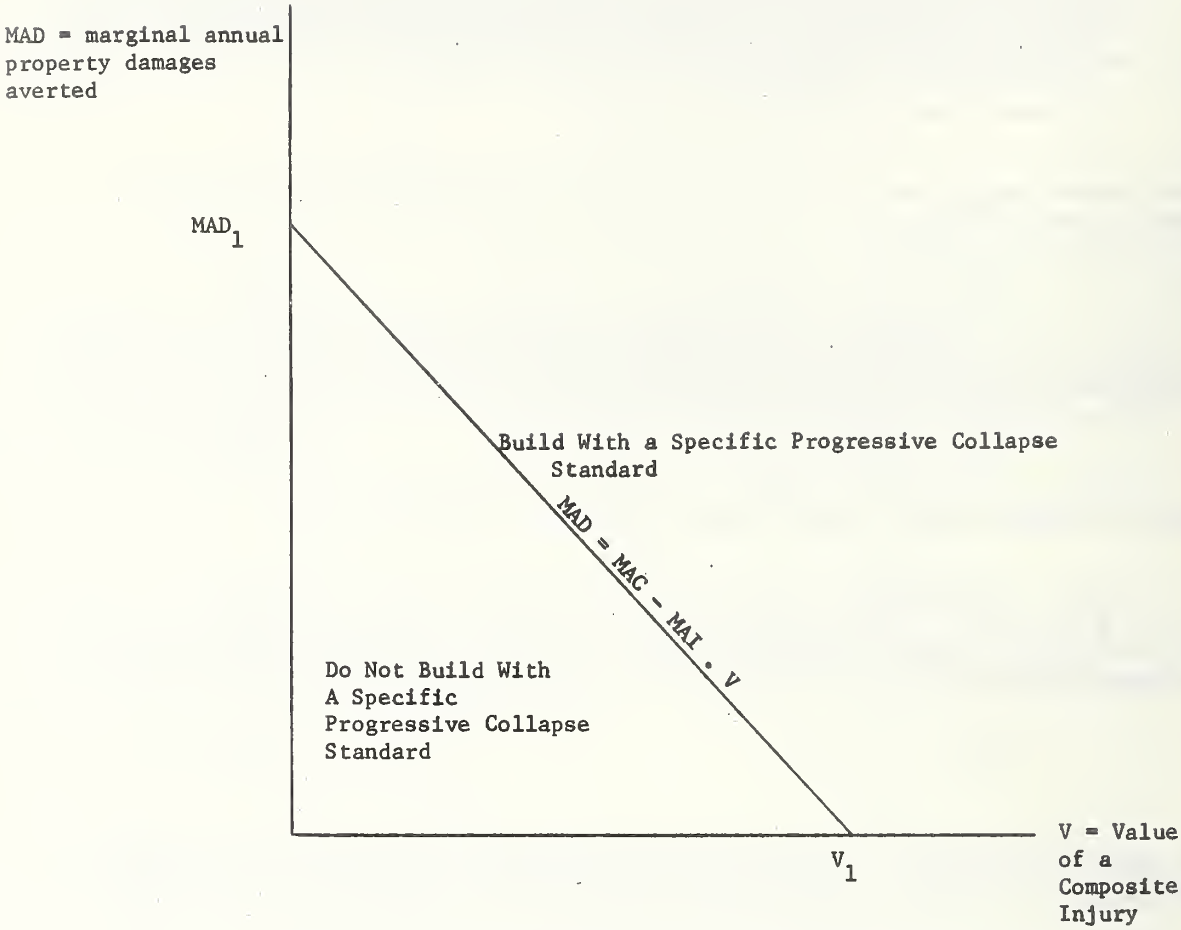

Figure 5. A SENSITIVITY DIAGRAM: ANNUAL PROPERTY DAMAGE AVERTED (MAD) VERSUS VALUE OF AVERTING A COMPOSITE INJURY (V)

the composite. In determining the number of composite injuries, the number of each injury type is weighted by its relative value.[1]

The two axes of Figure 5 measure the value of averting a composite injury[1] (V) and the annual marginal property damage averted (i.e., $MAD = MAD^b + MAD^p$) by incorporating the progressive collapse standard. The indifference line shows tradeoffs between marginal property damage averted and the values of a composite injury averted to which a public decision maker would be indifferent (i.e., all points on the indifference line are equally desirable).

The MAD intercept of the indifference line (MAD_1) equals the annual marginal cost (MAC) of incorporating the standard being evaluated. This means that, if the marginal annual property damage averted just equals the annual marginal cost of averting the extra damage, the most efficient level of protection would be identified (assuming $V = 0$). The V intercept of the indifference line (V_1) equals the ratio of the annual marginal cost of incorporating the standard (MAC) to the marginal number of composite injuries (MAI). This ratio can also be interpreted as the cost per unit of averting a composite injury. Assuming no extra damage is averted, the most efficient level of protection would be identified if the value of averting a composite injury just equals the cost of averting an additional composite injury.

Along the indifference line, MAD_1V_1, marginal social benefits equal marginal social costs. That is, the indifference line yields all the combinations of MAD and V at which the level of protection called for in the standard being evaluated would be the most efficient one. The equation of the indifference line in Figure 4 is as follows:

$$MAD = MAC - MAI \cdot V.$$

Any combination of property damages averted and value of a composite injury averted which falls above the indifference line indicates that marginal social benefits exceed marginal social costs and that the standard being evaluated falls short of requiring the most efficient level of protection. Similarly, a combination which falls below the indifference line indicates that marginal social costs exceed marginal social benefits and the standard being evaluated exceeds the most efficient level of protection.

Thus Figure 5 can be used to make a decision as to whether a standard increases or decreases efficiency for the building being considered. Suppose a particular progressive collapse standard produces a certain reduction in damage, MAD*. Given MAD* and society's determination of the value of a composite injury, V*, a point in Figure 5 is determined. If that point is be low the indifference line, the correct decision based on efficiency considerations would be not to incorporate the standard. If the point is above the indifference line, the correct decision would then be to build with the standard. If the point falls on the indifference line, the most efficient level of protection and the most efficient standard would be identified.

As its name implies, a sensitivity diagram may be used to determine the extent to which a result regarding the efficiency of a change in the level of protection is sensitive to changes in cost and benefit components. It may be especially interesting to see whether a change in the value of a composite injury would affect the outcome. Of course, it is possible to examine the sensitivity of the results to change in any other aspect of the evaluation (e.g., estimates of the extent or value of damage or injury averted and estimates of the cost of averting damages and injuries) with the use of a sensitivity diagram.

2.3 A Methodology for Comprehensively Evaluating the Efficiency of Progressive Collapse Standards

A comprehensive evaluation of the efficiency of a mandatory progressive collapse standard must go well beyond its effects on a single building. If one standard is to be applied to all buildings within certain categories, the standards would be expected to have diverse

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[1] For a more precise discussion of the composite injury or concept and the indifference curve, see the Appendix.

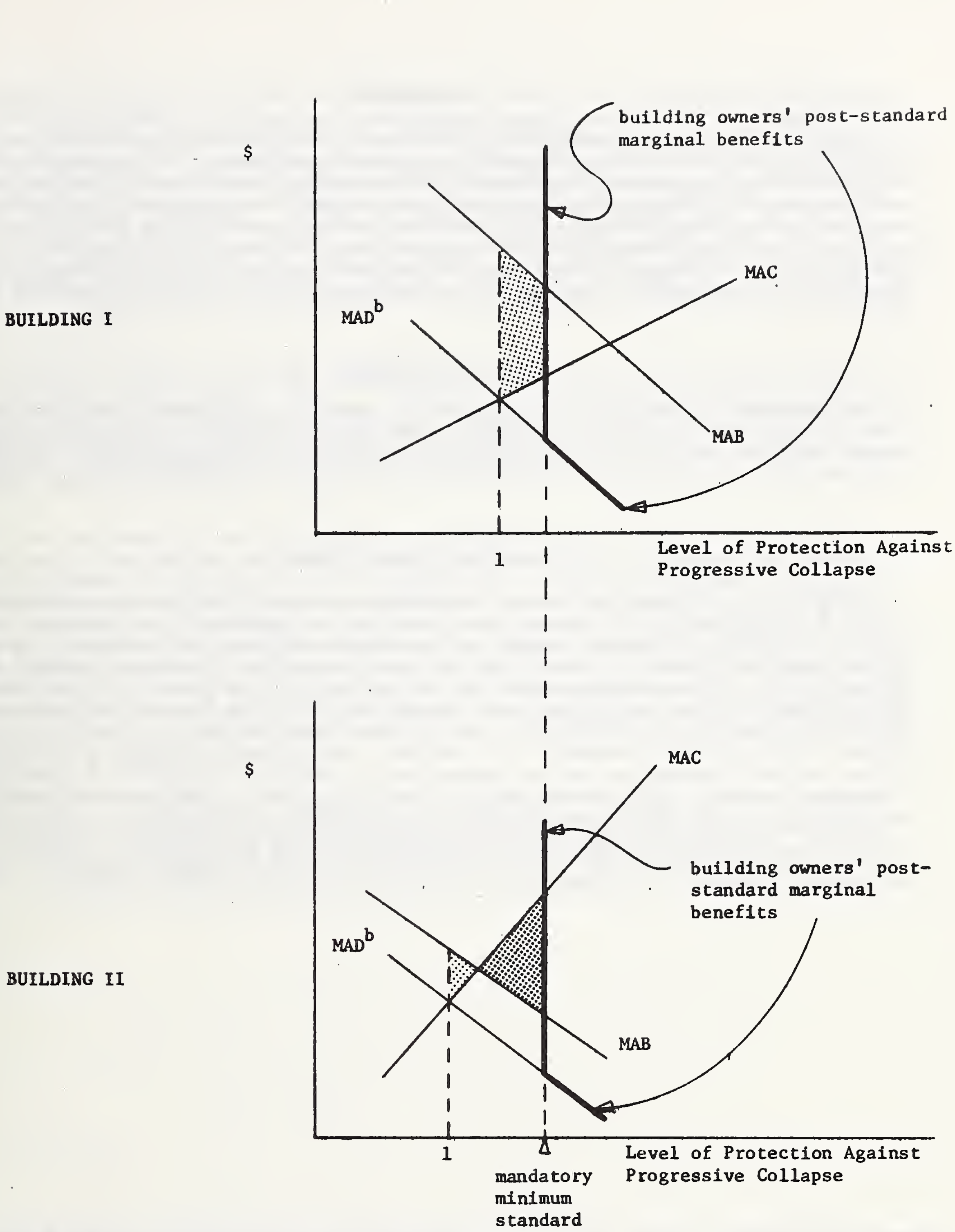
efficiency effects. A more efficient standard may result in less efficient levels of protection for some buildings while producing more than offsetting increases in efficiency for other buildings. Thus, the whole range of effects must be considered when evaluating a progressive collapse standard.

Figure 6 illustrates that a progressive collapse standard will have diverse efficiency effects by showing two of the many possible effects. In Figure 6, it is assumed that the building owner will not be held liable for any personal property damage or human injury caused by a progressive collapse. Therefore, the pre-standard level of protection (i.e., the level which will maximize the building owner's net benefits) will be found where the marginal annual building damage averted (MAD^b) equals the marginal annual cost of providing protection (MAC). The post-standard marginal benefits which accrue to the building owner are indicated by the kinked, dark line which is vertical at the standard level of protection (i.e., assuming that the standard is perfectly enforced) and follows the marginal building damage averted at higher than standard levels. One could think of this as being the owner's post-standard demand for protection. The standard level of protection will maximize the owners' net benefits for Buildings I and II. This is because the marginal costs and the post-standard marginal benefits which accrue to the owner are equal at the standard level of protection. Therefore, the standard level will be provided in both buildings in Figure 6.

For Building I, the standard level of protection is below the most efficient level (i.e., where MAB = MAC) while the standard exceeds the most efficient level of protection for Building II. The lightly shaded area in the part of Figure 6 devoted to analyzing Building I indicates the net social benefits of implementing the standard in Building I. The difference between the lightly shaded and darkly shaded areas for Building II indicates the net social benefits for that building. Whether the standard results in an increase in efficiency is determined by whether the sum of the net social benefits for all affected buildings is positive after deducing the administrative costs of the standard. The most efficient standard would be the one which maximizes this sum of net social benefits after administration expenses.

An investigation into whether a specific progressive collapse standard increases efficiency should divide the buildings affected into groups. A representative building or representative buildings should be selected from each group. The net social benefits for each representative building (or the average net social benefits where more than one building was selected from a group) should be weighted by the size of the group.

Finally, the sum of the weighted net social benefits across all building groups should be determined. If this sum is greater than the administrative costs of the standard, the standard can be said to increase efficiency. A sensitivity diagram similar to Figure 5 may be constructed to assess how sensitive the aggregate effects of a standard are to changes in the estimate of various cost and benefit components.



1 indicates the pre-standard level of protection.

Figure 6. DIVERSE EFFICIENCY EFFECTS OF A STANDARD

3. A CASE STUDY

This hypothetical case study is a partial evaluation of the impact of incorporating draft HUD progressive collapse standards[1] in a specific building. This evaluation does not indicate whether the standard is efficient in this particular application, because only the benefits, and not the costs, of incorporating the standard are estimated. Furthermore, the case study is not comprehensive in that the impact of incorporating the standard in a single building is evaluated rather than evaluating the impact across all buildings which might be affected by such a standard. Therefore, the case study is but a modest beginning toward quantifying the magnitudes called for in the benefit-cost model which was developed in Chapter 2.

3.1 The Building

An apartment building of a type deemed susceptible to progressive collapse by HUD's draft standards was considered. This building is approximately 200 feet long (61 meters), 54 feet wide (16.5 meters), 12 stories high, and contains 141 dwelling units. The structural system is concrete masonry bearing walls with pre-cast reinforced concrete flooring.

3.2 Averting Property Damage

Progressive collapse is a function of abnormal loading. Therefore, a meaningful estimate of the probability of progressive collapse can be computed if the parameter specifying the probability of abnormal loading is known with some degree of certainty. To date, studies have concentrated on establishing relative frequencies of abnormal loading, emphasizing the role of gas explosion and motor vehicle impact as its cause.[2] A theoretical estimate based on these studies has been computed for the United States.[3] Unfortunately, due to the sparseness of available data, only a lower bound estimate for the frequency of abnormal loading could be obtained. This estimate asserts that a probability of 1.037×10^{-5} of abnormal loading per year per housing unit is the lower bound for the probability of abnormal loading. (This corresponds to an annual frequency of 702 abnormal loadings.) Throughout this study, this figure is used as the probability of abnormal loading. Since 1.037×10^{-5} represents a lower bound estimate of the annual probability of abnormal loading, it is assumed that the expected benefits from adopting design changes for protection against progressive collapse will be biased downward from their true value.

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[1] U. S. Department of Housing and Urban Development, "Structural Design Guidelines to Increase Resistance of Buildings to Progressive Collapse," May 1973, unpublished.

[2] See Somes, N. F., "Abnormal Loading on Buildings and Progressive Collapse," p. 458; and Fribush, S. L., Bowser, D., Chapman, R., "Estimates of Vehicular Collisions with Multistory Residential Buildings," NBS, TAD, NBSIR 73-175, p. 18.

[3] Somes, N. F., "Abnormal Loadings on Buildings and Progressive Collapse," p. 458.

The quantification of benefits is dependent, in part, upon calculations showing the extent of the building's collapse with some bearing member removed, first without the standard incorporated, and then with it incorporated. In some cases, the theoretical calculations for the extent of the collapse are simplified by the requirements of the design. For example, the HUD draft standard specifies the maximum allowable collapse for a given condition of abnormal loading as: "structural failure will not comprise more than three stories vertically nor more than 1,000 square feet or 20% of the horizontal area (whichever is less) of each story affected."[1] Once the extent of collapse has been established, it is then possible to calculate the expected annual value of the building and personal property damage suffered by each of the two structures and the marginal damages averted by incorporating the standard.

The expected extent of collapse is obtained by calculating the sum of the products of the probability that a bearing wall is removed on any particular floor times the number of units affected by this removal. That is, for any random bearing wall removed, what is the expected extent of the collapse? For the sake of simplicity, it is assumed that the probability of the removal of a bearing wall in any story is the same as the removal of a bearing wall in any other story.

In the structure without the progressive collapse standards incorporated, it is assumed that if any bearing wall except in the first story or the top story is removed,[2] all floors beneath would collapse. The arching effect of the walls in the first story would enable it to resist collapse; whereas the top floor could sustain the dead load impact of the roof, thus preventing any extensive collapse. For any story other than the top or bottom, the increased load generated by the impact of the falling debris on the precast reinforced concrete floor panels would cause them to shear away from the masonry bearing wall. Once this chain reaction has begun, the collapse would continue to the level of the basement. Due to the nature of the layout of the bearing walls in this building, collapse would be limited to one 12-story apartment stack, each of which contains two housing units sharing a common bearing wall.

The number of housing units susceptible to progressive collapse[3] (Z), the expected annual number of collapses[4] (z), and the expected number of housing units affected given that a collapse occurs (H_1 and H_2) are required for the computation of annual property damage. These magnitudes are given as follows:

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[1] U. S. Department of Housing and Urban Development, "Structural Design Guidelines to Increase Resistance of Buildings to Progressive Collapse," p. 2.

[2] A removal of 65% of the bearing wall under consideration is assumed.

[3] Fribush, S., Bowser, D., Chapman, R., Estimates of Vehicular Collisions with Multistory Buildings, p. 60.

[4] One abnormal loading condition in five is assumed to be of sufficient violence and location to remove a bearing wall in a building deemed susceptible to progressive collapse.

$Z = 6.77 \times 10^6$,

$z = 14.04$,

$H_1 = 12.08$, and

$H_2 = 2.00$.

Using these figures the expected annual probabilities of a housing unit being affected by progressive collapse, U_1 and U_2, are

$U_1 = 2.505 \times 10^{-5}$ and

$U_2 = 0.415 \times 10^{-5}$.

Annual building damage is the following:

$AD_1^b = U_1 \cdot D_1^b \cdot N = \$48.152$, and

$AD_2^b = U_2 \cdot D_1^b \cdot N = \$7.966$,

where both D_1^b and D_2^b are assumed to be $13,622, the cost per housing unit inclusive of demolition and removal costs. The resulting marginal annual building damage averted (MAD^b) is $40.19.

Assuming that there is an average of $4,000 in personal property per housing unit and that 75% of that would be destroyed if a unit were affected by progressive collapse, D_1^b and D_2^b equal $3,000. Thus, annual personal property damage (AD_k) equals $10.60 for the building without the standard and $1.75 for the building with the standard. The marginal annual personal property damage averted (MAD^p) is $8.85.

3.3 Averting Human Injury

In Chapter 2, the model was generalized to include n types of injuries. For the purpose of the case study, injuries are divided into three types: deaths, serious injuries, and minor injuries. The probability distribution for the effect that a collapse is assumed to be as follows:[1]

the probability of death given a collapse = .25,

the probability of a serious injury given a collapse = .25,[2]

the probability of a minor injury given a collapse = .30, and

the probability of no injury given a collapse = .20.

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[1] [illegible] which would, in part, support this assumed probability distribution are [illegible] Blume, J. A., "Civil Structures and Earthquake Safety," p. 113.

[2] A serious injury results in partial or total disability.

Assuming that the probability a resident is an occupant (F) is .62 and that the average number of residents per housing unit (R) is 3.19, it is now possible to compute the marginal number of deaths, serious injuries, and minor injuries averted by incorporating the progressive collapse standard.[1] For each housing unit affected by a collapse, it is expected that there will be .494 deaths, .494 serious injuries, and .593 minor injuries. For each collapse, the expected number of deaths, serious injuries, and minor injuries is 5.968, 5.968, and 7.164, respectively, without the standard and 0.988, 0.988, and 1.186, respectively with the standard. Annually, 1.745 x 10^{-3} fatalities and the same number of serious injuries are expected without the standard, while 0.289 x 10^{-3} injuries of each of these types are expected with the standard. Minor injuries are expected to number 0.289 x 10^{-3} annually without the standard and 0.347 x 10^{-3} with the standard. Thus, there is the expectation that 1.456 x 10^{-3} fatalities, 1.456 x 10 serious injuries, and 1.784 x 10^{-3} minor injuries are averted annually by incorporating the standard. In order to translate these annual marginal numbers of injuries into annual benefits of incorporating the standard, it is necessary to determine the values of averting a fatality, a serious injury, and a minor injury.

To determine the value of averting an injury, economists most frequently estimate the amount by which the income earned by the injured individual would be reduced as a result of the injury. This amount is projected into the future and then discounted to obtain a present value. Finally, expenses arising from the injury are added to the present value of reduced income. Although this procedure is used in this case study, it can more easily be justified on the basis of computational ease than conceptual correctness.[2]

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[1] Blume, J. A., "Civil Structures and Earthquake Safety," p. 112.

[2] Mishan, E. J., "Evaluation of Life and Limb: A Theoretical Approach," in <u>Benefit Cost Analysis</u> 1971.

Assuming that income would grow at the rate of inflation, the value of averting a fatality (v_1) is as follows:

$$v_1 = \sum_{t=1}^{T} \frac{Y(1+\theta)^t}{(1+r)^t} + E_e + E_m$$

where Y = annual per capita income,

T = average number of years remaining in the individual's life,

r = nominal rate of time preference or discount rate,

θ = expected annual rate of inflation,

E_e = expense of training another individual to take the place of the deceased,[1] and

E_m = the premature mortuary expenses.[2]

These magnitudes are assumed to be as follows:

Y = \$6,000,[3]

T = 43 years,[4]

r = .10,[5]

θ = .03,[5]

E_e = \$2,000,[5] and

E_m = \$1,500.[5]

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[1] Starr, C. "Benefit Cost Studies in Sociotechnical Systems," Perspectives on Benefit-Risk Decision Making".

[2] Mishan, E. J., Cost-Benefit Analysis, An Introduction, p. 154.

[3] U. S. Department of Commerce, Statistical Abstracts of the United States, 1972, p. 125.

[4] Ibid, p. 38.

[5] Assumed magnitudes.

Thus, the value of averting a fatality is \$86,246. The annual value of fatalities averted by incorporating the progressive collapse standard is \$125.57.

In determining the value of averting a serious injury, it is assumed that future income will be reduced by 20% with an average hospitalization period of 45 days during which time all wages are foregone. The value of averting a serious injury is computed as follows:[1]

$$v_2 = .2 \sum_{t=1}^{T} \frac{Y(1+\theta)^t}{(1+r)^t} + 45 \left(h + \frac{Y}{365}\right)$$

where h = long-term daily hospital expenses. Assuming that h = \$36.17,[2] the value of averting a serious injury, is \$19,616. The annual value of serious injuries averted by incorporating the standard is \$28.56.

Minor injuries are assumed to average 10 days of hospitalization plus 5 additional days of recuperation during which all wages are goregone. Thus, the value of averting a minor injury is computed as follows:

$$v_3 = 10S + 15 \left(\frac{Y}{365}\right)$$

where S = short-term daily hospital expenses. Assuming that S = \$81.01,[3] the value of averting a minor injury is \$1,056. The annual value of minor injuries averted by incorporating the standard is \$1.85.

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[1] All costs falling within the first year are assumed to be instantaneous (i.e., they are not discounted).

[2] Statistical Abstracts, p. 74.

[3] Statistical Abstracts, p. 74.

3.4 Analysis of Results

Table 1 summarizes the results. The marginal annual benefits of incorporating the standard in a specific building were found to be \$204. If the marginal annual costs of meeting the standard are less than this amount, the standard is efficient for the building under consideration. This corresponds to a capital cost differential of \$2433.[1] That is, if the standard could be met for an addition to first cost of .12% or less,[2] the standard level of protection would be efficient. However, the efficiency of the standard level of protection for a specific building is not necessarily indicative of the efficiency of applying the single standard to diverse building types. Thus, estimates are needed of both the benefits and the costs of incorporating the standard in various types of buildings in order to determine the efficiency of HUD's draft progressive collapse standard or any other such standard.

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[1] This capital cost differential assumes a building life of 40 years and a building owner's real discount rate of 8%.

Since the design changes required to satisfy the draft HUD standards are all associated with the building's structural system, and since the operation and maintenance costs of the structural system are small, it is assumed that the annual marginal operation and maintenance costs would be negligible and are therefore not necessary for the economic evaluation of the draft HUD standards in this case.

[2] A computer estimate of the cost of the existing building without the incorporation of the standard was made. This estimate is \$2,008,655.

TABLE 1

CASE STUDY BENEFITS

ITEM	ANNUAL AMOUNT FOR BUILDING I	ANNUAL AMOUNT FOR BUILDING II	ANNUAL MARGINAL AMOUNT
Personal Property Damages**	\$11	\$2	\$9
Building Damages**	\$48	\$8	\$40
Fatalities	1.745×10^{-3}	0.289×10^{-3}	1.456×10^{-3}
Serious Injuries	1.745×10^{-3}	0.289×10^{-3}	1.456×10^{-3}
Minor Injuries	2.095×10^{-3}	0.347×10^{-3}	1.748×10^{-3}
Value of Fatalities Averted** (\$86,246)*	\$150	\$25	\$125
Value of Serious Injuries Averted** (19,616)*	\$34	\$6	\$28
Value of Minor Injuries Averted** (\$1,057)*	\$2	\$0	\$2
Sum of Benefits	\$245	\$4	\$204

*The value per composite injury is \$106,919, and the weighting factors are $W_1 = 0.807$, $W_2 = 0.183$, and $W_3 = 0.010$. (See Appendix B).

**Rounded to the nearest dollar.

4. SUMMARY AND RECOMMENDATIONS FOR FURTHER RESEARCH

4.1 Summary

In the United States there has not been an incident of progressive collapse approaching the magnitude of England's Ronan Point disaster; however, the potential exists. Interest in standards intended to provide protection against progressive collapse will grow as the number of buildings susceptible to progressive collapse grows. A method for determining the efficiency of standards is needed to ensure that the standards which are developed will increase the efficiency of resource allocation.

This study develops an economic model for the evaluation of levels of protection against progressive collapse. The model provides a framework for determining the annual social benefits and costs of a change in the level of protection. An increase in efficiency is indicated if the social benefits of increased protection exceed the social costs of the increased protection. The social benefits which accrue from additional protection include the value of injuries and property damage averted. The social costs of additional protection depend on the methods used to reduce the probability of a progressive collapse. The consideration of more levels of protection and smaller intervals between levels increases the liklihood of finding the most efficient level (i.e., the most efficient standard).

Sensitivity diagrams are discussed as a guide for the public decision maker to aid in the evaluation of standards intended to protect against progressive collapse. The concept of a composite injury is introduced in order to improve sensitivity diagrams. As its name implies, a sensitivity diagram amy be used to determine the extent to which a result regarding the efficiency of a change in the level of protection is sensitive to changes in the estimates of cost and benefit components.

A comprehensive evaluation of the efficiency of a mandatory progressive collapse standard is shown to require going well beyond the effects of the standard on a single building. If one standard is to be applied to all buildings within certain categories, the standard would be expected to have diverse efficiency effects. A more efficient standard may result in less efficient levels of protection for some buildings while producing more than offsetting increases in efficiency for other buildings. Thus, the whole range of effects must be considered when evaluating a progressive collapse standard.

A case study is presented which partially evaluates the potential impact of draft HUD progressive collapse standards. First, the evaluation is limited by only considering the impact on a single building. Second, the case study does not indicate whether the incorporation of the standard in the specific building considered would increase efficiency. This is because only the benefits, and not the costs, of incorporating the standard are estimated. However, the case study may be considered a first step toward quantifying the magnitudes called for in the benefit-cost model.

4.2 Recommendations for Further Research

In order to further refine the economic model developed in this study, to determine the optimal level of protection against progressive collapse, and to gain a fuller knowledge of the danger which progressive collapse imposes on society, further research on several additional topics would be useful.

Previous studies have determined which building types were potentially the most susceptible to progressive collapse. But at present only crude estimates are available for the number of these units in use and their future growth pattern. It would be helpful if better estimates were available.

To determine the probability of a building undergoing collapse, the frequency of abnormal loading is an issue of utmost importance. A lower bound estimate, as used in this study, biases expected benefits below the true annual average. This bias could cause the rejection of a standard which is efficient. Along this line, an attempt could be made to determine whether or not the frequency of abnormal loading is dependent on the susceptibility of a structure to progressive collapse.

More consideration might be given to alternative techniques for providing protection against progressive collapse. More innovative techniques of treating progressive collapse may be available than those set forth in previous studies in this country and Europe. For example, standards may be considered which would reduce the probability of abnormal loading. It may be useful to investigate policy alternatives stressing concepts which are more economic than engineering in viewpoint, such as increasing private liability, thus bringing the most efficient level of progressive collapse prevention from a private viewpoint closer to the most efficient level from a social viewpoint. Economic models of the kind developed in this study offer a way to evaluate such innovative techniques. Further research should also be conducted on the probability of death and injury given a collapse, as the quantification of these figures is of primary concern in a benefit-cost study involving problems in disaster mitigation. In addition, methods of valuing deaths and injuries may be developed which have more conceptual validity.

To determine whether the level of protection called for in a specific progressive collapse standard increases efficiency, a number of case studies must be completed. The costs as well as the benefits of incorporating the standard must be estimated for a variety of building types. To determine the most efficient level of protection (i.e., the one which maximizes net social benefits) the case studies must be repeated for each of several levels of protection.

A decision rule based on efficiency, as determined by benefit-cost analysis, is not the only criterion for public decision making, and others ought to be considered. Distributive justice is another criterion. This means that a policy on building safety which is justified by benefit-cost analysis may be rejected because its effects on the distribution of income are considered to be unjust. For example, we must consider the possibility that policies to make buildings safer will redistribute income away from the poor. If the standard which increases protection also increases costs, the poor may be driven out of the market for the buildings covered by the policy. This could result in the poor consuming less safety at higher prices. It is not the economist's role to judge this redistribution as being just or unjust; economists can, however, describe such distributional possibilities so that they may be judged in the political arena.

APPENDIX

The Indifference Line and the Composite Injury concept

The slope of the indifference line in Figure 5 (i.e., the negative marginal annual composite injuries averted) is equal to the weighted sum of the marginal annual injuries of all types. The weight for each injury type (w_j) is its relative price.[1] The weights are defined as follows:

$$w_j = \frac{v_j}{\sum_{j=1}^{n} v_j} .$$

The marginal number of composite injuries (MAI) is then given as

$$MAI = \sum_{j=1}^{n} \frac{v_j}{\sum_{j=1}^{n} v_j} \cdot MAI_j = \frac{\sum_{j=1}^{n} v_j \cdot MAI_j}{\sum_{j=1}^{n} v_j} .$$

The V intercept may now be defined as follows:

$$V_1 = \frac{MAC \cdot \sum_{j=1}^{n} v_j}{\sum_{j=1}^{n} v_j \cdot MAI_j} .$$

Now the indifference line may be defined in more detail as

$$MAD = MAC - \left[\frac{\sum_{j=1}^{n} v_j \cdot MAI_j}{\sum_{j=1}^{n} v_j} \right] V.$$

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[1] Thus, it is implicitly assumed that the relative prices for the threee injury categories are constant, although the price of a composite injury is a variable.

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Public and government concern about the progressive collapse of buildings caused by abnormal loading has resulted in the development of draft standards to provide protection against progressive collapse. From society's viewpoint, standards for protection against progressive collapse should result in a level of protection which is more efficient (i.e., the net social benefits from protection should be increased). An economic model utilizing the principles of benefit-cost analysis is developed which establishes a methodology for determining the efficiency of various levels of protection against progressive collapse. An application of the model to a partial evaluation of a specific standard demonstrates some of the capabilities of the model. Recommendations are made for a complete evaluation of this standard and for the further refinement of the model.

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)*

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