Risk Analysis Using the Engineering Method for Building Firesafety

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ABSTRACT

The analytical techniques incorporated in the engineering method for building firesafety make it possible to evaluate a comparative level of firesafety risk today. At the same time, the structure of the method serves as a bridge between research and practice to facilitate technology translation and communication between those two groups. This paper describes briefly the parts of the engineering method, the quantifications and development activities, and some applications that have been addressed.

I. INTRODUCTION

In the early 1970's, Harold E. Nelson developed a method for evaluating relative levels of building fire risk. This method was described at that time as a "Goal Oriented Systems Approach to Building Firesafety" (1). The descriptor of risk was a cumulative curve of the probability of success in limiting fire involvement to selected floor areas within a building. The "L-Curve", as this cumulative success curve was called, was obtained by calculation using fault tree techniques.

Since that time, considerable work has been done at Worcester Polytechnic Institute toward extending and adapting Nelson's original concepts into a rigorous, disciplined, and practical method by which consistent results can be achieved in building evaluations. This work has focussed on two major areas. The first is the theoretical foundation. Much effort has been devoted toward identifying the complex interactions of fire and buildings. Major attention (2) has been given to the logic and structure of these interactions by utilizing classical mathematical and systems procedures that have proven to be effective in other engineering fields. The second area of focus has been directed toward practical application of the method. The evolution of the theoretical treatment has always been accompanied by testing it in field applications.

The goal of this work is to develop a method of analysis and design for building firesafety for use by professional engineering practitioners. That procedure, called the "engineering method" in this paper, is envisioned to function in a manner analogous to structural and mechanical engineering methods. Although the building firesafety method has reached a level of maturity where it can be used for engineering applications today, it has evolved only part of the way toward the complete engineering procedure. Four stages are envisioned to complete the method.

The first, and possibly the most difficult stage, is the identification of the major components of the system and the basis for their evaluation. This was done by Nelson (1) in 1972. The second stage is the identification of the anatomy of a system that links the complex interactions in a manner that can be utilized in general engineering practice. Temporary quantification techniques and calculation procedures have been developed to determine measures of performance.

The third stage is the quantification of the components and their linkages by the development of relatively simple equations that enable the behavior or performance of components to be predicted within normal engineering accuracy. The final stage is the establishment of a rational, mathematically based design method suitable for routine engineering practice. Incorporation of recognized factors of safety is an integral part of this work.

At the present time some components are in Stage 3, most are at Stage 2, and a few are still at Stage 1. Nevertheless, the method can be used for a variety of practical applications at its present state of development. More importantly, the tasks needed to reach the goal are recognizable.

II. PARTS OF THE ENGINEERING METHOD

The complete engineering method involves eight major parts that can be grouped into three categories (3):

A. Performance Identification and Needs
    1. Establish Performance Criteria
B. Building Analyses
    2. Prevent Established Burning Analysis
    3. Flame Movement Analysis
    4. Smoke Movement Analysis
    5. Structural Frame Analysis
C. Engineering Design
    6. People Protection
    7. Property Protection
    8. Continuity of Operations Protection

The first category addresses the single aspect of identifying needs and establishing performance criteria for a building. These firesafety criteria describe the following:

a. Life safety. Identify the acceptable time interval between when the occupant is alerted to a fire and the time when the critical rooms or segments of a building are expected to be untenable with regard to products of combustion. Anticipated occupant needs, as well as the level of tenability and its measurement scale, are incorporated within this requirement.

b. Property. Identify an acceptable value or level for property damage in a building fire. Property may include the contents or the building structure itself. Often specific items or rooms are identified as requiring special attention.

c. Continuity of operations. Identify an acceptable period of operational downtime that an owner or an occupant may tolerate after a building fire. Again certain spaces normally are more sensitive to operational needs and require special attention.

Building analyses described as parts 2 - 5 above involve engineering procedures to predict the performance of an existing or a proposed building and its firesafety system. Established Burning is the demarkation between prevention activities and the building's firesafety performance. Established Burning (EB) is the size of fire the engineer identifies as the start of the threat of the building. For most buildings a flame 250 mm high is a practical and logically convenient flame size to define as EB.

Parts 6 - 8 involve engineering solutions for the firesafety problem areas. Here, the engineer compares the results of the technical analyses to the performance criteria and to any special needs the owner, an occupant, an insurance carrier, a lender, or an authority having jurisdiction. When the building does not meet a performance criteria, the engineer identifies alternative solutions, their costs, and their effectiveness. Solutions are tailored to meet specific needs, and may involve one or a combination of operational, economic, or technical features.

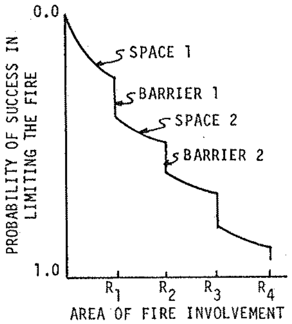
III. FLAME MOVEMENT ANALYSIS

Flame movement analysis is the central focus of the engineering method because the building response to the products of combustion is time and fire size dependent. From a flame movement perspective, every building can be described as a grouping of spaces and barriers. The probability of success in limiting a fire is evaluated within each space and at each barrier. Large, open buildings, such as warehouses and industrial buildings, can be subdivided with "zero strength barriers." This technique enables large areas to be evaluated in a manner consistent with compartmented buildings.

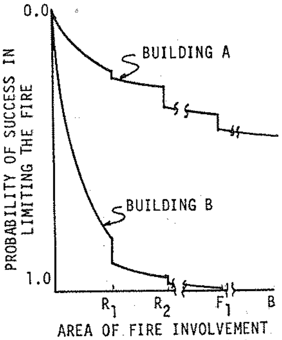
At the present time, the quantifiable descriptor of building firesafety performance is the L-Curve. The L-Curve describes the cumulative probability of success in limiting flame movement within sequential rooms along a specific path of possible fire propagation. Consequently, the L-Curve can be used to identify a numerical level of risk for all parts of a building, such as within a specified area, in a room, at a barrier, or within n connecting rooms, as well as for the entire building or group of buildings.

Figure 1 shows the format of the L-Curve. Note that the origin is located at the top of the graph. The curved lines describe the probability of limiting the flames to the space. The vertical lines describe the probability that a barrier will prevent extension of flames into the next space. A short vertical line indicates a weak barrier, while a long line describes a strong barrier.

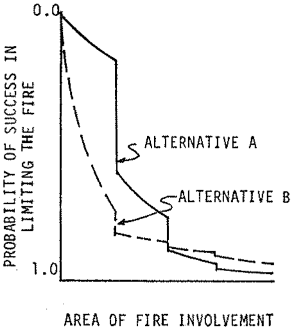
Because each building is unique, the L-Curve can be used to compare different buildings, as shown in Figure 2(a). In addition, different design alternatives for the same building can be compared, as shown in Figure 2(b).



TYPICAL L-CURVE
FIGURE 1



BUILDING COMPARISONS
FIGURE 2(a)



ALTERNATIVE COMPARISONS
FIGURE 2(b)

Building analysis and design for fire is an extremely complex process. Not only are there many human and phenomenological components that influence events and their outcomes, but also their interactions are often conditional. In order to describe the logic of this complex system, an organized structure of networks has been developed to identify the interrelationships. The networks serve a dual role. First, they allow a probabilistic firesafety analysis today for any building regardless of size, construction, use, or occupancy. Second, they serve to guide the future development of a deterministic procedure to analyze the performance of the components.

The flame movement analysis first evaluates a room as a room of origin. Then, it evaluates the performance of the barriers surrounding that room and the succeeding spaces and barriers along any path of fire propagation. Within any space, a fire can be limited by self-termination of the fire itself, by automatic suppression from a sprinkler system, or by manual extinguishment by the fire department. These events are given the symbols I, A, and M respectively. Figure 3 shows the network that is used to evaluate the limit for any area within a room of origin. The evaluation of I, A, and M are described by cumulative probability curves that show the liklihood of success in terminating a fire within a room. For convenience of notation, the conditional terms $A/\overline{I}$ and $M/\overline{I}$ are simply called the A-Curve and the M-Curve. The conditionality is understood to exist.

After the limit (L) for the room of origin is determined, the expected barrier performance is assessed. Given full room involvement, $(\overline{L})$, the barriers are evaluated both for the occurrence of small, localized penetration failures $(\overline{T})$ and for the existence of large, massive failures, $(\overline{D})$. The analysis evaluates field performance of the barriers. Consequently, construction features, loading conditions, barrier openings, and automatic barrier protection are incorporated into the evaluation.

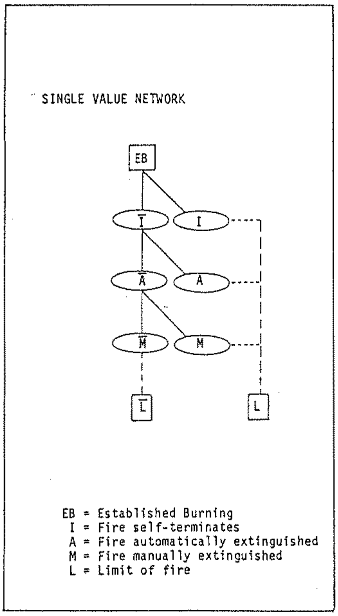
When these components are evaluated probabilistically, the evaluation can consider first the probability that full room involvement occurs, represented by $P(\overline{L})$, and then the conditional probability of failure, given full room involvement. This allows the isolation of the components as,

$$P(\overline{D}) = P(\overline{L})P(\overline{D}/\overline{L}) \qquad (1)$$

$$P(\overline{T}) + P(\overline{L})P(\overline{T}/\overline{L}) \qquad (2)$$

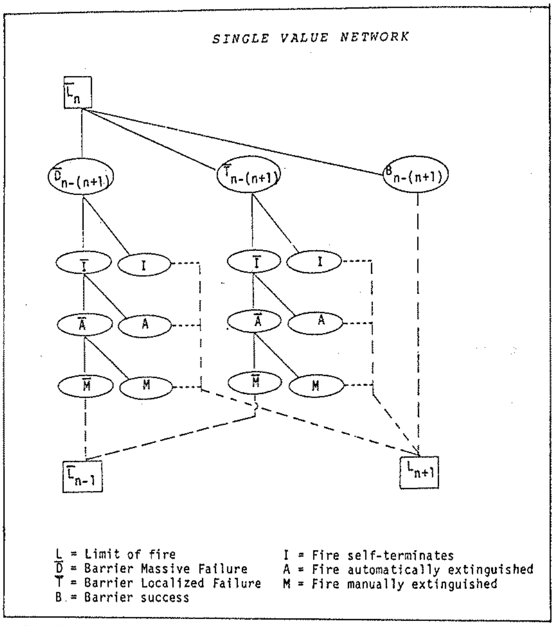
The values of $P(\overline{D}/\overline{L})$ and $P(\overline{T}/\overline{L})$ are time dependent. Their values will change for each increment of time beyond full room involvement. Therefore, as the fire continues to burn without extinguishment, the type of barrier deterioration becomes an integral part of the analysis of the next room.

The type of barrier failure influences the success in terminating a fire in the adjacent space. Therefore, the evaluation of the I-, A-, and M- values for the adjacent space is conditional on the type of barrier failure. Figure 4 shows the network for the combined barrier-space module for any segment beyond the room or origin.



ANALYTICAL NETWORK FOR ROOM OF ORIGIN

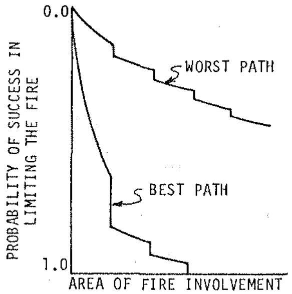
FIGURE 3



ANALYTICAL NETWORK MODULE FOR ROOMS BEYOND THE ROOM OF ORIGIN

FIGURE 4

The L-Curve analysis evaluates any or all possible space-barrier paths of propagation by combining the networks of Figures 3 and 4 for the sequence of rooms emanating from any room of origin. For any given time increment, hand calculations could be used to calculate values of L and $\overline{L}$. However, this becomes tedious for a continuum since the values of L and $\overline{L}$ vary with time due to the barrier deterioration as the fire continues, and because of the introduction of intervention methods, such as automatic sprinkler effectiveness and fire department suppression, which change as time progresses. Consequently, a computer model has been constructed that calculates the L-Curve for any or all paths of fire propagation in time and space. With this computer analysis it is possible to construct an envelope of L-Curves, such as that shown in Figure 5, for any room of origin or for an entire building.



TYPICAL ENVELOPE OF
BUILDING PERFORMANCE
FIGURE 5

IV. QUANTIFICATION OF FLAME MOVEMENT ANALYSIS COMPONENTS

The quantification of the engineering method today utilizes a knowledge base including such factors as

a. Physical and chemical phenomena
b. Fire test results
c. Code and standards experience
d. Building analyses
e. Computer models

Engineering judgment provides the link between the available scientific and experiential knowledge and the expected fire performance of the unique building being evaluated. The expected performance of the components is expressed in terms of their probability of success. Other than in the expression of results, the present application of the engineering method is similar in approach to those used in traditional structural and mechanical design methods. The anatomy of the method keeps the complex interactions of the fire and the building in order so that the components may be integrated into the complete system.

The fundamental organization of the hierarchial networks and framework has been structured in a manner that allows new knowledge to be incorporated without disruption or change to the basic analytical framework. This allows each component to be evaluated in a manner analogous to a free body analysis of structural mechanics. That is, each component can be evaluated in isolation and then returned to the framework with confidence that its interactions will be addressed. Consequently, all new findings can serve to increase the confidence in the results. The basic analytical structure need not change. This feature will allow a transition from the probabilistic judgmental engineering evaluations of today to deterministic equations as the evolution continues.

The quantification "tomorrow" will involve the use of relatively simple deterministic equations to evaluate the major components. When the deterministic equations are developed, the probabilistic descriptors used today will become obsolete. The probability assessments then assume an entirely different role. They change character and become reliability evaluations of the equations, their interactions, and the ancillary design requirements that are the parts of the engineering method.

The design method must incorporate a factor of safety or a safety index. This may be achieved by adjusting the deterministic equations and design requirements by a safety index that incorporates an acceptable probability of failure. The acceptable probability of failure will reflect the level of risk and the related cost of protection that society is willing to accept. An assessment of existing code complying buildings will provide a useful base to assist in identifying the safety level. Techniques for doing this are a regular part of contemporary engineering literature. Magnusson (4) described procedures for structural fire resistances in 1974.

To illustrate this technique, consider the load, S, and the resistance, R, functions shown in Figure 6(a). In flame movement analysis, the load, S, would be the design fire. The resistance, R, could be the automatic sprinkler capability; or the fire department capability; or the barrier effectiveness. The probability of failure can be described as

$$P_f = P\ (R<S) \qquad (3)$$

(where P_f is the probability of failure)

When we combine the distributions of R and S, as shown in Figure 6(b), the probability of failure becomes,

$$P_f = P(R-S) < 0.0 \qquad (4)$$

The safety index, β, times the mean, μ, will define the level of safety achieved by the design equations and procedures.

Obviously, each component has many variables and conditions that will influence its behavior. However, since we are interested only in the probability of (R-S) < 0, many of the variables which are important influences for the fire or the suppression behavior may become insignificant, depending on the form of the design equation. This allows a reliability analysis to be conducted by load and resistence evaluations similar to those described by Galambos (5).

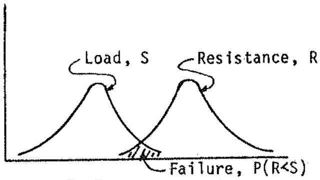


ILLUSTRATION OF LOAD AND
RESISTANCE DISTRIBUTIONS
FIGURE 6(a)

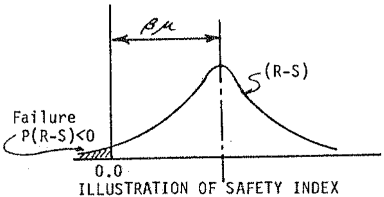


ILLUSTRATION OF SAFETY INDEX
FIGURE 6(b)

V. SMOKE, STRUCTURAL, AND ESTABLISHED BURNING ANALYSES

The smoke movement analysis currently evaluates the time and probability that a selected space will remain tenable. At the present time, tenability evaluations are described by obscuration levels.

The evaluation is done in two parts. The first evaluates for each increment of time the probability that the space will remain tenable given that no suppression occurs, P (tenable/$\overline{L}$). The second part incorporates the probability that the fire is not limited, P($\overline{L}$), as evaluated by the flame movement analysis. The S-Curve is then obtained from the conditional evaluations of

$$P\ (\text{tenable}) = P\ (\text{tenable}/\overline{L})\ P(\overline{L}) \tag{5}$$

Structural fire protection has received considerable attention over the years. The European fire community in particular has assumed such a leadership role that quantification and design procedures are well advanced.

The evaluation of the probability of failure using safety index procedures becomes feasible because one can separate the structural situation after full room involvement, P(structural failure/$\overline{L}$), from the probability of full room involvement, P($\overline{L}$). In this way, the conditionality allows the two parts to be evaluated as separate entities and then combined as

$$P(\text{structural failure}) = P(\text{structural failure}/\overline{L})\ P(\overline{L}) \tag{6}$$

Established Burning (EB) is an important concept in building analysis. As described in the "Anatomy of Building Firesafety" (2) the likelihood of ignition, fire growth, occupant extinguishment, and special hazards automatic suppression is incorporated into this analysis conveniently. This demarkation of EB becomes quite useful with regard to consistency of engineering analysis and design. It also allows the free body concept, described earlier, to be applied more readily to individual buildings.

Established Burning is composed of two parts. One is the probability of ignition, P(IG). The second is the probability of reaching the fire size defined as Established Burning, given ignition. Equation (7) shows these parts. As noted earlier, the free body concept allows these components to be evaluated separately and then combined later into a complete risk analysis of the entire building, if it is of value.

$$P(EB) = P(IG)\ P(EB/IG) \tag{7}$$

VI. APPLICATIONS

The development of the present status of the engineering method has involved the integration of several parts. One is the unfolding of the method itself. Great care has been taken to ensure that the structure has a sound theoretical and logical foundation. While much work remains to be completed, the basis still appears to be correct.

A second part has involved techniques of quantification. Temporary quantification measures have utilized research reports, basic theory, experiences, and engineering judgment. Reports from the fire research community have been integrated into the quantification wherever possible. More importantly, the general form and type of questions and results needed to translate research results into general use are more clearly understood.

The third major part of the process has included practical applications. The actual use of the method to solve real firesafety problems has been an essential ingredient.

The simultaneous attention to all three parts has been essential to the present state of the evolution of a disciplined engineering analysis and design process for building firesafety. The bridge between research and practice has been the engineering method. The method has provided both a framework to facilitate technology translation from research into practical tools, and also a conduit to enhance communication between the two paths. The range of application activities has been broad. Up to this point all activities have been unsponsored. Consequently, practice has been limited to specific problem areas. Frequently, when feasibility has been proved or the practicality has been demonstrated, the project is halted.

The following areas illustrate the type of applications that have been undertaken in conjunction with the engineering method. Listing does not imply completed techniques. Listing means that the application has been studied to a depth whereby one could recognize that further research on the topic could result in the refinement of procedures that would have a high probability of a project success.

1. Building firesafety analyses
    a) Risk assessments
    b) Cost-benefit analyses
2. Management science decision analyses
    a) Insurance underwriting
    b) Corporate fire risk management
3. Building code anlayses
4. Selected fire standards analyses
5. Building regulatory studies
6. Fire department management
    a) Indexing of buildings
    b) Prefire planning and training
7. Indexing of ships

VII. CONCLUSION

It is possible to evaluate the comparative level of risk today by the analytical techniques described in the engineering method for building firesafety. The numerical values are, of course, comparative and not absolute. Nevertheless, the engineering method does permit a relative consistency in building evaluations because of the structure of the analysis.

The method can incorporate new research findings without disruption of the basic framework and structure. If guidelines were prepared for numerical evaluation of the components, collection of statistical data on an ongoing basis, incorporated into a Bayesian updating would eventually produce an absolute level of risk.

The current approach is not so much to develop an absolute risk analysis for a building, even though it is possible to do so, but rather to integrate building analysis experiences with research results to develop deterministic equations that eventually can be used for office calculation in engineering practice. These deterministic equations will be subjected to realiability analyses to gain an insight into the important variables and incorporated into the equations to form a basis for a fire design code that is analogous to a structural design code.

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