Zeitschrift: IABSE congress report = Rapport du congrès AIPC = IVBH Kongressbericht

Band: 10 (1976)

Artikel: Application of a limit state concept to the performance of a structure under fire conditions

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DOI: https://doi.org/10.5169/seals-10430

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Application of a Limit State Concept to the Performance of a Structure under Fire Conditions

Application du concept de l'état limite aux réactions d'une structure en feu

Anwendung des Konzepts der Grenzzustände auf das Verhalten eines brandbelasteten Bauwerkes

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A RATIONAL PHILOSOPHY

The concept of structural fire protection as used currently was developed over half a century ago on the basis of fire experience and intuitive knowledge, and during the course of time has been marginally modified particularly following public reaction to large-scale fires. Most building codes and regulations base their requirements on assumed fire load, divide buildings into different risk categories and make some allowance for the height or the size of the building on a rule of thumb basis. The relationship between the fire load and fire resistance is basically that derived by Ingberg[1] nearly 60 years ago and is shown in Table 1 and Figure 1.

Combustible content		Fire load density		Duration of exposure in standard test
lb/ft^2	kg/m^2	Btu/ft^2	MJ/m^2	h
10	50	80×10^3	900	1.0
15	70	120×10^3	1360	1.5
20	100	160×10^3	1820	2.0
30	150	240×10^3	2720	3.0
40	200	320×10^3	3630	4.5
50	250	380×10^3	4310	6.0
60	300	432×10^3	4410	7.0

Table 1. Equivalent severities of building fires

The United Kingdom authorities accepted this with some simplifications on the basis of a study published in 1946[2]. On this basis domestic and residential buildings qualify for a fire resistance of half to one hour and office buildings and shops one to two hours. High buildings have been taken to mean those beyond the reach of the fire brigade rescue ladders ($\geqslant$ 25 m) and considered to require some increase in their fire resistance to compensate for the difficulty of fire control.

With the interest in the fundamental aspects of fire protection in recent years, the need for examining the rationale of this approach has been suggested by the research workers, specifiers of safety levels and the design engineers[3]. From a structural point of view the relevant areas of interest are the prediction of the severity of a fire to be expected in a given building and its effects on the structure of the building in the fire zone as well as others remote from it. Consequently a rational fire protection approach should be based on the following:

(a) The probability of a fire

(b) The probable severity of the fire

(c) The response of the structure to the fire

(d) The re-use of the structure after the fire.

Of these the first needs a statistical approach to establish the number of buildings at risk, the frequency of fires, records of fire control and the assessment of damage[4]. Study of such data should provide a predictive capability on the risk attached to different types of occupancies. Other technical, economical and social considerations should allow judgments to be made on the acceptable level of risk in a given situation.

PROBABLE SEVERITY OF FIRE

Over the last ten to fifteen years a number of studies have been carried out, notably in Japan[5], Sweden[6] and the United Kingdom[7] on the post flashover behaviour of a fire. These studies have clearly illustrated that a number of factors, shown below, govern the severity of a fire, of which the amount of fuel is one.

A Fire load: Total quantity and distribution

B Ventilation: Amount and disposition

C Compartment boundaries: Size, shape and thermal characteristics

The quantity of the fire load and its nature represents the total heat potential and rate of availability, roughly represented by the relationship between the surface area and the mass. The amount of ventilation available exercises a critical influence on the burning behaviour of the fuel[8], with restricted ventilation the decomposition rate is proportional to the availability of the air supply up to an optimum point (Figure 2) after which increase in ventilation has little effect. In the first regime the fire severity can be regarded as ventilation controlled and in the second as fuel controlled ie the availability of the fuel or the relationship between its mass and surface area has a critical effect. Ventilation to the fire is available from the windows and can be related to the window size as the glazing is usually destroyed by the time flashover occurs.

The compartment characteristics influence the heat balance of the fire. Some of the heat is dissipated through the exposed surfaces and consequently the surface area and the conductivity of the boundaries may be critical. In large compartments the progress of the fire may be by stages and the whole compartment may not undergo flashover conditions at the same time.

The traditional method of expressing the severity of a fire has been to relate it to a period of exposure in the standard fire resistance tests which follow the standard temperature/time relationship such as that specified in ISO 834 : 1975[9] . A simplified expression to take account of different factors allows the expected temperature conditions to be related to the standard curve by an expression of the following type[7]:

$$t_f = k \frac{L}{\sqrt{A_W \cdot A_T}}$$

where t_f = equivalent fire resistance time, L = fire load, k = fuel factor for the fire load, A_W = window area A_T = compartment surface area.

Another approach defines the temperature/time relationship for each situation and therefore provides a family of curves, with partially standardized heating and cooling rates. A comparison between the three approaches is shown in Figure 3.

THE LIMIT STATE APPROACH

Both the Comité Européen de Beton(CEB)[10] and ISO [11] (International Organization for Standardization) have adopted a semi-probablistic approach to the design of structures so that the structure will not become unfit for its intended function during its useful life ie it will not reach a limit state. CEB explains that 'The initial idea of referring to a single failure criterion has been replaced by the comprehensive concept of limit states'. A practical effect of this approach has been to consider the characteristic strength of the structure and the characteristic loads to which it will be subjected and to replace the global or overall safety factor by partial safety factors, each appropriate to the limit state being considered. The two limit states specified in a recent British Code[12] are the ultimate limit state and the serviceability limit state, the latter being concerned with deflections and widths of cracks in concrete. The characteristic load (W_k) can be defined as the load which is not likely to be exceeded during the useful life of the structure and the characteristic strength (S_k) as the strength that is normally expected to be exceeded. To take account of the effects of fire two special limit states need to be considered, one concerns the maintenance of stability and corresponds to the ultimate limit state and could be termed the 'limit state of stability' in a fire and the other the maintenance of integrity of the space separating components of a structure and could be termed the 'limit state of integrity' in a fire. These limit states are diagrammatically shown in Figure 4 together with the factors which influence their occurrence.

LIMIT STATE OF STABILITY

Assuming that a fire is likely to occur in a building and reach the post flashover stage without control it would subject the structure to high temperature conditions which have the effect of reducing its characteristic strength. If the probable severity of the fire is known or predictable, the design of the building should be such that the reduction in the characteristic strength is not sufficient to decrease it to the characteristic load level otherwise the structure will become unstable and collapse. Reduction in strength will be caused primarily by the heating of the materials used in its construction (eg steel and concrete); increased stresses and redistribution of stresses due to thermal movement and thermal restraint, deformation due to unequal heating, creep and physical rupture of some materials at high temperatures.

Some practical considerations may necessitate the imposition of additional requirements such as a limit on the deformation of floors and beams, prevention of progressive collapse, the need to retain a margin of residual strength after fire or the need to repair a building quickly particularly after a minor fire. These considerations will require the introduction of partial safety factors Figure 5 illustrates different factors which have to be considered in this connection.

The most important consideration from a structural point of view is the ability to estimate reduction in the characteristic strength and the onset of instability. The amount of reduction in the characteristic strength would depend upon the severity of fire, properties of the constructional materials at high temperatures and the design of the structure as shown in Figure 6.

The severity of fire specifies the exposure conditions and consequently the temperature regimes in various parts of the construction and at different depths in materials Data on material properties show the losses in physical properties which have been suffered and the consequent reduction in the strength of the structure. The design of the structure allows an analysis to be carried out to find the time at which the loss in strength approaches the critical limit state. The non-steady heating regime leads to a progressive reduction in strength which for simple cases can be fairly simply illustrated as in Figure 7, where two beams or floors are shown with the normal and the limit state moment distribution curves. The time taken for the ultimate moment capacity to be lowered to the same level as the applied or the design moment is the time to reach the limit state of stability.

For this analysis appropriate partial safety factors need to be established as shown in the example below.

If the characteristic load on the structure is assumed to be

$$W_k = W_o + k_1 \sigma_W$$

and its characteristic strength as

$$S_k = S_o - k_2 \sigma_S$$

where W_o and S_o are the mean load and the mean strength respectively k_1 and k_2 are the probability factors for load and for strength and σ_W and σ_S are the standard deviations

$$\text{The global safety factor } \lambda = \frac{S_o - k_2 \sigma_s}{W_o + k_1 \sigma_w} \qquad \ldots\ldots (1)$$

The exposure of the structure to a fire for time 't' will result in the strength being reduced to S_t, then

$$S_t = \gamma_t (S_o - k_2 \sigma_S)$$

γ_t being the reduction factor due to heating At the limit stage of stability

λ = 1 and therefore

$$\gamma_t (S_o - k_2 \sigma_S) = (W_o + k_1 \sigma_W)$$

ie the strength reduction factor has the same value as the global safety factor. Consequently the structure is on the verge of collapse at time t. In many practical situations it is desirable, and in some cases essential, to prevent this happening and an additional factor γ_a is used to amend the value of the characteristic load. The value of γ_a will vary between 1.0 and 1.5 depending upon the additional needs and following are some examples of the way in which its value could be adjusted:

limiting deflection criterion	=	1.1
residual strength criterion	=	1.2
tall structures	=	1.25
repairability criterion	=	1.3

LIMIT STATE OF INTEGRITY

This limit state is only applicable to those elements of construction which have a separating function to perform ie walls and floors. Even if these retain their structural stability it is still possible for fire penetration to occur in two ways. Excessive transfer of heat through the construction can raise the temperature of the face remote from the fire to a point at which combustible materials in contact are likely to become ignited. The other way is by the passage of hot gases and flames through gaps, openings, cracks or orifices. Factors which influence integrity failure are shown in Fig 8 below.

Heat transfer under the non-steady heating conditions is determined by the thermal diffusivity ($\alpha = k/\rho c$) of the barrier which is influenced by the thermal constants, the moisture content and the existence of air gaps. For materials such as concrete data are available to estimate the contribution made by a known quantity of moisture to delay the transfer of heat. Whilst it is possible to calculate heat transfer under the unsteady state by approximate methods, data are lacking on the precise thermal properties of materials at relatively high temperatures.

Flame barrier limit state is purely a mechanical feature of the construction and generally is not critical with monolithic constructions, masonry work, precast concrete blocks or panels 100 mm or more in thickness or constructions with a protective coating of plaster, asbestos or mineral fibres. Most problems due to the formation of gaps or openings are experienced with fabricated constructions where dry joints occur and particularly where combustible materials are involved. The solution lies in providing allowance for the expansion of metallic components, absence of through openings, staggering the joints and using sealing materials of an inert type.

The higher pressure on the fire side causes hot gases to flow through the gaps and orifices, the rate of flow depends upon the square root of the pressure difference, the area of the gap and the flow characteristics. Flames will find it difficult to pass through gaps of less than 5 mm width but hot gases, smoke and other products of combustion can penetrate in large quantities. These may not create a fire situation on the other side but are more than likely to lead to an unbearable atmosphere for the occupants. Safety considerations for the occupants demand that the quantity of gases so penetrated should be minimal.

CONCLUSION

Fire safety principles for high rise buildings should follow a rational approach proposed in this paper as a part of which the structural behaviour can be analysed using a limit state concept. This needs to be developed more fully into a set of relationships which form an adjunct to the normal analysis techniques.

ACKNOWLEDGEMENT

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SUMMARY

Structural fire protection in buildings should follow a rational philosophy and take account of the probability as well as probable severity of a fire. In analysing structurel behaviour the limit state concepts can be applied with a limit state of stability as a universal requirement and a limit state of integrity for separating structures. Partial safety factors need to be determined to deal with limits on deformation, retention of a specified residual strength, re-use after a fire and extra safety for tall structures.

RESUME

On devrait suivre une ligne de conduite logique en ce qui concerne les mesures de protection des structures des bâtiments contre le feu et l'on devrait tenir compte de la probabilité du feu autant que de son importance. Dans l'analyse des réactions d'une structure, le concept de l'état limite peut être mis en pratique en prenant l'état limite de stabilité comme une nécessité d'ordre général et en prenant un état limite d'intégrité pour la séparation entre les structures. Il faut déterminer les facteurs de sécurité partielle pour traiter les limites de déformation, une résistance post incendie donnée, une réutilisation des bâtiments après incendie et pour trouver des mesures de sécurité supplémentaires pour les maisons hautes.

ZUSAMMENFASSUNG

Der bauliche Brandschutz in Gebäuden sollte logischen Ueberlegungen folgen, und sowohl die Wahrscheinlichkeit als auch die wahrscheinliche Schwere eines Brandes in Betracht ziehen. Bei der Analyse des baulichen Verhaltens ist es möglich, das Konzept der Grenzzustände anzuwenden, mit einem Grenzzustand der Standsicherheit als allgemeine Anforderung und einem Grenzzustand der Unversehrtheit für räumlich getrennte Baukonstruktionen. Nötig ist die Festlegung partieller Sicherheitsfaktoren für Fälle von Verformungsgrenzen, von der Beibehaltung einer bestimmten Restfestigkeit, von Wiederverwendung nach einem Brand und von Reservesicherheit für hohe Bauwerke.

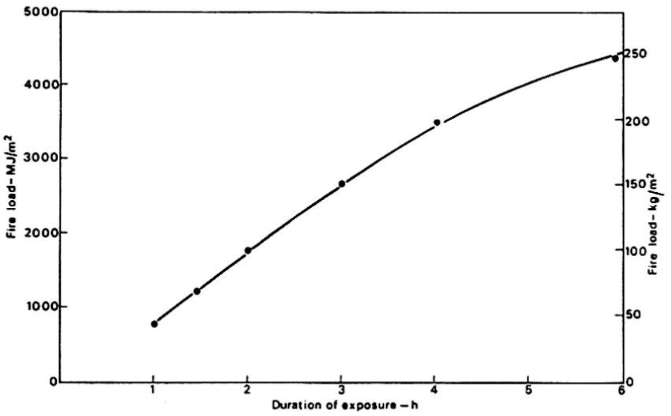

Figure 1 Inberg's relationship for fire severity

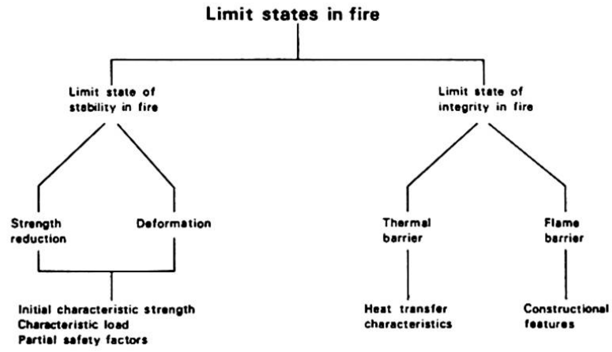

Figure 4 Limit states in fire for structures

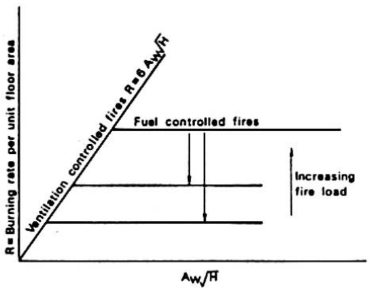

Figure 2 Burning rates of fully developed fires

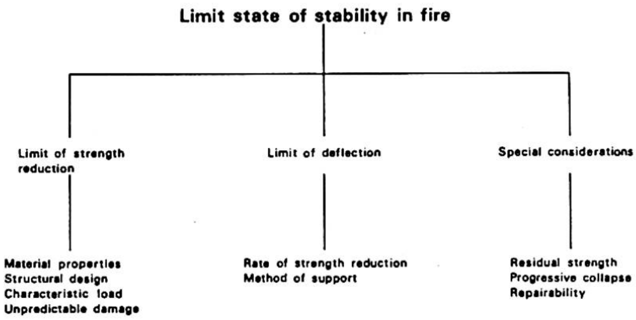

Figure 5 Main factors for limit state of stability in fire

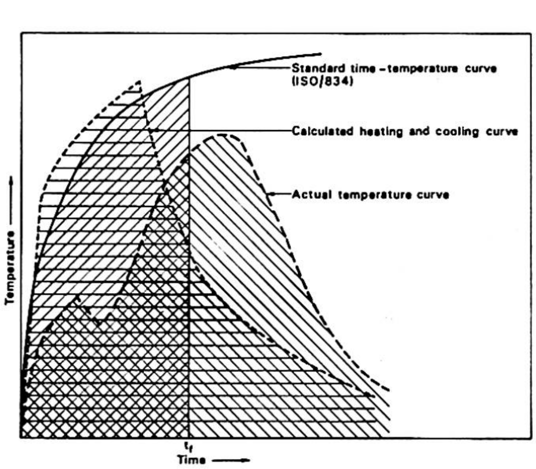

Figure 3 Different methods of expressing fire severity

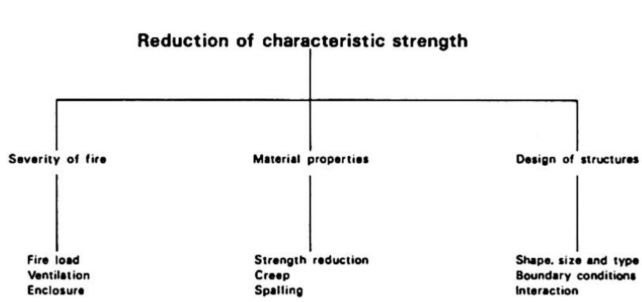

Figure 6 Factors affecting reduction of characteristic strength

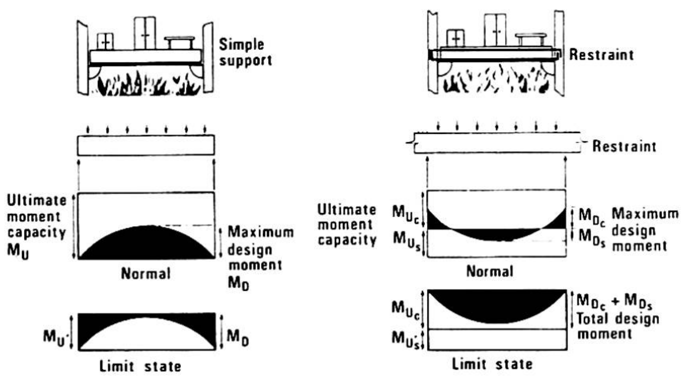

Figure 7 Effect of end restraint of a beam or slab

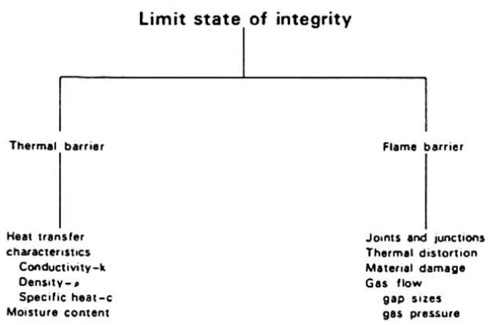

Figure 8 Factors affecting the integrity limit state

REFERENCES

1. INGBERG, S.H. Tests of the severity of building fires. Nat Fire Prot Ass Q., 1928, 22 (1) 43 - 61.

2. Fire grading of buildings Part 1. General principles and structural precautions. Ministry of Works Post-war Building Studies No 20. London, 1946. HMSO.

3. Fire resistance of concrete structures. Report of a joint committee. The Institution of Structural Engineers - London 1975.

4. BALDWIN, R and ALLEN, G. Some statistics of damage to buildings in fires. Fire Research Station. Fire Research Note 805. Borehamwood, 1970

5. KAWAGOE, S.K. and SEKINE, T. Estimation of fire temperature/time curves in rooms. Building Research Institute Occasional Reports, Nos 11 and 17. Tokyo, 1963 and 1964.

6. ODEEN, K. Experimental and theoretical study of the process of fire development in buildings. Building Research Institute Report 23/68. Stockholm, 1968.

7. LAW, M. Prediction of fire resistance - Paper 2. Fire resistance requirements for buildings - a new approach. Fire Research Station Symposium No 5, London, 1973. HMSO.

8 THOMAS, P.H. et al. Fully developed compartment fires, two kinds of behaviour. Fire Research Technical Paper No. 18. London, 1967, HMSO.

9 INTERNATIONAL STANDARD 834. First edition 1975-11-01 Fire resistance tests - elements of building construction The International Organization for Standardization, Geneva.

10 CEB Recommendations for an International Code of Practice for Reinforced Concrete - Cement and Concrete Association, London, 1964.

11. General principles for the verification of the safety of structures. ISO 2394/1973. International Organization for Standardization.

12. The Structural use of Concrete. CP 110 : Part 1 : 1972. British Standards Institution - London, 1972.