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Probabilistic Analysis of Fire Exposed Steel Structures

Détermination probabilistique de la sécurité au feu des éléments de structure métallique

Wahrscheinlichkeits-theoretische Auswertung der Brandsicherheit von Stahlbauteilen

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A large amount of work is presently in progress regarding the optimum level, in an economic sense, of the over-all fire protection of buildings. Structural damages can be prevented or limited by many measures, such as compartmentation, installation of detectors and sprinklers, reducing the attendance time of the fire brigade etc. Among those steps taken to reduce the fire damage, the oldest and most evident one is to increase the fire endurance of the individual structural member. For a high-rise building, the fire endurance must reach the level where the structural integrity of the building is maintained even during the most severe fire possible. For economic reasons, though, the fire endurance cannot be unlimitedly high. Some element of risk, however small, has to be accepted. Evidently, there is a need for a reliability analysis that makes it possible to identify this risk of structural collapse by fire and compare with the risks due to other kinds of catastrophic events.

This need has been accentuated by the different design rationales or systems put forward during the last few years. Particularly interesting in this connection is the differentiated Swedish method, see /1/, /2/. The special attention derives partly from the fact that for the first time the new developments have been transformed into a ready-to-use design manual. The manual permits, with the aid of charts, diagrams and tables, the practising engineer to make a rational design of fire-exposed steel structures. The method is based on the load factor concept, and as in any other design procedure, the choice of nominal loads (fire load density, live and dead load) and load factors will determine the final safety level.

The safety analysis of fire-exposed structures must begin with the procedure critical in every reliability evaluation; the assessment of underlying uncertainties.

Following the general outline of Fig. 1 in /1/, a general systematized scheme may be set up for the identification and evaluation of the various sources and kinds of uncertainty possible for a fire-exposed building component. Lack of space prohibits any attempt to account for the detailed process of data acquisition and evaluation, reference is made to /3/, where all particulars may be found. Here it can only be stated that, with Fig. 1 in /1/ as a functional basis and with the basic data variables selected (type of structural element, type of occupancy), the different uncertainty sources in the design procedure are identified and dissembled in such a way that available information from laboratory tests can be utilized in a manner as profitable as possible. The derivation of the total or system variance (R) in the load-carrying capacity R is divided into two main stages:

- variability $Var(T_{max})$ in maximal steel temperature T_{max} for a given design fire compartment
- variability in strength theory and material properties for known value of T_{max}.

Consecutively $Var(T_{max})$ is decomposed into three parts:

- equation error in the theory of compartment fires and heat transfer from fire process to structural component,
- variability in insulation material characteristics,
- possible difference between T_{max} obtained in laboratory test and in a real service condition.

In step number two, uncertainty in R for a given maximum steel temperature is, in the same way, broken down into three parts:

- variability in material strength,
- prediction error in strength theory,
- difference between laboratory test and a real life fire exposure.

These uncertainty terms must be superimposed upon the basic variability due to the stochastic character of fire load density. Mean and variance of load effect S are evaluated using results from publications covering the non-fire loading case.

To get appliable and efficient final safety measures, the reliability calculations are illustrated for the structural component, where the strength and deformation theories predicting the member performance under fire exposure seem most complete: an insulated simply supported steel beam of I-cross section as a part of a floor or roof assembly. The chosen statistics of dead and live load and fire load density are representative for office buildings.

The component variances are quantified, whenever possibel comparing the design theory with experiments. System variance is evaluated in two ways: by Monte Carlo simulation and by use of a truncated Taylor series expansion. Employing the Monte Carlo procedure, the mean and variance of R and S have been computed for different values of ventilation factor of fire compartment, insulation parameter κ and ratio D_n/L_n, where D_n = nominal dead and L_n = nominal live load used in the normal temperature design. The second moment reliability as a function of these design parameters is evaluated by the Cornell and Esteva-Rosenblueth safety index formulations /

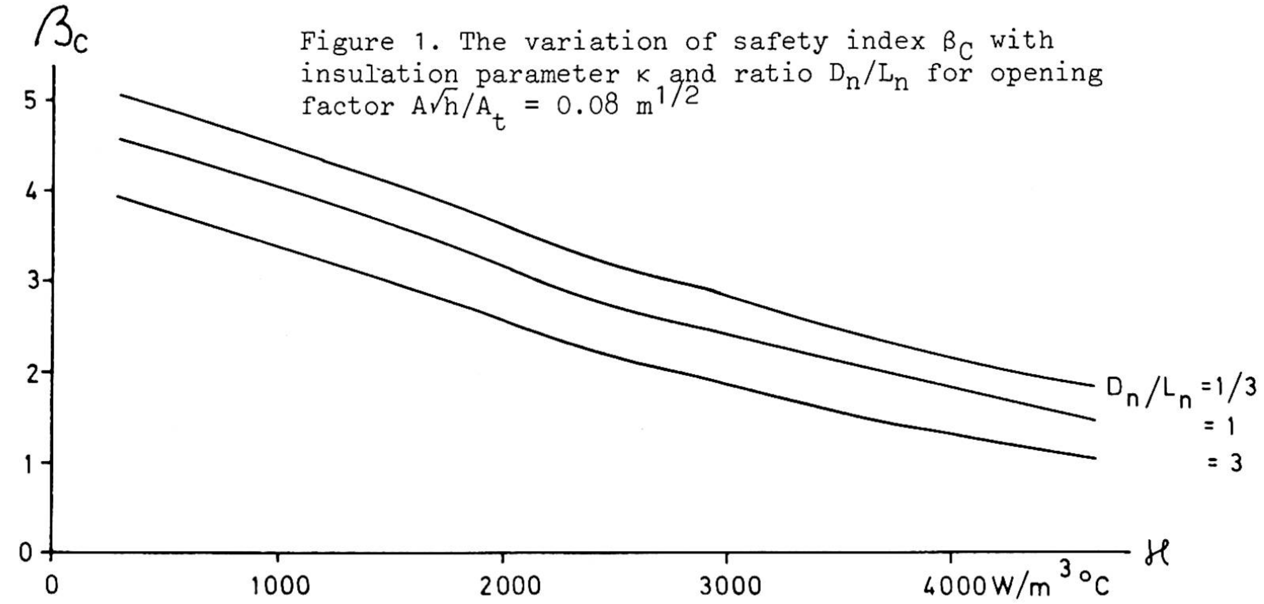

Figure 1. The variation of safety index β_C with insulation parameter κ and ratio D_n/L_n for opening factor $A\sqrt{h}/A_t$ = 0.08 m$^{1/2}$

Fig. 1 gives the safety index β_C,

$$\beta_C = \frac{\bar{R} - \bar{S}}{\sqrt{\sigma_R^2 + \sigma_S^2}} \tag{1}$$

for an insulated, fire-exposed steel member as a function of κ. The insulation parameter κ is defined by

$$\kappa = \frac{A_i \cdot \lambda_i}{V_s \cdot d_i} \quad (W/m^3\ {}^oC) \tag{2}$$

where

A_i = fire exposed area of steel element (m^2/m)

V_s = volume of steel (m^3/m)

d_i = insulation thickness (m)

λ_i = thermal conductivity of insulation material (W/m ^oC)

Continuing the summary of /3/, the accuracy of the distribution-free second moment theories to uniquely define the reliability is touched upon, and the variation in safety-index value with varying uncertainty measures characterizing the insulation and the degree of complete combustion is examplified.

The Taylor series expansion method is compared with the Monte Carlo method and demonstrated to give surprisingly good agreement. The mathematical structure of the partial derivatives method makes it natural to use it as a basis for a closer investigation of how the total uncertainty in e.g. load-carrying capacity R varies with the uncertainties arising from different sources. Such information is necessary in a systematic study of how to economically optimize the avoidance of a structural failure.

Table 1 gives an example of such a decomposition. Of special interest is the variability inherent in the largely empirical design gastemperature-time curves, see /1/, /2/. The variance of these curves was measured by comparing design maximum steel temperatures with the corresponding experimental values for 97 natural fire-exposed insulated steel columns. The comparison was made for well-known thermal characteristics of the insulation material, but includes scatter due to the approximate heat transfer theory used in computing steel temperature values. From Table 1 it may be deduced that the uncertainties deriving from ventilation-controlled gas-temperature-time curves is of minor importance for the final safety index value.

The following section turns to the problem of comparing the reliability levels of the traditional and the new, differentiated design method. It is demonstrated how the flexibility of the new method results in drastically improved consistency for the failure probability P_f.

At the same time it is shown that the temporary nominal loads and load factors given by the manual /2/ do not result in reliability levels that are independent of the ratio D_n/L_n. Using the linearization factor defined by Lind, see /4/, it is examplified how statistically more consistent load factors easily may be derived. Finally it is pointed out how mathematical programming algorithms may be employed to obtain load factors or partial safety factors that for a broader range of design parameters minimizes the difference between the demanded, preselected and the actual reliability level.

These load factor evaluation studies underline a fundamental fact. In sharp contrast to the standard design procedure, the design model of Figure 1 in /1/ has the capability of being systematically and rationally improved as knowledge increases.

Summing up, this pilot study has demonstrated that a safety analysis, using probabilistic methods, of fire exposed structural steel components is today well within the bounds of possibility. The implication is that one of the main components in the over-all fire-safety problem for the first time has been rationally assessed, thus opening the way for an integrated system approach with a reliability optimization as final objective.

Table 1. Decomposition of the total variance of load-carrying capacity into a sum of component variances for an insulated steel beam designed according to the differentiated Swedish model

Variability in load-carrying capacity R due to	per cent of total variance
stochastic character of fire load density	36
uncertainty in insulation material properties	10
uncertainty in theory transforming fire load density into maximum steel temperature (theory of compartment fires and theory of heat transfer burning environment - structural steel component)	10
difference between laboratory test and an actual complete process of fire	2
uncertainty in yield strength of steel at room temperature	12
uncertainty in the deformation analysis giving the design capacity	11
difference between the impact of fire on R in laboratory test and under service conditions	19

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SUMMARY - A first attempt has been made to assess the reliability of fire-exposed steel structural member, using the available tools of modern safety analysis.

RESUME - C'est une première tentative pour évaluer la probabilité de rupture d'une construction en acier exposée au feu, en appliquant les moyens disponibles de l'analyse de sécurité moderne.

ZUSAMMENFASSUNG - An diesem ersten Versuch wird gezeigt, dass eine wahrscheinlichkeitstheoretische Auswertung der Brandsicherheit von Stahlbauteilen entwickelt werden kann.