# Reliability-Based Evaluation Concept for Everyday Use

**Peter TANNER**
Research Engineer
Inst. of Constr. Science, IETcc-CSIC
Madrid, Spain

A graduate of ETH Zürich, in 1989 Peter Tanner joined ICOM (Steel Structures) of the Swiss Fed. Inst. of Technology, Lausanne where he worked in the fields of fatigue and fracture mechanics. Since 1992 he has worked with consultants, before joining IETcc in 1996. His research fields are durability of concrete structures and reliability of existing structures.

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## Summary

This paper describes an approach for the development of a method for considering actual loads and resistance during the evaluation of existing building structures. The method is based on the use of a live load model and partial safety factors for loads and resistance, calibrated by applying reliability methods, which can be determined as a function of site characteristics. The method enables the accurate evaluation of existing building structures for which the degree of uncertainty related to loads and resistance can be reduced compared to that assumed by design codes. Due to this reduction, acceptable reliability may be verified even for structures that are damaged or deteriorated, thus avoiding the need for strengthening or live load restriction.

**Keywords:** structural reliability, probability of failure, assessment, probabilistic analysis, deterministic analysis, site characteristics, model updating, calibration

## 1. Introduction

When assessing the safety of an existing structure, the information is different from that available during design, because many characteristics may be measured from the structure under consideration which, at the time of its design, were just anticipated quantities. It is always possible to improve the level of accuracy for the load and resistance models, which are needed for the assessment, by collecting more data about a particular structure. In most cases, the cost of updating of information by collecting site data is outweighed by a significant reduction in the cost of intervention: possible consequences of an over-conservative evaluation of an existing structure include unnecessary live load restrictions, strengthening or demolition.

The most accurate way for an engineer to consider actual load and resistance would be to carry out a probabilistic analysis using site data. However, this is a time consuming process, involving a considerable understanding of probabilistic methods, and is possibly not aimed at the practising engineer for everyday use. A simplified deterministic method for the assessment of structural safety should therefore be available, based on the same partial factor formulation adopted in codes for structural design.

Applying reliability methods, a procedure for the calibration of site specific deterministic load and resistance models for the assessment of existing building structures is proposed in the present paper. A realistic example shows the potential benefit of such a method.

# 2. Site Specific Load and Resistance Models for Deterministic Assessment

## 2.1 Deterministic representation of structural safety

Basic variables that are considered for the assessment of structural safety are associated with uncertainty. The safety of a structure can therefore be measured in terms, for example, of its reliability, which takes account of uncertainty and is represented by a probability of failure. The safety of a structure is expressed in terms of the basic variables by the Limit State Function (LSF). The simplest LSF defines safety as the requirement that resistance, R, is greater than or equal to the total action effect, S:

$$R - S \geq 0 \qquad (1)$$

The probability of failure, $p_f$, is thus equal to the probability that S is greater than R. The First Order Second Moment (FOSM) method [1] introduces a reliability index, $\beta$, for which a direct link to the failure probability exists. In addition to the reliability index, $\beta$, the method provides the design values, X*, of the variables involved in the LSF. These values correspond to the most probable set of values of the variables at failure, and they are the keys to the calibration of deterministic load and resistance models for the assessment of structural safety.

The aim of a deterministic assessment of structural safety is to verify that the inequality (1) is satisfied, by using nominal values of basic variables and partial safety factors in order to obtain the values that they would have at the design point in a reliability analysis. The link between reliability concepts and deterministic methods is therefore the design point [2]:

$$X^* = \gamma_X \cdot X_{nom} \qquad (2)$$

| | |
|---|---|
| $X^*$ | value of the basic variable at the design point in a reliability analysis |
| $\gamma_X$ | partial safety factor |
| $X_{nom}$ | nominal value of the basic variable |

The Limit State Function is the same for both methods (reliability and deterministic), only the representation of the variables is different. Partial safety factors, which are introduced in a deterministic analysis, are attributed individually to the variables in the LSF and vary according to the degree of uncertainty and the importance of the variable within the LSF. The aim of the collection of site specific data is the reduction of the uncertainty associated with the variables. The influence of this change can not be considered explicitly in a deterministic assessment (only changes in the mean value of a variable can be accounted for). Therefore, deterministic models of action effects and resistance are to be calibrated based on a probabilistic analysis of loads and resistance.

## 2.2 Live load effects

Floor loading is of a special nature since it is influenced by many factors including the possibility of human intervention. This, and the fact that relatively few observations are available, tends to produce greater uncertainty than might be expected in the modelling of other actions, e.g. natural loading. The live loads acting on a structural element of a building can be modelled by an equivalent uniformly distributed load (EUDL), producing the same particular action effect (e.g. bending moment at the midspan) as the real load. The effects of the EUDL on structural elements is described by a certain frequency distribution which determines the extreme action effects to be considered during the assessment of structural safety. These effects may be obtained based on numerical simulations by generating random live loads for the considered specific use, based on modelling parameters available from literature or previous surveys [3]. It is observed that the value of the EUDL can vary significantly with the tributary area. Results from live load simulations can thus be used to establish a relationship between the characteristic maximum value of the EUDL and the tributary area for a particular specific use (Figure 3a).

## 2.3 Calibration procedure

Even though the FOSM reliability method (sect. 2.1) only produces an estimate of failure probability, the resulting errors are small if it is used to compare the failure probabilities for a given LSF and varying basic variables. This is what the FOSM method is used for in the present study: Going out from the *axiom* that a correct application of the current codes results in a safe structure [4], the calibration procedure consists of the following five steps [5]:

- Dimensioning of the existing structure according to a consistent set of codes. Since conservative design has a very significant influence on reliability [2], the dimensioning should be carried out in a way that the design resistance is equal to the design load effect, $S_d = R_d$;
- Calculation of the reliability index, $\beta_{code}$, related to the dimensions obtained in the first step, considering the parameters (mean value, standard deviation, probability distribution) of the variables assumed to lie behind the rules of codes;
- Calculation of the reliability index, $\beta_{eval}$, for the actual structure using updated parameters of the variables. $\beta_{eval}$ may be greater or smaller than $\beta_{code}$, depending mainly on the actual resistance and the aggressivity of the live loads according to the actual specific use;
- Find the required actual resistance, $R_{eval,req}$, by multiplying the actual resistance, $R_{eval}$, by a factor, $\kappa_R$, in a way that results $\beta_{eval} = \beta_{code}$ for the actual effect of actions, $S_{eval}$ (Figure 1);
- Derive partial safety factors, in analogy with equation (2), which can be applied to the nominal values of basic variables used in a deterministic assessment (default or updated nominal values according to chapter 3): $S_{eval,nom}$ for action effects and $R_{eval,nom}$ for resistance

$$\gamma_{S,eval} = \frac{S^*_{eval}}{S_{eval,nom}} \tag{3}$$

| | |
|---|---|
| $\gamma_{S,eval}$ | partial safety factor for action effects used in a deterministic assessment |
| $S^*_{eval}$ | actual action effect at the design point |
| $S_{eval,nom}$ | nominal value of the action effect used in a deterministic assessment |

$$\gamma_{R,eval} = \frac{\kappa_R \cdot R_{eval,nom}}{R^*_{eval,req}} \tag{4}$$

| | |
|---|---|
| $\gamma_{R,eval}$ | partial safety factor for resistance used in a deterministic assessment |
| $R^*_{eval,req}$ | required actual resistance at the design point |
| $R_{eval,nom}$ | nominal value of the resistance used in a deterministic assessment |
| $\kappa_R$ | factor for the calculation of the required actual resistance |

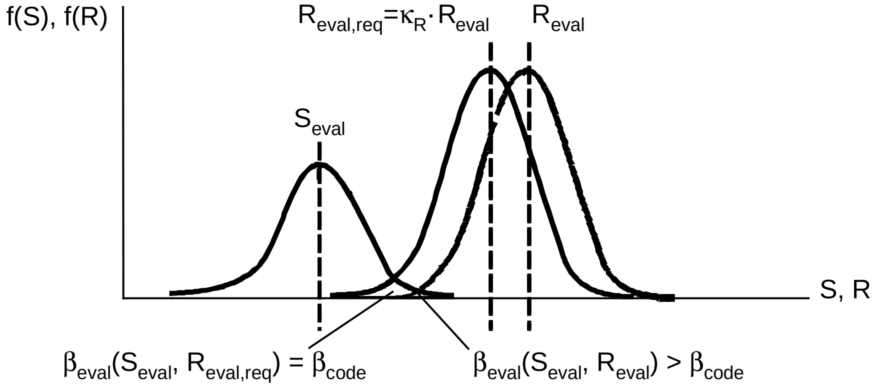

*Fig. 1 Calibration of load and resistance models for deterministic assessment*

This calibration has to be carried out for different types of structure, sections, materials and load effects. Limit state functions are to be formulated for midspan and support moment as well as for support shear force, for reinforced concrete, prestressed concrete and composite, continuous and simply supported beams of different span lengths, for which different tributary areas are to be considered. In a similar way different types of columns are to be analysed. These calculations are to be carried out separately for different load conditions corresponding to the most frequent types of specific use (residential areas, office areas, shopping areas, etc.). Partial safety factors are attributed individually to the basic variables in a Limit State Function. Therefore, the different variables are considered separately and partial safety factors can be derived for each.

In the case of self-weight, permanent actions and resistance, the obtained partial safety factors are presented according to the type of structure, as a function of the coefficient of variation used when modelling each variable. Partial safety factors used in a deterministic assessment are thus based on the coefficient of variation of the corresponding variable. This represents the change in the associated uncertainty (due to the collection of site specific data) in relation to the models that are assumed to lie behind the rules of codes. For the purpose of obtaining a simple set of values for practical evaluation of a particular type of structure, it is proposed to determine maximum factors as a function of only the coefficient of variation of the corresponding variable (Figure 2). It would however be possible to make more distinction between different types of specific use, the type of load effect, and possibly even the span length [2].

For live loads, it is proposed that the calculated partial safety factors are presented according to the type of specific use as a function of the tributary area only (Figure 3b). Also in this case, the aim is to obtain a simple set of values, so that possibly no distinction should be made between different types of structure or load effect. However, this still requires a detailed review.

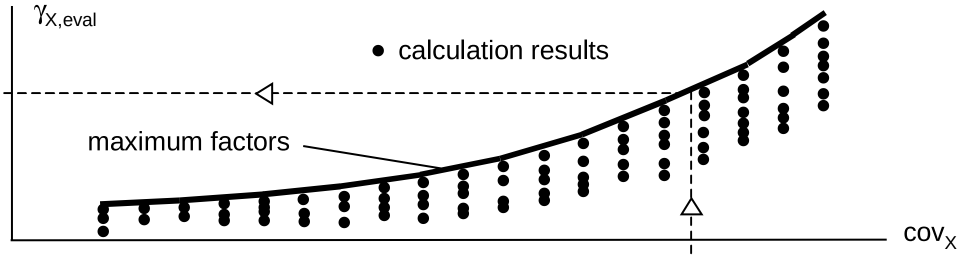

*Fig.2 Schematic representation of partial safety factors for deterministic assessment, $\gamma_{X,eval}$, as a function of the coefficient of variation of the corresponding variable, $cov_X$*

## 2.4 Partial factor formulation

Partial safety factors, which are attributed individually to the basic variables in a LSF, derived in the aforementioned way, can then be used in a deterministic evaluation of an existing structure, using the partial factor formulation adopted in design codes, e.g. [6, 7]. These factors are to be used together with the actual nominal values for action effects and resistance as described in chapter 3. The requirement for structural safety in its simplest form can be derived from the inequality (1) and is expressed by the following condition:

$$\gamma_{S,eval} \cdot S_{eval,nom} \leq \frac{R_{eval,nom}}{\gamma_{R,eval}} \tag{5}$$

# 3. Deterministic Assessment with Site Specific Models

Structural safety can be expressed by an updated deterministic rating factor, $r_{det,upd}$ [2]. Rearranging equation (5), the rating factor is defined by the expression:

$$r_{det,upd} = \frac{R_{eval,nom} / \gamma_{R,eval}}{\gamma_{S,eval} \cdot S_{eval,nom}} \tag{6}$$

If $r_{det,upd}$ is greater than or equal to 1.0, the investigated cross-section or element reaches the required structural safety level. If the rating factor is less than 1.0, then structural safety is not verified and there is a need to perform a more accurate evaluation based on further model updating or a full reliability analysis [2, 4, 5], or an intervention must be planned.

In the case of self-weight, permanent actions and resistance, site specific data is used to determine the coefficient of variation of the corresponding variable and its actual nominal value (mean values for permanent actions and cross-sectional properties, characteristic values based on a 5% fractile with a confidence level of 75% for material properties [5]). The partial safety factor to be used in a deterministic assessment can be selected as a function of the associated uncertainty, represented by the coefficient of variation determined from site data as mentioned before. Figure 2 shows schematically the relationship to be used for selecting a partial safety factor, $\gamma_{X,eval}$, as a function of the measured coefficient of variation, $cov_X$. Variables that are not measured should be considered along with those of the default models (nominal value and partial safety factor) prescribed in current design codes.

The live load model (characteristic value of the EUDL and partial safety factor) to be used in a deterministic assessment is selected as a function of site characteristics, which can be represented by the specific use of the building and the tributary area for the element under consideration (Figure 3). The tributary area, needed for the selection of site specific live load models, can be determined from available information about the structure, updated by visual inspection.

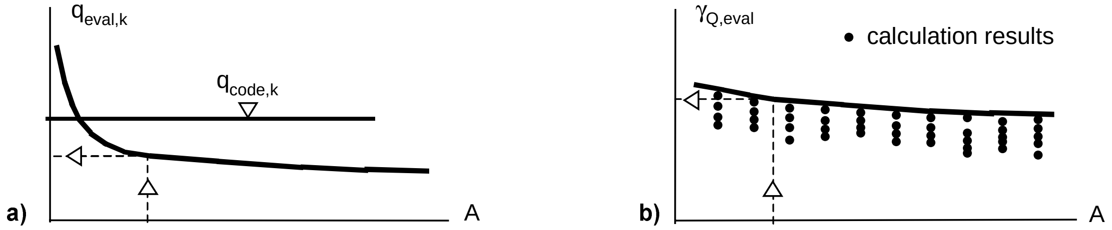

*Fig.3 Schematic representation of a live load model as a function of influence area, A. a) characteristic values of EUDL for evaluation, $q_{eval,k}$, and design, $q_{code,k}$, b) partial safety factor, $\gamma_{Q,eval}$*

## 4. Case Study

The transformation of an existing residential building into an office building implies an increase of the nominal live loads of 50% [6]. Furthermore, the design code in force at the time of construction might imply a design minimum safety that is different from that implied by current codes. For these two reasons it must be demonstrated that structural safety after the change of specific use of the building is greater than that suggested by design codes. To this end, a simply supported reinforced concrete beam (span length 8.00 m) out of a family of beams (separation 5.00 m), which are supporting the existing floor construction, is analysed. No shear connection exists between the floor and the beams. The available information about the structure includes the definition of the midspan cross-section as well as the nominal strength of the employed construction materials (Figure 4 also represents nominal values of loads according to current design codes, including live loads for office buildings).

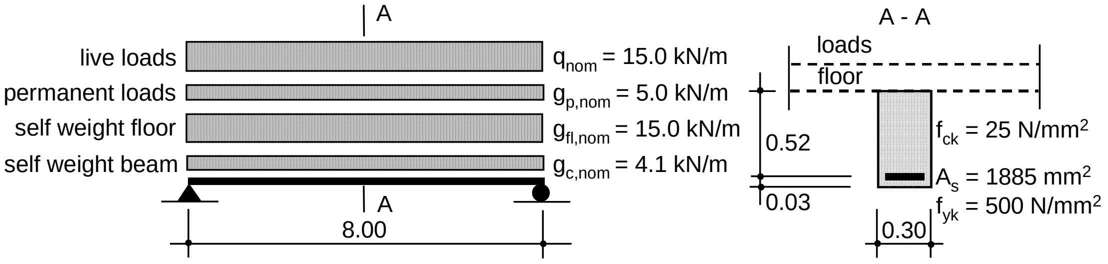

*Fig.4 Investigated beam and midspan cross-section*

The calibration of site specific, deterministic load and resistance models is carried out according to the procedure established in 2.3. The probabilistic characteristics assigned to the basic variables, which are needed for the calculation of the FOSM reliability index, were selected from the literature [2, 3, 4]. Updated parameters for the calculation of the actual reliability index, $\beta_{eval}$, were established for the effective depth of the cross-section and the bending moment due to live loads. The obtained results are listed in Table 1 (in terms of updated partial safety factors) and compared to the corresponding default values from the structural Eurocodes [6, 7].

In a deterministic assessment with the updated partial safety factors from table 1 and the actual nominal values for action effects and resistance, an updated deterministic rating factor (equation (6)) of $r_{det,upd}$ = 1.14 is obtained for the midspan bending moment. Structural safety is therefore verified and the planned transformation of the existing residential building into an office building is possible without any intervention.

For comparison, structural safety is evaluated by applying the verification criteria defined in the relevant structural Eurocodes [6, 7]. The structural safety can be expressed by a deterministic rating factor, defined in analogy with equation (6), $r_{det}= R_d/S_d$. For the midspan bending moment a value of $r_{det}$= 0.82 is obtained. Consequently, according to this over-conservative evaluation, the required structural safety level is not reached. Finally, the benefit of applying site specific deterministic models can be estimated from the calculated rating factors: in the present case it is 40%, approximately.

| | Action effects | | | | Resistance | |
|---|---|---|---|---|---|---|
| | Concrete $\gamma_{Gc}$ | Floor $\gamma_{Gfl}$ | Perman. Loads $\gamma_{Gp}$ | Live loads $\gamma_Q$ | Reinf. Steel $\gamma_s$ | Concrete $\gamma_c$ |
| Updated $\gamma_{X,eval}$ | 1.10 | 1.11 | 1.05 | 1.17 | 1.125 | 1.00 |
| Eurocode $\gamma_{X,EC}$ | 1.35 | 1.35 | 1.35 | 1.50 | 1.15 | 1.50 |

*Table 1 Updated partial safety factors for the example under consideration,* $\gamma_{X,eval}$, *compared to the corresponding default values defined in structural Eurocodes,* $\gamma_{X,EC}$

## 5. Conclusions

- Compared to structural design, uncertainty associated with the variables of a Limit State Function can be reduced in an evaluation by considering site characteristics. The influence of this change can only be taken into account explicitly in a probabilistic assessment, which is not appropriate for practical purposes.
- A simplified method has been proposed for the consideration of site characteristics in deterministic assessments of structural safety, and it has been shown how the corresponding load and resistance models can be calibrated applying reliability methods.
- Further work includes the calibration of load and resistance models for deterministic assessments of structural safety of a wide range of building structures, exposed to different types of specific use.

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