Safety requirements and structural design process

X

Safety Requirements and Structural Design Process

Critères de sécurité et dimensionnement des structures

Sicherheitsanforderungen und Tragwerksbemessung

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SUMMARY
This contribution presents a brief discussion on the requirements to meet for a level 1 design process capable of translating in simple rational code rules the actual reliability demand. The weight of the random uncertainty on load values and load combinations on structures is in particular emphasized and a policy, that has been recently proposed for calibrating the load safety factor values, is discussed.

RESUME
L'article traite des exigences à remplir par un projet de structures, au niveau 1, afin de pouvoir traduire en règles simples les critères de fiabilité. Le rôle joué par les charges aléatoires et leurs combinaisons sur la sécurité des constructions est en particulier considéré. Une méthode récemment proposée est analysée pour calibrer les valeurs des facteurs de sécurité à appliquer aux charges.

ZUSAMMENFASSUNG
Dieser Beitrag behandelt kurz die Anforderungen, die ein Bemessungsverfahren der ersten Stufe (Level 1) erfüllen muss, um die Fragen der Tragwerkszuverlässigkeit in einfache Normregeln überführen zu können. Auf die Wichtigkeit der zufallsbedingten Unsicherheiten von Lasten und Lastkombinationen bei Tragwerken wird besonders eingegangen. Schliesslich wird eine Methode vorgestellt, welche kürzlich für die Festlegung von Lastfaktoren vorgeschlagen wurde.

1. SAFETY REQUIREMENTS

The document "Common Unified Rules for Different Types of Constructions and Materials" |1|, that was proposed by the Joint Committee on Structural Safety and assumed as a basis for both concrete |2| and steel |3| european recommendations, states that the "aim of design is the achievement of accettable probabilities that the structure being designed will not become unfit for the use for which it is required during some reference period and having regard to its intended life". Thence each structure or structural element should be designed and constructed such that, with an appropriate degree of reliability, they:

a) perform adequately in normal use and sustain actions liable to occur during their life;
b) maintain sufficient structural integrity during exceptional events as fire, explosions, strong earthquakes;
c) have adequate durability against biological and chemical influences.

This contribution to the discussion on Theme X (Safety Concepts), planned for the 11th IABSE Congress, presents a brief survey of the requirements to meet for a level 1 design process capable of translating in practice the expected reliability demand.
A first aspect to emphasize concerns the appropriate degree of reliability. In fact it is very difficult to state a quantitative unambiguous definition of such a degree and only qualitative considerations are generally introduced in a code (f.i.: such a degree has to be correlated to the risk of consequences to human lifes or to social conveniences).
However this aspect is beyond the structural engineering role and hence, in the next point, attention is only devoted to the analysis of the possibilities of providing safety during the performance of the single design steps. Further, points 3, 4 and 5 are related to some aspects of item a) whose requirements are the basis of current design procedures.

2. ACTUAL DESIGN CRITERIA

Analysing items from a) to c), stated at the previous point, the following considerations may be pointed out.

- At present the durability of the structure against chemical and biological influences (item c) may be guaranteed by means of rules of good practice for design, construction, control, inspection and maintenance. The problem is not yet stated with the support of mathematical model because the relevant variables are not yet well known.

- It is not easy to provide design criteria in order to mantain integrity during exceptional events (item b). In fact the knowledge of the ultimate behaviour of structures, expecially in dynamic range,is not accurate enough. At present the design can only be based on global parameters as, for example, ductility factors.

- It is possible to state in a mathematical way the design for providing a good performance to the structure during normal use (item a). This leads to the three design levels presented in |1|. However only level 1 (semi-probabilistic method) appears to be fully applicable in common engineering practice.

3. CODE REQUIREMENTS

In order to perform a level 1 verification such as:

$$\gamma_{f3} S(\gamma_{F_i}, \psi_{o,i}, F_i) \leq R(f/\gamma_m) \qquad (1)$$

a code have to point out:

(i) the design methods for evaluating loading effect (S);

(ii) the input to design (i.e. loads F_i and resistance R that is generally a function of the properties f of the material);

(iii) the partial safety factors γ_F, $\psi_{o,i}$, γ_m, γ_{f3}.

Some considerations on these requirements are performed for the purpose of underlining lacks and open questions.

- Design methods have to be different depending on the type of limit state considered. Linear methods are sufficient for serviceability limit states: they are well known and improved by automatic techniques. For ultimate limit states non linear methods are necessary but they are not yet general enough to cover design needs. For this reason sometimes it is useful to state conventional ultimate limit states |3| in order to allow the designer to use linear methods in structural analysis.

- Resistance and stability of structural elements and ultimate behaviour of connections are widely explored. Many results still need but the most is already available. Permanent and live loads are not well known from a statistical view point but a good estimation may be done in many cases. Snow loads are not yet known everywhere. Wind speed is often stated with sufficient precision but interaction between gusts and ultimate behaviour of structures is not known. It follows that if the wind speed characteristic value is given as the 95% fractile of the maximum value during the structural lifetime most of existing steel constructions are...unsafe if analysed by a very recent code |4|. On the contrary the 98% fractile of the yearly maximum does not fulfill probability requirements.

- Safety factors depend on the probability level and on the type of structure or structural element considered. At present they are assumed so that the level 1 design is not very different from the one based on the past common practice. In other words the factors γ_{f3}, γ_m and γ_F may be stated on the basis of the old safety factor ν used in the allowable stress design and confirmed by fifty years of common practice. But such a correspondance between γ_{f3}, γ_m, γ_F and ν is not a one-to-one correspondence and hence the results is not unique.
  In order to obtain a better advantage from the degrees of freedom offered by level 1 approaches, a more rational choice of the safety factor values is necessary. In particular the loads require an accurate estimation of the safety factors as they are the structural parameters with greater random uncertainty. Finally, the combination factors $\psi_{o,i}$ cannot be worked out by ancient practice and so they have necessarily to be decided on the basis of a more rational approach.

4. EVALUATION OF THE LOAD COMBINATION FACTORS

A general policy for calibration of the load combination factors (i.e. of the load enhancement factors $\gamma_i = \gamma_{F_i} \psi_{o,i}$) may be summarized in the following steps:

a) choose the criteria for evaluation of the load enhancement factors;

b) define a procedure independent of the actual nature of the considered structure (i.e. of the type of material and construction and of the considered limit state).

Let $\underline{x}$ denote the set of parameters that define a design situation (i.e. loads, resistance and their variability) and D the definition field of the quantities $\underline{x}$ corresponding to the group of structures for which the partial safety factors are to apply. For every design situation $\underline{x}$, different reliability degrees can be obtained by level 1 design procedures making use of different values of the enhancement factors γ_i. In order to optimize these values, in a previous paper |5| suitable "safety" and "economy" requirements have been assumed.

The actual probability of failure p_f associated with this final level 1 design is always required to be lower than a given target level $\bar{p}_f$: $(\bar{p}_f - p_f) \geq 0$ for each $\underline{x}$ (safety requirement) and the sum over D of the deviations $(\bar{p}_f - p_f)$ must be the minimum (economy requirement). In such a way a mathematical programming problem is obtained:

$$\min \sum_j (\bar{p}_f - p_f(\gamma_i))_j \quad \text{(economy requirement)} \quad a)$$

$$(\bar{p}_f - p_f(\gamma_i))_j \geq 0 \quad \text{(safety requirement)} \quad b) \qquad 2)$$

where Eq. (2b) is written for each $\underline{x}$ and also for each of the considered safety domain shapes on which $p_f(\gamma_i)$ depends. Then the solution of the problem (2) may only be applied to the design situations accounted by the constraints (2b). Hence general results would require the solution of a problem with a number of constraints whose computational effort might not be sustained.

In order to formulate an operative procedure, the actual structural properties must be idealized by one conservative safety domain shape that model any structural behaviour. In this way, in fact, constraints (2b) must only be written with reference to different values of the parameters that describe the randomness of the considered actions and of the idealized safety domain (characteristic values, coefficients of variation, type of probability law). Therefore the obtained load enhancement factors hold for the wide group of structures whose parameters belong to the investigated definition field. Obviously a such approach involves a design altogether less economical.
For this purpose it is worth noting that if one considers a family of safety domains each of them may be expressed by one parameter r (i.e. a conventional resistance), the constraints (2b) become:

$$r(\bar{p}) - r(\gamma) \leq 0 \qquad (3)$$

The simplest safety domain for which Eq.(3) holds, is the "hypersphere" in the load space. Furthermore this hypersphere must be considered inscribed in the actual safety domain of the single structure so that a conservative approximation is obtained. Ref. |5| and |6| made use of such a conservative approximation to investigate one of the two tasks that are generally demanded to the enhancement load factors by a level 1 design procedure. It consists in ensuring that, in the load space, the boundary of the safety domain relevant to the limit state of interest is safe enough in the neighbourhood of the meaningful load combinations. The second task, that concerns the definition of the load combinations significant for design purposes, will be discussed in the next point 5. The analysis of the results determined under the hypersphere assumption has emphasized the following remarks (among others):

(i) the structural resistance against permanent loads must be estimated allowing for enhancement load factors associated with the selfweight and the imposed load that must have the same value. However in the case that different codes for steel and concrete structures are required, the factor of the selfweight is prevalent for concrete structures, while the steel structures are characterized by an higher value of the permanent load factor;

(ii) the safety factor corresponding to the environmental actions is much greater than the one of the permanent loads for both the greater value of the relevant coefficients of variation and the shape of the functions describing their probability law;

(iii) by a stochastic analysis of simultaneous action of two environmental forces, it is possible to point out that the importance of this combination in the design process was underestimated until now.

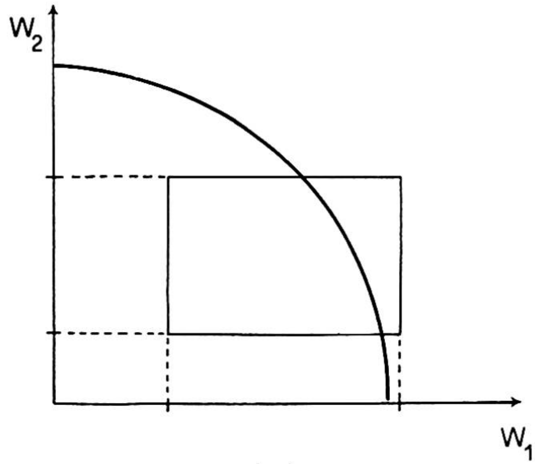

Fig. 1 (from Ref. |7|) - Circumference having as radius the characteristic value of the resistance and definition of two random actions.

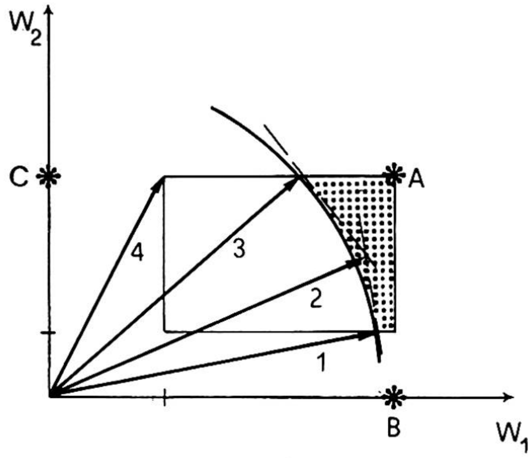

Fig. 2 (from Ref. |7|) - Load combinations meaningful for a level 1 design procedure (case of two loads).

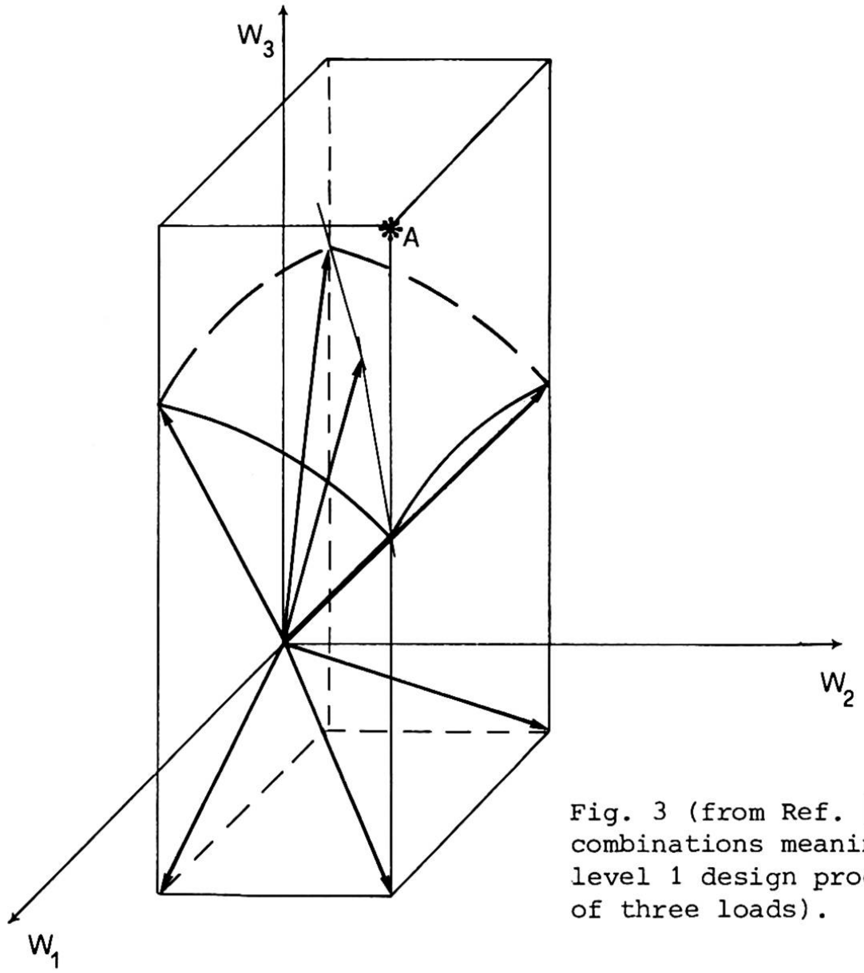

Fig. 3 (from Ref. |7|) - Load combinations meaningful for a level 1 design procedure (case of three loads).

Table 1 - Selfweight W_2 and permanent load W_1: values of γ_i's required to provide the reliability value $(1 - 10^{-5})$

Verification		1		2		3		4		4'	
μ_{W1}	μ_{W2}	γ_{W1}	γ_{W2}	γ_{W1}	γ_{W2}	γ_{W1}	γ_{W2}	γ_{W1}	γ_{W2}	γ_{W1}	γ_{W2}
1	0.2	1.22	0.44	1.22	0.86	1.20	1.29	0.44	1.29	-	-
1	1	1.29	1.20	1.20	1.20	1.20	1.29	0.44	1.29	1.29	0.44
1	4	1.29	1.19	0.86	1.22	0.43	1.23	-	-	0.44	1.29

5. SIGNIFICANT LOAD COMBINATIONS

It is worth noting that a level 1 code format making use of the results obtained by the above approach, would have to prescribe that the safety domain of the final design must be outside the hypersphere whose radius has components $\gamma_{F_i}\ \psi_{o,i}\ F_i$. Such a requirement may appear to be extremely conservative for same real cases. However the coefficients of variation of loads, generally, are not so large that all the load space has to be considered. For each load, one can generally introduce a definition range so that the probability that a value of the relevant load is out of this range is much lower than the target level $\bar{p}_f$ (f.i.: 10^{-7}, if $\bar{p}_f = 10^{-5}$). Thus the subset of the hypersphere safety domain of actual interest is the one shown in Figure 1 for a two-load case. Note that the radius of the drawn circonference is the characteristic value of the resistance.
The previous remark is the basis of a research that is in progress |7|. Some of the results obtained in this research are summarized in the following.

(i) Let W_1 and W_2 be the random loads that act upon a structure; further let their values be constant in time. The present level 1 formats require that the load combinations denoted by stars (points A, B, C) in Fig. 2 are checked. However, by introducing the circumference obtained in Ref. |5|, the dotted zone of Fig. 2 must not necessarily belong to the safety domain to provide the "appropriate" design reliability to the design. Nevertheless the advantage of neglecting the dotted zone is only obtained if the number of load combinations that have to be checked (Fig. 2) is increased. For instance, if W_1 and W_2 are normally distributed with coefficient of variation 10% and mean values μ_{W1} and μ_{W2} respectively, the verifications summarized in Table 1 are required in order to provide $\bar{p}_f = 10^{-5}$;

(ii) The previous approach may appear to be few advantageous for permanent loads, but it becomes very suitable when one must take into account "envi-romental" actions that are characterized by large coefficients of variation and extreme type probability distribution functions. Let W_3 be an enviromental force: in the space W_1, W_2, W_3 the point A (see Fig. 3) involves $\gamma_{W3} = 2.17 \div 2.41$ if a coefficient of variation $c_{W3} = 0.186$ is considered. But, by using the approach proposed in Ref. |7|, γ_{W3} is obtained lower than 1.90 when $\bar{p}_f = 10^{-5}$, $\mu_{W1} = 1$, $\mu_{W2} = 4$, $\mu_{W3} = 5$ and the resistance coefficient of variation is 5%.

(iii) It is worth noting finally that, if $\bar{p}_f = 10^{-5}$ is required in the W_1, W_2, W_3 space (Fig. 3), a greater reliability degree in the plane W_1, W_2 must be achieved |7|. It follows that the values of γ_{W1} and γ_{W2} obtained from the case of Fig. 2 are not conservative in the case of Fig. 3 and so on. Perhaps a solution for such a problem is to consider very high reliability level in estimating the enhancement factors of the permanent loads, so that their values can be maintained as the number of acting loads increases.

ACKNOWLEDGEMENT – The researches discussed in this contribution are supported by grants from Italian National Research Council (C.N.R.) Steel Structures Group

REFERENCES

1. JCSS - Common Unified Rules for Different Types of Constructions and Materials (Bulletin CEB n. 116)
2. "CEB-FIP Model Code for Concrete Structures" - Bulletin CEB n. 124-125
3. CECM-ECCS European Recommendations for Steel Structures, 1978
4. "Calcul des effets du vent sur les constructions" - Recommendations de la CECM, Construction Metallique, n. 3, 1979
5. Casciati, F., Faravelli, L. - Calibration of the Load Enhancement Factors - Engineering Structures, Vol. 2, April 1980, pp. 113-122
6. Casciati, F., Faravelli, L., Zanon, P. - Valutazione probabilistica dei coefficienti di ponderazione dei carichi agenti sulle strutture metalliche (in Italian), Costruzioni Metalliche, n. 6, 1979
7. Faravelli, L. - A Proposal on Load Combination for Level I Formats - to be published