Loading capacity and quality control of precast reinforced concrete structures

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Charge ultime et contrôle de qualité d'éléments préfabriqués en béton armé

Traglast und Qualitätskontrolle von vorgefertigten Stahlbetonbauteilen

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SUMMARY
On the basis of a probabilistic structural analysis it is shown that it may be possible and convenient to avoid the production control of precast structural elements in reinforced concrete provided that the materials themselves have been submitted to a production control by means of control charts.

RESUME
Sur la base d'une méthode d'analyse probabilistique de la sécurité des structures, il est possible d'éviter le contrôle de la production des éléments préfabriqués en béton armé, à condition que soit effectué un contrôle complet de la production du béton et de l'armature au moyen de cartes de contrôle.

ZUSAMMENFASSUNG
Es wird mittels einer wahrscheinlichkeitstheoretischen Erfassung der Tragwerksicherheit gezeigt, dass es möglich und nützlich ist, die Produktionskontrolle von Stahlbetonfertigteilen zu vermeiden, sofern die Produktionsprüfungen der Baustoffe mit "Kontrollkarten" durchgeführt werden.

INTRODUCTION

For some time now it has been accepted in construction practice that a probabilistic analysis is needed to assess structural safety, since the traditional deterministic method are too obviously limited [1]. This idea is gaining ground in Italy, too, as shown by its extension to the national Code in its periodic revision [2]. The CNR (National Research Council) also gives great importance to the probabilistic approach in its instructions on the design of reinforced concrete structures [3], [4].
Safety up to a given limit-state, which would be an indication that the structure was out of service, is worked out by comparing two randon variables (or stochastic processes) generally called "capacity" (strength) and "demand" (external actions). Generally speaking, demand can only be described in terms of statistics, since it is normally under the control of the designer.
On the other hand it certainly is possibe, at the design stage, to assign limits within which the capacity can vary (specified in the design), so as to make the most economic choices for a given safety level.
Recently, too, it has been shown that only through the application of probabilistics can the contrasting interests of structural safety and economic production be reconciled for precast elements [5]. In this case, with reference to the carrying capacity of a beam (shown by the ultimate load multiplier λ) the distribution function F (λ) is established.
Now, it can be shown [6] that the coefficients of variation for the geometrical imperfections are much smaller than for the strengths of the materials, so F (λ) depends above all on the probability density functions which describe the strengths of the steel and the concrete. So these functions can be taken as representing the "quality" of the materials (the r.v. being normal or gaussian) [7].
When the coefficients of variation for the geometrical imperfections are not negleagible the number of r.v. increases and the numerical processing is more burdensome (e.g. to work out the failure probability distribution function of a simply supported variable cross section r.c. beam using UNIVAC 1108, the CPU time is about 15 min.).
So for isostatic structures (widespread in prefabrication), and limited to the question of quality control, only capacity need be considered, and this can be done by examining the capacity of each individual member [8].
After working out the distribution function F(λ) of the failure probability (which describes the quality of the product) the necessary data become available for setting up the quality control, which can be carried out through the two following steps:

- statistical control of the load-bearing capacity of the structural elements through the production control of the mechanical characteristics of the materials, so as to minimize the time and labour dedicated to the testing side of control work;
- acceptance tests on the various lots produced, carried out according to sampling plans and testing methods previoulsy agreed between producer and client.

Generally the producers of precast r.c. structures do not perform a complete control of the production neither on structural elements nor on component materials. Acceptance tests of the materials call for the only control of the fraction of defectives which must comply with the expected characteristic values. These ones are conventionally associated with a proportion of defectives equal to 5%.
The only control of the fraction of defectives does not guarantee (in terms of probability) the reaching of a pre-established safety level of structures. Consequently it is necessary to put under control the whole distribution of the strengths of materials, taking care of concrete due to its greater coefficient of variation (from 15% to 30%).
Generally the strengths R_s and R_c of such materials have a normal law of distribution. Under this hypotesis and in view of finding the distribution function F(λ) of the failure probability it is necessary and sufficient to perform the control of two parameters for each r.v. (e.g. the mean value η and the standard

deviation σ) instead of one only, as usually happens.
As it will be shown in what follows by working out a simple structural model, it is interesting to notice that loading capacity especially depends on the s.d. σ_c of concrete being pre-established its characteristic strength R_{ck} (fig. 1).

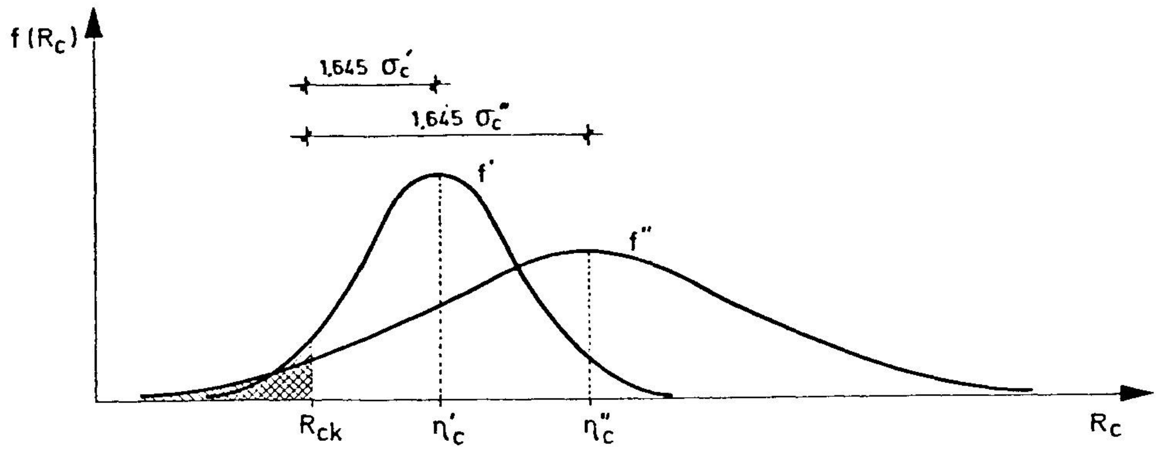

FIG. 1 Strength distributions of concrete

The randon variability of the geometrical imperfection of r.c. precast elements or structures and the one of the strength of materials are generally taken into account by proper design criteria partially or wholly based on the probabilistic methods of analysis.
By putting the production process under control the eventual changes of the law of distribution of randon variable may be avoided.
The control is exerted by means of two well-known statistical procedures based on the control charts (if reference is made to production control) and on the sampling planes (if reference is made to acceptance testing).
On the other hand if the systematic causes of deviation belong to the class of rare and temporary events (human errors, bad workmanship, unproper informations and so on) the inspection must be carried out on all r.c. precast elements or assembled structures.
Every event of the previous class can be represented throungh an impulsive function so that it is not influent on the law of distribution of r.v. which only refers to the stochastic variability of the production process of r.c. precast elements or structural assembling. Consequently such events do not modify the normal law of distribution of r.v. and therefore they are not taken into account in what follows.

THE MODEL

For sake of simplicity this research complies with a model of a particular frame (Fig. 2). This is made by rigid elements connected by two hinges and with three deformable cells quite similar to the Shanley's cell. Here two types of cells have been considered: the "beam" type and the "beam-column" type. The former is assumed to have a steel fiber (s) at the botton and a "composite" fiber (sc) at the top (made by a steel bar surrounded by concrete perfectly bonded).
The latter is assumed to have two composite fibers (sc); a proper choice of the e/l ratio succeeds in putting these fibers under compressive stresses so that cracking can be avoided.
Owing to the normal distribution of r.v. (R_c and R_s) the strength of the composite (sc) results a r.v. having the mean value and standard deviation respectively:

$$\eta_{sc} = \eta_c + \frac{1}{m}\eta_s \; ; \quad \sigma_{sc} = \sqrt{\sigma_c^2 + \frac{1}{m^2}\sigma_s^2},$$

being $m = A_c/A_s$ the ratio between the concrete cross section (A_c) and the steel one (A_s).

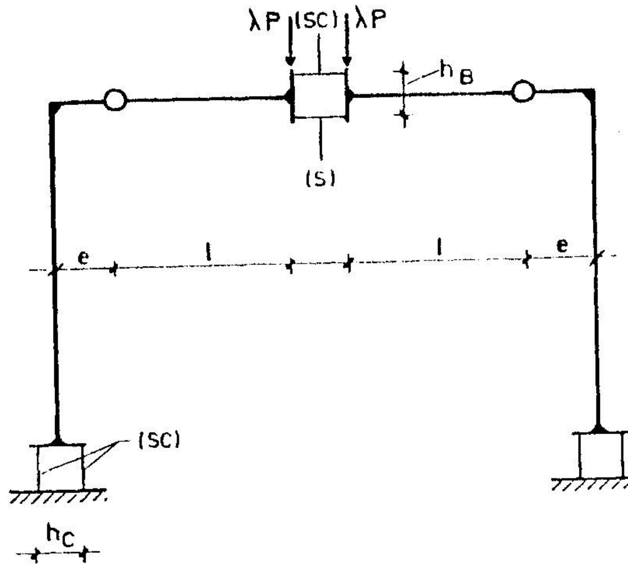

FIG. 2 The model of the frame

According to the model previously described and referring to the symbols of fig. 2, the failure probability Q_B of the beam is:

$$Q_B=1-P\{(N_{i(sc)}>N_{e(sc)})\cap(N_{i(s)}>N_{e(s)})\}=1-P\{(A_cR_c+\frac{A_c}{m}R_s)>\lambda\frac{Pl}{h_B}\}.P\{A_sR_s>\lambda\frac{Pl}{h_B}\}=$$

$$=1-[1-P\{(R_c+\frac{1}{m}R_s)\leqslant\lambda\frac{Pl}{A_ch_B}\}].[1-P\{R_s\leqslant\lambda\frac{Pl}{A_sh_B}\}]=1-[1-P\{\frac{R_{sc}-\eta_{sc}}{\sigma_{sc}}\leqslant\frac{\lambda\bar{s}_c-\eta_{sc}}{\sigma_{sc}}\}].$$

$$.[1-P\{\frac{R_s-\eta_s}{\sigma s}\leqslant\frac{\lambda\bar{s}_s-\eta_s}{\sigma_s}\}]$$

being $\bar{s}_c=\frac{Pl}{A_ch_B}$; $\bar{s}_s=\frac{Pl}{A_sh_B}$; $R_{sc}=R_c+\frac{1}{m}R_s$.

The failure probability Q_c of the column is:

$$Q_c=1-P\{(N_{iL}>N_{eL})\cap(N_{iR}>N_{eR})\}=1-P\{N_{il}>N_{eL}\}.P\{N_{iR}>N_{eR}\}=1-P\{(R_c+\frac{1}{m}R_s)>\lambda.$$

$$.(\frac{P}{2A_c}+\frac{Pe}{A_ch_c})\}.P\{(R_c+\frac{1}{m}R_s)>\lambda.(\frac{P}{2A_c}-\frac{Pe}{A_ch_c})\}=1-[1-P\{\frac{R_{sc}-\eta_{sc}}{\sigma_{sc}}\leqslant\frac{\lambda\bar{s}_c-\eta_{sc}}{\sigma_{sc}}\}].$$

$$.[1-P\{\frac{R_{sc}-\eta_{sc}}{\sigma_{sc}}\leqslant\frac{\alpha\lambda\bar{s}_c-\eta_{sc}}{\sigma_{sc}}\}],\ \text{being}\ \bar{s}_c=\frac{P}{2A_c}+\frac{P.e}{A_ch_c}\ \text{and}\ \alpha=1-2\frac{P.e}{\bar{s}_cA_ch_c}.$$

In the previous formulas indices i and e mean respectively "internal" and "external"; indices L and R respectively "left" and right".
The failure probability Q_T of the assembled structural elements is:

$$Q_T = 1 - (1 - Q_B) . (1 - Q_C)^2 .$$

The results of the numerical analysis are worked out with the aid of the table of the values of the standardized normal distribution.
As an example a typical result is given in Table I.
It is interesting to note that the function Q_T (λ) for $\lambda \geqslant 2.5$ is virtually insensitive to variations in the s.d. values σ_c that may result in constructive practice ($\sigma'_c = 4.25$ MPa $\leqslant \sigma_c \leqslant \sigma''_c = 8.5$ MPa).

TABLE I - Values of the failure probability.

λ	σ'_c = 4.25 MPa	σ''_c = 8.5 MPa	Q''_T/Q'_T	NOTE
	Q'_T	Q''_T		
1.	2.9×10^{-9}	3.2×10^{-5}	16000	R_{ck} = 25. MPa
1.5	3.2×10^{-5}	2.7×10^{-4}	8.5	$\bar{s}_c$ = 8.5 MPa
2.	2.2×10^{-2}	2.4×10^{-2}	1.1	R_{sk} = 320. MPa
2.5	50.1×10^{-2}	50.6×10^{-2}	$\simeq$ 1.	$\bar{s}_s$ = 160. MPa
3.	97.9×10^{-2}	97.9×10^{-2}	1.	σ_s = 40. MPa
$m \to \infty$ for the beam type cell ; $\alpha = 1$				

For our purposes the ratio Q''_T/Q'_T is significant.
For a given characteristic strength of the concrete (e.g. R_{ck} = 25 MPa and consequently $\eta_c = R_{ck} + 1,645\ \sigma_c$) varying the load multiplier within the interval $1.5 \geqslant \lambda \geqslant 1$ (the most interesting in the province of structural engineering) the failure probability increases with σ_c. Redoubling the s.d. value from σ'_c = 4.25 MPa (typical of production under control) to σ''_c = 8.5 MPa (typical of uncontrolled production) failure probability increases quite considerably even up to 16000 times.
Obviously the concrete having the s.d. equal to σ'_c allows a safer and less expensive technical solution (in fact $\eta'_c < \eta''_c$) than the one resulting from the use of concrete having the s.d. equal to σ''_c.
It is this which makes inseparable the problem of the structural safety (represented in probabilistic terms by Q_T (λ)) from the one of economic nature.
On the other hand the comparison within all the results so far obtained shows the inadequacy of the actual provisions of the national codes for the r.c. precast structures. Consequently it is necessary that codes improve the present instructions about the procedures of the production control of the materials compelling manifacturers to use control charts. So it is possible to get the probability distributions of the strength of component materials and the approach of structural production control suggested here (that is an indirect method to assess the "structural quality") becomes operating.

CONCLUSION

The results of a probabilistic analysis carried out on the loading capacity of the model of a simple precast r.c. frame show that is both possible and vantageous to replace direct with indirect production control of structures. Indirect quality control only checks the quality of the component materials and brings obvious advantages in terms of money and rapidity in dealing out of-services situations. Probabilistic analysis also offers design guide-lines for the best choice of the quality of the materials for a given safety level.
If the approach suggested here is adopted, the complete production control of the materials has to be peremptory exerted to get both the chosen safety level and highest economy.
Generally the production control of steel is carried out at steel plants. Therefore, referring to the production control of concrete, each manifacturer of precast r.c. structures takes up a position among those defined afterward.

- Concrete production control is not carried out; the mean value η_c of the r.v. R_c is reduced and the standard deviation σ_c increases. Therefore the probability of the structural failure is on the increase and overall costs bring down.

- Only the control of the fraction of defectives is carried out; both the probability of structural failure and the prime costs increase (being constant R_{ck}).
  The incomplete exertion of production control is doubly unfavourable.
- Production control is exerted through two parameters (usually the mean value η_c and the standard deviation σ_c). As a consequence of this position the probability distribution function of the ultimate load multiplier may be worked out and the assessment on the "structural quality" may be given by means of the indirect method of control, presented here. So it is possible to conciliate the problem of structural safety with the demand of cheap production control. The tendency (still widespread in Italy) to avoid any kind of control must inevitably be abandoned.

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