SUGGESTED NON-DESTRUCTIVE METHOD FOR STRENGTH ASSESSMENT

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1. Introduction

The most important field of application of non-destructive concrete tests is ulterior strength control of erected engineering structures or of mass concrete products. Strength can be assessed from stochastic relations between non-destructive characteristics (e.g. ultrasonic velocity, or concrete surface hardness) and mechanical strength characteristics. Stochastic relation means a relation though not unambiguous but where individual results exhibit residual standard deviation around a mean curve expressing the relationship.

Several methods have been developed both to determine the mean curves and to take standard deviation in account. Their analysis has led to the development of the method to be presented below. It was attempted to eliminate contradiction between non-destructive and destructive strength results in actual cases. This goal has been achieved by correct consideration of the standard deviation in accordance with the probability theory.

2. Quantile curves as mean curves

Most authors generally determined empirically possible mean curves by regression analysis. It is, however, wrong for establishing non-destructive strength assessment functions. Namely in regression analysis, one variable value is considered to be exact, and the other as a random variable of normal distribution. Results of both destructive and non-destructive tests being, however, random variables subject to standard deviation, starting conditions of regression analysis fail. The contradiction is manifest by the possibility to construct two regression functions assuming either the first or the second independent random variable to be exempt of standard deviation.

The suggested assessment functions will be given by Reimann's quantile functions rather than by regression analysis. REIMANN [1] stated a functional relationship to exist between stochastically related random variable values for identical probability levels. He named this function a quantile function, featured by the ability to minimize residual standard deviation simultaneously with respect to either random variable. The approximate value of quantile functions has been determined from ordered samples of random variables. In the subsequent description of our method, mean curves will always be understood as quantile curves.

3. Criticism of known strength assessment systems

Mean curves can be plotted from random samples tested to failure or from planned test results. A test on random samples may be erroneous if frequent occurrence of certain concrete types distorts the random character. In a planned test, the plan, the kind of examined characteristics may decisively affect the mean curves.

In either case, an important residual deviation from the mean curve results.

Residual standard deviation has been shown to have a real and a virtual part [2].

The virtual residual standard deviation depends on the mean curve slope, and its value varies with the slope. This is the simplest to illustrate by designating a point in the mean curve (*P* in Fig. 1). Shifting this point in direction x by Δx and in direction y by Δy results in P', seemingly at a distance $\Delta y'$ from the mean curve. Moving points *P* and P' along the mean curve with constant deviations Δx and Δy, the virtual residual deviation will vary. Obviously, a virtual residual deviation in direction y subsists even for zero deviation in this direction but non-zero deviation in direction x (Fig. 1b).

For safety's sake, strength of structures is generally assessed by means of a function much below the mean curve. Either the mean curves are assumed lower or a threshold curve is constructed at a given probability level of the residual standard deviation range, a principle underlying e.g. the Schmidt hammer of Proceg Co.

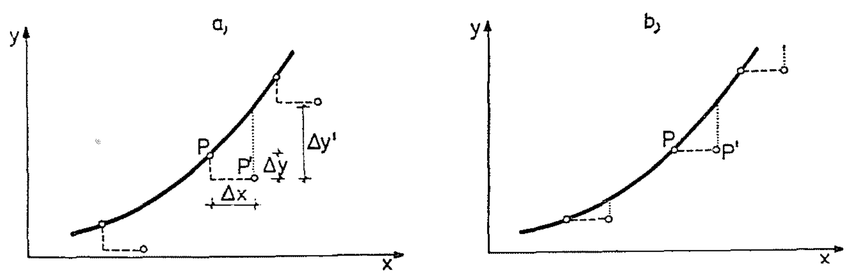

Fig. 1. Virtual and real residual standard deviation

The actual practice of reckoning with residual deviations at random is incorrect. Namely the distribution of residual standard deviations is applied to construct a threshold curve where e.g. 0.1 of individual test results fall below. (The value at $F(x) = 0.1$ of the distribution function of the residual standard deviations is taken into account.) Thereafter the deviation between the mean curve and the threshold curve is deduced from all the test results, hence from the 100%. Though, in case of a symmetric residual distribution, it would be justified to increase 0.1 of the results by as much. This is why non-destructive strength assessments generally yield low values, unsupported by mechanical control tests.

Another paper of this review [3] will show also parameters of non-destructive strength assessment mean curves to be random variables, individual mean curves fluctuating around an overall mean curve.

Deviations between test results and the overall mean curve are of no purely random character, the residual difference consists of a constant (systematic) and a random part. As a consequence, applying a mean curve not referring to the given test set (e.g. concrete in a structure) for strength assessment, the systematic error will affect the entire investigation. Thus, the practice to consider deviations as random fluctuations around the overall mean curve is faulty.

Concrete technology factors reducing the strength shift the strength assessment functions downward. Hence, a strength loss due to a significant change of the given concrete technology parameter but assessed on the overall mean curve will appear better than it really is.

Thus, the actual practice of non-destructive strength assessment is affected by fundamental contradictions, setting limits to the extension of non-destructive strength assessment.

4. The suggested strength assessment system

4.1. *Fundamentals of the method*

The method is based on separating deviations — systematic from the aspect of the structure — of the mean curve referring to that structure from the overall mean curve, and the in fact residual deviations of the individual test results from the mean curve referring to the structure.

The mean curve referring to the structure may be assumed differently, depending on the available information on the concrete.

Only differences between the mean curve referring to the structure and the individual measurement results are considered as residual deviation, and reckoned with as a random fluctuation with positive or negative sign as the case may be.

4.2 *Assumption of the overall mean curve*

The overall mean curve has been obtained from a test planned taking many concrete technology parameters into consideration. As a check, quantile functions from other sources have been examined. Also these empirical quantile functions were found to run in the field of probabilities obtained in our test.

4.3 *Assumption of mean curves referring to a structure*

Functions expressing the action and interaction of concrete technology parameters in ultrasonic tests fit a curve set derivable from the overall mean curve with multiplier and additive constants:

$$\sigma_i = \alpha_i(\sigma_0 + \Delta_i)$$

where σ_i — ordinate of the i-th function over some abscissa;
σ_0 — ordinate of the overall mean curve over the same abscissa;
α_i — multiplier constant;
Δ_i — additive constant.

Also, relationship

$$\alpha_i = f(\Delta_i)$$

is linear, hence correction terms can be calculated from each other. The field of curves is seen in Fig. 2. Considering them as class limits permitted to determine statistic characteristics (multiplication, probability levels) of the field of probabilities consisting of the mean curves.

Mean curves referring to the structure are determined directly from tests on the structure, or appointed in the probability field above. Threshold curve of 0.05 probability is seen in Fig. 2.

Practically, there are four cases of assuming the mean curves.

4.4 *Specific empirical function*

The specific quantile function is plotted from non-desctructive and destructive test results on great many specimens taken from, and identically treated with the structural concrete. In case of continuous prefabrication, the specific empirical relationship is established by a preliminary test, taking expected fluctuations into consideration. The function shape is perfectly independent of the overall field of curves (see Fig. 2). The obtained relationship is only valid for the given structure or product but offers the most reliable assessment. This method is accepted in expertize.

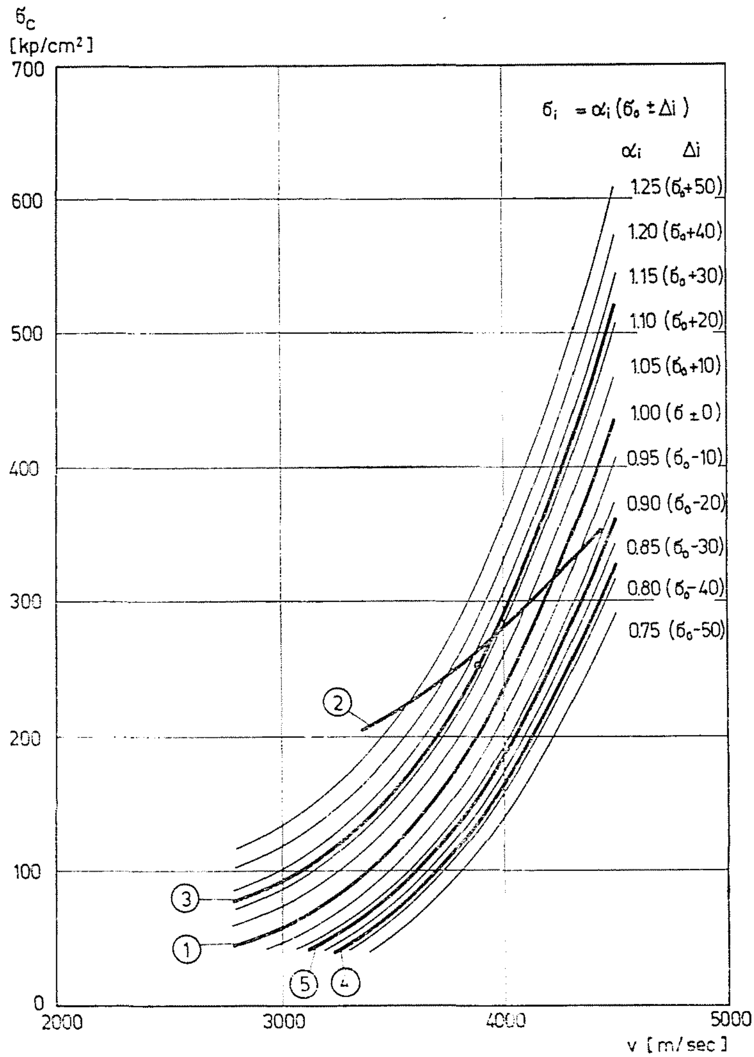

Fig. 2. Assumption of mean curves

4.5 *Strength assessment and accessory checking by tests to failure*

This method is based on assessing a point of the mean curve on the basis of non-destructive characteristic averages obtained on a low number of control specimens taken from the structure, using the mean curve passing through this point and fitting the described field of probabilities (see Fig. 2). In practice, strength values read off the overall mean curve are corrected by a and Δ values determined by the checking point. This method is involved in an agreed standard for non-destructive testing [4].

4.6 *Strength assessment exclusively from non-destructive tests*

This method yields only an informative strength value. Essentially, strength is assessed by a threshold curve of low probabilities (actually $F(x) = 0.05$). These mean curves of low probabilities are imposed by a complete lack of information on the concrete. Notice that neither this method is identical with the conventional assessment based on a threshold curve.

4.7 *Strength assessment from known concrete technology parameters*

This method may be applied when no control test to failure is made but certain concrete technology data are known at a sufficient confidence. The method consists essentially in increasing — until further tests — the strength values assessed on the low-probability mean curve according to item 4.6 by taking the average increasing effect of at most two known concrete technology values into consideration. The most probable value of assessed strength is given by relationship

$$\sigma_i = \sigma_i^5 + \Delta_1 + \Delta_2$$

where σ_i^5 — a value read off the threshold curve of 0.05 probability;
Δ_1 and Δ_2 — are the two highest values in Table I doubtless corresponding to a known concrete technology factor level.

Table I

Correction depending on concrete technology values

Factor	Level	Δkp/sq·cm
Cement	C 450	8
D_{max}	⌀ 16 mm	15
Grading	1st class	25
w/c	0.35	10
Cement dosage	300 kg/cu · m	20
Adequately compacted		10
Water cured		7

4.8 *Reckoning with the residual standard deviation*

According to our examinations, the deviation around the empirical mean curve is of normal distribution at a fair approximation. Its standard deviation s_{res} can be determined by known methods.

Individual test results are classified in a few (e.g. five) groups using a table of random numbers. One fifth of the results is reduced by Δ_r times the standard deviation, and another fifth increased by as many. Δ_r values have been compiled in Table 2 assuming normal distribution.

Table II

Correlation factor values from residual standard deviation

Class No.	Δ_r
1	−1.20
2	−0.50
3	±0.00
4	+0.50
5	+1.20

Individual assessed strength values are calculated by random correlation of strength values assessed on the mean curve:

$$\sigma_{i\,\mathrm{corr}} = \sigma_i + \Delta_r \cdot s_{\mathrm{res}}$$

where $\sigma_{i\,\mathrm{corr}}$ — corrected strength;
σ_i — strength assessed on the mean curve;
Δ_r — multiplier of the likely residual standard deviation;
s_{res} — the likely residual standard deviation.

In case of a specific empirical function, the likely residual standard deviation is the actual residual standard deviation; in case of a checking test to failure it is the standard deviation of deviations from the average, in other cases it is an empirically assumed value.

Practically, correlation is made by writing down the σ_i values in the order as observed, then all test results are assigned some Δ_r value by chance on the basis of its numeral (Table of random numbers).

The corrected assessed strength values can be considered as equivalent to ultimate strength values each from the aspects of both the average structural strength and the standard deviation of quality.

Summary

Ultimate strength as reference basis can be assessed by non-destructive methods. The assessment is based on stochastic relationship between ultimate strength and non-destructive characteristics.

Deviations between individual test results and the general main curve have been divided in two groups, differentiating between deviations of the mean curves for a given structure from the general mean curve, and those of individual test results from the mean curve for the structure, assumed in either of four ways.

Residual deviation from the mean curve for the structure is considered as of random character. Correction is applied in $\pm$ sense, reckoning with normal distribution.

Processing results in assessed strength values equivalent to cube strengths.

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