Design assisted by testing – a powerful tool for the evaluation of material properties and design resistances from test results

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***Abstract*—**Methods of the design assisted by testing philosophy can be used as the suitable and applicable tools for the determination of material properties and design resistances of structural members or components, especially if no other tools are usable. During the last two decades new advanced non-traditional building materials have been developed, but their physical-mechanical properties, namely their characteristic and design values and partial safety factor are not generally known. One of the possible ways how to determine characteristic and design values of material properties is the determination using the philosophy of the design assisted by testing. The paper is focused on the application of the methods of the design assisted by testing for the determination of material properties of cement composites reinforced by fibres using mainly for the building façade claddings, but also as a part of load-carrying structures, according to our experiences for the slab of steel-concrete composite beams, for example. The methods of the design assisted by testing are based on the evaluation of the experimental results arising from the statistical and probabilistic approaches. The procedures for the determination of characteristic and design value of the material property is usable not only for usual cases of the large test number, but also for small or very small test number, where the test number, type of the property distribution and its statistical characteristics are taken into account. In the recent period also new structures and structural details have been developed and used in practice, so that many times the design using test results only allows determine the design resistances of structural members, details or parts. On that account it is important and interesting to deal with the problems of the design resistance evaluation not only from the viewpoint of the influence of the test number and statistic parameters of variables directly determining the design resistance value, but also from the viewpoint of the mathematical function form of the design resistance model, which can be significant for the resulting design resistance. On several particular examples, the standard procedure for the design resistance evaluation with respect to the test number, mathematical exactness and complexity of the resistance model and variability of the basic variables is shown.

***Keywords*—**Design assisted by testing, design value, experiment, mathematical model, material property, statistic parameter, resistance model, standard procedure, test result, variable, variation coefficient.

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I. Introduction

THE philosophy and the principle approach of the design assisted by testing described e.g. in [4], [10], [24] and going to the procedures for the determination of characteristic and design values of material properties and for the evaluation of the design resistances are known generally. The procedures determining the characteristic and design material properties based on the statistical elaboration of test results, as well as are the standard procedures evaluating the design resistances are given in [24].

Within the framework of the extensive and permanent experimental research realized on the author's workplace in the last several years and oriented to the experimental verification of the actual behaviour, failure mechanism and load-carrying capacity of various civil engineering load-carrying structural members (see e.g. [5], [12], [13], [14], [16], [17]), the methods based on the design assisted by testing are utilized for the determination of design material properties and design resistances.

II. Methods of the Design Assisted by Testing – Generally

A. Characteristic and Design Values of Material Properties

Characteristic and design values of the material properties, taking into account number of the tests n, statistical distribution of the material property and its variability expressed by the variation coefficient, can be determined according to [24] as follows:

Assuming the normal distribution of the material property X, characteristic and design values X_k and X_d shall be determined using formulas:

$$X_k = m_X \cdot (1 - k_n \cdot v_X), X_d = m_X \cdot (1 - k_{d,n} \cdot v_X) \tag{1}$$

Assuming the log-normal distribution of material property, X_k and X_d shall be determined by:

$$\begin{aligned} X_k &= \exp(m_{\ln X} - k_n \cdot s_{\ln X}) \cong m_X \cdot \exp(-k_n \cdot v_X) \\ X_d &= \exp(m_{\ln X} - k_{d,n} \cdot s_{\ln X}) \cong m_X \cdot \exp(-k_{d,n} \cdot v_X) \end{aligned} \tag{2}$$

where m_X, $m_{\ln X}$ are mean values, v_X is variation coefficient; $s_{\ln X}$ is standard deviation; k_n, $k_{d,n}$ are fractile factors (values of fractiles for normalize normal distribution) respecting test number n and shall be taken from Table I (for detail see [24]) (usage of "v_X known" for v_X known from former experiences, "v_X unknown" for v_X determined from test data set).

Table I fractile factors

n	1	2	3	5	10	20	30	∞
fractiles	k for 5% characteristic value							
v_X known	2.31	2.01	1.89	1.80	1.72	1.68	1.67	1.64
v_X unknown	---	---	3.37	2.33	1.92	1.76	1.73	1.64
fractiles	k_d for 0.01% design value							
v_X known	4.36	3.77	3.56	3.37	3.23	3.16	3.13	3.04
v_X unknown	---	---	---	7.85	4.51	3.64	3.44	3.04

B. Characteristic and Design Resistances

The standard procedure [24] for the design resistance evaluation helping test results is generally based on the comparison of the experimental resistances $R_{ex,i}$ obtained from the tests and theoretical resistances $R_{th,i}$ calculated according to the apposite theoretical resistance model substituting (particularly for each test i) actual measured geometrical and mechanical properties for the quantities Xj, and subsequently on the statistic evaluation of the probabilistic resistance model with respect to the test number n, statistical variability of the input variables Xj influencing the resistance and uncertainties of the resistance model.

Characteristic and design resistances R_k, resp. R_d are based on the required probability that the resistance value R is less than R_k with the probability of 0.05, resp. R_d with the probability of 0.000 1. Considering the lognormal distribution, for the design resistance R_d the condition (1) must be satisfied

$$P\left(R < R_d\right) = P\left(\frac{R}{R_d} < 1\right) = P\left(\ln R - \ln R_d < 0\right) = \\ = P\left(\ln R < \ln R_d\right) = 0.0001 \tag{3}$$

Using the transformation of the quantity ln$R$ to the normalized quantity ln$R$ according to (2)

$$\underline{\ln R} = \frac{\ln R - m_{\ln R}}{s_{\ln R}} \Rightarrow \ln R = \underline{\ln R} \cdot s_{\ln R} + m_{\ln R} \tag{4}$$

the probability is given by the formula (3)

$$P\left(\ln R < \ln R_d\right) = P\left(\underline{\ln R} \cdot s_{\ln R} + m_{\ln R} < \ln R_d\right) = \\ = P\left(\underline{\ln R} < \frac{\ln R_d - m_{\ln R}}{s_{\ln R}}\right) = 0.000\,1 \tag{5}$$

where $m_{\ln R}$ and $s_{\ln R}$ are mean value and standard deviation of the resistance logarithm ln$R$.

If the test number n is small (n < 100), the design resistance R_d can be given by (6) (for more see [4], [10], [24])

$$R_d = m_R \cdot \exp\left(-k_{d,\infty} \cdot \frac{s^2_{\ln Rth}}{s_{\ln R}} - k_{d,n} \cdot \frac{s^2_{\ln \delta}}{s_{\ln R}} - 0.5 \cdot s^2_{\ln R}\right) \cong \\ \cong m_R \cdot \exp\left(-k_{d,\infty} \cdot \frac{v^2_{Rth}}{v_R} - k_{d,n} \cdot \frac{v^2_{\delta}}{v_R} - 0.5 \cdot v^2_R\right) \tag{6}$$

where for the variation coefficient small values $s_{\ln Rth} \cong v_{Rth}$, $s_{\ln\delta} \cong v_\delta$, $s_{\ln R} \cong v_R$, the fractile factor $k_{d,n}$ must be taken for "v_X unknown" and corresponding test number. The mean value m_R of the resistance is given by (7)

$$m_R = b \cdot g_{Rth}(m_{Xj}), \tag{7}$$

where the correction factor b is determined by regression analysis according to (8) and the error term δ can be calculated by the form (9)

$$b = \frac{\sum_{i=1}^{n} R_{th,i} \cdot R_{ex,i}}{\sum_{i=1}^{n} R_{th,i}^{\;\;2}}, \tag{8}$$

$$\delta_i = \frac{R_{ex,i}}{b \cdot R_{th,i}} \tag{9}$$

The variation coefficient v_R representing the resistance variability can be obtained using the variation coefficient v_{Rth} showing uncertainties in resistance model and the variation coefficient v_δ of the error term δ representing differences between experimental and theoretical resistance values, in the case of small values of v_{Rth} and v_δ from (10)

$$v_R = \sqrt{v^2_{Rth} + v^2_\delta}, \tag{10}$$

where v_{Rth} is given by the equation (11)

$$v^2_{Rth} = \frac{VAR[g_{Rth}(X)]^2}{g^2_{Rth}(m_{Xj})}. \tag{11}$$

The variation coefficient v_{Rth} is given by variation coefficients v_{Xj} (expressed by standard deviations s_{Xj}) of basic variables X_j and depends on the complexity of mathematic function significantly. Variation coefficients v_{Xj} should be used from previous experiences (recommended and preferred).

III. Characteristic and Design Values of Glass-Fibre-Concrete Properties from the Large Test Number

The paper author's workplace (Division of Metal and Timber Structures of the Faculty of Civil Engineering at the

Brno University of Technology) in the co-operation with the Research Institute of Buildings Materials “VUSTAH” (Brno) deals with the problems of the determination of the physical-mechanical properties of two types of glass-fibre-concrete produced by two different technologies. The works were directed towards the experimental determination of bending-tension strength and corresponding modulus of elasticity from the viewpoint of the influence of material type and production technology upon the properties. By the statistic and (partially, respectively) probabilistic evaluation of test results, characteristic and design values of investigated parameters have been obtained and compared with respect to utilized production technology. The first example of the determination of glass-fibre concrete properties is a case of larger number of the tests in the range of about of 70 to 80 tests, but less than 100 tests.

A. Test Specimens

The specimens of two types of glass-fibre-concrete from the viewpoint of material configuration and structure have been tested: (i) glass-fibre-concrete with spatially dispersed glass fibres; (ii) glass-fibre-concrete with glass-fibre reinforcement in the form of rectangular net. Test specimens had the form of the bar of the rectangle cross-section with nominal dimensions of 50 x 10 mm. The actual cross-section dimensions have been measured for each specimen. The length l was chosen 300 mm in the case of specimens (i) and 400 mm in the case of specimens (ii) with regards to the considered span L of tested beams and assumed different load-carrying capacity according to different material.

B. Test Set-up

For the determination of the bending tensile strength the test by three-point flexure (see illustration in Fig. 1) has been used: Test specimen was simple supported beam with the span of L and has been subjected to the force F in the span middle. Test specimens have been sorted to three groups according to the span, to investigate and eliminate the problem of possible size-effect. Test numbers in particular groups are seen from Tab. II.

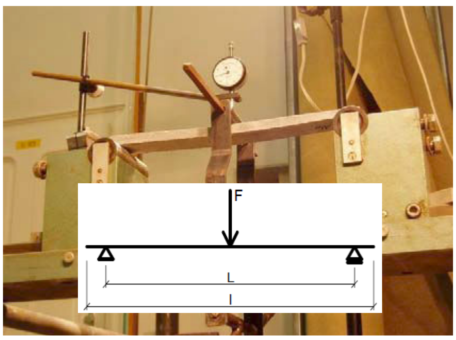

Fig. 1 test set-up

C. Test Realization

Because of the assumed low load-carrying capacity the loading have been realized mechanically using the weight set of the value 10 kg, 5 kg and 1 kg. Loading force was introduced step by step to be at least 10 loading steps in common. For each loading step the deflection w in the span middle has been measured. The loading process continued up to the reaching the ultimate load-carrying capacity with the failure of the specimens in parallel. The failed specimens are shown in Figs. 2 and 3. In figures the differences in the structure of material produced by different technologies are evidently seen.

D. Test Results

During the loading the behaviour of test specimens in the failure process has been monitored, to investigate strain and subsequent failure mechanism and to observe the force and deformation quantities available for the determination of mechanical material properties, hereto bending tensile strength and modulus of elasticity.

Fig. 2 failed test specimens – material (i)

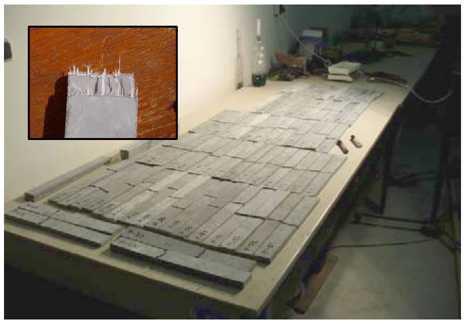

Fig. 3 failed test specimens – material (ii)

From the objective ultimate force F_u corresponding with the relevant failure state the ultimate bending moment M_u can be obtained as $M_u = F_u \cdot L / 4$, from where the maximum normal stress $\sigma_{bt,u} = M_u / W$ is the base for the determination of bending- tension strength $f_{bt,u} = \sigma_{bt,u}$, its mean value $f_{bt,m}$, characteristic value $f_{bt,k}$ and design value $f_{bt,d}$, eventually.

During the loading process the relationship between the force F and corresponding vertical deformation w in the place of the loading force. This relationship has been transformed to the relationship between the stress σ and deflection w. Selected illustrative example of „$\sigma - w$“ curves is depicted by Fig. 4 for material (ii). These relationships have been used also for the derivation of modulus of elasticity E.

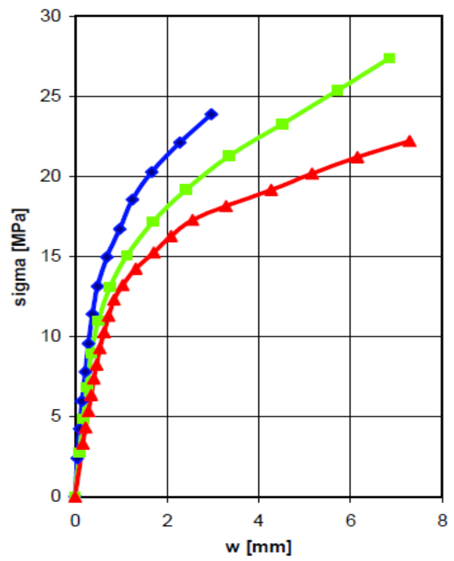

Fig. 4 example of „$\sigma - w$“ curves – material (ii)

E. Determination of Characteristic and Design Values of Material Properties

The experimental results have been elaborated using usual statistical methods and subsequently using the procedure for the evaluation of characteristic and design values of material properties according to the methodology of the design assisted by testing.

The ultimate stresses σu considered as the values of the ultimate bending tensile strength $f_{bt,u}$ have been elaborated using the procedure for the characteristic and design values material properties determination. The character of statistical distribution of bending tensile strength has been verified by the statistic tests. The log-normal distribution with the evident skew is shown by histogram in Fig. 5.

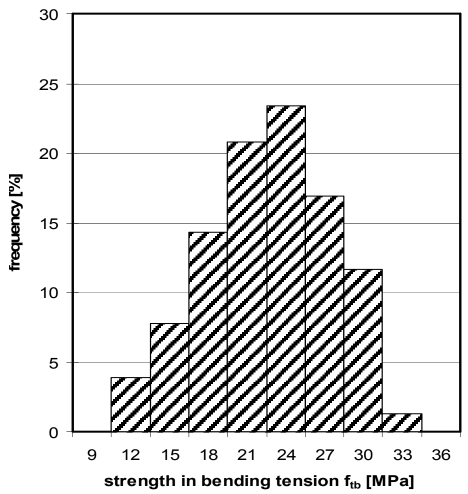

Fig. 5 Bending-tension strength distribution

Using procedures acc. to [24] the characteristic and design strengths have been calculated, important parameters are seen from Table II. Obtained design values are illustrative only, because are influenced by relatively small test number and high variation coefficient. However they can to show preliminary random of relations of design and characteristic values expressed by the safety factor $\gamma_M = f_{bt,k} / f_{bt,d}$.

In Tab. II the results in dependence on glass-fibre-concrete type given by production technology are overviewed. Though practically the same mean values, characteristic and design values for material (ii) are higher than for material (i) because of the large scatter expressed by the variation coefficient value. In the case of the material (i) it is influenced by significantly non-homogenous material structure caused by non-uniformly dispersed glass fibres, which is very good seen on some failed specimens. On the contrary, in the case of material (ii), where the reinforcing is created relatively uniformly by fibre net, the variability of the strength is lower.

Table II Bending tensile strength – glass-fibre-concrete

PARAMETER	material (i) (77 tests)	material (ii) (68 tests)
mean $f_{bt,m}$ [MPa]	21.06	21.62
var. coefficient v	0.231	0.207
char. $f_{bt,k}$ [MPa]	12.78	14.01
design $f_{bt,d}$ [MPa]	4.50	6.40
$\gamma_M = f_{bt,k} / f_{bt,d}$	2.84	2.19

The „$\sigma - w$“ curves, respectively their elastic zone only, should utilize for the modulus of elasticity determination. But the curve for materials based on concrete has non-linear character, so that the secant modulus of elasticity is determined usually. In this case the method usually applied for the modulus of elasticity of concrete. This method derives secant modulus of elasticity from the stress value given as 40% of the maximum stress, that means $\sigma_E = 0.4 \cdot \sigma_{tb,u}$, and the corresponding deflection value w_E. Obtained values of modulus of elasticity E have been statistically elaborated for both material types and mean values and variation coefficients (see Tab. III) giving the scatter of the observed quantity have been derived. From the variation coefficient value for material (i) it is evident, that the influence of non-uniform glass fibres dispersion upon the modulus of elasticity is more significant than upon the strength.

Table III Modulus of elasticity – first example

PARAMETER	material (i) (77 tests)	material (ii) (68 tests)
mean E_m [GPa]	14.95	22.01
var. coefficient v	0.438	0.293

IV. Characteristic and Design Values of Glass-Cement Properties from the Small Test Number

The second example is oriented to the physical-mechanical properties of the particular type of glass-cement used also for building façade panels. These works have been realized in co-operation with the structural design company “KONSEB” (Brno). The project authors and investors had the doubts about the material parameters declared by the producer, because after the installation during the structure erection the cracks occurred in some façade panels. In this case material parameters have been obtained from very small number of material tests realized on the specimens taken from the actual façade panels.

A. Test Specimens, Test Set-up, Test Realization

For material tests of glass-cement 6 specimens have been used only. The rectangle cross-sections had the nominal dimensions 100 x 10 mm and lengths about 300 mm. Material is based on the cement matrix reinforced by dispersed glass fibres. The illustration of the specimen in testing equipment is in Fig. 6.

Fig. 6 test realization

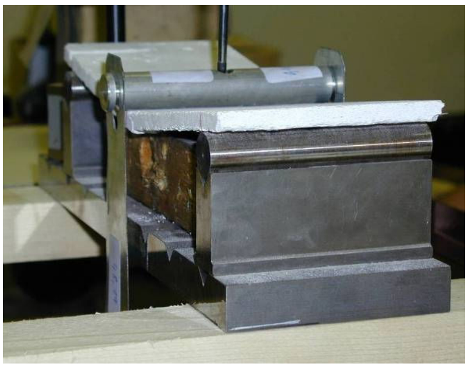

Fig. 7 failed specimen

Because of the similar character of material the test set-up and realization of material tests were practically the same as in the first example (see above) respectively very similar. Test specimens, test set-up, loading process, measurement of quantities, types of test results and their elaboration were in principle the same as in the first example.

B. Test Results

The direct and immediate measured results are information and knowledge on the behaviour of test specimens in the loading process, failure mechanism and load-carrying capacity. The illustration of the failed specimen is in Fig. 7. Graphs of the relationships between loading force F and deflection w for all specimens are drawn in Fig. 8.

C. Determination of Characteristic and Design Values of Material Properties

Also in this case characteristic and design values of material properties have been determined using the design assisted by testing. Because of very small test number here the variation coefficient calculated from the test data gave unusable design values, so that for the evaluation the variation coefficient known from the previous knowledge had to be used.

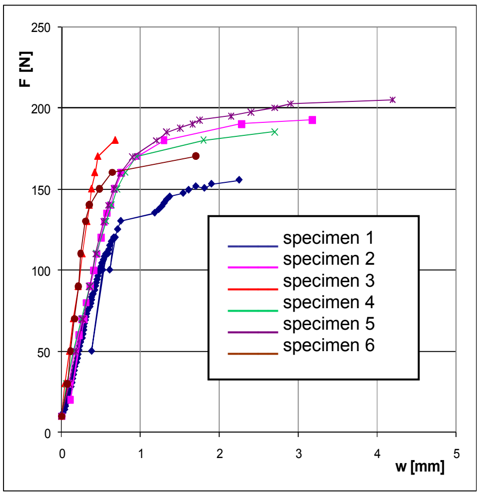

Fig. 8 „$\sigma - w$“ curves – second example

Table IV Bending tensile strength – glass-cement

PARAMETER	v_X unknown	v_X known
mean $f_{tb,m}$ [MPa]	7.485	
var. coefficient v	0.137	0.200
char. $f_{tb,k}$ [MPa]	5.254	0.976
design $f_{tb,d}$ [MPa]	4.835	2.500
$\gamma_M = f_{tb,k} / f_{tb,d}$	---	1.934

The stress calculated from the test results have been elaborated using the same procedure as in the first example. At first for characteristic and design values calculation the variation coefficient “v_X unknown” obtained from the test data has been applied. This approach gave non-economy design values, so that according to the [24] recommendation the variation coefficient known from the previous experiences with similar tests “v_X known” can be used. For this reason the variation coefficient v = 0.20 has been considered as the maximal real value for strengths of similar materials (concrete, glass-fibre-concrete with the behaviour similar to tested material).

Although the variation coefficient for "v_X known" is higher than variation coefficient for "v_X unknown", the resulting characteristic and design value are higher, because in the case of "v_X known" the fractile factors are less than in the case of "v_X unknown" and positively influence characteristic and design values. Overview of statistic parameters and characteristic and design values for both cases ("v_X unknown" vs. "v_X known") are in Tab. IV.

Modulus of elasticity has been calculated according the same principle as in the first example. Similarly to the first example, also here for the modulus of elasticity its mean value has been evaluated only, because static calculations work with mean values of modulus of elasticity. It is given by the principles of the (semi)probabilistic approach of the structural design, where the statistic, respectively probabilistic view on the problem are included by design values of the strength on one side and by design values of the loading actions on the other side.

From realized 6 tests the mean value of modulus of elasticity has been determined E_m = 12.34 GPa. Regarding very small test number the derived mean value may be consider as approximate random.

V. Design Resistance Analysis

From the viewpoint of the statistical evaluation the design resistance is influenced by the statistic characteristics of the various parameters, namely by the variation coefficients expressing the resistance variability and uncertainties of the resistance model. The influences of some parameters are shown on the examples of selected representative forms of the resistance models.

A. Test Number Influence

The influence of the test number is evident within the context of the use of fractile factors (see above), but the test number is included also through all "partial" variation coefficients v_{Xj} of basic variables, v_δ of the error term, from which the variation coefficients v_{Rth}, respectively v_R arise subsequently.

B. Test Results Variability and Resistance Model Uncertainties

The resistance model uncertainties expressed by the variation coefficient v_{Rth} mainly depends on basic variables variation coefficients v_{Xj} and on the form of the resistance model mathematical function. The variation coefficient v_{Rth} is given by the equation (11) presented here in the general format, which may be simplified. Frequently in practice the resistance model is a product function of two basic variables X_1 and X_2 in the general form of (12)

$$g_{Rth} = X_1^p \cdot X_2^r , \tag{12}$$

where the powers p, r can take values less or greater than 1 with the various combinations, which can significantly influence the value of the variation coefficient v_{Rth}. Then the variation coefficient v_{Rth} can be calculated according to the formula (13) derived from the equation (11) using (12) and going to the simplification

$$v_{Rth}^2 = p^2 \cdot v_{X1}^2 + r^2 \cdot v_{X2}^2 \tag{13}$$

and the variation coefficient v_R is given by (14)

$$v_R = \sqrt{p^2 \cdot v_{X1}^2 + r^2 \cdot v_{X2}^2 + v_\delta^2} \, . \tag{14}$$

In the equation (14) it is seen, that the variation coefficient v_R is very significantly influenced by the powers values p, r of variables X_1, X_2, because the value of v_R importantly increases with the power values, mainly if the power values are $p \geq 1$, $r \geq 1$, while the influence of the variation coefficient v_δ of the error term is not so important.

To investigate influences mentioned above upon the design resistance, for usual typical functions of the resistance model given by the general equation (12) the comparative study has been elaborated.

For the evaluation of these influences several following combinations of the powers p and r have been considered: a) $p = 1$, $r = 1$; b) $p = 1$, $r = 2$; c) $p = 1$, $r = 0.5$; d) $p = 2$, $r = 2$; e) $p = 0.5$, $r = 0.5$; f) $p = 0.5$, $r = 2$. The design resistances have been calculated according to formula (6), for the following test numbers n and the variation coefficients v_{X1} and v_{X2}: n = 10, 20, 30; v_δ = 0.1, 0.2, 0.3; v_{X1} = 0, 0.1, 0.2, 0.3; v_{X2} = 0, 0.1, 0.2, 0.3 and all their combinations.

For the illustration, the examples of the design resistance evaluation for two selected resistance models – $R_{th,\mathrm{I}} = X_1 \cdot X_2$ and $R_{th,\mathrm{II}} = X_1^{0.5} \cdot X_2^2$ are shown in Figs. 9 and 12. These figures show the design resistances related to mean values m_R in dependence on variation coefficients v_{X1}, v_{X2}, v_δ for the test number n = 10 and n = 30.

From Figs. 9 and 12 the differences between the design resistance models $R_{th,\mathrm{I}}$ and $R_{th,\mathrm{II}}$ are seen. For example, the influence of the power values of input variable X_2, i.e. r = 1 for $R_{th,\mathrm{I}}$ model and r = 2 for $R_{th,\mathrm{II}}$, is very significant. In the case of $R_{th,\mathrm{II}}$ model the decrease of the design resistance in dependence on the variation coefficient v_{X2} is more speedily than in the case of $R_{th,\mathrm{I}}$ model. Also the influence of the test number is evident. In the range of the variation coefficients v_{X1}, v_{X2}, v_δ from 0 to 0.3 (and their various combinations), the design resistance for 10 tests is by 20 to even 30 % lower than for 30 tests.

VI. Characteristic and Design Resistance Evaluation on Examples

The design resistance evaluation and influences of the parameters described above are shown using several practical examples. For the illustration of the input variables powers influence, resistance models formally corresponding with $R_{th,\mathrm{I}}$ and $R_{th,\mathrm{II}}$ have been selected. The following influences have been monitored: test number, test results variability, resistance model uncertainties and mathematical form.

A. Characteristic and Design Resistance of Compression Steel Circular Tubes

The first example is a resistance N_c of steel circular tube short columns in pure compression with the resistance model corresponding with $R_{th,\mathrm{I}}$ and given as $N_{c,th} = A \cdot f_y$ (A is section area, f_y is yield strength).

The design resistance for 61 tests [4], [6], [10] is given as $N_{c,d} = 0.606\, m_N$ if yield strength variation coefficient v_{fy} is taken from the tests, and $N_{c,d} = 0.665\, m_N$ if v_{fy} is taken from the previous experiences, where m_N is mean value of the resistance (calculated with mean values of variables). These design resistance values are illustrated in Fig. 9 in comparison with the lines of the design resistances drawn for the general resistance model in the form $R_{th,\mathrm{I}}$ and for selected test numbers and variation coefficients.

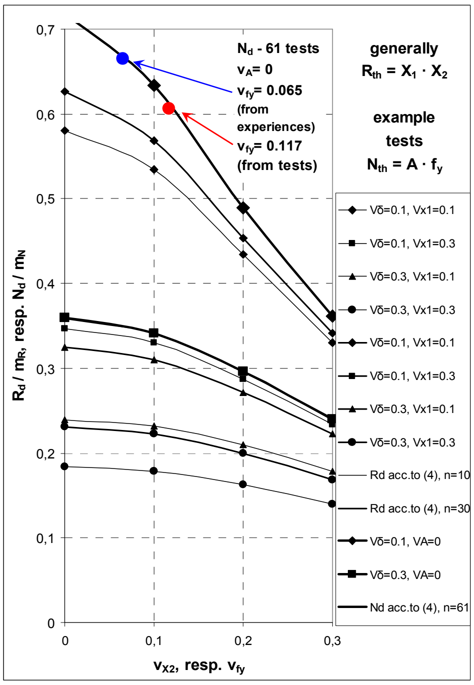

Fig. 9 design resistance N_{Rd} of compression steel tubes: compression resistance model $N_{th} = A \cdot f_y$, test number $n = 61$, variation coefficients v_A, v_{fy}, v_δ

B. Characteristic and Design Resistance of Expansion Anchors

The second example represents the resistances of expansion anchors subjected by tensile force (see Fig. 10) or expansion anchors closed to concrete edge subjected by shear loading (see Fig. 11).

Resistance models correspond with the general model $R_{th,\mathrm{II}}$ and are given by $N_{th} = f_{cc}^{\,0.5} \cdot h_{ef}^{\,2}$ or by $V_{th} = f_{cc}^{\,0.5} \cdot e^2$, respectively (there f_{cc} is concrete cube strength, h_{ef} is effective anchorage depth, e is edge distance). The design resistance N_d for 86 anchors in tension [4], [8], [11], [14], and the design resistance V_d for 43 anchors in shear [8], [9], [12], calculated for typical variation coefficients of basic variables are shown in Fig. 12 in comparison with the lines of design resistances drawn for model $R_{th,\mathrm{II}}$ and for usual representative test numbers and variation coefficient values.

Fig. 10 expansion anchor subjected to tension

Fig. 11 expansion anchor subjected to shear

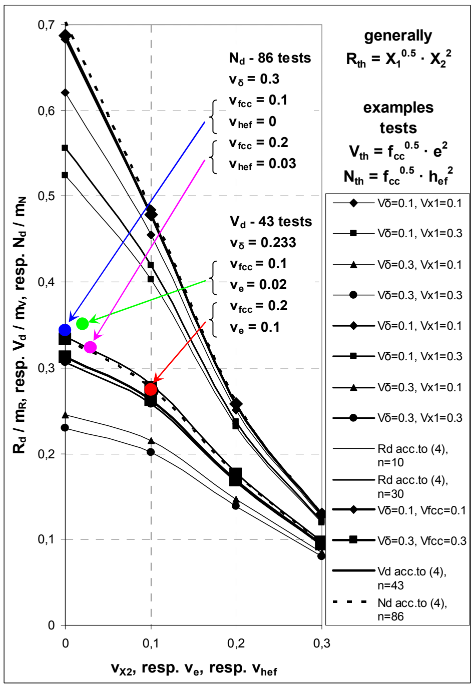

Fig. 12 design resistances N_d, V_d of expansion anchors
a) tensile resistance model $N_{th} = f_{cc}^{0.5} \cdot h_{ef}^2$,
test number n = 86, variation coefficients v_{fcc}, v_{hef}, v_δ
b) shear resistance model $V_{th} = f_{cc}^{0.5} \cdot e^2$,
test number n = 43, variation coefficients v_{fcc}, v_e, v_δ

C. Characteristic and Design Resistance of Steel-Concrete Columns

The third example shows the design buckling resistance $N_{b,d}$ of steel-concrete columns composed of circular tubes filled by high-strength concrete (see Fig. 13). This research is at the forefront on the authors' workplace as well as on many workplaces active in the field of steel, concrete or steel-concrete composite structures (see [3], [5], [13], [16], [17], for example).

This case represents somewhat special resistance model in the form of $N_{b,th} = \chi \cdot N_{pl}$, which seemingly formally corresponds with the resistance model $R_{th,\mathrm{I}}$, but really includes other variables and parameters in the full plastic resistance N_{pl}, so that it cannot be simply assigned to any general resistance model (see above or [2], [3], [5], [13], [16], [25]).

The design buckling resistance $N_{b,d}$ for 16 tested columns (for more see [5], [6], [16]) has been evaluated for the following variation coefficients (taken from previous experiences): yield strength – $v_{fy} = 0.05$, concrete strength – $v_{fc} = 0.2$, elasticity modulus has been taken deterministically. For these parameters the design buckling resistance has been determined as $N_{b,d} = 0.569 \cdot N_{b,m}$, so it is approximately decreased to 57 % of the resistance mean value.

Fig. 13 steel-concrete column composed of high-strength materials subjected to compression

VII. Conclusions

Partial conclusions for the particular examples of the application of the design assisted by testing for the determination of characteristic and design values of material properties and for the evaluation of the design resistance are presented separately in text above. Generally, the possibility of this method usage, especially from the viewpoint of the problems arising from the test number and the property variability, is evident and seen from the worked examples.

In the case of the typical mathematical resistance model in the general form of (12) the values of the powers $p \geq 1$, $r \geq 1$ of variables X_j can decrease the design resistance even five times, the values of the powers $p < 1$, $r < 1$ of variables X_j can decrease the design resistance to 80 – 70 %, both in the case of the variation coefficients v_{Xj} in the usual range from 0.1 to 0.3. For more correct evaluation the probabilistic, reliability, respectively stochastic and sensitivity analysis is available – see e.g. [2], [8], [19], [20], [21], [22], [23].

Although the methods based on the philosophy of the design assisted by testing can be effective and very often the only one tool for the design values determination (mainly if no other tools are available), unfortunately the insufficient attention is paid to the practical usage of this method.

Sometimes the problem of the determination of material properties is discussed in publications (see e.g. [2], [15], [17]), but the usage by designers in practice, though other designing methods absent, is not so usual. Often in practice, only the usual statistic determination using fractile factor for the infinite test number is used, in spite of the understand ability and simplicity of the design material property value. Then design material property determined without consideration of the test number can give incorrect and unsafe results. So it is necessary to pay adequate attention to correct determinate the material properties, especially in the case of new materials with unknown properties and their design values.

In the case of the design resistance evaluation using the design assisted by testing the absolutely insufficient attention is paid to the practical usage and theoretical analysis (for possible subsequent generalization or simplification) of this method. Sometimes, but very sporadically, some specialists (besides standard [24] authors) oriented just to this method publish some particular contributions (see [1], [3], [18]). Greatly this problem has been investigated on the workplace of the paper authors (see e.g. [3], [4], [6], [7], [8], [10], [11], [17]), in connection with its long-time specialization oriented to the experimental verification of various structures and structural members and to the evaluation of the design material properties and design resistances. However, the usage by designers in practice, though other designing methods absent, is not so usual. It can be probably, but partially only, because of the relative complicated and laborious calculation, particularly in the case of more complex resistance model mathematical function. Then the design resistance is often determined not using correct probabilistic approach and not taking into account the test number, which can lead to incorrect and unreliable results.

For these reasons mentioned above there is an effort to elaborate the design tools for the design resistance evaluation using test results for the needs of producers and designers. Recently, the graphic tools for the design resistance derivation for typical basic resistance models (see above) and variation coefficients in the ranges of the usual values are created. These tools are elaborated in the formats according to Figs. 3 or 4 not only for the various resistance models, but also for the different values of the variation coefficients and their combinations.

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