Methods based on the approaches of the design assisted by testing applied for the determination of material properties

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Abstract: The paper is focused on the application of the methods based on the approach of the design assisted by testing for the determination of material properties of fibre-reinforced cement-based composites used mainly for the building façade claddings, but also as a part of load-carrying structures for the slabs of steel-concrete composite beams, for example. In the recent period new advanced non-traditional building materials exist and have been developed, but their physical-mechanical properties, namely characteristic and design values and partial safety factor are not generally known. The application of the philosophy of the design assisted by testing is one of the possible ways, how effectively and reliably to determine characteristic and design values of material properties. The methods of the design assisted by testing are based on experimental results evaluation arising from the statistical and probabilistic approaches. The procedures for the determination of characteristic and design value of the material property implemented in standard rules are 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 shall be considered.

Key-Words: Design assisted by testing, test result, experiment, material property, characteristic value, design value, statistic parameter, variation coefficient.

1 Introduction
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. This 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.

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.

2 Design assisted by testing generally
Principles of the design assisted by testing described in [18] and going to the procedures for the design material properties determination and for the design resistances evaluation are known generally.

2.1 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 [14] 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:

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

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

$$X_k = \exp(m_{m_X} - k_n \cdot s_{m_X}) \equiv m_X \cdot \exp(-k_n \cdot v_X)$$

$$X_d = \exp(m_{m_X} - k_{d,n} \cdot s_{m_X}) \equiv m_X \cdot \exp(-k_{d,n} \cdot v_X)$$  \(2\)

where $m_X$, $m_{m_X}$ are mean values, $v_X$ is variation coefficient; $s_{m_X}$ 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 tables D.1 or D.2 [14] (usage of “$v_X$ known” for $v_X$ known from former experiences, “$v_X$ unknown” for $v_X$ determined from test data set).

3 Glass-fibre-concrete properties obtained from large test number

For the material experiments the test specimens cut from the non-failed parts of façade panels earlier subjected to loading tests within the framework of experimental verification of the actual behaviour of glass-fibre-concrete cassette panels developed in the company of “VUSTAH” (see above).

3.1 Test specimens subscription

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.

3.2 Test arrangement

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 Table 1.

3.3 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.

3.4 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-tension strength and modulus of elasticity.
3.4.1 Objective ultimate loading
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 \( \sigma_{tb,u} = M_u / W \) is the base for the determination of bending-tension strength \( f_{tb,u} = \sigma_{tb,u} \), its mean value \( f_{tb,m} \), characteristic value \( f_{tb,k} \) and design value \( f_{tb,d} \), eventually.

3.4.2 Load–deflection relationship
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 \( \sigma \) 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 the flexural stiffness \( EI \) or modulus of elasticity \( E \), eventually.

3.5 Mechanical properties determination
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.

3.5.1 Bending-tension strength
The ultimate stresses \( \sigma_u \) considered as the values of the ultimate bending-tension strength \( f_{tu} \) have been elaborated using the procedure for the characteristic and design values material properties determination. The character of statistical distribution of bending-tension strength has been verified by the statistic tests. The log-normal distribution with the evident skew is shown by histogram in Fig. 5.

Using procedures acc. to [14] the characteristic and design strengths have been calculated, important parameters are seen from Table 1. 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 the relations of design and characteristic values expressed by the safety factor \( \gamma_M = f_{tk} / f_{td} \).

Table 1 Bending-tension strength – first example

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>material (i) (77 tests)</th>
<th>material (ii) (68 tests)</th>
</tr>
</thead>
<tbody>
<tr>
<td>mean ( f_{tb,m} ) [MPa]</td>
<td>21.06</td>
<td>21.62</td>
</tr>
<tr>
<td>var. coefficient ( \nu )</td>
<td>0.231</td>
<td>0.207</td>
</tr>
<tr>
<td>char. ( f_{tb,k} ) [MPa]</td>
<td>12.78</td>
<td>14.01</td>
</tr>
<tr>
<td>design ( f_{tb,d} ) [MPa]</td>
<td>4.50</td>
<td>6.40</td>
</tr>
<tr>
<td>( \gamma_M = f_{tb,k} / f_{tb,d} )</td>
<td>2.84</td>
<td>2.19</td>
</tr>
</tbody>
</table>

Fig. 3 Failed specimens – material (ii)

Fig. 4 \( \sigma - w \) curves – material (ii)

Fig. 5 Bending-tension strength distribution
In Table 1 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.

3.5.2 Modulus of elasticity
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 strength, that means $\sigma_E = 0.4 \cdot f_u$, 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 Table 2) 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>
<thead>
<tr>
<th>PARAMETER</th>
<th>material (i) (77 tests)</th>
<th>material (ii) (68 tests)</th>
</tr>
</thead>
<tbody>
<tr>
<td>mean $E_m$ [GPa]</td>
<td>14.95</td>
<td>22.01</td>
</tr>
<tr>
<td>var. coefficient $v$</td>
<td>0.438</td>
<td>0.293</td>
</tr>
</tbody>
</table>

4 Glass-cement properties obtained from small test number
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.

Because of the similar character of material the arrangement and realization of material tests were practically the same as in the first example (see above) respectively very similar. Test specimens, test arrangement, loading process, measurement of quantities, types of test results and their elaboration were in principle the same as in the first example. Next text is oriented to the test inputs and the fact results, i.e. mechanical properties, only.
4.2 Mechanical properties determination

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 “σ – w” curves – second example

4.2.1 Bending-tension strength

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 [14] 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).

Table 3 Bending-tension strength – second example

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>(v_X) unknown</th>
<th>(v_X) known</th>
</tr>
</thead>
<tbody>
<tr>
<td>mean (f_{th,m}) [MPa]</td>
<td>7.485</td>
<td></td>
</tr>
<tr>
<td>var. coefficient (v)</td>
<td>0.137</td>
<td>0.200</td>
</tr>
<tr>
<td>char. (f_{th,k}) [MPa]</td>
<td>5.254</td>
<td>0.976</td>
</tr>
<tr>
<td>design (f_{th,d}) [MPa]</td>
<td>4.835</td>
<td>2.500</td>
</tr>
<tr>
<td>(\gamma_M = \frac{f_{th,k}}{f_{th,d}})</td>
<td>---</td>
<td>1.934</td>
</tr>
</tbody>
</table>

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”) is in Table 3.

4.2.2 Modulus of elasticity

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 \(E_{in} = 12.34\) GPa. Regarding very small test number the derived mean value may be consider as approximate random.

5 Conclusions

Partial conclusions for the particular examples of the application of the design assisted by testing for the material properties determination 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 are evident and seen from the worked examples.

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 value of material property determination (mainly if no other tools are available), unfortunately the insufficient attention is paid to the practical usage of this method. Sometimes, but sporadically, some papers in journals or conference proceedings are published (see e.g. [2], [3], [5], [6], [7], [8], [12], [13]), 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 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 the correct determination of the material properties, especially in the case of new materials with unknown properties and their design values.
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