STOCHASTIC PROPERTIES OF CONCRETE EXPERIMENTALLY DETERMINED FOR MONITORING

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The reliability approach, based on the principles of probability and statistics, provides a rational basis for the quantitative modeling of uncertainty and the analysis of its effects on the performance and safety of engineering systems. However, the implementation of the reliability approach in engineering practice is not simple or straightforward. Major developments were and are required, in order to render the approach more acceptable to the practicing professional. Foremost, beyond the introduction of the reliability index and the first-order reliability method (FORM), there is the requirement for providing stochastic models for materials characterized in the new code specifications to make the reliability approach more practice-oriented and "user friendly". Therefore, this contribution focuses on the characterization of stochastic mechanical properties of specified concrete classes, based on comprehensive experimental tests in compressive strength and fracture energy, among others. An additional target was to capture time dependent effects in the investigated stochastic models and the effects of testing procedures on the mechanical properties of interest. The knowledge associated with stochastic material parameters is an important issue for the realistic reliability assessment of the monitored performance of structures.

Keywords: concrete material parameter, stochastic modeling, compressive strength, fracture energy

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STOCHASTIC PROPERTIES OF CONCRETE EXPERIMENTALLY DETERMINED FOR MONITORING ISSUES

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ABSTRACT:

The reliability approach, based on the principles of probability and statistics, provides a rational basis for the quantitative modeling of uncertainty and the analysis of its effects on the performance and safety of engineering systems. However, the implementation of the reliability approach in engineering practice is not simple or straightforward. Major developments were and are required, in order to render the approach more acceptable to the practicing professional. Foremost, beyond the introduction of the reliability index and the first-order reliability method (FORM) there is the requirement for providing stochastic models for materials characterized in the new code specifications to make the reliability approach more practice-oriented and "user friendly". Therefore, this contribution focuses on the characterization of stochastic mechanical properties of specified concrete classes, based on comprehensive experimental tests in compressive strength and fracture energy, among others. An additional target was to capture time dependent effects in the investigated stochastic models and the effects of testing procedures on the mechanical properties of interest. The knowledge associated with stochastic material parameters is an important issue for the realistic reliability assessment of the monitored performance of structures.

1 INTRODUCTION

Design, computation and construction of engineering structures are generally based on linear static analyses and on linear or multi-linear material models (Pukl et al. 2008). In the new generation of design specifications, dispersion effects and associated uncertainties, e.g. in material properties, are covered in the so-called semi-probabilistic safety concept (SPSC) (Ellingwood 2008). The SPSC guarantees desired reliability levels over the life cycle of a structure by careful selection of (a) suitable safety factors for the resistance and for the action side, and of (b) load combination factors.

The SPSC provides for particular structures, using fractiles of material properties and loads as inputs, the means for a standardized verification of the usability and the static safety of the structures (Holicky et al. 2009). The demanded general validity of the

SPSC for a wide range of structure types gives rise to reliability levels that may turn out to be even higher than originally intended (Strauss et al. 2008).

Nevertheless, the SPSC can also result in a lower level of reliability. For instance, integral concrete structures or joint-less abutment bridges generally require higher manufacturing conditions than given in the code specific standards, due to the high dependency of internal forces on the uncertainties of (a) the structural stiffness distribution, and of (b) the soil structure interaction (Taylor 1998).

These uncertainties can be captured by probabilistic methods, which allow the incorporation of previously mentioned existing geometrical as well as material uncertainties both at the time of construction and during the entire life cycle of a structure in form of probability density functions (PDFs) and/or cumulative distributions (Diamantidis 1999, Ang 2007, Strauss et al. 2008). Probabilistic methods are generally based on advanced Monte Carlo simulation techniques (Bayer and Bucher 1999), where e.g. multiple evaluations of a problem are carried out with different input values. These input values are extracted from the aforementioned PDFs of the properties under investigation. Consequently, the probability of failure p_f and the reliability index β may be calculated from the total number of simulations and the number of cases where a defined limit value is exceeded.

Such advanced Monte Carlo simulation techniques, as well as the First Order Reliability Method (FORM) or the Second Order Reliability Method (SORM), both of which are simplified analytical tools (Abdo and Rackwitz 1991, Sindel and Rackwitz 1996, Melchers et al. 2003), provide the means for probabilistic reliability assessment and life cycle analysis (PA) of new and existing structures with acceptable computing complexity and therefore within a reasonable computing time (Diamantidis 1999). The scattering input quantities, e.g., concrete compressive f_c or tensile strength f_{ct}) for PA, must be defined based on literature (Strauss and Bergmeister 2005, Strauss 2003, Spaethe 1992, Melchers 2001) or on experimental tests. However, the scattering properties of numerous materials of the new code specifications have in most cases not yet found their way into the literature (Ellingwood 2008). The properties are frequently derived from historically based experiments (e.g. Rüsch 1969), and specified material development is usually disregarded (Braml et al. 2011). Nevertheless, the effective application and acceptance of PA as a module for design and development depends considerably upon the accessibility of information about the scattering properties (Pukl et al. 2008). Hence, the practical implementation of PA and thereby of an integrative approach in design and dimensioning calls for a stochastic database system that enables systematic storage and retrieval of the scattering properties of the continuously evolving materials (Strauss et al. 2003). Such a stochastic database containing a multitude of materials with their scattering properties also offers high potential for the Design by Testing Concept method as outlined in the EN 1990:2002/A1:2005 2005, which enables the development and adaptation of dimensioning models based on monitored experimental data.

2 TESTING PROCEDURES FOR CONCERTE PROPERTIES

In general, the properties of concrete are characterized based on the compressive strengths according to EN 206-1 “Concrete – Part 1: Specification, Performance, Production and Conformity”, on the exposure classes and on the slump value. Nevertheless, the realistic modeling of structures requires the incorporation of (a)

nonlinear effects in the analysis and material properties, which can be captured for e.g., concrete by a variable modulus of elasticity, E_c the tensile strength, f_{ct} and the fracture energy, G_f, and of (b) uncertainties in material and geometrical properties caused by nature, manufacturing processes and curing among others. These requirements, together with the newly characterized concrete classes in the Eurocode concept, gave rise to experimental investigations with commonly used concrete types, e.g. C25/30 according to EN 206-1 or ÖNORM B 4710-1 2003. In particular, the standardized compressive test, the standardized three-point bending test and the wedge-splitting test were applied. The experiments allowed a partially redundant determination of the above mentioned properties and consequently an effective comparison and a verification of testing procedures. These investigations were divided into four parts: (a) concrete C25/30 with a slump value F45 (series 1) tested after 28 days of curing, (b) concrete C25/30 with a slump value F70 (series 2) tested after 28 days of curing, and both series tested after a long term curing period. Beyond the determination of the scattering mechanical parameters of concrete and the validation of testing procedures, as briefly outlined above, the effect of the considered slump values on the scattering properties was also of high interest.

Compressive tests: In order to determine the compressive strength according to EN 206-1, test cubes with the dimensions 150mm/150mm/150mm were loaded with a gradual increase of the stress level of 0.5 N/mm²/sec until 0.8 N/mm²/min/sec (max 102 sec, (EN 12390-3 2009)) respectively until the maximum load was reached. The maximum load was defined at the test load at which an increase within a time frame of 4 seconds was no longer possible. For series 1 and 2, the concrete mixture shown in Table 1 was used, which corresponds to a C25/30 according to ÖNORM B 4710-1 2003. The first test cubes of series 1 were tested after 7 days of immersion in water and 21 days of exposure to air at an average air humidity of 60% and an air temperature of 21°. The second batch of series 1 test cubes was tested after 169 days exposure to air and exhibited. The fracturing phenomenon in the cement matrix in the first series may be evaluated as more ductile when compared to fractures resulting from the mineral skeleton, and may generally be identified at an earlier stage (see Figure 1).

Table 1: Concrete mixture of series 1 & 2; compressive cube strength C25/30

Concrete Properties*)	Density	Dry	
	kg/m³	Amount	kg/m³
Aggregate 0-4 mm	2650.00	0.296	785.000
Aggregate 4-16 mm	2670.00	0.198	528.440
Aggregate 16-32 mm	2670.00	0.165	439.469
Water content	1000.00	0.175	175.000
LZF	1080.00	0.003	2.783
Stone meal	2700.00	0.018	49.583
Fluamix C	2900.00	0.026	74.857
CEM I 42,5R	3100.00	0.097	299.760

*) Consistence series 1, F = 70; consistence series 2, F = 45, k –value = 0.80 acc. to ÖNORM EN 206; w/c = 0.58; w/b = 0.49; water storage 28 days

Figure 1: Three-point bending flexural test set for characterization of stochastic concrete properties & cement matrix fracturing phenomena of the investigated concrete class C25/30

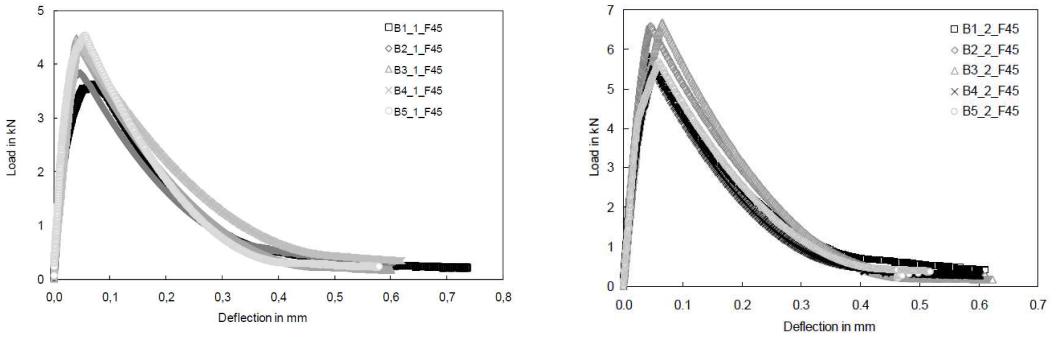

Figure 2: Corrected experimental load–deflection diagrams obtained from three-point bending and wedge splitting tests for C25/30/F45, 28 days (set #1) and 176 days (set#2) of curing

Table 2: Experimental extracted mechanical qualities of concrete C25/30 (series ,1) with a slump value F45 (series #1) and F70 (series #2) tested after **28 days (set #1)** and 176 days (set #2) of curing, based on 2 · 12 samples

Parameter specimen		Mean value	Standard deviation	COV [%]
Compressive strength f_{ck} (MPa) C1 – C10	F45 F70	**48.25**, 56.59 **55.46**, 68.10	**2.10**, 1.26 **2.82**, 2.34	**4.34**, 2.22 **5.08**, 3.44
Compressive strength, f_c [MPa] B1 – B5	F45 F70	**49.00**, 52.80 **56.20**, 56.50	**3.20**, 3.60 **3.40**, 3.20	**6.50**, 6.90 **6.00**, 5.70
Modulus of Elasticity, E_c [GPa] B1 – B5	F45 F70	**29.60**, 37.40 **34.70**, 48.50	**5.40**, 3.20 **6.70**, 5.50	**18.20**, 8.50 **19.20**, 11.30
Fracture energy, G_{Fm}	F45	**182.2,** 249.4	**10.80,** 24.70	**5.90,** 9.90

[J/m2] B1 – B5	F70	**195.6,** 275.90	**37.50,** 62.20	**19.20,** 22.50

The *three-point bending flexural test* had been selected for the characterization of concrete stochastic models. It provides values for the modulus of elasticity in bending E_f, flexural stress σ_f, flexural strain ε_f the flexural stress-strain response and the fracture energy G_f of concrete. The main advantage of a three-point flexural test is the ease of the specimen preparation and testing. However, this method also has several disadvantages: the results of the testing method are sensitive to specimen and loading geometry and strain rate. Figure 2 presents the load-deflection curves of several selected specimens from set #1 (curing period 28 days) and set #2 (curing period > 120 days).The stochastic material parameters extracted by this test method are presented in more detail in Table 2. In particular, these values present a significant dependency of the investigated stochastic concrete models on the curing period, which has to be taken into account by monitoring based reliability assessment of concrete structures.

The third testing procedure applied for the characterization of the stochastic concrete properties was the *wedge splitting test method*. Figure 3 illustrates the principle of the wedge splitting method for uniaxial loading of a disk-shaped specimen. A starter notch is cut into the rectangular groove of the specimen. The load transmission pieces (comprising rollers or roller bearings) are inserted into this groove, into which the slender wedge is then laid. The force F_M from the testing machine is transmitted via the load transmission pieces onto the wedge, leading to the splitting of the specimen. The friction between wedge and force transmission pieces is negligible and the splitting force F_H can be determined by means of a simple calculation. The vertical force F_V is low and does not disturb the fracture behavior. The displacement (δ or CMOD for crack mouth opening displacement) is determined at the height of the load application line on both sides by electronic displacement transducers which are attached to a metal frame.

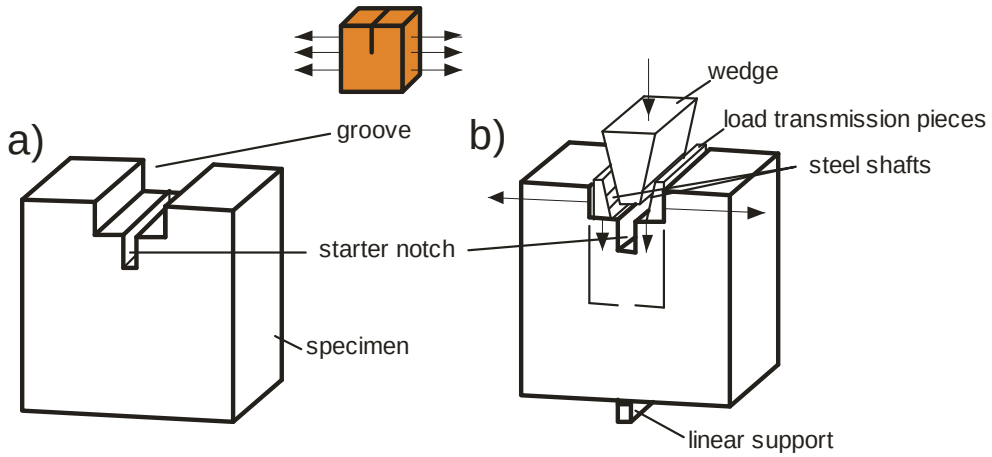

Figure 3: Specimen shape (a) and principle (b) of the wedge splitting test for uniaxial load

In the present study, the specimens consisted of cubes with dimensions of 150mm / 150mm / 130mm, in which a starter notch (depth 25 mm and width 2 mm) was cut. The implementation of the rectangular groove on the upper side of the cube – only

for uniaxial fracture testing – was described above and is shown in Figure 3a. The question arises what the implications are if the specimen sizes for determining fracture mechanical values are too small according to the "size effect" (Bažant et al. 1999, Koolman 2000). The authors studied different beam sizes of concrete under uniaxial loading and found that the cross section of 150x150 mm² was large enough and the "size effect" did not play an important role. Consequently, the used specimen shape can be accepted for the wedge splitting method in the current study. Table 3 presents the obtained stochastic material parameters by this test method. In this study, all specific fracture energies G_f were determined until CMOD was 4 mm. This CMOD is a usual value for concrete according to the literature (e.g. (Löfgren 2005) and therefore a suitable choice.

Table 3: Wedge splitting test: fracture energies G_f (J/m2) of concrete C25/30 (series #1) with a slump value F45 and concrete C20/25 (series #2) with a slump value F70, both tested after 175 days of curing

Specimen		Mean value	Standard deviation	COV [%]
W1 – W7	F45	248.87	34.18	13.74
	F70	211.31	44.58	21.10

3 CONCLUSION

Within the current research project, three different testing methods were applied for determining the material parameters of interest in experiment. For the assessment of the material characteristics of concrete, the compressive strength f_c, the tensile strength f_{ct} and the fracture energy G_f were considered. Small deviations between the Vienna test results and the results of tests performed at TU Brno arose. Several of the stochastic concrete parameters, which were characterized by the Brno team, were modeled numerically based on data from three-point bending tests. In particular, the comparison of the fracture energy obtained from the three-point bending test with that one of the wedge splitting test revealed only minor divergence. These results allow the conclusion that all three test methods are reliable, comparable which each other, and provide consistent stochastic concrete methods. In addition to the verification of the test methods, the evaluation of the influence of concrete additives on the stochastic models where of interest. The investigations revealed a high dependency of stochastic models on slump value properties (e.g. indicated as F45 or F70) and on curing. For instance, the curing time of the concrete is identified as the most important influence factor for the fracture energy quantity. It increases disproportionately up to a curing time of approx. 120 days.

The relevance of this time dependent phenomena for the assessment of the structural performance lies in the fact that micro crack formations in concrete structures, which are associated with the fracture energy performance, are required for activating the reinforcement. Consequently, a monitoring based reliability assessment requires detailed knowledge of the stochastic concrete models mentioned above.

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