7 STATISTICAL PROPERTIES OF STRENGTH OF GLASS FILAMENTS AND TEXTILE-REINFORCED CONCRETE

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SUMMARY: The strength and other material properties of glass fibers are extremely sensitive to several conditions during testing. Small alterations in the test set-up can lead to different results. Such alterations are unwanted, but real, and the problem arises of detecting such changes in the results in order to calculate the most realistic strength value. Based on strength tests on glass filaments, as well as on glass textile-reinforced specimens, such detection has been carried out using statistical procedures. It is well known that inconsistencies in test data can be detected through procedures, such as, for example, the search for outliers, consideration of censored data and multimodal data or skewness of data. Also, theoretical considerations about the statistical properties of the strength of the materials are useful for comparison with the experimental results. Such considerations have either been taken from the literature (Hohenbichler and Rackwitz, Gollwitzer) or have been carried out by the authors. In the paper the authors describe the influence of mounting the test specimen (pressure force, handling) and give recommendations for changes in the statistical properties of the strength of glass filaments and textile-reinforced concrete specimens to control strength tests.
KEYWORDS: Censored data, multimodal data, outliers, statistical distribution, statistical properties, strength, test set-up.

INTRODUCTION

The composite material reinforced concrete was the most successful building material in the last century. Reasons for this are to be found in the combination of two specialised materials, which complement each other almost perfectly: concrete is a material that can carry compression forces in a very economical way; steel on the other hand has an excellent price/performance ratio for tensile forces. Additionally, the steel is protected from corrosion by the alkaline environment in the concrete. To provide this protection for the entire life time of the structure, a minimum thickness of structural elements is required. This leads, for example, to a minimum thickness of reinforced concrete elements of 6cm. Values lower than 6cm are only possible if another material is used as reinforcement.

For several decades, fibres made from different materials have been used as reinforcement. Due to simple production methods, short fibres with a length between a few millimetres and several centimetres are preferred. The fibres are more or less randomly distributed in the concrete. By this technology the cracking behaviour of the concrete can be improved considerably, but the ultimate load cannot be increased by much, due to the random orientation of the fibres.

By using directional endless fibres, an increase in the ultimate load of the structure can be achieved if fibres are inserted according to the direction of the load trajectories. Only within the last few years, have technologies been advanced enough for producing such fibres. The progress is due to the further developments in the technology-based production of textile surface structures. These textile structures made of endless high performance fibres can be adapted to any load pattern. The Centre of Research Excellence in Science and Technology 'Textile reinforcement for the strengthening of building structures' at the Dresden University of Technology investigates the option of the strengthening of reinforced concrete structures with textile structures in fine concrete/mortar.

In order to introduce an economical application of a new material in the civil engineering sector, one has to provide a procedure to design a structural element using the new material. Such a design procedure requires safety elements. First estimations of a safety factor have been suggested by the authors[1,2]. Unfortunately, whereas reinforced concrete is built upon only two materials, textile reinforcements consist of many elements influencing the strength and the statistical properties of the strength (Figure 1).

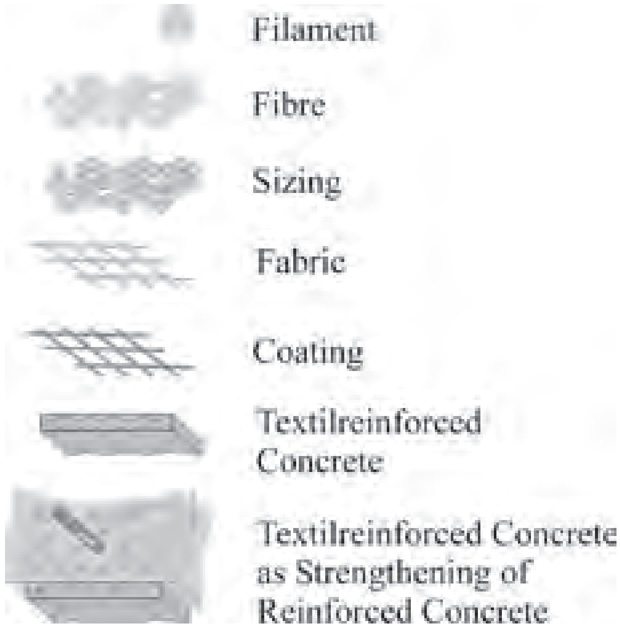

Figure 1 - Assembly of textile-reinforced concrete as strengthening element for reinforced concrete structural elements

First, the textile structures, which are inserted into the concrete, can be manufactured from different materials. Examples exist of textile structures made of carbon fibres[3], fibres made of so-called alkali-resistant (AR) glass or polypropylene[4]. For the following tests AR glass fibres with a fineness of 310tex is used. A group of glass fibres is called a roving and can be built up in many different ways. The roving used in the experiments consists of several hundred or thousand single filaments. In the production process, the fibres are coated with a so-called sizing material. Unfortunately, the sizing material is not a homogeneous layer. The sizing material is irregularly distributed over the surface of the filaments. This material not only makes the production of textile structures possible, but it also has a significant effect on the properties of the compound in the concrete. In addition to the sizing, a coating can be applied to the fabric as well, which will influence the strength properties.

In the state of the embedding into the concrete, only the outside filaments of a fibre have direct contact to the cement matrix. Thereby, we can find different grades of bonds and different properties of the bond. On the outside of the fibre, high bond forces are possible, whereas inside the fibre those values are much lower. Additionally, the contact of the filaments inside the fibres takes place only in certain places. A theoretical description of the behaviour of such multifilament bundles in a brittle matrix has already been introduced by Ohno and Hannant[4].

RELATION BETWEEN STATISTICAL AND MECHANICAL PROPERTIES

Although some researchers[5,6] suggest that a development of a strength value and the statistical properties of the strength of the textile reinforcement based on tests of the single elements, such as fibre and roving, will never succeed, the authors are strongly convinced that this is possible. Additionally, the authors are convinced that statistical properties might include further information about the functionality of the textile reinforcement. This will be explained in detail in this paper.

Several mechanical models have been developed in order to explain the behaviour of textile reinforcement, for example see[7,8]. A simple model is shown in Figure 2. The more sophisticated such models are, the more input data is required. Indeed many different tests are carried out to obtain values, but this is in general not possible for all required values. Therefore, some values or properties have to be estimated.

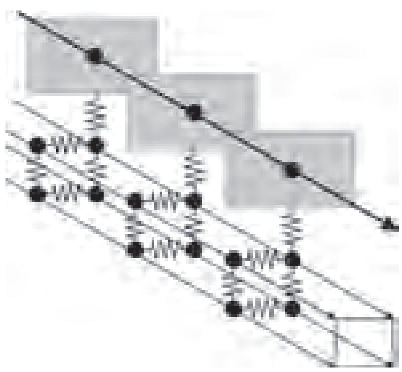

Figure 2 - Numerical model of the textile-reinforced concrete

It is well known that statistical properties of the strength of a filament include data about the test set-up and the mechanical properties of the filament. This will first be explained for the case of statistical properties of a roving. A roving is considered to be a so-called Daniels system. A Daniels system is a system of parallel fibres[9]. Daniels presented theoretical considerations about the statistical properties of the strength of such a bundle. His research was continued by, for example, Rackwitz and Hohenbichler[10] and Gollwitzer and Rackwitz[11]. Figure 3 summarizes the work of Gollwitzer and Rackwitz. The diagram shows the safety index as a parameter for the probability of failure according to the number of the single elements in the Daniels system and according to the stress–strain behaviour of the single elements. This in reverse means: if the stress–strain behaviour of the single elements is unknown, a high number of simple tensile tests of the bundle (in this case the roving) have to be carried out. According to the frequency of failure for a certain load, the stress–strain behaviour of the single filaments can be estimated.

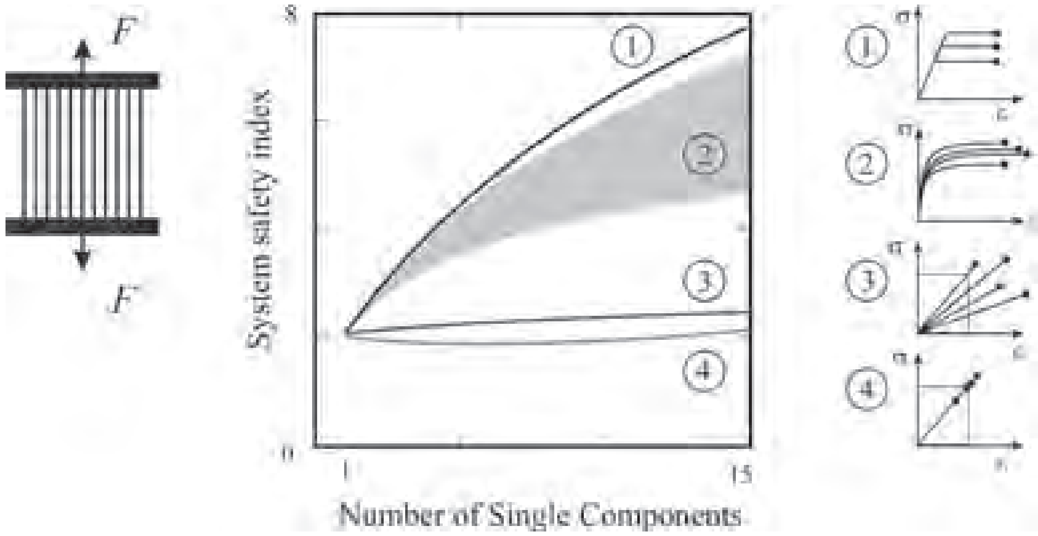

Figure 3 - Safety index of a Daniels system (left) depending on the number of single components and the stress–strain properties of the system (right)[11]

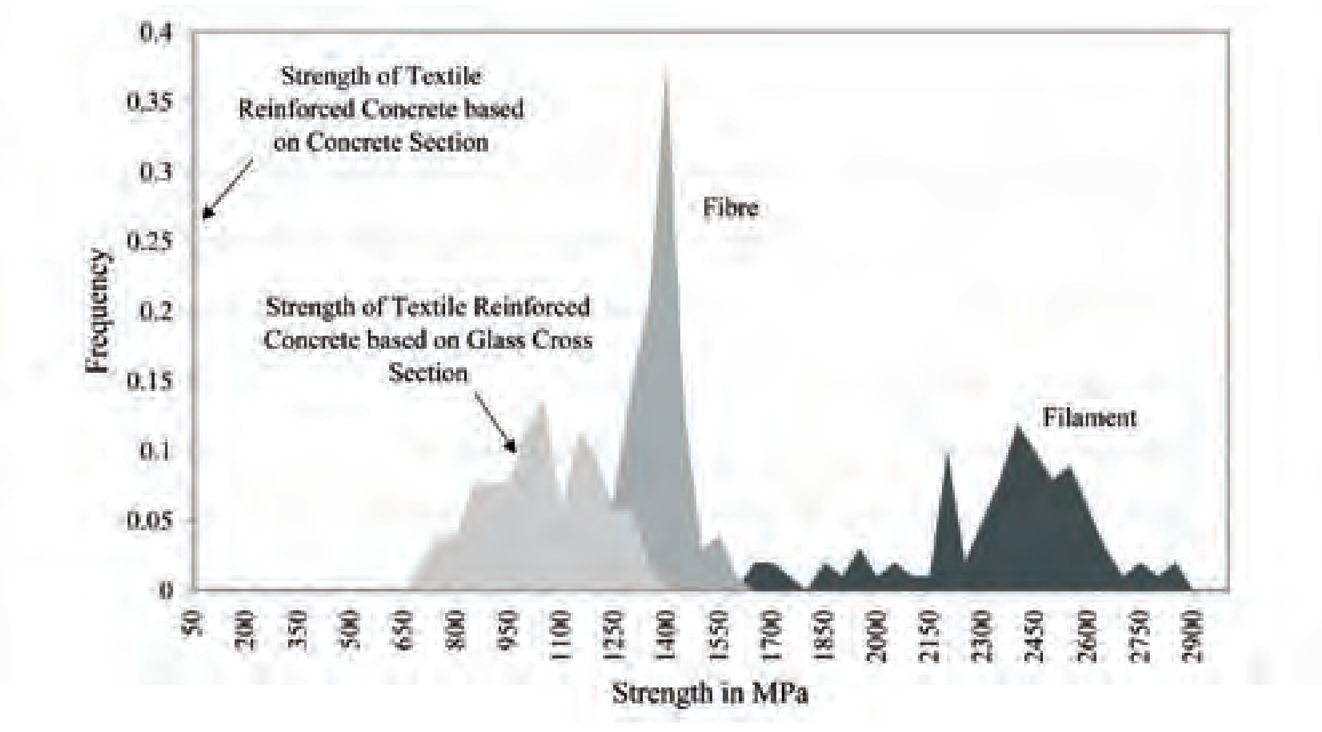

Figure 4 - Frequency of strength of the different elements of the textile-reinforced concrete

Unfortunately, the statistical properties of the strength of the bundle are difficult to estimate. Figure 4 shows the wide range of frequencies for different elements of the material. In addition, data from material tests, for example for single filaments or for bond strength evolution of textile reinforcement shown in Figure 5, is usually biased. Therefore, the development of testing standards is a major task if new materials are developed. Fortunately, biased data can in many cases be easily detected using statistical information. Such statistical information varies; it can also give evidence of censored data, appearance of outliers or multimodal distributions. Such effects are shown in Figure 6. Many procedures for detecting such statistical effects are known.

Investigations for the statistical properties of textile fibres have been known since 1880[12–14]. Newer results connected to textile reinforcement are based on works from[1,2,5,6,15–17].

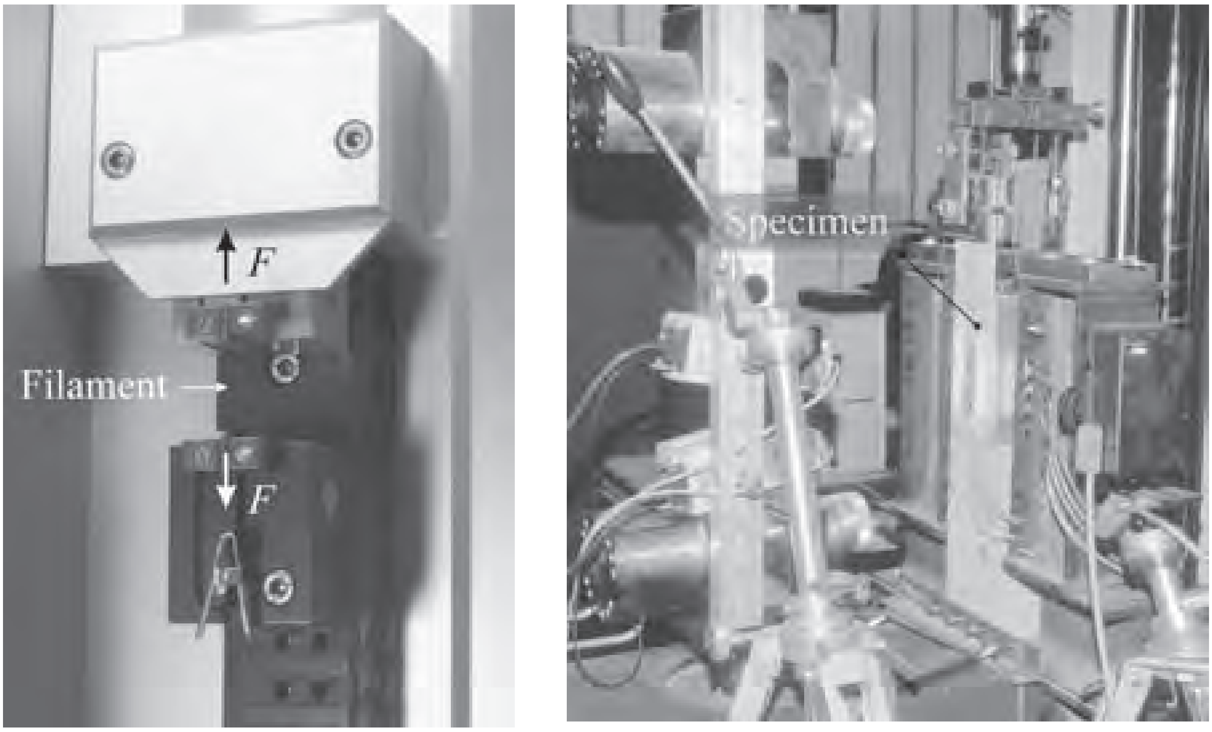

Figure 5 - Test set-up for strength evaluation of a filament (left) and bond strength of a textile-reinforced layer

Figure 6 - Statistical effects describing possible limitations in the test set-up

In the publications mentioned, the error caused by testing was not considered. Therefore, this has to be done. This includes in the first step the identification of the type of statistical distribution based on the data. The following kinds of fitting tests were applied[18,19]:

- connection between coefficient of variation[2] and type of distribution
- connection between skewness and kurtosis and type of distribution
- minimum sum square error based on histograms
- χ^2 test and $n\omega^2$ – test, respectively, and Kolmogoroff–Smirnoff test
- Shapiro–Wilk test or Shapiro–Francia test, respectively
- probability plots and quantile – correlations – values[3]
- rotograms for the normal distribution

For the check of censored data the following tests were applied[18,19]:

- Cohen's test
- Aitchison's method

For the check of outliers in the data the following tests were applied[18,19]:

- Barnett and Lewis's outlier detection test
- Chauvenet's criterion
- Dixon's test
- David–Hartley–Pearson test

The check for multimodal data was done with the help of a program by Hartmann[20].

ENHANCEMENT OF FILAMENT STRENGTH TESTS

Not only based on the tests, but also supported by the intensive data investigation, errors in the experimental data could be observed. Most apparent in the case of the tensile strength of the filaments is the great range: values between 1200MPa and 3000MPa (Figure 7). According to a rule of thumb the range should in this case not be higher than 1500–2500MPa with a mean value of 2000MPa to 2400MPa. The filaments would actually behave accordingly; if not, only a small number showed a great difference from the mean value. By the procedures mentioned above these values can be identified as outliers. The question arises: what causes the outliers? A detailed observation of the test proved that the clamping technique, the clamping material, and the extraction of the filament from the fibre by disassembly might cause errors in the data. Additionally, the significance of clamping breaks of the filaments was considered. Although the work is still in progress, the first slight changes of the statistical properties based on 100 samples are visible in Figure 8. Especially, the bimodal behaviour could be eliminated with leather as the clamping material.

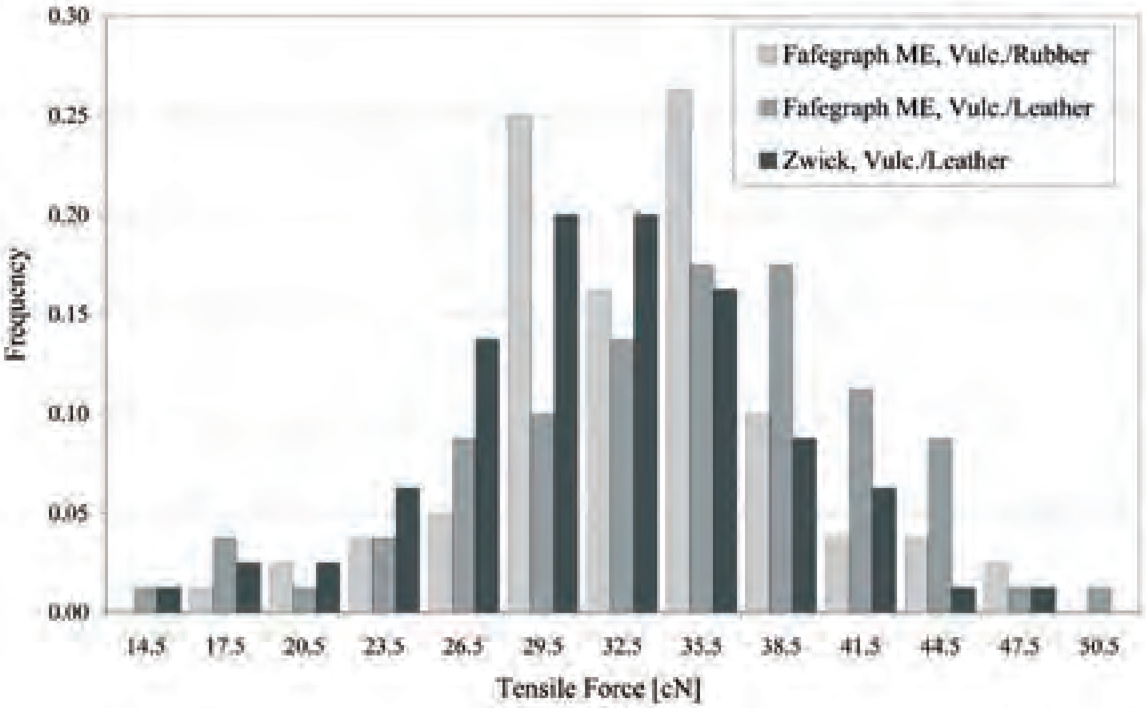

Figure 7 - Frequency of filaments, NEG 100tex with traditional testing set-up

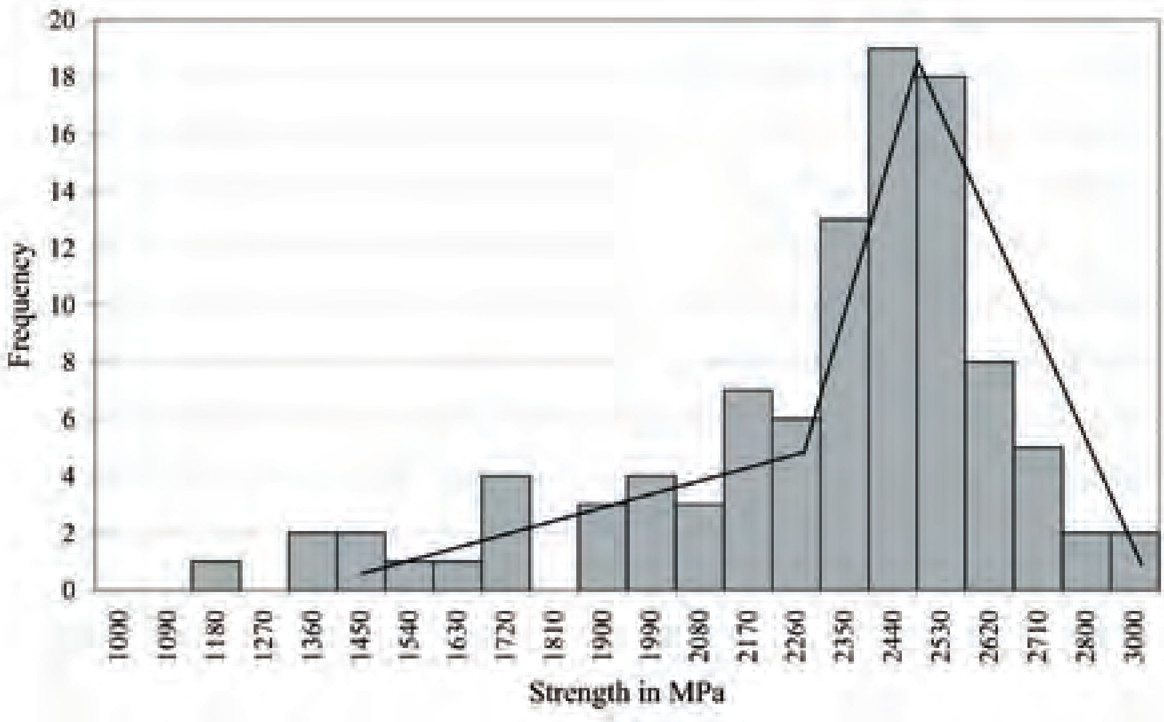

Figure 8 - Frequency of ultimate tensile force for the filaments according to different clamping materials

At the moment, the test set-up of the filament strength test is investigated in detail and future changes of the statistical properties are expected. Changes of the test set-up include the change of the clamping material (rubber, leather), new clamping techniques or different clamping forces.

OTHER CONNECTED TESTS

The evaluation of the filament strength is only one part of the creation of the model for textile-reinforced concrete. Other tests, such as the fibre strength test(15), the fabric test(21), the textile-reinforced concrete specimen test(22) or tests of steel-reinforced structural elements with textile-reinforced layers(23,24) are carried out. Biased data could be found in all these tests. Already for the textile-reinforced concrete specimen, a statistical supervision was carried out and will be continued. Rules of the acceptance of tests have been introduced.

MISSING MODELLING DATA

As noted in the introduction, clearing the data of flawed parts due to limited test set-ups is only the first step. The next step is the evaluation of variables, which are not directly measurable during testing. This can be done by considering observed statistical properties as additional data.

Since theoretical considerations of the statistical properties of fibres, fabrics and textile reinforcement are not finished yet, numerical modelling was preferred. First, numerical models based on random variables have been published in(2) or(16). Latest models consider stochastic fields such as in(5,6) or fuzzy stochastic fields(17). The authors of this paper suggest a Monte Carlo simulation-based stochastic field, which is incorporated into a newly developed model for describing the behaviour of textile-reinforced concrete. The entire calculation model is shown in Figure 9. The statistically described uncertainty of the input data of the mechanical model will be incorporated into the calculation. The calculation then yields statistical information about properties, which has also been investigated by testing. The free parameters inside the mechanical model now have to be used in order to meet the statistical properties of the tests. Of course, this will not be possible by a simple calculation. Therefore, response–surface techniques have to be used in order to find the optimal choice of parameters. Figure 10 shows on the left a response surface for a result value from the calculation, which includes not only a measure of central tendency (value of EM1), but also the measure of the dispersion of the data (grey scale). Both can be used as iteration parameters to find the vector of input variables, which describe the test data best.

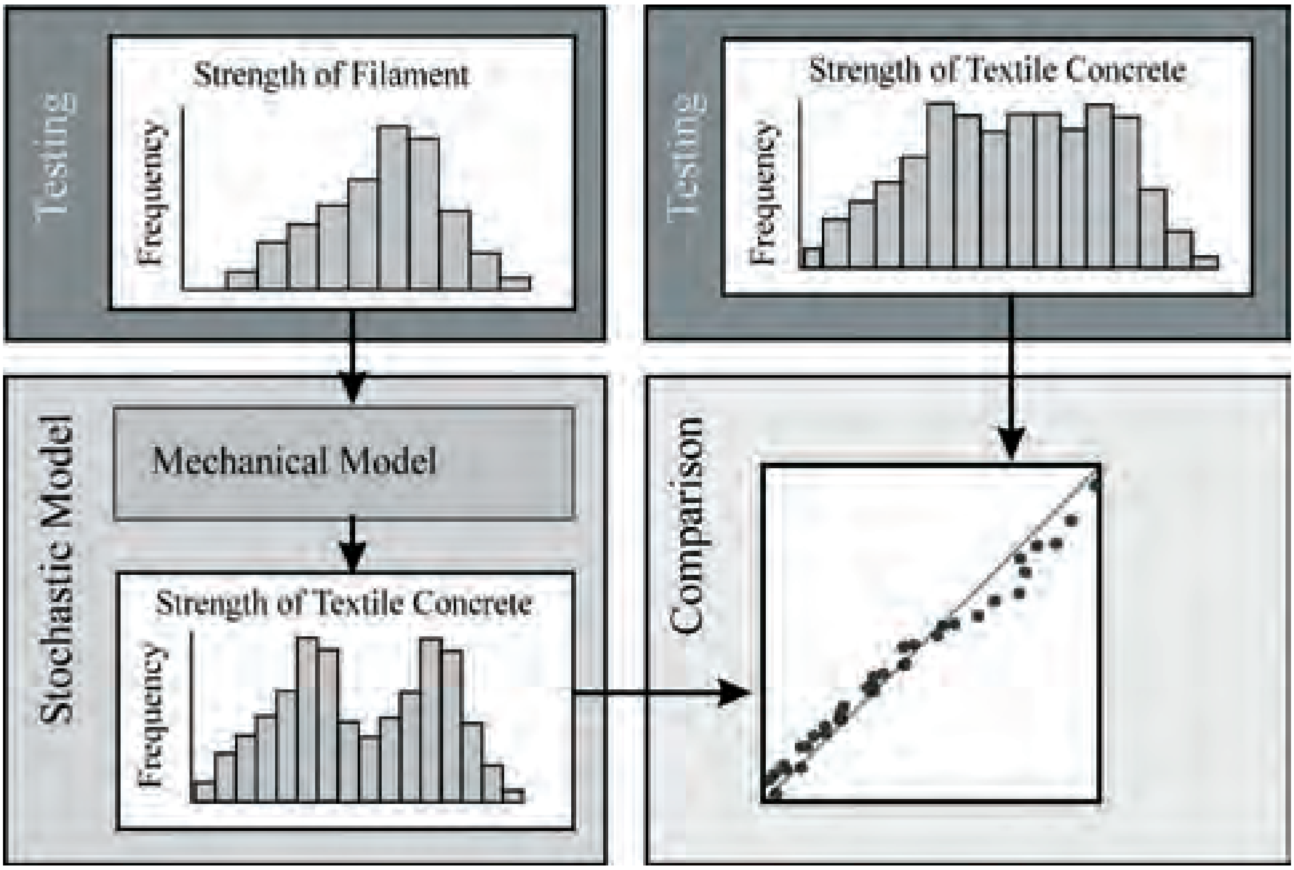

Figure 9 - Flowchart of investigation

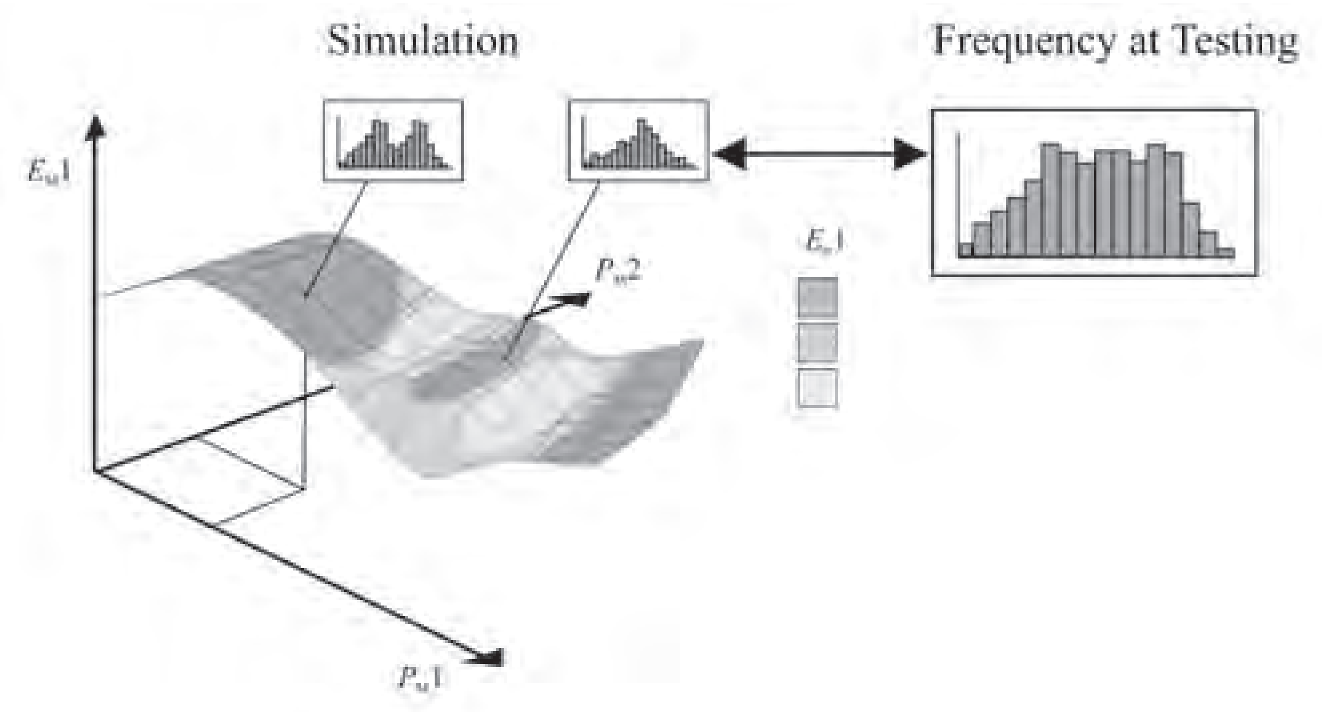

Figure 10 - Comparison of simulated statistical properties and statistical properties at testing

Whereas the statistical investigation of the test data is already under way, and changes of the test set-up are carried out, the development of the techniques to estimate the unknown input variables is at present not fully developed yet, because the mechanical models are under research at this time.

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