NUMERICAL INVESTIGATIONS FOR CUTTING OF WIRES AND THREADS

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Abstract

Strengthening threads or strings are incorporated in technical textiles for example to protect against vandalism. Among other things, the resistance to mechanical destruction (e.g. cut) depends on the material, the cross-section of the strengthening threads and the support points in the base fabric. An essential criterion for durability is the maximum size of the cutting force, which increases with the decrease in the span. In preceding investigations with spring steel wire, it was shown that an optimum apparently exists for this span. The purpose of the investigations was the development of methods for ascertaining the maximum cutter strengths on the basis of standardised experiments (tensile test) and the proof of the existence of a span optimum. The investigations will be focused on monofilament wire.

Key words: *cutting experiment, bearable cutter strength, span optimum*

Introduction

In /1/, two models were developed for establishing the optimal support point distance. However, the analytical model of bending the beam with axial force according to second order theory did not provide a solution to the problem. At least the developed Finite Element Method model (FEM model) was able reflect the tendency of the phenomenon correctly. However, the main problem was the large deviation between the cutting forces computed and the optimal span to the experimental values. For further processing, the simultaneous investigations of analytical and FEM solutions were retained. The investigation of failure behaviour as well as the definition and modelling of a break criterion proved to be a central point. Since the quality of the prediction is influenced primarily by the material, great attention was paid to the models of material during model preparation. In this case, the numeric considerations are based on the present experiments;
- Tensile test,
- Cutting experiment with variation of the span,

for the following monofilament thread structures: spring steel wire, PES and weaving wire.

The force-elongation diagram of the tensile test represents the only basis for the definition of the material constants. For failure indication, the stress and strain state in the thread needs to be known. This is essentially determined by the specific properties of the material. In this case, for example, anisotropy has a great influence. Due to the geometric dimensions of the structures, the determination of respective parameters as usually carried out for bulk forming becomes very difficult, or is not possible at all. In addition to the local FEA around the working point of the cutting edge, there will be investigations to describe the failure behaviour by integral models based on phenomenological aspects.

The fracture surfaces of three different materials were scanned by a SCM (Scanning Electron Microscope). This has shown that the material properties have a significant influence on failure behaviour.

FEM-Computations

The first step during the preparation of the FEM-model consisted in determining the specific material parameters. A elastic-plastic model was chosen for the weaving wire. For the PES-thread a non-linear-elastic model was used, and for the spring steel wire both an elastic-plastic and a non-linear-elastic model were chosen. The tensile test was simulated, and the computed force-displacement curves were matched with the measuring data to check the parameters. The wire was modelled in this case by linear 4-node ring elements. The next step represented the calculations of the cutting experiments. In Figure 1, the basic model construction as well as the chosen cutting edge geometry is shown.

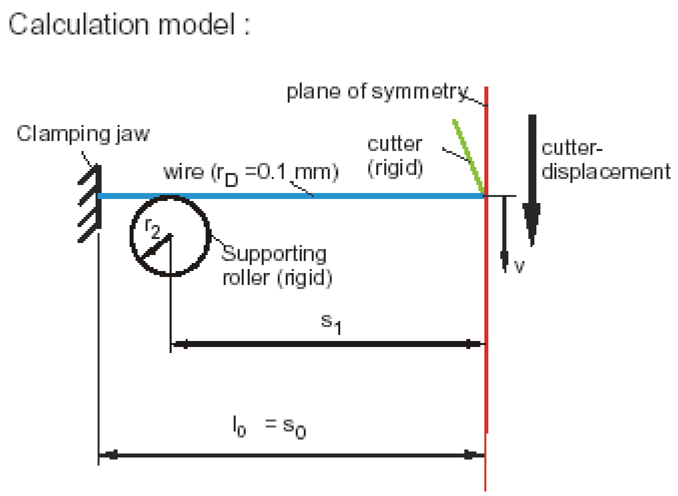

Figure 1. Principle model and cutter geometry

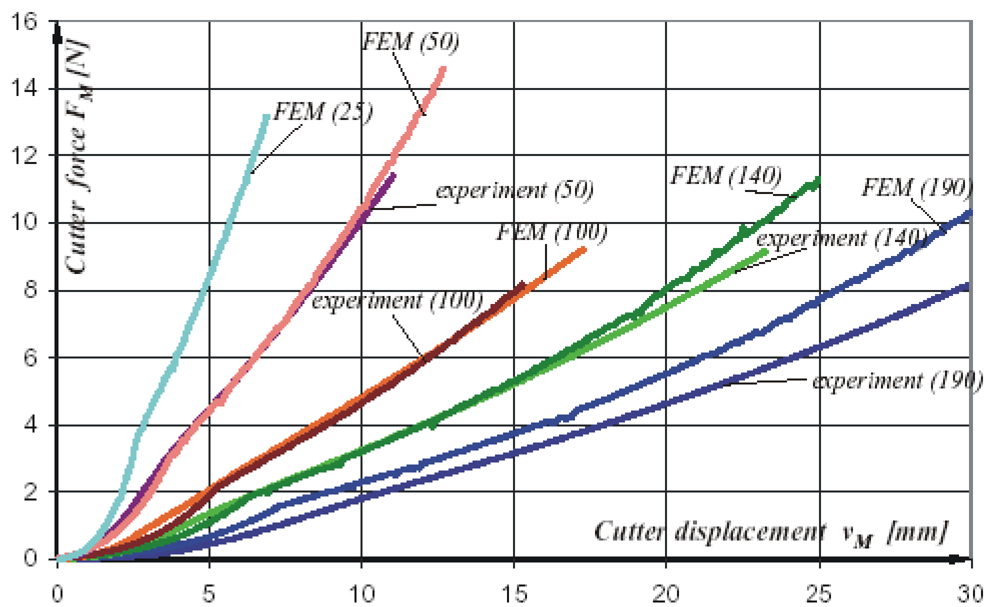

Figure 2. Weaving wire - comparison experiment-FEM (spans 190,140,100,50,25 mm)

The computation of the cutting experiments at different wire spans also ensures the validity of the employed models for the multi-axial case under certain conditions. The comparison between the computed and the experimentally determined values for the weaving wire is exemplified in Figure 2. It is obvious that the deviation of the experimental data decreases in the case of greater cutting forces.

The representation confirms the observed tendency of a rise in the cutting force during the decrease in the span. A local extreme is not in this way detectable. The cutting force maximum, which was observed in the experiment, especially for the spring steel wire, lies by very greater deflection angles and refers to an experiment (cutting experiment with thread/wire reserve) which is qualitatively not comparable, since in this case a considerable deformation of bending exists.

Examined fracture criteria

Based on the fracture pictures, different cases are distinguished depending on the material cut:
- great smooth cutting part → failure by shearing → strong ductility (PES, weaving wire)
- small smooth cut part → lower ductility (spring steel)

The criteria investigated are based on models known from bulk forming and sheet cutting respectively (Cockroft-Latham, Kolmogorov, Frobin etc.):

$$\textit{Frobin} \qquad C_F = \frac{\varphi_v}{\varphi_B} = \int_0^{\varphi_v} \frac{e^{b\left(\frac{\sigma_m}{\sigma_V} - \frac{1}{3}\right)}}{\varphi_{BZ}} \, d\varphi_v$$

with :

- σ_V - *equivalent stress*
- σ_m - *mean principal stress*
- φ_V - *effective strain*
- φ_B - *effective strain fracture*
- φ_{BZ} - *effective strain fracture (tensile test)*

Additionally, the hypothesis of critical maximum shear stress was considered. However, during evaluation of the FEM-calculations it was realised that the selected local fracture criteria for determination of the failure point do not result in any compatible or unambiguous statements respectively. In addition, there was no correlation between the fracture characteristics which are obtained in the cutting experiment to those which were determined in the tensile test (as a reference). For this reason, the investigations were focused on a possible global fracture criterion for the definition of the failure point in FEM-simulation. By determining the increase in external work from the computed cutting force curves for different spans, an extreme value for external work may be detected (Figure 3), if the span becomes closer.

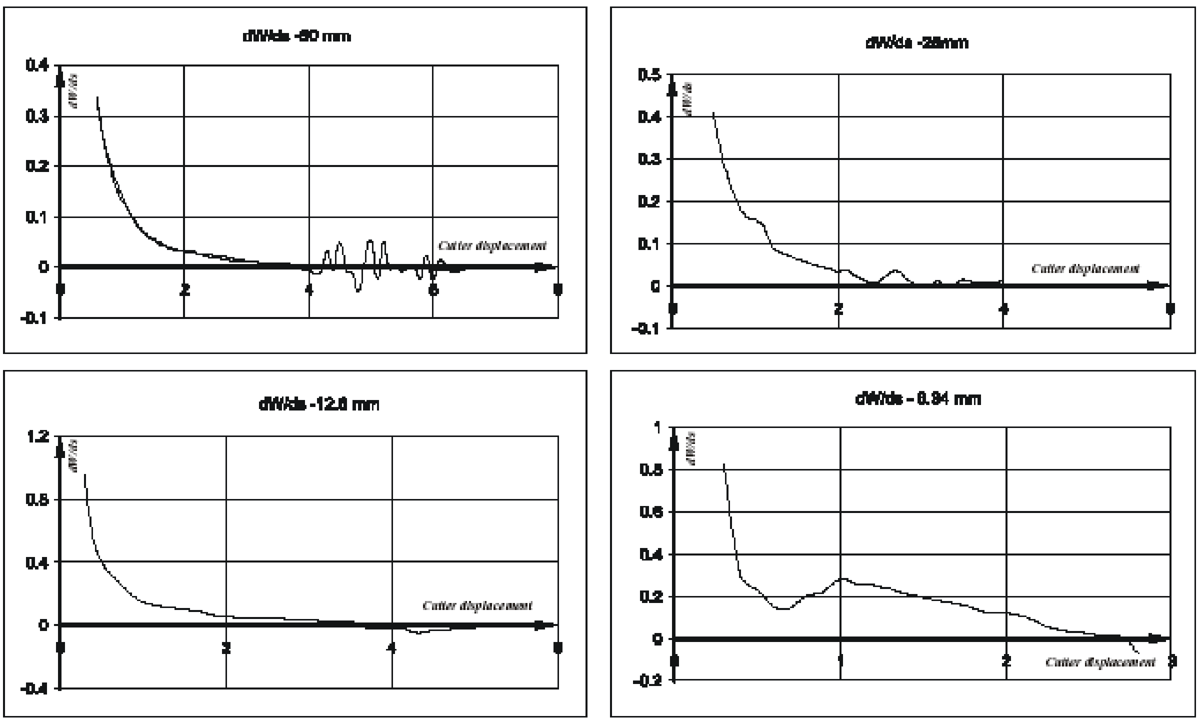

Figure 3. Increase of external work in dependence of different spans

Span optimum

In /1/ it was found that the force maximum for an optimal span, which was observed in the experiment with the spring steel wire, can be traced back to the fact of counter-rotating influences for the incidence of the failure: at a large span (small deflection angle α), notch influence together with the axial strength of the wire seems to be responsible for the fracture. In contrast, the superposition of axial tensile and bending stresses at a small span (large deflection angle α) evidently leads to the fracture. In the first case a fracture initiation from the top face (cutting edge) appears to be valid, while in the second case the break probably comes from the bottom of the wire (free surface). Depending on the span, both influences have a different weighting. The force maximum is to be interpreted as a point of balance of both influences. For the inspection of the hypothesis established in /1/, the span variation was simulated by consecutively halving the free thread/wire length for the spring steel wire in a 2-D model.

Computation was based on the cutting experiment with a span of 50 mm. By use of the failure criterion explained above, the fracture cutting forces and the corresponding cutter displacements from the computed cutting force curves were determined. For the spring steel wire, the following relation between the cutting force and the span was obtained (Figure 4):

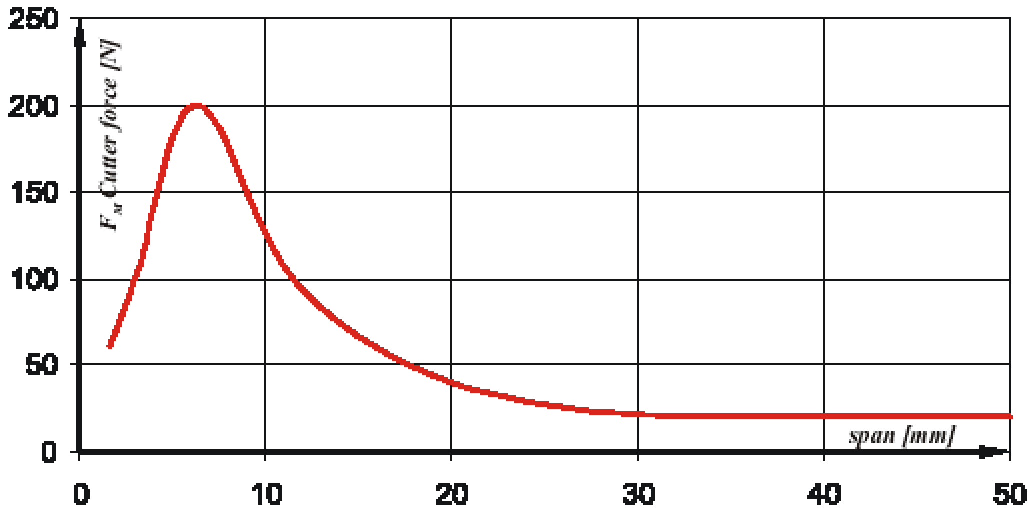

Figure 4. Cutting force in dependence of span

For the present spring steel wire, a maximum of critical cutting force is to be expected with a span of approximately 7.5 mm (support point distance). In a cutting experiment with wired textures, maximum cutting forces of 45 and 53 N respectively were determined /5/. The associated support point distance lies within a range of 6 to 10 mm. Consequently, the location of the support point distance optimum well matches the experiment. No statements can be made concerning the validity of the size of maximum strength, since an exact assigned experimental inspection was not possible for technical reasons. It is safe to say that the computed value is too high. In reality it is restricted to a lower level, for instance by reaching the ultimate strength. Possible causes are to be sought in the definitions of the material properties and geometrical determination of the FEM model employed, e.g.
- assumption of isotropy;
- 2-D model (with approximately the same stiffness as the real wire in the case of tensile stress only, greater stiffness in the case of mainly bending stress);
- support points are non-relocatable in the cutting direction.

Taking the cutting forces determined experimentally as a reference, o the estimation for the cutter force on span optimum of approximately 65-75 N is realistic. The position of the extremum is only marginally affected by the height of maximal strength.

Analytical investigations

The starting point is the assumption that for spring steel and weaving wire, plastic instability represents an upper bound for failure for both metallic materials. For the PES wire on the other hand, shear resistance is evidently decisive. The experimental determination of shear resistance leads to great difficulties due to the present geometrical proportions. In addition, an approximate determination (such as is commonly used for the cutting of metals and also of plane plastic materials /2/),

$$\tau_s = 0.8 \cdot R_m$$

with :
R_m - *tensile strength*
τ_S - *shearing strength*

was proven not to be useful in analysis of the cutting and tensile tests. Therefore, the investigations are focused on a suitable stability criterion as a failure indicator for the wires, which are used as strengthening threads. If a uniaxial stress state together with rigid-plastic deformation behaviour is assumed for the cutting experiment, the critical strength can be determined from the force-elongation diagram of the tensile test data. However two facts are neglected: firstly, no homogenous distribution of the material properties over the cross-section exists. A further critical fact is the transfer of the properties of tensile stress to the case of bending /3/. The strength maximum as a point of the incidence of plastic instability is too high, as expected (Figure 5*).*

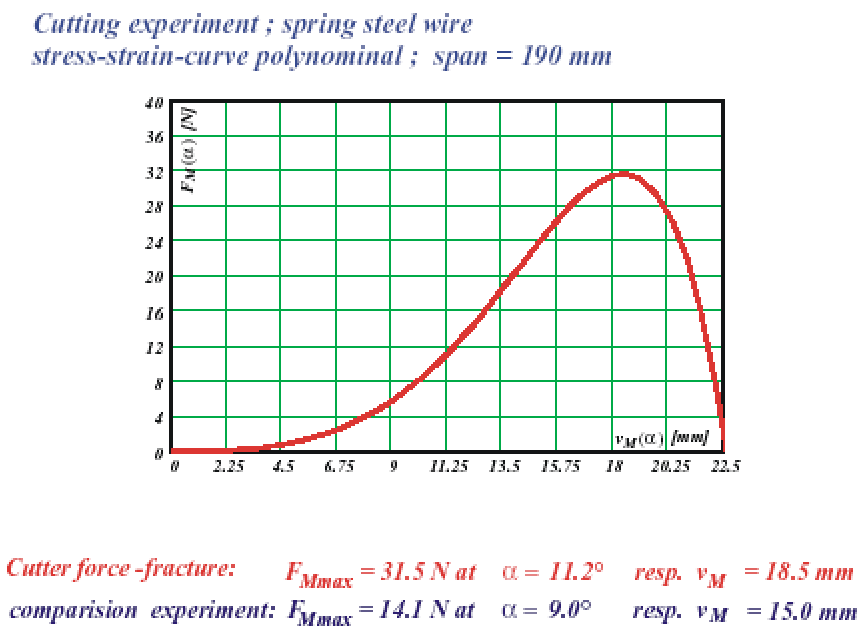

Figure 5. Critical cutting force; criterion: plastic instability

Figure 6 shows the critical axial tensile loading and the corresponding lateral load. We can thereby observe a decrease in axial tensile strength with the increase in lateral load (Figure 6). This confirms the observation indicated in /4/, that for a wire the axial fracture tensile force decreases approximately with the increase in lateral force. Considering this decrease in the critical tensile load during lateral load, an approximation for the fracture or cutting force respectively on the basis of the tensile test data can be obtained.

Since no unloading exists, no restrictions on the approximation of the stress-strain curve are necessary. In the present case, this approximation was made through a polynomial*.* A comparison of the cutting forces which are determined by approximation, as well as of the corresponding cutter deflections, is shown in Figure 7*.*

In this way, a possibility is provided for determining a rough calculation of the critical cutting force if the axial fracture force is known. However, the reproduction of an optimal span distance, which is characterised by a maximum of the cutting force, is not possible with this kind of model since the ending of the wire at the cutting edge is ignored.

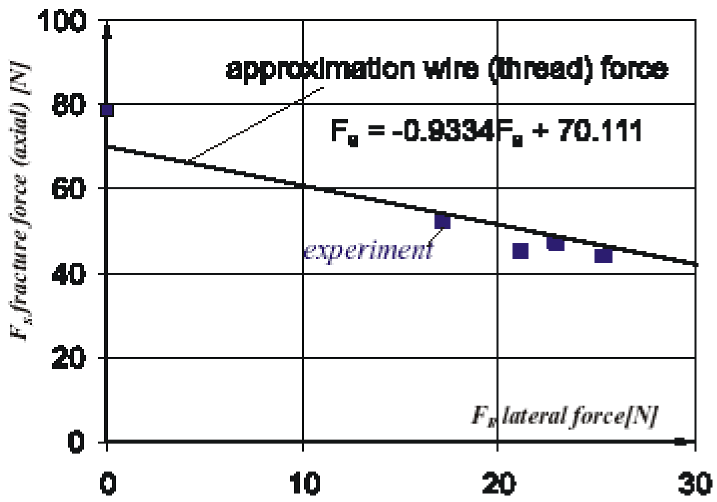

Figure 6. Correlation critical cutting force: axial an lateral stress

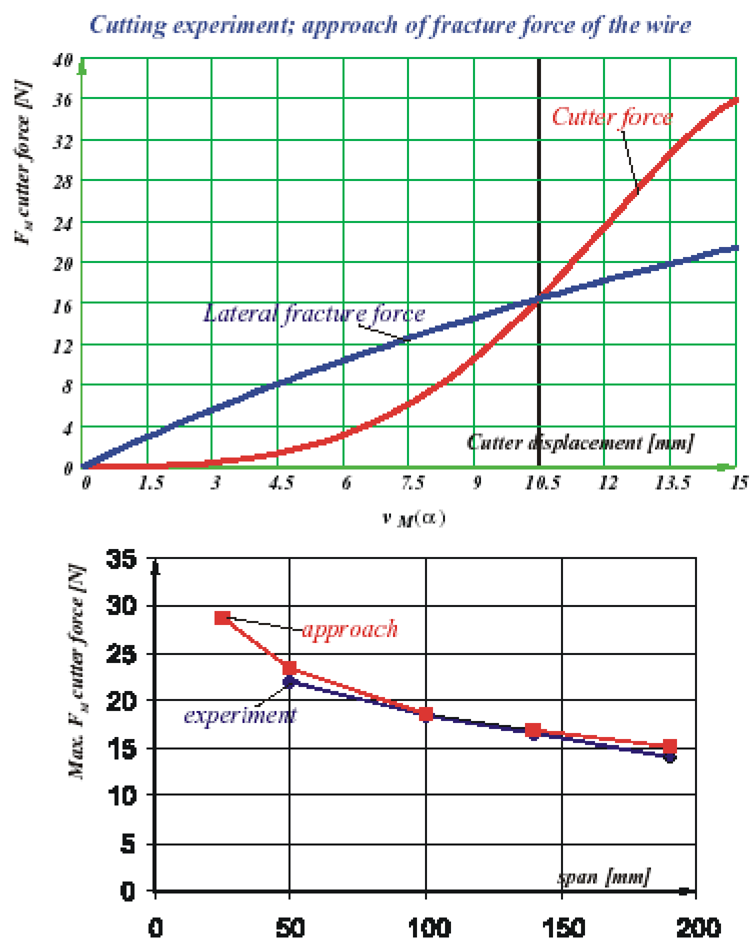

Figure 7. Determination of critical cutting force and comparison with experiment at different spans

Summary

For the monofilament, we have succeeded in proving the existence of a span optimum on the basis of according experiments. Thereby, the FEM model is adjusted with the results of the tensile test and of a cutting experiment. The extrapolation to experimentally unrealisable small spans is made with a validated FEM model.
The position determined of the optimum matches well with comparable experimental results. The corresponding size of the maximum cutting force is discussed against the background of simplifications in the FEM model.
With the aid of an analytical model on the basis of the tensile test data, critical cutting force can be approximately determined.

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