EXPERIMENTAL-COMPUTATIONAL MODELLING OF DAMAGE OF STEEL REINFORCED RUBBER COMPOSITE

J. BURŠA[1], P. JANÍČEK[1] AND F. PEŠLOVÁ[2]

[1]*Brno University of Technology, Faculty of Mechanical Engineering, Institute of Mechanics of Solids, Technická 2, 61669 Brno, Czech Republic*
[2]*University of Pardubice, DFJP, Slovanská 452, 56002 Česká Třebová, Czech Republic*

ABSTRACT

The paper deals with experimental and computational evaluation of adhesion between rubber and steel wire or steel wire rope used in production of tyres. The measured rip-out forces for samples with various ropes structures and various joint lengths show that the forces are influenced only by several millimetres of the joint near the end of the rope. Further, adhesive forces in samples with a steel wire rope are much lower than in samples with only one wire, which has the same total dimensions as the rope. Computational models using FEM system ANSYS have shown that the stress state character in the concentration region near the end of the wire is very strange, different from the other composites: the values of all the three principal stresses are nearly the same. The influence of notches on limit states is investigated as well.

KEYWORDS

Adhesive force, fibre composite, large strain, stress non-homogeneity factor, compressibility.

1. INTRODUCTION

There were two principal stepwise qualitative changes in the level of computational mechanics in a few last decades. The former one as it is generally accepted, was induced by broad uses of numerical methods, in the field of stress-strain analysis especially of the Finite Element Method (FEM). The latter, in its consequences not less important, has been realised in the last decade. An enormous increase of computer abilities, in hardware as well as in software, enabled using of FEM in solving complex non-linear problems. But these possibilities brought a lack of knowledge in two basic fields: a lack of input material data and of testing equipment for their measuring, and, on the other side, a lack of theories for evaluating limit states of more complex materials. A good example of these problems can be found in special types of composites used in production of tyres, i.e. long fibre composites with rubber matrix, and steel, textile, nylon or polyethylene reinforcing fibres. The problem is extremely difficult not only because of the large difference in stiffness between the matrix and fibres, but also by the fact that the producers of tyres keep all the results of their own investigation secret.

2. EXPERIMENTAL METHODS USED

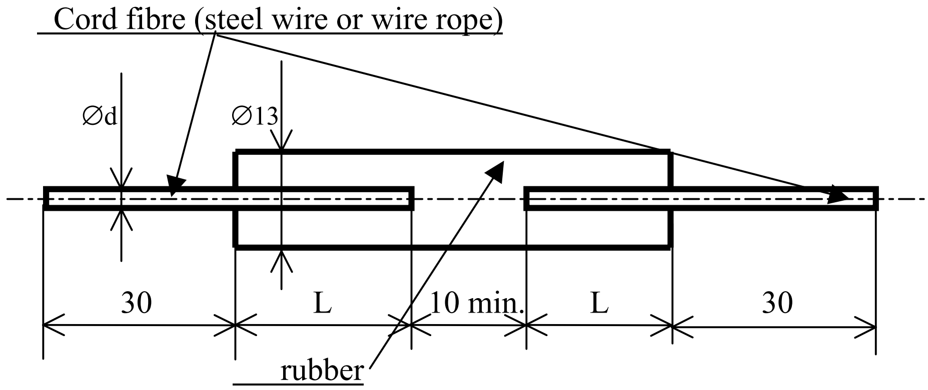

Fig. 1: Samples for measuring the rip-out force

2.1 Evaluation of adhesive forces

Evaluation of adhesion between rubber and steel fibre was realised by measuring the rip-out forces at samples according to fig. 1. The samples were prepared in five groups, differing from each other by the type of the wire or wire rope used, each of them counting nine pieces. Steel wires or steel wire ropes for tyre production were used as cord fibres. In these samples, similar to real tyres, a high degree of adhesion is achieved by brass coating of the steel wires and creating a chemical coupling between brass and rubber. Before the samples were prepared, the convenient joint length L (see fig.1) was predicted using computational modelling of this experiment. It is well known that only a short part of fibre near its end transmits the load between the fibre and the matrix. It should be mentioned that this is only true in the case the fibre is much stiffer than the matrix. The results of computational modelling showed that the joint lengths L>10 mm do not more influence the stress state near the fibre end significantly. To verify these results, the samples with joint lengths L = 5, 10, 20 mm were drawn. Unfortunately, problems with fibre fixation during the sample production caused that these parameters were not maintained and the joint lengths L had to be measured subsequently after the sample destruction. The experimental results are displayed in the fig.2, basic parameters of the steel fibres used and mean values of the single sets of samples can be found in table 1. Analysis of these results gives the following conclusions:

- There is no significant correlation between the joint length L and the rip-out force value for the lengths L>10 mm. This fact agrees with the results of computational modelling.
- For the lengths L<10 mm, the decrease of the rip-out force is evident. However, the number of these samples in the groups tested was not sufficient for quantification of this dependence.
- The increase of the rip-out force at the wire ropes in comparison with a single wire is substantially lower than the increase of the rope circumference. This fact can be explained either by a limited filling of the gaps among the wires with rubber, or by a negligible stiffness of such a thin rubber layer. A larger amount of experiments is necessary to quantify this influence, as well. The experiments realised till now seem to show that the relative increase of the rip-out force is about one half of the relative increase of contact

surface between the steel fibre and rubber matrix, being proportional to the wire rope diameter.

- The investigation of the samples has shown that according to our expectation the crack initiation begins at the fibre end, in the location with maximum stress concentration evaluated by computational modelling. The crack spreads then along the fibre length against the bottom of the rubber cylinder.

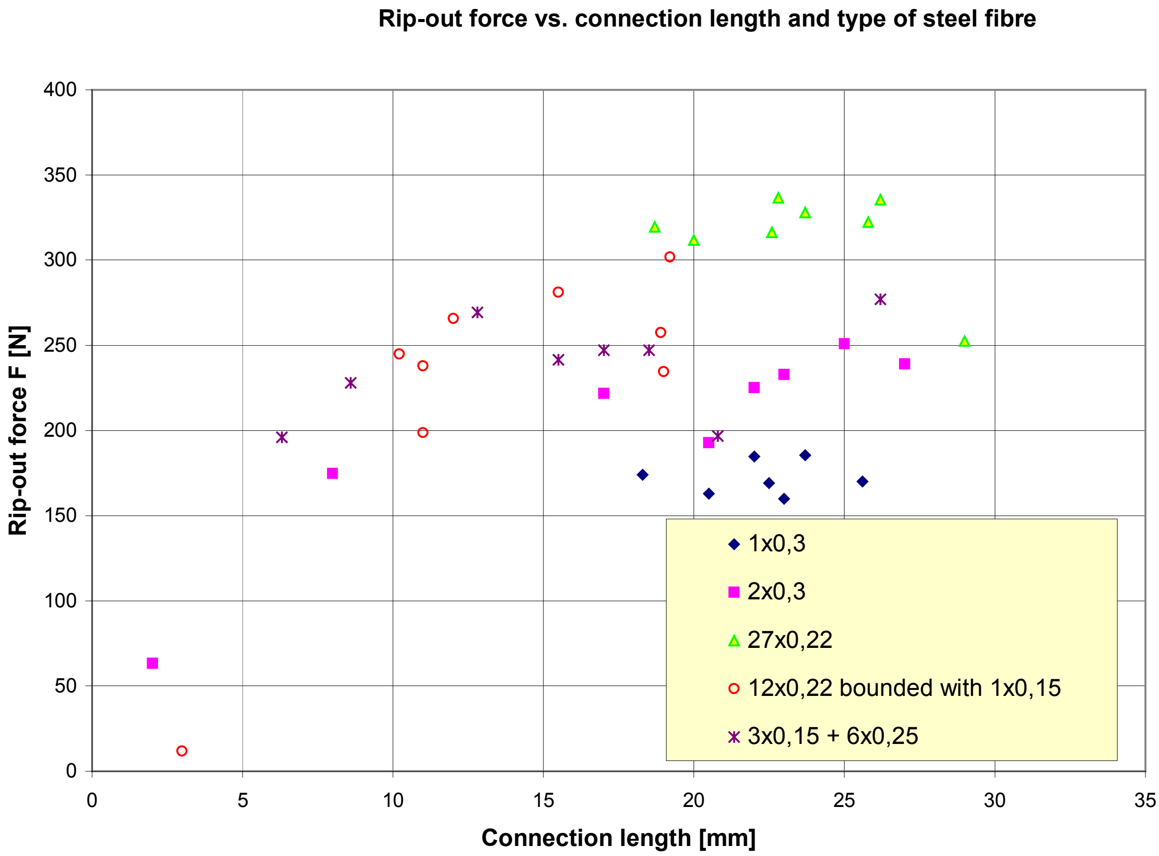

Fig. 2: Experimental results of adhesive forces measuring

Table 1: Rip-out forces measured at various types of steel fibres

Set number	Number of wires * wire diameter [mm]	Square section of fibre [mm^2]	Total diameter of fibre [mm]	Fibre circumference [mm]	Mean connection length [mm]	Mean rip-out force value [N]	Force per circumference length unit [N/mm]
1	1 * 0,3	0,07	0,3	0,94	22,2	175	186
2	2 * 0,3	0,14	not defined	1,54	22,4	227*)	147
3	27 * 0,22, bounded with 1*0,15	1,026	1,35	4,24	23,6	315	74
4	12 * 0,22, bounded with 1*0,15	0,456	0,85	2,67	17,3	268*)	100

5	3 * 0,15 + 6 * 0,25	0,348	0,83	2,60	18,5	241*)	93

**) The samples with a significantly lower connection length are not accounted in this mean value.*

2.2 Investigation of notch influence

Fig.3: Tension test at a sample with a circular notch

The influence of various types of notches on the tensional strength of rubber was investigated experimentally. The tests were realised using normalised flat samples (cross section 5,8 x 2,75 mm) with a circular hole. The diameter of this hole was varied from 0 mm (punctured with a needle) to 2 mm. The decrease of limit force in comparison with a sample without any hole was 25 – 35 %. At the samples with a larger hole diameter, however, the force decrease was influenced significantly by the cross section change. A better comparison can be achieved by comparing the sample strength, evaluated as nominal engineering stress value in the ruptured samples, i.e. the maximal force divided by the minimal (the hole section subtracted) sample cross section in its undeformed state. This stress value decreases with diminution of the hole diameter and, for the minimal diameter, it achieves about 70 % of the strength of a full sample (i.e. sample without any hole). The results with a double-sided U-shaped notch were similar, as well as those ones with notches realised as a sharp crack. Therefore it can be stated that, in comparison with usual technical materials (metals), the notch sensitivity of rubber is very low. This fact can be explained by large deformations of rubber (on the order of hundreds percent) so that the notch tip radius is always very large in the time of rupture and nearly independent on its initial value. Nevertheless, a computational modelling of this problem is necessary for better understanding how the stress distribution differs from that in similar shaped metal samples.

2.3 Properties of steel wires

As the rubber undergoes large deformations, it can be expected that also a composite material with rubber matrix reinforced by steel wires can be distorted in such a way that the yield stress of the steel (labelled HT) can be reached. For computational modelling of stress-strain states, it is therefore necessary to know, in addition to the basic elastic constants, the stress strain curve of this steel. However, this curve was not known for this type of steel and there was no more material at our disposal than thin steel wires or wire ropes (wire diameter of 0,15 to 0,30 mm) used in production of tyres. Therefore it was not possible to realise the standardised tension test and the test was realised only at several samples of these wires. The results of these tests can be summarised as follows:

- Elasticity modulus value was 183,5±1 GPa.
- Yield stress $R_{p0,2}$ of this steel is not lower than 2500 MPa.

The strength limit stress could not be evaluated in this way. Some of the samples ruptured before reaching the yield stress value $R_{p0,2}$ but always in the jaws where the rupture can be expected as the stress state is not uniaxial there. The samples ruptured at stress values near $R_{p0,2}$, the lowest measured value was 2400 MPa. It can be concluded that the strength limit stress must be higher than these measured values.

The needed stress-strain curves of the HT steel cannot be defined from these simplified tests. However, it can be stated that, in the case the stress values in steel wires are less than 2500 MPa (it means strains can be as large as 1,2%), the linear elastic model of behaviour is sufficient for this steel.

3. ANALYSIS OF COMPUTATIONAL MODELLING RESULTS

The experiments evaluating adhesion forces were modelled numerically using FEM program system ANSYS to evaluate the stress and strain states in the sample. It was found by this modelling that the principle stresses computed in the fibre end vicinity where the stress concentration is the highest are nearly equal. As far as it was found in literature (e.g. [2], [3]), a stress state like this was not yet found in short-fibre composites. In classical materials this stress state is judged as very dangerous, because it intensifies the material tendencies to brittle fracture. Therefore the quantities were sought for, which induce this type of stress state. An amount of testing computations were made therefore, in which the elastic parameters of matrix were changed while fibre parameters were kept constant (elasticity modulus 210 GPa and Poisson's ratio 0.3). To evaluate this stresses and to facilitate the comparison of components, a **stress non-homogeneity factor** $(\sigma 1 - \sigma 3)/\sigma 1$ was defined in the investigated point, i. e. the difference of the maximal and minimal principal stresses divided by the maximal principal stress. The results are shown in graphical form in fig. 4.

Unlike the linear elastic materials a significant influence of the load value was found. Therefore all the published results are under the same relative load size. The nominal stress

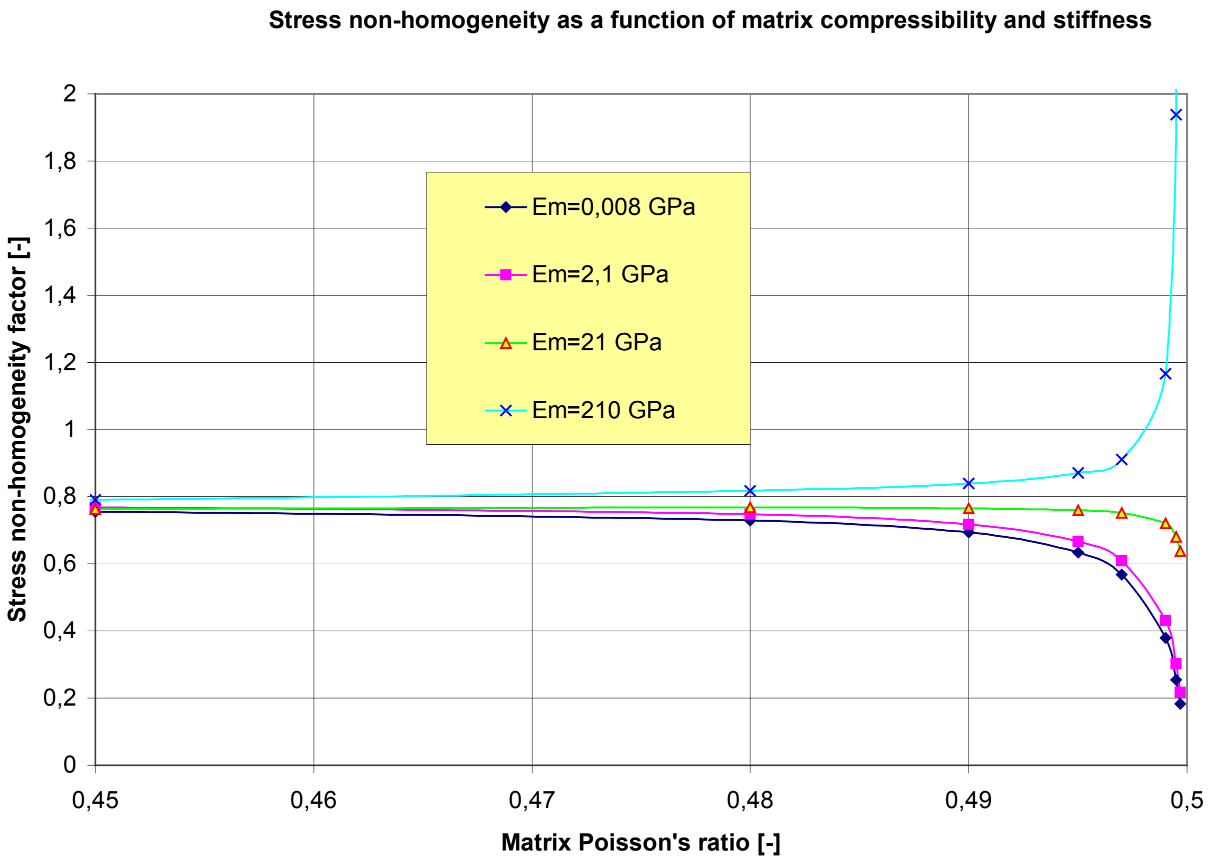

Fig.4: Stress non-homogeneity against matrix Poisson's ratio. Fibre elasticity modulus and fibre Poisson's ratio kept constant (E_f = 210 GPa, μ_f = 0,3).

in the steel fibre achieves about 50% of the matrix elasticity moduli E_m. The following conclusions can be formulated:

- The most important factor influencing the decrease of the non-homogeneity factor is the matrix incompressibility. For the Poisson's ratio value greater than 0,49, this factor decreases extremely and its value approximates to zero.
- The above mentioned decrease of stress non-homogeneity factor was found only at materials with the ratio of elasticity moduli counting at least two orders. Therefore this effect was not found at most short-fibre composite, where this combination of properties is not usual.

- The computationally evaluated stress non-homogeneity factor achieved values less than 0,1 and this value decreases further with increasing load. At matrixes with very low elasticity moduli, where nominal stress in fibres can be several times higher than the matrix elasticity modulus, the stress nonhomogeneity factor is even lower (the maximal and minimal principal stresses are nearly equal).
- If the material is nearly incompressible, a small change in Poisson's ratio induces large changes in stress state and the problem is non correctly conditioned. Therefore bulk modulus is a more convenient material characteristic than Poisson's ratio.

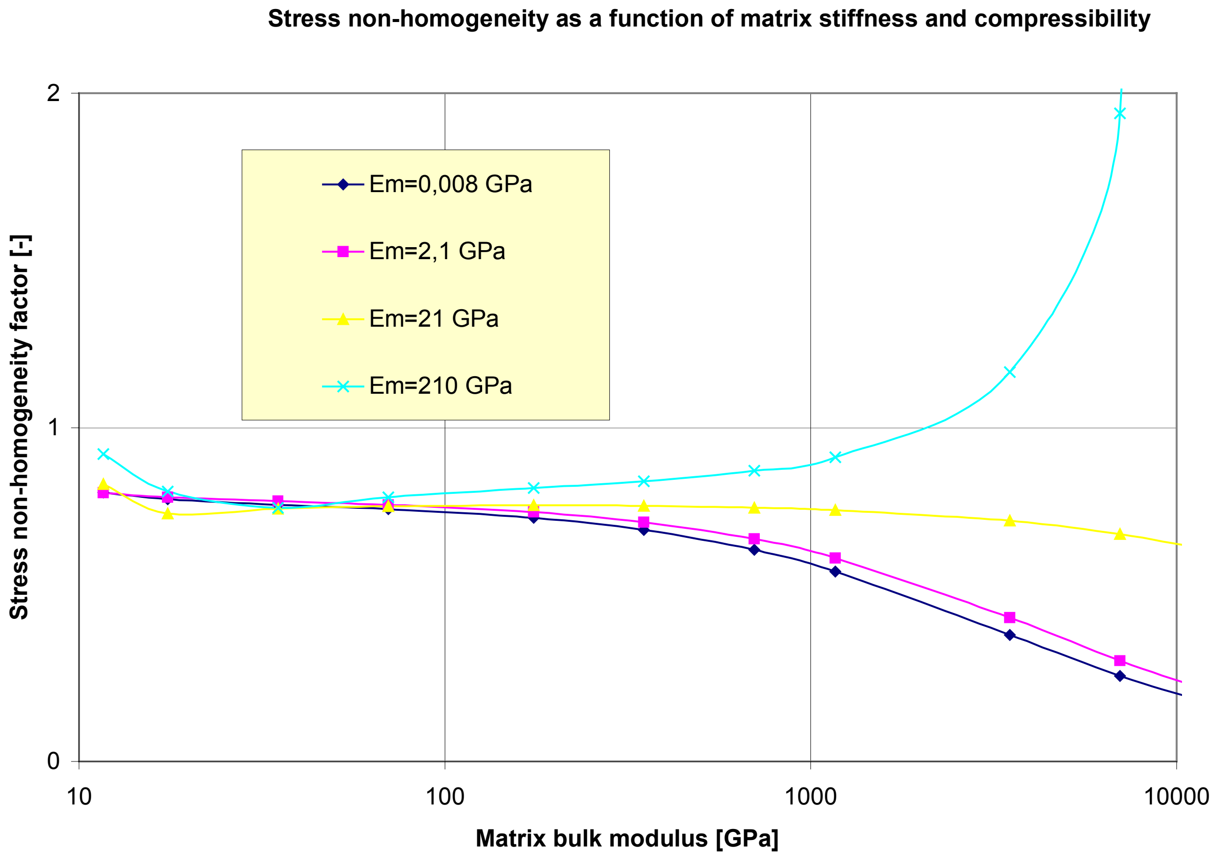

Fig.5: Stress non-homogeneity vs. matrix bulk modulus. Fibre elasticity modulus and fibre Poisson's ratio kept constant (E_f = 210 GPa, μ_f = 0,3).

The matrix bulk modulus K can be computed from its Poisson's ratio μ using the well-known equation

$$K = \frac{E}{3(1-2\mu)}$$

and then the curves from the fig. 4 can be transformed into the graph shown in fig. 5.

This graph shows that the large decrease of the stress non-homogeneity factor is found only in the case that the matrix, although having a much lower elasticity modulus (two orders at least) has its bulk modulus larger than that of the fibres (K=175 GPa for steel). The credible computational modelling of stress and strain states in a composite „rubber - steel wire“

requires much more exact information than the general statement „rubber is volumetric nearly incompressible“. The cause of the problem instability can lie in the large difference in elasticity moduli between steel and rubber. In comparison with elasticity modulus of rubber, its bulk modulus is several orders higher, i.e. really „very high“, and the rubber can be modelled as volumetric incompressible. But in combination with steel, the rubber bulk modulus can be on the same order and it is hardly correct to handle one of the both material as incompressible in this case. As it can be seen from fig.4, the Poisson's ratio is not sufficienly accurate to be a criterion of incompressibility. For the values higher than 0,49, a change of 0,001 (i.e.0,2%) in Poisson's ratio equals a change of dozens percent in bulk modulus. Therefore, at these materials, bulk modulus have to be investigated directly by appropriate experiments to achieve a credible computational modelling of stress and strain states in a composite „rubber-steel wire“.

4. CONCLUSION

The experiments realised till now have shown that the limit force needed for ripping-out the steel fibre from the rubber sample depends on the joint length only for short joints and it is much lower at a wire rope than at a single wire of the same diameter as the rope.

The computational modelling of the experiment showed that the stress state computed in the rubber near the wire end has all the three principal stress components values nearly the same, if the rubber is of a very low compressibility. The analysis concluded that, in a short-fibre composite, this state comes into being in the case the matrix elasticity modulus is several orders lower than this of the fibres and, on the other side, its bulk modulus is higher in comparison with that of the fibres. The exact value of bulk modulus is a very important parameter influencing the credibility of stress analysis in these types of composite materials.

The question of limit states in the composite "rubber - steel wire" was not solved, there is a lack in theories describing limit states of such strange composite materials. Therefore the prediction of limit states in this materials cannot be reliable if the stress state is more complex.

5. REFERENCES

- Burša J., Pešlová F., Janíček P.: Evaluation of fatigue tests of fiber composites undergoing large deformations. *Conference Engineering mechanics 2000*, Svratka, Vol. IV, pp.75-80.
- MacLaughlin T.F., Barker R.M.: Effect of Modulus Ratio on Stress Near a Discontinuous Fiber. *Experimental Mechanics*, April 1972, pp. 178-183.
- Agarwal B.D., Bansal R.K.: Plastic Analysis of Fibre Interactions in Discontinuous Fibre Composites. *Fibre Science and Technology*, Applied Science Publishers Ltd., England, 1977, 10., pp. 281-297.

This work was supported by the MSMT of the CR, Research project No. MSM 262100001.