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The strength investigation of the composite material with implanted sensors

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1. Introduction

The homogeneity of the composite material is crucial property during the manufacture process, empty cavities should be avoided and the rate of the epoxy curing should be smoothened through the whole volume. Thus, viscosity and its variation is the key of technological parameters, which qualitatively describes the process of the composite material formation.

It is enough to know the character of the viscosity variation but not an absolute value of it. The variation of the viscosity should be observed within the certain amount of points, in order to examine the formation of cavities and to evaluate the curing rate within the volume.

The lines of the piezoelectric or magnetostrictive sensors [1, 2] were suggested to implant into the specimen material for the viscosity measurement of separate points. These lines of sensors could be used to determine the physical parameters: temperature, viscosity variation (i.e. curing rate) and stress level. If necessary the whole technological process could be modified as well.

At the beginning of the technological process of composite material manufacturing, the diagnostic lines are implanted into the material. These lines of sensors remain implanted after the end of the manufacturing process of the composite material. The strength characteristic of the composite material is affected insignificantly by implanted piezoelectric or magnetostrictive sensor lines [3, 4, 5]. The sensor lines implanted during the manufacturing process could also be employed to diagnose tension stresses appearing during the exploitation of the composite material.

For experimental research composite material was made using glass fibre, L285 epoxy resin with H285 hardener ("*Kunstharzprodukte*", Germany). Composite plate structure was about 50% glass fibre and about 50% epoxy resin with hardener. This combination of the epoxy resin and hardener is used in the manufacturing of the gliders, ships and components of the wind power plants.

The strength investigation is performed in order to determine the strength variation due to implanted sensors [6]. During this investigation the actual strength of the material could be determined [4, 5, 7].

2. Longitudinal tensile strength of composite material

The strength of the composite materials could be described also with the special software or mathematically [8]. A simple mechanics of materials approach model is presented at Fig. 1. Assume that:

- Fibre and matrix are isotropic, homogeneous, and linearly elastic until failure.
- The failure strain for the matrix is higher than for the fibre, which is the case for polymeric matrix composites. For example, glass fibres fail at strain of 3 to 5%, but an epoxy fails at strains of 9 to 10%.

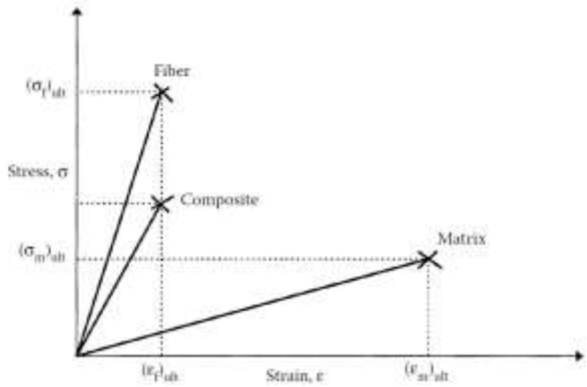


Fig. 1 Stress-strain curve for a unidirectional composite under uniaxial tensile load along fibres [8]

Now, if: $(\sigma_f)_{ult}$ = ultimate tensile strength of fibre; E_f = Young's modulus of fibre; $(\sigma_m)_{ult}$ = ultimate tensile strength of matrix; E_m = Young's modulus of matrix, then the ultimate failure strain of the fibre is [8]:

$$(\varepsilon_f)_{ult} = \frac{(\sigma_f)_{ult}}{E_f} \quad (1)$$

and the ultimate failure strain of the matrix is [8]:

$$(\varepsilon_m)_{ult} = \frac{(\sigma_m)_{ult}}{E_m}. \quad (2)$$

Because the fibres carry most of the load in polymeric matrix composites, it is assumed that, when the fibres fail at the strain of $(\varepsilon_f)_{ult}$, the whole composite fails. Thus, the composite tensile strength is given by [8]:

$$(\sigma_1^T)_{ult} = (\sigma_f)_{ult} V_f + (\varepsilon_f)_{ult} E_m (1 - V_f). \quad (3)$$

Once the fibres is broken, the stress that the matrix can take alone is given by $(\sigma_{ult})(1\text{-}V_f)$. Only if this stress is greater than $\left(\sigma_1^T\right)_{ult}$, it is possible for the composite to take more loads. The volume fraction of fibres for which is possible is called the minimum fibre volume fraction, $(V_f)_{min}$, and is [8]:

$$\left.\begin{array}{l}\left(\sigma_m\right)_{ult}\left[1-\left(V_f\right)_{min}\right]>\left(\sigma_f\right)_{ult}\left(V_f\right)_{min}+\\+\left(\varepsilon_f\right)_{ult}E_m\left[1-\left(V_f\right)_{min}\right],\\\left(V_f\right)_{min}<\dfrac{\left(\sigma_m\right)_{ult}-E_m\left(\varepsilon_f\right)_{ult}}{\left(\sigma_f\right)_{ult}-E_m\left(\varepsilon_f\right)_{ult}+\left(\sigma_m\right)_{ult}}.\end{array}\right\}\quad(4)$$

It is also possible that, by adding fibres to the matrix, the composite will have lower ultimate tensile strength than the matrix. In that case, the fibre volume fraction for which this is possible is called the critical fibre volume fraction, $(V_f)_{critical}$, and is [8]:

$$\left.\begin{array}{l}\left(\sigma_m\right)_{ult}>\left(\sigma_f\right)_{ult}\left(V_f\right)_{critical}+\\+\left(\varepsilon_f\right)_{ult}E_m\left[1-\left(V_f\right)_{critical}\right],\\\left(V_f\right)_{critical}<\dfrac{\left(\sigma_m\right)_{ult}-E_m\left(\varepsilon_f\right)_{ult}}{\left(\sigma_f\right)_{ult}-E_m\left(\varepsilon_f\right)_{ult}}.\end{array}\right\}\quad(5)$$

During composite material tensile strength overview, tensile stress-strain test was performed [9]. Tests were carried out at temperature of 23°C and humidity at 54% inside the laboratory at rate of 10 mm/min. Two different composite materials were tested. The first one was made using 60% epoxy and 40% e-glass fibre and the second one was made using 50% epoxy and 50% e-glass fibre. During the tensile strength research by stretching, the strength of the specimens varied from the 120 to 140 MPa.

The larger strength limit was reached in the case of the specimen that was manufactured with 50% epoxy resin and 50% e-glass fibre. The research showed that variation of the V_f parameter in the 4th function the strength of the composite material.

3. Theoretical research

SolidWorks Simulation software was used for the creation of the computational model for the specimens ultimate strength determination.

There were two stages of the theoretic research performed:

a) specimen without the implant,
b) specimen with implant.

During the calculations one end of the specimen was fixed while the other end was stretched 10 millimetres towards the *s* direction. Fig. 2 represents geometrical parameters of the specimens (a) and (b), calculation model, which was divided into finite elements (c) and the specimen stretching direction (d). The computational model of the specimen without implant was divided into 18609 finite elements with 29327 nodes, while the model with the implant has 14215 finite elements with 23820 nodes. The mechanical characteristics of the composite material are presented in Table 1 and the Table 2 represent the characteristics of the implant. Non-linear characteristics were composed from the data provided in literature [9].

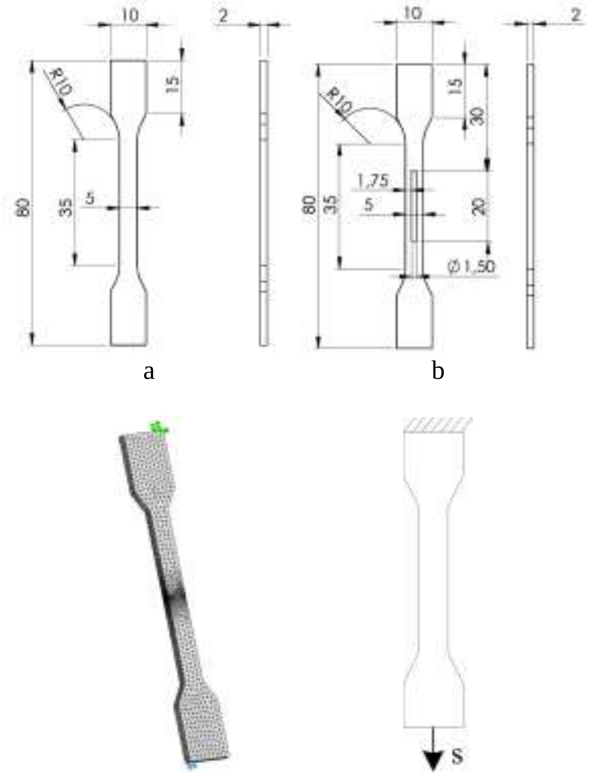


Fig. 2 The specimens of the composite material: a) the specimen without implant, b) specimen with the 1.5 mm x 20 mm piezoelectric implant, c) computational model, divided into finite elements, d) the stretching direction of the specimen

Table 1

The characteristics of the composite material

Parameter	Measurement unit	Value
Reinforcement material of composite material		Glass fibre
Binder material (resin + hardener)		L285+H285
Young's modulus of composite material	GPa	25
Poisson's coefficient of composite material		0.2
Density of composite material	kg/m^3	1900

Table 2

Mechanical characteristics of the implant

Parameter	Measurement unit	Value
Young's modulus of piezoelectric material	GPa	74
Poisson's ratio of piezoelectric material		0.35
Density of piezoelectric material	kg/m^3	7300

During the calculation, the specimen was stretched for about 10 millimetres (s = 10 mm) in a 0.5 s. The tensile speed of the specimen was v = 20 mm/s. During the calculation the appropriate force value was reached and the specimen fractured. The fracture appeared before the time set for the specimen tensile, but the software was able to calculate the force increase until the specimen fracture.

After performing several calculations with the different specimens, the results of force response variation were received, where the response values varied from zero to appropriate value, up until the specimen fracture.

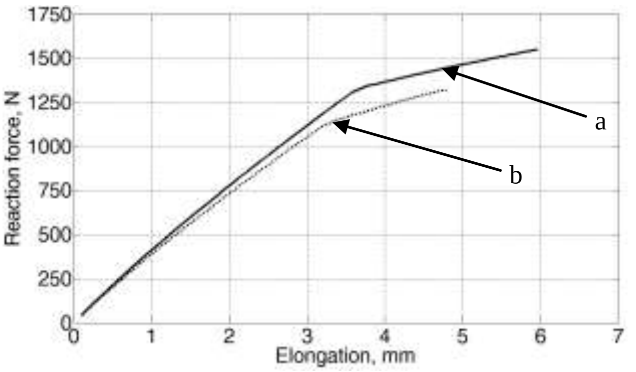


Fig. 3 The reaction force variation of the specimen: *a* - the specimen without implant, *b* - the specimen with the piezoelectric implant

The reaction of the force variation is presented in Fig. 3. The *a* curve is the reaction of the force where the specimen is without implant, and marked as the *b* curve is the specimen with the piezoelectric implant. The curves show, that the stretched specimens had not only different forces responses, but they fractured at different times as well. Firstly, the stretched specimen reached ultimate strength at 1350 N and elongation of 3.8mm. The force limit of specimen was reached at 1555 N and elongation of 5.8mm. Then, the specimen started to stretch and applied force decreased. The stretched specimen finally fractured at elongation of 5.9 mm. Thus, in the second case (curve *b*) ultimate strength of the specimen was reached at applied tension force of the 1127 N and elongation of 3.2 mm. The strength limit of specimen was reached with 1325 N and elongation of 4.8 mm. The stretched specimen with implant finally fractured at the stretching at elongation of 4.9 mm. The analysis of the investigation results showed, that the specimen with the implant reached ultimate strength with the 16.5% less of applied tension force, compared to the specimen without the implant, and the ultimate strength was reached 14.7% less of applied reaction force than the specimen without the implant.

The results presented in Fig. 4 show the total displacements as well as the elongation of the specimen and preliminary location of the fracture.

In the Fig. 4, the specimen with the withered site on the central part is presented. The specimen should break in this place if the additional force is applied. This case of investigation showed that the available elongation was 5.55 mm.

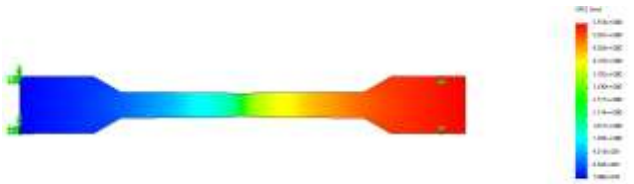


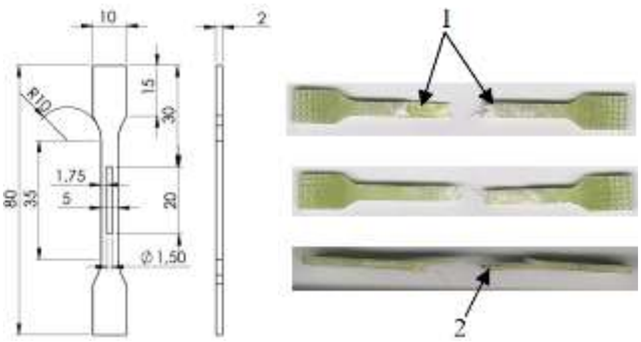
Fig. 4 The total displacement fields of the specimen with the implant

4. Experimental research

The composite material (plate) with glass fibre and epoxy resin L285 with hardener H285 ("*Kunstharzprodukte*", Germany) were manufactured at Berlin technical university.

The specimens for the tensile tests were created from this panel of composite material. Several groups of specimens were manufactured: specimens with implanted piezoelectric sensors and without them. The cut direction of the specimens without the implanted sensors was parallel to specimens with implanted sensor. The manufactured specimens were stretched by using „Tinius Olsen“ Benchtop Tester: Model H25K-T UTM stretching machine.

The diagnostic lines were mounted on the narrow glass fibre strips (about 10 mm width) before sensor implantation into composite material. The character of the specimen breaking lead to conclusion that the epoxy resin was incorrectly soaked into glass fibre strips and it adhered to the other layers improperly (Fig. 5).



a b

Fig. 5 The specimen with implanted sensors: a) geometrical dimensions; b) broken specimen: *1* – the broken connecting wire of piezoelectric element, *2* – delamination of piezoelectric element and the specimen

The results presented in Fig. 6 show that the specimens with the piezoelectric implant withstand 27% less load than the specimens without the implanted sensors. The comparison of the experimental and theoretical results shows that the specimens withstand a larger force during the theoretical calculations. These results could be influenced by many criteria, the composite material is not monolithic and it is quite difficult to maintain the material homogeneity during the manufacturing process.

It should be noted, that the force increased constantly during the experimental investigation until the specimen fracture, while the theoretical calculations showed that the force decreased after the reaching the maximum value and then fractured. The disagreement in results shows that at first, the specimen had very small thinning in the place where the specimen fractured during the experimental investigation. The theoretical investigation estimated larger thinning values of the composite material and thus force decreasing appeared.

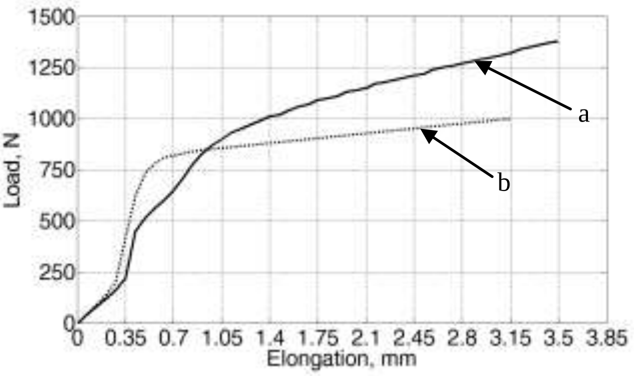


Fig. 6 The results of the tensile tests: *a* - specimens without the implanted sensor, *b* - specimens with implanted sensor

The results show that the diagnostic systems comprised of miniature piezoelectric sensors decrease the ultimate strength of the composite material by 27%. Thus, to avoid this, the implantation of the diagnostic line should be performed exactly on the same type of glass fibre texture from which the composite material was made.

5. Conclusion

1. The results of the theoretical investigation showed that the strength of the composite material with implanted sensor decreased by 15%, than the strength of composite material without sensor. The results of experimental investigation showed that the strength of the composite material with implanted sensor decreased by 27%, than the strength of composite material without sensor. The large mismatch (~ 1.8 times) between theoretical and experimental investigations was obtained due to the fact that the software evaluated the specimen as homogenous and solid composite material.

2. The experimental investigation showed that composite material breaks suddenly as it reach ultimate tensile strength limit. The theoretical investigation showed that before break point this material have small deformations and shape changes.

3. The results of the theoretical and experimental investigation showed that composite material strength decreasing was influenced by the implanted sensor. At this specimen zone, implanted sensor uses about 1.77 mm^2 area of the composite material.

Acknowledgement

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THE STRENGTH INVESTIGATION OF THE COMPOSITE MATERIAL WITH IMPLANTED SENSOR

S u m m a r y

The homogeneity of the composite material is crucial property during the manufacture process, empty cavities should be avoided and the rate of the epoxy curing should be smoothened through the whole volume. Thus, viscosity and its variation is the key of technological parameters, which qualitatively describes the process of the composite material formation. It is enough to know the character of the viscosity variation but not an absolute value of it. The variation of the viscosity should be observed within the certain amount of points, in order to examine the formation of cavities and to evaluate the curing rate within the volume. The lines of the piezoelectric or magnetostrictive sensors were suggested to implant into the specimen material for the viscosity measurement of separate points. At the beginning of the technological process of composite material manufacturing, the diagnostic lines are implanted into the material. These lines of sensors remain implanted after the end of the manufacturing process of the composite material. The strength characteristic of the composite material is affected by implanted piezoelectric or magnetostrictive sensor lines.

This article describes the processes of ultimate strength of composite material after the sensor implantation. Every material is investigated separately. The specimens without implant and the specimens with the piezoelectric implant of 1.5 mm and 20 mm width were investigated theoretically and experimentally. During the experiment the specimen was stretched by the ends until they fracture.

Keywords: piezoelectric sensor, composite materials, the composite strength investigation, strength analysis.

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