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COMPOSITES THEORY AND PRACTICE

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# THREE POINT BENDING OF HAND LAMINATED FIBER COMPOSITES

**The article describes the course and results of research on a composite laminate. Specimens were made from glass-reinforced epoxy resin using the hand lamination technique with the fibres arranged unidirectionally along the specimen. The dimensions were selected on the basis of DIN EN ISO 14125. Strain gauges were placed on the surface of every specimen, then testing was conducted - three point bending. The specimen was placed so that the strain gauge was at the stretched side during bending in order to measure the strain. The stress was also calculated analytically, based on the process parameters. As a result, the theoretical stresses were compared with the experimental ones.**

**Keywords:** **composite laminates, three-point bending, strain gauges**

## TRÓJPUNKTOWE ZGINANIE KOMPOZYTÓW WŁÓKNISTYCH LAMINOWANYCH RĘCZNIE

**Opisano przebieg i wyniki badań laminatu kompozytowego. Materiałem, z którego wykonano próbki, była żywica epoksydowa wzmocniona włóknem szklanym. Próbki do badań zostały przygotowane w technologii laminowania ręcznego. Włókna ułożone były jednokierunkowo, wzdłuż próbki. Wymiary zostały dobrane na podstawie normy DIN EN ISO 14125. Na powierzchni próbki umieszczono tensometry. Następnie przeprowadzono badania - zginanie trójpunktowe. Próbkę umieszczono tak, aby tensometr był od strony rozciągania podczas zginania, dzięki czemu mierzone było odkształcenie. Naprężenia były obliczane również w sposób analityczny, na podstawie parametrów procesu. W wyniku uzyskano porównanie naprężeń teoretycznych z doświadczalnymi.**

**Słowa kluczowe:** **laminaty kompozytowe, zginanie trójpunktowe, tensometry**

## INTRODUCTION

There is an increasingly more frequent tendency in industry to obtain lightweight products featuring good mechanical properties. Therefore, the area of applying composite materials in structural elements replacing similar ones made of classic materials is increasingly growing.

The subsequent stage in the development of composite structures is to introduce, already on the production stage, sensors integrated into elements made of these materials, performing various functions in the finished element, for example effort state monitoring (measuring strain and determining stress), sensory circuits controlling the operation of other equipment (for example, the floor selection panel in a passenger lift), or also visualization of the operational state of equipment, into which theses sensors are embedded (e.g. light or audible signals generating displays).The work undertakes the task of studying selected mechanical properties of composite specimens with embedded sensors monitoring the strain condition, thus the stress in the element. The work was started by preparing specimens, which were subsequently experimentally tested.

The purpose of the work was to analyse the relation between stresses and strains when bending hand-made epoxy composites and to verify if they coincide with the knowledge of the strength of such materials. Most of the published research on composite materials concerns tensile or compressive strength [1, 2], but there are also some publications where the value of flexural strength is presented [3]. Nevertheless, it is worth carrying out similar research as composite materials are becoming increasingly more popular.

The tensile strength in such material is 1062 MPa and the compressive strength is 610 MPa [4]. As the tensile strength is usually greater than the compressive strength in composite materials, bending tests are very important. An important difference to common research is that the specimens tested in the present study were thick-walled. Even in European standards, the proposed thickness of tested specimens is 5 times smaller than in the ones tested for the present article. The aim was to verify if thickness of the laminate has an influence of its strength.

Three-point bending was performed on the prepared specimens and knowledge of the mechanical properties of the material that could be used in an element loaded at the bending moment was obtained. The test was started with preparing specimens using hand laminating technology. Electrical leads were attached to the strain gauges embedded in the specimens, while the remaining laminate elements were semi-finished products. Then the three-point bending test was performed, based on recommendations given in the DIN EN ISO 14125 standard [5].

## COURSE OF TEST

According to the standard, a specimen for three-point bending should be prepared so that its dimensions are 3 mm x 15 mm x 60 mm, however, the possibility of preparing a specimen having other dimensions was also taken into account, which was of key importance considering the large dimensions of the strain gauge (16 mm x 44 mm). Otherwise, the strain gauge would indicate false results, as the value read from the gauge would also be influenced by places where the strain is minor, while on the specimen boundaries the strain gauge would be bent. Following this extrapolation, preparation of specimens having dimensions 7 mm x 24 mm x 210 mm was planned. The strain gauges were fastened to the finished specimens longitudinally, which can be seen in the diagram of a single specimen (Fig. 1).

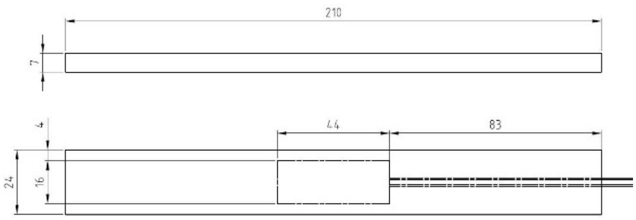


Fig. 1. Diagram of tested specimen

Rys. 1. Poglądowy schemat badanej próbki

The strain gauge was made available by the LSE company (Lightweight Structures Engineering GmbH). It was a sensor featuring a strain gauge constant equal to 2, produced in the technology of embroidering wire to a layer of fleece with red thread (Fig. 2). The resistance of a single, non-loaded strain gauge was 127 Ω.

According to the recommendation contained in the DIN EN ISO 14125 standard, 5 identical specimens were prepared. In order to ensure the same volume proportions of fibres to matrix, one larger plate of laminate was prepared, from which specimens of specified dimensions were cut out.

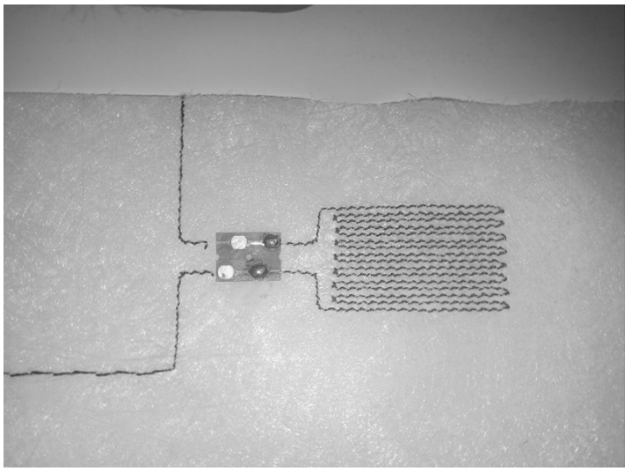

Fig. 2. Strain gauge sewn to filter fleece

Rys. 2. Tensometr przyszyty do materiału

After the stand was prepared, cutting of UD glass fibres, E-Glass type (parallel ones, of the same orientation), was started. The fibres were made in China by the Garrett company. Glass fibres are currently the most frequently used material in the production of all composite structures, first of all because of their low price. Their characteristic feature, which could be both a drawback and advantage, is that they do not conduct electrical current. There are various versions of glass fibres, but E-type fibres are the basic ones that have been used for the longest time. They are most frequently used in the aviation and automotive industries because of their ability to absorb energy to a high degree. Glass fibres are the most frequently used type of polymer composite reinforcements, and constitute an approx. 85% share by weight worldwide. This is connected with broad knowledge concerning the physical and chemical properties of these materials. The technology of glass fibre product processing is widely developed, therefore their utilisation in many types of finished products is possible, independently of their size and application. There is a characteristic rule that during glass fibre tensioning, only elastic deformations occur as the failure stage is approximately equal to the elasticity limit [6, 7].

E-type glass fibres feature the following parameters: Young's modulus $E_1 = E_2 = 72000$ MPa, Kirchhoff modulus $G = 29920$ MPa, Poisson's ratio $\upsilon = 0.22$, superficial density $\rho = 254$ g/m$^2$, coefficient of thermal expansion $\alpha_T = 5.1 \cdot 10^{-6}$/K [8].

In this case, the fibres were wound on a reel and connected in the UD manner. This is a material suitable for fabricating products with continuous fibres because fibres of an arbitrary length can be used. A view of areel with fibres is presented in Figure 3. In order to obtain a total laminate thickness equal to 7 mm, 43 layers were prepared, each having an approx. 0.17 mm thickness.

Afterwards, a hardening plastic material was prepared, functioning as the matrix. The "L" epoxy resin was mixed with a special "EPH 161" hardener. Both the resin and hardener were products of R&G Faserverbundwerkstoffe GmbH. Epoxy resins are chemically resistant materials, hence they are used in the manufacturing processes of chemically resistant varnishes, enamels, binders and bonds. Epoxy resins have anticorrosion properties and protect against light. They do not conduct electrical current, therefore may function as an insulator. Owing to that, epoxy resin takes over large share of stress and also provides good shear strength [9, 10]. Epoxy L resin was used, which features high strength, both static and dynamic. The EPH 161 preparation was used as the hardener, which enabled the laminate to be formed in 90 minutes. The mixture, produced in a 100:25 proportion by weight, was characterised by the following parameters: Young's modulus at bending $E$ = 3600 MPa, tensile strength $R_m$ = 70 MPa, compressive strength $R_m$ = 125 MPa, bending strength $R_m$ = 130 MPa, density $\rho$ = 1.158 g/m$^3$, Dynamic viscosity $\mu$ = 560 ±100 mPa·s [11].

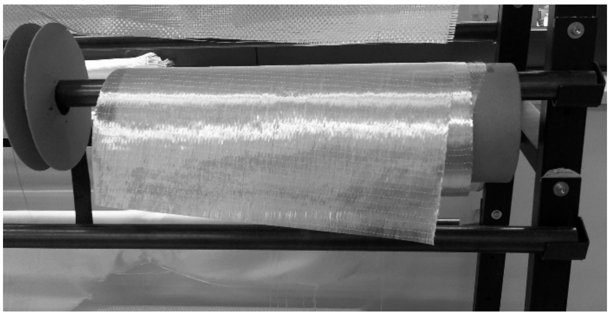

Fig. 3. Reel with wound fibres
Rys. 3. Szpula z nawiniętymi włóknami

Figure 4 illustrates a view from the hand laminating process, where the glass fibres were soaked with the epoxy resin matrix. It can be seen in the picture that a printing roller was used for spreading the hardening plastic over the mould, while removing air bubbles from the laminate in this manner. There are different reinforcing phases that may be used and they have an influence on the results of three-point testing [12]. Referring to the description of elements in the DIN EN ISO 14125 standard concerning composite materials bending, the fibres were arranged in the UD manner, i.e. all the fibres were parallel to each other. This method was unequivocally defined in Section III of this standard.

After all the layers were applied, the strain gauge was placed on the laminate surface in such a manner so that cutting out five specimens in the manner shown in Figure 5 would be possible. Considering the fact that the strain gauge was placed during the laminating process when the matrix was in the liquid form, the material with the strain gauge inside was soaked with the resin and fastened permanently after it hardened. Since no other materials were used, no problems with additional stress between them was encountered.

The thickness is also greater than planned because during the hand laminating process it is difficult to maintain such accurate results as in the case of pressing individual layers together on a hydraulic press. The standards considered, however, calculating the stress with consideration given to arbitrary thickness.

Fig. 4. Hand laminating process
Rys. 4. Proces laminowania ręcznego

Figure 5 illustrates a picture of a single specimen after cutting it out. The figure also has individual dimensions marked, which are as follows: $l$ = 210 mm - specimen length, $b$ = 24 mm - specimen width, $h$ = 12 mm - specimen height.


Fig. 5. Single specimen with dimensions marked
Rys. 5. Pojedyncza próbka z oznaczeniami wymiarów

In order to perform three-point bending, the distance between the supports equal to 140 mm was selected. The load increment rate was constant and amounted to 2 ±0.2 mm/min. While bending by the three-point method and knowing the required values, the stress and strain were calculated according to formulas:

$$\sigma_f = \frac{3FL}{2bh^2} \tag{1}$$

$$\varepsilon = \frac{6sh}{L^2} \tag{2}$$

where: $\sigma_f$ - stress [MPa], $\varepsilon$ - strain [%], $F$ - applied force [N], $h$ - specimen thickness [mm], $L$ - distance between the supports [mm], $b$ - specimen width [mm], $s$ - punch displacement [mm].

While bending arbitrary material, symmetrical in relation to the centre plane, various behaviour of individual material layers is observed. Despite the fact that the layers adhere to each other, part of them is tensioned, and part compressed. In the situation illustrated in Figure 7, the fibres in the lower half of the specimen were tensioned, whereas they were compressed in the upper half. In the middle there is a neutral plane whose length does not change. The sensors were located on the side subjected to tensioning.

The specimens were arranged symmetrically on a WPM ZDM 10/91 versatile tester, available in the laboratory of the Mechanics and Machine Design Department at Opole University of Technology, Mechanical Engineering Faculty. The loading rate was 2 mm/min. The displacement speed was constant, at a rate of 2 mm/min. The measurements were performed at room temperature equal to 22°C, while the ambient humidity was 60%. Figure 6 shows the specimen fastened in the manner described in the standard.

Fig. 6. Specimen fastened according to standard

Rys. 6. Próbka zamocowana zgodnie z normą

Three parameters were measured during the test: the force, the punch displacement and the strain. The force value was needed to calculate the stress c, based on relation (1) stated in section 2, while the punch displacement was necessary to determine specimen deformation during bending, according to relation (2). The results from the strain gauge were collected in the LabView program, with a measuring circuit based on a quarter Wheatstone bridge.

According to relation:

$$\varepsilon = \frac{4 \cdot \Delta U}{U \cdot k}, \tag{3}$$

where: $\varepsilon$ - strain, $U$ - input voltage, $\Delta U$ - voltage change, transferred to analogue-digital converter, $k$ - strain gauge constant,
it is possible to determine the strain when the voltage change is known.

The following phenomena were observed during bending on the testing machine. According to the theory resulting from the strength of materials, the first signs of fracture emerged in the middle of the specimen, in the place of punch application. As can be seen, the damage initially occurred along the force action direction. Each fibre broke separately, and subsequent failures were accompanied by a characteristic cracking noise.

Despite the evidence of damage, the measurements were continued in order to observe further behaviour of the specimen. It was observed that during further punch displacement, fractures emerged not only along the force action direction, but also between the layers, which can be seen in Figure 7. This confirms the very high strength of the fibres.

The fact that after displacing the punch almost by 20 mm part of fibres was still intact, also testifies to the very good strength properties of the material. However, the strain gauge became unstuck and there was no sense in continuing the measurements. In order to present the degree of specimen deformation and the scope of damage, a picture of destructive testing, in which the punch was displaced by over 18 mm, is shown in Figure 7.

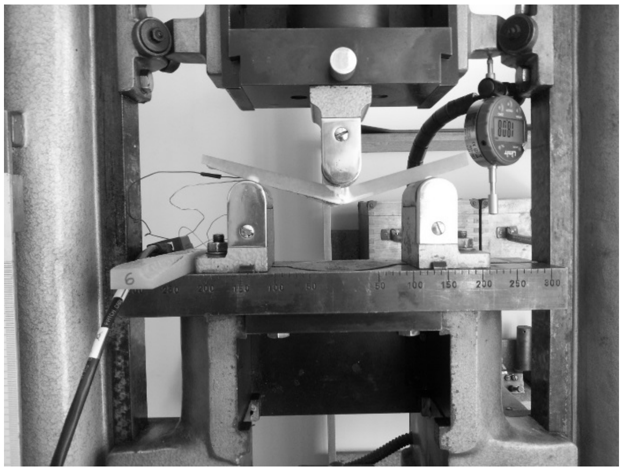

Fig. 7. Specimen in critical state

Rys. 7. Próbka w sytuacji krytycznej

## PRESENTATION AND ANALYSIS OF LAMINATE TESTING

In order to complete the calculations, it was necessary to determine the percentage of fibres in the laminate. In connection with this, a polished cross-section in the direction perpendicular to the fibres was performed, presented in Figure 8.

It was determined that the percentage of fibres in the laminate does not exceed 40%. On the grounds of the obtained result and using the ElamX program that utilises the theory of mixtures, the Young's modulus of the material in the longitudinal direction was obtained. This value amounted to 31 000 MPa.

With relation (1), the calculated stress values were determined, while relation (2) was used to determine the strains corresponding to them. The collected data is shown in Table 1, where the following designations were assumed: $F$ - the force read out from the meter during measurement, $S$ - punch displacement, $\varepsilon_{rd}$ - strain value, read from the strain gauge, $\varepsilon_{clc}$ - strain value, obtained from calculations, $\sigma_{rd}$ - stress values calculated based on strain gauge readings, $\sigma_{clc}$ - stress values, determined by calculations.

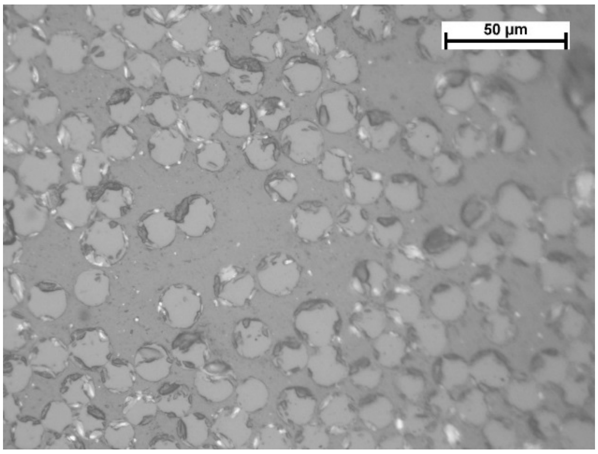


Fig. 8. Polished cross-section of prepared specimen

Rys. 8. Zgład wykonanej próbki

TABLE 1. **Test results**
TABELA 1. **Wyniki badania**

| *F* [daN] | *S* [mm] | $\varepsilon_{rd}$ [‰] | $\varepsilon_{clc}$ [‰] | $\sigma_{rd}$ [MPa] | $\sigma_{clc}$ [MPa] |
|---|---|---|---|---|---|
| 0 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 55 | 0.50 | 1.28 | 1.64 | 40 | 36 |
| 138 | 1.00 | 2.42 | 3.28 | 75 | 91 |
| 200 | 1.50 | 3.47 | 4.92 | 108 | 132 |
| 285 | 2.00 | 4.75 | 6.56 | 147 | 188 |
| 365 | 2.50 | 6.02 | 8.20 | 187 | 241 |
| 430 | 3.00 | 7.15 | 9.85 | 222 | 284 |
| 520 | 3.50 | 8.54 | 11.49 | 265 | 343 |
| 595 | 4.00 | 9.76 | 13.13 | 303 | 393 |
| 680 | 4.50 | 10.61 | 14.77 | 329 | 449 |
| 765 | 5.00 | 12.56 | 16.41 | 389 | 505 |
| 845 | 5.50 | 13.86 | 18.05 | 430 | 558 |
| 920 | 6.00 | 15.38 | 19.69 | 477 | 607 |
| 995 | 6.50 | 16.83 | 21.33 | 522 | 657 |
| 1000 | 7.00 | 17.44 | 22.97 | 541 | 660 |
| 900 | 7.50 | 18.89 | 24.61 | 586 | 594 |
| 950 | 8.00 | 20.37 | 26.25 | 631 | 627 |
| 900 | 8.50 | 21.80 | 27.90 | 676 | 594 |
| 845 | 9.00 | 21.97 | 29.54 | 681 | 558 |
| 890 | 9.00 | 23.96 | 29.54 | 743 | 587 |

Using the performed calculations, the stress curve was obtained, which is shown in Figure 9. The diagram shows the stress-strain dependence both for the strain gauge readings and for the calculations made based on the determined force and punch displacement. As can be seen, these values coincide within the elasticity range. Thereafter the course of calculations is irregular, while the course obtained on the grounds of strain gauge readings remains linear, considering the stress calculation method based on Hook's law.

Considering the fact that the strain gauge was placed parallel to the layers being "tensioned" during bending, the use of equations resulting from classical theory of laminates was not necessary, only assumptions coming from it were used. The ordinary Hooke's law, stating the linear stress dependence on strain, with a coefficient equal to the Young's modulus in the longitudinal direction, was used. The obtained relation is also presented in Figure 9.

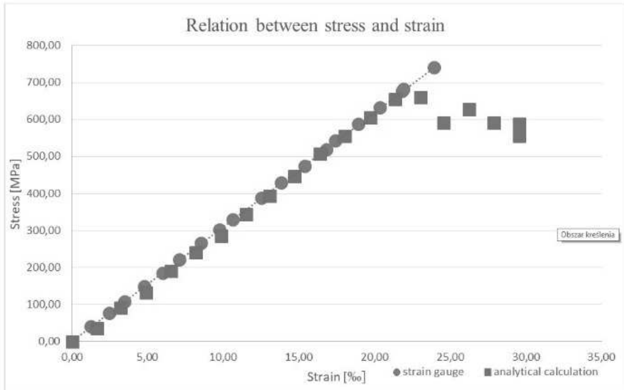


Fig. 9. Stress dependence on strain

Rys. 9. Zależność naprężeń od odkształceń

Analysis of Figure 9 reveals that the material elasticity range is present up to a strain equal to approx. 20‰. This situation was accompanied by the first material cracks during three-point bending. Such a deformation was obtained in the situation when the force was equal to 920 daN, and the punch displacement was equal to 6 mm. The stress in such a situation was over 600 MPa.

As comes from completed tests, whose results are shown in Table 1, the values read out from the strain gauge did not fully coincide with the results calculated with the formulas presented in the DIN EN ISO 14125 standard. The differences in the results were connected with measurement inaccuracy, both the first and second ones.

The results of strain gauge measurements was not fully true because of the strain gauge length and its location. In this sensor the strain value is integrated and presented in point form. Considering the fact that when a strain gauge was not fastened perfectly in the middle of the specimen, in the place of highest stress, the recorded values might not be the maximum ones that occurred in the specimen. A strain gauge not located in the central position recorded lower measurement results. The strain values, and hence stress, were not fully true because of at least two factors. The punch displacement was theoretically calculated in the direction conforming to the movement of the punch. However, providing a displacement sensor located precisely perpendicular to the specimen did not succeeded. Therefore the punch displacement indicated a value higher than the actual one This value was proportional to the strain value, which resulted in obtaining strain values higher than the actual ones.

Additionally the strain gauge was sewn into a layer of the material, which increased the thickness of the specimens, not improving, however, its mechanical properties. The strain value is also proportional to specimen thickness, so that when the determined thickness was higher than the actual one, the strain value was also higher.

## SUMMARY

The conducted research confirms the very good mechanical properties of composite materials. Considering the low density of the materials used for producing them, the elements making up the composites have a low mass. For the examined laminate, i.e. glass fibre reinforced epoxy resin, with a fibre percentage equal to 40%, the density was 1.52 g/cm$^3$. Because of the low material density, composites can be used for producing equipment components for which a low mass is required.

At the moment of crack, taking into consideration both calculation methods, the normal stress was over 600 MPa. There are a few publications where the results of similar tests are presented, but in most of them the authors present tensile or compressive strength values.

Nevertheless, in the literature it was found that other research has shown almost the same values of normal stress strength for glass fibre reinforced epoxy resin with the same fiber arrangement [13]. In the case of material without additional fillers in [14], the flexural strength was 650 MPa, which confirms that the obtained value is realistic. Since in other studies the same value was obtained, we can assume that the thickness of the laminate does not have an influence on its strength. The results of the tests indicate the high impact of sensor placement position on the resulting strain value. Nonetheless, the relation between stress and strain, determined by two different methods, almost coincided. Specimen failure started from breaking in the place of load application, but the most important fractures occurred between individual layers. The application of the tested composite may be arbitrary, and sensors can be fastened to arbitrary structures. This creates wide possibilities for monitoring the condition of machinery and equipment components, as well as protecting them against overload conditions, as the results within the elasticity range coincided. It is worth noting that placing sensors on composites has a great advantage, mainly due to the fact that they break suddenly, unlike metals.

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