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COMPOSITES THEORY AND PRACTICE

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INFLUENCE OF RESIN PARAMETERS ON STRENGTH PROPERTIES OF POLYMER COMPOSITE PRODUCED BY VACUUM METHOD

The paper presents the process of producing composite material by the vacuum bag method and its numerical analysis. The composite is made of three layers of two-directional combimat with a [0.90] orientation. Then it is cut at angles and subjected to a tensile test in the Laboratory of Composite Materials, Kielce University of Technology. The data obtained from the tensile test were used to construct three tubular elements that were designed in the ABAQUS program using the finite element method. The tube was treated as a thin-walled shell component, at both ends infinitely rigid rod-shaped Rigid links are formed, at the center of their intersection the point of attachment is generated. On both sides of the rigid restraint, the element is subjected to a uniform internal pressure of a 10 MPa amplitude, which would be very difficult to obtain under laboratory conditions. The conducted experiment gives very precise information about the stresses created in the composite and the behavior of both the fibers and the matrix at different layup angles.

Keywords: **composite, laminate, Shell, FEM, polyester resin, yield point, vacuum bag method, Rigid links**

WPŁYW PARAMETRÓW ŻYWICY NA WŁAŚCIWOŚCI WYTRZYMAŁOŚCIOWE KOMPOZYTU POLIMEROWEGO WYTWORZONEGO METODĄ PRÓŻNIOWĄ

Przedstawiono proces produkcji materiału kompozytowego metodą worka próżniowego oraz jego analizę numeryczną. Kompozyt jest zbudowany z trzech warstw matotkaniny dwukierunkowej o ułożeniu [0,90]. Następnie zostaje pocięty pod kątami i poddany próbie rozciągania w laboratorium materiałów kompozytowych Politechniki Świętokrzyskiej. Dane uzyskane z próby rozciągania posłużyły do budowy trzech elementów rurowych, które zostały zaprojektowane w programie ABAQUS, wykorzystującym metodę elementów skończonych. Rura została potraktowana jako element cienkościenny typu Shell (powłokowy), na obu końcach utworzone są nieskończenie sztywne elementy prętowe Rigid links, w centralnym punkcie ich przecięcia wygenerowany zostaje punkt zamocowania. Po obustronnym sztywnym utwierdzeniu element zostaje poddany od wewnątrz równomiernemu działaniu ciśnienia o amplitudzie 10 MPa, co byłoby bardzo trudne do uzyskania w warunkach laboratoryjnych. Przeprowadzony eksperyment daje bardzo precyzyjne informacje o naprężeniach powstających w kompozycie oraz o zachowaniu się zarówno włókien, jak i matrycy w różnych kątach ułożenia.

Słowa kluczowe: **kompozyt, laminat, powłoka, MES, żywica poliestrowa, granica plastyczności, metoda worka próżniowego, Rigid links**

INTRODUCTION

The first research on the buckling of pipes was carried out in London in 1850 by William Fairbairn. They were experimental studies, and their comparison with numerical calculations was made by Andrew Robertson in 1928. Extensive experiments with pipes tubes were carried out only in the 1930s because such elements were used in aviation (Fig. 1). In the 1980s there was a significant increase in the demand for materials lighter than traditional ones, with metal materials being replaced by composite materials as they are much lighter and more resistant to atmospheric phenomena. Nowadays composite pipes made of carbon fiber have a wide range of applications; they are used as the arms of NASA's space shuttle manipulators (Fig. 2). These elements are characterized by high quality workmanship, a specific way of fixing, variability of transferred loads and light weight.

Very often nowadays, the finite element method is used to design this type of elements, which allows production costs to be reduced and the highest durability properties to be achieved.

Figures 3a and b show a tubular element designed with FEM using a certain number of stiffening rings its structure.

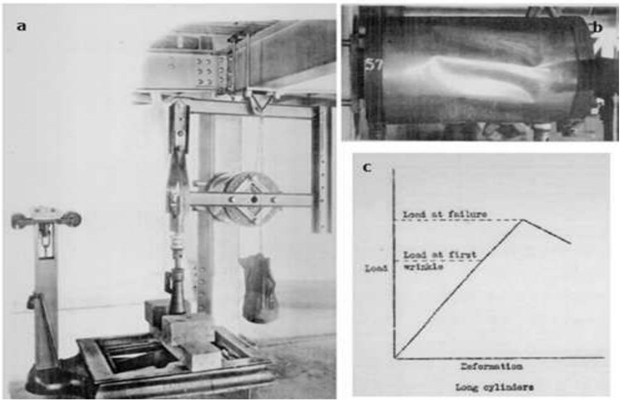

Fig. 1. Apparatus for testing stresses in duralumin pipes 1930s [1]

Rys. 1. Aparatura do badania naprężeń w rurach z duraluminium powszechnie stosowanych w lotnictwie w latach 30 [1]

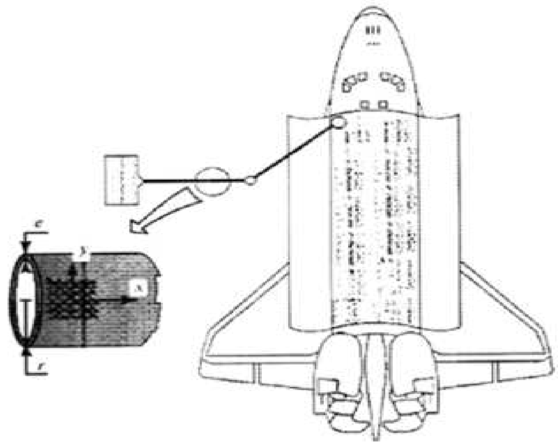

Fig. 2. Application commonly used in aviation in of composite pipes for construction of space shuttles [2]

Rys. 2. Zastosowanie rur kompozytowych do budowy promów kosmicznych [2]

a)

b)

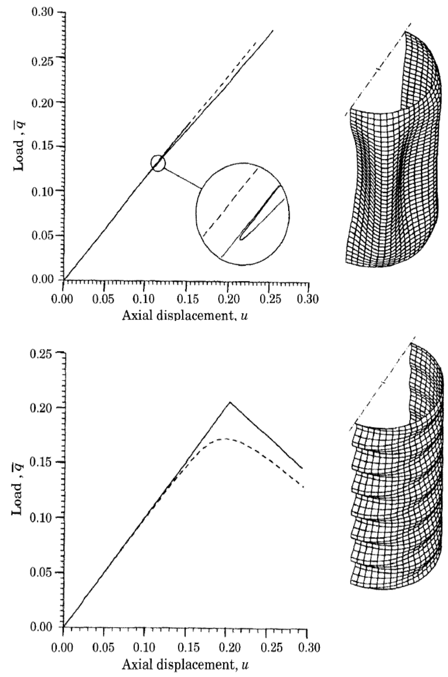

Fig. 3. Plot of axial deflection vs. load for different values of imperfection: a) cylinder with 40 *axial stiffeners*, b) cylinder with 20 *ring stiffeners* [3]

Rys. 3. Wykres odchylenia funkcji obciążenia dla różnych wartości niedoskonałości typu: a) cylinder z 40 pierścieniami usztywnienia, b) cylinder z 20 pierścieniowymi usztywnieniami [3]

PRODUCTION METHOD

One of the least expensive and simplest, yet very effective methods of producing composites with very good strength properties is the vacuum bag method, whose individual stages are shown in Figure 4.

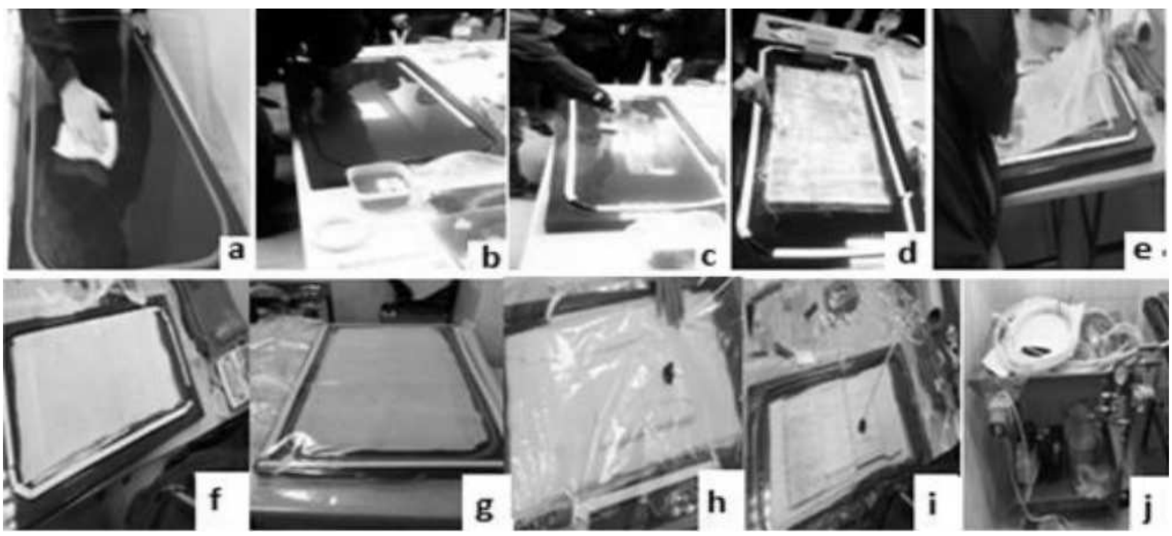

Fig. 4. Individual stages of making polymer composite using vacuum bag method: a) polishing the form, b) sticking double-sided assembly tape, c) applying first layer of resin, d) applying first layer of combimat, e) applying delaminating layer, f) breathing fabric, g) a layer of perforated film, h) fixing vacuum bag with suction opening, i) material subjected to pressure, j) vacuum aggregate [4]

Rys. 4. Poszczególne etapy wykonywania kompozytu polimerowego metodą worka próżniowego: a) polerowanie formy, b) naklejanie dwustronnej taśmy montażowej, c) nałożenie pierwszej warstwy żywicy, d) nałożenie pierwszej warstwy matotkaniny, e) nakładanie warstwy delaminującej, f) tkanina oddychająca, g) warstwa folii perforowanej, h) zamocowanie worka próżniowego wraz z otworem odsysającym, i) materiał poddany działaniu ciśnienia, j) agregat próżniowy [4]

The primary advantage of this method is injection of the resin under pressure into the mold, which significantly reduces the emission of styrene and increases the strength of the material. The resin injection speed must be adapted to the type of material, layup angle and variety of resin.

TABLE 1. **Parameters of produced composite [4]**
TABELA 1. **Parametry wykonanego kompozytu [4]**

Average strength of glass composite with polymer matrix (designated for four samples)			
Composite produced by vacuum bag method			
Layup angle	0^0	45^0	90^0
σ, MPa	126.71	88.67	174.60
E, GPa	11.27	9.26	14.18

TABLE 2. **Technological parameters of the resin [4]**
TABELA 2. **Parametry technologiczne żywicy [4]**

Composite produced by vacuum bag method	
Component volume ratio	50:50
Gel time [min]	3÷4 (25÷26)
Curing time [h]	60
Pressure [atm]	0.6

The laminate stacking sequence significantly affects its mechanical properties and character of the stress and strain states arising therein. Among the different stacking sequences, there are several specific types: symmetrical, quasi-symmetrical or asymmetric laminate stacking sequences (Figs. 5 and 6) [3]. A separate group of laminates are those reinforced with mats, in this case the weave in the fabric affects the mechanical properties. Depending on the needs it can be made uniformly, in which case, it is possible to obtain gradient layer laminates for increased strength in these areas of the structure which will be subjected to the greatest loads and further reduce the weight of the structure through the use of reinforcement of lower grammage in areas subjected to smaller loads [5]. The reinforcement usually gives laminates orthotropic or anisotropic properties.

In the case of laminates, two coordinate systems are usually distinguished: material and geometric. The material coordinate system is defined by the orientations of the reinforcement in the layer. However, in order to consider the laminate as a whole, a geometric coordinate system must be introduced due to the fact that the stiffness and strength properties of laminates are not generally isotropic [6]. The mechanical properties of laminates are affected not only by the materials they are made from but also the way they are joined, the technical parameters, as well as the degree of saturation of the fiber with the polymer [7]. From the point of view of chemistry, a polymer is a multi-molecular compound built from repeating units called monomers. A polymer is obtained by a polymerization reaction in which the substrates are monomers. One of the basic features of monomers is functionality, i.e. their ability to combine into microparticles. Depending on the functional groups of monomers, polymers gain a different structure in the topological sense [8]. To make the model, a polyester resin was used, which is a resin derived from the group of synthetic resins, whose primary component is different kinds of polyesters. Polyesters are polymers containing ester bonds in their main chains. Polyesters have stiffer and more polar main chains than vinyl polymers, which have a greater tendency to form a crystalline phase and are more brittle, harder and more difficult to melt.

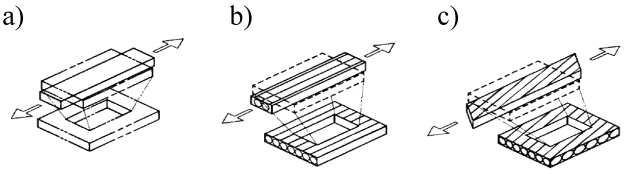

Fig. 5. Isotropic 2 elastic constants (a), orthotropic 4 elastic constants (b), anisotropic 6 elastic constants (c) [9]
Rys. 5 Materiał izotropowy (a), materiał ortotropowy (b), materiał anizotropowy (c) [9]

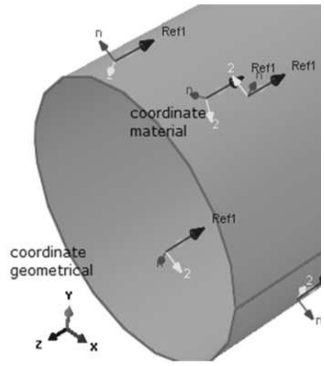

Fig. 6. Material and geometric coordinates
Rys. 6. Współrzędne materiałowe i geometryczne

TABLE 3. **Mechanical properties of resin [10]**
TABELA 3. **Właściwości mechaniczne żywicy [10]**

Polyester resin	Properties
1100÷1460	Density [kg]
1.5÷4.5	Young's Modulus [GPa]
5÷70	Tensile strength [MPa]
80÷250	Compression strength [MPa]
10÷127	Bending strength [MPa]

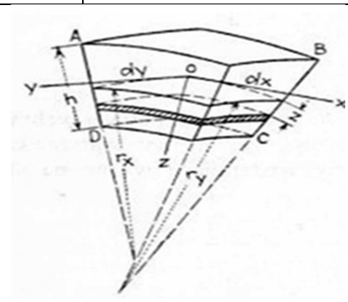

Fig. 7. Infinitely small element [11]
Rys. 7. Nieskończenie mały element [11]

THEORETICAL ANALYSIS

Deformation of a thin-walled tube element If an infinitesimal fragment of the shell is marked by ABCD, it will be "cut" from the element. The markings will be adopted in the Figures 7 and 8.

In further bending analysis it is assumed that the thickness of the coating is small compared to the radii of curvature. Therefore dependencies, will be omitted $\frac{z}{r_x}, \frac{z}{r_y}$ as well as the effect of deformation, ε_1 , ε_2. Thus, the expressions concerning deformations in the direction of the x and y axes will take the following form:

$$\varepsilon_x = \varepsilon_1 - \chi_{x^z} \quad (1)$$

$$\varepsilon_y = \varepsilon_1 - \chi_{y^z} \quad (2)$$

where χ_z and χ_y are increments of curvature.
Using equations (1) and (2) and equations:

$$\varepsilon_1 = \frac{\partial u}{\partial x}, \quad \varepsilon_2 = \frac{\partial \upsilon}{a\partial\theta} - \frac{\omega}{a}, \; \gamma = \frac{\partial \upsilon}{a\partial\theta} + \frac{\partial \upsilon}{\partial x},$$

$$\chi_x = \frac{1}{a^2}\left(\frac{\partial \upsilon}{\partial\theta} + \frac{\partial^2\omega}{\partial\theta^2}\right), \; \chi_{xy} = \frac{1}{a}\left(\frac{\partial \upsilon}{\partial x} + \frac{\partial^2\omega}{\partial x\partial\theta}\right) \quad (3\text{-}8)$$

all accidental forces, moments and displacements of *u*, υ, ω are expressed by substituting these expressions into equations:

$$a\frac{\partial N_x}{\partial x} + \frac{\partial N_{yx}}{\partial\theta} + qa\left(\frac{\partial^2\upsilon}{\partial x\partial\theta} - \frac{\partial\omega}{\partial x}\right) = 0 \quad (9)$$

$$\frac{\partial N'_x}{\partial\theta} + a\frac{\partial N_{xy}}{\partial x} - \frac{\partial M_y}{a\partial\theta} + \frac{\partial M_{xy}}{\partial x} = 0 \quad (10)$$

$$\frac{\partial^2 M_{yx}}{\partial x\partial\theta} + a\frac{\partial^2 M_x}{\partial x^2} + \frac{\partial^2 M_y}{a\partial\theta^2} - \frac{\partial^2 M_{xy}}{\partial x\partial\theta} + + N'_y - q\left(\omega + \frac{\partial^2\omega}{\partial\theta^2}\right) = 0 \quad (11)$$

After entering the following markings:

$$\frac{qa(1-\nu^2)}{Eh} = \Phi \text{ and } \frac{h^2}{12a^2} = \alpha \quad (12, 13)$$

we obtain the following equations:

$$a\frac{\partial^2 u}{\partial x^2} + \frac{1+\nu}{2}\frac{a\partial^2\upsilon}{\partial x\partial\theta} - \nu a\frac{\partial\omega}{\partial x} + a\phi_1\left(\frac{\partial^2\upsilon}{\partial x\partial\theta} - \frac{\partial\omega}{\partial x}\right) + + \frac{1+\nu}{2}\frac{\partial^2 u}{\partial\theta^2} = 0 \quad (14)$$

$$\frac{1+\nu}{2}\frac{a\partial^2 u}{\partial x\partial\theta} + \frac{1-\nu}{2}a^2\frac{\partial^2\upsilon\partial^2\upsilon}{\partial x^2} + \frac{\partial^2\upsilon}{\partial\theta^2} - \frac{\partial\omega}{\partial\theta} + \alpha\left[\frac{\partial^2\upsilon}{\partial\theta^2} + \frac{\partial^3\omega}{\partial\theta^3} + a^2\frac{\partial^3\omega}{\partial x^2\partial\theta} + a^2(1-\nu)\frac{\partial^2\upsilon}{\partial x^2}\right] = 0 \quad (15)$$

$$a\nu\frac{\partial u}{\partial x}\frac{\partial\upsilon}{\partial\theta} - \omega - \alpha\left[\frac{\partial^3\upsilon}{\partial\theta^3} + (2-\nu)a^2\frac{\partial^3\upsilon}{\partial x^2\partial\theta} + a^4\frac{\partial^4\omega}{\partial x^4} + \frac{\partial^4\omega}{\partial\theta^4} + 2a^2\frac{\partial^4\omega}{\partial x^2\partial\theta^2}\right] = \left(\omega + \frac{\partial^2\omega}{\partial\theta^2}\right) \quad (16)$$

Determination of the critical pressure value results from the solution of equations (14), (15) and (16), and the adoption of appropriate boundary conditions. Assuming that the length of the cylinder is equal to 1 and distance *x* is measured from the center of the pipe cross-section, we assume a solution (15) that satisfies the boundary conditions, and for the buckling displacement *u*, *v* and *ω* are equal to:

$$u = A\sin n\theta \sin\frac{\pi x}{l}, \; \upsilon = B\cos n\theta\cos\frac{\pi x}{l}, \; \omega = C\sin n\theta\cos\frac{\pi x}{l} \quad (17)$$

From equations (17) it follows that during buckling in the shaping direction, one half-wave of the sinusoid occurs while buckling, while 2 n half-waves form at the circumference of the tube. At the edges of the shell displacement ω and derivative $\partial^2\omega/\partial x^2$ are equal to 0 because of the free support of the edges of the shell [11].

NUMERICAL MODELING

The selection and design of the reinforcement is the most important step in the laminate design process, as the reinforcement material, as well as its stacking sequence and volume share determine the strength properties as well as the capabilities and manner of load transfer by the designed element. The basic criteria for selecting the reinforcing fibers is their tensile strength and weight [10].

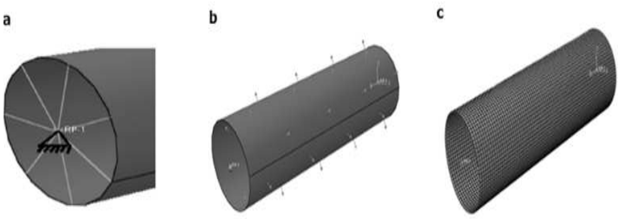

Fig. 8. a) Mounting on both sides of model in central point of Rigid Links connection (500 mm in length, 75 mm radius), b) Load in form of 10 MPa pressure amplitude, c) FEM mesh model

Rys. 8. a) Mocowanie obustronne modelu w centralnym punkcie połączenia Rigid Links (długość modelu 500 mm, promień 75 mm), b) Obciążenie w postaci ciśnienia o amplitudzie 10 MPa, c) Model z siatką elementów skończonych

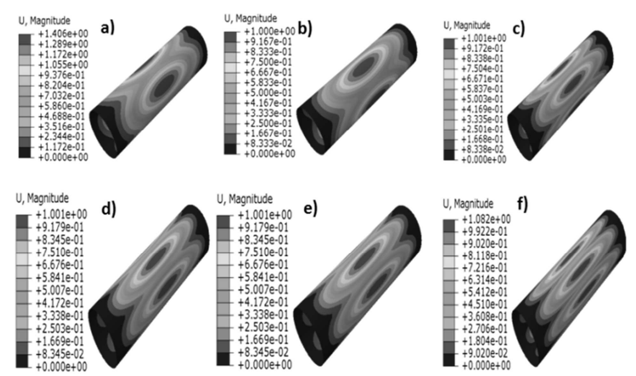

Fig. 9. Composite shell with layup angle 0^0, subjected to uniform pressure: a-e) cracking of matrix and formation of greatest stress in middle section of element in direction of fiber orientation up to complete destruction at position f)

Rys. 9. Powłoka kompozytowa o kącie ułożenia 0^0 poddana działaniu równomiernego ciśnienie: a-e) pękanie osnowy i powstawaniu największych naprężeń w środkowej części elementu zgodnie z kierunkiem ułożenia włókien aż do całkowitego zniszczenia w położeniu f)

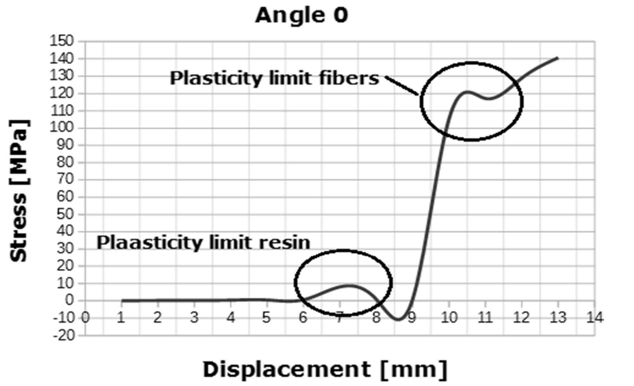

Fig. 10. Stress strain displacement with clear yield point of resin and fibers

Rys. 10. Wykres naprężenie przemieszczenie z wyraźną granicą plastyczności żywicy i włókien

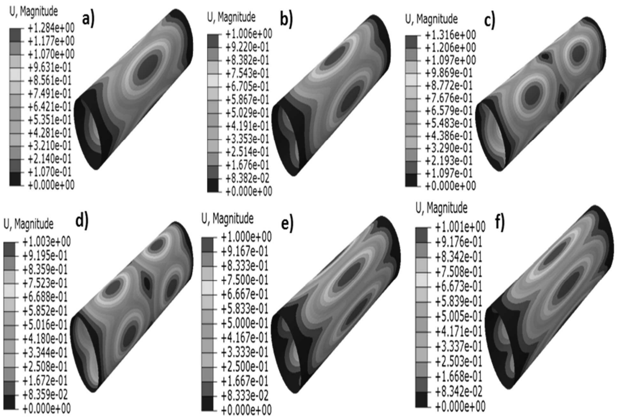

Fig. 11. Composite shell with layup angle 90°, subjected to uniform pressure: a) cracking of matrix and formation of greatest stress in middle section of element, b) enlargement of stress fields, c), d) end of matrix cracking process and emergence of two stress concentration centers in the fibers, e), f) rupture of element and expansion of critical stress along the element

Rys. 11. Powłoka kompozytowa o kącie ułożenia 90° poddana działaniu równomiernego ciśnienie: a) pękanie osnowy i powstawanie największych naprężeń w środkowej części elementu, b) powiększenie się pól naprężeń, c),d) zakończenie procesu pękania osnowy i pojawienie się dwóch ośrodków koncentracji naprężeń we włóknach, e), f) zerwanie elementu i rozrost naprężeń krytycznych wzdłuż elementu

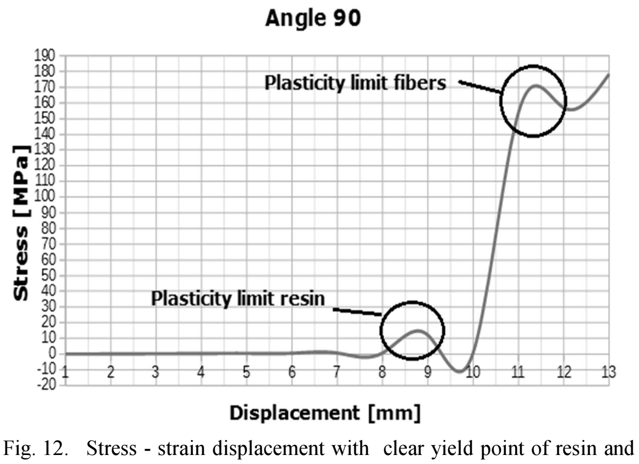

Fig. 12. Stress - strain displacement with clear yield point of resin and fibers

Rys.12. Wykres naprężenie - przemieszczenie z wyraźną granicą plastyczności żywicy i włókien

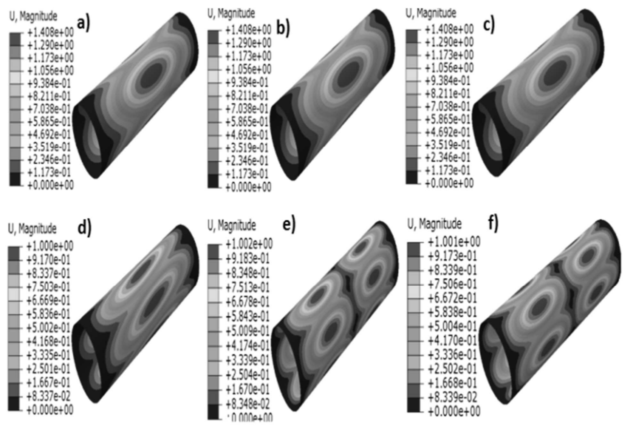

Fig. 13. Composite shell with layup angle 45°, subjected to uniform pressure: a) cracking of matrix and formation of greatest stress in middle section of element, b), c), d) expansion of stress fields in accordance with direction of fiber orientation, e), f) final stages of fiber cracking

Rys. 13. Powłoka kompozytowa o kącie ułożenia 45° poddana działaniu równomiernego ciśnienie: a) pękanie osnowy i powstawanie największych naprężeń w środkowej części elementu, b), c), d) powiększenie się pól naprężeń zgodnie z kierunkiem ułożenia włókien, e), f) końcowe etapy pękania włókien

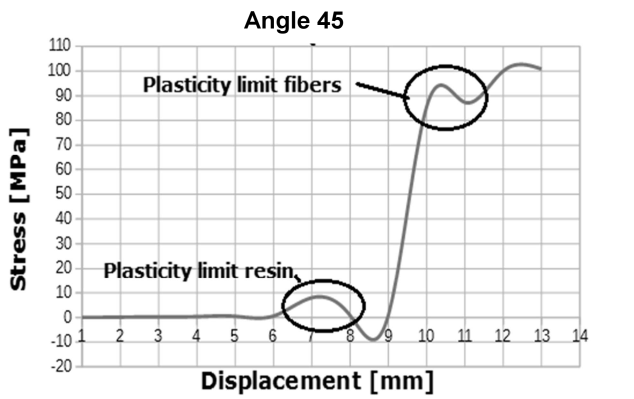

Fig. 14. Stress - strain displacement with clear yield point of resin and fibers

Rys. 14. Wykres naprężenie - przemieszczenie z wyraźną granicą plastyczności żywicy i włókien

CONCLUSIONS

From the displacement force graphs, it follows that the value of the resin yield point is proportional to the fiber layup angle. The resin parameters have a slight impact on the composite strength properties. The resin forms mainly the matrix of the composite material which, subjected to external factors, breaks first, as can be seen in the diagrams (Fig.10, 12, 14). The tensile properties of the polyester resin range from 5 to 70 MPa (Tab. 3). The deformations of the whole elements are shown in Figures 9, 10 and 11.

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