ISSN 1330-3651
UDC/UDK 620.172.21/.22:678.742.2.017

EXPERIMENTAL ANALYSIS OF THE STRENGTH OF A POLYMER PRODUCED FROM RECYCLED MATERIAL

Aleksandar Jurić, Tihomir Štefić, Zlatko Arbanas

Preliminary notes

The subject of this paper is experimental testing of a polymer and definition of the idealised stress/strain diagram, from which the modulus of elasticity can be easily defined. The analysis was conducted on polymer straps made of ethylene polymer of high density (HDPE). In this case the polyethylene (PE) was produced almost entirely from recycled material and that defines its cost. PE generally has high density and very good mechanical characteristics and resistance to chemicals. As a material it is used in production of reservoirs and containers for various purposes. This paper is trying to define the basic characteristics of polymers by observing their tensile strength, to propose an idealised stress/strain diagram and to define the numerical values of the modulus of elasticity. Also the intention is to create a tool which would enable the definition of the stress / strain diagram for any similar material and broaden the application and use of such types of materials.

Key words: *polymer, polyethylene, recycled material, strength, modulus of elasticity, stress/strain diagram, elastoplastic material*

Eksperimentalna analiza nosivosti polimera dobivenog iz recikliranog materijala

Prethodno priopćenje

Predmet ovog rada je ispitivanje nosivosti polimera dobivenog iz recikliranog materijala i definiranje idealiziranog dijagrama naprezanje/deformacija, iz kojeg se lako može definirati modul elastičnosti. Analiza je provedena pomoću polimernih traka koje su izrađene od polimera etilena visoke gustoće (HDPE). U ovom slučaju polietilen (PE) je dobiven, gotovo u cijelosti, od recikliranog materijala, što u konačnici uvjetuje i njegovu cijenu. U pravilu je visoke gustoće i ima vrlo dobre mehaničke karakteristike i otpornost prema kemikalijama. Kao materijal prisutan je u proizvodnji rezervoara te posuda raznih namjena. U ovom radu nastoje se definirati osnovne karakteristike polimera kao materijala kroz rasteznu čvrstoću te predložiti idealizirani radni dijagram. Namjera je također kako bi ovaj rad postao alat kojim bi se mogao definirati dijagram naprezanje/deformacija za bilo koji drugi sličan materijal te otvoriti mogućnosti širokog spektra primjene.

Ključne riječi: *polimer, polietilen, reciklirani materijal, rastezna čvrstoća, modul elastičnosti, dijagram naprezanje/deformacija, elastoplastični materijal*

1
Introduction

Because of the constant use of new materials there is a need to define their basic characteristics. This can be done through the stress/strain diagram obtained by tensile testing of specific samples. Polymers found their broad use in civil engineering as a component of many modern composite materials, the use and analysis of which was studied by various authors in many papers [1, 2, 3] and [4] as well as books and manuals [5] and [6]. Present composites mainly consist of a matrix, which has distinct elastic characteristics, and fillers which are light and brittle. In this paper an ethylene polymer, polyethylene (PE) in the shape of straps was tested. A polymer is a matter consisting of molecules with high relative molecular mass, whose structure consists of many units with low relative molecular mass (monomers).

The number of monomers is huge and usually it is not defined so one molecule of a polymer is called macromolecule. The tested straps were made of high density polymer ethylene (HDPE), more exactly of thermoplastic polyolefin with density from 0,941 g/cm^3 to 0,960 g/cm^3, produced from recycled material. Polyethylene is a macromolecular product made by polymerization of ethylene and it is a most commonly used plastic material. High density polyethylene has good mechanical properties and resistance to chemicals and is therefore mainly used in the production of reservoirs and containers for various purposes.

The basic characteristic of a material, through Hooke's law, is the modulus of elasticity known as the Young's modulus ($E = \sigma/\varepsilon$). Its value is known in the elastic area, and for the materials which have a distinct plastic area it is specific that its value is exact only in the elastic area. By the use of an idealised stress / strain diagram, which is made to be linear, the area of elastic behaviour, where the modulus is exact, and the plastic area where the modulus decreases, is defined. In nature all materials behave as elastic and plastic, that is they have both areas. In order to simplify the design procedure one value of the modulus is used and the beginning of the plastic behaviour is defined to start after a certain irreversible (plastic) deformation (strain).

2
Description of used samples and testing machine

Samples of polymer used in this paper were in the shape of thin straps of different thickness, width and length, Figs. 1 and 2. Multiple layer straps were made only by overlapping (multiplying) two types of single layer straps. Dimensions were measured prior to the testing of samples. In order to avoid any initial imperfections and slipping of samples two wooden elements were added in the jaws of the testing machine. First sample was tested by cyclically applying and realising the stress, and after that the load was applied until the sample broke. This was done for all samples. After realising and reapplying the stress new plastic deformation begun with the increase of the force in comparison to the previous increment. And for every increase of the force the curve on the stress / strain, that is the value of the modulus, slightly decreased. In total, six samples with different widths and lengths were tested and they showed very similar shapes of the stress / strain curves. The machine used for testing was Schimadzu AG-X with the software Trapezium Version 1.1.5, as shown in Fig. 2. The machine can apply compressive and tensile force of up to 300 kN and measure displacement and force during the testing. With these measurements the software can produce

Figure 1 Testing machine and single strap sample

Figure 2 Testing machine and multiple strap samples

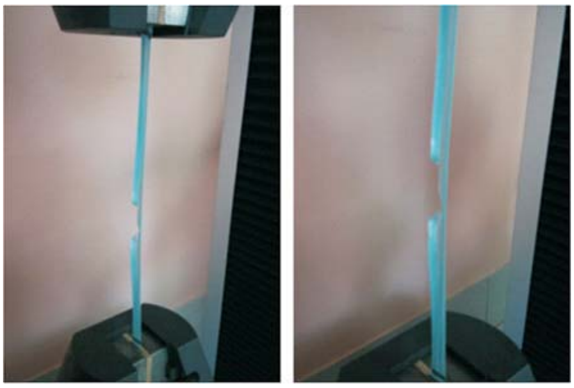


Figure 3 Breaking of the single strap sample

diagrams as shown later in the text. It is also possible to define the way the force is applied, increase of force in time or displacement in time (for this testing the force/time increase was used). Fig. 3 shows the beginning of failure and breaking of one of the samples.

3 Results of testing

Samples have shown characteristic elastoplastic behaviour which can be seen from the output diagram force/displacement. During cyclic applying and removing strain (force) the curve seems fairly linear. This indicates how the material almost completely and instantly takes its initial shape (Figs. 4 and 5).

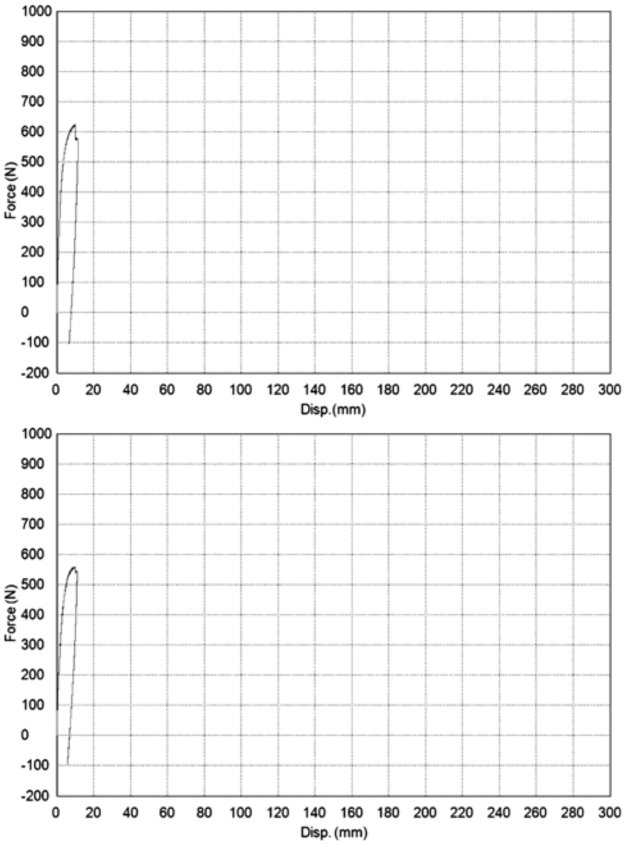


Figure 4 Cyclic applying and removing of stress

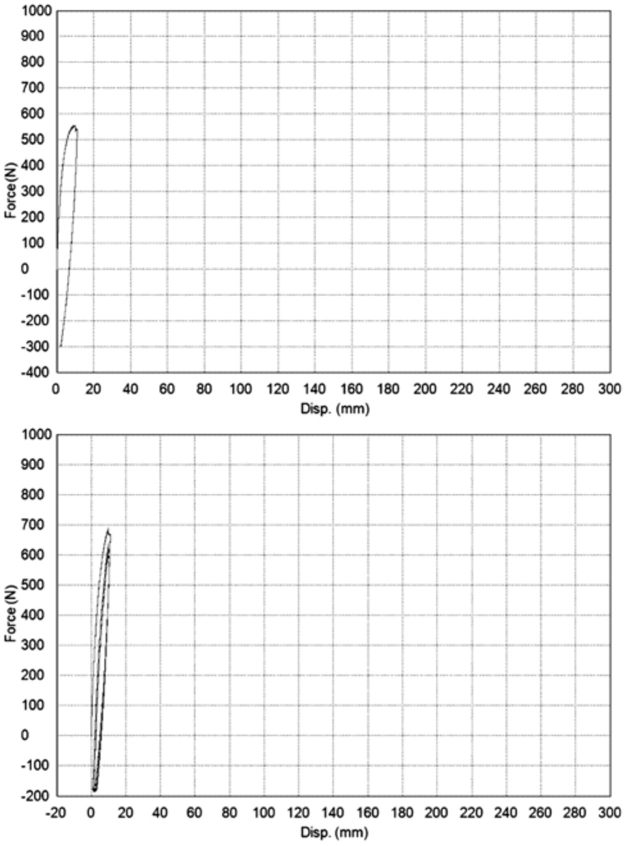


Figure 5 Cyclic applying and removing of stress

Testing data have shown that polymers behave as elastic to approximately 1/4 of breaking force and then begin to deform plastically. After that the samples begin to experience large plastic deformation and when the deformation reaches certain value the samples break. A characteristic elastoplastic shape of the stress/strain diagram is used to produce four simple suggestions of an idealised stress/strain diagram. The testing and breaking of a single strap, with the cross section *b*/*h* = 57/0,3 mm and length of 150 mm can be seen in Fig. 6 and testing and breaking of a double strap, with the cross section 2*b*/*h* = 2×57/0,3 mm and length of 154 mm can be seen in Fig. 7.

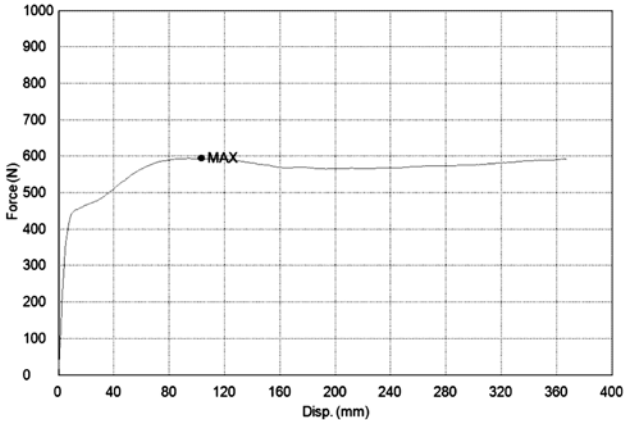


Figure 6 Breaking of a single strap sample

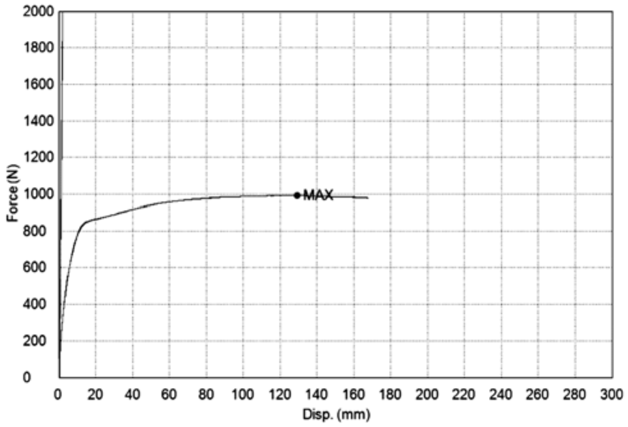


Figure 7 Breaking of a double strap sample

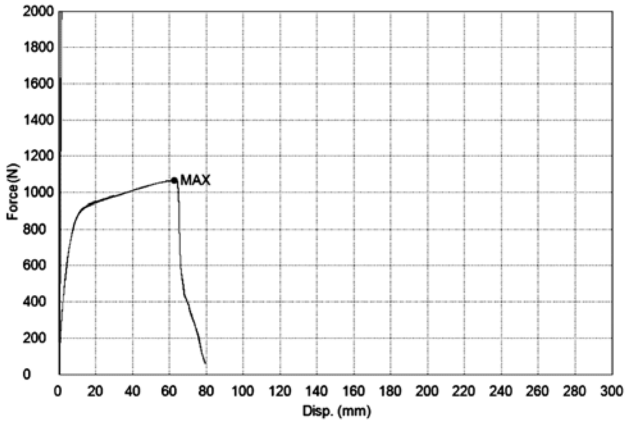
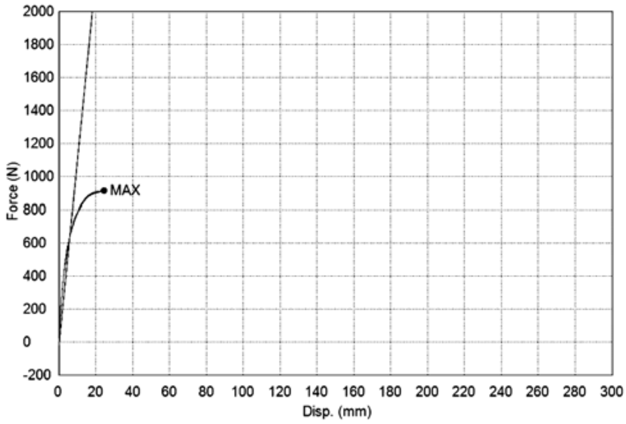


Figure 8 Breaking of a triple strap sample

Testing and breaking of a triple strap sample, with the cross section 3*b*/*h*=3×57/0,3 mm and length of 162 mm can be seen in Figs. 8 and 9.

Testing and breaking of a single strap sample, with the cross section *b*/*h*=22/0,5 mm and length of 150 mm can be seen in Fig. 10, and in Fig. 11 testing and breaking of a six layer strap with the cross section 6*b*/*h*=6×22/0,5 mm and length of 108 mm.



Slika 9 Breaking of a triple strap sample

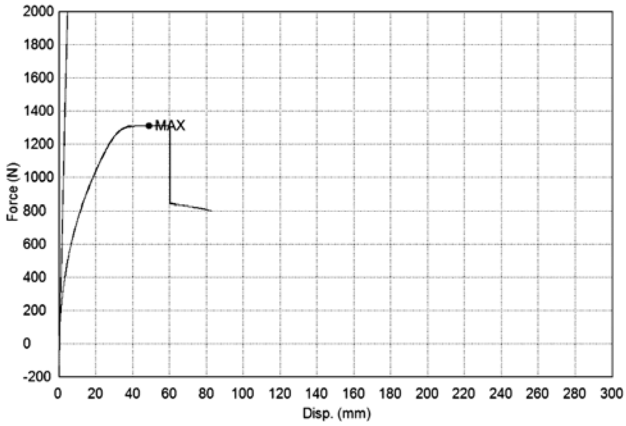
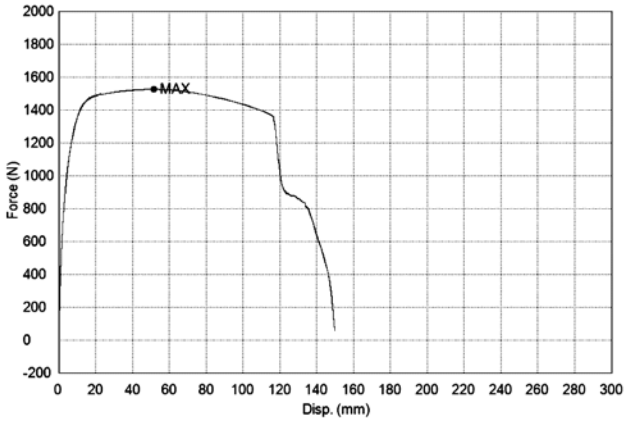


Figure 10 Breaking of a single strap sample



Slika 11 Breaking of a six strap sample

4
The stress/strain diagram

In Fig. 12 the stress/strain diagrams for all five samples can be seen. Bigger values of stress accompany a single layer strap which means that the stress decreases with the number of layers of polymer which can be attributed to slipping of yaws of the testing machine or the pure nature of the material. In order to clarify this further research and testing should be done.

After analysing all diagrams some idealised diagrams are presented. In total four diagrams based on single strap samples were chosen. Fig. 13 illustrates the first suggestion which has a bilinear shape. Along with the diagram the mathematical definition of the curves (lines) is presented.

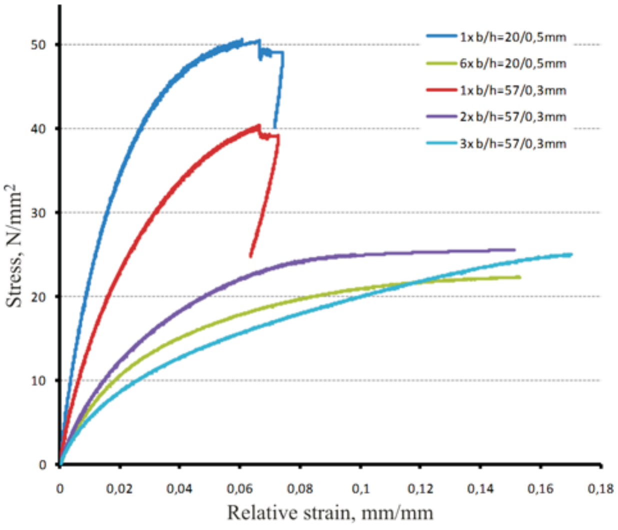


Figure 12 Stress/strain diagram for five samples

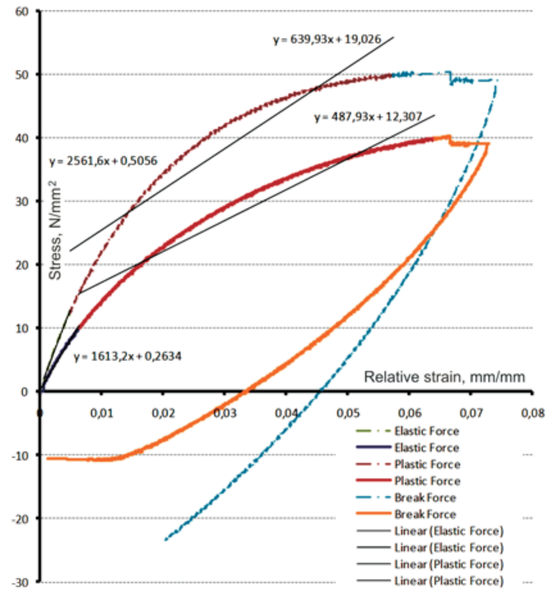


Figure 13 Bilinear idealisation of the stress/strain diagram

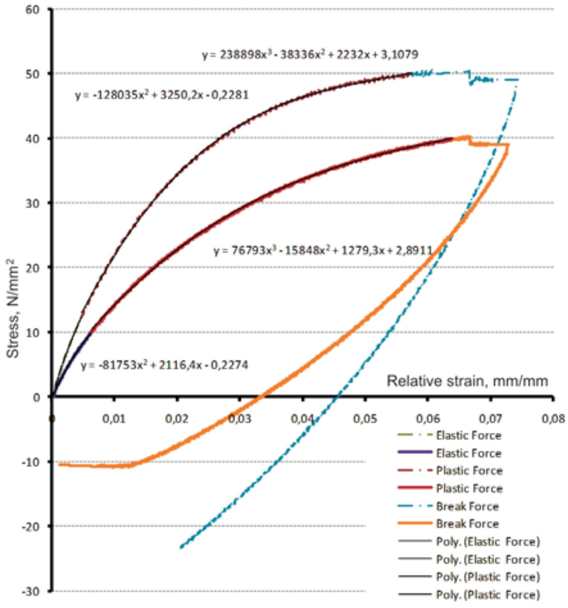


Figure 14 Idealised stress/strain diagram with a quadratic and a cubic curve

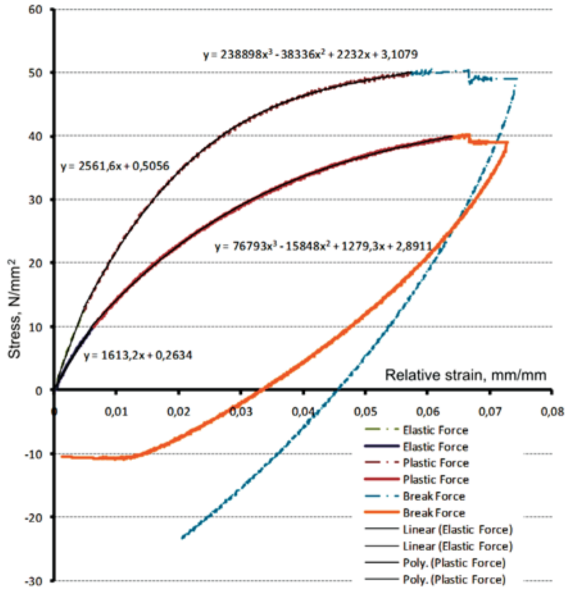


Figure 15 Idealised stress/strain diagram with a linear line and a cubic curve

The second idealised diagram combines a second order curve (elastic area) and a third order curve (plastic area), and is presented in Fig. 14.

The third idealised diagram is a combination of a linear line for the elastic area and a third order curve for the plastic area as shown in Fig. 15.

The fourth idealised diagram is a very simple third order curve diagram both for elastic and plastic area, shown in Fig. 16.

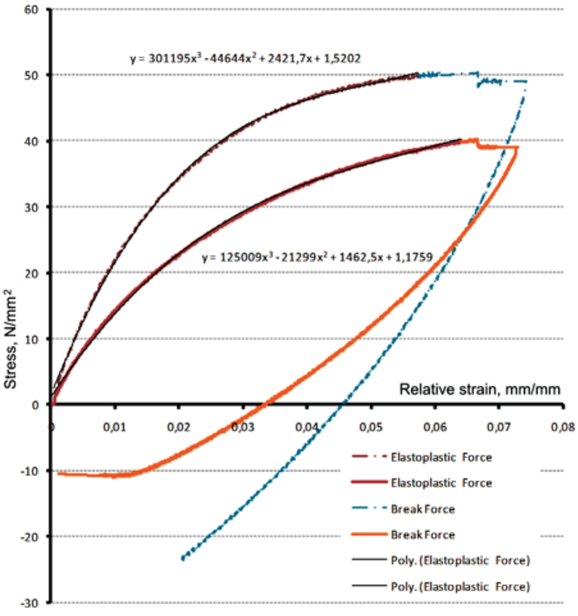


Figure 16 Idealised stress/strain diagram with a cubic curve

As mentioned above the diagrams describe an elastic area up to the 1/4 of the breaking stress in the shape of a linear line. Because of this fact the third idealised diagram represents most accurately the behaviour of the tested polymers (Fig. 15).

According to this idealised approximation for both single strap samples the linear (elastic) area can be mathematically described with the expressions:

$$y = 2561{,}6x + 0{,}5056, \tag{1}$$

$$y = 1613{,}2x + 0{,}2634, \tag{2}$$

and the nonlinear (plastic) area can be mathematically described with the expressions:

$$y = 238898x^3 + 38336x^2 + 2232x + 3{,}1079, \tag{3}$$

$$y = 76793x^3 + 15848x^2 + 1279{,}3x + 2{,}8911. \tag{4}$$

To simplify these expressions we can make an average expression for both linear and nonlinear area.

In order to determine the modulus for the chosen idealised diagrams and accompanied expressions we must accept that in the nonlinear area the modulus behaves by the third order curve, while in the elastic area its value is already given with the expressions (1) and/or (2). In total this approximation describes the material characteristics almost completely.

5
Conclusion

The intention of this paper was to analyse polymers produced from recycled material and to define an idealised stress/strain diagram. According to the results the use of idealised linear-cubic curve is recommended, which with its shape almost completely describes the testing data. It can be seen that the stress/strain diagram consists of a linear part, where stress and strain interact linearly, up to 1/4 of the breaking force. After that comes the plastic area with the 3/4 of the breaking force, which is well described with a third order curve.

Furthermore the division on elastic area (up to approximately 1/4 of the breaking force), and plastic area from 1/4 till breaking point is considered to be obligatory.

This idealisation can be of great assistance for testing and application of such and similar materials in civil engineering either as a part of a composite material or as a load bearing material.

6
References

[1] Štefić, T.; Jurić, A.; Marović, P. Definition of module of elasticity for fibre reinforced polymers. // Technical Gazette, 18, 1 (2011), 69-72.

[2] Štefić, T.; Jurić, A.; Maričić, S. Strength of glass fibre reinforced polymers tested using strain gauges and displacement meters (LVDT-s) (Nosivost uzoraka od stakloplastike ispitivana tenzometrima i mjeračima pomaka (LVDT-ima), 3rd International Conference Civil Engineering - Science and Practice (2010), 759-764 (in Croatian).

[3] Hollaway, L. C. The evolution of and the way forward for advanced polymer composites in the civil infrastructure. // Construction and Building Materials, 17 (2003), 365–378.

[4] Lacković, V.; Šimić, V. Behaviour of composite materials subjected to combined load (Ponašanje kompozitnih materijala pri složenom opterećenju), Journal "Gradjevinar", 58, 7(2006), 549-557 (in Croatian).

[5] Šimunić, Ž. Polymers in civil engineering (Polimeri u graditeljstvu), Faculty of Civil Engineering of the University of Zagreb, 2006. (in Croatian).

[6] Gerdeen, J. C.; Lord, H. W.; Rorrer, R. A. Engineering Design with Polymers and Composites. // CRC Press, Taylor & Fancis Group, Boca Raton, 2006.

Authors' addresses:

Doc. dr. sc. Aleksandar Jurić, dipl. ing. građ.
Građevinski fakultet u Osijeku
Drinska 16a
31000 Osijek, Croatia
e-mail: ajuric@gfos.hr

Tihomir Štefić, dipl. ing. građ., asistent
Građevinski fakultet u Osijeku
Drinska 16a
31000 Osijek, Croatia
e-mail: tstefic@gfos.hr

Zlatko Arbanas, dipl, ing. agr.
Regeneracija d.o.o.
Bana Josipa Jelačića 9
31550 Valpovo, Croatia
e-mail: zlatko.regeneracija@gmail.com