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## PRAĆENJE OŠTEĆENJA KOMPOZITNIH LAMINATA POMOĆU FIBEROPTIČKIH SENZORA INTENZITETNOG TIPRA

### DAMAGE MONITORING OF COMPOSITE LAMINATES BY MEANS OF INTENSITY BASED FIBEROPTIC SENSORS

Originalni naučni rad / Original scientific paper  
UDK / UDC: 687.7-19.017  
Rad primljen / Paper received: 17.02.2005.

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#### Ključne reči

- praćenje oštećenja
- termoplastični kompozitni materijali
- intenzitetni fiberoptički senzori
- utiskivanje

#### Izvod

*Cilj ovoga rada je istraživanje primene optičkih vlakana (OV) kao intenzitetnih senzora za detekciju oštećenja laminarnih kompozitnih materijala u realnom vremenu.*

*Za eksperimentalne potrebe su izrađeni termoplastični laminarni kompozitni materijali sa ugrađenim optičkim vlaknima. Izrađeni uzorci aramidno vlakno/poli(vinil-butiral) sa ugrađenim optičkim vlaknima izlagani su različitim vrstama opterećenja: statičkom opterećenju utiskivanjem na adaptiranoj kidalici, udarima niske energije Šarpijevim klatnom i balističkim udarima standardnim oružjem i municijom. Inicijacija oštećenja i loma laminata tokom ispitivanja su detektovani praćenjem pada intenziteta svetlosnog signala propuštenog kroz optička vlakna.*

*Rezultati eksperimenta su potvrdili da se optička vlakna mogu koristiti u toku rada (u realnom vremenu) kao intenzitetni senzori za detekciju strukturnih promena u laminarnim kompozitnim materijalima.*

#### UVOD

Pored klasičnih metoda za otkrivanje oštećenja u kompozitnim materijalima sa polimernom matricom (ultrazvuk /1/, akustična emisija /2,3/), optički fiber senzori (OFS) se široko koriste za precizno određivanje ponašanja materijala tokom proizvodnje i upotrebe. Različite konfiguracije OFS se mogu koristiti zavisno od vrste i svojstava optičkih vlakana (OV). Izvedena su brojna istraživanja inteligentnih (*Smart*) materijala sa ugrađenim interferometrijskim OFS tipa Fabry-Pero /4-6/ ili Majkelson /7/, a izvedeni su senzori sa Bragovim rešetkama /8-13/.

#### Keywords

- damage monitoring
- thermoplastic composite materials
- intensity-based fibre optic sensors
- indentation

#### Abstract

*The paper deals with the research in applying optical fibres (OF) as intensity-based sensors in real-time damage detection of laminar composite materials.*

*For experimental purposes, thermoplastic laminar composite materials with embedded optical fibres were made. Manufactured specimens of aramid fiber/poly(vinyl butyral) with embedded optical fibres were subjected to various loads: static loading by indentation on the adapted tensile testing machine, low blow on Charpy pendulum, and ballistic impact by standard weaponry and ammunition. Initiation of damage and fracture during laminate testing was observed from the intensity drop of the light signal transmitted through the optical fibre.*

*Experimental results confirmed that optical fibres could be applied as intensity sensors in real-time monitoring of structural changes in thermoplastic laminar composite materials.*

#### INTRODUCTION

In addition to classical methods for damage detection in composite materials with a polymer matrix (ultrasonic /1/, acoustic emission /2,3/), optical fibre sensors (OFS) are widely used to monitor and precisely estimate material behaviour during manufacture and exploitation. Various OFS configurations may be used depending on the optical fibre type and their light sensitivity. Numerous investigations on *Smart* materials with embedded interferometric OFS such as Fabry-Perot /4-6/, Michelson /7/, and Bragg grating sensors /8-13/ were performed.

Oblik i struktura intenzitetnih optičkih fiber senzora omogućavaju njihovu jednostavnu ugradnju u materijal, pri tom ne narušavajući njegova osnovna mehanička svojstva. Zbog toga se oni mogu koristiti kao pouzdani, dugoročni automatski senzori za praćenje oštećenja i deformacije strukture u realnom vremenu /14,15/. Mnogi autori su uočili delaminaciju u kompozitnim strukturama primenom intenzitetnih OFS /16-19/ i izučavali detekciju oštećenja usled udara niske energije /20,21/. Hofer /22/ je ugradio mrežu ogoljenih OFS različitih prečnika u kompozite ojačane grafitnim i karbonskim vlaknima. Svrha njegovog istraživanja je mogućnost upotrebe *smart* materijala za delove aviona Airbus. Tokom analize uspeo je da razvije sistem automatskog otkrivanja oštećenja, nevidljivih golim okom, ali uočljivih u realnom vremenu iz pilotske kabine. Ovaj sistem otvara mogućnost smanjenja broja neophodnih rutinskih kontrola, ili čak i njihovo potpuno ukidanje.

Većina do sada istraženih kompozita kao matricu koristi termoreaktivni polimer. Preliminarna istraživanja, izvedena na termoplastičnom laminarnom kompozitnom materijalu aramidno vlakno/poli(vinil-butiral) /23/, su pokazala da ovaj materijal ima 5,5 puta veću apsorpciju energije od tradicionalno korišćenih materijala sa istim ojačanjem. Međutim, njegovi mehanizmi apsorpcije energije nisu dovoljno objašnjeni, što i predstavlja predmet istraživanja u ovom radu. Intenzitetni OFS su ugrađeni u navedeni termoplastični kompozit i dobijeni *smart* materijal je ispitivan različitim vrstama opterećenja: statički (utiskivanjem na adaptiranoj kidalici), udarima niske energije (Šarpijevim klatnom) i balističkim udarima (standardnim oružjem i municijom). Dobijeni rezultati su analizirani radi razvoja odgovarajućih matematičkih modela.

#### SWOJSTVA MATERIJALA KOMPONENATA

Kao ojačanje korišćena je aramidna tkanina. Svojstva aramidne tkanine Kevlar 129<sup>1</sup> su: površinska masa 280 g/m<sup>2</sup>, gustina 1,44 g/cm<sup>3</sup>, zatezna čvrstoća vlakna 235 cN/tex, zatezna čvrstoća 3380 MPa, izduženje pri lomu 3,4%, temperatura razgradnje 560°C. Kao matrice korišćene su folije poli(vinil butiral) (PVB). Svojstva termoplastičnog PVB<sup>2</sup> su: gustina 1,058 g/cm<sup>3</sup>, zatezna čvrstoća 23 MPa, izduženje pri lomu 210%, modul elastičnosti 5 MPa, Poasonov koeficijent ±0,5, temperatura staklastog stanja 16°C i tvrdoća po Šoru "A" 64.

Multimodna optička vlakna su ugrađena kao senzori. Svojstva optičkih vlakana<sup>3</sup> su: prečnik jezgra 62,5 μm, prečnik presvlake 125 μm, prečnik obloge 250 μm, opseg talasnih dužina 850–1300 nm, propusni opseg 522–748 MHz/km, numerička apertura 0,27. Izabrani materijali su uniformno slagani naizmeničnim pakovanjem 25 ojačavajućih slojeva i 24 sloja matrice.

Laminati su toplo presovani u zatvorenom kalupu, obloženim silikonskim uljem. Nakon toga uzorci su ostavljeni u kalupu pod neznatno povećanim pritiskom radi hlađenja sa

Shape and structure of intensity based optical fibre sensors allow their simple embedding in the host material without disturbing its basic mechanical properties. Therefore, they can be used as reliable, long-term automated sensors for real time structure damage and deformation detection /14,15/. Many authors noticed delamination within composite structures by using intensity based OFS /16-19/ and studied damage detection caused by low energy impact /20,21/. Hofer /22/ has embedded a net of uncoated FOS of different diameters into laminates reinforced by graphite and carbon fibre. Purpose of his investigation was a possibility of exploitation of such smart material as a component in Airbus production line. During his study, he managed to develop the system for automated indication of the damage that is invisible to the naked eye, but detectable from pilot cabin in real time. This system opened a possibility for routine control minimization or even its abrogation.

Most of investigated composites contain thermoreactive polymer as a matrix. Preliminary investigation made on thermoplastic composite material aramid fiber/poly(vinyl butyral) /23/ has shown that this specific material has energy absorption capacity 5.5 times higher than the traditionally used materials with the same reinforcement. However, energy absorption mechanisms are not adequately explained, which is a subject of research in this paper. Intensity based OFS are embedded in referred material and the obtained *smart* material is tested by various types of loading: static loading (indentation by the adapted tensile testing machine), low energy impact (Charpy pendulum), and ballistic impact (standard weapons and ammunition). The obtained results are analysed in order to develop appropriate mathematical models.

#### COMPONENTS MATERIAL PROPERTIES

Aramid fabric was used as reinforcement. Aramid fabric Kevlar 129<sup>1</sup> properties are: superficial mass of 280 g/m<sup>2</sup>, density 1.44 g/cm<sup>3</sup>, fibre ultimate tensile strength 235 cN/tex, tensile strength 3380 MPa, elongation at break 3.4%, decomposition temperature 560°C. Thin poly(vinyl butyral) (PVB) foils were used as matrix. Thermoplastic PVB<sup>2</sup> properties are: density 1.058 g/cm<sup>3</sup>, tensile strength 23 MPa, elongation at break 210%, tensile modulus 5 MPa, Poisson's ratio ±0.5, glass transition temperature 16°C and Shore "A" hardness 64.

Multimode optical fibres were used as intrinsic embedded sensors. Optical fiber<sup>3</sup> properties are: diameter of core 62.5 μm, cladding diameter 125 μm, coating diameter 250 μm, wavelength range 850–1300 nm, numerical aperture 0.27, bandwidth 522–748 MHz/km. The chosen materials are combined by uniform alternative packing 25 reinforcement layers and 24 matrix layers.

Laminates were hot-pressed inside closed mould coated with silicon oil. Afterwards, specimens were left in a mould under slightly increased working pressure to cool from

<sup>1</sup> Originalna svojstva po proizvođaču – Kevlar® (DiPon zaštićeno ime za poli(p-fenilenetereftalamid))

<sup>2</sup> Originalna svojstva po proizvođaču – Saflex® (Zaštićeno ime Monsanto kompanije za poli(vinilbutiral))

<sup>3</sup> Originalna svojstva po proizvođaču (Iskra Opto-elektronika)

<sup>1</sup> Original properties given by manufacturer – Kevlar® (DuPont's registered trademark for poly(p-phenyleneterephthalamide))

<sup>2</sup> Original properties given by manufacturer – Saflex® (Monsanto Company's registered trademark for poly(vinylbutyral))

<sup>3</sup> Original properties given by producer (Iskra Opto-elektronika)

maksimalne radne temperature od 190°C do 100°C, a zatim su izvađeni iz kalupa i hlađeni do sobne temperature pod opterećenjem od 10 kg /23,24/. Konačno su izmerene ukupne mase uzoraka i izračunati su maseni procenti sastavnih komponentata. Rezultati su prikazani u tabeli 1.

maximal working temperature of 190°C to 100°C, and then were taken out of mould to cool to room temperature under load of 10 kg /23,24/. Finally, total masses of specimens were measured and mass percentages of specific content were calculated. Results are shown in Table 1.

Tabela 1. Ukupna masa uzoraka, maseni procenti sastavnih komponentata  
Table 1. Specimens total mass, mass percentage of specific components.

Vrsta ojačanja Reinforcement type	Masa ojačanja, g Reinforcement mass, g	Ukupna masa uzorka, g Total specimen mass, g	Maseni udeo ojačanja, % Reinforcement mass, %	Maseni udeo matrice, % Matrix mass, %
Aramidno vlakno (Aramid fibre)	150.0	230.0	65.2	34.8

Mehanička svojstva izrađenog laminarnog kompozitnog materijala su prikazana u tabeli 2.

Pripremljeni su uzorci dimenzija 142×157×7,3 mm<sup>3</sup>. Za ispitivanje Šarpijevim klatnom jedan od uzoraka je isečen na standardne epruvete. Optička vlakna su ugrađena u dodati poslednji sloj kompozitnog materijala prema ranije opisanoj proceduri /25/.

Mechanical properties of manufactured laminar composite material are shown in Table 2.

Samples sized 142×157×7.3 mm<sup>3</sup> are prepared. One sample was cut into standard test specimen for Charpy impact testing. Optical fibre sensors were embedded into the final layer of the composite material according to the previously described procedure /25/.

Tabela 2. Mehanička svojstva kompozitnog materijala. Moduli elastičnosti i klizanja u karakterističnim pravcima, gustina i Poasonov broj

$E_{11}$ , GPa	14,99
$E_{22}$ , GPa	14,98
$E_{33}$ , MPa	450
$G_{12}$ , MPa	400
$G_{13}$ , MPa	200
$G_{23}$ , MPa	200
$\rho$ , kg/m <sup>3</sup>	1413
$\nu_{12}, \nu_{13}, \nu_{23}$	0,3; 0,2; 0,2

Table 2. Mechanical properties of composite material. Modules of elasticity and shear in characteristic directions, density and Poisson number.

$E_{11}$ , GPa	14.99
$E_{22}$ , GPa	14.98
$E_{33}$ , MPa	450
$G_{12}$ , MPa	400
$G_{13}$ , MPa	200
$G_{23}$ , MPa	200
$\rho$ , kg/m <sup>3</sup>	1413
$\nu_{12}, \nu_{13}, \nu_{23}$	0.3; 0.2; 0.2

## OPIS EKSPERIMENTATA

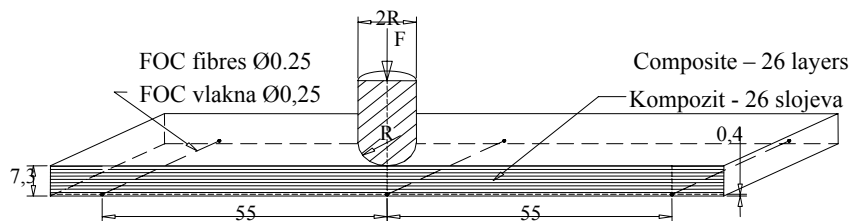
Proizvedeni kompozitni uzorci sa ugrađenim optičkim vlaknima u poslednjem sloju su izloženi statičkom opterećenju, udaru niske energije i balističkom udaru.

**Statičko opterećenje:** Uzorci su ispitivani na dva načina. U prvom slučaju opterećenje se uvodi direktno na sloj ispod koga su postavljena optička vlakna (gornja strana, optička vlakna najbliža tački dejstva opterećenja), a u drugom su optička vlakna u poslednjem sloju u odnosu na tačku dejstva opterećenja (donja strana, optička vlakna su maksimalno udaljena od delovanja opterećenja, sl. 1).

## DESCRIPTION OF EXPERIMENTS

Manufactured composite samples with embedded optical fibres in the final layer were subjected to static loading, low energy impact and ballistic impact.

**Static loading:** Specimens were tested in two different modes. In the first case, loading was directed to the top layer with optical fibres beneath (upper side, optical fibres are nearest to the loading point), and in second mode, loading was directed to the bottom layer (bottom side, optical fibres are in the farthest position from loading point, Fig. 1).



Slika 1. Pozicija utiskivača tokom ispitivanja statičkim opterećenjem.

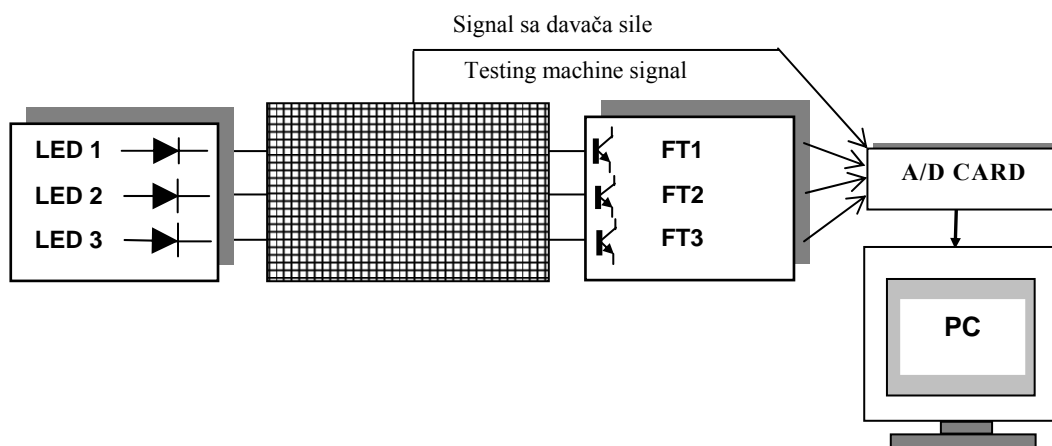
Figure 1. Position of indenter in the static loading test.

Optoelektronski deo mernog sistema se sastoji od tri emitorske diode (LED), koje se koriste kao izvori svetlosti za optička vlakna, i tri fotodetektora kojima se meri intenzitet optičkog signala. Sistem je prikazan na sl. 2. Akvizicija izlaznih signala sa fotodetektora izvodi se pomoću AD kartice i personalnog računara. Razvijen program za akvizi-

Opto-electronic part of measurement system consists of three light emitting diodes (LED) as light sources for optical fibres, and three photo detectors for light intensity measurement. The system is shown in Fig. 2. Output signal was acquisitioned from the photo detecting device by AD converter card and personal computer. Developed acquisition

ciju, napisan u Paskalu, omogućava istovremeno merenje na 16 kanala i promenu vremena uzorkovanja u zavisnosti od vrste merenja. Na taj način su sva tri signala na uzorku merena istovremeno.

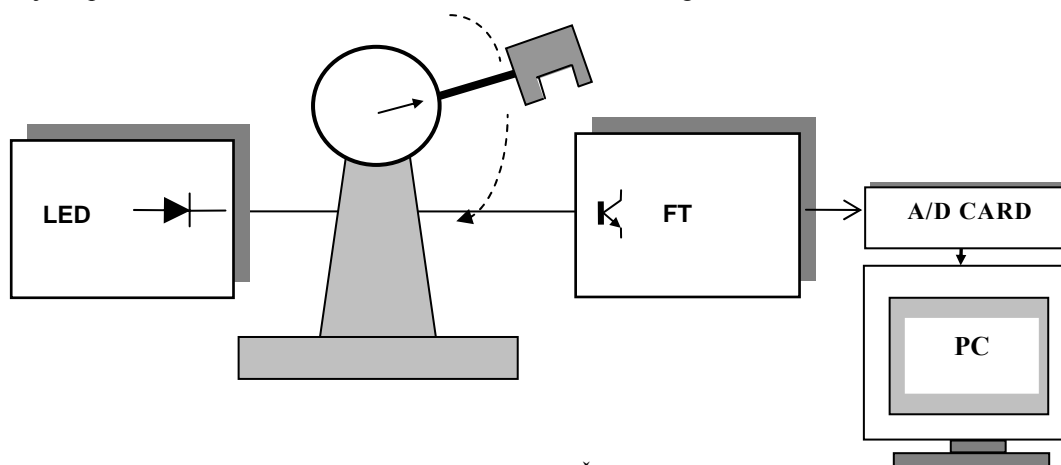
software, written in Pascal, provides simultaneous 16-channel signal sampling and sample timing depending on type of measurement. In this way all three signals in one specimen are measured at the same time.



Slika 2. Optoelektronski meri sistem  
Figure 2. Optoelectronic measurement system.

**Udar niske energije:** Transmisioni tip intenzitetnog FOS je ugrađen u kompozitni materijal koji je izlagan opterećenju kao što je to prikazano na sl. 3.

**Low energy impact:** The transmissive type intensity FOS was configured on the embedded optical fibre as shown in Fig. 3.



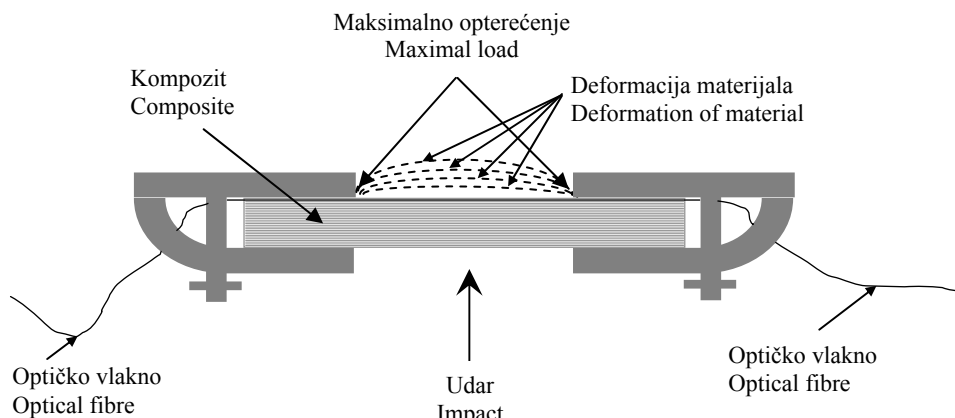
Slika 3. Meri sistem primenjen na Šarpi uređaj za ispitivanje  
Figure 3. Measuring system applied to Charpy testing device.

Svetlosni signal iz emitorske diode (LED) (talasne dužine 840 nm) uveden je u OV i njegov intenzitet na izlazu OV je meren fotodetektorom. Izlazni signal sa fotodetektora je povezan na sistem za akviziciju podataka, baziranog na AD kartici i personalnom računaru. Vreme uzorkovanja je 40  $\mu$ s sa vremenom akvizicije 80 ms nakon udara i 4 ms pre udara. Svaki uzorak je pričvršćen kao što je prikazano na sl. 4. Mesto udara Šarpijevog klatna, na kome se javlja deformacija materijala i promena u intenzitetu signala kroz optičko vlakno, prikazano je takođe na sl. 4.

Totalna energija udara iznosila je 1,5 J, od čega je približno 1,4 J apsorbovano u materijalu, a preostalih 0,1 J zadržano u klatnu (ovo je zabeleženo digitalnom kamerom i izračunato iz ugla koji je klatno doseglo nakon odbijanja od materijala). Sekundarni udar klatna je ručno sprečavan.

Light from the emitting diode (LED) (wavelength of 840 nm) was launched into the embedded OF and its intensity at the OF exit was measured by photo detector. The output signal from the photo detector was connected to the data acquisition system based on AD card and personal computer. Sampling time was 40  $\mu$ s with acquisition time of 80 ms after impact and 4 ms before the impact. Each specimen was fixed according to Fig. 4. The point of Charpy pendulum impact, at which deformation of material and change of signal in optical fibre occurred, is also shown in Fig. 4.

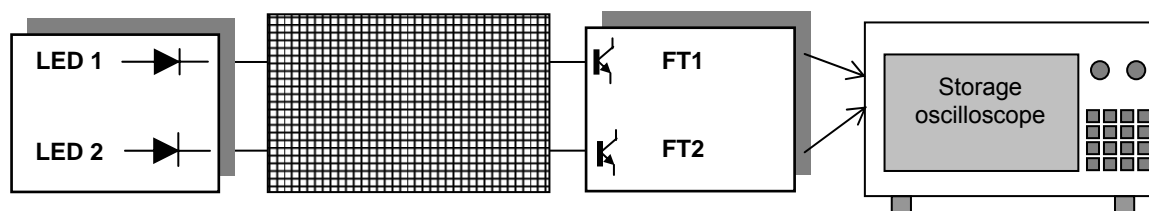
Total impact energy is 1.5 J, approximately 1.4 J is absorbed by the material, and the remaining 0.1 J is conserved by the pendulum (this is recorded by digital camera and calculated from the angle the pendulum had reached after impact). Secondary impacts were prevented manually.



Slika 4. Držać uzorka  
Figure 4. Specimen placeholder.

**Balistički udar:** Pripremljeni uzorci sa po dva paralelno ugrađena optička vlakna su izloženi balističkom ispitivanju oružjem i municijom u skladu sa međunarodnim standardom NIJ 0101.03. Korišćen je revolver RUGER 0.44 MAGNUM 6" i municija 0.44 REMINGTON MAGNUM FPJ (metak 15,6 g ili 240 grejna). Ispitivanje je izvedeno na sobnoj temperaturi od 19,5°C i relativnoj vlažnosti od 70%. Razdaljina između usta cevi i uzorka bila je 5 m, a hici su ispaljeni pod uglom od 90°. Sa leđne strane uzorka je postavljena ploča od plastelina radi merenja dimenzija otiska. Merni sistem prikazan je na sl. 5.

**Ballistic impact:** Specimens are prepared with two parallel optical fibres and subjected to handgun ballistic tests with ammunition according to international standard NIJ 0101.03. Ballistic testing included a RUGER 0.44 MAGNUM 6" revolver and 0.44 REMINGTON MAGNUM FPJ ammunition (15.6 g or 240 grain bullet). Testing was performed at room temperature 19.5°C and 70% of relative humidity. The distance between gun bore and target specimen was 5 m with 90° angle of fire. A clay plate was placed at the rear side of specimens in order to measure indent size. The measuring system is given in Fig. 5.



Slika 5. Merni sistem za balistički udar  
Figure 5. Measurement system for ballistic impact.

Uzorci su ispitani višestrukim udarom (pet metaka). Optoelektronski deo mernog sistema se sastojao od dve emiter-ske diode kao izvora svetlosti koja se uvodi u optička vlakna i dva fotodetektora za merenje intenziteta svetlosti propuštene kroz optička vlakna. Izlazni signal sa fotodetektora se meri pomoću dvokanalnog *storage* osciloskopa.

Specimens were tested at multiple impact conditions (five rounds). The optoelectronic part of the measuring system consists of two light emitting diodes as light source for optical fibres, and two photo detectors for light intensity measurement. The output signal was acquired by photo detectors and storage oscilloscope with two channels.

## REZULTATI I DISKUSIJA

### Statičko opterećenje

Slike 6–8 prikazuju rezultate dobijene ispitivanjem uzorka O2 tokom utiskivanja.

Rezultati merenja pri delujućoj sili od 18250 N su prikazani na sl. 6. Tačka 1 se nalazi na gornjoj strani između vlakna 2 i 3, bliža vlaknu 2.

Dijagram na sl. 6 prikazuje primetan pad signala kroz vlakno 2. Nakon rasterećenja, intenzitet signala se vraća na početnu vrednost, što ukazuje na to da vlakno nije oštećeno tokom ispitivanja.

Tačka 4 je na gornjoj strani, iznad vlakna 3. Rezultati merenja pri delujućoj sili od 17650 N su prikazani na sl. 7.

## RESULTS AND DISCUSSION

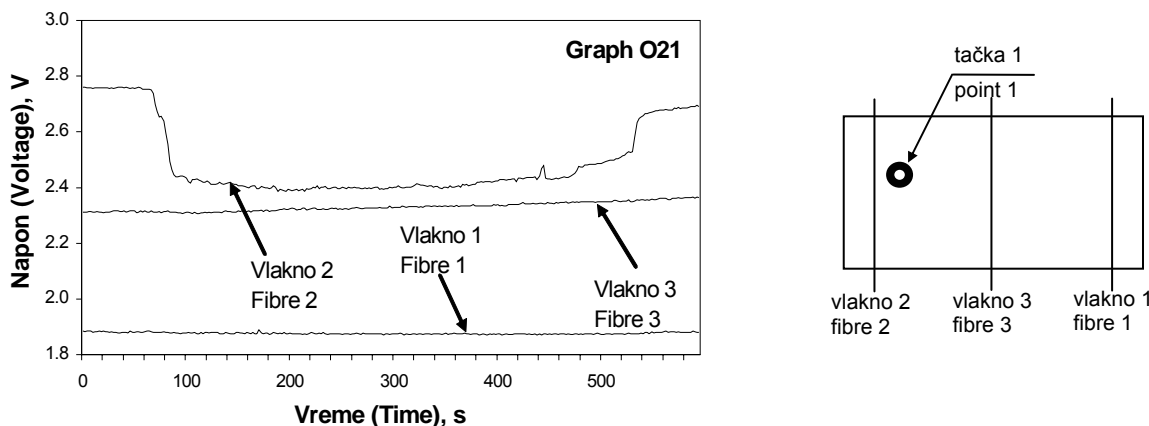
### Static loading

Figures 6–8 show results obtained from specimen O2 during indentation.

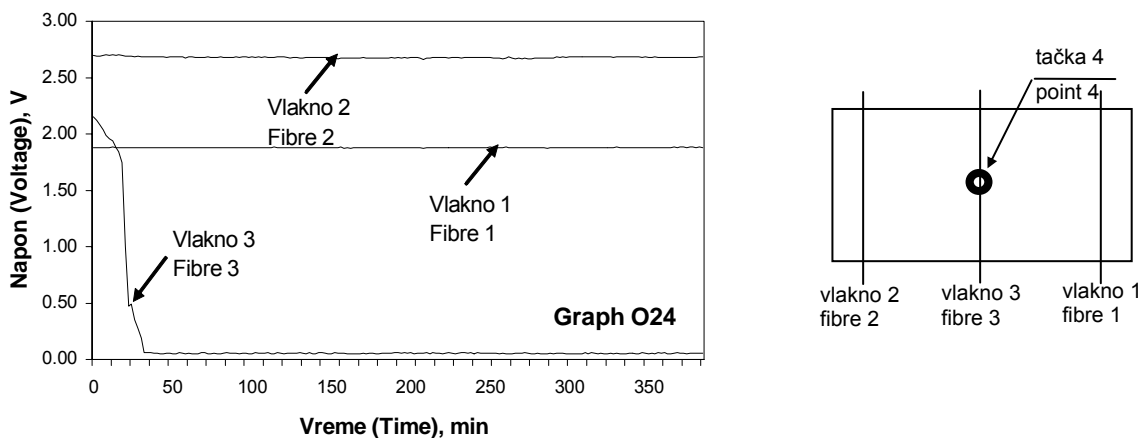
Measurement results at loading force of 18250 N are shown in Fig. 6. Point 1 is at the upper side between fibre 2 and 3, closer to fiber 2.

Diagram in Fig. 2 shows noticeable drop in the signal through fibre 2. After unloading, the signal intensity had restored its starting value, indicating that fibres were not damaged during the tests.

Point 4 is on the upper side above fibre 3. Measurement results at loading force of 17650 N are shown in Fig. 7.



Slika 6. Pad intenziteta optičkog signala za vreme utiskivanja u tački 1  
Figure 6. Light signal intensity drop during indentation at point 1.



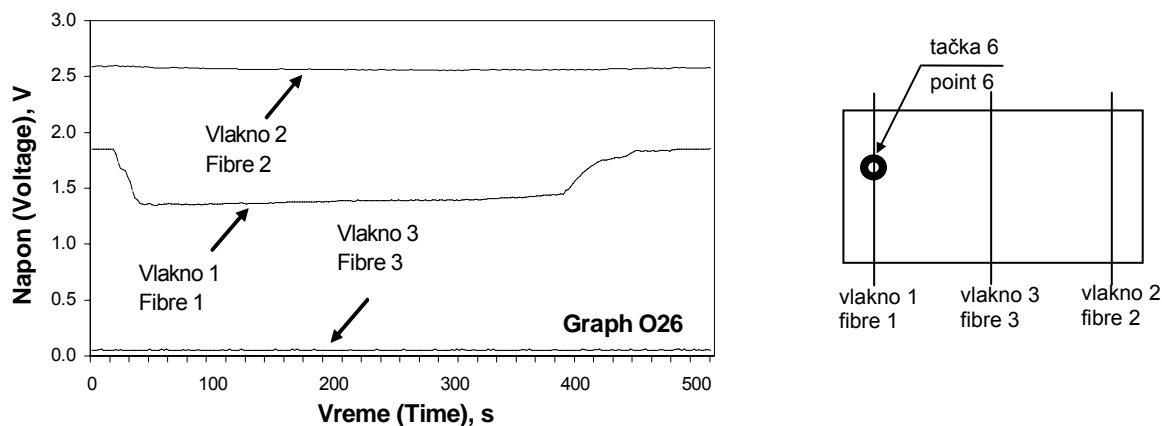
Slika 7. Pad intenziteta optičkog signala tokom utiskivanja u tački 4  
Figure 7. Light signal intensity drop during indentation at point 4.

Dijagram pokazuje značajan pad intenziteta signala kroz vlakno 3. Nakon rasterćenja, intenzitet signala se nije vratio na početnu vrednost, što ukazuje da na trajno oštećenje vlakna 3 tokom ispitivanja.

Tačka 6 je sa donje strane iznad vlakna 1. Rezultati merenja pri delujućoj sili od 17650 N su prikazani na sl. 8.

Diagram shows noticeable signal drop though fibre 3. After unloading, the signal had not restored its starting value intensity, indicating that fibre 3 was damaged during testing.

Point 6 is on the lower side above fiber 1. Measurement results at loading force of 17650 N are shown in Fig. 8.



Slika 8. Pad intenziteta optičkog signala tokom utiskivanja u tački 6, uzorak O2  
Figure 8. Light signal intensity drop during indentation at point 6, specimen O2

Dijagram prikazuje pad signala kroz vlakno 1. Nakon rasterćenja intenzitet signala se vraća na početnu vrednost.

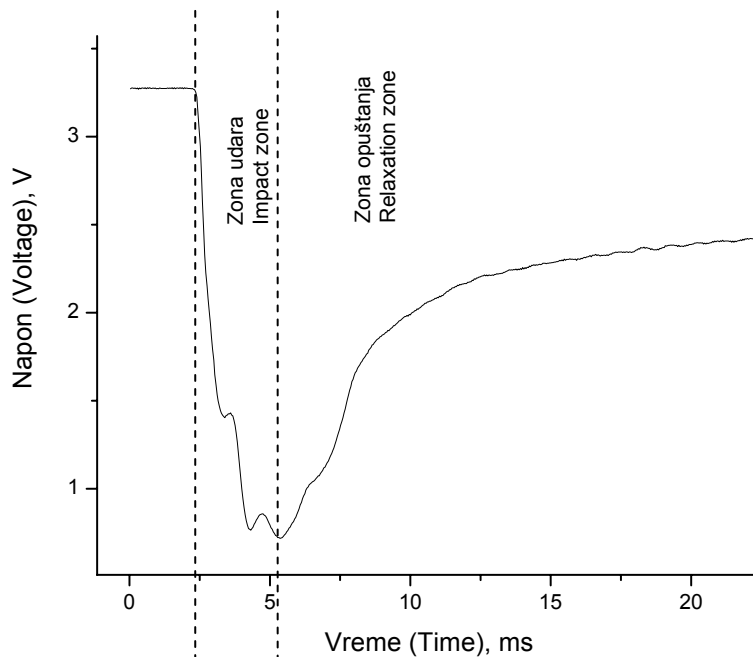
The diagram shows signal drop through fiber 1. After unloading, the signal intensity had regained its starting value.

**Udar niske energije**

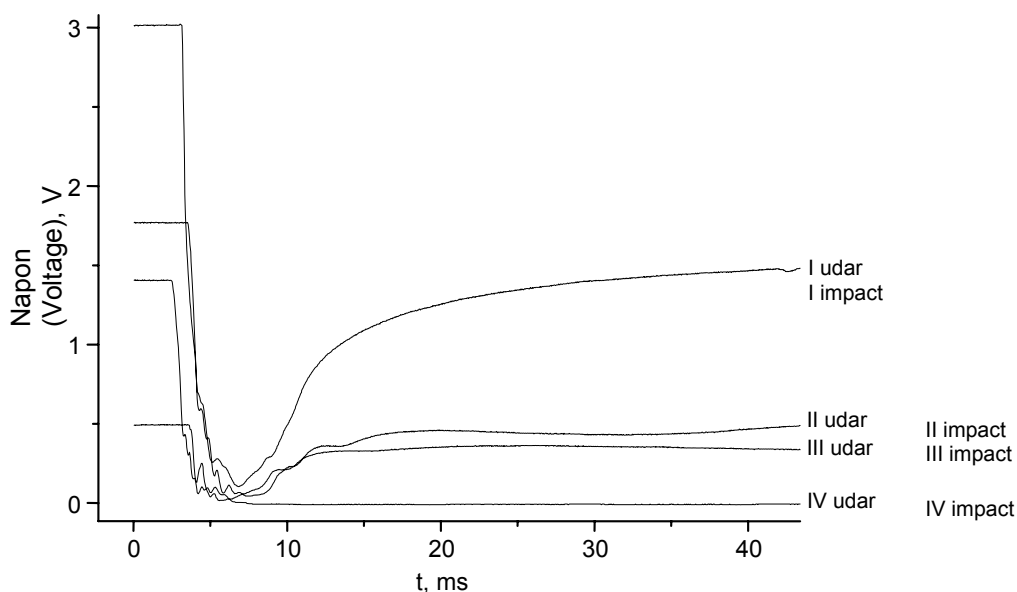
Karakterističan oblik signala tokom udara prikazan je na sl. 9. Tokom udara nivo signala, koji je proporcionalan intenzitetu svetlosti u optičkom vlaknu, opada, a zatim se lagano vraća ka početnoj vrednosti. Naprezanja u materijalu uzrokuju pojavu lokalnog napona oko optičkog vlakna usled čega dolazi do pada intenziteta optičkog signala. Na sl. 9 se mogu prepoznati dve različite zone koje ukazuju na ponašanje materijala. Prva je zona udara i traje oko 4 ms. Druga je zona relaksacije i traje mnogo duže. Konačna vrednost signala nakon relaksacije se može videti kao početna vrednost izmerenog signala u sledećem udaru, na istom uzorku.

**Low energy impact**

The characteristic shape of signal during impact is displayed on Fig. 9. During impact, level of signal which is proportional to light intensity in the optical fibre, drops and then slowly recovers. Stress in the material causes local stress around optical fibre and a signal drop in the optical fibre. In Fig. 9 there are two distinguished zones accordingly to the response of the material. The first is the impact zone, and lasts about 4 ms; the second is the relaxation zone which lasts much longer. The resulting value of relaxation is seen as the starting point of measurement curve in the next impact, for the same specimen.



Slika 9. Karakterističan oblik signala tokom udara  
Figure 9. Characteristic signal change during impact.



Slika 10. Signali na uzorku do kritičnog oštećenja  
Figure 10. Signals on specimen until critical damage.

Oporavak signala nikada nije potpun što se vidi na sl. 10. Uopšteno, za vreme svakog udara signal opada, ali pri opadanju dolazi do povremenog rasta nivoa signala koji je uzrokovao lokalnim poljem naprezanja oko optičkog vlakna. Ovaj deo signala ukazuje na oštećenje u kompozitnom materijalu, a površine ispod ovih delova krive predstavljaju veličinu apsorbirane energije tokom udara. Dobijena vrednost je samo relativna i karakteriše ponašanje materijala u istim eksperimentalnim uslovima. Ukupna vrednost apsorbirane energije je izračunata i približno je ista za svaki uzorak.

Glavni deo oštećenja nastaje tokom udara. Oštećenje se ogleda u lokalnom, privremenom smanjenju naprezanja u optičkom vlaknu i rastu nivoa signala kao što je to prikazano na sl. 11, koja predstavlja uvećani oblik dela karakterističnog signala koji je interesantan za analizu.

Merenja su pokazala da osenčene površine ispod krive mogu predstavljati obim oštećenja u materijalu. Merenje je izvedeno sa rezolucijom od 40  $\mu$ s u trajanju od 84 ms pri čemu se prve 4 ms odnose na signal pre udara.

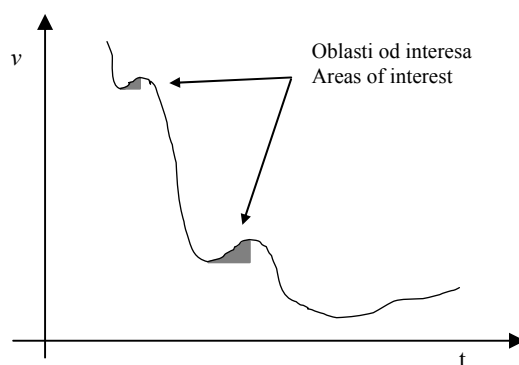
Ukupna vrednost D predstavlja količinu oštećenja koju kompozitni materijal može apsorbirati, a da i dalje štiti optičko vlakno. Ovo je relativna vrednost, specifična za materijal pri istim uslovima ispitivanja.

Recovery of the signal has never fully completed, see Fig. 10. Generally, during each impact the signal decreases, but there are a few temporary rises in signal level caused by the local stress field around the optical fibre. These parts of the signal curve show composite material damage, and areas under these parts of the curve represent the amount of absorbed energy during impact. The obtained value is relative, and characterizes material behaviour in same experimental conditions. The cumulative value of absorbed energy is calculated and it is approximately the same for each specimen.

Major part of the damage occurs during impact. Damage reflects in local, temporary release of strain in optical fibre, and rise of signal level, as shown in Fig. 11 which represents an enlarged shape of the most interesting part of the characteristic signal.

Measurements showed that shaded areas under the curve could represent the amount of material damage. Measurement resolution was 40  $\mu$ s and duration was 84 ms, where the first 4 ms represent the signal before impact.

Cumulative value D represents the amount of damage the composite material may absorb and still protect the integrated optical fibre. This is a relative value, specific for material in same testing conditions.



Slika 11. Područja signala za pojavu oštećenja  
Figure 11. Signal regions for damage occurrence

Tabela 3. Izračunate vrednosti za oblasti  $A_j$  i D za svaki uzorak  
Table 3. Calculated values of areas  $A_j$  and D for each specimen.

Udar j Impact j	Uzorak 1 Specimen 1	Uzorak 2 Specimen 2	Uzorak 3 Specimen 3	Uzorak 4 Specimen 4	Uzorak 5 Specimen 5	Uzorak 6 Specimen 6
1	0.0299	0.9426	0.1614	0.1698	0.6443	0.2449
2	0.2383	0.2317	0.1131	0.0008	0.2460	0.5390
3	0.2405	0.3953	0.0038	0.3619	0.6519	0.4486
4	1.4755	0.5364	0.0323	0.1671	0.4130	0.2899
5	0	0	0.1111	0.0530	0	0.1714
6	0	0	fall out	0.7458	0	0.1176
D	<b>1.9842</b>	<b>2.106</b>	-	<b>1.4984</b>	<b>1.9552</b>	<b>1.8114</b>

Rezultati za uzorak 3 nisu uzeti u razmatranje zato što je uzorak ispao iz ležišta pre nego što je došlo do kritičnog oštećenja. Međutim i u ovom slučaju ukupna vrednost D je manja od vrednosti za koju nastupa kritično oštećenje, kao što je proračunato kod ostalih uzoraka. Ovo je u skladu sa zaključkom da kritično oštećenje nastaje kada D postane veće od neke vrednosti specifične za materijal i eksperimentalne uslove.

Results for specimen 3 are not valid since this specimen fell out from its placeholder before critical damage occurred. However, the accumulated value D is smaller than the value needed for fatal damage as calculated for other specimens. This is in correspondence with the conclusion that fatal damage in optical fibre occurs when D becomes greater than a value specific for material and experimental conditions.



Tabela 4. Izračunate vrednosti parametra D i odstupanja od srednje vrednosti  $\bar{D}$ Table 4. Calculated D values and offsets from the mean value  $\bar{D}$ .

Uzorak Specimen	1	2	4	5	6	Srednja vrednost Mean value, $\bar{D}$
$\bar{D}$	1.9842	2.106	1.4984	1.9552	1.8114	1.87104
$(D - \bar{D}) / \bar{D}$	+6.05%	+12.56%	-19.92%	+4.5%	-3.19%	

Standardna devijacija za D je 0,2332, a srednja vrednost 1,87104, kao što je dato u tabeli 4. Ako izuzmemo četvrto merenje, koje se najviše razlikuje, maksimalno odstupanje vrednosti D je manje od 8%.

#### Balistički udar

Slika 12 predstavlja fotografiju uzorka kompozitnog materijala sa ugrađenim OFS nakon pet uzastopnih balističkih ispitivanja. Koordinate udara su prikazane u tabeli 5.

Standard deviation for D is 0.2332 and its mean value is 1.87104, as given in Table 4. If the fourth measurement is omitted, differing the most, the maximal offset of D is less than 8%.

#### Ballistic impact

Figure 12 is a photograph of the composite material specimen with embedded OFS after five successive ballistic tests. Coordinates of hits are shown in Table 5.

Tabela 5. Koordinate udara

Table 5. Coordinates of hits.

Metak Bullet	prvi first	drugi second	treći third	četvrti fourth	peti fifth
Razdaljina od prvog vlakna, mm Distance from first fibre, mm	16	36	39	22	47
Razdaljina od drugog vlakna, mm Distance from second fibre, mm	44	24	21	38	13
Razdaljina od leve ivice, mm Distance from left edge, mm	82	120	92	33	55



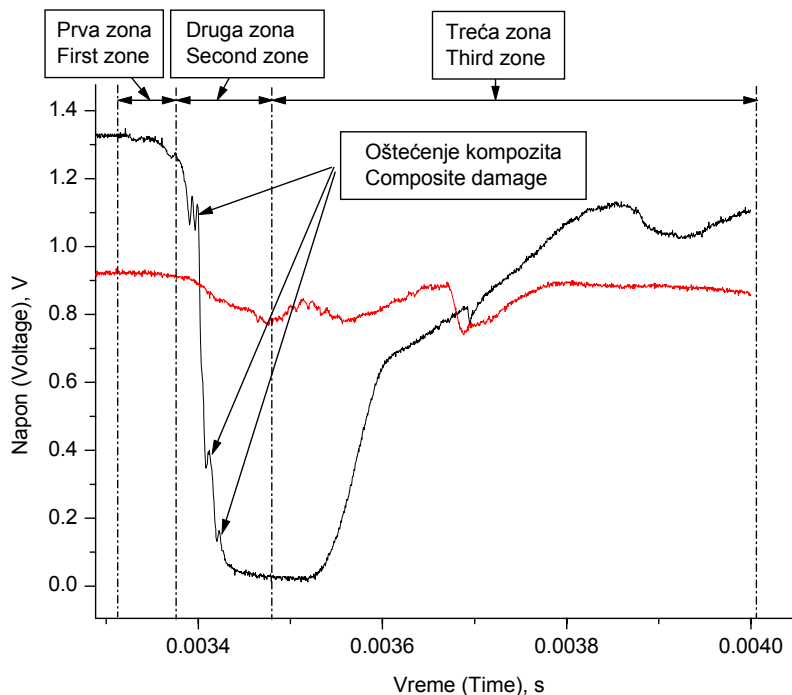
Slika 12. Fotografija uzorka kompozitnog materijala sa ugrađenim OFS nakon pet uzastopnih balističkih ispitivanja  
Figure 12. Photo of composite material specimen with embedded optical fibres after five consecutive ballistic tests.

Slika 13 prikazuje pad intenziteta optičkog signala tokom prvog balističkog udara. Mesto pogotka je bliže prvom vlaknu. Dijagram prikazuje primetan pad signala kroz oba vlakna, ali značajno veći kroz prvo vlakno. Nakon prvog balističkog udara, intenzitet signala se približno vraća na početnu vrednost, što ukazuje da vlakna nisu značajno oštećena tokom ispitivanja.

Dijagrami svih balističkih udara pokazuju slično ponašanje intenziteta svetlosnog signala. U stvari svaki od njih se može podeliti na tri zone - zonu probijanja prvog sloja kompozita, zonu putovanja metka kroz kompozitni materijal do njegovog konačnog zaustavljanja, i zonu relaksacije materijala (sl. 13). Dijagram takođe pokazuje da maksimalni pad intenziteta signala dostiže nultu vrednost, što znači da nema transmisije svetlosti kroz senzor na delu gde polje lokalnog napona dostiže maksimalnu vrednost.

Figure 13 shows the light signal intensity drop during the first bullet ballistic test. Position of hit is closer to the first fibre. Diagram shows noticeable signal drop through both fibres, but a considerably larger drop through the first one. After the first ballistic event, the signal intensity has nearly restored to its starting value, indicating that fibres were not heavily damaged during the test.

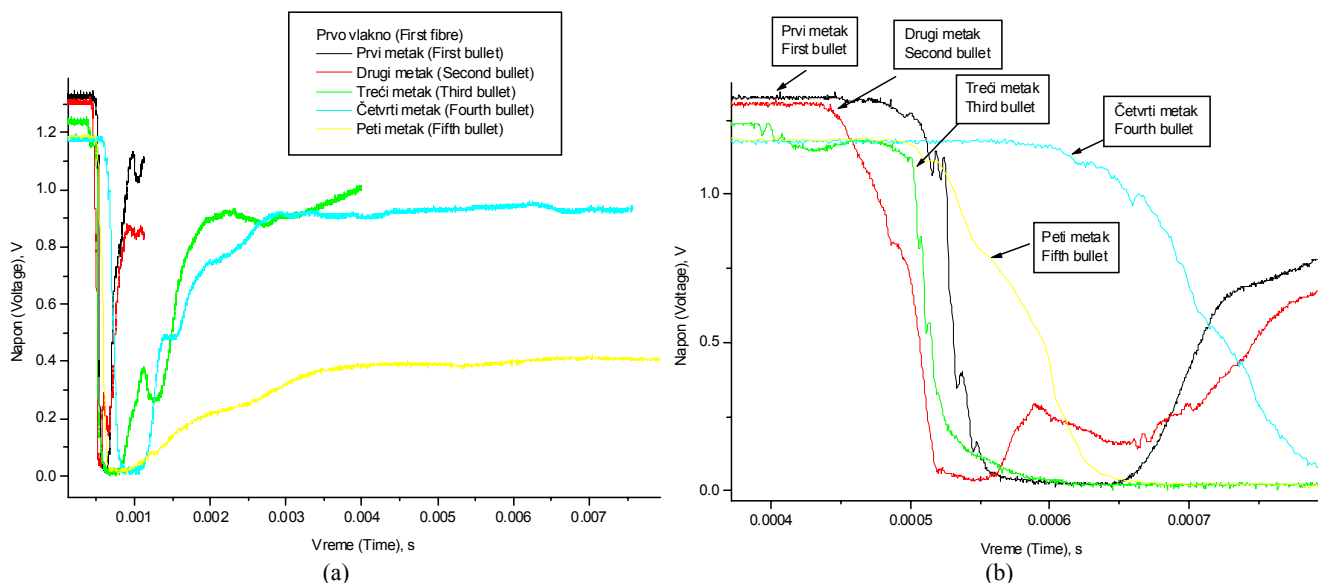
All ballistic impact diagrams show similar behaviour of light signal intensity. In fact, all of them can be divided into three zones - zone of bullet penetration in the first composite layer, bullet travelling zone through composite material till its final stop, and the material relaxation zone (Fig. 13). The diagram also shows that maximal light signal intensity drop actually reaches zero value, which means that there is no light transmission through the sensor in the region of maximal local stress field.



Slika 13. Oblasti reagovanja materijala tokom balističkog udara  
 Figure 13. Zone of material response during ballistic impact.

Slabljenje intenziteta optičkog signala tokom udara je uzrokovano uticajem dinamičkog naprežanja na ugrađena optička vlakna. Primenjeno naprežanje uzrokuje mikrosavijanje, promenu oblika poprečnog preseka i nejednake promene indeksa prelamanja jezgra i omotača optičkog vlakna zbog naponsko-optičkog efekta. Intenzitet optičkog signala pada na nulu kada indeks prelamanja omotača optičkog vlakna dostigne vrednost jezgra, pa se gube uslovi za totalnu refleksiju na površi jezgro-omotač.

The attenuation of the light signal intensity during impact is caused by the effect of the applied dynamic stress on the embedded optical fibres. Applied stress causes microbending of the optical fibre, changing the shape of its cross section, and unequal changes in indices of refraction of the core and cladding due to the stress-optical effect. The optical signal intensity drops to zero when the index of refraction of the cladding reaches the value at the core, and so the conditions for total reflection on the core-cladding interface are lost.



Slika 14. Uporedni dijagram pada intenziteta signala u prvom vlaknu tokom svih pet balističkih udara, (a) potpun interval merenja i (b) uvećano  
 Figure 14. Parallel diagram of light signal intensity drop through first fibre during all five ballistic impacts, (a) full measurement interval and (b) enlarged.

Slika 14 prikazuje pad intenziteta optičkog signala kroz prvo vlakno tokom svih pet balističkih udara. Nakon svakog udara intenzitet signala teži da se vrati na početnu vrednost, ali je nikada ne dostiže, što ukazuje na zaostala naprezanja u materijalu i optičkom vlaknu. Nakon petog udara došlo je do značajnog oštećenja optičkog vlakna.

## ZAKLJUČAK

Ortotropni laminarni kompozitni uzorci su napravljeni naizmeničnim slaganjem 25 slojeva ojačanja i 24 sloja termoplastične matrice, a zatim zbijeni metodom toplog presovanja. Kao ojačanje korišćena je aramidna tkanina, a kao matrica u kompozitnom materijalu su upotrebljene tanke PVB folije. Paralelno postavljena optička vlakna su ugrađena u pomenute kompozitne uzorke. Intenzitet optičkog signala kroz svako optičko vlakno je praćen tokom procesa ugradnje. Dobijeni rezultati su pokazali da ne dolazi do oštećenja optičkih vlakana pri procesu ugradnje.

Optička vlakna su ugrađena u kompozitni materijal kao intenzitetni senzori za praćenje oštećenja materijala usled statičkog utiskivanja, udara niske energije i balističkog udara u realnom vremenu. Inicijacije oštećenja i loma tokom ispitivanja se detektuju padom intenziteta optičkog signala propuštenog kroz optičko vlakno kao odgovor na delujuće statičko ili dinamičko opterećenje.

Željeni rezultat izvedenih eksperimenata je razvoj pogodnog i jeftinog sistema za praćenje oštećenja kompozitne konstrukcije u realnom vremenu, upotrebljivog za kontrolu procesa proizvodnje kompozitnog materijala kao i njegovog ponašanja tokom ispitivanja ili upotrebe.

Rezultati merenja pokazuju pad intenziteta propuštenog svetlosnog signala kroz sva optička vlakna, kao odgovor na uvedeno opterećenje na kompozitnu konstrukciju. Kod balističkog udara eksperimenti su izvedeni sa pet balističkih ispitivanja istog uzorka. Svi dijagrami pokazuju slično ponašanje pada intenziteta optičkog signala. U stvari, svaki od njih se može podeliti na tri zone: zonu probijanja prvog sloja kompozita, zonu putovanja metka kroz materijal do njegovog konačnog zaustavljanja i zonu relaksacije materijala. Dijagram takođe pokazuje da maksimalni pad intenziteta signala dostiže nultu vrednost, što znači da nema transmisije svetlosti kroz optičko vlakno na delu gde polje lokalnog napona dostiže maksimalnu vrednost. Slabljenje intenziteta optičkog signala tokom udara je uzrokovano uticajem delujućeg dinamičkog naprezanja na ugrađena optička vlakna. Delujuće naprezanje uzrokuje mikrosavijanje, promenu oblika poprečnog preseka i promenu indeksa prelamanja jezgra i omotača optičkog vlakna zbog naponsko-optičkog efekta. Pad intenziteta optičkog signala na nulu se javlja kada indeks prelamanja omotača dostigne vrednost indeksa prelamanja jezgra, te se na taj način gube uslovi za totalnu refleksiju na graničnoj površini jezgro-omotač.

Rezultati eksperimenata potvrđuju da se optička vlakna mogu koristiti kao intenzitetni senzori za praćenje strukturalnih promena u realnom vremenu u termoplastičnom laminarnom kompozitnom materijalu aramidno vlakno/poli(vinil butiral), usled statičkog utiskivanja, udara niske energije i balističkog udara.

Figure 14 shows diagram of light signal intensity drop through the first fibre during all five ballistic impacts. After each impact the light signal intensity nearly restores at starting value but never totally recovers indicating residual stress in the material and optical fibre. After the fifth impact, the optical fibre was considerably damaged.

## CONCLUSION

Orthotropic laminar composite samples were made by packing 25 reinforcement layers and 24 thermoplastic matrix layers alternately, and then compacted by hot-press method. An aramid fabric was used as reinforcement and thin PVB foils were used as matrix in the composite material. Parallel optical fibres were embedded in mentioned composite samples. Intensity of the light signal transmitted through each optical fibre was monitored during embedding process. Obtained results show that none of the embedded fibres was damaged during the embedding procedure.

Optical fibres were embedded in composite material as intensity sensors for monitoring of damage caused by static indentation, low energy impact and ballistic impact in real-time. Initiation of damage and fracture during testing was detected by intensity drop of light signal transmitted through optical fiber, as response to applied static or dynamic loading.

The desired effect of the performed experiments is in the development of reliable and cost-effective composite structure real-time monitoring system, useful both in controlling composite material manufacturing process and its behaviour during testing or exploitation.

Measurement results have shown intensity drop of transmitted light signal through all optical fibres as a response to applied loading on composite structure. In the ballistic impact experimental work, five ballistic tests of the same samples were performed. All diagrams show similar behaviour in light signal intensity drop. In fact, all of them can be divided into three zones: zone of penetration in the first composite layer, bullet travelling zone through composite material till its final stop, and material relaxation zone. Diagrams also show that the maximum drop of light signal intensity actually reaches zero value, which means that there is no light transmitting through the sensor at point of maximal local stress field. The attenuation of the light signal intensity during impact is caused by the influence of the applied dynamic stress on the embedded optical fibres. Applied stress caused microbending of the optical fibre, changing shape of its cross section and the unequal changes of refraction indices of core and cladding due to stress-optical effect. The optical signal drop to zero had occurred when the index of refraction of the cladding reached the value in the core, and so the condition for total internal reflection on the core-cladding interface is lost.

Results of experiments confirmed that optical fibres could be applied as intensity sensors in real-time monitoring of structural changes in thermoplastic laminar composite materials as aramid fibre/poly(vinyl butyral) under static indentation, low energy impact and ballistic impact.

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