JOURNAL OF OPTOELECTRONICS AND ADVANCED MATERIALS Vol. 14, No. 5- 6, May – June 2012, p. 544 - 550

Analysis of low velocity impact behaviour of aramid-linen fibre reinforced composites using Taguchi method

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Impact damage is a major target in designing advanced composite materials reinforced with 3D knitted structures because composites are often used in applications which imply dynamic loads. 3D knitted fabrics present a large range of applications in the technical field, including advanced composites. Textile reinforcements are known for their unique combination of light weight, controlled anisotropy, formability and flexibility, as well as their strength and toughness. Epoxy and polyester composite materials reinforced with sandwich knitted fabrics made of Kevlar®, Twaron® and linen yarns are developed in the paper. Low velocity impact behaviour of composite materials reinforced with 3D weft knitted fabrics is modelled using the Taguchi method based on orthogonal arrays, in order to maximize the composite characteristics significant for this type of impact. The theoretical results obtained were validated by experimental data.

(Received April 9, 2012; accepted June 6, 2012)

Keywords: Composite, Reinforced fibers, Armand linen, Taguchi method

1. Introduction

A composite material is an advanced material compound from two or more distinct materials that are combined at macroscopic scale. Composites are materials that are choice for designing light-weight structures due to their excellent weight/strength and weight/stiffness properties and may be subjected to low velocity impacts.

The applicability of textiles in engineering has grown exponentially in the recent decades. These materials are known as technical textiles and they are used for: transport, geotextiles, civil engineering, road construction, aerospace, military, medical, sports equipment, protective clothing, etc. Composite materials with textile reinforcements represent one of the most significant domains of use [8].

Advanced composite materials are based on textile fabrics with complex forms that are very different from the traditional ones, being used together with plastics, glass, films, and paper [2].

In the last decades a significant research effort has been made to study the impact behaviour of composite materials with textile reinforcements. Several researchers [11, 16, 17] have studied the problem by examining the material properties before and after impact.

According to Padaki et. all [16] impact phenomena has been classified into low velocity impact, if the impactor speed is under 0.25 km/s, medium velocity impact, if the impactor speed is between 0.25 and 2 km/s, ballistic impact if the impactor speed is between 2 and 12 km/s and hyper velocity impacts when impactor speed is higher than 12 km/s.

Carbon – graphite reinforced composites materials are widely used due to their high specific stiffness and strength. Vulnerability of carbon – epoxy composites to low velocity impact has been proved by the significant reduction of mechanical properties.

Hosur [10] reported that carbon – epoxy composites failed under impact loading through partial penetration. Gustin [9] studied the carbon and Kevlar woven sandwich composites. He observed that carbon fibre composites have relatively low impact properties but these can be improved by adding Kevlar fibres on face sheet. The addition of Kevlar fibres increases the impact forces by approximately 10%. Akin [5] and Mahapatra [14] and Mathivanan [15] have documented efforts over the past years in order to study the behaviour of glass fibres reinforced composites and notes that the system response depends on the elastic properties of the fibre material. At an impact velocity lower than 0.1 km/s there was a catastrophic failure of composites and perforation of laminates has been observed.

Textile sandwich fabrics are used as 3D performs for advanced composite materials. A sandwich fabric, woven or knitted, represents a three-dimensional construction made of two independent layers connected together through other connecting layers. The sandwich fabrics with connection through knitted layers (single or double) are characterized by a complex geometry, for which the shape and dimensions of the cross section depend on the connecting layer [3] [7]. The shape of the connecting layer can be different, varying from rectangular to elliptic, V shaped, trapeze, etc. Their advantages include high specific strength and stiffness, corrosion resistance, tailorability, stability and very good impact resistance.

The survey of literature conducted presented no mention regarding the low velocity impact behaviour of knitted sandwich fabrics.

The optimization of mechanical properties of composite materials reinforced with 3D sandwich knitted performs was carried out by classical method [1]. These one involves varying one parameter at a time and keeping the other ones constant. These procedures are time consuming, require a lot of experimental samples and do not provide information regarding the interactions between the parameters, costing too much time and money.

In order to solve these problems, Taguchi method was designed based on the concept of orthogonal arrays. Although Taguchi method was successfully applied in many fields, such as chemical engineering, electronics, genetic algorithm [4, 18, 20, 21], it is not widely used in textile areas [12-14].

The statistically based Taguchi method was used to identify the importance of factor designs and to suggest an optimized design that can produce the optimal impact resistance for composite materials reinforced with 3D sandwich knitted fabrics.

2. Materials and methods

2.1 Materials

In order to complete this research para-aramid (Steel Kevlar and Twaron) and technical natural yarns (Linen) were used.

Para-aramid fibres are the choice for any products used to improve impact behaviour, but they are rather expensive. Currently, the trend is to use Kevlar fibres in combination with other raw materials that are less costly. For this research Steel-Kevlar yarns were chosen for their multi-functionality (steel allows for conductivity/EM shielding). Linen is a technical fibre that is cheap and presents acceptable tensile characteristics.

Physical and mechanical properties characterisation was carried out by studying the tensile strength, according to ISO 2062/1993 test standard and using a Housenfield H10 KS testing machine with following configuration:

- force cell of 5 kN
- pretension of 0.18N for Steel – Kevlar yarns, 0.25N for Linen yarns and 0.85N for Twaron yarns.
- Testing speed: 250 mm/min.
- Clamping distance: 250 mm

The experimental data that were obtained are presented in Table 1. For all of them has been calculated tenacity, Young modulus, breaking force and extension according to ISO 2062/1993 standard specifications.

Fig. 1 presents the effort elongation curves for Steel-Kevlar, Twaron and Linen yarns that were tested in standard conditions. The Twaron yarns have a very high elasticity modulus, around 23 times higher than elasticity modulus of Steel-Kevlar and Linen yarns.

Twaron yarns are also characterised by a very small elongation at break and high breaking force. Their Young modulus is 46.48 N/tex, indicating high forces at low elongations, while, in comparison, the linen yarn's Young modulus is only 1.941 N/tex and the steel Kevlar is 1.693 N/tex. If the values for Young modulus are similar for the last two yarns, the corresponding elongations are extremely different – the linen yarn has a high elongation (at low forces), while the steel Kevlar yarn presents a low elongation at similar forces.

Table 1 Characteristic values for tensile.

Fir		Breaking force [N]	Tenacity [N/tex]	Young Modulus [N/tex]	Extension [%]
Linen	Mean	**9.16**	**0.183**	**1.941**	**23.62**
	Min	7.22	0.144	1.076	17.88
	Max	10.73	0.214	3.487	28.59
	C_v	11.15	11.15	38.93	11.29
Steel Kevlar	Mean	**11.67**	**0.324**	**1.693**	**5.77**
	Min	9.77	0.271	1.299	5.2
	Max	13.2	0.366	2.302	6.4
	C_v	8.61	8.61	18.13	7.16
Twaron	Mean	**293.6**	**1.747**	**46.48**	**3.6**
	Min	260.8	1.552	44.82	3.208
	Max	316	1.881	48.47	3.912
	C_v	5.84	5.84	2.68	5.6

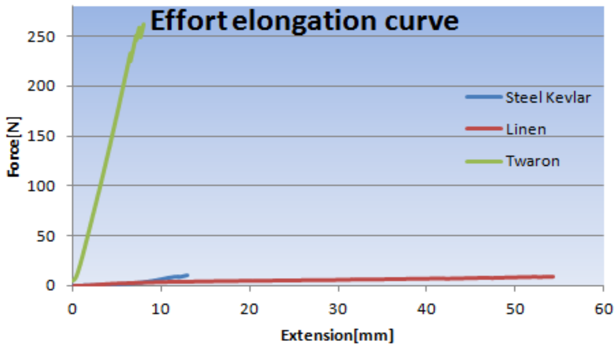


Fig. 1. Effort elongation curves.

All tests were made at University of Minho, Portugal

2.2. Development of knitted reinforcement

The experimental work focused on the production of U shaped sandwich knitted fabrics. The 3D knitted fabrics were produced on STOLL CMS 320 TC flat knitting machine, gauge 10E. The raw material for the outer and connecting layers was different, as presented in Table 2.

All fabric variants were produced at University of Minho, Portugal.

The fabric compactness, required to increase the volume fraction of the composites, was improved by introducing transversal Twaron yarns, as shown in Fig. 2.

Table 2 Raw materials used for producing sandwich fabrics

Fabric	Outer layers		Connecting layer	
	Yarn type	Linear density (tex)	Yarn type	Linear density (tex)
1	Kevlar 49®	28	Kevlar 49®	28
2	Kevlar 49®	28	Linen	20
3	Kevlar 49®	28	Kevlar 49®	28
	Twaron®	6		
4	Kevlar 49®	2	Linen®	20
	Twaron®	6		

Fig. 2. Production of sandwich fabric (machine view).

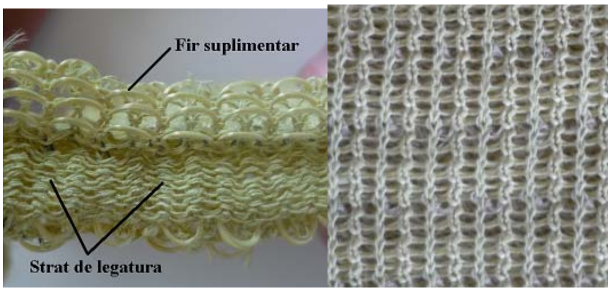


Fig. 3. Connecting and outer layer aspect

Fig. 4 presents the 3D sandwich knitted fabrics that were obtained using Kevlar® and linen yarns (fabric variant 1 and 2).

a) Fabric variant 1 b) Fabric variant 2

Fig. 4. U-shaped sandwich knitted fabrics

2.3 Development of composite materials

The 3D composite materials studied in this paper were produced using 3D knitted fabrics as performs and epoxy EPICURE 04908 and polyester DISTITRON 3501S as matrices. The composite materials were made using the Vacuum Assisted Resin Transfer Moulding (VARTM) technology. Table 3 presents the principal characteristics of the resins.

Table 3 Properties of epoxy and polyester resins.

Property	Unit	Epoxy Resin	Polyester resin
Viscosity at 25 °C	Mpa.s	10	150
Density	g/cm3	1.15	1.07
Tensile strength	MPa	74	65
Tensile strain	%	9.4	2.0
Tensile modulus	MPa	2900	4000
Flexural strength	MPa	112	110
Modulus in flexure	MPa	3100	4200
Water absorption after 24h, 23°C	pbw	0.18	-
Water absorption after 168h, 23°C	pbw	0.432	-

Both resins were cured at room temperature (23°C), the composite with epoxy for 46 hours and the one with polyester for 23 hours. The epoxy matrix had a mixing ratio of 30% EPIKURE Curing Agent 04908 and 5% Dearing agent BYK A535, while for the polyester resin the mixing contained 1.5% of initiator for unsaturated polyester resin NOROX MCP 75 and 0.08% polyester inhibitor NLC 10.

The final aspect of the composite materials that were obtained and the main steps that must be followed in order to obtain a composite material using VARTM technique is exemplified in Figure 4.

All fabric variants were produced at University of Minho, Portugal.

Fig. 5. Manufacturing of composite materials with 3D textile reinforcements.

Comparing the production of the composite material using the two matrix systems, the following observations can be made:

- The polyester resin is easier to work with due to its higher viscosity and lower density
- The composite processability was better in the case of the polyester resin during the insertion of the inner moulds and their subsequent removal

2.4 Impact testing of advanced composite materials

The low velocity impact behaviour of composite materials reinforced with knitted sandwich fabrics was evaluated using a Ceast Fractovis Plus 2000 impact testing machine. The impactor (Ø 20 mm) had a hemispherical

tip, and a 75x75 mm specimen plate was used. The Impact test was made according to ISO 6603 and ISO 7765.
The machine had the following settings:

- Impact height: 750 mm
- Carriage mass: 4.3 kg
- Support diameter: 20000 mm

All tests were made at University of Minho, Portugal.

3. Modelling of impact behaviour using Taguchi method

3.1 General aspects

In order to realize the experiments in an efficient an correct manner must be defined the input variables so that the studied process to achieve the expected performance and have a minimum sensitivity to noises.
The main differences reported between the classical DOE (design of experiments) method and Taguchi method are [6]:

- Classical DOE method does not consider the average values of the parameters that must be optimized, sometimes being completed with analysis of variance;
- Taguchi method unitary treats the average values and the variability of the parameters that must be optimized;
- Taguchi method use performance indicators, such the signal-noise (S/N) ratio, that simultaneously taking into consideration the desired response value (signal) and the variability thereof (noise).

In parallel with the S/N ratio Taguchi method use the quality loss function. It is recommended to maximize of performance indicator to correspond with minimize of quality loss function.

The way of determination for the quality loss function is given by relation:

$$L(y) = k(s^2 + (\bar{y} - y_N)^2) \tag{1}$$

Where:

- L(y) – average loss/unit;
- s – standard deviation;
- y_N – nominal value
- $\bar{y}$ - average of determined values;
- k – constant;

The S/N ration must be determined according to the system outputs.

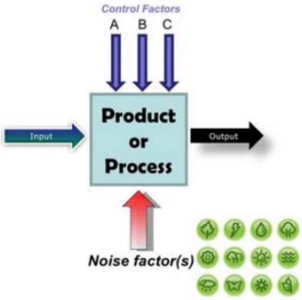


Fig. 6. Principle of application of the Taguchi method.

General steps that must be followed in order to complete a Taguchi experiment are:

- Define the system objectives. This can be represented either by a parameter optimisation, either by reaching a minimum or maximum value. The deviation from optimum performance is used to define the quality loss function;
- The determination of parameters that influence the system and the specific levels of each. As the number of levels is higher for each parameter, the number of experiments to be conducted increases;
- Define the orthogonal array used in conducting the experiment, according to the number of parameters and their specific levels;
- Implementation of experiment and collect the experimental data;
- Statistically analysis and interpretation of obtained raw data;
- Results validation.

A well designed product should always respond in the same manner to the signals provided by the users. If the answer varies randomly when is applied the same stimulus the quality of the signal is not optimal. Taguchi method aims to minimize the parameters variability reported to the noise factors and to maximize the variability reported to the signal factors [19].

The main purpose followed by applying the S/N ratio is to find the optimal combination of signal parameters that influence the system in order to maximize their S/N ratio. In this way these parameters become system control factors.

The S/N ratio is determinate using the following relations:

- Smaller the better

$$\frac{S}{N} = -10\log(s^2 + \bar{y}^2) \tag{2}$$

- Nominal is the best

$$\frac{S}{N} = 10\log\left[\left(\frac{\bar{y}^2}{s^2}\right) - \frac{1}{n}\right] \tag{3}$$

- Larger the better

$$\frac{S}{N} = -10\log\left[\sqrt{y^2}\left(1 + 3s^2 * \sqrt{y^2}\right)\right] \tag{4}$$

Where:

- s – standard deviation;
- y – nominal value;
- $\bar{y}$ - average of determined values;
- n – number of runs.

After applying the S/N ratio test the generated loss will be lower as the calculated value will be higher. In this way will result a better optimisation of the studied system.

3.2. Selection of orthogonal array and signal factors

Using Taguchi plans one can study the effect of several parameters on the system performance using only a condensed set of experiments

After the analysis of orthogonal array models, the signal parameters and specific levels of each has been deemed adequate the L16 orthogonal array, presented in Table 4.

Table 4 Orthogonal array selection.

Experiment	Structure	Resin type	Cell Dimension
1	1	1	1
2	1	1	1
3	1	2	2
4	1	2	2
5	2	1	1
6	2	1	1
7	2	2	2
8	2	2	2
9	3	1	2
10	3	1	2
11	3	2	1
12	3	2	1
13	4	1	2
14	4	1	2
15	4	2	1
16	4	2	1

Table 5 Signal factors selection.

Parameters Levels	Structure	Resin type	Cell dimension
1	Kevlar	Epoxy	1 cm
2	Kevlar Twaron	Polyester	1,5 cm
3	Kevlar Linen	-	-
4	Kevlar Twaron Linen	-	-
Symbol	A	B	C

The main purpose of this research is to find the optimal signal parameters for obtaining a higher low velocity impact resistance of composite materials that use three-dimensional sandwich knitted fabrics made of steel-Kevlar, Twaron and linen technical yarns as reinforcement and epoxy and polyester resins as matrix.

Selection of the noise factors takes into consideration the parameters considered significant for the dynamic behaviour of composite materials, as is shown in Table 5.

4. Results and discussions

The current study targeted the influence of signal parameters on the impact resistance of advanced composite materials. The first three columns of Table 6, noted A, B, and C, represent the signal factors (structure, resin type and cell dimension), while the following two, noted p1 and p2, are the noise factors (impact resistance of composite materials).

In order to complete the experiment, three different sets of eight runs, according to L16 orthogonal array were conducted. The definition of the signal and noise factors is followed by statistic analysis, as is shown in Table 6. The response resulting from Taguchi analysis revealed the significance of the signal factors reported to S/N ratio and the average. The classification of influence level, presented in Table 7, is:

- Maximum influence – the factor A (knitted structure);
- Average influence – the factor B (resin type);
- Minimum influence – the factor C (cell dimension)

Table 6 Experimental design using L16 array and experimental results

Experiment	A	B	C	p1	p2	S/N	LSTD	STDE	MEAN	CV
1	1	1	1	1198.7	1245.3	61.71	3.09	22.00	1217.36	0.02
2	1	1	1	1224.56	1200.87	*	*	*	*	*
3	1	2	2	1005.4	1009.25	60.03	1.45	4.28	1003.92	0.00
4	1	2	2	999.78	1001.25	*	*	*	*	*
5	2	1	1	2328.65	2430.59	67.56	3.79	44.40	2389.80	0.02
6	2	1	1	2412.3	2387.65	*	*	*	*	*
7	2	2	2	995.42	1086.27	60.17	4.04	57.09	1022.90	0.06
8	2	2	2	1051.65	958.24	*	*	*	*	*
9	3	1	2	1086.58	1161.28	60.75	4.20	66.84	1094.42	0.06
10	3	1	2	1005.2	1124.62	*	*	*	*	*
11	3	2	1	742.8	745.18	57.32	2.55	12.86	735.10	0.02
12	3	2	1	716.8	735.6	*	*	*	*	*
13	4	1	2	1120.98	1170.29	61.08	3.65	38.35	1133.77	0.03
14	4	1	2	1085.62	1158.2	*	*	*	*	*
15	4	2	1	1020.45	1063.01	60.25	3.54	34.49	1030.42	0.03
16	4	2	1	1051.9	986.3	*	*	*	*	*

Table 7 *Response table for S/N Ratios*
Larger is better

Level	A	B	C
1	60.87	62.77	61.71
2	63.86	59.44	60.51
3	59.03		
4	60.66		
Delta	4.83	3.33	1.20
Rank	1	2	3

The values that were obtained for S/N ratio, average and standard deviation from Table 6 are graphically represented in Figs. 7, 8 and 9. The S/N ratio has been calculated using the formula defined for larger the better case. The optimal combination of signal parameters is A_2 B_1 C_1 meaning a composite materials made by steel Kevlar and Twaron yarns for reinforcement, epoxy resin as matrix and a cell dimension of 1 cm. As can be seen in Table 8, after applying the prediction method, the S/N ratio is maximal reported to the S/N ratio obtained from statistical processing of experimental data according to Taguchi experiment matrix.

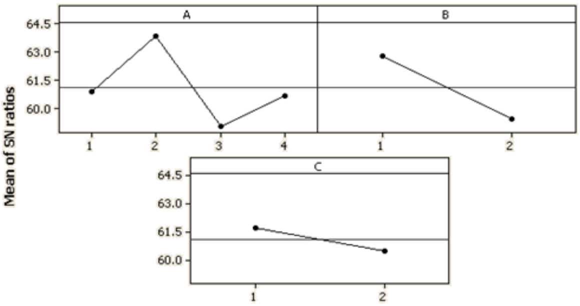


Fig. 7. Main effects plot for S/N ratio

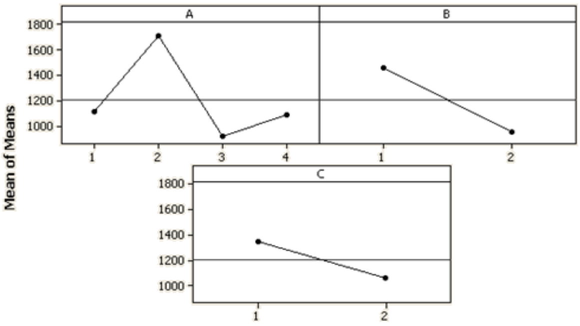


Fig. 8. Main effects plot for means

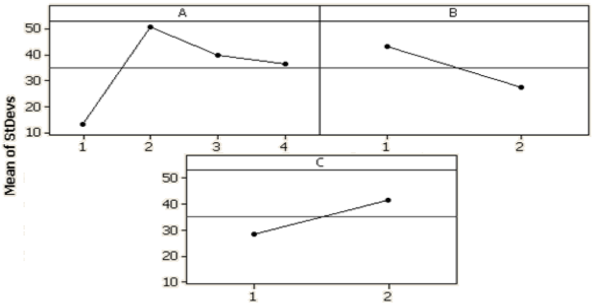
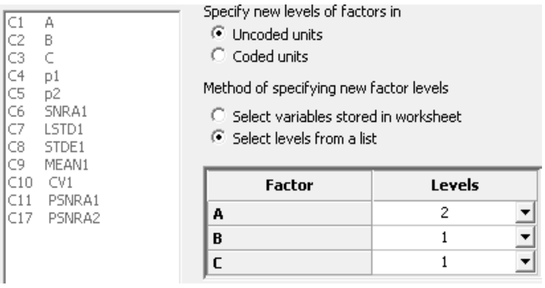


Fig. 9. Main effects for standard deviations

In order to do this the parameters levels must be set according to the results that were obtained from graphic analysis.



C1 A
C2 B
C3 C
C4 p1
C5 p2
C6 SNRA1
C7 LSTD1
C8 STDE1
C9 MEAN1
C10 CV1
C11 PSNRA1
C17 PSNRA2

Specify new levels of factors in
● Uncoded units
○ Coded units

Method of specifying new factor levels
○ Select variables stored in worksheet
● Select levels from a list

Factor	Levels
A	2
B	1
C	1

Fig. 10. Definition of the parameters levels for result prediction

Table 8. Predicted values.

S/N Ratio	Mean	St Dev	Ln (StDev)
66.13	2010.43	52	4.26

This method can be used for predicting results characterized by different combinations of the considered signal parameters.

5. Model validation

In order to determine the accuracy of Taguchi analysis, a model validation is required.

In this case, model validation was made by performing a number of tests, taking into account the intervals for the defined signal parameters.

Samples have been tested at low velocity impact according to the presented methodology. A part of experimental result is graphically exemplified in Figure 11.

From the graphical analysis of the experimental samples, Taguchi results correspond to the experimental results. The level of forces in the system determined through testing correspond to variant A_2 B_1 C_1 defined in the Taguchi analysis and present the maximum value – 2482 N.

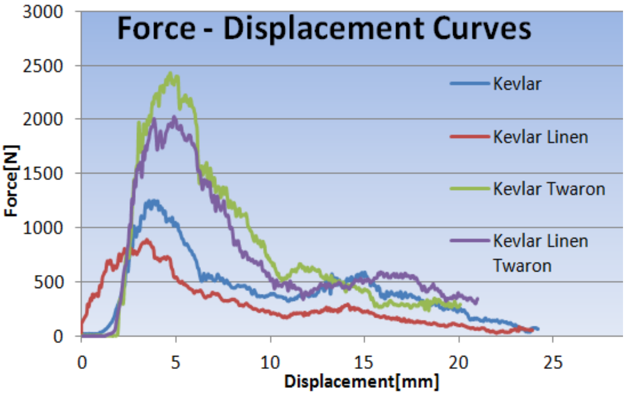


Fig. 11. Force displacement curves.

6. Conclusions

Advanced composite materials have known important developments in last decades. They require the use of 3D preforms that are produced in one stage through textile specific processes.

Impact behaviour is well documented throughout literature, but the bulk of it refers to 2D and 3D woven fabrics and high velocity loads. The paper targets the study of low velocity impact in the case of composites reinforced with 3D knitted sandwich fabrics with epoxy and polyester resins. The novelty of this study resides in the combination of production process, raw materials and type of impact (low velocity).

Taguchi method presents the advantage of generating accurate results based on a small number of runs in comparison to classical DOE methods. Currently, its use in textile modelling is somewhat limited. The orthogonal array was defined based on structure, resin type and cell dimension as signal parameters and impact resistance of advanced composite materials as noise factors.

The model was validated based on experimental results obtained by testing sandwich composites produced with similar parameters in similar technical conditions.

Acknowledgement

This paper is financially supported by EURODOC "Doctoral Scholarships for research performance at European level" project, financed by the European Social Found and Romanian Government.

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