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ANALYSIS OF THE PHYSICAL AND MECHANICAL PROPERTIES OF A FIBREGLASS COMPOSITE PIPE WITH BINDER MODIFIED BY PLASTICIZERS

Sergey V. Shashkin, Tatyana A. Matseevich

Moscow State University of Civil Engineering, Moscow, RUSSIA
Ishlinsky Institute for Problems in Mechanics of the Russian Academy of Sciences, Moscow, RUSSIA

Abstract: This paper considers an approach to improving the service performance of fiberglass composite pipelines under seismic conditions by modifying the thermosetting binder with plasticizing and toughening additives aimed at increasing fracture toughness and reducing the material's tendency to brittle failure under alternating-sign and impulse actions. The relevance of the study is driven by the fact that conventional pipeline materials (steel, reinforced concrete) have significant limitations when operated in seismically hazardous regions, whereas fiberglass reinforced plastics manufactured by continuous filament winding are characterized by high specific strength, corrosion resistance, and durability, but often demonstrate linear-elastic behavior up to failure. The object of the study was fiberglass composite pipes with a three-layer wall (surface, structurally reinforced, and liner layers). The following binder modifiers were considered: Polyplex; a modifier produced by JSC "Poliplast" (PoliPlast M); and a powder impact modifier of the "core–shell" type Clearstrength® XT100, introduced in different mass percentages. For each formulation, a series of repeated measurements was performed to ensure comparability and statistical evaluation of the results. The experimental program included determination of the initial specific ring stiffness and resistance to initial ring deflection, the initial hoop tensile strength and tensile modulus, the initial axial tensile strength and tensile modulus, as well as Charpy impact toughness in accordance with the applicable standards. Based on the combined indicators, the necessity for multi-criteria selection of binder composition is discussed, enabling preservation of the design stiffness–strength characteristics while improving the dynamic resistance of the material.

Keywords: fiberglass composite pipe, continuous winding, plasticizer, impact modifier, seismic resistance

ИССЛЕДОВАНИЕ ФИЗИКО-МЕХАНИЧЕСКИХ СВОЙСТВ ТРУБЫ ИЗ МОДИФИЦИРОВАННОГО ПЛАСТИФИКАТОРАМИ СТЕКЛОКОМПОЗИТА

С.В. Шашкин, Т.А. Мацеевич

Национальный исследовательский Московский государственный строительный университет, г. Москва, РОССИЯ
Институт Проблем Механики им. А.Ю. Ишлинского РАН, г. Москва, РОССИЯ

Аннотация: В работе рассмотрен подход к повышению работоспособности стеклокомпозитных трубопроводов в сейсмических условиях за счет модификации термореактивного связующего пластифицирующими и упрочняющими добавками, направленными на увеличение вязкости разрушения и снижение склонности материала к хрупкому разрушению при знакопеременных и импульсных воздействиях. Актуальность исследования обусловлена тем, что традиционные материалы трубопроводов (сталь, железобетон) обладают существенными ограничениями при эксплуатации в сейсмоопасных районах, тогда как стеклопластики, получаемые методом непрерывной намотки, характеризуются высокой удельной прочностью, коррозионной стойкостью и долговечностью, но при этом часто демонстрируют линейно-упругое поведение до момента разрушения. Объектом исследования являлись стеклокомпозитные трубы с трехслойной стенкой (поверхностный, структурно-армированный и футеровочный слои). В качестве модификаторов связующего рассмотрены Polyplex, модификатор АО «Полипласт» (ПолиПласт М) и порошковый модификатор ударной вязкости типа «ядро-оболочка» Clearstrength® XT100, вводимые в разных процентных соотношениях. Для каждого состава выполнялась серия повторных измерений, обеспечивающая сопоставимость и статистическую оценку результатов. Экспериментальная программа включала определение начальной удельной кольцевой жесткости и устойчивости к начальной кольцевой деформации, начального окружного предела прочности и модуля упругости при растяжении, начального осевого предела прочности и модуля упругости при растяжении, а также ударной вязкости по методу маятникового удара (Шарпи) в соответствии с действующими стандартами. На основе совокупности показателей обсуждается необходимость многокритериального подбора состава связующего, позволяющего одновременно сохранять расчетные жесткостно-прочностные характеристики и повышать динамическую стойкость материала.

Ключевые слова: стеклокомпозитная труба, непрерывная намотка, пластификатор, модификатор ударной вязкости, сейсмостойкость

INTRODUCTION

Modern trends in construction are characterized by continuously increasing complexity of architectural, planning, and structural solutions, driven by growing economic and social requirements. Under these conditions, the task of ensuring comprehensive safety of buildings and structures becomes particularly relevant; it goes beyond accounting for individual extreme actions and requires considering their combinations [1, 2]. The importance of the present research is additionally обусловлена by the implementation of the national project “Infrastructure for Life” [3], aimed at modernizing and improving the reliability of engineering and transport infrastructure facilities, including water supply, wastewater disposal, and other pipeline networks, whose serviceability largely determines the resilience of territorial systems.

For pipeline systems, which are critical infrastructure elements, the issue of combined actions is especially important. The high seismicity of a significant part of the territory of the Russian Federation (more than 26% of the area, including the Caucasus, Crimea, Altai, Sayan Mountains, Transbaikalia, Kamchatka, and the Kuril Islands) creates prerequisites for the realization of various scenarios of extreme impacts [4]. Statistical data confirm that regions with high seismic activity show an increased frequency of technogenic accidents, including damage to pipeline systems [5].

Traditional materials for pipelines—steel and reinforced concrete—have several serious disadvantages under seismic conditions: high mass, susceptibility to brittle fracture, and low corrosion resistance [6]. Composite materials, in particular fiberglass reinforced plastics manufactured by continuous filament winding, represent a promising alternative combining high specific strength, corrosion resistance, and durability [7–10].

However, conventional epoxy and polyester fiberglass composites are characterized by predominantly linear-elastic behavior up to the moment of brittle failure. This means that under complex alternating-sign and impulse loads typical of earthquakes, such structures cannot effectively redistribute peak stresses through plastic deformations, which increases the probability of sudden catastrophic failure [11]. In this context, the impact toughness becomes a critical controlled parameter, since it reflects the material’s energy absorption capacity under dynamic loading and its resistance to crack initiation and unstable crack propagation. Consequently, ensuring a stable and sufficiently high level of impact toughness is essential for preventing the transition from local damage accumulation to rapid, brittle, and system-level failure in seismic conditions.

Specialized studies on the seismic stability of pipelines are presented in [12–21]. The authors established that the main earthquake-related damage mechanisms for polymer composite pipelines are associated with:

- Stress concentrations in joint and branch zones [17];
- Failure under bending deformations [18];
- Loss of stability (buckling) of the pipe wall under compression [19];
- Fatigue failure under repeated cyclic actions [20, 21].

Study [22] raised the issue of predicting the physical and mechanical properties of polymer materials. The authors described a property prediction methodology; however, optimal compositions were not determined.

Thus, it is necessary to develop a composite pipe material with enhanced resistance to impact cyclic loads, while maintaining the required stiffness and strength characteristics for safe operation under combined extreme actions.

MATERIALS AND METHODS

The investigated object — a fiberglass composite pipe—consists of the following main components:

- **Binder:** unsaturated polyester resin on an orthophthalic base (PN-1 grade), isophthalic base (Depol X-400 grade), or vinyl ester base (Divinyl 911 grade);
- **Reinforcement:** fiberglass in the form of continuous and chopped E, ECR rovings;
- **Filler:** enriched quartz sand of grade VS-050-1;
- **Plasticizer.**

A plasticizer is a substance thermodynamically compatible with a polymer that reduces the density of intermolecular interactions in the polymer phase. This additive makes polymer materials less brittle and more ductile.

The following plasticizers were considered:

- **Polyplex** — a flexible unsaturated polyester resin modifier for UPR matrices.
- **Clearstrength® XT100 (Arkema)** — a powder “core–shell” impact modifier for thermosetting binders.
- **Flexible isophthalic UPR resin modifier (JSC “Poliplast”)** — an isophthalic unsaturated polyester resin modifier for thermosetting binders used in continuous winding (PoliPlast M).

In addition, a number of auxiliary components were used in small amounts: cobalt octoates, methyl ethyl ketone peroxides, C-glass surface veils, and others.

Fiberglass composite pipes (Figure 1) were manufactured with plasticizer addition based on the need to increase the impact toughness of each specimen. For each formulation (Table 1), a series of at least three measurements was performed for the key indicators, enabling statistical assessment of result scatter.

The pipe cross-section consists of three layers: (1) surface layer, (2) structurally reinforced layer, and (3) liner layer. The surface and liner serve as protective layers for the external and internal pipe surfaces against weathering, UV radiation, and aggressive and/or abrasive service fluids, while the reinforced layers provide mechanical strength.

Figure 1. Specimens with modified binder

Table 1. Experimental series of binder formulations for a DN1000 pipe

Series	Plasticizer	Plasticizer content, wt.% of resin
Control	No plasticizer	0
PoliPlast M	UPR modifier (JSC “Poliplast”)	10; 15; 20
Polyplex	Elastomeric additive (Polyplex Flexible)	10; 15; 20
Clearstrength XT100	“Core–shell” particles	10; 15; 20

For each formulation, a series of at least three measurements was performed for the key indicators, enabling statistical assessment of result scatter. The pipe cross-section (Figure 2) consists of three layers: (1) surface layer, (2) structurally reinforced layer, and (3) liner layer. The surface and liner protect the pipe from environmental impacts, UV exposure, and aggressive and/or abrasive fluids; the reinforced layers provide mechanical strength.

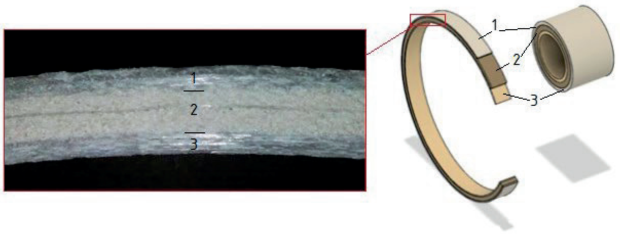

Figure 2. Wall structure of a fiberglass composite pipe

The specimen preparation scheme for the fiberglass composite pipes studied is shown in Figure 3. Specimens were cut from the manufactured pipe for: (1) impact toughness determination, (2) ring stiffness and resistance to initial ring deflection, (3) initial hoop tensile strength and tensile modulus, and (4) initial axial tensile strength and tensile modulus.

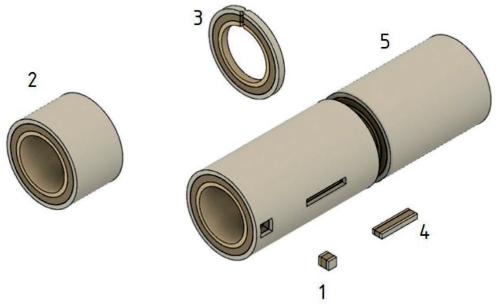

Figure 3. Specimen preparation scheme

RESULTS AND DISCUSSION

Determination of initial specific ring stiffness

Specimens for testing the initial specific ring stiffness by Method A specified in [23] and resistance to initial ring deflection according to [24] were rings cut from the fiberglass composite pipe with a width of 300 mm.

Test results are presented in Table 2. Plots of initial specific ring stiffness are shown in Figure 4.

Table 2. Initial specific ring stiffness SN, N/m²

Series	Plasticizer content, wt.% of resin	Meas. 1	Meas. 2	Meas. 3	Meas. 4	Average
Control	0	10682.5	10449.2	10738.0	10782.0	10702.5
PoliPlast M	10	10265.3	10782.6	10165.6	10433.9	10399.9
	15	10021.2	9669.0	10688.2	9602.5	10039.7
	20	10248.7	9894.3	9943.4	9661.9	9900.6
Polyplex	10	9936.4	9535.2	10067.0	9863.2	9694.0
	15	9516.1	9720.6	9639.4	9926.2	9664.3
	20	8604.2	9293.0	8692.2	9069.2	9070.2
Clearstrength XT100	10	11201.2	10099.9	10114.8	10161.7	10529.9
	15	10145.8	9651.3	10205.7	9488.2	9974.7
	20	10011.0	10431.3	10210.6	9409.9	9960.9

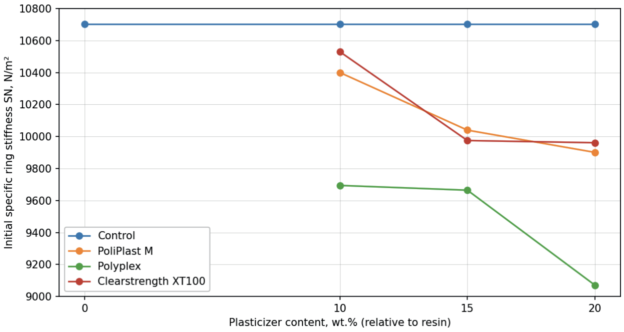

Figure 4. Plots of initial specific ring stiffness SN versus plasticizer content

Determination of initial hoop tensile strength and tensile modulus

Specimens for testing initial hoop tensile strength and tensile modules by Method B specified in [25] were cut from fiberglass composite pipes in the circumferential direction as rings 25 mm wide with a reduced section (stress concentrator) 10 mm wide.

Results are given in Table 3. Plots of initial hoop tensile strength and tensile modulus are shown in Figures 5 and 6.

Table 3. Results for initial hoop tensile strength and tensile modulus

Series	Plasticizer content, wt.% of resin	Specimen No	Initial hoop strength, MPa	Hoop tensile modulus, MPa
Control	0	1	205,3	16853
		2	204,3	16561
		3	205,6	16561
PoliPlast M	10	1	204,6	16236
		2	203,0	16041
		3	203,0	16041
	15	1	196,1	15450
		2	197,9	15564
		3	195,7	15464
	20	1	191,2	15252
		2	191,1	15134
		3	191,4	14980
Polyplex	10	1	194,4	15084
		2	191,2	14861
		3	191,7	15126
	15	1	190,1	15033
		2	189,0	15028
		3	189,7	14843
	20	1	184,8	13935
		2	182,2	14260
		3	182,6	14019
Clearstrength XT100	10	1	201,8	16179
		2	202,3	16195
		3	202,0	16041
	15	1	196,2	15300
		2	197,0	15352
		3	196,0	15452
	20	1	196,3	15467
		2	194,7	15226
		3	196,8	15419

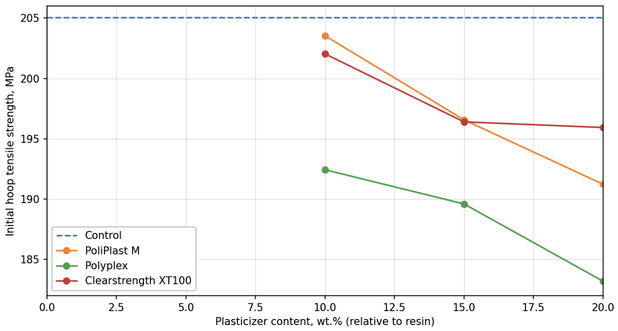

Figure 5. Initial hoop tensile strength versus plasticizer content

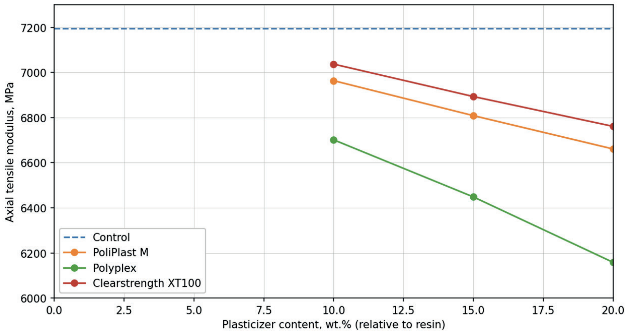

Figure 6. Initial axial tensile modulus versus plasticizer content

Testing of initial specific ring stiffness SN showed that introducing plasticizers into the binder generally reduces pipe ring stiffness compared with the control formulation (SN_avg = 10702.5 N/m²), and the reduction degree depends on the plasticizer type and content. Values closest to the control level were obtained for Clearstrength XT100 10% (SN_avg = 10529.9 N/m²; ~1–2% decrease) and PoliPlast M 10% (SN_avg = 10399.9 N/m²; ~3% decrease); PoliPlast M 15% maintains SN near the required level (SN_avg = 10039.7 N/m²). When increasing content to 20%, some formulations fall below SN = 10000 N/m² (PoliPlast M 20%—9900.6 N/m²; "PESU" 15–20%—9974.7–9960.9 N/m²), and the most pronounced stiffness drop is recorded for Polyplex (down to 9070.2 N/m² at 20%). Therefore, from the standpoint of maintaining ring stiffness within this section, formulations with 10% (PoliPlast M, Clearstrength XT100) and 15% (PoliPlast M) are the most preferable, whereas increasing content to 20% and using Polyplex are accompanied by a significant decrease in SN.

Determination of initial hoop tensile strength and tensile modulus

Specimens for testing initial axial tensile strength and tensile modulus were determined in accordance with Method B described in [26]; they were cut from fiberglass composite pipes in the axial direction as strips 25 mm wide and 450 mm long.

Results are presented in Table 4. Plots are shown in Figures 7 and 8.

Table 4. Results for initial axial tensile strength and tensile modulus

Series	Plasticizer content, wt.% of resin	Specimen No.	Initial axial strength, MPa	Axial tensile modulus, MPa
Control	0	1	103,5	7155
		2	102,6	7291
		3	102,9	7133
		4	103,9	7205
		5	103,4	7193
PoliPlast M	10	1	102,0	7010
		2	99,4	6885
		3	99,9	6926
		4	101,0	7036
		5	101,0	6961
	15	1	99,9	6865
		2	97,4	6743

		3	97,9	6783
		4	97,5	6794
		5	99,1	6858
	20	1	96,8	6684
		2	94,4	6565
		3	94,8	6605
		4	95,3	6753
		5	95,2	6697
Polyplex	10	1	98,8	6793
		2	96,4	6672
		3	96,9	6712
		4	96,3	6694
		5	96,0	6636
	15	1	95,7	6504
		2	93,4	6388
		3	93,8	6426
		4	94,7	6353
		5	96,8	6570
	20	1	91,6	6215
		2	89,3	6104
		3	89,7	6141
		4	89,6	6185
		5	92,7	6146
Clearstrength XT100	10	1	103,0	7118
		2	100,5	6991
		3	101,0	7033
		4	103,0	6977
		5	100,5	7066
	15	1	100,9	6973
		2	98,4	6849
		3	98,9	6891
		4	96,0	6907
		5	99,0	6846
	20	1	98,8	6829
		2	96,4	6707
		3	96,9	6748
		4	99,5	6715
		5	98,1	6806

Based on the average values (Figures 4.12 and 4.13), introducing the considered plasticizers leads to a decrease in axial tensile modulus and initial axial tensile strength. The most pronounced reduction is observed for the Polyplex formulation at 20% content, whereas the Clearstrength XT100 modifier better preserves strength characteristics with a moderate decrease in stiffness.

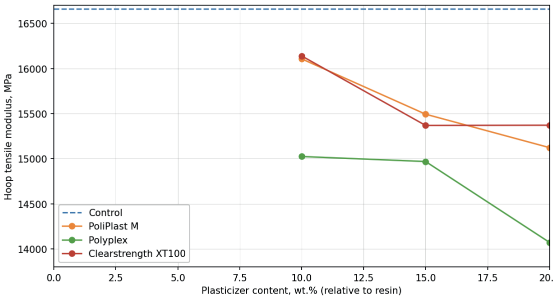

Figure 7. Initial axial tensile strength versus plasticizer content

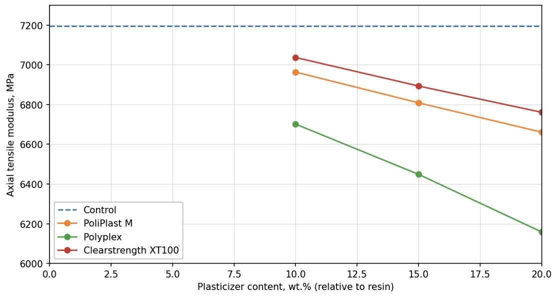

Figure 8. Axial tensile modulus versus plasticizer content

Determination of the impact toughness

Impact toughness was determined by the Charpy pendulum impact method on notched and/or unnotched specimens in accordance with [27]. To ensure comparability, the specimen size recommended by the standard was used: Type 2, length 80 mm, width 10.0 mm.
Test results are presented in Table 5. The impact toughness plot is shown in Figure 8.

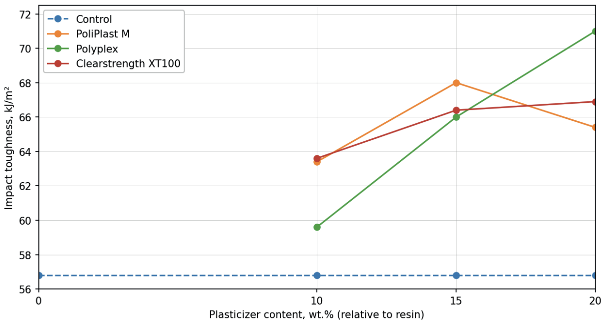

Figure 8. Impact toughness versus plasticizer content

Table 5. Charpy impact toughness, kJ/m²

Series	Plasticizer content, wt.% of resin	Meas. 1	Meas. 2	Meas. 3	Meas. 4	Average
Control	0	56,6	55,6	56,8	58,2	56,8
PoliPlast M	10	62,1	62,1	65,3	63,9	63,4
	15	67,6	69,4	67,6	67,6	68,0
	20	67,6	63,8	64,1	66,2	65,4
Polyplex	10	59,1	61,5	59,3	58,4	59,6
	15	68,7	65,7	66,2	63,5	66,0
	20	70,5	71,7	69,4	72,2	71,0
Clearstrength XT100	10	62,3	62,9	62,3	66,7	63,6
	15	67,0	65,1	68,5	64,8	66,4
	20	68,6	64,7	65,8	68,6	66,9

The most pronounced increase in impact toughness was obtained for the Polyplex series at 20% content: 71.0 kJ/m², corresponding to an increase of about 25% relative to the control level. For PoliPlast M, the maximum is achieved at 15% content (68.0 kJ/m², increase about 19.7%); with a further increase to 20%, the value decreases to 65.4 kJ/m² (increase about 15.1%), which can be interpreted as manifestation of an "over-toughening/over-plasticization" effect of the matrix and deterioration of interfacial interaction at excessive additive content. For Clearstrength XT100, a steady increase in impact toughness is observed with increasing content from 10 to 20% (up to 66.9 kJ/m², increase about 17.8%).

CONCLUSION

The performed study established that introducing plasticizing and elastomeric modifiers (including dispersed "core–shell" systems) into the thermosetting binder of fiberglass composite pipes is an effective tool for targeted increase in material impact toughness. Increasing this parameter is considered one of the determining factors in improving crack resistance and, consequently, the performance of pipe elements under seismic actions characterized by impulse nature and alternating-sign loading.

At the same time, it was revealed that the increase in impact toughness is accompanied by a decrease in stiffness–strength characteristics; the changes are systematic and dose-dependent and are governed by the nature of the plasticizer and its concentration in the matrix.

The maximum increase in impact toughness was recorded for the Polyplex formulation at 20% content; however, this series also exhibits the most pronounced decrease in ring stiffness, which limits its applicability where stiffness requirements are regulated. Formulations modified with PoliPlast M and Clearstrength XT100 demonstrate a more rational "toughness–stiffness" compromise: at moderate dosages, ring stiffness remains comparable to the control material, while a statistically significant increase in impact toughness is achieved.

The obtained data confirm the prospects of using plasticizing additives for purposeful modification of the viscoelastic response and for improving resistance to dynamic failure of fiberglass composite pipes under seismic activity.

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Sergey V. Shashkin — PhD student, National Research Moscow State University of Civil Engineering (NRU MSUCE), Junior Researcher at the Laboratory of Mechanics of Strength and Fracture of Materials and Structures, IPM RAS, 26 Yaroslavskoye Shosse, Moscow 129337, Russia, E-mail: forbic@list.ru; ORCID: 0000-0003-3334-8604

Tatyana A. Matseevich — Doctor of Physical and Mechanical Sciences, Professor, Department of Higher Mathematics NRU MSUCE, Leading Researcher at the Laboratory of Mechanics of Strength and Fracture of Materials and Structures, IPM RAS, 26 Yaroslavskoye Shosse, Moscow 129337, Russia, E-mail: Matseevichta@mgsu.ru; ORCID: 0000-0001-6292-0759.

Шашкин Сергей Владимирович – аспирант Национального исследовательского государственного строительного университета, младший научный сотрудник лаборатории механики прочности и разрушения материалов и конструкций ИПМ РАН, 129337, Ярославское шоссе, 26, Москва, Россия, E-mail: forbic@list.ru; ORCID: 0000-0003-3334-8604

Мацеевич Татьяна Анатольевна – доктор физико-механических наук, профессор кафедры высшей математики Национального исследовательского государственного строительного университета, ведущий научный сотрудник лаборатории механики прочности и разрушения материалов и конструкций ИПМ РАН, 129337, Ярославское шоссе, 26, Москва, Россия, Matseevichta@mgsu.ru; ORCID: 0000-0001-6292-0759.