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MODELING OF A STRESS-STRAIN STATE OF DETACHABLE CONNECTION IN DETAILS OF REINFORCED COMPOSITE MATERIALS WITH CEA METHOD

DOVHOPOLOV Andrii[1], NEKRASOV Sergiy[1], ZHYHYLII Dmytro[2], SAVCHENKO Yevheniy[2], STUPIN Borys[1]

[1] *Sumy State University, Faculty of Technical Systems and Energy Efficient Technologies, Department of Manufacturing Engineering, Machines and Tools, Rymskogo-Korsakova St. 2, Sumy, 40007, Ukraine, e-mail: a.dovhopolov@tmvi.sumdu.edu.ua*

[2] *Sumy State University, Faculty of Technical Systems and Energy Efficient Technologies, Department of General Mechanics and Machine Dynamics, Rymskogo-Korsakova St. 2, Sumy, 40007, Ukraine*

Abstract: In order to study the strength of the proposed rope threaded joint for machine parts made of reinforced composite materials, a modeling of a stress-strain state was conducted using the software of finite-element analysis LS-DYNA. Stress-strain state modeling was conducted for a rope threaded joint, affecting on the main performance parameters considered to be p – thread pitch (p = 4 mm), and t – thread depth (t = 1 mm). The main thread parameters taken for the model were up to the metric thread M6 (ISO 724:1993) parameters.

KEYWORDS: reinforced composite materials (RCM); detachable threaded joint; FEM modelling; strength; rope thread; deformations

1 Introduction. Problem statement

Today, composite materials are widely used in technologically advanced industries such as the aviation, marine and automotive industries, for which the weight reduction provides increase in dynamic characteristics and decline in fuel consumption. The complexity of structures in these areas of production requires a large number of joints. For the most part, the joining of parts made of reinforced composite materials (RCM), are implemented by gluing or welding them together to create a non-separable joint. That is why most studies are conducted to determine the stress-strain state of classical non-detachable joints of RCM parts, such as bolted, riveting, adhesive, the results of some of them are described in details in the works [1, 2, 3].

As for the detachable connections of details made of RCM, the most applicable are screw connections, which have their own specifics of manufacturing and application, but the very design of this type of connection is detachable [4].

This type of connecting of details made of reinforced composites is realized either by making the thread on the surfaces of the connecting details, or by inserting metal fasteners into the RCM part (fig. 1 a, b), in which the thread has already been made, through which there is a further joint. The design of the thread, if it is shaped on the detail of the reinforced composite (its diameter and profile), differs from the design of standard thread types [5], which in turn causes additional difficulties during its manufacturing. That is why most of the designs made of reinforced composite materials, which involve the combination of elements by means of thread, are connected by means of metal elements that comprise a thread, which further will be formed in this material.

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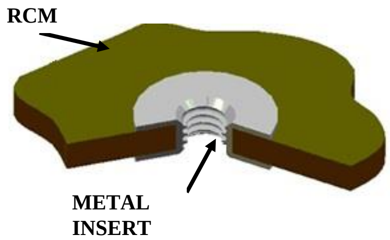

a) b)

Fig. 1 Implementation of threaded connection in reinforced composite with insert:
a – metal insert, located in a detail made of RCM; b – photo of metal inserts

In recent years, a large number of scientific works, devoted to the research of strength of threaded inserts formed in RCM, have been published. Among them, L. Adam conducted an experimental numerical study [6] of these inserts' strength, formed in various types of reinforced composite materials. From his research, dependence between the results of modeling and experimental data in terms of load curves and fracture prediction is obtained.

In work [7], an experimental numerical investigation of various types of fiberglass fracture in the places of filling inserts depending on the type of matrix used (epoxy resin) was carried out. A similar study was carried out in work [8], but in this case, composite material reinforced with carbon fibers was used.

As for the study of the strength of the threaded joint with a special profile in which the threading surface is shaped on parts made of RCM, today they remain little explored. In turn, according to the work of V.G. Komarov [9], a threaded joint with a rope thread on surfaces of details made of reinforced composites should have rather good indexes of strength. This profile due to design features, namely the absence of sharp stress raisers through the appropriate shape, is best suited for the implementation of a detachable threaded joint in the machine parts made of the abovementioned materials [10].

On the basis of the above statement, it was decided to conduct a modeling of a stress-strain state of a detachable threaded joint with a rope thread, using a method of finite-element analysis to test the hypothesis of high strength indexes of this connection.

1.1 Work objective

Modelling of a stress-strain state of detachable threaded joint with a rope thread in parts made of reinforced composite materials using the finite-element analysis software LS-DYNA.

2 Statement of basic materials

To solve the problem of modelling a stress-strain state of the proposed threaded joint with a rope thread, using the finite-element analysis method the following algorithm was developed – Figure 2.

Main parameters for functional capability were considered $\boldsymbol{p}$ – thread pitch, and $\boldsymbol{t}$ – thread depth of the profile, (profile is depicted in Fig. 3). Also, Figure 3 shows the outside $\boldsymbol{D}$ and the inside $\boldsymbol{D_1}$ diameters of the thread and $\boldsymbol{R_1}$ and $\boldsymbol{R_2}$ – are the radii of projections and recesses of the profile respectively. The choice of profile was due to its constructive features, as described in detail in work [10].

The main parameters of the thread taken for the model were up to the parameters of the metric thread M6 (ISO 724:1993) [10].

Incoming data:

1. Creating geometric model
2. Defining structural material model behaviour
3. Creating finite element mesh
4. Applying initial and boundary conditions
5. Setting properties RCM and properties of material insert

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Calculation of stress and strain state of the RCM nuts and fracture criterion verification

Fig. 2 Algorithm for calculating the stress-strain state of a joint by the finite-element analysis method.

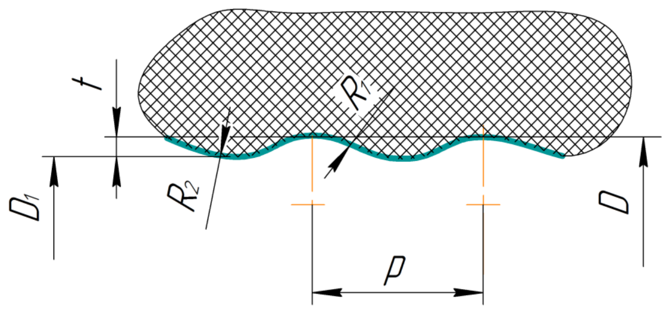

Fig. 3 Basic parameters of the inside thread profile

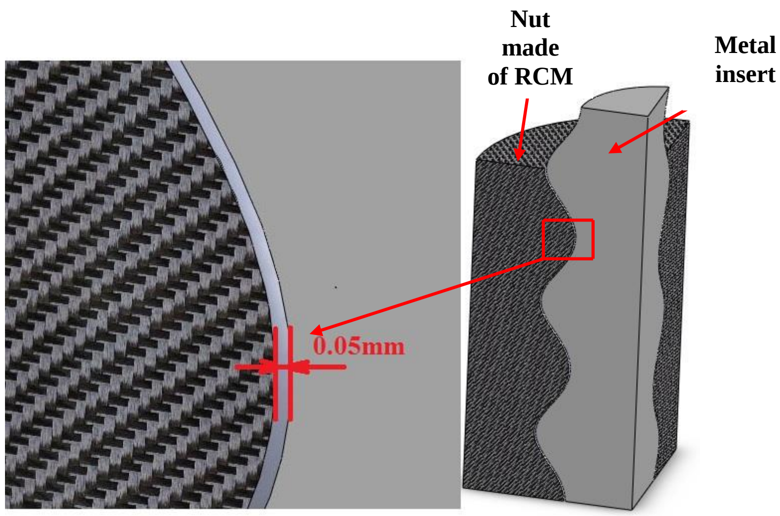

Fig. 4 3D-CAD-model of joint

The modeling of the stress-strain state in the finite-element analysis software LS-DYNA is given for a variant of a rope thread with parameters p = 4 mm and t = 1 mm. A nut made of RCM with round inside thread and metal insert with outside thread for modelling were executed in the form of 3D-CAD-models. All further operations are performed with a separate segment that is cut from the connection to reduce the calculation time. (Fig. 4). According to the recommendations given in the work of D.V. Krivoruchko [12], for obtaining reliable data on the modeling by the finite-element analysis method between the external and internal screw surfaces of the connection, a guaranteed gap was set 0.05 mm (Fig. 4).

The models were meshed into finite-element mesh of 10 nodes tetrahedral finite elements (FE). The size of finite elements of nuts made of RCM was selected based on the fact that the calculation took a reasonable amount of time. The size of the facet of the finite element was from 0.05 to 0.15 mm. In the contact region between two screw surfaces, the dimensions of the FE were made smaller to obtain more reliable results. The finite elements far from contact surfaces were made significantly larger, since it affects the time of calculations, and the stresses and deformations in it will be much smaller than in the RCM parts. Figure 5 shows the FE element mesh of the proposed joint.

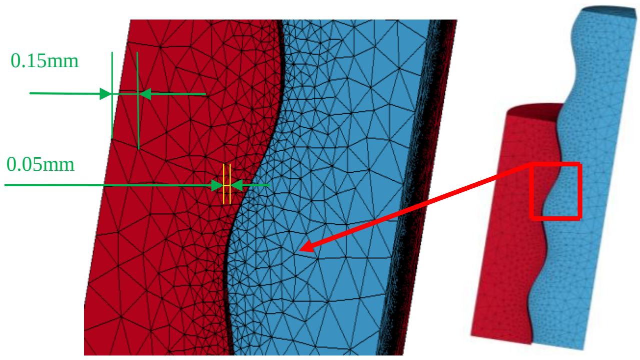

Fig. 5 Finite-element grid of components of the modeling system

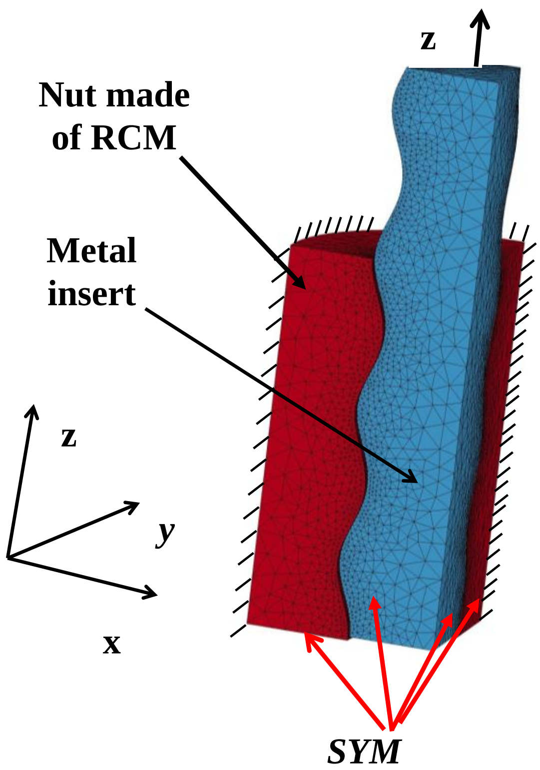

Fig. 6 The computational scheme and boundary conditions of the FE simulation model of the joint made of reinforced composite materials

The mechanical boundary conditions were set with the rigid fixing of several boundaries of the RCM nut. In this case, the nut was firmly fixed on the outside diametrical surface (Fig. 6). The restrictions for the insertion were set along the axes X and Y. Initial conditions for insertion were set by translational movement along its axis Z and mechanical loads were set by moving the insert according to the fastening scheme along its axis at an appropriate speed.

In order to perform the last point of the algorithm of incoming data (figure 2), namely, to introduce into our simulation model the properties of reinforced material, its mechanical properties have to be determined, and a set of experiments has to be carried out for their determination.

3 Searching for material data

Tests of reinforced composite materials are characterized by a number of features and differ from metals of different types of destruction under load in identical conditions. Anisotropy and heterogeneity of reinforced composites, as well as practically complete absence of plastic deformations with all possible types of destruction, cause considerable difficulties in obtaining objective characteristics even in single-piece loading [13, 14, 15]. The rationale for choosing a sample often requires more effort than designing a constructive element from a composite [16]. Creating a homogeneous field of deformation at the working site is a prerequisite for the correctness of the tests for tension and compression.

The principle of Saint-Venant in anisotropic materials in comparison with traditional isotropic materials is manifested in the sharp extension of regions of the boundary effect, which requires an increase in the length of the sample. The length of the working part of the samples while compressing is limited by the possibility of their stability loss [16].

In our case, the matrix and fiber with the following parameters were used for the determination of the physical and mechanical properties of the reinforced fiberglass material when prototype samples were created. T13-270 fiberglass fabric was used with the size of the cell (0.5 x 0.5 mm), the thickness of the fabric is 0.2 mm, according to ISO 1886-90 [17] (Table 1).

Table 1 Technical characteristics of the T20 – 270 glass fiber [17]

Tensile strength, MPa	1100
Modulus of elasticity, GPa	45
Poisson ratio	0.24
Mass per unit glass fiber area, kg/m^2	1500

Epoxy resin EPOXY-520 was used as a matrix manufactured by the Czech company Spolchemie. The main physical and mechanical characteristics of the filler are given in table 2.

Table 2 Basic physical and mechanical characteristics of epoxy resin EPOXY-520 [18]

Strength at tensile, MPa	220
Strength at compression, MPa	55
Strength at bending, MPa	110
Modulus of elasticity, МПа	1793
Poisson ratio	0.33
Density of the matrix, кg/m3	1150
Relative permanent elongation under tension, %	5

To determine the mechanical characteristics of the fiberglass, tension was carried out using flat samples in the form of strips cut from the multilayer plates of width 15 to 17 mm reinforced in two mutually perpendicular directions (stacking sequence [0°/90°]12) according to ISO 527-2:2012 [19]. Plates were made by manual stacking from unidirectional layers of fiberglass. The dimensions of the glass fiber cell were (0.5x0.5 mm) 0.2 mm fabric thickness, a modified epoxy resin EPOXY-520 was used to link the reinforcing elements together, and it was mixed with the curing agent in mass proportions 100:33. Resin and fiber were weighed on electronic scales with an absolute error of ± 0.1 g. The total thickness of the plate was 12 layers, with a mass fraction of fibrous filler not less than 60%. For the removal of excess epoxy resin, compression under pressure was applied using a modified universal testing machine UME-10TM with a force of 30kN (Fig.7).

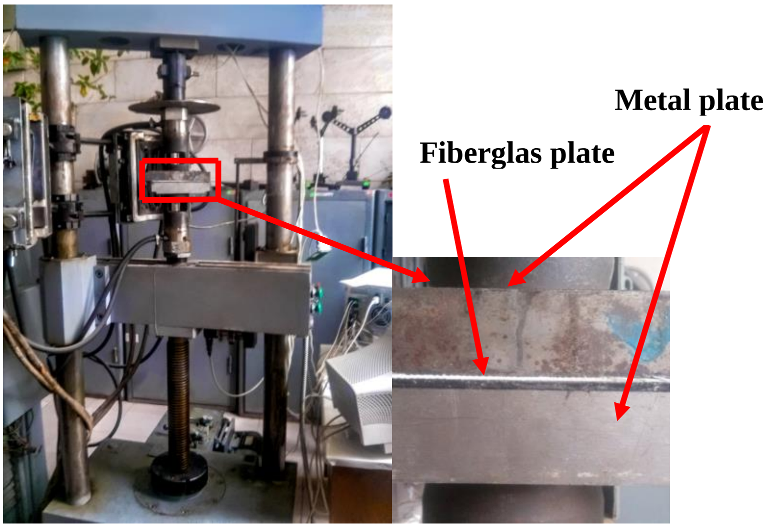

Fig.7 General view of machine for the production of prototypes

The experimental samples were made by the proposed technology, since it has been experimentally established that the fiberglass specimens manufactured under this technology have a tensile strength of almost two times greater than those manufactured without application of external force during the formation. Two samples with the same number of layers were obtained according to different technologies, the first one – without the application of external force, its dimensions were 150-16-2 mm, the second one – the size 150-16-1 mm, the number of layers of fiberglass tissue is the same 12 layers. The thickness varies by removing the excess of the matrix under the action of external loading.

After studying the samples submitted for tension and obtaining the value of tensile strength for each of them, for the first σ_{u1}=116MPa, for the second σ_{u2}=203MPa, it was decided to make all further experimental samples manufactured using the above-described technology with the application of external force.

Examination of the strength of samples at stretching was carried out using specially designed fixation, which is fastened by screws (Fig. 8). The photographs of the samples for tests for stretching are shown in figure 9. To prevent the destruction of samples from local contact stresses in their places of fixing succeeded with glued overlays. The length of the lining was chosen from the condition of the adhesive bonding share strength [20].

Fig. 8 Photo of fixators with fiberglass sample fixed in them

Fig. 9 Photo of fiberglass sample

Figure 10 shows a photo of the fiberglass sample test on tensile strength. The sample is fixed in the fixators, and it is installed in the modified universal testing machine UME-10TM.

Fig. 10 Experimental installation on the basis of UME-10TM in the collection for research of a fiberglass sample for tension

Five samples which sizes are summarized in Table 3 were made for study on tensile. Tensile strength of the material during the study on tensile is given in Table 4.

The study of fiberglass samples for compression was also carried out on a modified universal testing machine UME-10TM. For this, five samples were additionally made, the sizes of which are summarized in Table 3. Figure 11 shows a sample photo set up in a testing machine.

Table 3 Sizes of test samples for studying them on stretching and compression

Sample	Distance between supports l, mm	Width b, mm	Thickness, mm
$1_{\text{tens.}}$	150	14.6	1.2
$2_{\text{tens.}}$	150	15.4	1.2
$3_{\text{tens.}}$	150	14.9	1.2
$4_{\text{tens.}}$	150	15.4	1.2
$5_{\text{tens.}}$	150	14.9	1.2
$1_{\text{comp.}}$	11.2	17.0	1.9
$2_{\text{comp.}}$	11.2	17.2	1.9
$3_{\text{comp.}}$	11.2	17.3	1.8
$4_{\text{comp.}}$	11.2	17.1	1.8
$5_{\text{comp.}}$	11.2	16.0	1.9

Fig. 11 The photo of the sample fixed in the experimental machine

Table 4 gives the obtained characteristics of the strength of the samples presented.

Table 4 Parameters of the strength of the samples presented

Sample	Ultimate loading force, F_B кN	Ultimate strength σ_u, MPa	Type of destruction in accordance with ASTM D 3039/D	Type of destruction in accordance with ASTM D 6641/D
$1_{\text{tens.}}$	3.45	198.1	AGM	-
$2_{\text{tens.}}$	3.07	168.6	LAT	-
$3_{\text{tens.}}$	3.45	198.1	LAT	-
$4_{\text{tens.}}$	3.45	192.5	LAT	-
$5_{\text{tens.}}$	3.81	205.7	LAT	-
1_{comp}	2.34	70.3	-	HAT
2_{comp}	2.92	80.9	-	HAT
3_{comp}	2.46	75.2	-	HAT
4_{comp}	2.87	79.5	-	HAT
5_{comp}	2.94	98.3	-	HAT
HAT – through-thickness at grip/tab top; AGM – angled gage middle; LAT – lateral at grip/tab top				

Consider our reinforced fiberglass material, as for a linear elastic orthotropic body, the mathematical formulation of its physical and mechanical characteristics, described in the work of S. M. Vereshchaka [21]. Having determined the strength parameters by examining samples of reinforced fiberglass material for tension and compression, and substituting them in the calculated dependencies specified in work [21, 22], we obtain the mechanical characteristics of the material for inclusion in the LS-DYNA command file (Table 5).

The introduction of the mechanical characteristics of the proposed model material to the LS-DYNA command file was implemented using the keyword *MAT_COMPOSITE_DAMAGE – material model type 22. The presented keyword when creating the model of anisotropic body has allowed to fully determining all the mechanical properties of reinforced fiberglass material for modeling. Table 6 provides a description of the models of the material in the LS-DYNA command file.

Table 5 Mechanical characteristics of reinforced material

$E_1 = E_x$, GPa	$E_2 = E_y$, GPa	$E_3 = E_z$, GPa
26.902	26.902	11.439
$\nu_{21} = \nu_{yx}$	$\nu_{31} = \nu_{zx}$	$\nu_{32} = \nu_{zy}$
0.101	0.188	0.188
$G_{12} = G_{xy}$, GPa	$G_{23} = G_{yz}$, GPa	$G_{31} = G_{zx}$, GPa
4.342	2.713	2.713

Table 6 Description of the models of the material in the LS-DYNA command file

*MAT_COMPOSITE_DAMAGE									
MID	**RO**	**EA**	**EB**	**EC**	**PRBA**	**PRCA**	**PRCB**	**GAB**	–
22	$2.0{*}E^{-6}$	26.9	26.9	11.4	0.10	0.18	0.18	4.34	–
GBC	**GCA**	**K_{fail}**	**AOPT**	**MACF**	–	–	–	–	–
2.7	2.7	0	2.0	1.0	–	–	–	–	–
XP	**YP**	**ZP**	**A_1**	**A_2**	**A_3**	–	–	–	–
0	0	0	1.0	0	0	–	–	–	–
V_1	**V_2**	**V_3**	**D_1**	**D_2**	**D_3**	**BETA**	–	–	–
0	0	0	0	1.0	0	0	–	–	–
SC	**XT**	**YT**	**YC**	**ALPH**	**SN**	**SYZ**	**SZX**	–	–
50	200	200	180	0	16	30	30	–	–

As for the model of the insertion material with the outside thread, then the keyword *MAT_RIGID – material type 20 was used for it. The details described by this material are considered to be absolutely rigid bodies.

The contact form during the execution of the modeling was set to be: initial close gaps (it means the gap and initial offset are not taken into account), separation of the geometries is not allowed, sliding can occur along contact geometries. The contact was set between two formed threaded surfaces using the keyword *CONTROL_CONTACT, the contact type was determined by the module CONTACT_AUTOMATIC_SURFACE_TO_SURFACE_ID. With this algorithm you can obtain a stable solution of the contact problem, the advantage of which is the possibility of creating a generalized dependence d = d(v, p), where p – contact pressure by creating a table of the corresponding function on the map *DEFINE_TABLE and reference to it in the parameter FD at FS = 2. What is what was done.

The friction model was considered for modeling as follows: it was noted that the friction that occurs between the elements of the connection is Coulomb friction. The basic parameter required for simulation is the coefficient of friction that was determined experimentally by determining the friction angle, in this case, the difference between sliding friction and resting friction was not taken into account, there is also no dependence on slip speed[23],.

As a result of the calculation, stress tensor in the Gaussian points of finite elements are obtained.

For the mentioned variant in the beginning of the calculations with the main parameters of the thread ***p = 4 mm, t = 1 mm,*** the following data of maximum stresses and deformations is calculated. It is shown in Figure 12.

The LS-PrePost-2.4 postprocessor graphics modules allow to build the graph of the dependence of the resulting force from the displacement, but in this case, the graph obtained using these modules is four times smaller since one fourth part modeled, to accelerate the calculation time, and, therefore, for the full power indices, the data obtained need to be increased by 4 times. Figure 13 shows the graph of the dependence of the resulting force on the displacement executed in the table processor MS-Excel to work with spreadsheets.

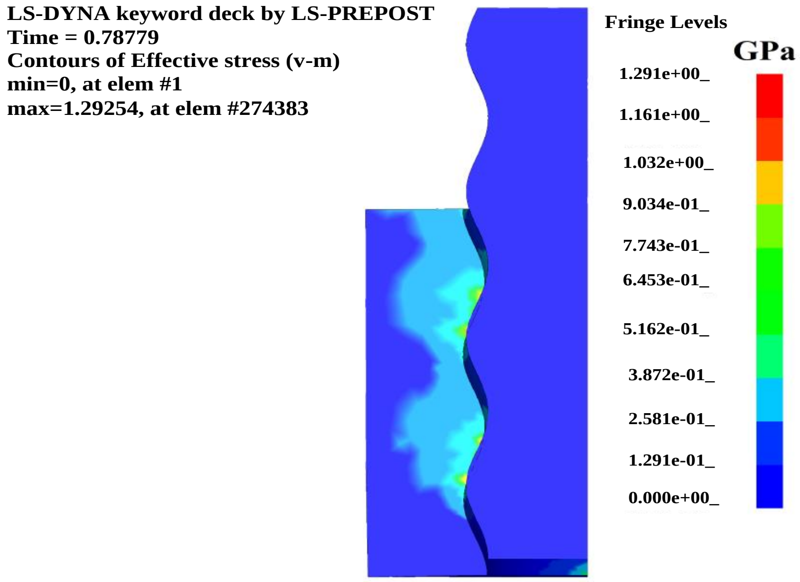

Fig.12 Indicators of maximum stresses and deformations in the environment LS-DYNA

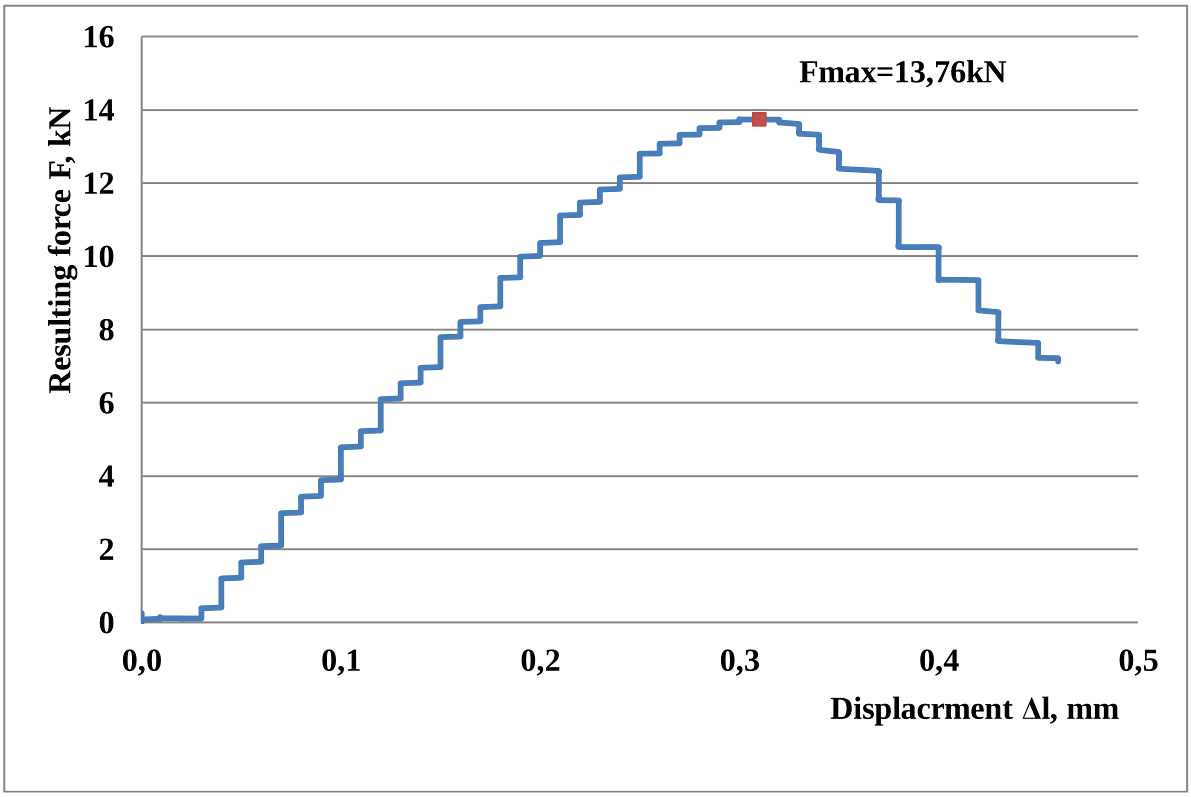

Fig. 13 Graph of the dependence of the resulting force from displacement

According to this graph, it is shown that the maximum force for this case is F_{max} = *13.76 κN*, which confirms the proposed hypothesis at the beginning, according to which the rope threaded joint should have high strength parameters when forming it in details made of reinforced composite materials.

CONCLUSION

As a result of the modeling stress-strain state with finite element method by LS-DYNA of a detachable rope threaded joint in machine parts made of reinforced composite materials, the basic parameters of the strength of this connection were obtained, which turned out to be quite high. According to the results of the modelling, the connection can bear the following maximum force $\boldsymbol{F_{max} = 13.76}$ ***κN.*** The values of the maximum stresses and deformations according to the data processed in the postprocessor LS-PrePost-2.4 vary in rather high limits, which confirms the initial hypothesis and gives grounds for further conducting an experimental study of strength.

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