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INFLUENCE OF THE SHAPE OF THE TEST SPECIMEN PRODUCED BY 3D PRINTING ON THE STRESS DISTRIBUTION IN THE MATRIX AND IN LONG REINFORCING FIBERS

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Abstract: The stress distribution in specimens designed for the tensile testing is evaluated in the article. The reinforcement consists of long fibers that copy the outer contour of the specimen. The fibers are inserted within the curvature at the edge of the specimen with the neck. The stress distribution in fibers and matrix of dogbone specimen and specimen of rectangular shape is analyzed and compared. The analysis of stress state is analyzed in FEM software ADINA. Long fibers deposited in specimen were modeled using rebar elements.

KEYWORDS: carbon fiber, reinforced composite, tensile test, 3D printing, ADINA, FE analysis, MATLAB

1 Introduction

3D printing becomes an emerging production technology, which is gradually gaining the market place. We consider it as an additive manufacturing technology that, which in contrast to conventional subtractive technologies, is based on the addition of the material layer-by-layer according to data from the digital model of object [1, 2]. The technology has been developing for 35 years. It currently includes several methods that differ in many parameters, for instance in used materials, in accuracy, speed of production, etc. [3]. The most widely used 3D printing method is Fused Filament Fabrication - FFF [4]. The principle of the method is based on feeding the thermoplastic filament into a nozzle in which the filament is heated. The extrusion head with the nozzle follows defined trajectory and melted material falling at the specified locations. The method was patented by Stratasys in 1989 [5]. In addition, the method allows to printing fiber reinforced thermoplastic composites which are reinforced with short or continuous fibers [6]. Continuous fiber reinforced thermoplastic (CFRTP) composites achieve better mechanical properties than their counterpart but recent research continues to improve the properties [7, 8]. CFRTP composites printing is available using augmented FFF method, when the printer is equipped with two nozzles; the second nozzle is used to lay fiber into thermoplastic part [9]. The mechanical properties of composites produced by conventional methods are better compared to 3D printed reinforced thermoplastic composites [10, 11]; therefore primary objective is to obtain comparable results. Two main concepts, how to predict the mechanical properties of the composite structures are FEM calculations and tests performing. In FEM program ADINA, continuous fibers are modeled using rebar elements. The program automatically finds intersections of each rebar line with 3D solid element surfaces and generates nodes at the intersections. These generated nodes and three closest corner nodes of 3D solid element faces are connected using constraint equations [12]. This concept allows modeling of real continuous fiber in a matrix using real mechanical properties of the matrix and the fiber.

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The tensile tests for 3D printed reinforced thermoplastic composites are not defined yet. Hence specimen shape and testing parameters according to standards for plastics (ASTM D638-14) [13] or composites manufactured by conventional technologies (ASTM D3039) [14] are applied. The tensile tests demonstrated that dog bone specimen is inappropriate for this type of test due to occurrence of stress concentrations close to specimen attachment, in its rounding, or near the end of fibers [15, 16]. For this reason, it is necessary to design the suitable shape of printed CFRTP specimen for tensile testing. In assessing process of the specimen shape suitability, the mechanical properties of reinforcing continuous fiber should be taken into account.

2 Analysis of stress distribution in specimen

Fiber deposition and its location were determined from software Eiger. Program, which generates models for FEM software ADINA was created using MATLAB [12, 17]. The degrees of freedom were removed at one end of the specimen and displacements were prescribed on other side (Fig. 1).

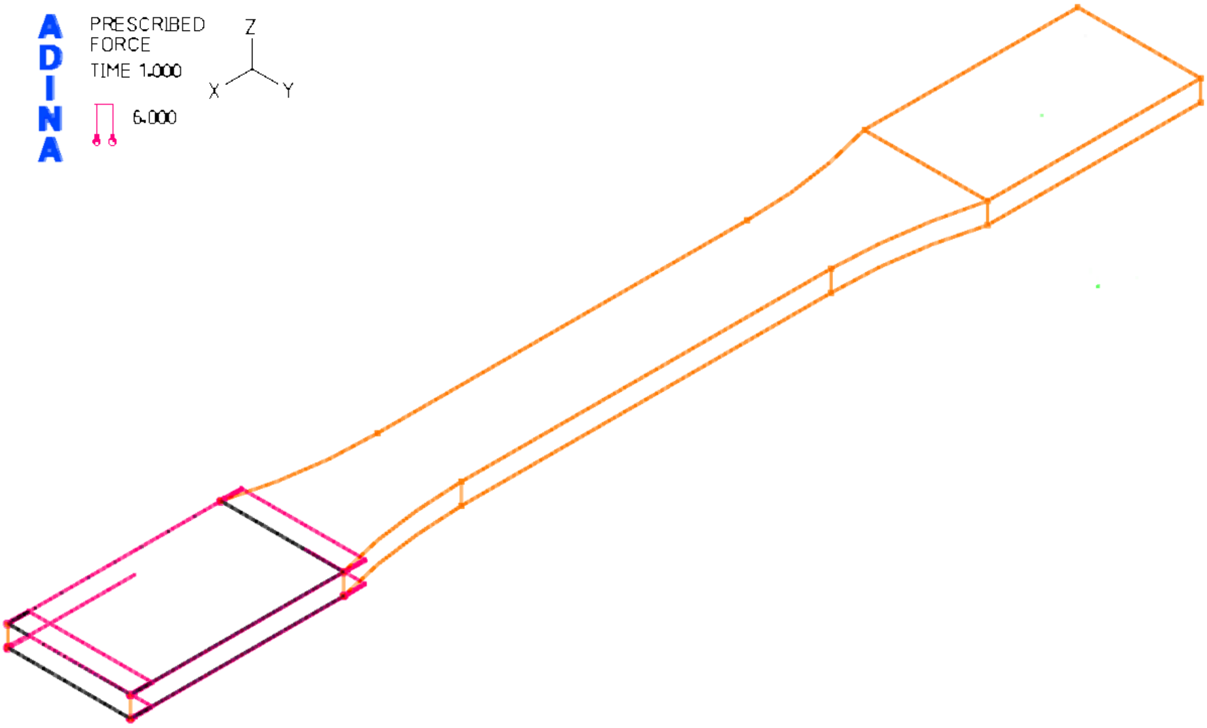

Fig. 1 Boundary conditions

The multilinear material model was used to create the specimen matrix (ONYX, Fig. 2, left) and the carbon fiber (Fig. 2, right) model. The material model of matrix and fibers was determined from experimental measurements of mechanical properties of the materials [18]. The finite element mesh was generated using 0.4 mm linear tetrahedron elements. These mesh elements sizing was used because provides comparable results to 0.2 mm elements but the usage of 0.2 mm elements requires more computational time. In computational process was observed the influence of elements size to resultant stress values. The sizes of assessed elements were 0.4, 0.2 and 0.1 mm. The assessment was performed on the structure without reinforcement fibers. The stress variation affected by element sizing does not exceed 5%.

In the next step, the influence of convergence criterion to solution accuracy in the reinforced model was performed. The convergence criterion of deformations was applied and the presented results are for value 1e-9. The selection of 1e-10 criterion leads to loss of convergence.

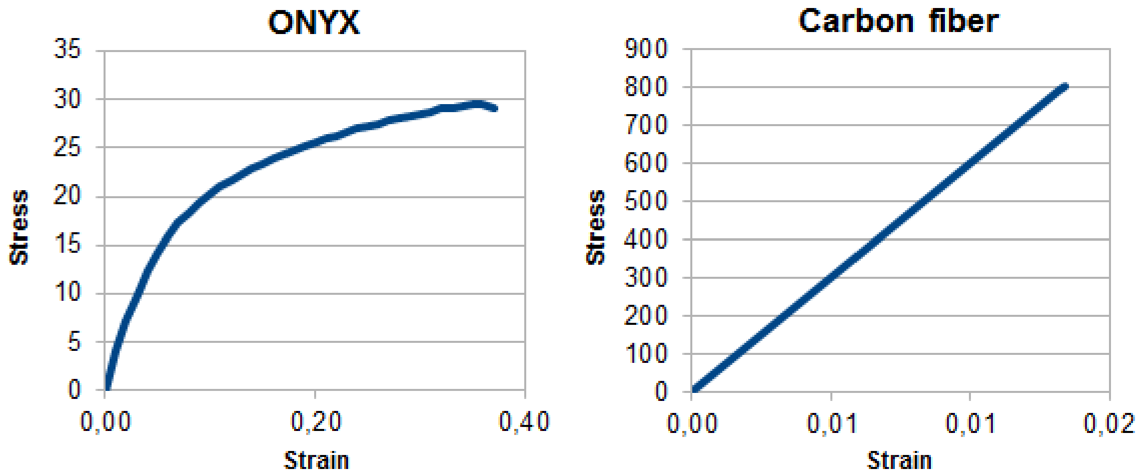

Fig. 2 Multilinear material model for the matrix (left) and for the carbon fiber (right)

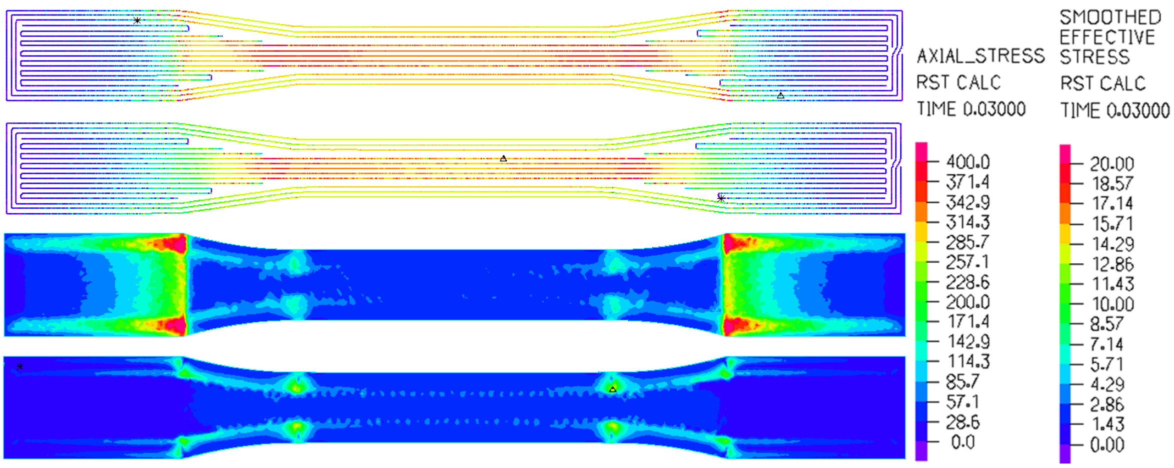

Fig. 3 Dog bone specimen reinforced with three concentric rings and isotropic fiber fill [13]

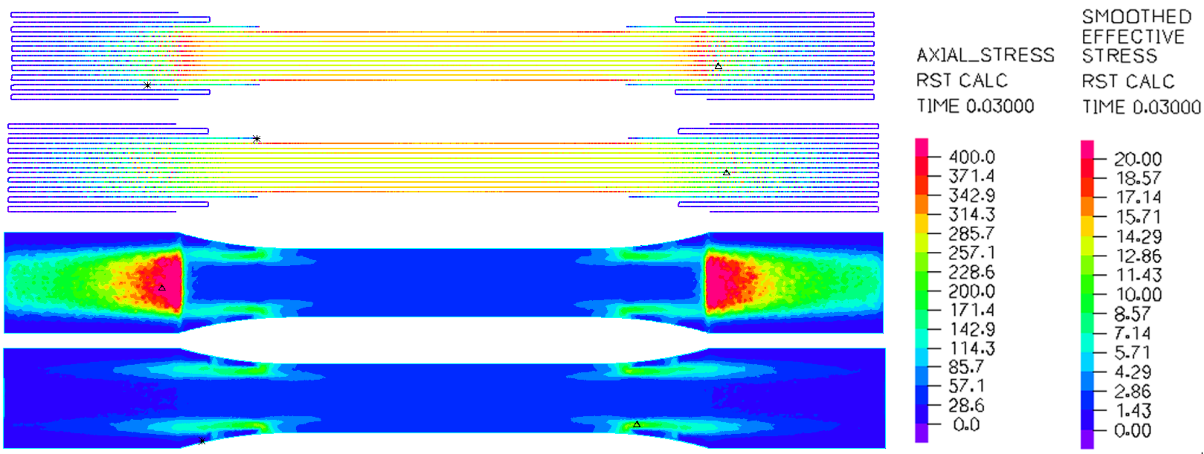

Fig. 4 Dog bone specimen reinforced with unidirectional fiber fill [13]

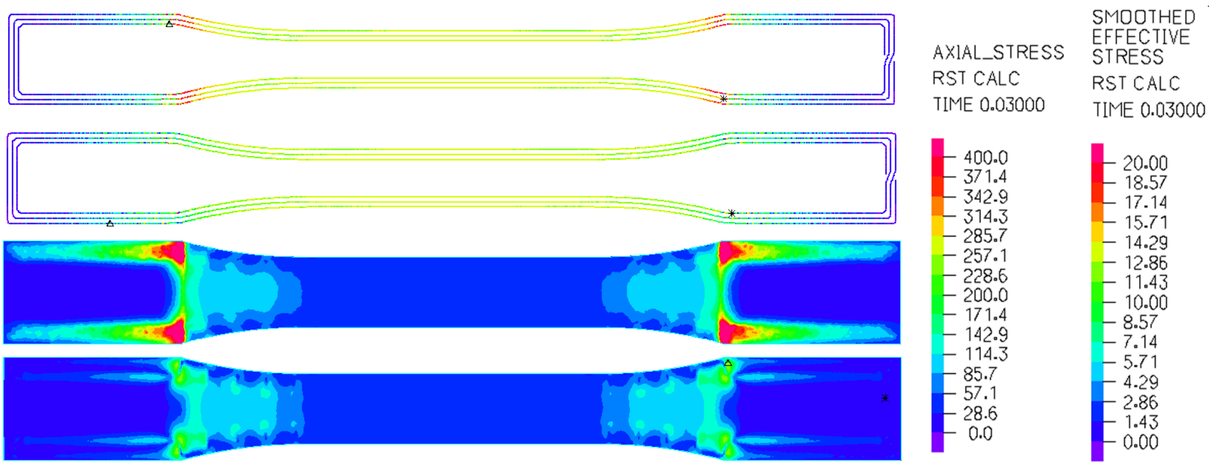

Fig. 5 Dog bone specimen reinforced with three concentric rings of fiber fill [13]

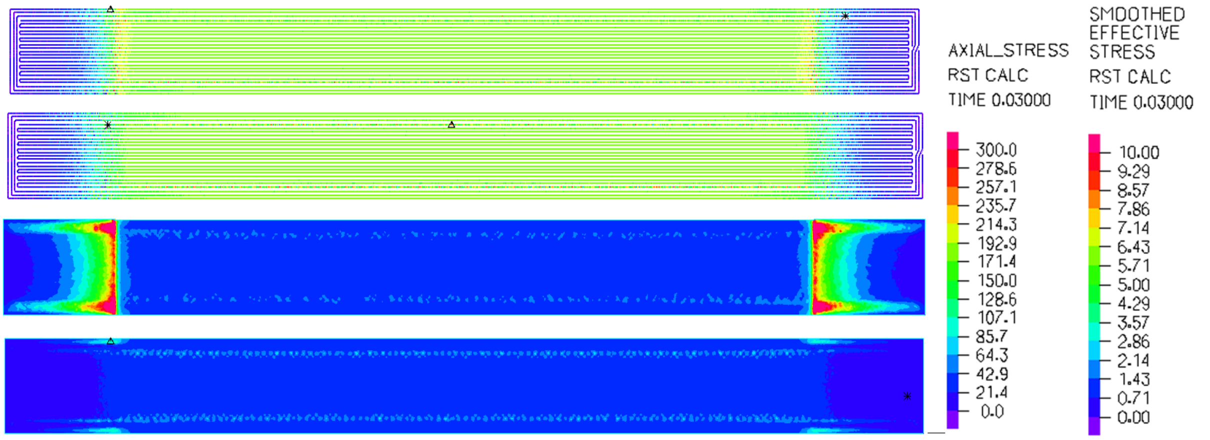

Fig. 6 Rectangular specimen reinforced with three concentric rings and isotropic fiber fill [14]

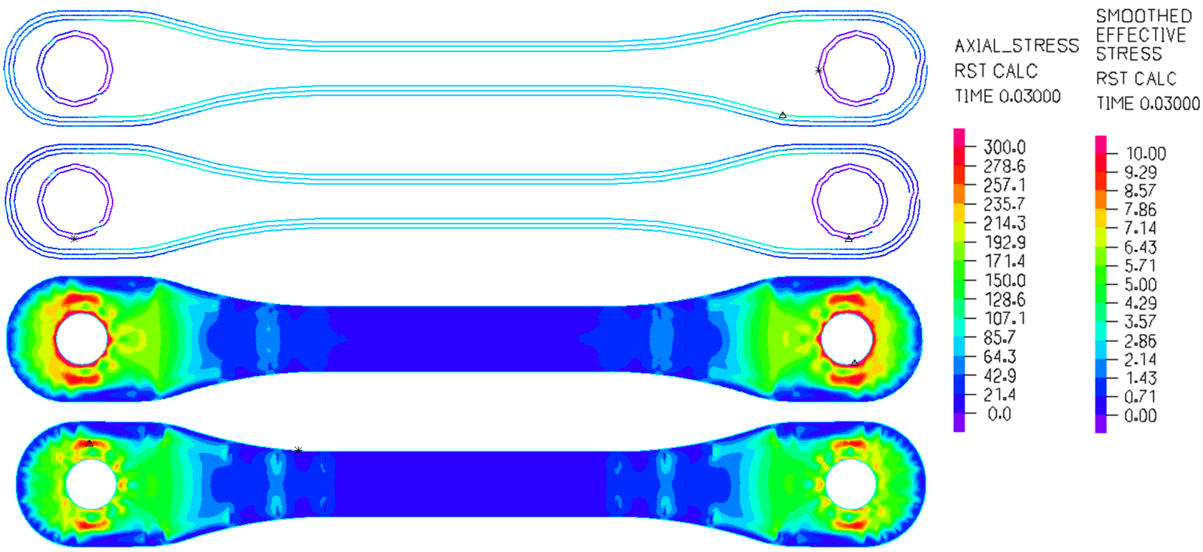

Fig. 7 Adjusted dog bone specimen reinforced with three concentric rings of fiber fill [19]

The stress distribution in specimens is shown in Fig. 3 to Fig. 7 in defined order:

- stress distribution in the fiber, which is closest to outer surface of the specimen,

- stress distribution in the fiber, which is deposited in the middle layer of the specimen,
- stress distribution in the matrix on the specimen outer surface,
- stress distribution in the matrix in the middle of the specimen.

The stress distribution inhomogeneity on the specimen outer surface and in the middle of the specimen can be observed in four assessed specimen shapes (from Fig. 3 to Fig. 6). This uneven stress distribution is due to the boundary condition - attachment of the specimen to the jaws. Increased values of stress occur in the specimen matrix surface and in outer reinforced layers. Therefore, for these specimens the attachments cause beginning of the specimen breakage. The last analyzed specimen shape (Fig. 7) has equal stress distribution in the outer fibers and in the fibers localized in the middle of the specimen. This specimen has significantly higher stress values around the attachment hole. We can assume, that start of the breakage occurs at this location. Significantly different dimensions of specimens results to differences of stress values in matrix and fibers.

3 Proposal of new specimen shape

In general, each analyzed specimen shape in the article is inappropriate for the experimental measurements of mechanical properties of continuous fiber reinforced composites produced by 3D printing. The suitable specimen shape for tensile testing should satisfy the following conditions:

- the specimen waist should be significantly narrower than the end of the specimen,
- the radiuses on the specimens should be significantly larger, it is necessary to minimize changes in the direction of the fiber in the arc,
- reinforcing fibers should be deposited in rings because the fiber ends result to significant stress concentration.

Proposed specimen shape is in Fig. 8. The specimen was divided into eleven layers and reinforced with carbon fiber in three layers. Fiber fill type was concentric with four fiber rings. The reinforcing fiber has tensile strength 700 MPa at strain 0,0134 and fiber diameter 0,37 mm. Total number of fibers in the narrowest part of specimen was 24. Therefore the force required to rupture of the fibers is 1800 N. The matrix in the narrowest part of specimen has cross section area 13,75 mm^2. Onyx has tensile strength 5,2 MPa at strain 0,0134 and force required to rupture is 143 N.

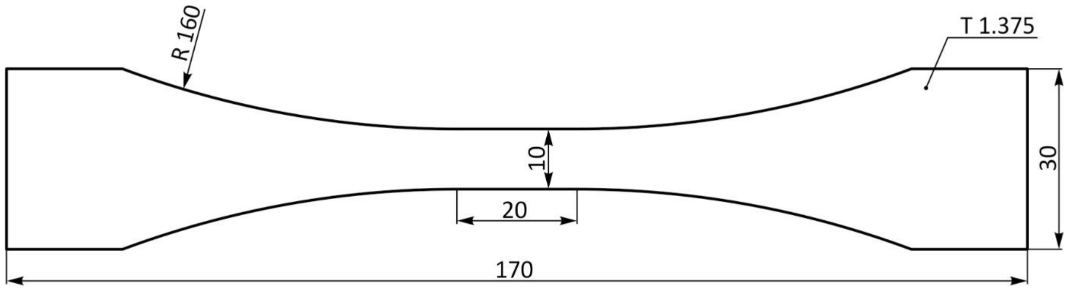

Fig. 8 Proposed specimen shape for tensile testing

Therefore reinforcing fibers have significant influence on specimen strength. State of stress in the specimen is showed in Fig. 9. There are minimal differences in stress distributions between outer and middle reinforced layers. The maximum stress in fibers occurs in the narrow part of specimen. Curved fiber deposition has minimal effect on stress state in specimen.

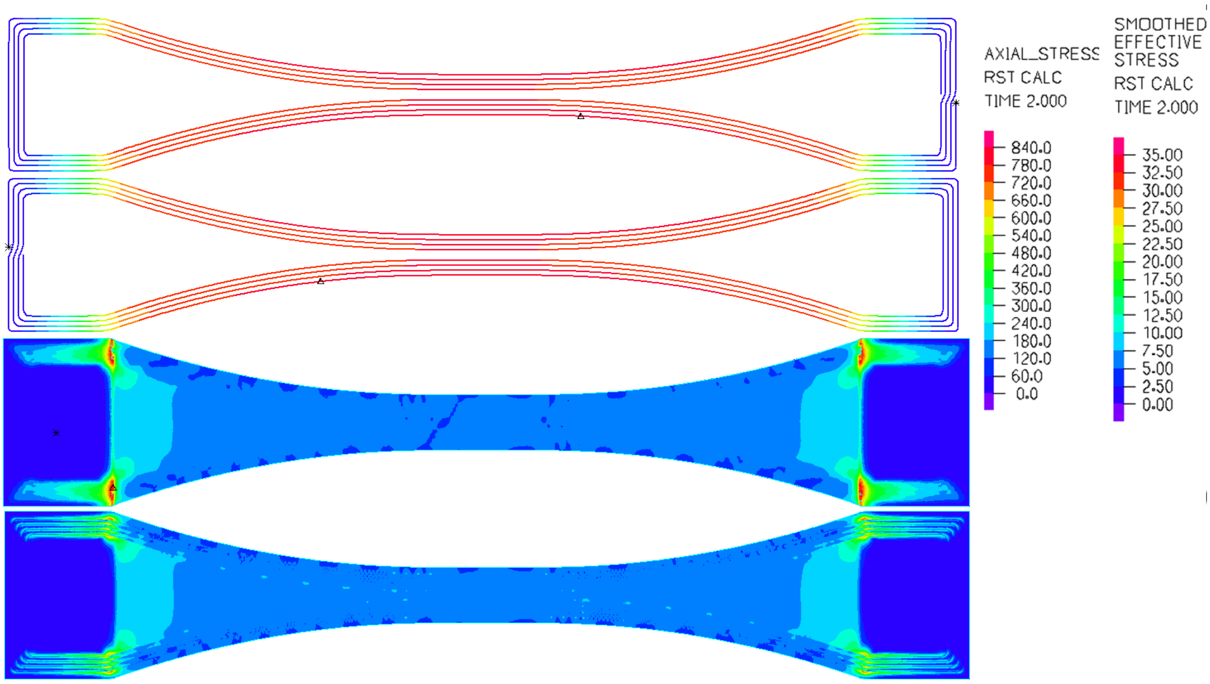

Fig. 9 Von Mises stress distribution in proposed specimen

CONCLUSION

Based on the analysis of the stress state in assessed three tensile test specimens for long-reinforcing fibers, we can make the following statement. Specimens shapes defined in standards ASTM D3039, ASTM D638-14 and article [17] are inappropriate for tensile testing of 3D printed CFRTP composites. Large differences of stress state in outer and middle reinforced layers may result to rupture of fibers from outer layers to the middle of the specimen. Wide variations of specimen shapes cause the occurrence of stress concentrations in these locations, that may influence crack formation. Specimen shape unsuitability affects material inhomogeneity on a macroscopic scale. The proposed new shape of the specimen eliminates these described deficiencies. The proposed number of reinforcing layers, the shape of fibers and deposition of fibers in the matrix has a significant influence on the resultant strength of the specimen. These parameters are the primary factors determining the strength of the composite structure. Extension of specimen ends eliminates the generation of stress concentrators caused by the attachment of specimen to test machine.

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