ANALYSIS OF RESIDUAL STRESSES INHERITED DURING MANUFACTURING OF CARBON-EPOXY COMPOSITES WITH CONCENTRATOR

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Abstract

In the present study, the effect of specimen sizes on the residual stresses inherited during manufacturing of IM7/8552-1 carbon-epoxy composites with concentrator was investigated. The first part of the research is devoted to the understanding of residual stresses in regular specimens during cure cycle depending on different ply and laminate thickness. To describe the behavior of the composite material during the manufacturing process - including processes of formation, polymerization, development of residual strains and stresses the special user subroutine was developed and implemented into ABAQUS FEM software.

The second part of this paper concerns the study of the «hole-size effect» on the value of residual stress in composites with concentrator. The most important variables have been identified as notch size, and ply and laminate thickness. These have been scaled in two ways: independently and simultaneously. Obtained by modelling values for stress components are essential and cannot be ignored in consequent structural analysis.

1. Introduction

Last decades, increased attention is paid to the deep understanding of the process induced by residual (locked-in) stresses in composites, namely the effect of shape distortion and fracture. Residual stresses can cause several defects in composite laminates and structures such as fiber and tow misalignment, transverse cracking (known as microcracking) delamination and warpage [1,2].

In particular, for aviation structures the residual stresses can be unlikely ignored and should be taken into consideration during the process of design and production in view of the high cost and high reliability requirements. The stress-gradient effects on the fracture strength of metals in contrast to composites have been recognized for a long time. The approach, known as Neuber's elementary block theory, has been used for explanation of actual strength reduction in metals by the stress-concentration factor. In fiber-reinforced composites, by analogy with metals the same effect was renamed as the “hole-size effect”. This effect on the strength of composites has been investigated by several researchers [3,4]. In [5] it was experimentally shown that for notched composites failure and stress mechanism depend upon hole size and thickness. There is a guess that internal/residual stresses may affect on this fracture of composite. That is why it is useful to study the stress through the sample thickness obtained after the hole cutout and stress which one obtained before for regular specimen in respect to the different ply and the laminate thickness. In the present study, the effect of specimen sizes on residual stresses inherited during manufacturing of thermoset composites was considered using an example of IM7/8552-1 carbon-epoxy specimens with concentrator. The study was realized by means of ABAQUS FEM and developed material model that was implemented in user subroutine.

2. Constitutive material model

One of the key processes during manufacturing of composite part and at the same time a bottle neck is a polymerization of the resin that takes place inside the die. Residual stresses developing during manufacturing of thermoset composites have a direct influence on the product quality and can cause problems with assembly process as it requires to use additional spacers to ensure close contact between parts. Main factors responsible for residual stresses and shape distortions on a modern high performance composite are the following: anisotropic thermal shrinkage that occurs during material cooling from cure to room temperature, chemical shrinkage during the polymerization reaction, the degree of cure gradients through the composite thickness and interaction between die and part.

To describe the behavior of the IM7/8552-1 carbon-epoxy composite during solidification the linear viscous-elastic model [6] was used. The effective mechanical properties as well as the thermal and chemical shrinkage strains for the composite part are calculated using micromechanical approaches [7] on the basis of the material data provided in [5]. The constitutive equations were implemented in developed user subroutine UMAT for Abaqus FEM software. Figure 1 shows the history of the degree of cure, the glass transition temperature, Young's modulus and volumetric strains for resin obtained by modelling. The polymerization material model was verified on the example of warping of plate. Difference between the curvature of sample obtained from the FE simulation and data provided in [8] is less than 3%. The developed model shows the good correlation with literature sources [6], [8] and can be reliably used for analysis of composite polymerization.

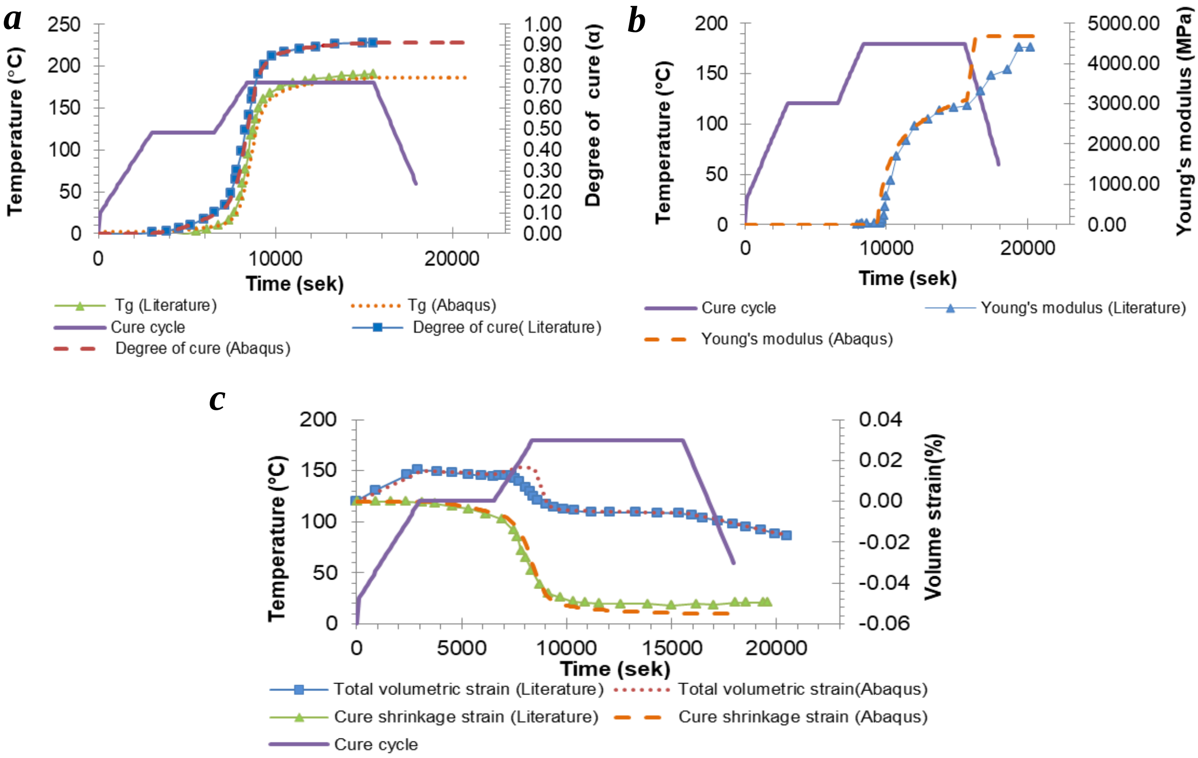


Figure 1. Developemebt of properties of resin **a** the degree of cure and glass transition temperature **b** Young's modulus **c** volumetric strains.

3. Residual stresses

In the present study, the effect of specimen sizes on the residual stresses inherited during manufacturing of thermoset composites with concentrator was analyzed. Firstly, the investigation of residual stresses in regular specimens during cure cycle depending on different ply and laminate thickness was performed. The «simulation» matrix for different specimen configurations is shown in Table 1. In the present work the mold from excluded from the analysis as it is insignificant for a such sample. Specimen considered free to move during all calculation stages. The coupled temperature-analysis was used for simulation in Abaqus FEM. The model is built up using 8-node thermally coupled bricks, trilinear displacement and temperature elements (C3D8T in Abaqus notation). The FE model is shown on Figure 2.

Table 1. Simulation program.

t (mm)	**Sublaminate-level scaling**	**Ply-level scaling**
1	l=63.5 mm w= 15.875 mm $[45^0/90^0/-45^0/0^0]_S$	l=63.5 mm w= 15.875mm $[45^0/90^0/-45^0/0^0]_S$
4	l=63.5 mm w= 15.875 mm $[45^0/90^0/-45^0/0^0]_S$	l=63.5mm w=15.875mm $[45^0{}_4/90^0{}_4/-45^0{}_4/0^0{}_4]_S$
	l=254 mm w= 63.5 mm $[45^0/90^0/-45^0/0^0]_S$	l=254 mm w=63.5 mm $[45^0{}_4/90^0{}_4/-45^0{}_4/0^0{}_4]_S$

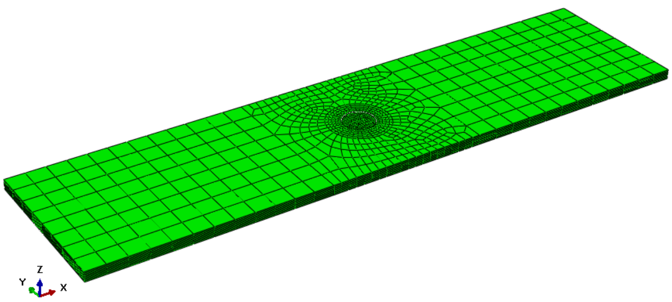


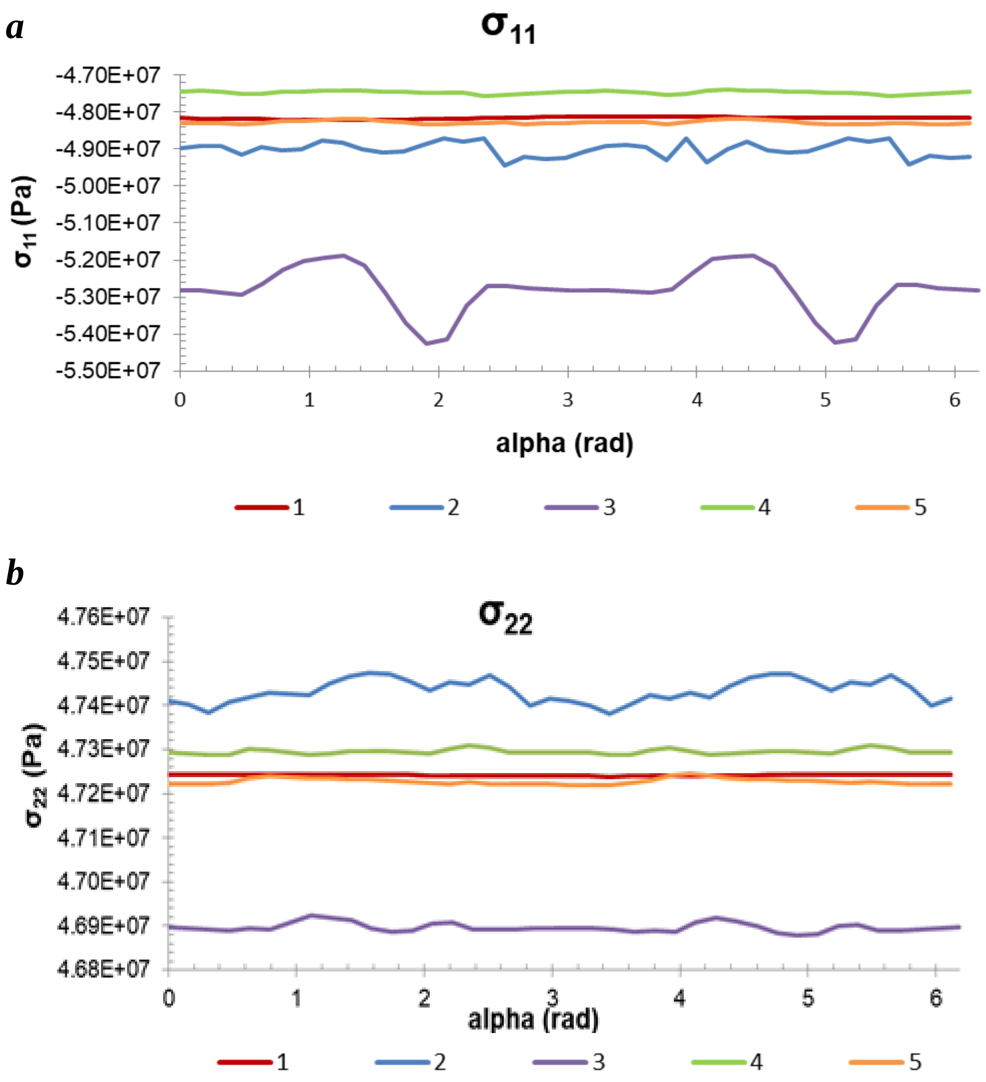
Figure 2. FE model for sample 1 mm thick with hole d=3.175 mm and layup $[45^0/90^0/-45^0/0^0]_S$.

The extensive simulation program (Table 1.) has confirmed that residual stresses depend on ply and sample thickness. Table 2 shows a summary and the comparison of the effect of different extrinsic parameters on σ_{11}, σ_{22}, σ_{33} and interlaminar stresses for samples before cut-out.

Table 2. The effect of different extrinsic parameters on stresses before cut out.

Parameter	**Impact**
Part thickness	Slight dependence
Part length and width	No significant dependence
Lay up	Slight dependence

The σ_{11} decreases approximately 2%, σ_{22} stays identical and interlaminar stress dramatically increases with an increase of sample thickness. The change in layup, in particular an increase in the thickness of the layer, causes an increase in σ_{11} by 7% and σ_{22} by less than 1%. With regard to changes in length and width of samples, it demonstrates only small effect on the change in σ_{11} and σ_{22} stresses (less than 1%) in contrast to effect on interlaminar stress (increases by 75%). The Figure 3 represents distribution of stress through the sample thickness obtained before drilling the hole cutout for regular specimen.



1- Sample 1mm thick with hole d=3.175 mm and orientation $[45/90/-45/0]_S$

2- Sample 4 mm thick with hole d=3.175 mm and orientation $[45/90/-45/0]_{8S}$

3- Sample 4 mm thick with hole d=3.175 mm and orientation $[45_4/90_4/-45_4/0_4]_S$

4- Sample 4 mm thick with hole d=12.7 mm and orientation $[45/90/-45/0]_{8S}$

5- Sample 4 mm thick with hole d=12.7 mm and orientation $[45_4/90_4/-45_4/0_4]_S$

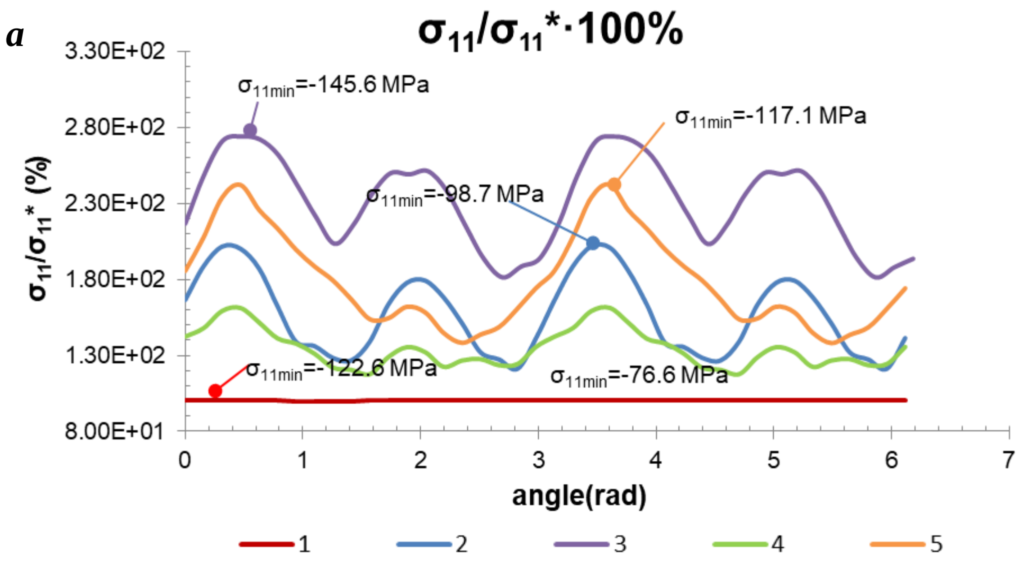
Figure 3. σ_{11}, σ_{22} and interlaminar stress (Pa) distribution through the sample thickness obtained for regular specimen.

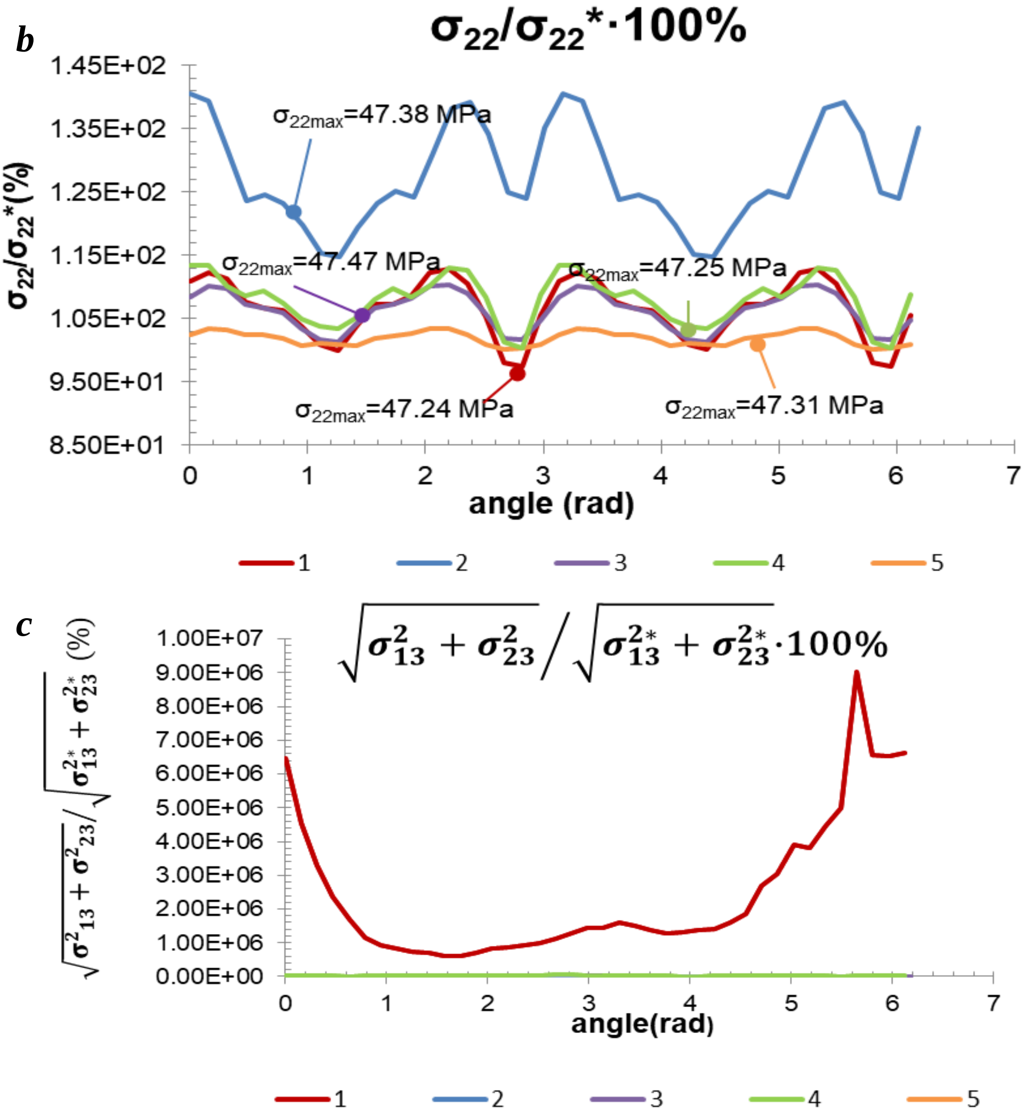
The investigation of the «hole-size effect» on the value of residual stress in composites with concentrator was provided. The most important variables have been identified as notch size, and ply and laminate thickness. These have been scaled in two ways: independently and simultaneously. The «simulation» matrix is shown in Table 2. The drilling process was realized by special modeling technique which removes material after cure cycle simulation using additional step of analysis.

Table 3. Simulation configurations for samples with concentrator.

t (mm)	Sublaminate-level scaling Hole diameter (mm)		Ply-level scaling Hole diameter (mm)	
	3.175	12.7	3.175	12.7
1	l=63.5mm w=15.875mm $[45^0/90^0/-45^0/0^0]_S$		l=63.5mm w=15.875mm $[45^0/90^0/-45^0/0^0]_S$	
4	l=63.5mm w=15.875mm $[45^0/90^0/-45^0/0^0]_S$	l=254mm w=63.5mm $[45^0/90^0/-45^0/0^0]_S$	l=63.5mm w=15.875mm $[45^0{}_4/90^0{}_4/-45^0{}_4/0^0{}_4]_S$	l=254mm w=63.5mm $[45^0{}_4/90^0{}_4/-45^0{}_4/0^0{}_4]_S$

Figure 4 shows the ratio of maximum of absolute values of stress components (σ_{11}, σ_{22} and interlaminar shear stress) through the sample thickness obtained after the hole cutout to the maximum one obtained for regular specimen (σ_{11}*, σ_{22}* and interlaminar shear stress*). The analysis of effects of 1D (only thickness scaling), 2D (width, length of sample and hole diameter scaling) and 3D (width, length, and thickness of sample and hole diameter scaling) scaling of notched composites has shown that with an increase of diameter or thickness the values of residual stresses decrease approximately by 20%. The highest effect takes place for σ_{11} and interlaminar shear stress. On the other hand, with increasing quantities of each layer (ply thickness), residual stresses increase. The $\sigma_{11}$and interlaminar thickness rised by nearly 25% (except sample with thickness 1 mm) and σ_{22} by 15%.





1- Sample 1mm thick with hole d=3.175 mm and orientation $[45/90/-45/0]_S$

2- Sample 4 mm thick with hole d=3.175 mm and orientation $[45/90/-45/0]_{8S}$

3- Sample 4 mm thick with hole d=3.175 mm and orientation $[45_4/90_4/-45_4/0_4]_S$

4- Sample 4 mm thick with hole d=12.7 mm and orientation $[45/90/-45/0]_{8S}$

5- Sample 4 mm thick with hole d=12.7 mm and orientation $[45_4/90_4/-45_4/0_4]_S$

Figure 4.

a- the ratio of minimum σ_{11} stress (Pa) through the sample thickness obtained after the hole cutout to the minimum one obtained before for regular specimen (σ_{11}*).

b- the ratio of maximum σ22 stress (Pa) through the sample thickness obtained after the hole cutout to the maximum one obtained before for regular specimen (σ22*).

c- the ratio of maximum interlaminar stress (Pa) through the sample thickness obtained after the hole cutout to the maximum one obtained before for regular specimen.

The stress σ_{11} distribution for sample 4 mm thick with hole d=3.175 mm and layup $[45_4/90_4/-45_4/0_4]_S$ before and after cut out presented on Figure 5. After cut out we have redistribution of stresses which has the form of relaxation.

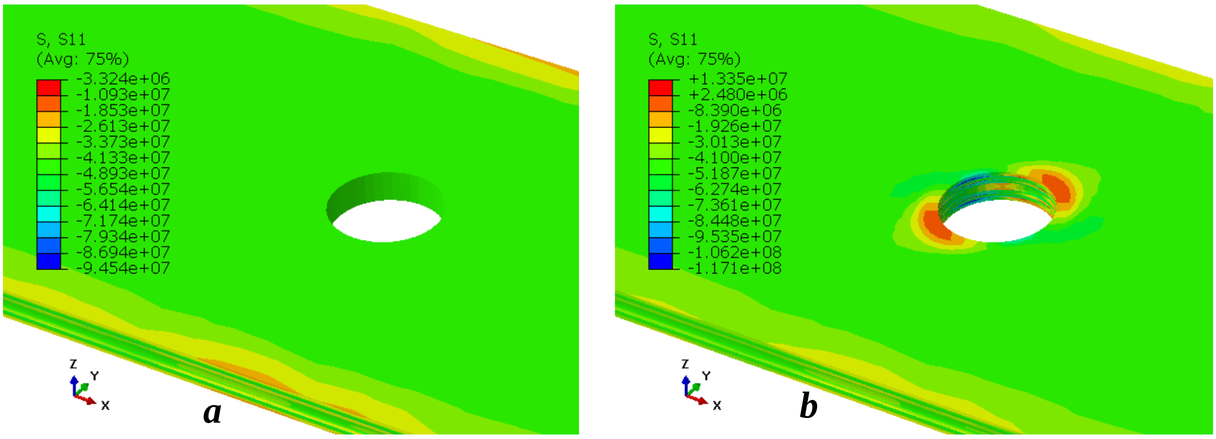


Figure 5. σ_{11} (Pa) for sample 4 mm thick with hole d=12.7 mm and layup $[45_4/90_4/-45_4/0_4]_S$ ***a***-before cut out (the material in hole is deliberately not shown) ***b***- after cut out.

4. Conclusions

An extensive investigation by means of FE into effects of scaling of regular specimens and notched composites has confirmed that residual stresses depend on part thickness, lay up and hole size. According to data provided in product data sheet for HexPly 8552 [5], the tensile strength of neat resin 8552 is 121 MPa and 90^0 tensile strength for prepreg IM7/8552 -is 64 MPa. The obtained stress for samples after polimerisation without concentrator are 77 MPa to 146 MPa and for samples with concentrator even higher. This fact indicates a presence of defects in composite. Work [9] showed that the thermoset matrices that are mostly brittle in comparison with thermoplast [10] have transverse cracks during curing. Thus, the values for stresses are essential and cannot be ignored in consequent structural analysis. It is worth noting that the data provided for particular composite material by manufacture contains data for UD composite where stacking of prepreg layers has one direction which in fact are not entirely valid for composites with complex laying since they do not take into account the effects described before.

In [3] it was experimentally shown that notched composites with the hole diameter, thickness, lay up scaling demonstrate the following failure mechanisms: brittle, pull out and delamination. The reason for such a different failure mechanism is not clear and there is a guess that this effect can be explained by residual stresses.

The developed model (of polymerization) can be used for prediction of failure in composite without the need for a large number of tests.

References

[1] Fedulov, B. N., Safonov, A. A., Sergeichev, I. V., Ushakov, A. E., Klenin, Y. G., & Makarenko, I. V. (2016). Strength analysis and process simulation of subway contact rail support bracket of composite materials. *Applied Composite Materials*, *23*(5), 999-1013.

[2] Ushakov, A. E., Safonov, A. A., Sergeichev, I. V., Fedulov, B. N., Kornienko, E. I., Timofeev, M. A., ... & Rozin, N. V. (2015). Design and optimization of a vacuum infusion technological

process for hopper car fabrication using polymeric composite materials. *Journal of Machinery Manufacture and Reliability*, *44*(3), 276-282.

[3] An experimental investigation into the tensile strength scaling of notched composites. / Green, BG; Wisnom, MR; Hallett, SR. In: Composites Part A: Applied Science and Manufacturing, Vol. 38 (3), 03.2007, p. 867 - 878.

[4] Harris CE, Morris DH. Role of delamination and damage development on the strength of the thick notched laminates. In:Johnson, WS editor. Delamination and debonding of materials, ASTM STP 876, Philadelphia, 1985.

[5] Hexply 8552, Epoxy Matrix Product Datasheet. Pdf downloaded from: http://www.hexcel.com/user_area/content_media/raw/HexPly_8552_eu_DataSheet.pdf. (Last viewed:12/04/18).

[6] Baran, Ismet & Çınar, Kenan & Ersoy, Nuri & Akkerman, Remko & Hattel, J.H.. (2016). A Review on the Mechanical Modeling of Composite Manufacturing Processes. Archives of Computational Methods in Engineering. 24. 10.1007/s11831-016-9167-2.

[7] Fedulov, B. N., Safonov, A. A., Kantor, M. M., & Lomov, S. V. (2017). Modelling of thermoplastic polymer failure in fiber reinforced composites. Composite Structures, 163, 293-301.

[8] Wijskamp, S., Akkerman, R., & Lamers, E. A. D. (2003). Residual stresses in non-symmetrical carbon-epoxy laminates. In M. J. Martin, & H. T. Hahn (Eds.), Proceedings of the 14th International conference on Composite Materials, ICCM14 (pp. -). San Diego, USA.

[9] Filiou C, Galiotis C. In situ monitoring of the fibre strain distribution in carbon-fibre thermoplastic composites. 1. Application of a tensile stress field. Compos Sci Technol 1999;59(14): 2149–61.

[10] Parlevliet, Patricia & Bersee, Harald & Beukers, Adriaan. (2007). Residual stresses in thermoplastic composites – a study of the literature. Part III: Effects of thermal residual stresses. Composites Part A: Applied Science and Manufacturing. 38. 1581-1596. 10.1016/j.compositesa.2006.12.005.