THE INFLUENCE OF AUTOCLAVING PROCESS PARAMETERS ON LOAD CARRYING-CAPACITY OF THIN-WALLED CHANNEL SECTION COLUMNS

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Abstract

The papers deals with postbuckling behaviour and load carrying capacity of thin-walled composite channel sections subjected to uniform compression. The authors decided to perform analysis the influence of the parameters of manufacturing process of composites on its strength properties and the load carrying capacity of thin-walled structure made of this composite. The microstructure characteristics of composites are presented and discussed. Postbuckling behaviour and load carrying capacity of thin-walled channel section columns subjected to compression have been determined using finite element method. The ANSYS software has been employed.

1. Introduction

Laminates are present in everyday life, this type of materials used in both simple everyday household structures (housings of cellular phones) as well as in the advanced structures (airplanes, yachts, cars). The manufacturing costs compared to steel elements are still higher, however, laminates have a very good strength to density ratio, which, combined with the requirements for energy minimization are gaining popularity. Currently one of the most advanced methods of producing composite laminates allows achieving the highest quality and repeatability of the structures is an autoclaving method. The main disadvantages of the autoclaving method may be a relatively high cost and the limited capacity [1, 2].

Currently, work is underway on reducing manufacturing costs while maintaining high quality products. Main directions of research on lowering manufacturing costs are focused on the optimization of the process parameters, automation of lamination and the use of resins with short curing time. Modification of the process parameters such as temperature, pressure and cure time has a significant influence on the physical-chemical properties, the risk of porosity, distribution and volume content of reinforcing fibres in the laminate and consequently may substantially affect the mechanical properties [3, 4, 5, 6, 7].

In the world literature a lot of work on composite materials can find, however, relatively little are papers dealing with the stability and carrying capacity of thin-walled composite structures with flat walls [8, 9]. Therefore, the authors of this study decided to prepare numerical models allowing calculating buckling load, to analyse postbuckling behaviour and to estimate the load-carrying capacity of thin-walled composite structures. The channel section beams made of GFRP laminate and subjected to pure bending have been examined. It was assumed that the examined beams have walls consist of the eight layers with two different ply arrangements denoted as B1 $[0/90/0/90]_s$ and B2 $[45/-45/45/-45]_s$.

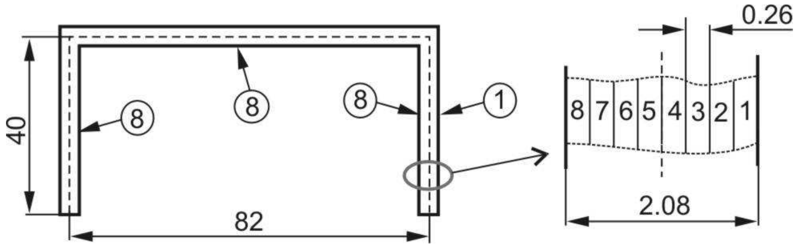

Figure 1. Dimension and ply enumeration of considered channel section beam.

The channel section columns (see Figure 1) with length 250 mm and following cross-section dimension: width of the flange 40 mm, width of the web 82 mm and a wall thickness 2.08 mm have been taken into consideration. The impact of manufacturing parameters on the stability, postbuckling behaviour and carrying-capacity load have been analysed.

2. Material models

In order to create a numerical model of considered thin-walled structures the appropriate material model should be adopted with the proper material properties. For laminates of glass fibres the sufficient is a linear, elastic material model. Necessary data for numerical material model was determined based on the stress tests carried out. The specimens for tensile, compression and shear test have been prepared according to EN ISO 14.129[1] standard. They have been prepared using autoclaving technique with three different values of the basic manufacturing parameters (i.e. time and temperature). The first group of setting denoted as OPTI was exactly the same as the recommendation of the producer of prepreg. The next two extreme settings was taken and denote as follow: SLOW - low temperature and long time of autoclaving process; QUICK - high temperature and short process time. The exact process parameters are presented in Table 1.

Process ID	Curing temp. [°C]	Heating/cooling rate [°C/min]	Curing time [min]	Pressure [MPa]	Vacuum [MPa]
QUICK	120	2	25	0.4	0.085
OPTI	100	1	60	0.4	0.085
SLOW	70	1	960	0.4	0.085

Table 1. Assumed autoclaving parameters for composite laminates structures manufactured.

Process ID	E_{12} [GPa]	E_{21} [GPa]	G_{12} [GPa]	ν_{12} [-]	T_1 [MPa]	T_2 [MPa]	S_{12} [MPa]	C_1 [MPa]	C_2 [MPa]
SLOW	36.7	9.0	2.7	0.32	845	54	103	547	70
OPTI	37.4	8.0	2.0	0.33	792	39	108	679	71
QUICK	35.4	8.2	2.1	0.31	825	40	111	501	67

Table 2. Material properties for composite laminates obtained with different parameters of autoclaving process.

For such prepared samples the tensile, compression and shear the tests was carried out. The following material properties have been determined: the Young's modules in two orthogonal directions E_1 and E_2, a Poisson's ratio ν_{12}, Kirchhoff's module G_{12}, ultimate strength in tensile

(T_1 in fibres direction and T_2 in transverse direction) and in compression (C_1 and C_2) as well as maximum shear stress S_{12}. The obtained value for each assumed process is presented in Table 2.

Comparing obtained in the experimental investigation results one can see that the adopted manufacturing parameters have a significant influence on the ultimate compressive stress in fibre direction (c.a. 30%), ultimate tensile stress in transverse to fibre direction (c.a. 28%) and Kirchhoff modulus (c.a. 26%).

3. Microstructure analysis

For the laminates manufactured using three different sets of process' parameters the specimens to microstructural test have been also prepared. After manufacturing process the macroscopic visual inspection, ultrasonic non-destructive testing (phased array method) and microstructural observations in chosen cross-sections were made.

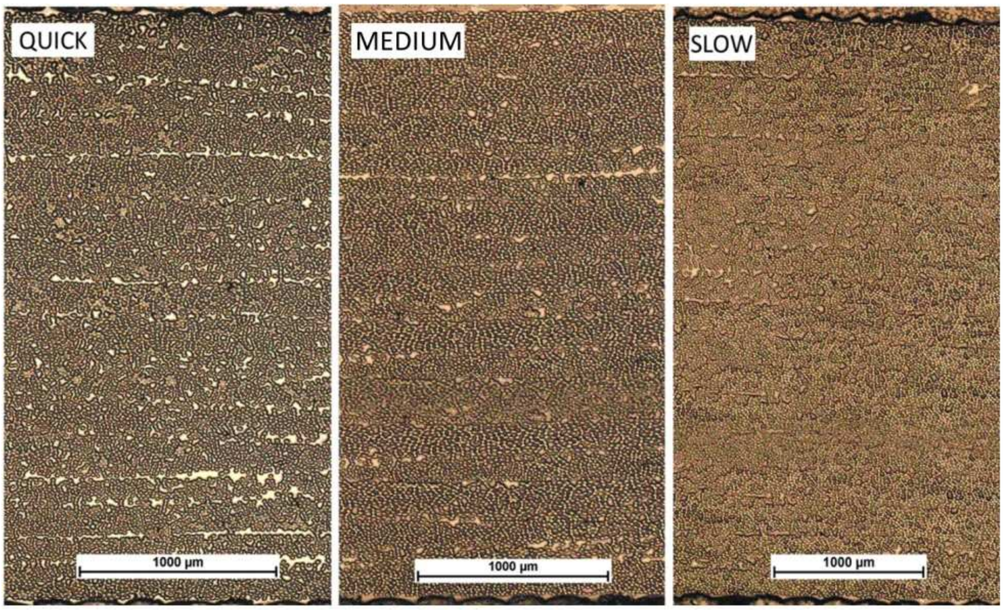

Figure 2. The microstructures of composite laminates for various production parameters.

Visual observations did not reveal any visible defects on a macroscopic scale. Similarly, the carried out NDT inspection confirmed the absence of defects in the form of inclusions foreign material. On the basis of the ultrasound images, it was found that the quality of the laminates should be assessed as very good: there was no delamination, the thickness is uniform, and there was no occurrence of porosity.

Microscopic observations show that the composite laminate structure is made uniform. There was no discontinuity in the form of voids or delamination. The microstructure of composite laminates produced with various production parameters are presented in Figure 2.

In all analysed cases, the distribution of the reinforcing fibres is correct, however, together with increases the temperature and the dynamic of process the areas with more resin were observed. The areas rich in resin are located in the zones between the individual layers of the laminate. Microscopic observations showed that the laminate obtained in process denoted as SLOW characterized by a high density of reinforcing fibres.

A lower heating rate combined with a low curing temperature results in that the dynamic of rheological processes is relatively low. Although it reaches a minimum viscosity is usually higher than in the processes with a higher temperature gradient the length of the minimum plateau of viscosity (viscosity minimal platform) increases, which is advantageous because of the reduced risk of thermally induced residual stresses and provides good conditions for the flow of a preferred resin. However, there is a risk of an excessive discharge of resin into the drain fabric, which may result in surface contact of the individual fibres and consequently the stress distribution and abnormal decrease in load carrying capacity. In addition, the process with too low temperature can lead to too low degree of polymerization (degree of cure DOC) and changes in mechanical properties [6]. More detailed observations reveal the correct nature of the border between the fibres and the matrix - the fibres have a regular shape and their diameters are similar.

4. Numerical analysis of nonlinear stability

The nonlinear stability problem has been solved using finite element method – ANSYS software. The structure of the beam was discretised by four node multi-layered shell elements with six degree of freedom at each node. The geometrical and discretised models of analysed beam with assumed boundary conditions are presented on Figure 3. It was assumed that beam is subjected to pure bending in the plane with the minimum second moment of area. The loaded edges of the beam are simply supported and become straight after load. Load in the form of the bending moment introduced as the pressure distribution (Figure 4) acting on the leading edges of the beam with the distribution corresponding to the stress distribution as same as in case of pure bending in the prebuckling elastic range.

a)

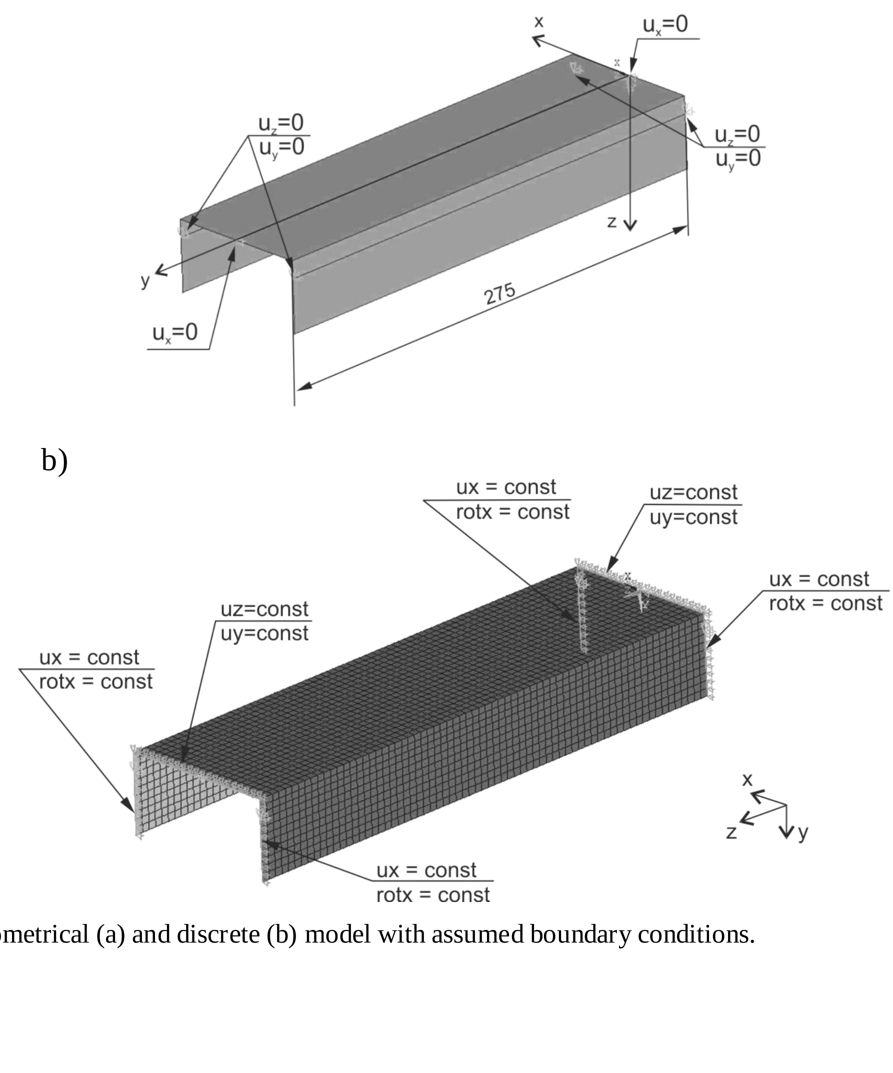

Figure 3. Geometrical (a) and discrete (b) model with assumed boundary conditions.

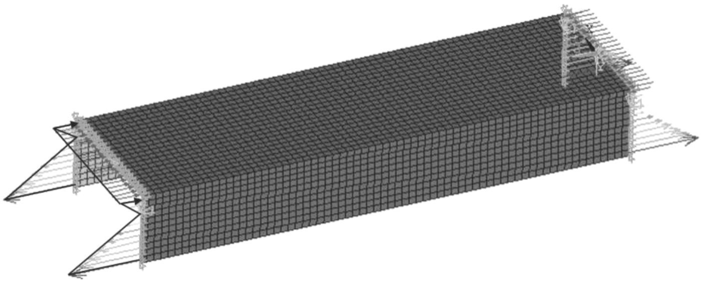

Figure 4. Discretised channel section beam with model of load.

Prepared finite element model have been used to calculate buckling bifurcation load M_{cr} (critical moment), postbuckling behaviour and failure load M_{ult}. The postbuckling behaviour is presented in form of graphs (Figure 5) presenting relation between loading moment and a deflection w^* of the web of the beam. The deflection w^* is calculated as a normal displacement of point lying in the middle of the length and in the middle of the width of the web minus vertical displacement of the web-flange edge in the half of length of the beam.
In Table 3 the buckling moment with number of half-waves corresponding to buckling mode for both ply arrangement and all process of manufacturing are presented.

Process ID:	SLOW	OPTI	QUICK
Ply Arrangement	**Buckling load M_{cr} [Nm] / number of half waves m [-]**		
B1 $[0/90/0/90]_s$	285 / 4	270 / 4	262 / 4
B2 $[45/-45/45/-45]_s$	350 / 4	329 / 4	321 / 4

Table 3. Buckling load with number of half-waves of buckling mode for analysed beams.

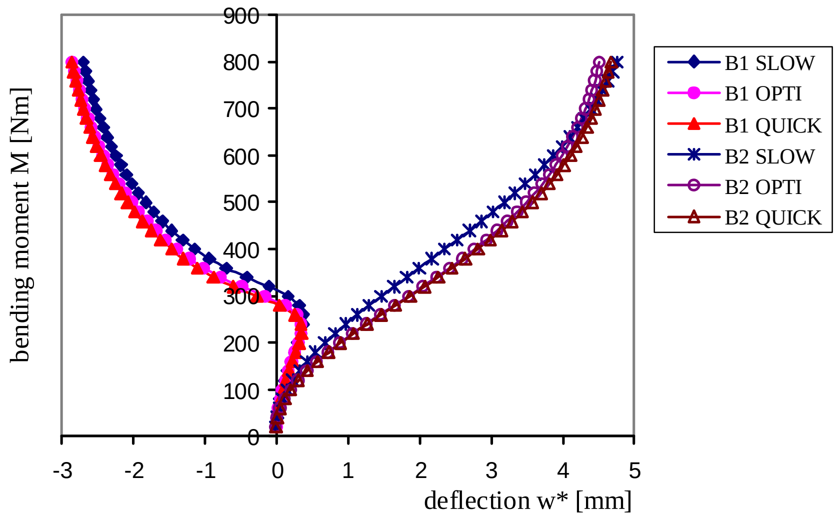

Figure 5. Equilibrium paths for beams with different lay-up and sets of parameters of autoclaving process.

Analysing the results presented in Figure 4 it can be said that the equilibrium paths for autoclaving parameters cases OPTI and QUICK are similar for given layer arrangements. The beam produced with parameters denoted as SLOW in postbuckling range are stiffer than beams with other parameters sets – the deflection of the web for given load are smaller than for cases OPTI and QUICK. It should be added that the stiffness of the beams with layer arrangements B1 are higher than in case B2.

The ultimate load M_{ult} leading to the beam failure for all analysed cases have been determined using Tsai-Wu failure criterion with two following assumption: the beam failure if the criterion is not fulfilled in the one layer (lower estimate), the beam failure if the criterion is not fulfilled in the all layers (upper estimate). The obtained estimations of failure loads for all analysed cases are presented in Table 4.

Process ID:	**SLOW**	**OPTI**	**QUICK**
	Failure load M_{ult} [Nm]		
Ply Arrangement	**lower estimate (layer No) / upper estimate**		
B1 $[0/90/0/90]_s$	269 (2) / 499	217 (2) / 477	208 (7) / 436
B2 $[45/-45/45/-45]_s$	299 (1) / 305	260 (1) / 264	269 (1) / 276

Table 4. Estimated failure loads according to Tsai-Wu criterion for all considered beams.

Additional for lower estimate failure moment the layer number (numeration according to Figure 1) in which the criterion is fulfilled are presented in brackets. It should be noted that the lower estimate of the failure loads for all cases under analysis are less than buckling load. It could mean that the beams failure before beams loses their stability. After the stress state analysis in the areas where the Tsai-Wu criterion was not fulfilled it was found that the stress in the fibres is much less than fibre ultimate stress - failure stresses have been exceeded in the matrices. It was decided to appoint load leading to fibre destruction even in a single layer. Obtained results, which now are higher than buckling load, are summarized in Table 5.

Process ID:	**SLOW**	**OPTI**	**QUICK**
Ply Arrangement	**Failure load M_{ult} [Nm] (layer No)**		
B1 $[0/90/0/90]_s$	660 (8)	709 (8)	598 (8)
B2 $[45/-45/45/-45]_s$	709 (2)	774 (2)	638 (2)

Table 5. Estimated failure loads according to assumption that stress in fibre direction are equal to ultimate stress obtained during tensile or compression tests.

Comparing results for all analysed cases it can be said that the lowest buckling load and lowest failure moment leading to the fibres failure (Table 5) have been obtained for beams with manufacturing parameters denoted as QUICK. The higher buckling load was obtained for sets SLOW of autoclaving parameters but the higher load leading to the fibres damage was obtain for manufacturing case OPTI. The results of failure load obtained according to Tsai-Wu criterion depends on layer arrangements. For layup case B1 the higher ultimate moment was obtain for manufacturing case SLOW and the lowest for QUICK, but for layer arrangement B2 the lowest failure load have been obtained for manufacturing parameters sets OPTI.

Summing above the highest buckling load, stiffness in postbuckling range and ultimate load according to Tsai-Wu criterion (matrices failure) have been obtained for beams manufactured with autoclaving parameters SLOW. It should be noted that beams manufactured in the autoclaving process with parameters OPTI have the highest ultimate bending moment leading to fibre failure.

5. Conclusion

The presented results of analysis allow to conclude that not only arrangement of layers in the laminate but also the manufacturing process have influence on the properties of the structure. The paper shows the relation between parameters of manufacturing process of laminates and

the following parameter of thin walled structures: buckling load, postbuckling stiffness and the load carrying capacity. Mentioned above relations have been confirmed by macro and microscopic observation of the laminate structures obtained with different autoclaving parameters.
The acceleration of the process causes: the formation of areas with a higher resin content, significant decrease of the compressive strength in the fibres direction and transverse to fibres directions, thereby lowering the buckling load, postbuckling stiffness and carrying- capacity load (matrix destructions).
For laminates marked as SLOW the microscopic studies indicate the increase the volume fibre fraction or even contact of the fibres, what could lead to decrease of failure load. Above observations have been confirmed in numerical calculation of thin-walled beams which shows the reduction in carrying-capacity load - the highest load capacity determined on the basis of the destruction of the fibres were obtained for beams with laminates marked as OPTI. To summarize it can be said that the conducted observations of macro and microstructure, the studies of material properties and the numerical analysis of nonlinear stability proved the legitimacy of use of autoclaving parameters denoted as OPTI, which compared with a SLOW characterized with less energy consumptions (lower cost) during production.

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