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*Abaqus, composite structures, numerical analysis, critical forces, buckling*

*Patryk RÓŻYŁO*[*]*, Katarzyna WRZESIŃSKA*[**]

# NUMERICAL ANALYSIS OF BUCKLING AND CRITICAL FORCES IN A CLOSED SECTION COMPOSITE PROFILE

**Abstract**

*This paper reports the results of a numerical analysis of buckling in a carbon-fibre reinforced plastic (CFRP). The analysis involved determination of the first buckling mode and critical forces for the tested composite. The composite was tested for six different ply orientations. The analysis was performed on a closed section composite column. The objective of the analysis was to determine critical forces affecting the composite profiles with the applied ply orientations and, thus, to determine the laminate ply orientations which can carry the heaviest loads. The numerical modelling and all computations were performed using the Abaqus 6.14 software. In the analysis, we took account of boundary conditions and performed a discretization process in order to obtain correct results.*

## 1. INTRODUCTION

The problem of modern engineering materials is important for mechanics, strength testing and machine design. Carbon-epoxy structures having higher strength properties compared to traditional materials are more and more widely used in many branches of industry.

The current trend in engineering is to use materials which are thin-walled, lightweight and have high mechanical properties at the same time. In contrast to structures made of traditional materials, the strength of modern carbon-epoxy composite materials subjected to a long-term operation decreases to a much lower extent.

[*] Politechnika Lubelska, Nadbystrzycka 36, 20-618 Lublin, p.rozylo@pollub.pl
[**] Maria Curie-Skłodowska University, Akademicka 19, 20-033 Lublin

CFRP profiles are much lightweight than steel or aluminium and have much higher strength properties. As a result of many years of research into composite materials, it was possible to clearly define their material properties via the properties of matrix and reinforcement which make up composite laminates.

Epoxy resin profiles are widely used in the aircraft industry. Due to technological progress, it is now required to implement lightweight structures which have a higher strength than those used at the beginning of development and production of aircraft subassemblies.

The load-carrying capacity of composite structures described in this paper is determined by a phenomenon which is commonly referred to as "loss of stability".

There are numerous works devoted to the investigation of composite profiles with different sections depending on their application in industry. A vast majority of the works on the problem of composite structures examine profiles with different types of open cross sections and geometric shapes.

The authors of the works [3, 4, 10, 11] introduced the fundamentals of design in the Abaqus system**.** Dealing with typically static problems, they demonstrated how to use the programme properly in order to describe a computational process correctly.

The publications [1, 2, 5, 7–9] report the results of investigations into composite structures. Their authors investigated the problems directly connected with buckling of thin-walled composite profiles having both open and closed sections. In addition to this, they also analyzed post-buckling states. They determined critical loads that given profiles can carry at the moment of stability loss. The results reported in these publications enabled the author of this paper to conduct further numerical analyses.

There is a growing interest in the problem of thin-walled composite structures due to mechanical properties of these materials. The design of composite structures is time-consuming and requires vast knowledge about properties of these structures in order to define and solve investigated problems correctly.

Problems connected with instability of composite profiles are one of the trends in both research studies and industrial development. Numerical environments such as Abaqus enable us to solve problems for suitably defined material properties and boundary conditions in real processes, and, as a result, we can perform a pre-production analysis of thin-walled composite structures.

If a numerical problem of profile buckling is defined correctly, the behaviour of real thin-walled structures will be modelled correctly, too.

## 2. MATERIALS AND METHODS

The study involved designing a numerical model of a profile made of carbon-fibre reinforced plastic (CFRP). The numerical model was designed using the Abaqus software. The material was ascribed linear-elastic properties in two-dimensional state of stress and had six independent material properties.

The test specimen was modelled as an orthotropic laminate, so its mechanical properties were typical of this kind of composite material, i.e. Young's modulus in fibre direction was equal to $E_1$ = 130.71 GPa, while that perpendicular to fibres was $E_2$ = 6.36 GPa; Poisson's ratio was v = 0.32; Kirchhoff's modulus describing non-dilatational strain was the same for all three directions, i.e. $G_{12} = G_{13} = G_{23}$ = 4.18 GPa. Finally, the total height of the tested thin-walled composite column with a square closed section (40 x 40 mm) was exactly 300 mm.

The structure of the laminate was modelled by standard shell elements consisting of 6 plies. The thickness of a single ply was 0.131 mm, so the total thickness of the composite was 0.786 mm.

The paper investigates six different configurations of composite ply orientations. Every investigated configuration of ply orientation was strictly symmetric.

The below table lists all tested ply orientations of thin-walled composite columns.

**Tab. 1. Comparison of composite ply orientations [source: own study]**

| Ply orientation | |
|---|---|
| K1 | 0/45/90/90/45/0 |
| K2 | 0/90/45/45/90/0 |
| K3 | 45/0/90/90/0/45 |
| K4 | 45/90/0/0/90/45 |
| K5 | 90/0/45/45/0/90 |
| K6 | 90/45/0/0/45/90 |

Ply orientation has a significant effect on strength properties of every structure. Structures with suitably selected ply orientations can carry much heavier loads than structures with random ply orientations. The essence of thin-walled composite structure design is to make them capable of operation under heavy load.

The solved problem was a typically static problem which did not took account of the object's weight or time of analysis. This work strictly refers to generally considered issues related to the strength test of thin-walled structures. Described issue is a typical problem to be solved in the analysis of stability.

A figure given below shows the Abaqus-generated numerical model of the tested composite and a ply orientation denoted as K4.

a) b)

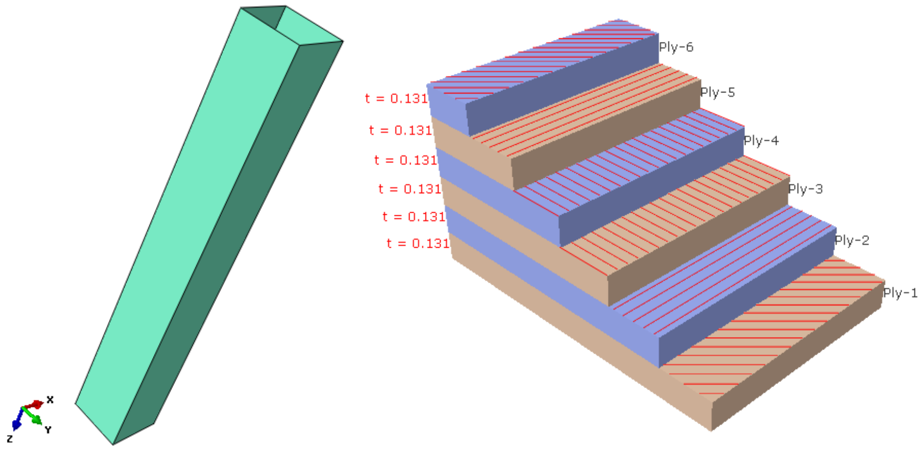


**Fig. 1. Test specimen: a) numerical model, b) ply orientation K4 [source: own study]**

The numerical model was analyzed only with respect to the state of instability. The objective of the analysis was to determine only the first mode of buckling and critical force for thin-walled profiles with all tested ply orientations.

The numerical model was defined by boundary conditions which enabled obtaining a correct mode of stability loss. The upper and lower edges of the profile were described by the relationships which made it possible to continue the analysis. The lower edges of the profile were fully blocked and prevented from displacement, hence U1 = U2 = U3 = 0. The translational degrees of freedom in the profile's upper edges were blocked only in the direction of axes X and Y, hence U1 = U2 = 0; however, the thin-walled structure could move towards axis Z.

The unit force applied to the profile's edges acted on each of the four edges in a uniform manner, thereby simulating compression of a thin-walled composite structure. The unit force describing the upper edges of the structure was the ratio of the unit load to the sum of lengths of all four upper edges of the profile – hence, the load was equal to 1 (as a unit force) / 160 (i.e. the sum of edge lengths).

Buckling is generated by the compressive unit force acting on the thin-walled profile. The instability of the numerical model led to generating a specific number and shape of corrugations (half waves) within the entire composite structure.

The boundary conditions describing the numerical model and the direction of load from the unit force are shown in a figure given below.

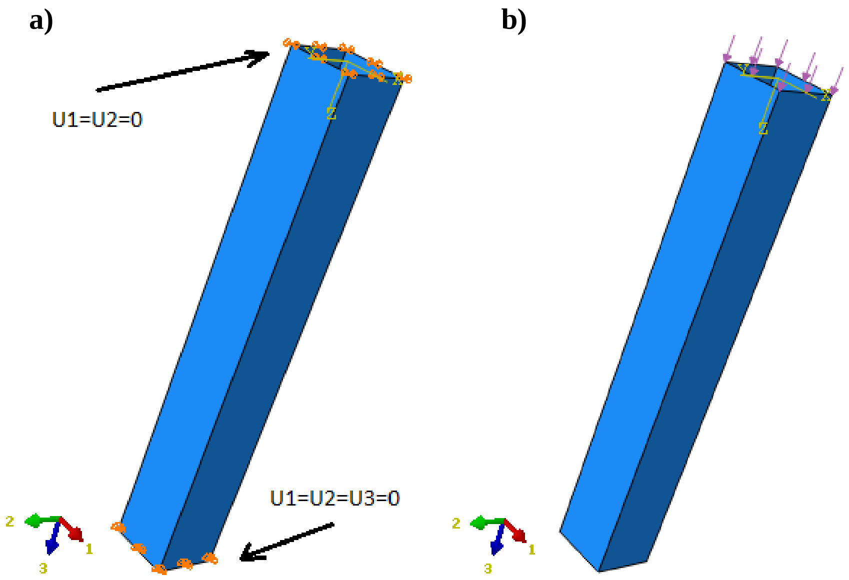


**Fig. 2. Boundary conditions of the numerical model [source: own study]**

The discretization of the numerical model was performed based on correctly defined mesh of finite elements. The shape of a thin-walled profile was a basic geometric solid, that is – a square stretched to an adequate length to create a composite column. The mesh was made of S4R elements, i.e. four-node, doubly curved elements with reduced integration.

The model consisted of 5200 finite elements and 5252 nodes. The mesh of the numerical model is shown below.

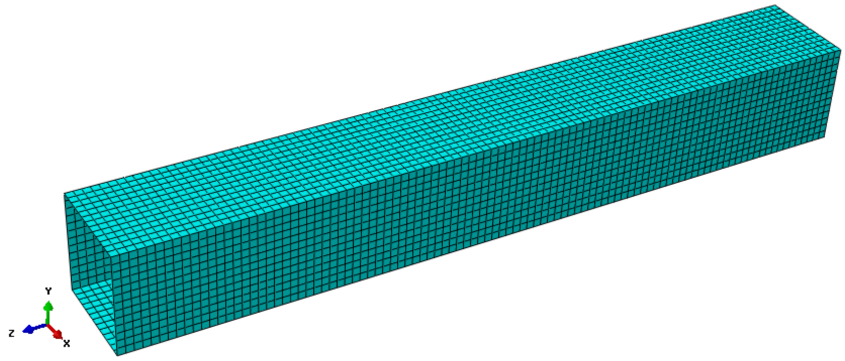

**Fig. 3. FEM mesh of the numerical model [source: own study]**

## 3. RESULTS

The numerical analysis involved determination of the first mode of buckling in composite columns for every tested ply orientation. In addition to this, critical forces were calculated for every ply orientation based on the pre-defined unit force.

The figures given below illustrate the first buckling mode for each of the analyzed ply orientation and the magnitudes of the critical force which causes buckling of the profile.

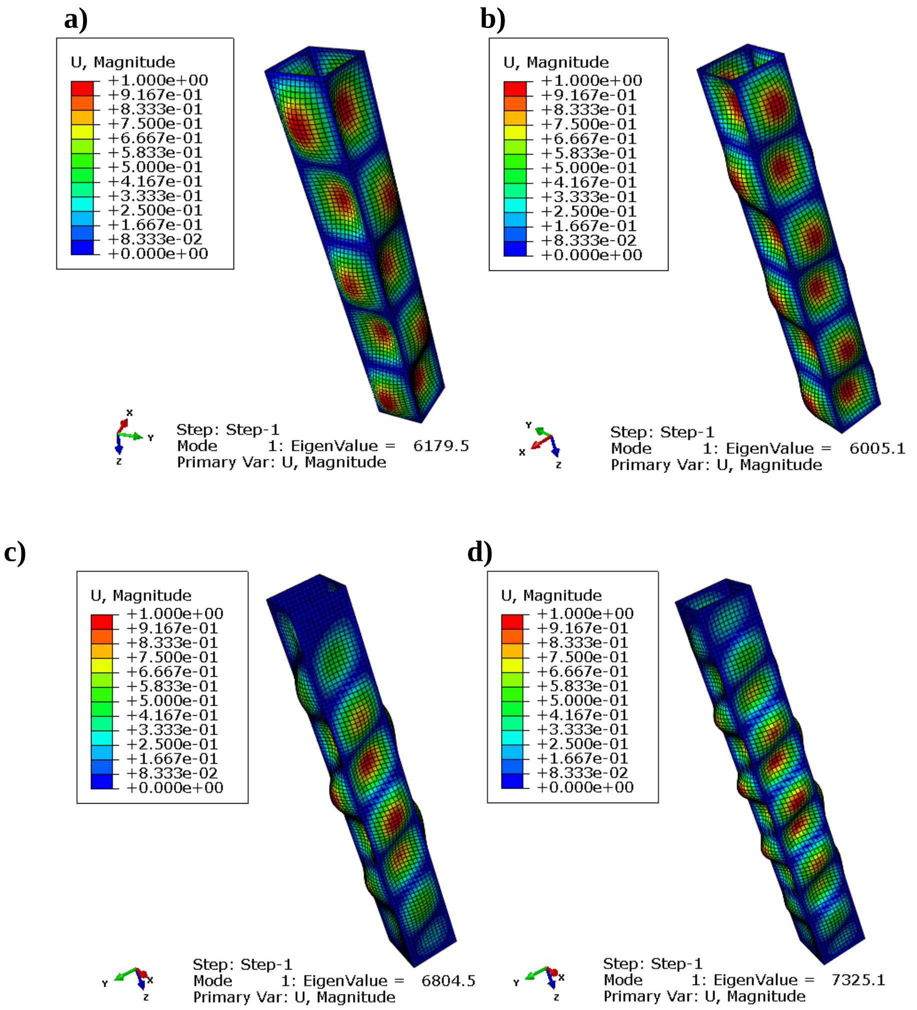


**Fig. 4. Modes of instability and critical forces (eigen value) for the following ply orientations: a) K1-0/45/90/90/45/0, b) K2-0/90/45/45/90/0, c) K3-45/0/90/90/45/0, d) K4-45/90/0/0/90/45 [source: own study]**

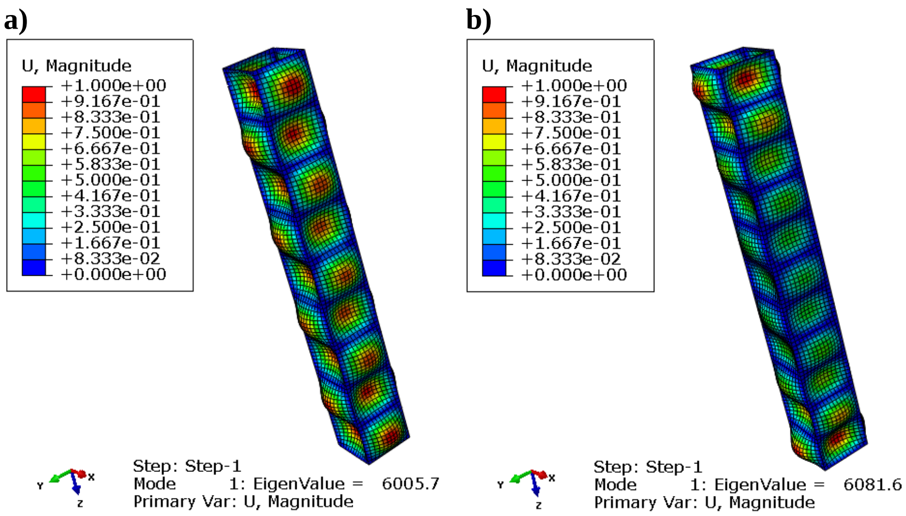


**Fig. 5. Modes of instability and critical forces (eigen value) for the following ply orientations: a) K5-90/0/45/45/0/90, b) K6-90/45/0/0/45/90 [source: own study]**

Based on the results of instability and critical forces (eigen values), it is possible to establish a hierarchy of thin-walled profiles in terms of their rigidity, from higher rigidity profiles to profiles having lower rigidity. The profiles with the ply orientations 0/90/45/45/90/0 (K2) and 90/0/45/45/0/90 (K5) had almost the same critical force. In the first case, this force is equal to 6005.1 N, while in the other – it is 6005.7 N, which proves that they were put under a very similar load.

The differences in operation of the analyzed profiles mainly consisted in a different number of generated half-waves. Other profiles reveal a significant discrepancy both in terms of critical forces and the number of half-waves produced in the compression process. Profiles described by the ply orientations 45/0/90/90/0/45 (K3) and 45/90/0/0/90/45 (K4) were characterized by the highest rigidity, as both of them could carry the highest loads. A thin-walled column with the ply orientation 45/90/0/0/90/45 (K4) was characterized by a critical force of 7325.1 N; this load was by 22% higher than that of the profile described as K2.

Profiles with lower critical forces such as K1, K2, K5, K6 are more energy-consuming than others. The higher rigidity and energy absorption of thin-walled composite structures results from their adequate laminate ply orientation. The analysis enabled thorough investigation of the behaviour of closed section composite profiles.

## 4. CONCLUSIONS

Numerical modelling is an ideal tool for simulating real processes and – provided a problem is defined correctly - can generate desired results.

The analysis of six different laminate ply orientations in a column made of carbon-fibre reinforces plastic (CFRP), give only initial information about the character of post-critical deformations. In addition, the next step in this study should be a non-linear analysis using FEM method. The results of numerical analysis should be confronted with the results obtained on the way of experimental analysis, in order to verify the results obtained by finite element method. The next steps of the research will be associated with the carrying out of experimental analysis.

In the aircraft and automotive industries, it is important to use light yet rigid and high-strength subassemblies which should often be capable of absorbing generated energy.

Laminate ply orientation has a vital effect on a composite structure, as a suitable ply orientation can ensure that the structure's load-carrying capacity will be by up to several dozen percent higher than it is the case with other basic ply orientations.

The results of investigation into the problem of instability and critical forces led to formulation of the following conclusions:

- thin-walled composite profiles with square closed section undergo buckling under specific critical forces,
- laminate ply orientation has an effect on loads that can be carried in a state of instability,
- depending on a laminate ply orientation, the composite operates under applied load at a different number of half-waves,
- the number of half-waves in a given ply orientation of a thin-walled composite structure only describes the behaviour of the composite material but has no effect on the determined critical force,
- depending on manufacturing and technological demand, it is possible to produce thin-walled composite columns which have higher rigidity or energy consumption,
- symmetric ply orientations beginning and ending with the 45º ply are characterized by a significantly higher rigidity, while the structures which begin with 90 º and 0 º plies have a considerably high energy absorption,
- profiles with a symmetric ply orientation are characterized by an even distribution of load over the entire length of the model, which is proven by the presence of symmetric and evenly distributed half-waves over a length of these structures.

The numerical results demonstrate initially that composite structures with square closed section, can carry diverse loads depending on a laminate ply orientation.

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