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A NEW APPROACH TO SHAPING THE PUSHROD TUBE AS THE MAIN COMPONENT OF THE CONTROL SYSTEM, OPTIMIZATION, AND MANUFACTURING TECHNOLOGY.

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Abstract

Purpose

The aim of the research described in this article is to increase the critical buckling force of a slender compression tube as the main component of a small aircraft control system.

Design/methodology/approach

The article describes an innovative approach to the design and manufacture of carbon composite tubes as the main elements of pushrods used in mechanical flight control systems of small aircraft. Exploiting the possibilities of free shape modelling obtained through the use of composite technology, the author is looking for a shape other than fixed section shape, offering a higher buckling strength. An optimization process, based on the results of finite element method strength calculations in a one- and three-dimensional approach, was used.

Findings

Obtained results show the possibility of increasing the buckling strength of the pushrod tube by 23% compared to a fixed section tube, assuming the same external surface area.

Practical implications

The paper describes the optimization process leading to the final geometry of a compression tube, the innovative technology enabling a tube with a variable cross-section to be produced and the manufacturing process of the tube.

Research limitations/implications

The possibility of increasing the critical buckling force by using a composite material for the pusher tube flows from two aspects. The first is that the composite material offers a higher Young's modulus with a lower specific weight, compared to the typical use of duralumin. This fact, being obvious, is not considered in this study. The other more interesting possibility offered by the use of composite material is that the pushrod tube can be freely shaped.

Originality/value

This paper's original idea, and the thesis, is that it is possible to increase the critical buckling force of a compression tube by using a shape other than a constant cross-section, without changing the material and for a constant mass and wall thickness of the tube.

Keywords: optimization, FEM, flight control system, buckling

1. Introduction

The pushrod type mechanical flight control system is the best choice for small general aviation aircraft. It provides high rigidity, using a simple and low-cost manufacturing solution. Typically, such a system consists of levers and pushrods. There are also link type control systems, but these are not considered in this text. The purpose of the control system is to transmit movement between the controls located in the cockpit and the aerodynamic control surfaces. The rigidity of the control system mechanism is the most important requirement here [10], [11], [12], [15].

The main component of a modern control system mechanism, responsible for its rigidity and strength, is the pushrod and the main part of the pushrod is the tube connecting its ends. The ability of the pushrod to transfer the load depends on the strength parameters of this tube. The most important parameter, in this case, is the critical buckling force of compression, that a pushrod tube can transfer. This is a well-known fact that the critical buckling force depends on the length of the tube, the stiffness of the applied material and the moment of inertia of the cross-section (according to Euler's formula) [1], [2], [4], [7], [9].

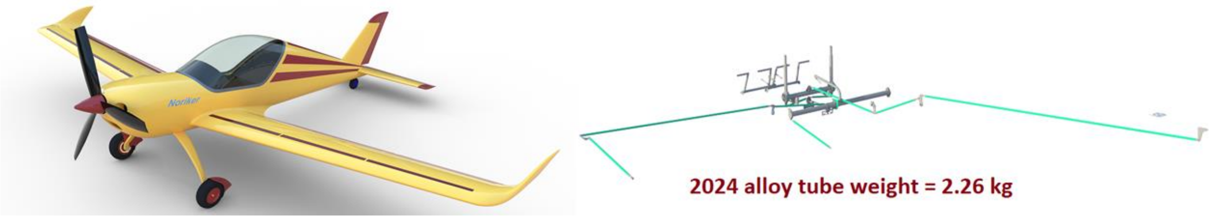


Figure 1 – Small aircraft control system mechanism - two-seater.

Figure 2 – Small aircraft control system mechanism - four-seater.

The weight of the small aircraft's control pushrod tubes can vary between 2 and 20 kg depending on the size of the aircraft. By using a carbon composite material for pushrod tubes, we can gain at least half of this weight due to the good material properties of the carbon composite. Using a non-constant section tube can further increase this gain by 20 per cent.

In this paper the author proves that it is possible to significantly increase the critical buckling force of a pushrod tube, assuming a constant length, mass, external diameter, and Young's module, only by appropriate shaping of its geometry. The activities described in this paper include both theoretical considerations and practical research.

In the first part, the author presents the finite element method-based optimization used to determine the optimal shape of the external pushrod tube geometry [5], [8], [13], [14], [16], [17].

The second part describes the authorial production technology of variable cross section, composite pushrod tubes. The new method of determining the optimum shape of the external geometry and the developed manufacturing technology for composite tubes with variable cross-sections, allowed to reduce the weight of the mechanical control system pushrod tube by approximately 60 percent.

The developed methodology has a wide application in all structures where compression thin-walled tubes are used as structural elements[3], [6].

2. Advantages of carbon epoxy composite material

The possibilities of increasing the critical buckling force, described in the following text, which result from the possibility of freely shaping the geometry of the pushrod tube, result from the tube manufacturing technology developed by the author and assume the use of a composite material in wet technology. The use of composite material also has more obvious advantages. Carbon composite is a particularly good material to use for pushrod tubes. This is due to its high stiffness compared to its low specific weight. Unfortunately, the use of composite technology also brings some disadvantages. In fact, from a practical point of view, the advantages, and disadvantages of using composite tubes as a pushrod component in the control system of a small aircraft balance each other out. This is the reason why this solution is rarely used. It was assumed that indicating another advantage of composite technology could outweigh this balance and lead to a wider use of carbon composite tubes as a control system element in small aircraft.

Typically, pushrods are manufactured using aluminium alloy tubes, for example 2024 alloy. It is reasonable to compare the advantages and disadvantages of carbon composite pipes with 2024 alloy pipes.

Figure 3 – Examples of carbon epoxy composite tubes.

Carbon – epoxy composite advantages:

- Low density – 1450 kg/m^3
- High stiffness – E = 160 GPa
- Easy to form free shapes
- Fatigue resistant
- Corrosion resistant

Disadvantages:

- High manufacturing cost - due to difficulties in automating the manufacturing process
- Human factor reducing safety factor.

Figure 4 – Examples of 2024 alloy tubes.

2024 aluminium alloy advantages:

- High production scale
- Low manufacturing cost

- High repeatability

Good but not great:

- Density – 2850 kg/m^3
- Stiffness – E = 73 GPa

Disadvantages:

- Low fatigue resistant
- Low corrosion resistant

The buckling phenomenon of a slender compression bar is well described by the Euler equation [1]. As can easily be seen, materials with a high Young's modulus are particularly favoured.

$$P_E = \frac{\pi^2 E I_{min}}{L^2} \qquad (1)$$

The high Young's modulus is a major advantage of carbon composite. However, it must be remembered that the value of the stiffness modulus for a heterogeneous material depends on several factors. Of course, the stiffness of the constituent materials, but also the percentage of volume, the direction of the fibres as well as the level of compression or corrugation of the fibres are important. The value of 160 GPa used for comparison is high, but achievable even for wet-formed carbon composite material. It is significantly higher than the stiffness of 2024 alloy but lower than the values suitable for steel alloys. The critical force formula (1) presented above, is valid for pinned-pinned attachment. This is an assumption that is valid for all further considerations.

3. One-dimensional finite element model as a simple confirmation of the thesis.

In a first step, a simple one-dimensional finite element-based model was created. The purpose of this model was to give preliminary confirmation of the correctness of the thesis. By its simplicity, that model is also good for presenting the assumptions of the author of this paper.

It was assumed that a compression tube of constant length (1500mm), constant wall thickness (1mm) and constant external surface area (141372mm^2) is being investigated. The cross-section of a tube is circular and can vary in radius in such a way that along the length of the pipe ends have a conical shape and on a centre part a constant cross-section. These assumptions allow the radius of the centre section to be increased by decreasing the average radius at the conical ends of the tube. In order to take into account technological constraints, an additional constraint is that the smallest diameter cannot be smaller than 20mm.

Figure 5 – One-dimensional model visualisation.

The FE model is built using one-dimensional CBEAM type beam elements. The length of a single element is 15mm, and the cross-section is circular with a constant thickness of 1 mm and variable diameter. The constraint at the ends of tube corresponds to the pinned-pinned case. As a calculation model based on one-dimensional elements does not allow for the composite material modelling, an isotropic material is used in this model.

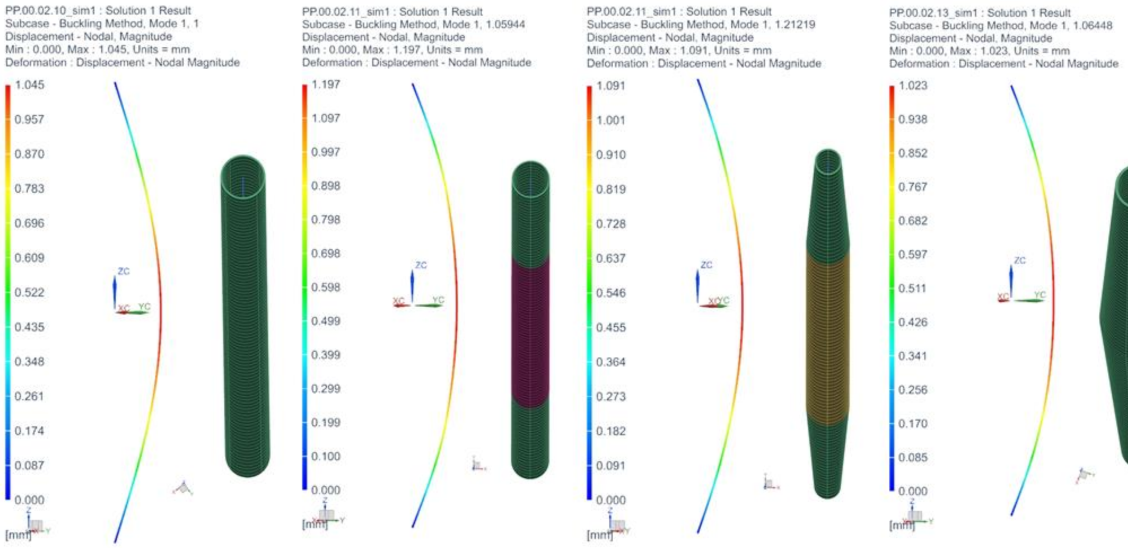


Figure 6 – Four cases of one-dimensional analysis.

A quick analysis of four different cases shows that the geometry with trapezoidal ends offers the possibility of significantly increasing the critical buckling force. It also shows that somewhere between the constant cross-section and the trapezoidal tube, there is an optimum that gives the maximum critical buckling force. The results of the above analysis, as well as the results of all subsequent analyses, are normalised to the value of the critical buckling force of the constant section tube.

A gradient optimisation process was used. This process searched for the optimum length of the trapezoidal sections, assuming a constant ends diameter and a constant external surface area.

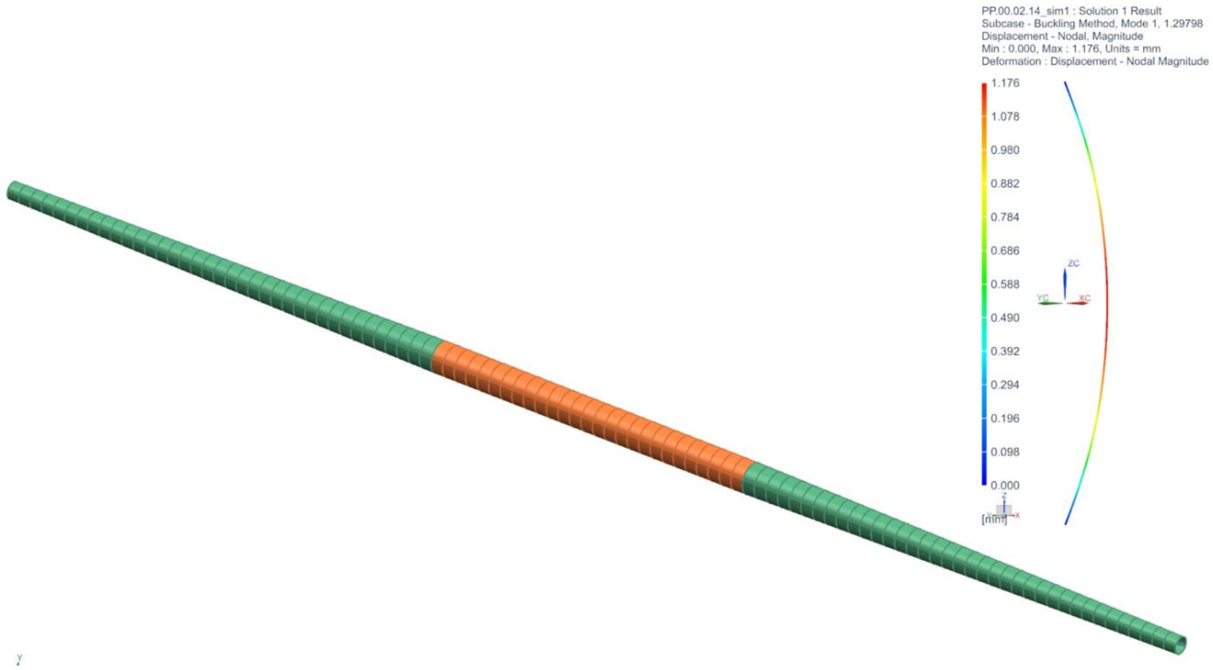


Figure 7 – The optimal case of a tube with trapezoidal sections.

The results of the analysis show that for parameter:

- Small diameter = 20mm
- Large diameter = 35.8mm
- Length of the tapered parts = 550mm

The critical buckling force can be up to **30%** higher than for a constant section tube.

4. Three-dimensional finite element model of a compression, composite, variable diameter tube.

In the next step, a model more closely corresponding to the assumed concept of a variable diameter tube was built. The geometry of the external surface of the tube is based on a circular cross-section varying in diameter according to the leading conic curve. The assumption of a constant outer surface area remains valid, which means that increasing the maximum diameter and moving the apex of the conic curve causes the diameter of the tube ends to decrease. The thickness of the shell remains constant at 1mm.

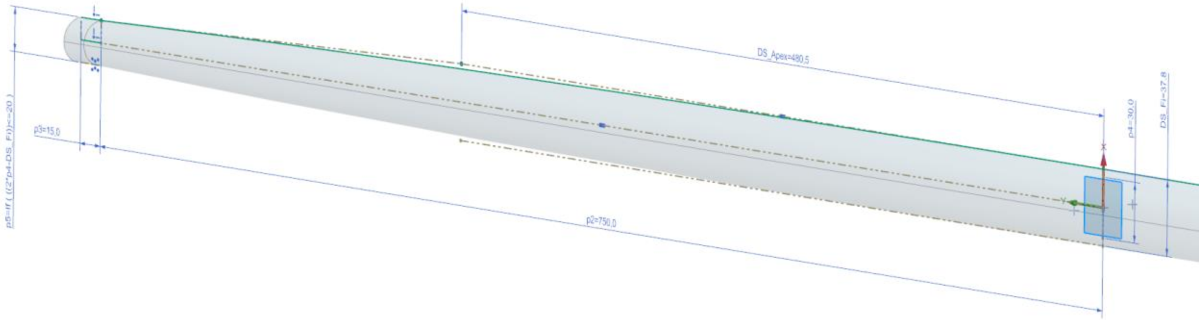
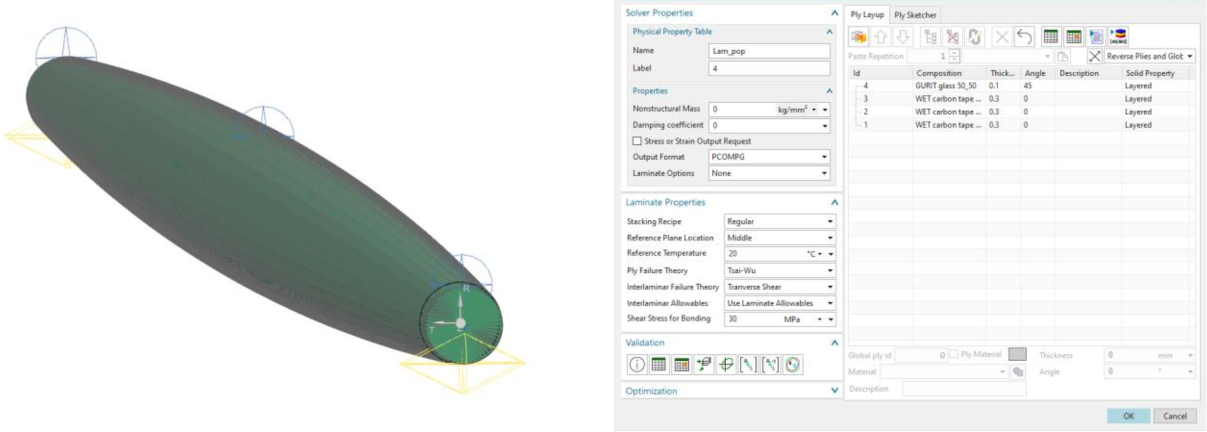


Figure 8 – Scheme of generating the external geometry of a tube.

The finite element model is based on shell elements of the laminate type. The size of an element's side is approximately 3mm, which makes it possible to build a structured grid of 21, thousand elements. The model has been fixed at the ends in a way that corresponds to pinned-pinned fixing. The surface model is supported using 1D connectors which allow the attachment to be transferred from the surface to a single point using one-dimensional beam elements. A compressive force was applied to the model. The force values correspond to the critical buckling force calculated for the constant cross-section tube.



Name: Lam_pop
Label: 4
Nonstructural Mass: 0 kg/mm²
Damping coefficient: 0
☐ Stress or Strain Output Request
Output Format: PCOMPG
Laminate Options: None
Stacking Recipe: Regular
Reference Plane Location: Middle
Reference Temperature: 20 °C
Ply Failure Theory: Tsai-Wu
Interlaminar Failure Theory: Tranverse Shear
Interlaminar Allowables: Use Laminate Allowables
Shear Stress for Bonding: 30 MPa

Id	Composition	Thick...	Angle	Description	Solid Property
4	GURIT glass 50_50	0.1	45		Layered
3	WET carbon tape ...	0.3	0		Layered
2	WET carbon tape ...	0.3	0		Layered
1	WET carbon tape ...	0.3	0		Layered

Global ply id: 0
☐ Ply Material
Thickness: 0 mm
Material
Angle: 0 °
Description

Figure 9 – Finite element mesh with definition of composite layers.

Four layers of composite were placed on the surface of the model. The three inner layers are made of unidirectional fabric and are layered along the length of the tube. The outer layer is made of orthotropic fabric draped at an angle of 45 degrees to the tube axis.

A model prepared in this way has two independent variables and a constraint that causes a change in the value of the independent variables not to change the external surface, which, assuming constant thickness, causes the mass of the tube to remain constant. Using an optimisation process based on the gradient method, the optimum tube geometry offering the highest critical buckling force was found.

$$maxP_{kr}(p0,\ p2) \qquad where$$

$$p0\ \in [50;650] - apex\ point\ location$$

$$p2\ \in [30;37]\ -\ \max diameter$$

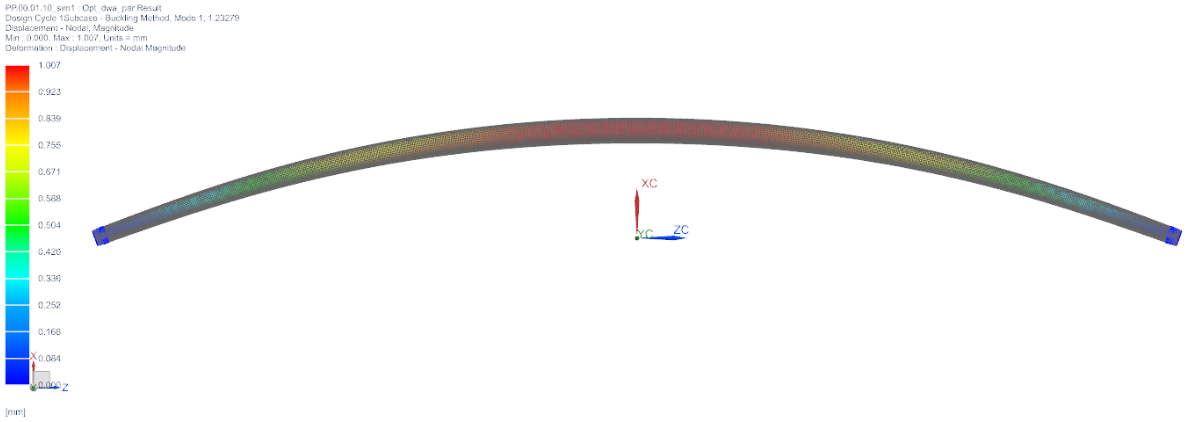


Figure 10 – Shape of the optimal compression tube after buckling.

The optimisation result shows that we can increase the critical buckling force by 23% by changing the shape of the pipe so that both mass and wall thickness remain constant. For the case of a 1500mm long tube, the optimal geometrical parameters are as follows:

$$p0 = 237mm - apex\ point\ location$$

$$p2 \ = 37mm \ - \ \max diameter$$

In the optimisation process, calculations were based on Linear Buckling analyses, but the final result was confirmed by Nonlinear Statics analysis assuming the possibility of large displacements.

5. Variable cross-section tube manufacturing technology.

As mentioned earlier, the disadvantage of using a composite material for the control system pushrod tube is that it is more difficult to manufacture than metal tubes. This disadvantage may in some cases disqualify the solution proposed here. I believe, however, that there will be technologically advanced constructions for which the application of the presented pushrod tubes will be a blessing. In order for this to happen, it is necessary to develop a technology allowing to manufacture a variable cross-section tube.

Variable cross-section tube manufacturing technology has been developed. This technology involves several steps as described below.

Geometry of the tube is formed using external moulds. The technology therefore requires the preparation of a two-part external mould. The composite fabrics are laid on an inner core. The inner core is made of a soft polymer so that it can be removed from the tube after curing.

Figure 11 – The mould and the inner core.

Laying of the epoxy resin saturated composite fabrics is carried out on an inflated inner core. There are three layers of unidirectional fabric and an outer layer in the form of a sleeve made of carbon fibres.

Figure 12 – Unidirectional layer prepared for layering on the core.

The layers of unidirectional fabric are cut in such a way that their local width corresponds to the local circumference of the tube.

Figure 13 – Outer layer application process.

The outer layer is made of orthotropic fabric in the form of a sleeve with a nominal diameter of 40mm. The angle of the composite fibres depends on the local tube diameter.

Once the fabrics have been laid, the core is enclosed in a mould. The mould is sealed with an external membrane and then the air is sucked out from under the membrane. This causes the composite layers to be compressed between the surface of the mould and the surface of the inner core and excess resin is removed.

Figure 14 – Closed and sealed mould.

In addition, for better compression of the composite, 100 kPa of overpressure is pumped into the core. After curing and de-moulding, we get a tube with the desired shape and a smooth outer surface with a good filling factor.

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Figure 15 – Tube after removal from the mould.

The inner core can be easily removed from the inside of the tube and used to make another tube.

Figure 16 – Close-up of tube surface.

6. Conclusions and further work

The idea of improving such a simple and perfect structure as a tube seems crazy. However, it turns out that for a specific application such as a compression tube in a control system pushrod, it is possible to significantly improve a major strength parameter such as the critical buckling force. Improving the strength of the component by taking advantage of the good strength properties of the composite material is an obvious benefit. In addition to this, we can increase the critical buckling force of the pushrod tube by 23% just by properly shaping its external geometry.

A technology for manufacturing a composite tube with a variable cross-section is proposed, allowing the manufacture of good quality components. The author is aware that this technology requires more effort compared to the use of a metal tube. The author is aware that this technology requires more labour input in comparison with using a metal pipe. This causes that the proposed solution can be used only in the most sophisticated constructions.

The obvious direction for further work is to carry out strength tests on the fabricated tubes. Obtaining strength confirmation based on actual compression tests of the tube would be the most valuable confirmation of the theory. However, such tests require making a considerable number of tubes and a series of tests to avoid possible errors. Such work will certainly be carried out and its results published in this journal.

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8. Copyright Statement

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