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MODELLING OF COMPOSITE REINFORCEMENTS IN AGRICULTURAL EQUIPMENT

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Abstract
The article is focused on the technology of polymer composite frame production by winding fibres on a non-load-bearing frame and their possibilities of use in the development of new agricultural machinery and equipment. An industrial robot and a winding head are used in the process of winding the fibres onto the frame. The main focus is attended on the process of winding fibres on a frame consisting of several parts with different cutting radii and the requirement to wind these parts at different angles due to the different loads of the future composite frame. The lengths of the individual parts of the frame, the radii of their circular cross-sections, and the required winding angles are determined on the basis of composite load modeling in some software systems. This type of composite frames has a wide range of applications in the production of agricultural machinery and equipment.

Key words: *agricultural machinery; polymer composite frame; model of composite load; composite lifespan; machine reinforcement.*

INTRODUCTION

At present, the production of modern agricultural machinery is focused primarily on increasing their power, reduction of fuel consumption, and reducing the machine weight. At the same time, a sufficiently long lifespan of the agricultural machine and its production at an acceptable financial cost is required. The use of composite materials in the production of many machine components significantly helps to meet the stated production requirements (*Gay, 2014; Agaroal, Broutman & Chandrashekhara, 2017*). Composites are increasingly replacing conventional materials in production. Composite materials increase the resistance of the machine to the stresses of its individual parts (elasticity, tensile strength, pressure, and torsion). Furthermore, the composites enable low machine weight (preventing of soil compaction, see Fig. 1) and weather resistance.

Fig. 1 Agricultural machines previously produced were constructed mainly of classic materials (iron, steel, aluminum, various metal alloys). Their weight was therefore significantly greater than the current machines. The two-row potato harvester is shown on the left, the grain harvester on the right.

The application of composite materials to the renovated surfaces of machines due to their wear (e.g. plowing parts of the machine) was used already in the past (*Mùller, Chotěborský & Hrabě, 2009*). At present, composite materials are increasingly used in agriculture (*Chen, G., 2018*). Polymer composite frames occupy an important place in the use of new materials.

Polymer composite frames are often used as machine chassis reinforcements, reinforcements of cargo space, doors, and driver's cabs. Composite frames are also applied as load-bearing structures for various agricultural machines and devices (e.g. trucks) and also as mechanical protective equipment for machines (for example external safety frames at the tractor cab, see Fig. 2).
The aim of this contribution is to describe the technology of winding several layers of fibres onto a non-load bearing composite frame. The winding process is implemented by using a mathematical model of winding, a winding head, and an industrial robot.

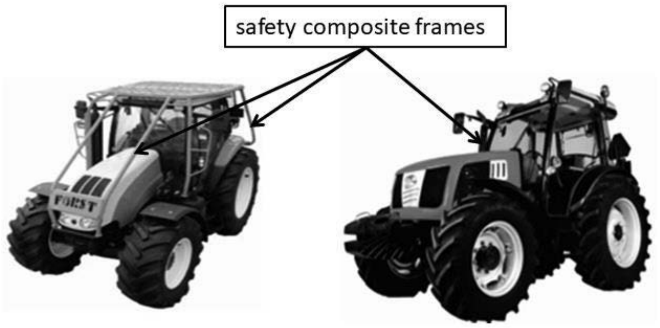

Fig. 2 Safety composite frames for the tractor cab.

MATERIALS AND METHODS

One of the possibilities for the production of composite frames is fibre winding technology. The non-load-bearing frame (usually made from polyurethane) is attached to the end of the working arm of the industrial robot (robot-end-effector). Based on a suitably determined trajectory of the robot (in more detail see (*Siciliano, Sciavicco, Villani, & Oriolo,2010; Martinec, Mlýnek & Petrů, 2015*)), the frame passes through the winding head, see Fig. 3 on the right and Fig. 4 on the right. The winding head comprises three rotating annular rings with spools of fibres. One layer of fibre windings is gradually formed by each annular ring as the frame passes through the winding head and the annular ring rotates. The technology of winding the fibres on the frame is described in detail in (*Mlýnek, Koloor, Martinec & Petrů, 2021*; *Mlýnek, Petrů & Martinec, 2019*). Composite frames have different geometric shapes, often highly 3D ragged (see Fig. 3 on the left). Frames can be closed (see Fig. 3 on the right) or open (see Fig. 3 on the left and Fig. 4 on the right) and have different cross-sections (e.g. circular, elliptical, trapezoidal).

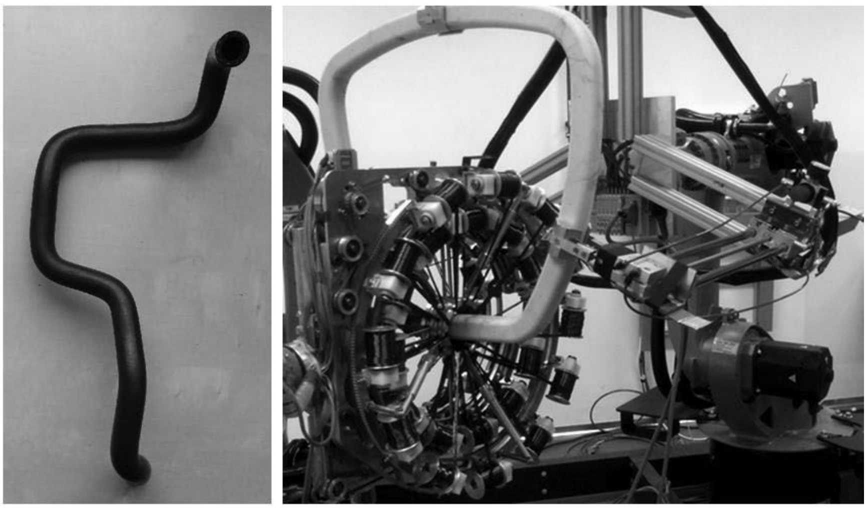

Fig. 3 Example of a 3D multi-shaped non-bearing hollow frame with circular cross-section (on the left). Closed non-bearing frame prepared to winding process. Frame is connected to robot working arm and goes through winding head (on the right).

In the remaining part of the article we will focus on the issue of winding frames consisting of several parts with different cross-sectional radii and the need to wind these parts in general at different angles (see Fig. 5 on the left). The parameters of such a frame and the required winding angles can be obtained on the basis of modeling the planned composite load, e.g. in the ANSYS and ABAQUS software tools.

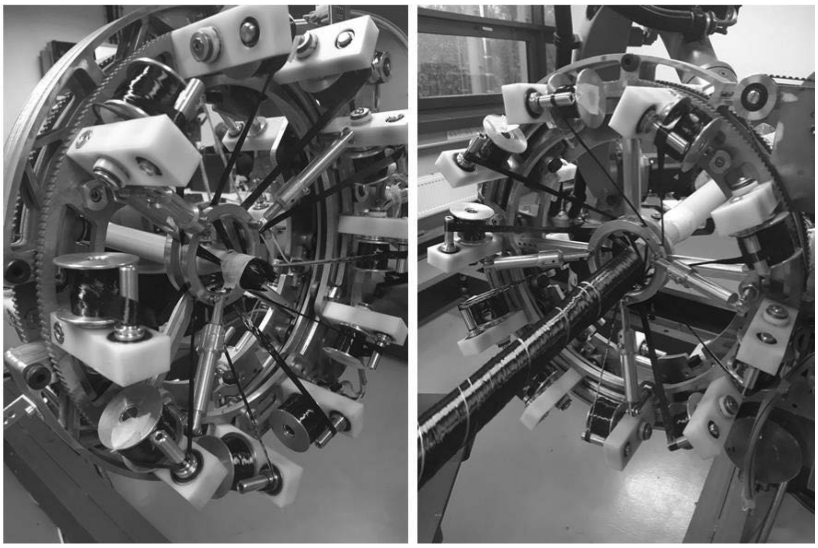

Fig. 4 Preparation of a winding head with three rotating rings with carbon fibre spools to start the winding process is shown on the left. The actual process of winding the fibres on a polyurethane frame, which is attached to the end of the working arm of the industrial robot, is displayed on the right. The frame passes through the winding head based on the movement of the robot arm, and at the same time three layers of fibres are wound simultaneously (each rotating annular ring winds one layer).

A mathematical model of the winding process is shown in Fig. 5 on the right. One rotating annular ring *k* with its center *S* and radius *R* is depicted in this figure. The annular ring is part of the winding head and lies in plane orthogonal to axis *s* of winding head.

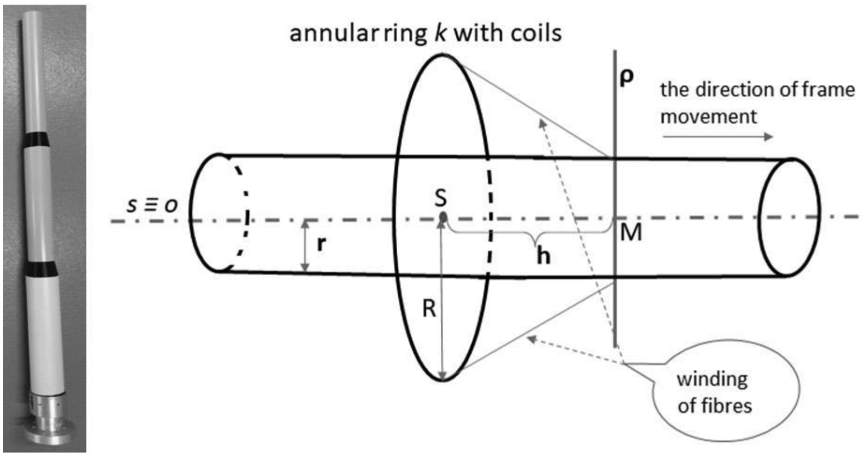

Fig. 5 Example of a straight-line frame with three parts with different radii of their circle cross-sections on the left. The mathematical model of annular ring *k* of the winding head, straight-line frame and winding plane ρ is shown on the right.

Central axis *o* of frame is identical with axis *s* of the winding head (see Fig. 5 on the right). Radius of cylindrical frame is denoted *r*. We suppose constant speed *w* of the passage of the frame through the winding head. Annular ring *k* with coils is rotated around axes *s*, frame goes through annular ring *k* by

speed *w* and on frame is created layer of wound fibres under winding angle α in distance h from the annular ring k (in plane ρ).
We need to determine the angular speed ω of the annular ring k so that the fibres are wound at the prescribed angle α. The angular speed ω is controlled by the external axis of the robot during the winding process.
It is also necessary to know at what distance *h* from the annular ring *k* the fibres are wound on the frame when winding at an α angle is specified. The procedure for deriving the calculation of required angular speed ω and the winding distance h at the required winding angle α is described in detail in (*Mlýnek, Koloor, Martinec & Petrů, 2021*).
The wound fibre (usually from carbon, glass or aramid) forms a helix on the surface of the frame with circular cross-section. The fibre forms a right-handed helix (positive winding angle α) or a left-handed helix (negative winding angle α). Winding angle $\alpha \in (0, \frac{\pi}{2})$ in positive winding orientation corresponds to the pitch angle α of the right-handed helix.
Pitch of helix v (height of helix when is created one thread at an α angle) is given by relation $v = 2\pi r.tg\alpha$ (see (*Pressley, 2010*)). To ensure winding at an α angle, the annular ring have to make one turn in the same amount of time as the frame travels the distance v.
Peripheral speed *u* of the annular ring *k* is given by relation $u = \omega.R$. Based on the validity of the relation

$\frac{u}{w} = \frac{2\pi R}{v} = \frac{2\pi R}{2\pi r.tg\alpha} = \frac{R}{r.tg\alpha}$, we can express angular speed ω in the form

$$\omega = \frac{1}{r.tg\alpha} \cdot w \,. \tag{1}$$

Distance *h* of winding the fibre onto the frame from the annular ring *k* can be derived from the parametric equation of the helix and the expression of the equation of the tangent of the helix at a given point. Distance *h* is given by relation (derivation is described in detail in (*Mlýnek, Koloor, Martinec & Petrů, 2021*))

$$h = tg\alpha \,.\, \sqrt{R^2 - r^2} \,. \tag{2}$$

Based on the use of equations (1) and (2), the desired winding angle of the fibres can be continuously and repeatedly changed. From relation (1) it can be seen that angular speed ω of the annular ring *k* depends on radius *r* of frame, at required winding angle α and constant movement *w* passage of the frame through winding head. Distance *h* in relation (2) depends on winding angle α, on radius *R* of annular ring *k*, and radius *r* of frame.

RESULTS AND DISCUSSION

Braiding technology and filament winding are the most used manufacturing procedures of composite frames productions. The advantage of braiding is the high adhesion of the fibres to the frame surface (see (*Eschler, Miadowitz, Zaremba, & Dreschsler, K., 2020*)). The main advantage of filament winding is the possibility of winding a closed frames and performing a continuous change of filament winding angle (see (*Mlýnek, Koloor, Martinec & Petrů, 2021*)). Relationships (1) and (2) make it possible to continuously wind frame parts with different radii of their circular cross-sections. Using relation (2), it is possible to determine at what distance from the annular ring the fibres are wound on the frame. At the same time, relation (1) provides us information on what angular speed ω the annular ring must rotate in order for the fibres to be wound at the desired angle α on a given part of the frame. Thus, assuming a constant speed *w* of the passage of the frame through the winding head, we know how it is necessary to ensure the angular speed of the annular ring at a given moment in order for the winding of the fibres to meet the requirement of winding angles. When the winding transition between two parts of the frame, it is necessary that the transition of the frame radius changes continuously (i.e. without a jump).
Three layers of fibre windings for the described frame type can be performed simultaneously in one pass of the frame through the winding head. If a larger number of fibre windings is required, the frame needs to pass through the winding head repeatedly.

Values of angular speed ω of annular ring depending on the parameters in relation (1) are shown in Tab. 1. This table shows that with increasing value of the winding angle $\alpha \in (0,\ \pi/2)$ (trigonometric function *tg* is increasing on this interval) and radius *r* of the frame, the angular speed ω of the rotating ring *k* decreases. Conversely, as the constant speed *w* of passage of the frame through the winding head increases, the angular speed ω increases

Tab. 1 Calculation of angular speed ω of ring rotation depending using relation (1)

w [mm/s]	*r*[mm]	α [°]	α [rad]	*tg* α	ω [rad/s]
20	20	30	0.5235	0,577 3	1,7322
		45	0.7853	1,000 0	1,0000
		60	1.0471	1,732 0	0,5773
	40	30	0.5235	0,577 3	0,8661
		45	0.7853	1,000 0	0,5000
		60	1.0471	1,732 0	0,2886
50	20	30	0.5235	0,577 3	4,3305
		45	0.7853	1,000 0	2,5000
		60	1.0471	1,732 0	1,4432
	40	30	0.5235	0,577 3	2,1652
		45	0.7853	1,000 0	1,2500
		60	1.0471	1,732 0	0,7215

Values of distance *h* of winding fibres on frame from annular ring depending on the parameters in relation (2) are shown in Tab. 2.

Tab. 2 Calculation of distance winding *h* of fibres on the frame from rotating ring *k* using relation (2)

R [mm/s]	*r*[mm]	α [°]	α [rad]	*tg* α	*h*[mm]
50	20	30	0.5235	0,5773	26,4403
		45	0.7853	1,0000	45,8000
		60	1.0471	1,7320	79,3256
	40	30	0.5235	0,5773	17,0319
		45	0.7853	1,0000	30,0000
		60	1.0471	1,7320	42,9600
100	20	30	0.5235	0,5773	56,5632
		45	0.7853	1,0000	97,9795
		60	1.0471	1,7320	169,7004
	40	30	0.5235	0,5773	52,9101
		45	0.7853	1,0000	91,6510
		60	1.0471	1,7320	158,7395

Tab. 2 indicates the values of distance *h* of winding fibres on the frame from the rotating annular ring *k* with the fibres for specific input parameters in relation (2). Distance *h* increases with growing of annular ring radius *R* and winding angle α, on the contrary it decreases with increasing value of frame radius *r*.

CONCLUSIONS

At present, composite materials are increasingly used in the production of agricultural machinery. Polymer composite frames have an irreplaceable place in production. The procedure described in this article allows the application of fibre winding technology to more complicated shapes of frames composed of several parts with different radii of circular cross-section. Different parts of the composite frame can be significantly loaded in different ways during the operation of an agricultural machine or equipment.

Based on modelling the planned load of the developed composite frame using a software tool, it is possible to determine the appropriate shape and radius of the cross-section of individual frame parts as well as the required fibre winding angle on individual frame parts for each fibre winding layer. The positive and negative winding orientations usually alternate between successive layers of fibres. The quality of winding fibres on the frame is addressed in this article mainly from a geometric point of view. The quality of the fibres used to winding also plays an important role. But the correct winding of fibres from a geometric point of view is a necessary prerequisite for the production of a high-quality composite frame.
The results and conclusions of this article can be successfully used in the development of polymer composite frames in agriculture when designing new machines and equipment.

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