Modelling the Winding of Composite Frames for the Automotive Industry

Jaroslav Mlýnek[1] and Roman Knobloch[1]

[1] Department of Mathematics, FP, Technical University of Liberec, Liberec 1, Studentská 2, Czech Republic
jaroslav.mlynek@tul.cz

Abstract. Composite materials are increasingly replacing conventional materials (e.g. steel, sheet metal, wood) in automotive production. Composite frames are also playing an important role in the development of new cars, SUVs and trucks. Composite frames are mainly used as reinforcements for chassis, cabs, doors, and other parts of cars. The modelling of production technology of composite frames with circular cross-section is described in the article. The winding head and the industrial robot are used for winding fibres onto a non-load-bearing frame. The most commonly used fibres are carbon, glass and aramid. The problem of winding a frame composed of several parts with different cross-sectional radii and continuous change of the winding angle is also addressed in the paper. Such frame composites are used when different loads are expected to be applied to the individual parts of the frame. During the winding process, several layers of fibres at different angles are wound simultaneously on the frame. The winding angles are determined by modelling the frame load using a suitable software tool (e.g. ANSYS, Abaqus).

Keywords: Frame Composite, Winding Head, Industrial Robot, Car Reinforcement, Frame Load, Winding Angle.

1 Introduction

Composite materials are being applied increasingly in automotive production. Composites are now replacing conventional materials. Low weight, flexibility, strength, weather resistance, long service life and maintenance-free operation are the main advantages of composites (see [1] – [3]). Composite frames occupy an irreplaceable place in the automotive industry. Composite frames are mainly used as chassis, as parts of cabs, doors, and protective safety frames for off-road vehicles (see Fig. 1). Composite frames are also replacing protective metal car frames to a large extent (see Fig. 2).

The main objective of this paper is to describe the technology of manufacturing polymer composite frames by winding fibres onto a non-load-bearing frame. Attention is paid to the mathematical modelling of the fibre winding process, especially from a geometrical point of view. Special attention is paid to the description of the process of winding of frames composed of several parts with different radii of their circular cross-

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section. A non-load-bearing frame with a circular cross-section, a winding head and an industrial robot are used during the winding process.

Fig. 1. Protective composite frames on an off-road vehicle.

Fig. 2. The front protective stainless steel frames are now often replaced by composite frames.

2 Materials and Methods

Currently, the following two technologies are the most widely used in the production of polymer composite frames: braiding and winding technologies. Frame composites made with braiding are more resistant to surface damage of the frame (cracks) during operation (see [4]). However, for technical reasons, a closed frame cannot be braided when using this technology. In contrast, fibre winding can be used on both open and closed frames. In the remainder of the article, the focus will be put on fibre winding technology.

The winding head and industrial robot are used in the fibre winding process (see Fig. 3). The winding head is fixed in the working area of the robot and contains three rotating annular rings with spools of fibres. A non-bearing frame (usually made of polyurethane) is attached to the end of the robot's working arm (robot-end-effector). Based on the suitably determined trajectory of the robot the frame goes through the winding head and three layers of fibres are simultaneously wound onto the frame generally at different winding angles. The perpendicular passage of the frame through the fibre winding plane at point M (see Fig. 4) and the identification of axes *o* of the frame and *s* of the winding head at point M ensure that the correct winding angle is maintained. Ensuring the correct winding angles can be achieved by determining an optimized robot trajectory based on a mathematical model of the winding process, matrix calculus and internal robot instructions.

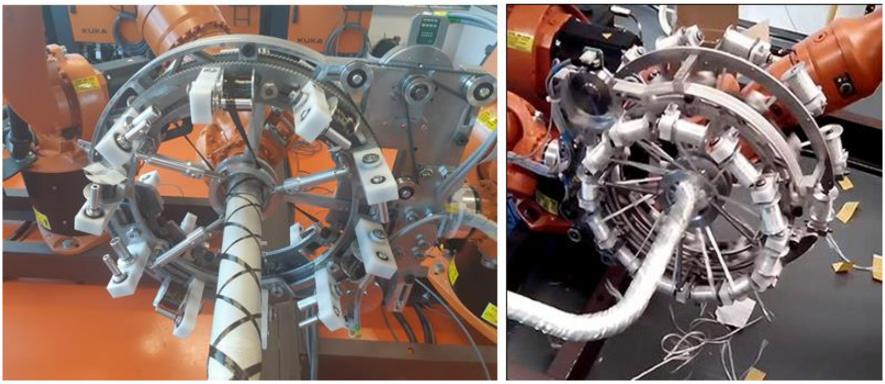

Fig. 3 Test winding of two strands of fibres at 45° and -45° angles (on the left). Winding 3 layers of fibres on a composite frame (on the right).

This issue is addressed in detail in [5]. Determining the robot trajectory is trivial in the case of a straight frame. Determining the optimized robot trajectory is more difficult with a geometrically complicated frame.

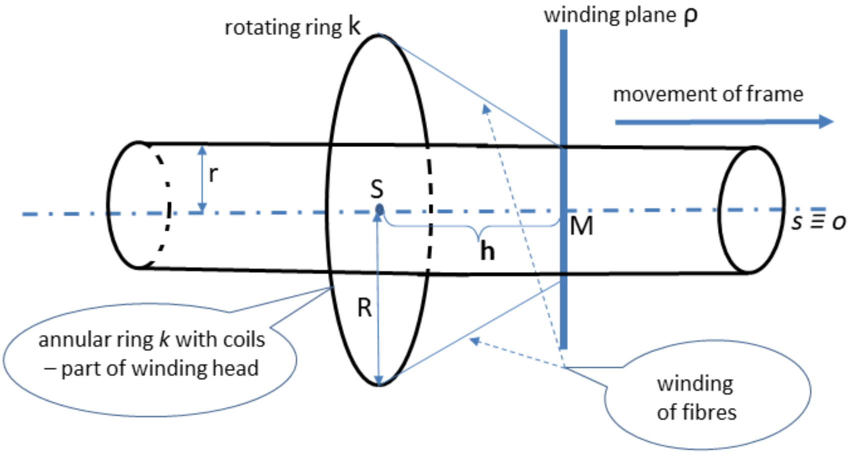

Fig. 4 A mathematical model for winding strands of fibres onto a frame.

In practice, the individual parts of the composite frame often have different loadings during operation. Therefore, frames with several parts with different radii of their circular cross-section may be developed. The strands of fibres are also often wound at different angles on individual parts of the frame. In order to ensure a smooth transition of winding to the different parts of frames generally with different cross-sectional radii at different angles, it is necessary to have the following two pieces of knowledge: 1/ distance h of the rotating ring from the winding plane (see Fig.4), 2/ angular velocity of the rotating ring.

2.1 Winding Distance of Fibres from Rotating Ring

The wound fibre forms a helix on the surface of the frame. The wound right-hand helix is referred to as positive winding and the left-hand helix as negative winding of the frame. One turn of right-handed helix h_R is displayed in Fig. 5.

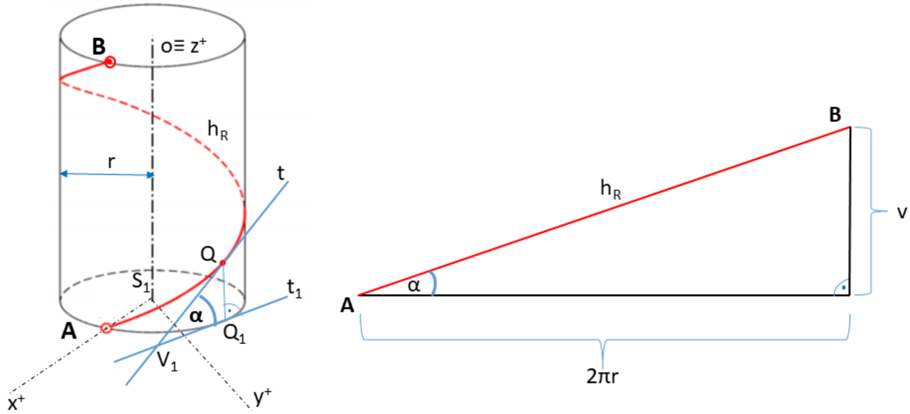

Fig. 5 Representation of one turn of the helix and the characteristic helix triangle.

Tangent t to the helix at point Q, its horizontal projection t_1 and winding angle α of fibres are shown in Fig. 5 on the left. The characteristic helix triangle is shown in Fig. 5 on the right. The length of the wound fibre at one turn and winding angle α is the length of line segment AB, v indicates the pitch of the helix (the height of one helix turn), for more details see [6].
Based on the expression for the parametric equation of the helix p_R in the form of $p_R(t) = (r\cos t, r\sin t, v_0 t,\ 1), t \in< 0, \infty)$, v_0 determines reduced pitch of helix (length of translation during rotation of fiber by one radian), and the expression for the tangent of the helix at a point, distance h of the fibre winding on the frame from the rotating ring k with coils with fibres (see Fig. 4) can be derived in the form (the detailed derivation is given in [7])

$$h = tg\alpha\, .\sqrt{R^2 - r^2}. \tag{1}$$

Here α is the angle of the fibre winding on the frame surface, R is the radius of the rotating ring k and r is the radius of the frame with a circular cross-section.

2.2 Angular Speed of Rotating Ring

Peripheral speed u of rotating ring k is given by relation $u = R.\omega$, where R denotes radius of rotating ring k (see Fig. 4) and ω denotes angular speed. Pitch ν of the helix can be express in the form $\nu = 2\pi r.tg\alpha$ (see Fig. 4 on the right). We assume that the frame passes through the winding head at a constant speed w. Then the following relations hold

$$\frac{u}{w} = \frac{2\pi R}{\nu} = \frac{2\pi R}{2\pi r.tg\alpha} = \frac{R}{r.tg\alpha} \ .$$

From here and the relation $u = R.\omega$ angular velocity ω can be expressed in the form

$$\omega = \frac{1}{r.tg\alpha} \, .w \tag{2}$$

Based on the knowledge of distance h and angular velocity ω determined by relations (1) and (2), it is possible to ensure the correct winding of the individual parts of the frame at generally different angles.
Note that the angular velocity of the winding rotating ring of the robot is controlled by the external axis of the industrial robot (see [7] for details).

3 Result and Discussion

Knowing the required angular speed of the winding rotating ring and the winding distance of the fibers on the frame from the winding rotating ring allows for smooth transitions to other winding angles on defined sections of the composite frame.
Winding distance h of the fibres on the frame from the rotating ring with coils containing fibres can be determined by applying relation (1) (for all three rotating rings when three layers of fibres are formed simultaneously). Table 1 contains the calculated winding distances h for the specified values of winding angle α, rotating ring radius R and frame radius r.

Table 1. Calculation of winding distance h.

R[mm]	r[mm]	α[°]	α[rad]	h[mm]
50	20	45	0.785	45.800
		60	1.047	79.325
	40	45	0.785	30.000
		60	1.047	42.960
100	20	45	0.785	97.979
		60	1.047	169.700
	40	45	0.785	91.651
		60	1.047	158.739

Properly set angular speed ω of rotating ring k (see Fig. 4) allows to ensure winding of fibres on the frame at the required angle α. Table 2 contains the calculation of the angular velocity of the rotating ring depending on the frame radius, the winding angle and constant speed w of the frame through the winding head using relation (2). Knowing the required angular speed of the winding rotating ring and the distance of the winding of the fibres on the frame from the rotating ring allows for a smooth change of the winding angle during the winding process.

Table 2. Calculation of angular speed of rotating ring ω.

w[mm/s]	r[mm]	α[°]	α[rad]	ω[rad/s]
20	20	45	0.785	1.000
		60	1.047	0.577
	40	45	0.785	0.500
		60	1.047	0.288
50	20	45	0.785	2.500
		60	1.047	1.443
	40	45	0.785	1.250
		60	1.047	0.721

At the same time, it is possible to wind individual parts of the frame with different cross-sectional radii both at the same angle and at different winding angles. The winding angles are usually determined by modelling the operating load of the frame.

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