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Holistic criteria-based optimization of filament wound high pressure vessels

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ABSTRACT

For dimensioning of wound fiber reinforced high pressure vessels the design engineer has to consider various requirements. Since in addition to the strength requirements, in particular the manufacturing constraints must be taken into account. In order to support the design engineer in the complex dimensioning process of such high-pressure vessels a holistic design strategy was developed on the basis of an ant colony optimization algorithm. The aim was to do this winding-optimization without costly dedicated software and instead develop basic design criteria. For this it was necessary in both carry out a holistic comparative quality evaluation of different solutions as well as providing a customizable objective function.

Introduction

The manufacture of continuous fiber reinforced rotationally symmetrical pressure vessels is usually done by using an automated winding process. Mainly numerically controlled winding machines are used. Here, the liner is rotated around its longitudinal axis and the tape feed takes place via the tape laying-down. Complete covering of the liner with the fiber tape is achieved by driving of the tape laying-down in the longitudinal direction. The changes in thickness during the winding process is controlled by the guideway in transverse direction. A wrinkle-free, geodetic dropping of the fiber tape at different winding angles Φ_i is carried out by a corresponding tracking of the tape laying-down. For economic reasons several fiber rovings are combined to form a band with the width *b*, wherein the rovings are fed via separate spools in a creel, which simultaneously ensures a defined preliminary tape tension; cf. Fig. 1.

The considered layer stackups are composed of a combination of layers of circumferential windings ($\Phi_i \approx 90^\circ$) and balanced cross windings ($0^\circ < |\pm \Phi_i| < 90^\circ$). At the circumferential winding the longitudinal feed of the thread laying-down is added after each complete rotation of the liner to the bandwidth. Thus reinforced only the cylindrical section. In contrast, the cross-winding is placed in two passes with a helically trace on the liner, with the orientation $+\Phi_i$ and return with $-\Phi_i$. With the cross winding a complete covering up to the bushing can be done [2].

Criteria-based optimization

The whole iterative dimensioning process of winding pressure vessels, starting from the design to the determination of the layer structure, the numerical analysis of the overall structure up to their evaluation, is very time-consuming and costly. In particular, for an optimal design which is suited to the production as well as the strength and weight requirements. Therefore, in order to make this process more efficient, a holistic criteria-based optimization strategy was developed, which takes into account individual structural and manufacturing constraints.

Design rules

For the purpose of dimensioning the textile reinforcement with respect to the structural strength the cylindrical pressure vessel is subdivided into three critical areas (cf. Fig. 2). For each critical areas different design rules has to be applied during the stacking construction. These rules are:

1. cylinder section $\hookrightarrow$ Barlow's formula ($\sigma_\Phi = 2\sigma_z$),
2. bottom with brim $\hookrightarrow$ average angle,
3. bushing area $\hookrightarrow$ minimum winding angle.

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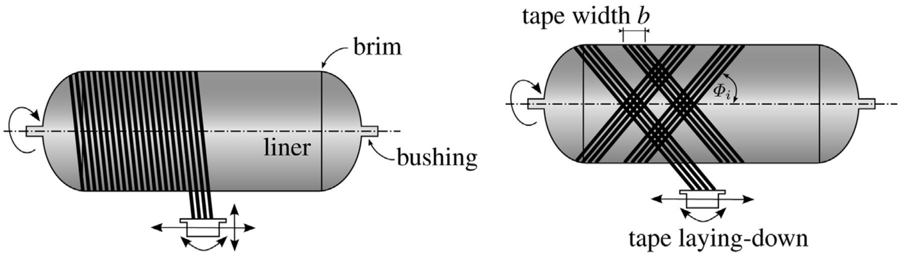

(a) circumferential winding (b) cross-winding

Fig. 1. Schematic representation of typical winding processes [1].

In order to calculate the axial as well as tangential strength of the cylindrical section under internal pressure load, the tensile strength values in the fiber direction $R_{\parallel}^{t}$ are used exclusively. The following criteria must be met for the acceptable membrane stresses (neglecting the load bearing capacity of the liner and the use of a single reinforcing material):

$$R_{\parallel}^{t}\frac{1}{t_{tot}}\sum_{i}^{n}t_{i}^{K}\cos(\Phi_{i})\geq\sigma_{z}, \tag{1a}$$

$$R_{\parallel}^{t}\frac{1}{t_{tot}}\sum_{i}^{n}t_{i}^{K,U}\sin(\Phi_{i})\geq\sigma_{\Phi}. \tag{1b}$$

In (1a), the relative layer proportions of the composite tensile strength in the longitudinal direction of the vessel and in (1b) the proportions of the corresponding components in the tangential direction are summed. For the individual layer thicknesses t_i, different values are generally to be applied for different orientations. This occurs due to different fiber stresses during the winding process on the liner. However, the layer thicknesses of the crosswindings differ only marginally from each other. Therefore, in the further dimensioning process, the layer thicknesses are distinguished only by the type of winding in cross-sectional t^K or circumferential t^U winding layer thicknesses. Considering the Barlow's formula, the strength criteria for the meridional and circumferential stresses of the cylindrical vessel section can be defined as:

$$R_{\parallel}^{t}\sum_{i}^{n}t_{i}^{K}\cos(\Phi_{i})-\frac{p\,D_{A}}{4}\geq0, \tag{2a}$$

$$R_{\parallel}^{t}\sum_{i}^{n}t_{i}^{K,U}\sin(\Phi_{i})-\frac{p\,D_{A}}{2}\geq0. \tag{2b}$$

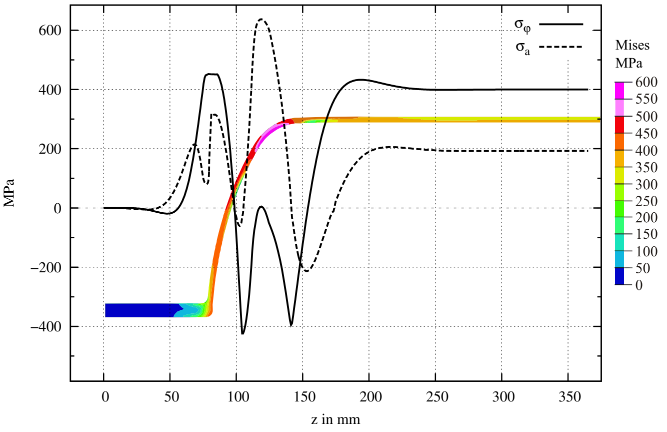

Fig. 2. Stress profile at internal pressure of $p = 100$ bar in the circumferential and meridional direction on the inside of an unreinforced metal vessel as well as the Mises stress (constant wall thickness $t_{tot} = 4$ mm) [3].

In order to ensure the structural failure in the prescribed cylindrical area of the pressure vessel, the ratio between the tangential and axial fiber reinforcement must not exceed a certain limit value. This fiber reinforcement ratio can be expressed in a maximum permissible effective average angle Φ_{max} of the total winding structure. This effective average angle $\Phi_{\emptyset}$ is calculated from the individual layer thicknesses and the corresponding orientations:

$$\Phi_{\emptyset}=\frac{\sum_{i}^{n}\Phi_{i}\,t_{i}^{K,U}}{t_{tot}}\leq\Phi_{max}. \tag{3}$$

The limiting value Φ_{max}, where the failure occurs just in the cylindrical area, cannot be specified as a general rule, but rather depends on the shape and local reinforcement of the bushing/bottom transition and has to be determined empirically. For the bumped boiler end of the liner used in this work a critical angle of $\Phi_{max}\approx45^{\circ}$ and $\approx51^{\circ}$ was chosen.

The winding angle which is at least required for a complete covering Φ_{min} of the liner with an outer diameter D_A is calculated as follows:

$$\Phi_{min}=\arcsin\left(\frac{d_{M}+b}{D_{A}}\right). \tag{4}$$

The geodetic of the fiber tape of a cross winding with bandwidth b then runs tangentially along the bushing (diameter d_M). This minimum number of required winding angles for complete coverage can also be specified as a restriction for manufacturing.

The analysis of various filament wound pressure vessels after bursting tests, with the aim of ensuring the support of the bottom between the bushing and brim, revealed a relative minimum number of crosswindings below $\pm30^{\circ}$ as a further design criterion.

In order to increase the fiber volume, circumferential windings are frequently provided as the last layers, which transfer a maximum fiber tension to the liner and thus press out excess resin (so-called compression-winding). The number of necessary compression-windings can also be specified as a manufacturing restriction.

The design criteria $\mathcal{R}_i$ on which basis an optimization of the winding structure should take place are summarized in Table 1. The criteria $\mathcal{R}_{1-5}$ were described so far. In addition, the discrete set of permissible layer orientations is given by $\mathcal{R}_6$. These

Table 1
Design criteria $\mathcal{R}_i$ for filament wound high pressure vessels [3].

i	Type
1	Axial and tangential margins of safety, cf. (2)
2	Maximum average angle, cf. (3)
3	Minimum number of windings with complete coverage, cf. (4)
4	Relative minimum number of winding angles $\leq\lvert30^{\circ}\rvert$
5	Minimum number of circumferential windings
6	Set of permissible discrete winding angles
7	Additionally permitted crosswindings depending on bandwidth
8	Winding angles, which must also be included in the solution

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