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Piping elements from textile reinforced composite materials for chemical apparatus construction

W. Hufenbach, L. Kroll, R. Böhm, A. Langkamp, A. Czulak

Institut für Leichtbau und Kunststofftechnik (ILK),
Technische Universität Dresden, D-01062 Dresden, Germany

Advancing globalisation in apparatus and plant construction is leading to ever higher demands being made as regards efficiency and performance on the many various components and in this respect on complex piping elements in particular. These construction elements usually need to resist not only the high internal pressures and temperatures but also the influence of aggressive media. Overcoming the diverse technical demands connected with this can often only be achieved by employing new materials as well as by using corresponding construction techniques and manufacturing technologies.

Both a lightweight relevant as well as low cost alternative to conventional metals and the now well-established apparatus construction material of glass fibre reinforced plastics in wire-wrap technique, form the group of novel textile composite materials, which apart from a very high design flexibility as regards shaping and the load-adapted reinforcing arrangement specifically offer a considerable cost saving potential. This makes the plastic composite structures with requisite textile reinforcement virtually predestined for cost-effective pipeline systems in chemical apparatus construction with its typical range of construction elements such as T-pipe pieces, angle pieces, reducing pieces or also pipe pieces.

1. INTRODUCTION

Because of their excellent strength properties and superb resistance to chemical attack, it is currently often the case that, as well as metal pipe structures, hybrid layered composite materials, which are composed of a supporting structure of reinforced glass fibre thermosetting and thermoplastic interior liners, find application as pipe elements in chemical apparatus construction. [1, 2]. These days such piping made of reinforced glass fibre plastics (GPR) principally serves to transport material as process and waste water pipes, sewage pipes as well as ventilation and exhaust gas pipes. Different thermosetting matrix materials are suitable for this task, in particular, reaction resins such as unsaturated polyester resins (UP) and vinyl ester resins (VE) that display a high degree of chemical resistance [3].

In the past few decades a fundamental improvement in composite components has taken place which has not only seen the range of applications of glass fibre reinforced plastics expand considerably, but also produced composite materials with a pronounced multifunctional property profile [4]. The development of suitable composite systems and manufacturing processes has also seen the focus on the primary demand for corrosion resistance being augmented by an emphasis on economical lightweight construction [5].

The standard manufacturing processes employed for making glass fibre reinforced hybrid pipes is the winding technique in which the directed reinforcing fibres are laid on the interior liner. On the one hand, the winding technique is principally suited to the manufacture of straight pipes of limited length [3]. However, using the winding process to produce more complex structural components such as, for example, pipe bends or T-pieces (see Fig. 1) necessitates time-consuming and cost-intensive manual work. Furthermore, no sufficiently strong and reproducible fibre arrangement can be achieved using the winding technique. Moreover, the manufacture of flange connections calls for a constructively complex solution that can only be realised in the course of several work stages [6, 7]. The braiding technology has established itself as an alternative to the winding technique in the past few years. Research work on the efficient employment of braiding technology to manufacture textile reinforced pipe elements is currently underway.

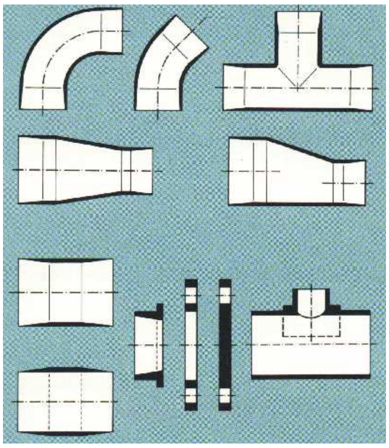

Fig. 1. Different pipe elements with bends, branches, flanges and cut-outs [8]

2. MANUFACTURING TECHNOLOGY

Braiding technology plays a leading role within the variety of textile manufacturing processes employed to produce pipe elements from novel textile composite materials. In contrast to the winding technique, braiding technology is, for instance, lower cost because it is a fast, automated textile surface process and is also characterised by a very high degree of variability of reinforcing arrangement. The braiding process has undergone further development in Germany in recent years, leading to the manufacture of technically reinforced preforms that closely follow the final contours; it has already achieved a high degree of technological maturity. A study conducted by Boeing (formerly McDonnell Douglas Aerospace) has found that the costs of braiding vis-à-vis winding costs can be reduced by more than half. These savings are due, firstly, to the amount of time that can be saved and, secondly, to the simplification possible in the reinforcement design, in particular for flange and fork elements [9].

Whereas hose-shaped textile preforms can be manufactured with the aid of conventional braiding processes, new process modifications such as, for example, shape braiding enables the manufacture of complex, multi-bend preform structures. In addition, computer-aided traces/winding configurations as well as the interlacing of standing threads can be employed to achieve a genuinely 3D reinforcing weave. A particularly broad variety of design possibilities is achieved if braiding machines are used in combination with multi-axial robots that permit spatial movement of the braiding mandrel (Fig. 2). This creates the possibility, for example, of manufacturing load-adapted reinforced T-pipe pieces in hybrid construction in one work stage, where the thermoplastic interior liner itself is already acting as a braiding mandrel. Over and above this, integral strong flange constructions can be interlaced in the same work stage [10].

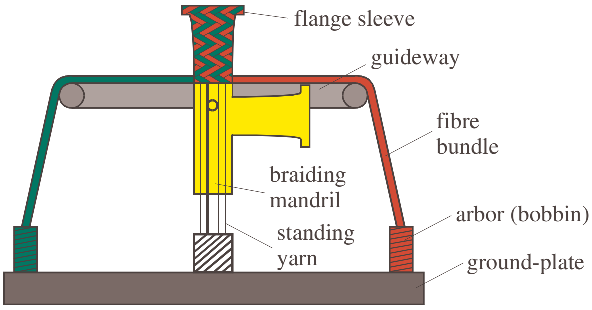

Fig. 2. Schematic diagram of the braiding machines to manufacture T-piping

To manufacture textile preform shapes from 3D brains of complex geometry that closely follow the final contours, the braiding machine depicted in Fig. 3 is used in conjunction with a 6-axial robot. In the process, not only the conventional resin infiltration by means of vacuum process is thoroughly investigated but also hot braiding with glass fibre thermoplastic hybrid yarn that permits an in-situ consolidation of the pipe structures during the braiding process. The finished technology demonstrators are then subject to appropriate structural component testing. The recorded findings serve to verify the design concepts that are to be developed to ensure a safe dimensioning of textile reinforced pipe elements and are arrived at in the course of the AiF Project 13646 BR.

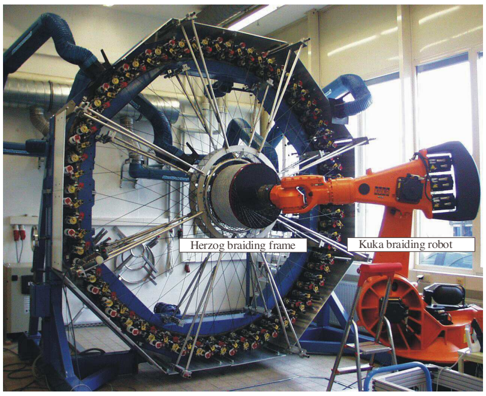

Fig. 3. Herzog braiding frame with Kuka 6-axial robot /EADS/

3. DESIGN OF MULTI-LAYERED CYLINDRICAL STRUCTURES

The mechanical as well as hygrothermal structural behaviour of the woven, balanced (WB) basic layer forms the basis for calculating pipes as multi-layered composite shells. Depending on the type of reinforcement, WB basic layers display to a greater or lesser extent a highly covered and crossed fibre and textile structure that cannot simply be separated into UD individual layers as part of the stress strain test or failure analysis [11].

In the fibre-adapted coordinate system, in which the material constants are usually given, such a WB basic layer possesses anisotropic material structure. The calculations are carried out in a global coordinate system in which the WB basic layer also displays anisotropic material behaviour. Polar transformation then enables the material properties of the layers to be known in this component-specific coordinate system. To calculate the multi-layer fibre-reinforced cylinder shell, the composite is conceived as being broken down in WB basic layers of random fibre orientation. The stress-strain analysis of composite structures made of reinforced woven basic layers can then be effected, despite the complicated fibre architecture, by means of layer theories (for example, the classical laminate theory), in which, if necessary, the mentioned structural homogeneities are considered in terms of weave-specific reducing coefficients. After solving the described differential equations for every WB basic layer the layers are united by means of boundary conditions, a complete adhesion between the layers being assumed. Moreover, depending on the problem even more boundary conditions, both for the deformation and stresses as well as for the temperature and media concentration, generate unexpectedly high internal stresses on account of the direction-dependent properties. The extremely complicated structural-mechanical relationships and the manufacturing parameters which are usually difficult to determine often mean in practice that the stresses induced by the temperature and media are often not taken into account in the evaluation. On highly precise applications, such influences can, however, no longer be neglected, in particular, when constructional reasons lead to an interruption of the flow of force in the fibres [12].

Different failure models are required corresponding to the typical reinforcements of the composite structure that permit a realistic description of the failure behaviour of WB basic layers. These models must cater both for individual layers as well as multi-layer composites. So-called action plane-related and fracture mode-based failure criteria are used as a basis for a realistic failure analysis that were verified by extensive single and multi-axial fracture tests [11].

4. FRACTURE MODE RELATED FAILURE CRITERIA

It is only the development of new so-called failure mode related failure criteria that has enabled, with the aid of realistic fracture conditions, a physically based description of the prevailing failure modes of braided composite structures. In accordance with this, the action plane related criterion of Hashin/Puck and the invariant criterion of Cuntze can be applied after modification for the failure analysis of braided pipe test pieces.

4.1. The action plane related failure criterion of HASHIN/PUCK

For the formulation of the action plane related failure criterion to evaluate 3D stress states, Hashin/Puck follow a completely new avenue in relation to the standard raft of interaction criteria. This criterion accommodates not only the decisive difference between fracture modes fibre fracture (FF) and inter-fibre fracture (IFF), but also contains a fracture angle as a free parameter that characterises the further fracture modes in the plane parallel to the fibre. Furthermore, attention needs to be paid so that corresponding material mechanical laws and phenomenological observations as well as compressive stresses vertical to the fibres in accordance with experiments prevent an inter-fibre fracture.

On the basis of this hypothesis, Hashin/Puck recorded the failure modes fibre fracture and inter-fibre fracture in different failure conditions, the stresses acting in the fracture plan being used to formulate the failure conditions. This presupposes that the fibre failure is triggered solely by the stress σ_1 parallel to the fibre and remains uninfluenced by other stresses that arise. A maximum normal stress criterion is applied for the numeric description of the fibre fracture.

The fracture conditions for inter-fibre fractures are perceptibly more complex compared to the FF criterion as different forms of failure such as adhesion fracture of the fibre matrix boundary surface or cohesion fracture of the matrix as well as various failure modes such as tensile, longitudinal shear and transverse shear failure need to be described realistically. Here, Puck formally assumes a mechanical fracture as the cause in the formulation of the IFF condition [13], which was demonstrated for the first time by Hahn. In accordance with this, micromechanical defects such as pore and hardening cracks are the origin of macromechanic cracks.

4.2. Fracture mode concept in invariant representation by CUNTZE

To improve the practical use of physically based failure criteria, Cuntze has developed a new approach to tackle problematical aspects of the Hashin/Puck criterion. One of these aspects is that the effective plane resistance $R_{\perp\perp}^{A}$ introduced by Puck cannot be directly measured experimentally so that no directly statistical verification of strength can be conducted. Another aspect is that composite failure does not always lead to a fracture plane in the sense of the hypothesis proposed by Mohr, such as, for example, can be the case with textile reinforced fibre ceramics. Moreover Cuntze assumes that micromechanic and statistical interactions, in particular during superimposed loading, cannot be clearly differentiated from each other. Cuntze took account of these factors by devising a failure mode related strength criterion that he formulated as an invariant representation in order to enable universal application, whilst simplifying mathematical handling [14].

5. ADAPTED TEST PROCEDURES TO VERIFY THE FRACTURE CRITERIA

To verify experimentally the fracture mode related failure criteria, it is necessary to develop adapted test techniques that enable a targeted multi-axial application of load. This is why test procedures for tension/compression torsional tests (T/C-T tests) and compression-internal pressure tests (C-p tests) on unidirectional (UD) and bidirectional (BD) reinforced pipe test pieces were devised to enable strength investigations in the (σ_1, σ_2, τ_{21}) stress space to be conducted. Fig. 4 shows the institute's own pipe test stand.

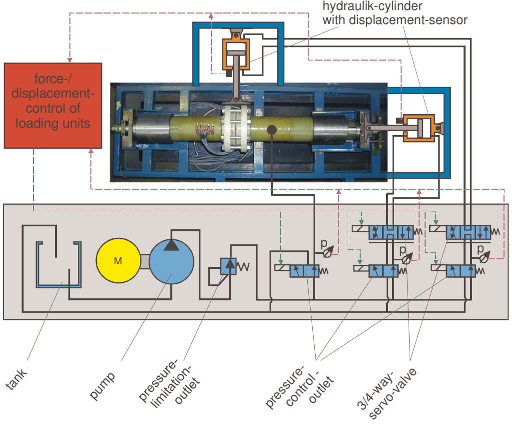

Fig. 4. The institute's own pipe test stand for superimposed loading T/C-p tests)

5.1. Tension/compression torsional tests

In the T/C-T tests the failure-critical stress combination along a prescribed path of loading was produced with the aid of a further developed load-controlled multi-axial test machine with an adapted elongation-twisting extensometer. This extensometer allows the elongation and the distortion to be recorded as well as the successive course of failure.

The tests carried out on the braided pipe test pieces serve, on the one hand, to determine fracture stresses as well as the associated fracture angles, and, on the other hand, to characterise the elementary fracture types (Fig. 5). Moreover, the knowledge of fracture angle and fracture mode enables a detailed description of the complicated failure phenomena encountered with braided composite structures. The fracture curve of the (σ_2, τ_{21})-stress plane contains, for example, the fracture types transverse normal fracture and transverse-longitudinal shear fracture. The large amount of information that the T/C-T test supplies permits initial fundamental physical fracture phenomena to be explained and demonstrates the inadequacies of general fracture criteria (for example, the Tsai-Wu failure criterion).

Fig 5. Different fracture modes of braided pipe test pieces under superimposed loading

5.2. Compression- internal pressure tests

In order to analyse the failure behaviour, in particular of braided composites under combined tension/compression loading (σ_1^+, σ_2^--stress plane), a compression-internal pressure test apparatus was developed [15]. The tensile stress σ_1^+ is applied by internal pressure, while the axial pressure force induces the stress σ_2^-. The compression stress σ_3^- of up to 10 MPa generated by the internal pressure is initially not considered in the failure analysis. Within these tests, it is analysed, how far the fracture modes mutually influence the tensile brittle fracture and compression instability failure.

6. CONCLUSIONS

The demand for a high degree of lightweight construction is, for scientific and technical interests, increasingly becoming the focus of design efforts in the development of a new generation of structural components in vessel and pipe construction. Currently, in the sense of a function integrating lightweight construction, endeavours have not only focused on a pure reduction of weight but also on designing a generally economical product cycle to reduce any warehousing, transport and assembly costs.

Research work on the employment of textile and, in particular, the braiding technology for the cost-effective manufacture of piping elements from fibre plastic composites is venturing into virgin territory of the greatest practical significance for innovative developments in apparatus and plant construction with synergy effects for other structural components.

The calculation and dimensioning concepts devised as well as the braiding investigations conducted on selected pipe structures constitute an initial basis for the configuration, design and manufacture of such piping elements. The rigidity parameter functions and strength coefficient of the different glass fibre reinforced plastics determined in multi-axial loading tests have been collated for this. The calculation models developed and design directives are to be prepared for new standards in easy to use formula or design directives. This format provides the design engineers with a practice-focused tool.

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