BRAIDED COMPOSITE PIPE ELEMENTS FOR APPLICATIONS IN CHEMICAL APPARATUS ENGINEERING

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SUMMARY: Advancing globalisation in chemical apparatus construction is leading to higher demands regarding efficiency and performance on 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 connected technical demands 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 regarding 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. This paper covers the significant design aspects varying from the efficient manufacturing technology to the calculation of multi-layered cylindrical structures made of braided composites.

KEYWORDS: Pipe elements, textile composites, braiding technology, material characterisation, failure criteria, testing

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 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. 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. These trends are of enormous practical importance for pipe elements in chemical apparatus construction. Thus, extensive research work on the efficient employment of braiding technology to manufacture textile reinforced pipe elements is currently underway.

MANUFACTURING TECHNOLOGY

Braiding 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. A study conducted by BOEING 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 [8].

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 yarns 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. 1). 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 [9].

To manufacture textile preform shapes from 3D brains of complex geometry that closely follow the final contours, a braiding machine (Fig. 1) 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.

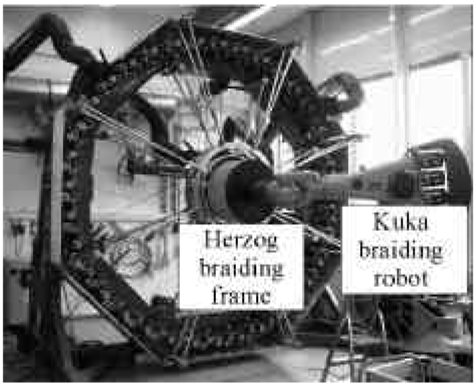

Fig. 1. Herzog braiding frame with Kuka 6-axial robot /EADS/

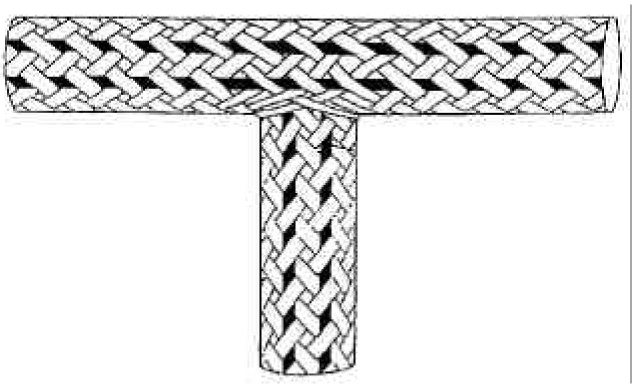

Fig. 2. T-pipe piece with braided reinforcement and standing yarns [5]

For the braiding process of novel pipe elements (like T-pipe pieces, Fig. 2) with load adapted reinforcement, adapted braiding strategies have been developed. They enable an optimal use of the available reinforcing potential and the substantial scope of design of the reinforcing braided structures and subsequently also provide an extensive cost-saving potential compared to metal pipes or composite pipes made in winding technique.

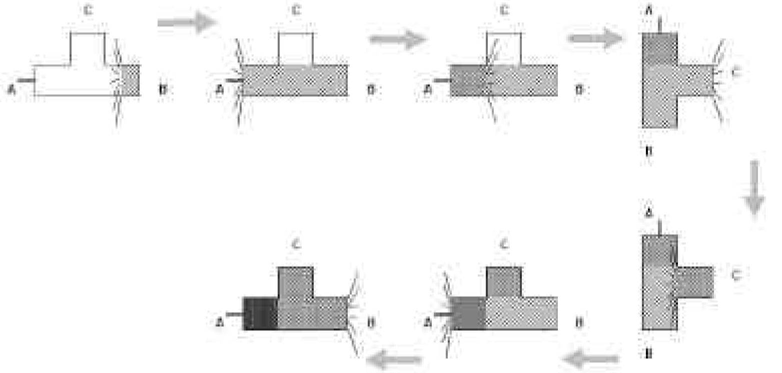

Fig. 3: Braiding strategy of a T-pipe without change of the clamping point in the multi-axial robot (point A)

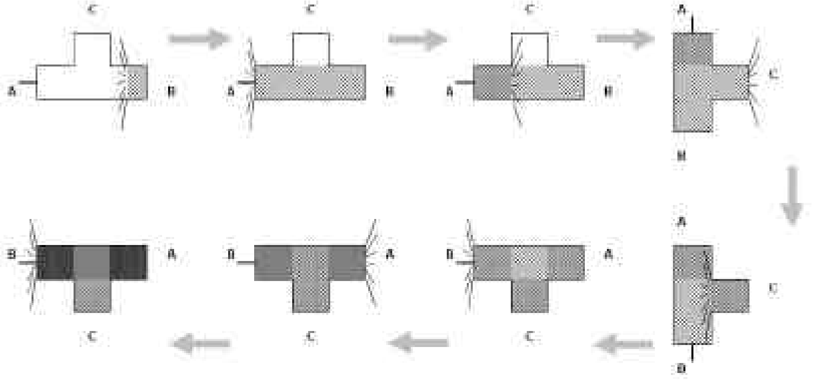

Fig. 4: Braiding strategy of a T-pipe with change of the clamping point in the multi-axial robot (from point A to B)

One important problem within the braiding process of T-pipes is the warranty of an equal number of braided layers in all parts of the structure. A symmetrical arrangement of reinforcing layers could only be achieved if clamping of the interior liner with the already placed fibres is changed during the braiding process (cp. Fig. 3 and Fig. 4) [10].

Due to stress concentrations, the highest stresses in the T-pipe will occur around the branch-off point. Thus, to guarantee a load-adapted reinforcement, additional braiding steps must be taken into account.

For that purpose, the T-pipe is turned during the braiding process to different ex ante calculated directions in order to ensure an optimal orientation of the fibres according to the loading directions (Fig. 5) [10].

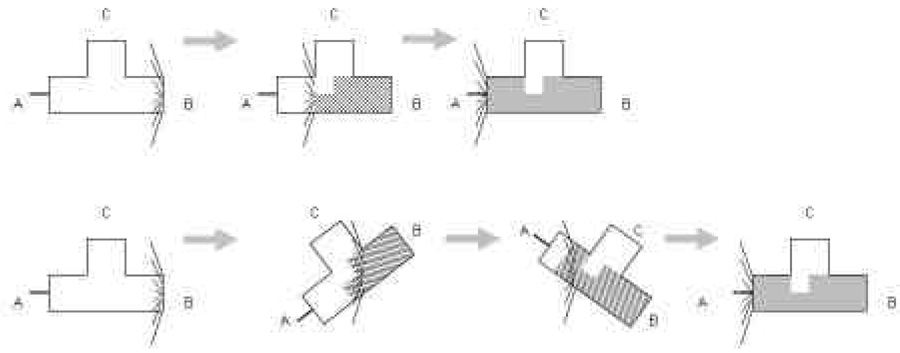

Fig. 5: Change of the braiding direction in order to improve the reinforcement in the branch areas of the T-pipe

Manufacturing of structural elements

In the production process of braided structural elements the braided hose is hoisted onto a cylindrical liner of the favored diameter using winding or woven sleeves techniques. The basic method of manufacturing of regular tube elements is shown in Fig. 6 and 7. In detail, the following work steps must be performed [11]:

- apply the resin on the liner or a metal mandrel,
- add the weave pipe (first layer, Fig. 6) and paint of the resin,
- winding of a roving in end of the tube (Fig. 7) and brushing of the resin,
- add the weave pipe (second layer),
- winding of the roving in end of the tube (a little more than in step one),
- add the weave pipe (third layer),
- winding of the roving in end of the tube and brushing of the resin.

These steps could be repeated until the final thickness of the pipe is achieved.

Fig. 6: Adding the weave pipe

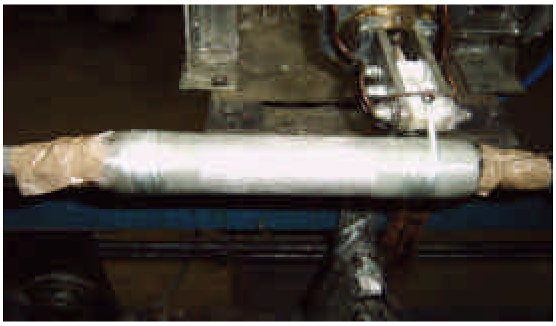

Fig. 7: Winding of the roving

In the next step, various finishing techniques have been tested for removing the resin overflow, air includes and flattening of impregnated fiber layers, achieving a smooth and homogenous outer surface. The chosen technique should be optimal in consideration of repeatability and costs of production. Especially the following finishing techniques were tested:

- Multiple applications of stretched fabric with pressure pad (weight round 3 kg) and removal of the resin overflow
- Use of thermo-shrinking sleeve (Fig. 8)
- Use of perforate thermo-shrinking sleeve
- Application of vacuum technology with gel technique
- Addition of antifoam component into the resin
- Wrapping with plastic tape
- Wrapping with fabric tape (Fig. 9)

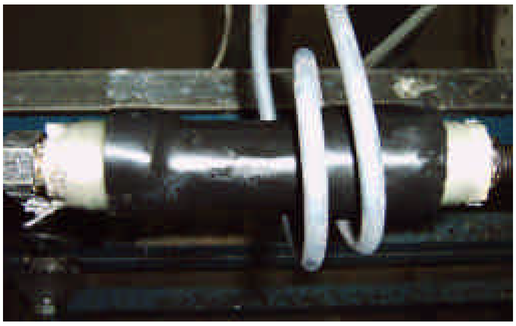

Fig. 8: Pressing of a thermo-shrinking sleeve

Fig. 9: Wrapping with fabric tape

Wrapping with fabric tape achieved the best results due to removing the air includes and also forming the external surface. The remaining methods have not assured sufficient outgassing of resin, formation of external surface, or the removal of surplus resin [12].

DESIGN OF MULTI-LAYERED CYLINDRILCAL STRUCTURES

An additional essential requirement is the appliance of a textile-optimised design strategy based on computational simulation models and experimental material characterisation. Thus, under consideration concerning manufacturing restrictions, the material properties of the anisotropic braided composite structure could only be optimally adapted to the acting loads by means of this design strategy.

Based on the performed theoretical and experimental investigations regarding the material characterisation of basic braided tube structures, the dimensioning of selected hybrid pipe elements (with or without bifurcations) takes place. In detail, the succeeding tube shapes with inner liners and bolted joints have been analysed using FEM as well as analytical methods [13]: tube section, reducer, T-piece, bow fitting 45° and bolted joint.

Experimental material characterisation

The knowledge about material behaviour of braided composites under multi-axial loading conditions is not very deep so far. However, for a reliable application for complex lightweight components, a realistic description of the stiffnesses, the failure behaviour and the successive degradation behaviour is particularly necessary. For this purpose, several tests with flat specimen and tube specimen were performed in the institutes own testing devices to observe the phenomenological background of the material behaviour [13, 14]. Several lay-ups and loading paths have been chosen according to Tab. 1.

Adapted test procedures

To verify experimentally the fracture behaviour of the novel braided pipe elements, 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-torsion tests (T/C-To tests) and compression-internal pressure- tests (C-p tests) on complex reinforced pipe test pieces were devised to enable strength investigations in the (σ_1, σ_2, τ_{21}) stress space to be conducted [15]. 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.

Tab. 1: Performed basic tests

Braiding angle	loading														
	uniaxial flat specimen						uniaxial tube specimen				biaxial tube specimen				
	T 0°	T 45°	T 90°	C 0°	C 90°	S 0°	T 0°	C 0°	p1) 0°	To 0°	T-To 0°	C-To 0°	p2) 0°	T-p 0°	C-p 0°
30°	5	5	5	5	5	5	6	6	6	6	6	6	9	9	9
45°	5	5	5	5	5	5	6	6	6	6	6	6	9	9	9
60°	5	5	5	5	5	5	6	6	6	6	6	6	9	9	9
total	90						72				117				

1) pipe loading, 2) vessel loading

T: tension test, C: compression test, p: inner pressure test, To: torsion test, T-To: tension-torsion-test, C-To: compression-torsion-test, T-p: tension-inner pressure-test, C-p: compression-inner pressure-test

The tests carried out on the braided pipe test pieces serve, on the one hand, to determine stiffnesses, strengths as well as the associated material degradation, and, on the other hand, to characterise the elementary fracture types. Moreover, the knowledge of the fracture modes enables a detailed description of the complicated failure phenomena encountered with braided composite structures. The large amount of information that the T/C-To 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).

Among others combined tension/ compression – internal pressure – tests are performed [16]. Here, the tests pressure was achieved by the use of rubber as working medium. A heap of cylindrical rubber blocks with a height of 100 mm was put into the pipe. This heap was compressed bilaterally by steel pushers fixed in clamped support of tension testing machine (Fig. 10.). During this investigation the size of dislocation of rammers and increase of the compression force was recorded. Acoustic emission and the size of dislocation were the parameters of the destruction level of the composite material (Fig. 10).

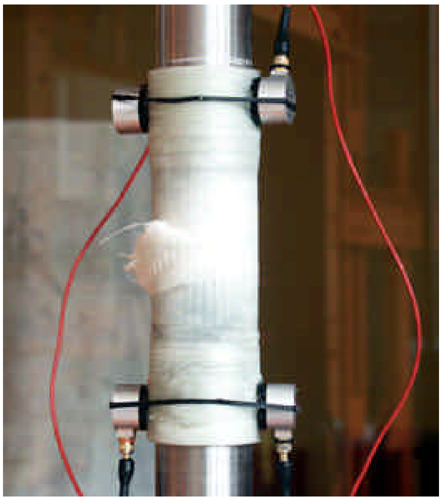

Fig. 10. Tube specimen during a C-p test

Dimensioning concepts

Analytical models

For the pre-designing of the heterogeneous tube lay-up of the selected pilot structures with braided reinforcement, analytical models basing on the homogenisation technique will be applied. Subsequently, the micromechanical heterogeneous fibre-matrix-composite could be phenomenologically treated as a mesoscopical structure with anisotropic properties. If continuum mechanics based methods are used, the anent braiding structure has to be controlled in respect of the demands made on the homogenisation technique, namely periodicity of the fibre arrangement and equability of the fibre form. Under these requirements, the constitutive equations for the anisotropic homogenised composite could be formulated and pre-designing becomes feasible [17].

The mechanical as well as hygrothermal structural behaviour of idealised uni-directional (i-UD) basic layer and the woven, balanced (WB) basic layer, respectively (Fig. 8), form 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 [18]. 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.

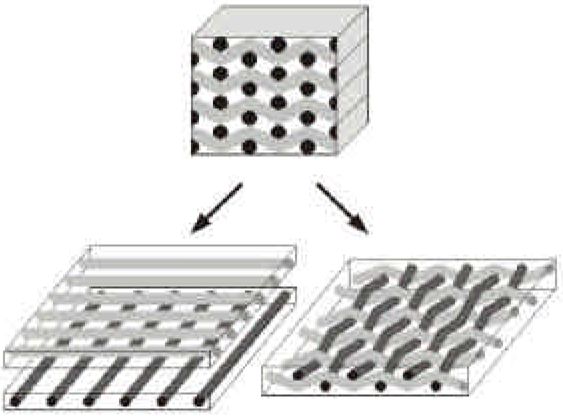
Fig. 11: Equivalent single layer model: idealised unidirectional (i-UD) layer and woven balanced (WB) layer [18]

Polar transformation then enables the material properties of the layers to be known in the component-specific coordinate system. 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.

Numerical models

Whereas the analytical methods of calculation provide fundamental and global valuable clues about the textile reinforcing system and the composite material, continuative finite-element simulations and further optimisations conduce to a best possible arrangement of the textile reinforcing structure in complexly loaded zones of the prototype pipes (tube section, reducer, T-piece, bow fitting 45° and bolted joint).

To analyse the complete structural behaviour of the pipes numerically, the braided tube elements have been modelled at large. The numerical stress analysis is performed using the FE-system ANSYS 7.0 [19]. For the meshing of the structures the shell element Shell 99 has been applied (Fig. 12). For every prototype pipe the critical points in the structure have been determined depending on the load (design load: 10 or 16 bar, limit load: 96 bar) and on the specific lay-up (±30°, ±45°, ±60° and others).

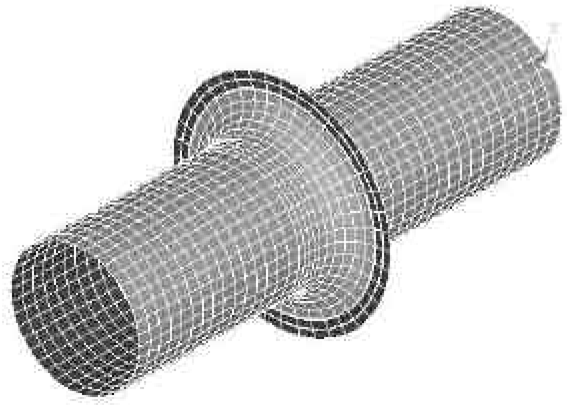
Fig. 12: FE-model of a bolted joint

The figures 13 and 14 exemplify these critical points and zones. It must be emphasized that the modelling of the exact fiber direction, especially in complexly shaped regions, is essential for a reasonable stress output. For the evaluation of the stress combinations at the various critical points, adapted failure criteria for anisotropic materials will be used. Analytical programs, such as ESA-COMP, as well as new failure criteria, such as the criterion of CUNTZE or PUCK, have been used to evaluate the areas of high stresses with respect to relevance of failure and residual load carrying capacity. Where required, the structural elements have been modified in terms of the thickness and the different layer orientations. The resulting optimised lay-ups (Fig. 15, 16) serve as a foundation for the dimensioning of pipe elements that need to be manufactured in the future.

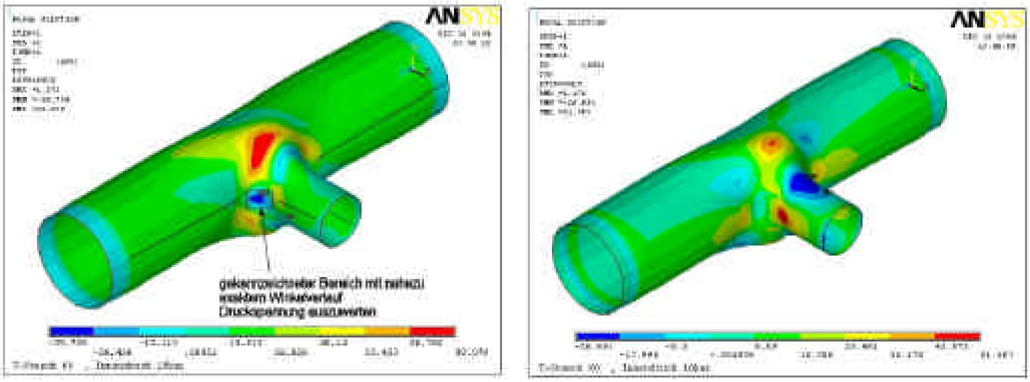

Fig. 13: gradient of the axial stresses of a T-pipe (±60°) with exactly modelled fiber orientation at the branch-off point (left) and with approximated fiber orientation (right)

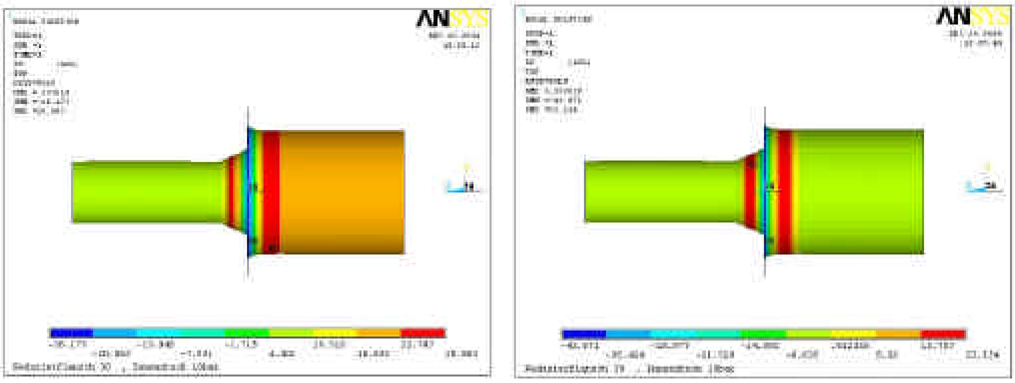

Fig. 14: gradient of the circumferential stresses (left) and the axial stresses (right) of a reducing bolted joint (±30°) at inner pressure of 10 bar

Layer	Angle	reserve factors
1	± 30°	1,27
2	± 45°	1,45
3	± 60°	2,37
4	± 60°	2,34
5	± 60°	2,32
6	± 60°	2,30
7	± 60°	2,28
8	± 60°	2,25
9	± 45°	1,50
10	± 30°	1,35

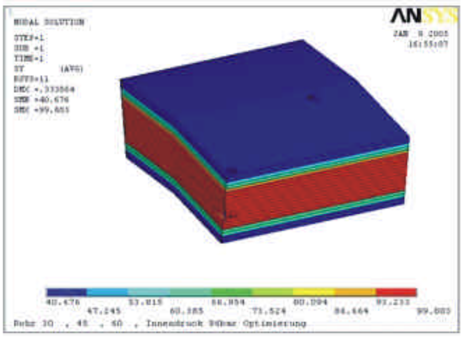

Fig. 15: Load optimised lay-up for elementary tube sections (96 bar)

Layer	Angle	reserve factors
1	± 45°	1,22
2	± 45°	1,21
3	± 60°	1,34
4	± 60°	1,31
5	± 60°	1,28
6	± 60°	1,25
7	± 60°	1,22
8	± 60°	1,20
9	± 45°	1,15
10	± 45°	1,14

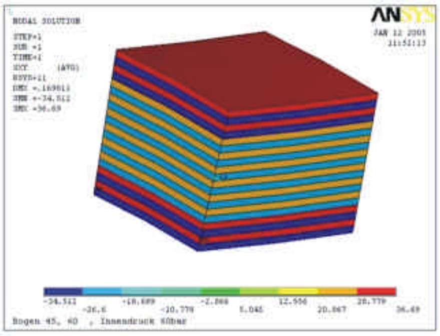

Fig. 16: Load optimised lay-up for bow fitting 45° (96 bar)

TESTING OF STRUCTURAL COMPONENTS

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. The performed tests contribute simultaneously to the 'Proof of Design' and to the verification of the developed dimensioning concepts, calculation methods and associated manufacturing technologies.

The prototype pipes (tube section, reducer, T-piece, bow fitting 45° and bolted joint) have been undergone to extensive structural tests in the institutes own pipe test stand (Fig. 17) [11, 13, 14]. For that purpose, the upgrading of the pipe test stand as well as the conception of selected structural tests became necessary. In doing so, hydraulic cylinders for axial loading and bending have been constructed. Thereby, the test loads must be designed according to the multi-axial operational loads. For the simulation of pipe loading, the prototype pipes have to be pressurized and bended by means of radial loading. The regulation of the hydraulic cylinder takes place using servo valves in a way that enables load control as well as strain control with the corresponding control unit. In contrast, to simulate vessel loading, the inner pressure and the bending force have to be applied together with a boundary condition where only one end of the pipe is clamped. Moreover, with an further axial hydraulic cylinder, additional axial forces could be superimposed with the afore mentioned loads. Such a loading unit enables the realisation of stress states between the "pure" pipe stress state and the "pure" vessel stress state. Due to the chosen realistic loading conditions, a direct transfer of the results to the chemical apparatus engineers is given.

Fig. 17: Assembly of the pipe test stand for superimposed loading (T/C-p-b tests)

CONCLUSIONS

The demand for a high degree of lightweight construction is 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. 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.

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