FLEXIBLE SPACER FABRICS FOR REINFORCEMENT OF RIGID POLYURETHANE FOAMS IN SANDWICH STRUCTURES

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ABSTRACT

The development and characterization of sandwich structures made from rigid polyurethane (PUR) foams reinforced with spacer fabrics offers a wide field of investigation. Due to the textile structure of warp-knitted spacer fabrics an intrinsic sandwich layer construction is given. The two textile surfaces are held by monofilaments at a defined distance. It is possible to manufacture spacer with a height of 65 mm. With its open diffusion thread architecture and the associated low mass and high dimensional stability, they can be used as reinforcement structure for fiber-reinforced composites. The polyurethane formulations must have the fluidity for penetration of the spacer fabric and has to be adjusted to the conditions of mechanical processing. The macro- and microstructure of textiles must be reconsidered and interpreted in terms of the function as reinforcement of foam molding. In this study the process for reaction injection molding of sandwich structures with warp-knitted spacer fabrics and polyurethane foam is investigated. A commercial PUR-foam formulation and different types of spacer fabrics, varying in the textile structure are used for the experiments. The impregnation of the fabrics with the PUR-foam is done in a closed mold with a rectangular cavity, thus molding a sandwich panel suitable for 3-point-bending test. For the textile reinforced polyurethane foams significant increases in both the absolute and the specific mechanical properties can be demonstrated. The textile structure achieves this with a fiber volume content of less than 5%. The reinforcement effect is caused by hindering the spacer threads in bending and buckling by the lack of space occupied by the PUR-foam. This results in a special deformation behavior of the composite structure.

1 INTRODUCTION

The development and characterization of sandwich structures made from rigid polyurethane (PUR) foams reinforced with spacer fabrics offers a wide field of investigation. Due to the textile structure of warp-knitted spacer fabrics an intrinsic sandwich layer construction is given. The two textile surfaces are held by monofilaments at a defined distance [1]. It is possible to manufacture spacer with a height of 65 mm [2, 3]. With its open diffusion thread architecture and the associated low mass and high dimensional stability, they can be used also as reinforcement structure for fiber-reinforced composites.

By local or complete filling of warp-knitted spacer fabrics with rigid PUR foam new fields of applications in lightweight constructions can be explored. The combination of warp-knitted spacer fabrics as reinforcement and PUR foam as surrounding matrix leads to characteristic reinforcement effects due to the textile structure in three-dimensional arrangement [4-6]. PUR foam is produced by the chemical reaction of polyol, and di- or polyisocyanate. The foam expansion results from the released carbon dioxide [7]. By varying the PUR formulation rigid or flexible foams can be produced in comparable processes. Since the reactants have a high fluidity and expand during the cross linking reaction, specially adapted mold design is required. During the reaction the viscosity decreases due to the CO2 propellant, which promotes the penetration of the complex textile macro structure and impregnation of single filaments with the foam [8]. At the same time a temporary ongoing fluid pressure in the cavity builds up through the foam expansion. Sink marks are avoided, integrated reinforcing components are mechanically stressed only slightly and structural shifts are largely excluded. From this and from the reductions in weight due to the cellular foam structure results the high potential of such lightweight composite materials.

To maximize the lightweight a minimal amount of reactants will used, which is sufficient for the complete penetration of the textile reinforcement. Otherwise the PUR density will rise without any further benefit. However, an expansion inhibiting effect of the spacer threads is known, which inevitably leads to a compression of the foam and the demand for increased reaction amounts [4-6]. To assess the specific mechanical performance of composite structures a appropriately targeted overfill of the mold cavity with polyurethane reaction mass is made for reference samples, which consist exclusively of foam and have composite foam comparable bulk densities.

For the prediction of the resulting pore distribution and density, the modeling and simulation of the propagation characteristics of PUR is of vital importance. Also the process parameters such as pressure and temperature can be estimated. The quest for optimally controlled molding processes has led to the formulation of various mathematical models capable of describing mass and heat transfer in reacting PUR setups; either from a mesoscale view [16, 17] or macroscale view [18-21]. The modeling of the flow behavior of PUR foam through textile structures during reaction injection molding is much more complicated due to the consideration of the flow resistance of the textile structure and is subject of future work. We use CoRheoS; a complex rheology simulation platform developed at Fraunhofer Institute for Industrial Mathematics, Kaiserslautern, Germany. It predicts the complex dynamics exhibited by the reacting isocyanate - polyol mixture in the production process of PUR foams. This is done in a first step without the presence of the warp-knitted spacer fabric.

The focus of the experiments in this study is to determine the mechanical properties of the novel composite structures to ensure an application-oriented design method. The individual components PUR foam and spacer fabrics are examined by the same methods to draw conclusions about its influence on the mechanical properties of the composite. In comparisons of the characteristics of the three different types of material (PUR foam, warp-knitted spacer fabric and composite of both) special consideration is given to the bulk density and its influence on the properties. It is generally true that the sum of the bulk density of the individual components is equal to the density of the composite structure. For a direct comparison between the textile reinforced foam and pure foam specific characteristics will be considered taking into account the average specific bulk densities.

2 EXPERIMENTAL

2.1 Materials and processing effects

In the present study, a commercially available polyurethane rigid foam formulation was used. The mixing of chemicals and the discharge of the reaction mixture were realised with a two-component mixing and dosing low pressure system of Unipre GmbH. The volume expansion and hardening of the foam took place in a specially designed mould tooling system made of aluminum. The cavity (500 mm length x 50 mm width x 40 mm height) was filled with the reaction mixture via a runner system and slot gate of 0.6 mm height. It ran across the entire length in a height of 15 mm. The geometry of the formed test specimen was a prerequisite for the performed material tests. For the production of textile-reinforced composite structures 3D knitted fabrics were positioned as inserts in cut-outs, which were largely consistent with the cavity measurements in the moulding tool. For this study, two compact 3D-knits were selected. Details of their construction are shown in Table 1 below.

Both spacer fabric 1 (SF1) and spacer fabric 2 (SF2) are made of polyester yarns and are similar in terms of bond, 3D structures and 3D thread densities. From the comparable textile technological parameters result approximately similar fibre volume contents (FVC) of less than 5%. Accordingly low bulk densities (W/V) establish the lightweight potential of 3D woven fabric for use as a reinforcing structure. Striking difference between the selected spacer fabrics is their height, which is 40mm in SF1 and 20mm in SF2. In order to test comparable composite materials 40mm high test specimens were produced in which the 3D-knitted fabric SF1 single-layered and the 3D-knitted fabric SF2 double-layered as reinforcement for rigid polyurethane foam were used. In the case of SF2 the foam must therefore expand for the complete filling of the reinforcement structure in the Z-direction by two superimposed knitted fabrics with compact surface.

Spacer fabric		SF1	SF2
H	[mm]	40	20
W/V	[kg/m^3]	61	68
$\phi_{surface}$	[%]	8.0	9.5
FVC	[%]	4.4	4.9
$N_{monofilaments}$	[1/in^2]	520	416
$\varnothing_{monofilament}$	[mm]	0.2	0.2

Table 1: Textile construction of the warp knitted spacer fabrics [5]

This can result in two different foam structures in the two 3D layers. Table 1 lists regarding this the macroscopic surface porosity of the tow different textile fabrics. Less than 10% of a knitted 2D surface is freely permeable to the foam spread. Additionally, the slight microstructural permeability of the threads comes into play. Table 1 also lists the distance number of threads per square inch and the distance thread diameter. The variety of over 400 very fine barriers to expansion per square inch illustrates quantitatively the enormous influence by the textile insert on the foam propagation. Nevertheless, both SF1 single-layer and SF2 two-layer were completely filled with foam in the described production process, which is shown in Figure 1 on an exemplary composite structure and the two textile 3D designs.

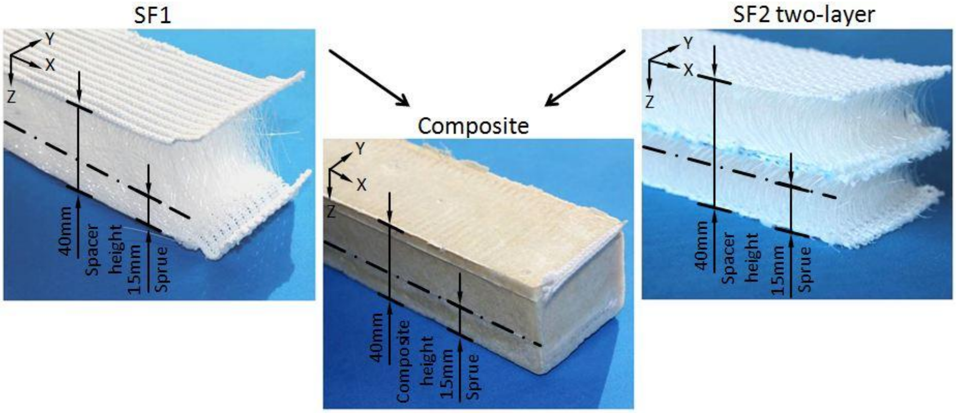


Figure 1: Spacer fabric 1 (SF1) and Spacer fabric 2 (SF2) two-layer for manufacturing of textile-reinforced PUR rigid foam composites [5]

Despite the described very low fibre volume contents the complex structure of the spacer fabrics affects with its fine and regular thread arrangement the foam spread to a considerable extent, so that about 80% more chemicals were necessary to complete the cavity filling compared to the minimum amount in the foaming of the free cavity space. The desired low densities of the composites would be thus relativised, but special interest for the specific material power arises as well. In the manufactured series of composite structures fibre mass contents formed of each about 40%. The approximately equal densities of the rigid foams of 106 kg/m³ contained therein for SF1 and 96 kg/m³ for SF2 are within typical process and product tolerances. Corresponding series of reference samples which consist exclusively of rigid foam were also produced.

2.2 Material testing and results

The characterisation of the novel composite structures takes place primarily by identifying their mechanical properties and characteristics in order to make application-oriented designs. In addition, the single-component PUR foam and spacer fabrics are investigated by the same methods to draw conclusions about their influence on the mechanical properties of the composite. Comparing the characteristics of the three different types of material, the bulk density and its influence on the property profile will be given special consideration. Generally, the sum of the densities of the individual components is equal to the density of the composite structure. For a direct comparison between textile reinforced and pure foam specific characteristics will be considered regarding the middle densities.

Bending properties

The 3-point bending test was performed for both composite structures and their individual components in accordance with DIN EN ISO 178. Adaptations to the norm can be justified entirely by the tool and process-specific test specimen dimensions (500 mm x 50 mm x 40 mm). Figure 2 shows the recorded, typical measurement curves to the bending stress courses of the three materials.

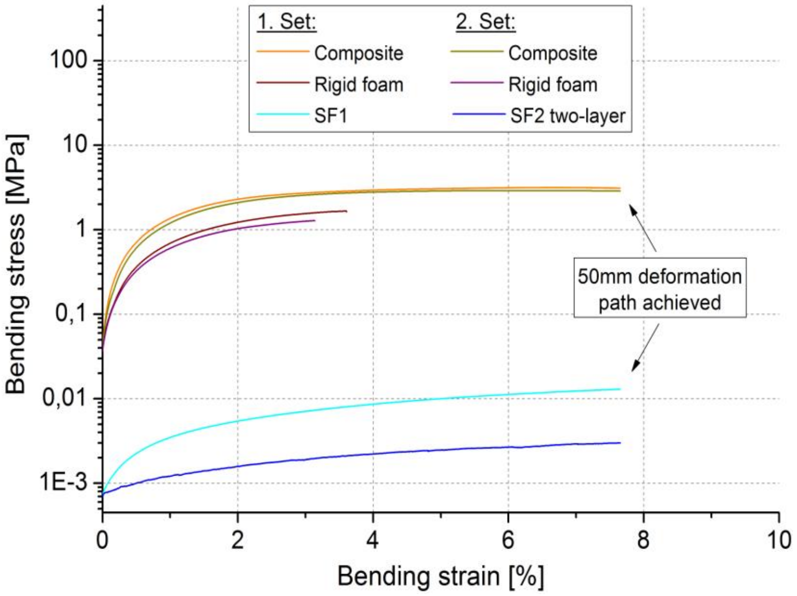


Figure 2: Exemplary measurement curves (left) and characteristic values (right) of the bending test according to DIN EN ISO 178 of composite structures and their components

The results indicate clearly significantly different material behaviour. Due to the expected compliance of spacer fabrics to bending stress, they show little resistance with bending stresses of up to 10 kPa, however, they pass completely through the deformation path restricted to 50 mm (ie 7.5% bending strain) and then remain without structural damage in their bent state. The reference foam beams reach bending stresses of over 1.2 MPa, but fail at about 23 mm on the bending path with a brittle fracture, which is exemplified in Figure 3 on the left.

By reinforcing the rigid polyurethane foam with 3D knitted fabrics the bending stiffness and bending strength are doubled compared to the unreinforced rigid foam. However, particularly outstanding is the qualitatively completely different deformation behaviour of composites. The significant increase in flexural strength of about 3 MPa remains almost intact on the limited technical testing deformation path of 50 mm. The hard-rigid composite structures are seamlessly bent with minor structural material damage at the point of load introduction and deform after discharge by about 70% to original state (Figure 3, right). Thanks to the combination with the pliable textile 3D knitted fabric a good-natured failure behaviour emerged from the catastrophic fracture behaviour of the foams.

Figure 3: Process of the bending test according to DIN EN ISO 178 (snapshots) of a reference foam sample (left) and a composite specimen of the SF2 series in two layers (right) [5]

To determine precise mechanical parameters ten specimens of both composite structures and individual components were subjected to the bending test and the results were statistically analyzed. Furthermore, for the direct performance comparison specific parameters were calculated taking into account the different densities of sample materials. Figure 4 summarises this. In addition to the significant increases in flexural strength and flexural modulus in the absolute comparison of characteristic values, the composite structures achieve higher characteristic values in the specific comparison. Compared to the non-reinforced polyurethane rigid foam, a basis for the generation of lightweight structures with simultaneous extended properties profile in the composite material is thus created.

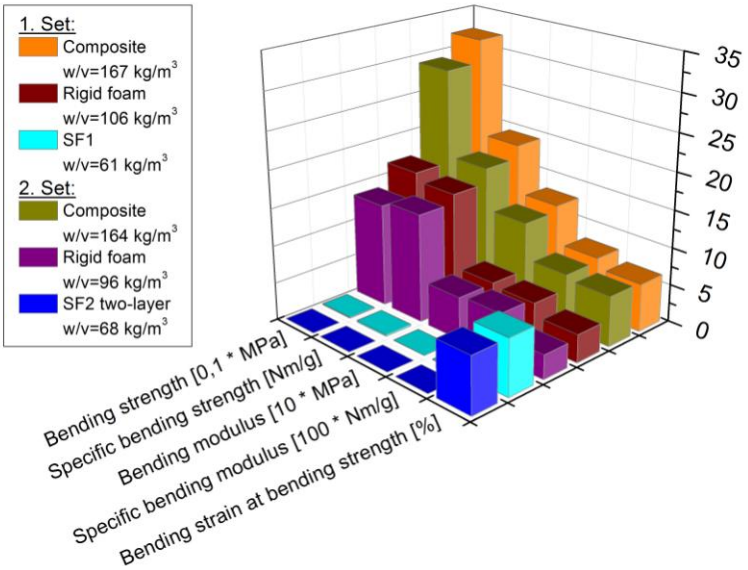


Figure 4: Summarized properties of the composite structures and their components in the bending test [5]

Pressure properties

The pressure test of the elastic spacer fabrics was carried out according to DIN EN ISO 3386-1. This provides for a four-time compression of the specimen at 30% of its original height. In the last loading cycle, the characteristic values are acquired. For the pressure test of rigid composite structures and their reference foams DIN EN ISO 844 was used, which defines a unique deformation to 85% of the original sample height. To allow comparability with soft elastic material, the deformation path was extended and chosen to be identical to DIN EN ISO 3386-1. Apart from the number of load cycles and the predetermined deformation path both norms are consistent in the relevant provisions and therefore can be compared to one another. With the methodology used, the pressure-elastic behaviour of 3D knitted fabrics in the material comparison with the rigid foams is taken into account. For the norm-compliant implementation of the materials testing, the beams produced were cut into test specimens of geometry 50 mm x 50 mm x 40 mm. Figure 5 shows exemplary measurement curves of the performed pressure tests, which illustrate the characteristic differences between the types of materials. The spacer fabrics show compressive stress values of about 10 kPa in the range of 20% to 70% compression. The hundred fold of this performance is achieved by the foams and the 3D knitted foam composites.

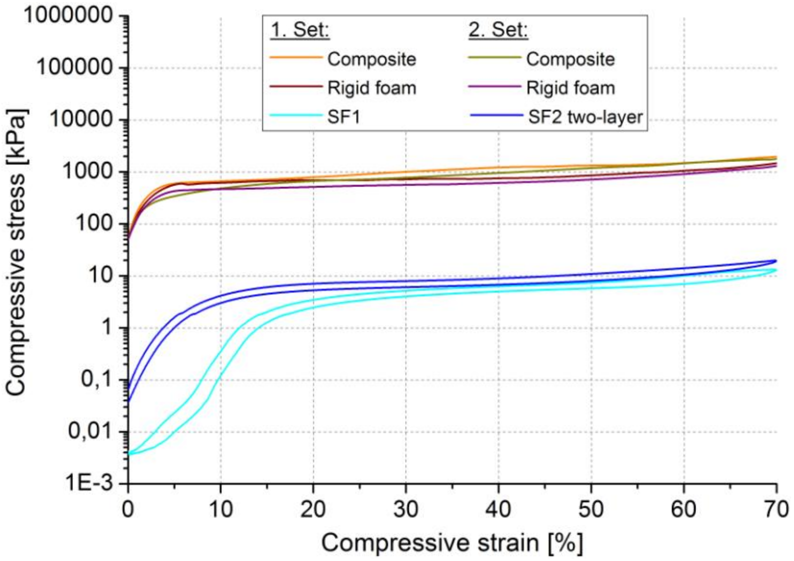


Figure 5: Exemplary measurement curves of pressure testing of composite structures and reference foams according to DIN EN ISO 844 and the 3D knitted fabric according to DIN EN ISO 3386-1

By comparison, the super soft elastic 3D textiles deform immediately when released, minus a minimum reduction, almost completely to their original thickness. In contrast, both the reference foams and their textile-reinforced composite structures reach after the pressure relief only 60% of their initial thickness. The reasons for this are permanent plastic deformations. In addition, a strong influence of the spacer threads on the deformation behaviour of composite test specimen when loaded in the Z-direction can be seen, shown in Figure 6. The spacer threads pull the foam in the X-direction with their original curvature. The composite was given a preferred direction in the deformation behaviour. This concludes inter alia to good bonding of the polymer matrix to the textile reinforcement structure.

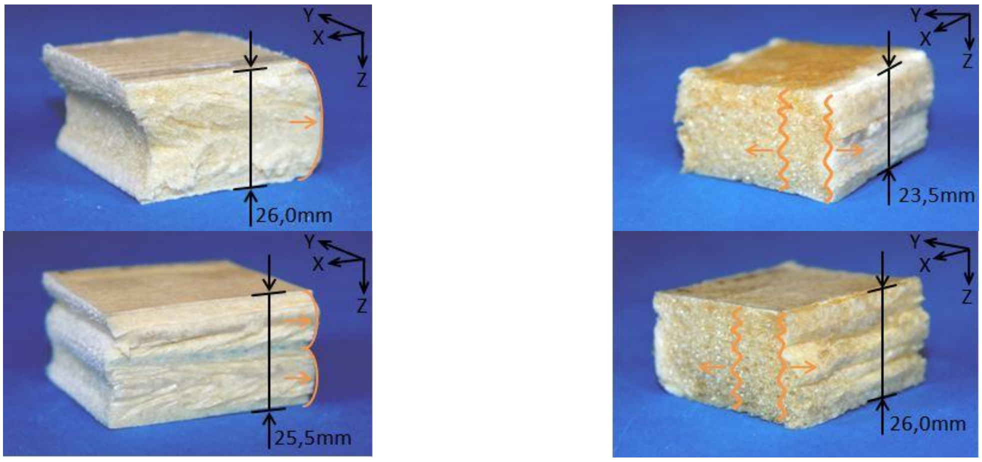


Figure 6: Permanent deformations of composite structures (left) and the reference foams (right) of the series SF1 (top) and the SF2 series in two layers (below) [5]

Moreover, a distributed load capacity was determined in the composite structure of the two-layer spacer fabric, which is due to the increased expansion inhibition in the central area of the test specimen during production (Fig. 1). As a result, during the penetration of PUR-foam in the bottom and top half of the composite two different foam phases formed. Weight measurements of the composite structure individual layers showed 12% more polyurethane foam composition in the upper layer, which leads to a specific load-bearing behaviour. Under pressure, the more unstable lower layer was first deforms before the top layer was also compressed by increasing deformation. In distinction to the declining compressive stress behaviour of the composite structure of series 1, this results in a progressive characteristic course.

For the determination of the average mechanical properties 25 specimens of both composite structures and their individual components were subjected to the pressure test. Using the example of the compressive stresses and the bulk modulus (stiffness pressure), the absolute and specific material properties were compared (Fig. 7). An increase in the absolute voltage characteristics through the textile 3D reinforcement of the rigid foams in the larger deformation zones was clearly identified. However, the single-layer structure has a much greater influence on the compressive stress characteristics compared to multi-layer constructions, which in the compression module drops behind the reference foams in the two-stage load-carrying behaviour. In the specific characteristics the composite structures with integrated 3D knitted fabrics and thus higher component masses, under otherwise identical rigid foam densities, bear a higher weight. The series with SF2 falls despite high absolute mechanical characteristics with its specific performance behind the foams. The mass influence is less pronounced in single layer reinforced 3D knitted rigid foam composites. This provides therefore the greatest performance improvements and a high degree of lightweight degree under pressure load. From an advanced compression of approximately 25% to 65% a specific, effective increase in performance has been demonstrated.

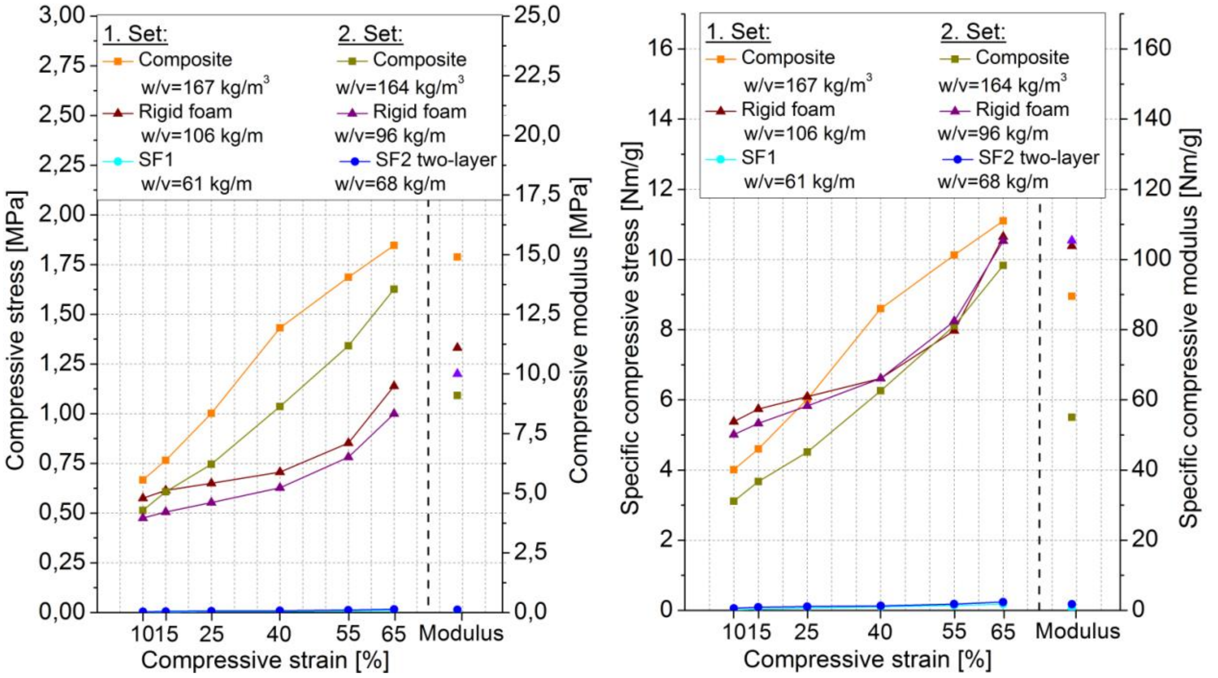


Figure 7: absolute (left) and specific (right) characteristics of the pressure testing of composite structures and reference foams according to DIN EN ISO 844 and the 3D knitted fabric according to DIN EN ISO 3386-1 [5]

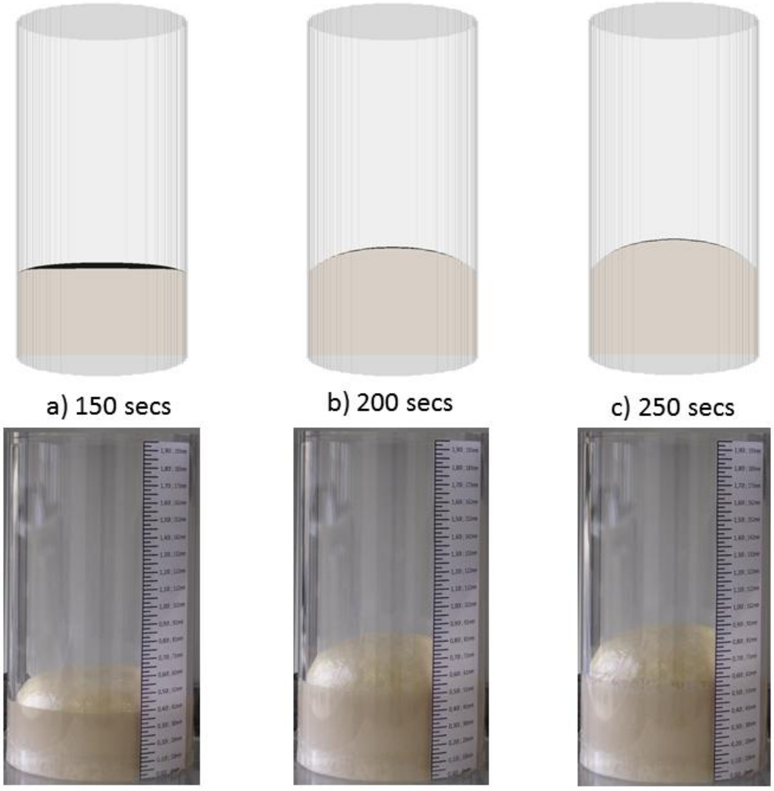
3 SIMULATION OF PUR EXPANSION

The simulation of the PUR expansion process gives important informations of the flow front behavior, necessary amount of the reactants and resulting pore density. The textile structure leads to a compaction of the PUR foam, which must be considered in the calculation of the bulk density. In a first step, the simulation of the PUR expansion is done with a novel experimentally motivated mathematical model capable of predicting the complex dynamics exhibited by the reacting isocyanate-polyol mixture in the production process of PUR foams. The experimental setup consists of a premixed mixture of reactants in a homogeneous phase, injected into a calibrated tube of known volume. The material is then allowed to expand and rise in the tube, while the expansion volumes are recorded as a function of time. For the simulation CoRheoS; a complex rheology simulation platform developed at Fraunhofer Institute for Industrial Mathematics, Kaiserslautern, Germany is used. The complex rheology solver is developed to simulate the flow behavior of polymer systems, polymer suspensions and flow of fluids through porous media. The solver is considering that the viscocity is non-constant but depends nonlinearly on flow parameters. Generalized Navier-Stokes and Navier-Stokes-Brinkmann equations for macroscopic description of flow behavior in cavities with and without porous textile media were used, respectively. This was first presented in [9] with a numerical approach to simulate injection molding processes for problems, where the considered geometry posses both free fluid and porous parts simultaneously.

In this study for the mathematical formulation the dependence of material viscosity on the cure/polymerization rate, gas volume fraction and non-isothermal temperatures as well as independence of mixture density on pressure is assumed. The foam curing is modeled with an adapted Kamal type model [10]. The fluid viscosity is seen to increase with decrease in temperature and increase in polymerization values as the gelling point is approached. Stable numerical simulations are thus satisfied by a full implicit discretization of the viscous term in conservation of momentum equation without necessarily decreasing the time steps, whilst the fluid viscosity increases. A Chorin algorithm is employed as discussed in [11] (and with successful implementation in [9, 12, 13] for non-Newtonian fluids), to resolve conservation of mass and momentum equations. The dynamics of the system are described with unsteady nonlinear coupled partial differential equations and solved numerically for state variables. The finite volume technique is used so that the front of the flow is tracked with high resolution interface capturing schemes. For details on the discretization approach used in this work we refer to [14, 15] and the references therein.

For the experimental verification of the foam expansion a PUR reaction mixture was performed with a semi-automatic working injection unit of the company Unipre GmbH in Werl, Germany. With a mixing head the components were injected with a ratio of 100:67 mass parts (isocyanate to polyol) in transparent polycarbonate tubes. The tube inner diameter was 112 mm, the wall thickness 4 mm and the height 200 mm. All the experiments were carried out at room temperature and recorded with a digital video camera for the creation of the time-volume curves. As soon as the expansion in volume set in each time of crossing of the PUR foam was recorded on a scale division. In the described manner, the curve progressions on the inner tube wall and the tube centre were determined, based on the parabolic flow front of the foam propagation.

Figure 8 shows the expansion behavior of the PUR foam in the tubes. The appearance of the flow front depends strongly of the viscosity with regard to the advancement of the reaction and prevailing temperature. At the walls the mixture viscosity increases faster than in the middle of the tube, which leads to the typical curvature of the flow front. The simulation of the foam expansion and obtained flow front curvature shows good agreement with those obtained in the experiment.



a) 150 secs b) 200 secs c) 250 secs

Figure 8: Comparison of the flow fronts from the simulation (above) and the experiment (below)

In Figure 9 the propagation of the foam heights at the middle (Hm) and at the walls (Hw) over time are compared. In the middle of the tube the curves of simulation and experiment show good agreement, on the wall the simulation results seem to overestimate experimental values. This observation may be attributed to the assumed uniform expansion model. In the future work, the possibility of non-uniform expansion will be explored.

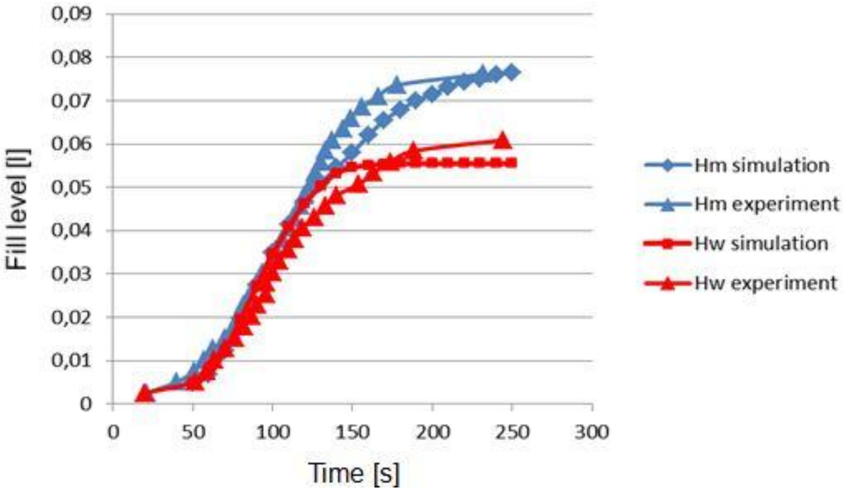


Figure 9: Comparison of fit functions for the simulation calculation with the determined experimentally time-volume curves

4 CONCLUSION AND OUTLOOK

For the polyurethane rigid foams textile reinforced with spacing fabrics significant increases in both the absolute and the specific mechanical properties have been demonstrated by means of the bending and pressure test. The complex textile 3D structures achieve this with fibre volume contents of less than 5%. From the use of single-layer 3D fabric reinforcements a higher lightweight potential can be derived. If large composite thicknesses are necessary, multi-layer structures can also lead to powerful 3D knitted rigid foam composites. Mechanically the reinforcing effect arises by blocking the flexural buckling of the spacer threads in the load case by the lack of space occupied by the PUR. A good fibre-matrix adhesion is advantageous. By the special deformation behaviour of composite structures, this was already suspected. Micrographs of the interfaces between the reinforcing fibres and foam provide further insights in this regard. Figure 10 shows sheared PET fibres of the composite structure of the Test series with AG2. Despite the mechanical action the PUR foam remains adherent on large areas of the spacer threads. To investigate the fibre-matrix adhesion in the complex 3D composite structures further scientific works are provided.

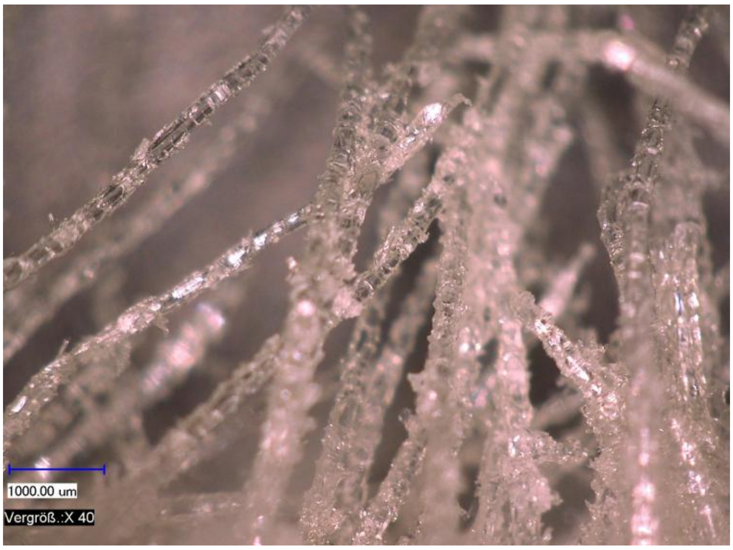


Figure 10: Light microscope images of spacer threads of SF2 after shearing the PUR matrix [5]

The development and investigation of 3D knitted to increase the lightweight degree in combination with rigid polyurethane foams is purposefully pursued on the basis of these results to further explore reinforcement mechanisms and make them usable application-oriented. Using the same methodology the material combination of 3D knitted and PUR flexible foams and the resulting property profiles will be investigated in the project Pafatherm II [4, 6].

The research in the field of textile-reinforced polyurethane foams is being continued. The projects are concerned with the dependence of the foam expansion of fibre volume content and the architecture of the 3D reinforcement textiles and the effect of textile microstructures on the composite manufacturing. The knowledge gained will be transferred to the scientific and technical description of the process behaviour into models for process simulation. The validation and verification of structural and component variable simulation models is carried out by experimental comparisons. Through process and application-specific adaptation of the ratio of volume contents of textile 3D reinforcements and foam densities the lightweight potential for composite materials will be further explored. The 3D-knitted foam composites based thereon are transferred as structural and property formative components in the multi-material design of innovative lightweight constructions. The simulation of the flow expansion is a useful step for the estimation of needed mass of reactants and mold filluing possibility in the presence of the warp-knitted spacer fabric. In a first step the simulation of the foam expansion has been developed and has to be combined in future work with some impregnation model for porous structures.

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