BOLTED JOINTS WITH MOULDED HOLES FOR TEXTILE THERMOPLASTIC COMPOSITES

W. Hufenbach[1], R. Gottwald[1], R. Kupfer[2]*
[1] Institute of Lightweight Engineering and Polymer Technology
Technische Universität Dresden, Dresden, Germany
[2] Leichtbau-Zentrum Sachsen GmbH, Dresden, Germany
* Corresponding author (Kupfer@lzs-dd.de)

Keywords: *joints, bearing behaviour, thermoplastic composite materials, textile composites, modelling*

1 Introduction

In recent years textile-reinforced thermoplastic composites gain increasing relevance for high-volume applications particularly in transportation industry. This results from both, their adjustable high-level mechanical properties and the ability of effective and reproducible manufacturing in short cycle times using press technology. In order to fully exploit the bearing capacity of such structures suitable load-introduction systems are required considering both structural aspects and manufacturing restrictions. As bolted and riveted connections are common and proven joint systems for composite materials [1], their efficient integration into the manufacturing process of thermoplastic composites is of special interest. Since the holes which are needed for these connections are usually manufactured by drilling, the fibre-reinforcement is locally interrupted and the component is structurally weakened in those areas [2, 3]. In the presented investigations a non-destructive manufacturing method for such holes was developed and the properties of the joining zones were analyzed by means of experimental, analytical, and numerical methods.

2 Moulding Technology

As an alternative notching-method for textile-reinforced thermoplastics, holes can be formed by locally shifting the fibres aside [4-6]. In order to transfer this moulding technique into industrial operation, their integration in existing process chains was focused. Since shaping of textile-reinforced thermoplastics is usually performed by compression moulding, the pressing and notching sequences were combined into one process as shown in Fig.1. The manufacturing cycle starts by warming up the semi-finished thermoplastic sheet up to moulding temperature. Subsequently it is quickly transferred into the open mould with a handling tool (a), the mould is closed and the composite material gets shaped. By the pressing force it is clamped at the border of the forming zone (b) and a hole is moulded by shifting forward a tapered pin (c). Immediately after this step, the moulding zone becomes compressed by a ring shaped plunger. After cooling and solidification the mould opens and the notched part is lead to further processing (d).

The capability of this technique was demonstrated in an application oriented manufacturing process with fully automated pressing cycles. For these tests, a generic multi-pin pressing die with integrated notching kinematics was developed. The investigations on processing were performed on organic sheets made of glass fibre reinforced polypropylene as specified in Tab.1 [7].

By the identification of an adequate processing latitude it was shown that a reproducible manufacturing of components with moulded holes can be realised without increasing cycle time. Moreover the hole diameter and hole pattern can be varied in a wide range for the specified composite material (Tab.1).

3 Structural Phenomena

Fig. 2 shows exemplary the X-ray images of joining zones with moulded hole patterns. As it can be seen in the left picture the residual fibre course is a result of interacting deformation zones, if the hole distance falls below a critical value. In the middle picture the distance of the vertical arranged holes exceeds that value. For the chosen material – in this case GF/PP – and test setup the critical value was determined to $s/D = 6$.

As expected, another observed characteristic of moulded joining zones is a cylindrical offset around the hole. Here the displaced fibres and matrix accumulate during pin movement and solidify under the pressure of the ring plunger. Additionally, in experimental investigations with a single pin moulding device analogue Fig.1 a dependency of the offset-height from the plunger force was determined (Fig.3).

Beside these geometric issues, the local reinforcement structure is significantly changed. Due to the shifting of fibres during the moulding process, a local material structure is constituted which features different fibre directions and fibre contents. Fig.4 schematically illustrates the local reinforcement structure of drilled (a) and moulded (b) joining zones and contrasts it with an X-ray picture of a twill woven glass-fibre reinforced polypropylene composite with a 10 mm diameter hole (c).

4 Bearing Behaviour

In order to deduce first design rules for bolted and riveted joints, load bearing tests were performed on specimens with drilled and moulded holes (Tab.2).

As shown in Fig.3, one main structural attribute of moulded joining zones is the offset-height t_0 nearby the hole. The experimental studies confirm the significant influence of this parameter on the load bearing capacity. In Fig.5 the measured ultimate loads F_U for a chosen set of geometrical conditions normalized to the values of drilled specimen are summarised. As a consequence of the rising projected surface an increasing offset thickness induces up to 36 % higher ultimate loads F_U (white bars). If the normalized bearing strengths $R_M = F_U/(D\cdot[t_0+s])$ are focused, this increase is less distinct (grey bars). Thus for our test setup, the ultimate loads are rather influenced by the local laminate thickness than by the constituted material structure.

According to these results, a minimal force of the ring-plunger, leading to a maximum height in the offset area, would be desirable. However micrographs show an increasing appearance of pores in the moulding zone, if the plunger force is reduced. Also the surface quality and geometry mapping decrease at lower pressing forces. In these investigations, a plunger force of 20 bars inducing a laminate thickness of 5.5 mm leads to a maximum offset height at acceptable moulding quality.

Based on these results bearing investigations on specimens with varying characteristic dimensions (Tab.2) were performed. Additionally, the results were compared to those of drilled specimens. For sample manufacturing a slightly modified notching method was used, whereas not the whole structure but only the moulding zone is plasticised [8].

Depending on the specimen’s dimensions different failure modes were detected in the bearing tests. As a result of the biaxial reinforcement and the high plasticity of the thermoplastic matrix, a distinct failure classification is not possible. Rather, mixed failure modes can be observed, arising from successive fibre and matrix failure. Additionally, the failure behaviour is influenced by the notching method. Exemplary, drilled samples with 10 mm hole diameter show at $w/D = 2$ and $e/D = 2$ (cf. Tab.2) a combination of net tension, bearing and interlaminar failure (Fig.6, B). In contrast moulded specimens at the same geometrical conditions show net tension failure (Fig.6, F).

Due to its high residual strength and good energy dissipation in case of structural overload, bearing failure is often the aspired failure mode for bolted joints. In the accomplished tests, for all specimens with relative sample widths $w \geq 3$ and relative edge distances $e \geq 2$ bearing failure was observed. Fig.7 shows the measured ultimate loads of drilled and moulded specimens with these geometrical specifications. It can be seen, that connections with moulded holes transmit higher loads in comparison to the drilled configuration.

5 Structural Model

Although the measured ultimate loads F_U of moulded specimens without any offset t_0 are nearly equal to the values of drilled samples (cf. Fig.5), it was observed during bearing tests (e.g. with grey scale correlation method, Fig.10 a, c) that the load paths and local elongations differ significantly. This can be tracked back to the local material structure of the joining zone constituted during moulding process. It is characterized by varying fibre content and fibre direction, which results in differing material properties nearby the hole boundary (Fig.8 left). In biaxial woven fabrics, this leads to four triangular unidirectional zones (c) which are characterized by the presence of only one fibre direction and an increased fibre content nearby the hole boundary (a). In the diagonal crossing zones (b), where the fibres of the unidirectional zones intersect, the fibre content exhibits its maximum. In order to quantify the distribution of the fibre content optical microscopy and digital image correlation technique were used [9]. Fig.8 (right) shows the measured fibre content in the cross section of a chosen laminate symmetry axis.

Based on the description of the fibre volume content in the symmetry cross-section nearby the hole, the local material structure of the whole moulding zone can be modelled. To handle the model, the bidirectional weave at the moment is assumed as crosswise arranged unidirectional layers. Considering the geometrical symmetries in the moulding zone (cf. Fig.8) the material structure can be described at a quarter model of the single UD-ply (Fig.9). Hereto the amount of fibres N penetrating a cross-sectional area is described by geometric parameters and the locally varying fibre content φ according to

$$N = \frac{A_Q}{A_F} \cdot \frac{1}{y} \cdot \int \varphi(y)dy \tag{1}$$

with A_Q cross sectional area,
A_F single fibre cross section,
y distance from the hole axis.

The correlation between the starting position of a fibre at y_{Li} nearby the hole and its ending position at y_{Ui} in the undisturbed cross-section is given by equalizing the numbers of fibres in these areas:

$$\int_{y_{L=R}}^{y_{Li}} \varphi_L(y_L)dy_L = \int_0^{y_{Ui}} \varphi_U(y_U)dy_U \tag{2}$$

With a cubic approach for the fibre course, the main boundary conditions resulting from symmetries and transition into undisturbed composite can be considered. A first determination of the material structure of bidirectional fabrics can be performed by averaging the calculated fibre contents of two orthogonal layers. Fig.9 (right) displays the calculated fibre courses and fibre contents of the specimen shown in Fig.8. Based on that, the distribution of the elastic material properties nearby the moulded hole can be calculated by means of micromechanical approaches [10]. For an automated analysis a MATLAB-based analytical tool was programmed, calculating the local material properties (fibre angles, stiffnesses, Poisson’s ratio) nearby moulded holes.

6 Numerical Analysis

As a precondition for the numerical modelling of moulded joining zones, a mapping method was developed, which enables the discrete assignment between the analytical determined material properties and the pre-processed finite element mesh. For that purpose a simplified parametric FE-model was built up as half model in ANSYS V11.0 using the multilayered shell element SHELL181. Subsequent to the meshing procedure the centroid location of each element is exported automatically into the MATLAB-based tool. After the calculation of the local engineering constants for each set of element coordinates these values are imported into the FE-program and mapped to the according elements of the FE-model.

For validation of the modelling and mapping strategies bearing tests on specimens with drilled and moulded holes were analysed experimentally and numerically. In these investigations only low forces were applied causing small deformations (Tab.3). The occurring local deformations during experimental bearing tests were measured by digital image correlation technique (ARAMIS) and compared to analytical results.

As displayed in Fig.10 the measured local elongations of specimens with moulded and drilled holes show significant differences. On drilled holes (a) the elongations are concentrated on two slim bands nearly tangential to the hole boundary following tensile direction. In opposition the modified material structure of moulded joining zones leads to concentrated deformation fields beside and above the hole (c).

The comparison of Fig.10 (a) and (b) shows clearly that the vital effects like load paths and elongation distribution of samples with drilled holes are reproduced correctly by numerical analysis. On moulded holes the calculated tensile elongations are concentrated beside and transverse above the hole (d) reflecting the measured elongation distribution (c).

Based on these first studies, a proper accordance between numerical and experimental analysis can be constituted. However the calculated elongations above the moulded hole are currently not reproduced correctly in detail. This for instance can be tracked back to the chosen linear elastic material model, neglected textile effects like fibre crimping or processing induced residual stresses.

7. Conclusions

Due to the short manufacturing cycle times composites with thermoplastic matrices gain increasing relevance especially for high volume lightweight applications. For fast and reproducible joining of composites bolted and riveted joints are established and widely spread. The holes needed for those joints are usually manufactured by drilling, locally cutting and weakening the reinforcement structure. In contrast an alternative hole moulding technique based on fibre shifting enables a non destructive manufacturing of the holes.

To enable a transfer of the moulding technique into industrial operation, its efficient process integration, e.g. in compression moulding, was focused in these investigations. By constructively integrating the perforation kinematics into the pressing mould the shaping and notching sequences were combined into a single process step. For validation of the processing concept experimental investigations in laboratory scale as well as in application oriented manufacturing studies were performed. In these tests basic relations between processing parameters and characteristic properties of moulded joining zones were identified. Additional load bearing tests on specimens with varying characteristic dimensions showed that connections with moulded holes are able to transmit significant higher loads in comparison to drilled samples, if specific processing conditions are considered.

As a result of the moulding process, the local material structure of the joining zone is characterized by varying fibre content and fibre direction. Based on experimental analyses of the micro structure nearby the hole, the local material properties are described using a novel semi-analytical approach. For the numerical analysis of moulded joining zones, a mapping method was developed, which enables the discrete assignment between the analytical calculated material properties and a pre-processed finite element mesh. The deformation behaviour of moulded joining zones under bearing load was calculated for small deformations using shell elements. Comparing the results to the measured local deformations during bearing tests it was shown that the vital effects like load paths and distortion distribution in the moulding zone are reproduced correctly.

Acknowledgements

The authors would like to express their gratitude towards the Deutsche Forschungsgemeinschaft (DFG) for funding the subproject B3 within the scope of Collaborative Research Centre 639.

References

[1] J.R. Vinson and R.L. Sierakowski: The Behaviour of structures composed of composite materials, 2nd Edition, Kluwer Academic Publishers, New York, 2004.
[2] A. Langella and M. Durante: Comparison of tensile strength of composite material elements with drilled and molded-in holes. *Applied Composite Materials*, Vol. 15, pp. 227-239, 2008.
[3] A. Nakai, T. Ohki, N. Takeda and H. Hamada: Mechanical properties and micro-fracture behaviours of flat braided composites with a circular hole. *Composite Structures,* Vol. 52, pp. 315-322, 2001.
[4] H.J. Lin and Y.J. Lee: Strength of composites with continuous fiber around hole. *Composite Structures* 21 (1992), pp. 155-162.
[5] S.P. Ng, P.C. Tse and K.J. Lau, Progressive failure analysis of 2/2 twill weave fabric composites with moulded-in circular hole. *Composites Part B: Engineering* 32 (2001), pp. 139–152.
[6] W. Hufenbach, O. Helms and R. Kupfer: Design of textile-adapted joining zones with moulded-in holes for riveted and bolted joints. *Journal of Plastics Technology*, Vol. 6, pp. 255-269, 2010.
[7] TWINTEX® TPP, product information. Owens Corning Composite Materials, LLC, Toledo, 2008
[8] W. Hufenbach, F. Adam and R. Kupfer: A novel textile-adapted notching technology for bolted joints in textile-reinforced thermoplastic composites. *Inproceedings ECCM 14*, Budapest, 06/07-06/10/2010, Paper ID 461, S.1-9.
[9] W. Hufenbach, N. Modler, A. Winkler and R. Kupfer: Untersuchungen zur Charakterisierung des gradierten Faseranteils im Randbereich warmgeformter Fügezonen in textilverstärkten Thermoplasten. *Inproceeding DGM-Tagung Werkstoffpruefung*, 12/02-12/03/2010, S. 311-316.
[10] R.M. Jones: Mechanics of composite materials, 2nd edition, Taylor and Francis, 1999

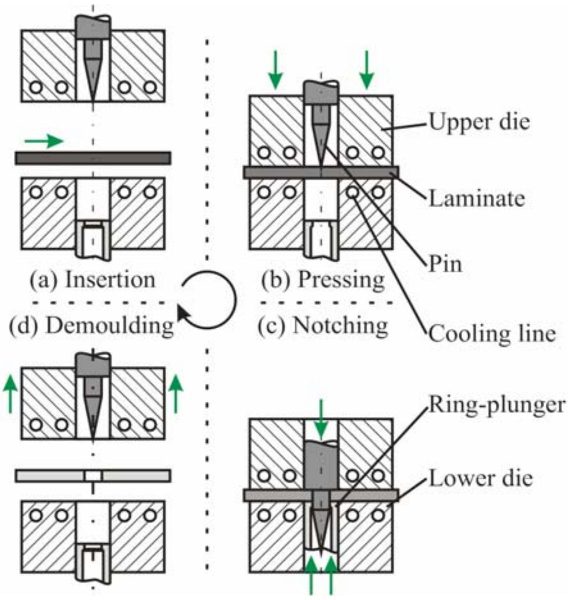


Fig.1. Processing principle of mould-integrated notching of textile thermoplastic composites.

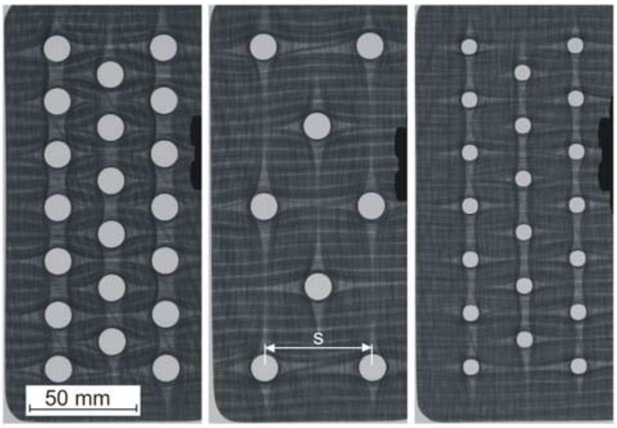


Fig.2. X-ray images of joining zones with moulded holes at different hole diameters and hole patterns

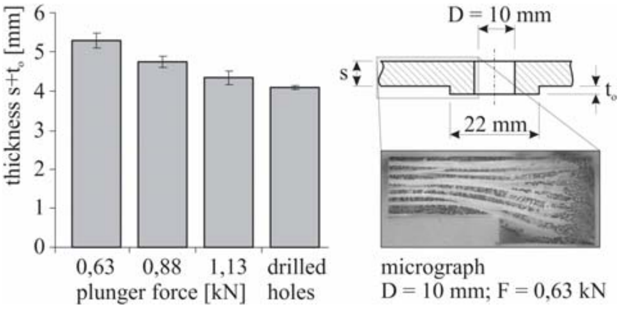


Fig.3. Pressure-dependency of the laminate thickness nearby moulded holes in 4 mm woven composites (cf. Tab.1)

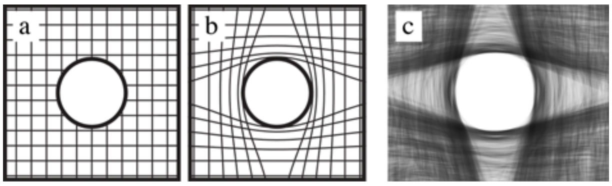
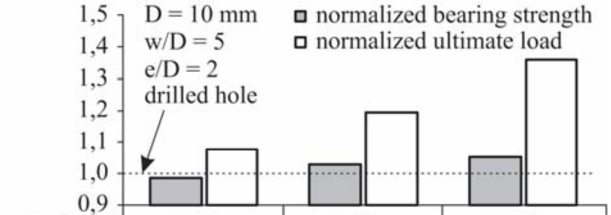


Fig.4. Reinforcement structure of drilled (a) and moulded specimen (b); X-ray picture of glass-fibre/polypropylene weave with a moulded hole.



$s + t_0$ [mm]	4.3	4.8	5.3
R_M [MPa]	148.3	150.6	154.0
F_U [kN]	6.4	7.2	8.1

Fig.5. ultimate load and bearing strength of moulded holes with different offset heights normalized to drilled holes

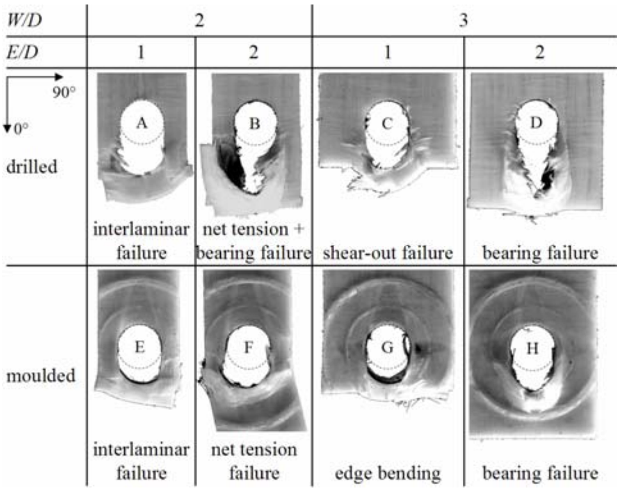


Fig.6. Failure analysis of drilled and moulded samples

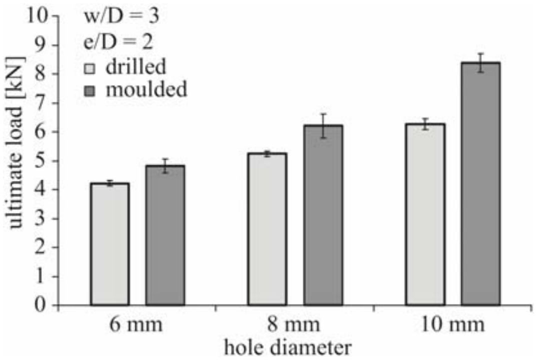


Fig.7. Ultimate loads of 4 mm thick glass-fibre/polypropylene composites with drilled and moulded holes under bearing load

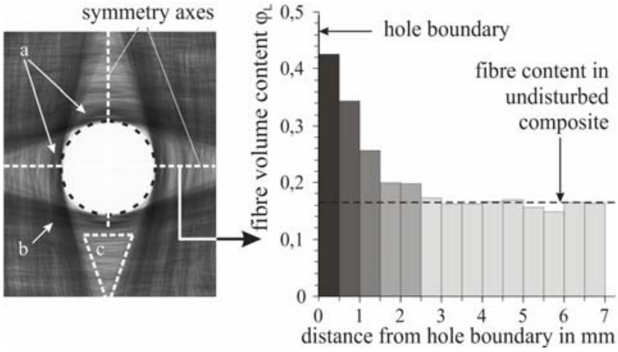


Fig.8. Material structure (left); measured fibre content nearby a moulded hole (right)

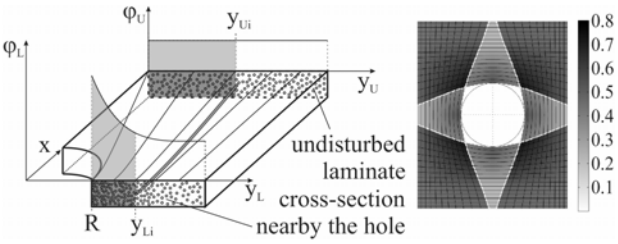


Fig.9. Simplified quarter-model (left); calculated distribution of the fibre content (right)

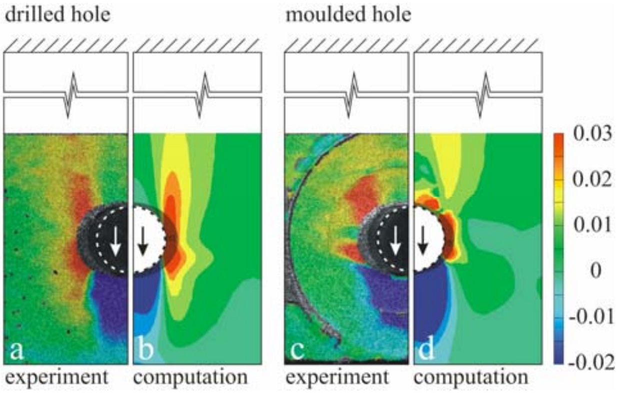
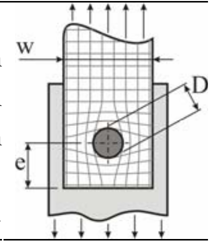


Fig.10. Experimental and analytical determined strains in load direction

Tab.1. Laminate properties and processing conditions for manufacturing trials

fabric	Twintex® TPP 60 745
weave	Twill 2/2
laminate structure	$[(0°/90°)]_4$
fibre volume content	0.35
laminate thickness *t*	2 mm
heating temperature	200 °C
mould temperature	80 °C
cooling time	35 s
hole diameter *D*	6, 10 mm
hole distances *s*	20, 50 mm

Tab.2. Specimen properties for bearing tests

material	comp. Tab.1	
laminate thickness *t*	4.1 mm	
hole diameter *D*	10 mm	
offset thickness t_0	1.4 mm	
relative sample width *w*	2, 3, 4, 5	
relative edge distance *e*	1, 2	

Tab.3. Specimen properties for numerical analysis

material	comp. Tab.1
laminate thickness *s*	5.2 mm
hole diameter *D*	8 mm
offset thickness t_0	0.45 mm
relative sample width *w*	4
relative edge distance *e*	2
load	2.5 kN
element type	SHELL181