WARM-SHAPED LOOP CONNECTIONS - A NOVEL JOINING SYSTEM FOR THERMOPLASTIC COMPOSITES

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Abstract
Due to the continuous fibre course in the joining zone, loop joints are known to be very efficient especially for high strength connections. In the present investigations a novel manufacturing process for loop joints is designed, which can be efficiently integrated into the pressing cycle of thermoplastic composite components. To evaluate the forming technology, a process chain for manufacture of components with loop-joints is established on laboratory scale. With this device, specimens with plain welding zones are manufactured. The mechanical properties and the failure behaviour of these connections are characterised in quasi-static tensile tests. Additionally, a numerical study of the damage behaviour of the loop joints is performed using an adapted material model.

1 Introduction

For high-volume production, thermoplastic composites have proven to be very economic. This is due to the short cycle time and high level of automation during processing, which is usually performed by pressing technique. The connection of thermoplastic composite components to other structures requires adapted joining methods.

For joining of continuous fibre-reinforced composites with the same or different materials adhesive joints as well as bolted and loop connections are established. Adhesive bonding is characterised by a variety of joining options for different material combinations. However, especially bonding of composites with thermoplastic matrices is characterised by specific difficulties resulting from low polarity and poor wettability of many thermoplastic polymers. Additionally, plasticisers and other additives hamper an adhesive bonding, so these joints mostly require an extensive surface treatment of the joining partners. These additional process steps make an adhesive bonding usually not suitable for high volume production. [1-3]

Bolted and riveted joints are one of the most common connections for composite structures in aviation enabling short cycle times and high reproducibility. As the required holes are mostly manufactured by drilling, the composite structure is locally weakened. Additionally, drilling of fibre-reinforced plastics causes specific problems like local delamination and high tool wear. Above that, the required joining elements increase the mass of the joining zone and cause extra costs. [4-6]

With their repeatable meltability, thermoplastic composites – in contrast to thermosetting materials – enable a variety of additional joining techniques by utilising forming and welding processes. In this respect, joining methods like laser or ultrasonic welding of composites are

well known [7, 8]. Technological investigations were performed on pressure welding [9], inductive welding [10, 11] and vibration welding [12, 13] of thermoplastic composites. The usage of classical deformation-based joints like thermoplastic rivets for continuous fibre-reinforced materials is confined as they have a limited deformation potential compared to short- and long-fibre-reinforced polymers [14, 15].
Due to the continuous fibre course in the joining zone, loop joints are known to be very efficient especially for high strength connections. They are actually applied at highly stressed components with mainly tensile load in the joining zone, e.g. at helicopter rotor blades [16]. Contrary to most connections, the joining zones have to be integrated into the component already during part manufacture. Usually, the loops are manufactured by winding processes and subsequent impregnation with a thermosetting matrix system. Although these processes are commonly applied in high-performance components they are highly complex and only restricted applicable for automated manufacturing [17]. In contrast, the mouldability and weldability of thermoplastic composites offer a new potential of producing such joining zones: an additional flap on the component can be warmed up to moulding temperature, formed around a load introduction element and welded afterwards to the main body of the component (Figure 1).

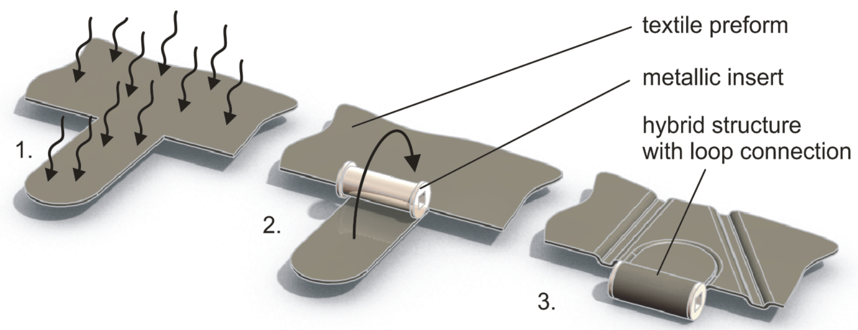

Figure 1. Concept of warm-shaped loop connections in thermoplastic composite structures

In the present investigation a manufacturing process for loop joints is developed and integrated into the pressing cycle of thermoplastic composite components. For processing studies and specimen manufacturing a process chain is established in laboratory scale. The load bearing behaviour of the loop joints is characterised by means of tensile tests. Beyond that, a numerical analysis with respect to the load bearing behaviour of loop joints is performed using a self-developed material model for textile composites including damage and failure mechanisms.

2 Manufacturing studies

In industrial applications, textile thermoplastic composite components are usually manufactured by fully automated pressing technique. Therefore, a tailored pre-consolidated thermoplastic composite sheet is clamped into a transfer frame and warmed up to the forming temperature in an infrared oven. Afterwards, a robot-mounted handling unit picks up the handling system and transfers it quickly into the open mould. By closing the mould, the preform is formed and then cooled down under high pressure. When the thermoplastic matrix is solidified, the part can be demoulded and led to further processing like trimming. [18, 19]
In the present investigations the forming of the loop joints is integrated into this processing cycle. The underlying concept provides a thermoplastic composite preform containing special mounting tongues, which are formed and pressed to loop structures. Basically, this process can be performed as a separate downstream operation or preferably during component manu-

facturing. For efficient processing with high reproducibility, a process-active handling system was designed. With this device, the forming of the loop is done during the transfer of the warmed preform from the heating station into the cooled pressing die. The according welding step is integrated into the shaping and pressing procedure (Figure 2).

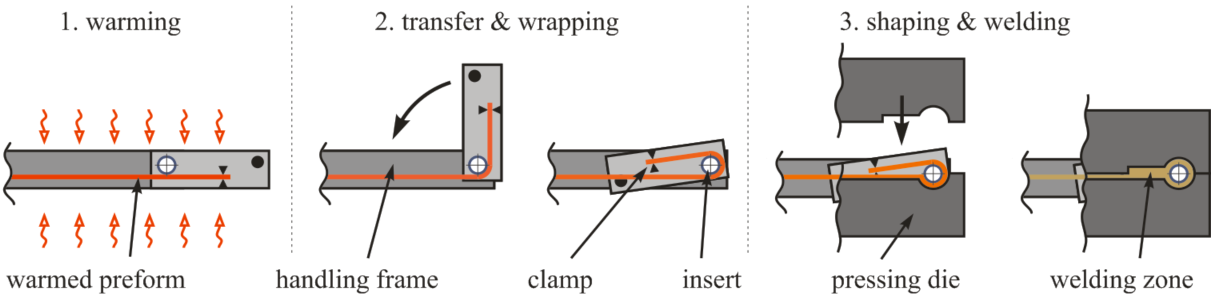

Figure 2. Manufacturing concept for warm-shaped loop connections.

For first technological studies on the warm-shaping of loop connections, a manufacturing process containing an infrared heating station (1), a transfer system, and a fast stroke press was established on laboratory scale. The central element of this process is the handling frame with an additional pivoted draping flap where the mounting tongue is fixed. This flap is rotated 180° during transfer, wrapping the mouldable textile composite around a metal bushing (2). This insert enables a reproducible positioning of the loop and serves additionally as load introduction element. Inside the mould, the mounting tongue - now lying on top of the structure - is welded to the main body (3).
For first processing studies the textile reinforced polypropylene (Table 1) is used. By the identification of an adequate processing window, it was shown that a reproducible manufacturing of components with warm-shaped loop connections can be realised without an increasing the cycle time.

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	205 °C
mould temperature	100 °C
cooling time	60 s
bushing diameter	10 mm
overlapping length	45 mm

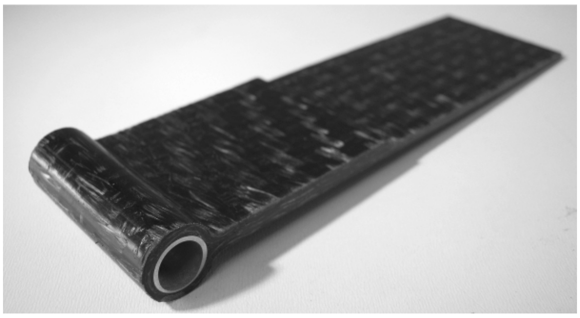

Table 1. Laminate properties and processing conditions for manufacturing trials (left); warm-shaped loop connection with flat welding zone (right).

3 Experimental investigations

The mechanical properties of the loop joints are evaluated in quasi-static tensile tests. Therefore, the manufactured samples are cut to 40 mm width. For testing, a metal shaft is pushed through the embedded bushing and fixed in a lower clamp. To reduce bending of the shaft, the axial tolerance between bushing and clamp is minimised. On the upper side, the specimen is fixed by the standard hydraulic clamp of the tensile testing machine (Figure 3). As in these structural tests no overall elongation can be measured and local measurement is highly elaborate, only the crosshead travel is logged for this study, enabling a comparison between the tensile tests and numerical results.

During testing a successive failure can be observed (Figure 3). As expected, the initial failure occurs in the welding zone next to the metal insert. Here, delaminations initiate and afterwards propagate through the welding zone moving away from the insert. The final failure takes place as the delamination reaches the end of the welding zone.

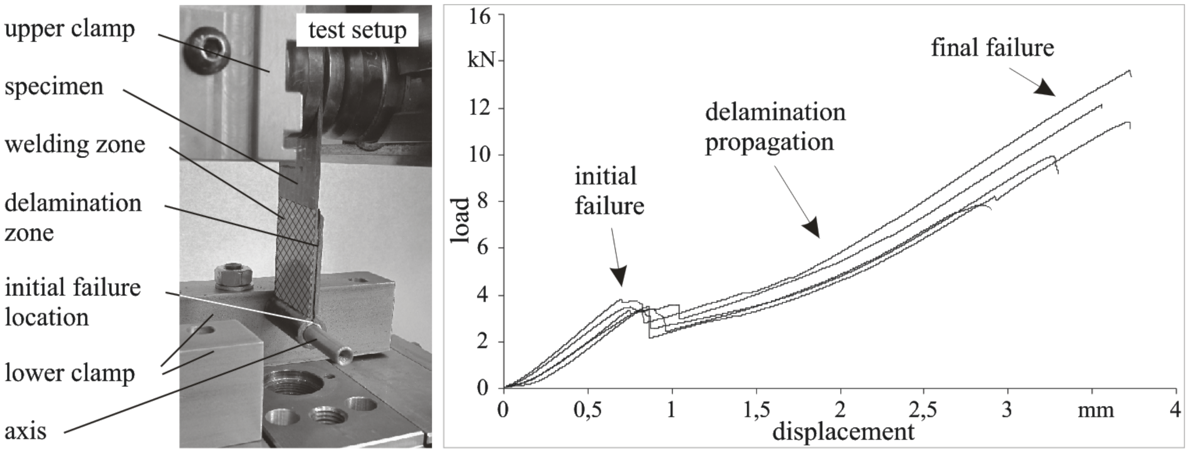

Figure 3. Test setup (left); results of tensile tests on warm-shaped loop connections (right)

The experimental studies show that with the chosen specimen geometry loads up to 13.5 kN can be transferred by the loop joint. Since the failure load of the undisturbed cross section is about 24 kN, a joint efficiency up to 56 % is reached. However, first damage occurs already at 12...16 % of the materials bearing capacity. This is basically caused by the flat welding zone of the specimen, which barely hampers crack initiation and propagation. For further studies, an additional three-dimensional shaping of the welding zone is proposed to locally enlarge the peel strength and increase failure loads.

4 Numerical investigations

In addition to the performed experimental analysis, the loop joints are investigated numerically using the finite element (FE) system Abaqus/Explicit. Therefore, the loop joint specimen is modelled by eight-node brick elements with reduced integration (C3D8R) and six-node triangular elements (C3D6); the metal insert shaft by four-node rigid shell elements (Figure 4). Due to the geometrical symmetry of the specimen, its width is approximated by one element. The thickness of the single textile preform is represented by five elements. In the welding zone the mesh is consistent. The nodes on the upper side, according to the experimental test setup, are fully restrained. A constant displacement constraint of 20 mm/s is defined on the insert.

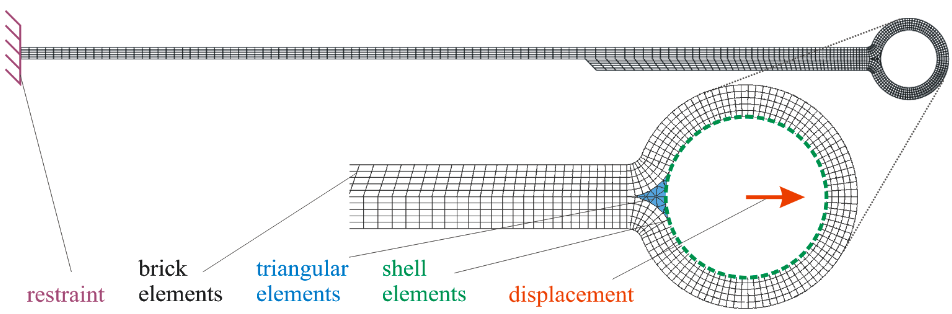

Figure 4. FE-model of the loop connection

In order to investigate damage and failure behaviour like crack initiation and propagation, a phenomenological three-dimensional material model has been implemented by means of a user defined material model (VUMAT). This material model is based on a continuum mechanical approach proposed by Cuntze to predict directional and mode related failure [20]. A successive stiffness degradation of each orthotropic textile layer is modelled by an accumulative and mode related damage evolution [21, 22]. It uses the assumption of linear-elastic material behaviour up to an initial damage threshold characterised by the damage strength $R_{di\ t/c}$ for each direction, with t denoting tension and c compression. The damage evolution effects induce stress-strain non-linearities up to final failure $R_{it/c}$. The onset of damage is described by the following criterion:

$$H^n = \left(\frac{\sigma_1^+}{R_{d1t}}\right)^n + \left(\frac{\sigma_1^-}{R_{d1c}}\right)^n + \left(\frac{\sigma_2^+}{R_{d2t}}\right)^n + \left(\frac{\sigma_2^-}{R_{d2c}}\right)^n + \left(\frac{\sigma_3^+}{R_{d3t}}\right)^n + \left(\frac{\sigma_3^-}{R_{d3c}}\right)^n + \left(\frac{\tau_{12}}{R_{d12}}\right)^n + \left(\frac{\tau_{31}}{R_{d31}}\right)^n + \left(\frac{\tau_{23}}{R_{d23}}\right)^n = 1 \quad (1)$$

with n defining the failure envelope. Final failure, resulting in element erosion, is calculated by

$$F^m = \left(\frac{\sigma_1^+}{R_{1t}}\right)^m + \left(\frac{\sigma_1^-}{R_{1c}}\right)^m + \left(\frac{\sigma_2^+}{R_{2t}}\right)^m + \left(\frac{\sigma_2^-}{R_{2c}}\right)^m + \left(\frac{\sigma_3^+}{R_{3t}}\right)^m + \left(\frac{\sigma_3^-}{R_{3c}}\right)^m + \left(\frac{\tau_{12}}{R_{12}}\right)^m + \left(\frac{\tau_{31}}{R_{31}}\right)^m + \left(\frac{\tau_{23}}{R_{32}}\right)^m = 1 \quad (2)$$

The required through-thickness properties are obtained in [23]; the material properties can be found in [24].
As observed during experimental analysis, the simulation indicates the initial failure in the welding zone next to the metal shaft. Afterwards the crack is propagating away from the insert through the welding zone. The dominating failure mode is tensile failure in the direction of thickness representing the delamination between the layers. The failure results of the numerical analysis are displayed in Figure 5.

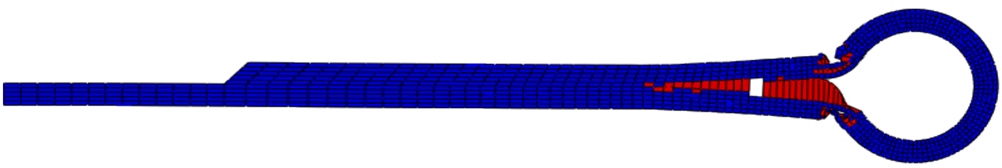

Figure 5. Element erosion (red elements are deleted)

The numerical analysis shows a good agreement with the experimental test in terms of initial failure load, failure location and delamination propagation. However, the failure timing and load-displacement relation diverge from experimental data (Figure 6). These differences probably result from the applied element erosion strategy. Upon reaching their strength in thickness direction, the elements are deleted immediately, so that still remaining in-plane properties (e.g. stiffness) cannot be considered in the case of delamination failure.

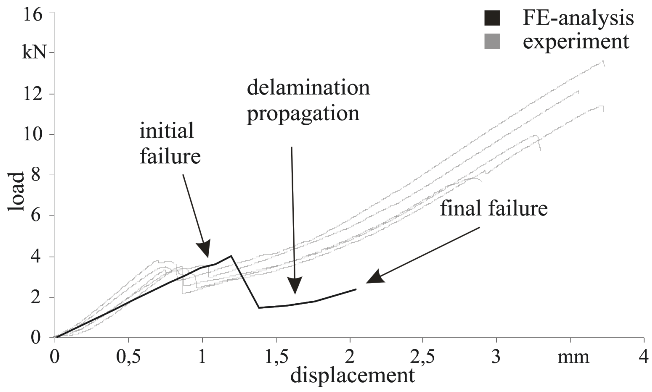

Figure 6. Experimentally and numerically determined load-displacement behaviour of loop joints

5 Conclusions

In this study a novel method for manufacturing of loop joints in thermoplastic composite structures is presented. In order to achieve a reproducible and efficient processing, this procedure was integrated into the pressing cycle of the composite component. Therefore, a process-active handling system was designed, which is forming the loop during the transfer of the warmed preform from the heating station into the pressing die. The according welding step was integrated into the shaping and pressing procedure. To evaluate the forming technology, a process chain for manufacturing of components with those loop-joints was established on laboratory scale. With this device, specimens with plain welding zones were manufactured.
The mechanical properties and the failure behaviour of the loop joint connections were characterised by quasi-static tensile tests. The failure behaviour is dominated by successive crack propagation, starting next to the metal insert and running steadily through the welding zone. The measured ultimate loads correspond to about 55 % of the bearing capacity of the structure beside the loop joint.
Beyond the technological investigations, numerical studies on the load bearing behaviour of loop joints were performed using a material model for textile composites including damage and failure mechanisms. Thereby, a good agreement between experimental and computational analysis was observed as the initial failure load and crack initiation as well as the crack propagation process were satisfactorily predicted.
To enhance failure tolerance of the loop joints, connections with wavy welding zones will be produced and experimentally analysed as well in further investigations.

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