Werner Hufenbach[1]
Technische Universität Dresden, Institut für Leichtbau und Kunststofftechnik, 01062 Dresden, e-mail: ilk@mw.tu-dresden.de
Nikica Petrinic[2]
Oxford University, Department of Engineering Science, e-mail: nik.petrinic@eng.ox.ac.uk
Andreas Hornig[3], **Albert Langkamp**[4]
Technische Universität Dresden, Institut für Leichtbau und Kunststofftechnik, 01062 Dresden, e-mail: anh@mw.tu-dresden.de, al@ilk.mw.tu-dresden.de
Jens Wiegand[5]
Oxford University, Department of Engineering Science, e-mail: jens.wiegand@eng.ox.ac.uk

EXPERIMENTAL INVESTIGATIONS ON 3D REINFORCED MULTILAYER WEFT KNITTED FABRIC LAMINATES UNDER IMPACT LOADING CONDITIONS

The requirements on aircraft engine design have increased rapidly over the last decades. Future aircrafts engines are expected to be more efficient with lower operation costs and without compromising safety. Concerning the complex requirements for fan systems or fan containments composite materials are able to fully avail their high potential with regard to a significant weight reduction and an increased efficiency by using their high specific strength and stiffness. In this respect, the almost unexplored field of through thickness reinforced structures is expected to be a very promising way to optimise 2D textile reinforced materials. An experimental investigation approach for 3D reinforced materials under impact loading conditions is presented in this article, which includes the description of the testing procedure as well as the tested material configurations and test results. Two layers of multi-layered weft knitted fabrics were used to manufacture the laminates using the Bakelite L1000 epoxy resin in a resin transfer moulding process. For fabrication of stitched laminates by the double locked stitch technology two different stitching thread materials, glass and aramid, were used. In order to compare stitching configuration effects, the lengths from 1.0 to 4.8 st/10 mm and stitch distances of 5 and 10 mm were used as well as unstitched specimens. The laminates were subjected to a subcritical impact velocity of 8 m/s at the impact-bending-test device, which is explained in detail here. The damage was characterised with the focus on delamination and matrix cracking through computer tomography, optical, x-ray and ultrasonic inspections. The results of the study indicate that the used testing device is capable to evaluate the influence of the stitching pattern on the damage resistance, where particular stitching setups tend to result in higher delamination resistance.

Keywords: **3D reinforcement, crash and impact test, stitching, composites**

BADANIA EKSPERYMENTALNE LAMINATÓW WZMACNIANYCH TRÓJWYMIAROWO WIELOWARSTWOWĄ DZIANINĄ RZĄDKOWĄ W WARUNKACH OBCIĄŻENIA UDAROWEGO

W ostatnich latach gwałtownie wzrosły wymagania dotyczące projektowania silników lotniczych. W przyszłości silniki lotnicze powinny mieć jeszcze większą sprawność przy niższych kosztach eksploatacji i bez pogorszenia bezpieczeństwa. Materiały kompozytowe mogą spełnić złożone wymagania stawiane systemom wirnikowym czy obudowom wirników, w pełni wykorzystując swój potencjał, gdyż ich specyficzna wytrzymałość i sztywność pozwalają na znaczące obniżenie ciężaru i podwyższenie sprawności tych urządzeń. Obiecującą drogą optymalizacji dwuwymiarowych materiałów wzmacnianych wyrobami włókienniczymi może być prawie niezbadana dziedzina konstrukcji wzmacnianych także w kierunku grubości. Niniejszy artykuł omawia badania eksperymentalne dla trójwymiarowo wzmocnionych materiałów w warunkach obciążenia udarowego, zawiera również opis procedury badawczej oraz parametrów badanego materiału i wyniki badań. Do wytworzenia laminatów użyto dwóch warstw wielowarstwowej dzianiny nasyconej żywicą epoksydową Bakelite L1000 w procesie RTM. Laminaty igłowane uzyskano, używając dwóch rodzajów włókna: szklanego i aramidowego. W celu porównania wpływu parametrów igłowania użyto długości od 1,0 do 4,8 ściegów/10 mm i odległości igłowania 5 i 10 mm, badaniom poddano także próbkę nieigłowaną. Laminaty zostały poddane testom przy podkrytycznej prędkości udarowej 8 m/s na urządzeniu do badania zginania przy udarze, które zostało tu szczegółowo opisane. Charakterystyka zniszczenia skupiała się na delaminacji i pękaniu osnowy, które było wykrywane za pomocą tomografii komputerowej oraz badań optycznych, rentgenowskich i ultradźwiękowych. Wyniki pracy wskazują, że zastosowane urządzenie badawcze jest w stanie oszacować wpływ parametrów splotu na odporność laminatu na zniszczenie, wyznaczając konkretne nastawy igłowania, które zwiększają odporność na delaminację.

Słowa kluczowe: **zbrojenie/wzmocnienie 3D, badanie udarności i zniszczenia, igłowanie, kompozyty**

[1] Prof. Dr.-Ing. habil., [2] Dr.-Ing., [3, 4, 5] Dipl.-Ing.

INTRODUCTION

Fibre and textile reinforced composites have firmed their position as lightweight materials for structural aircraft components like wings and fuselage. In this field, unlike the conventionally used isotropic materials like titanium and steel, the material properties of fibre and textile reinforced composites can be specifically customised for the loading situations by modifying fibre architecture and material combination. The current predominantly used textile preforms are appearing to have excellent in-plane properties, whereas the laminate properties in through thickness direction are merely dominated by its matrix and fibre-matrix strengths. Especially, for applications with highly dynamic crash and impact loading conditions an increasing inter fibre strength often doesn't lead to the designated effects. The fast growing development and recently invented high performance composite materials combined with its growing advantages from the viewpoint of manufacturing efficiency put 3D reinforced materials in the main focus of interest.

3D textile preforms are commonly considered to enhance the through-the-thickness properties, such as interlaminar shear and normal strength, damage tolerance, the fracture toughness and particularly the highly relevant delamination resistance, which are essential for most of the structural applications. In this manner such materials can be fabricated with newly invented methods for laminar textile fabrics with global uniformly distributed 3D-reinforcements like the flat bed weft knitting technique on the one hand and confectioned technologies like stitching for local 3D reinforcements on the other hand.

An efficient usage of composites with this kind of 3D reinforcements, especially for crash and impact loadings, is strongly dependent on the fundamental understanding of its structural and failure behaviour to evaluate and determine the materials response and phenomenology under complex loading situations. As shown in previous studies [1], the impact-bending-test device (IBT) is capable of evaluating the materials impact resistance. Therefore, this device was used to investigate the influence of different stitching configurations (stitch density and thread material). The plate specimens consist of 2 layers flat bed weft knitted textile glass preforms with an epoxy resin matrix, tested under impact loading conditions with the focus on its delamination resistance and energy dissipation.

EXPERIMENTAL APPROACHES AND TESTING SETUP

The impact experiments with the IBT (Fig. 1) are based on a modified split-Hopkinson-bar apparatus [2], which allows impact velocities up to 15 m/s. The projectile is accelerated by air pressure and hits the impactor bar. Both bars are made of titanium and have the same shape, size and mass. This constitution affects the kinetic energy to be transferred entirely to the impactor bar which continues moving theoretically unstressed and impacts the specimen. This target is a plate of 100×100 mm and positioned free, to move in front of a support with a circular opening.

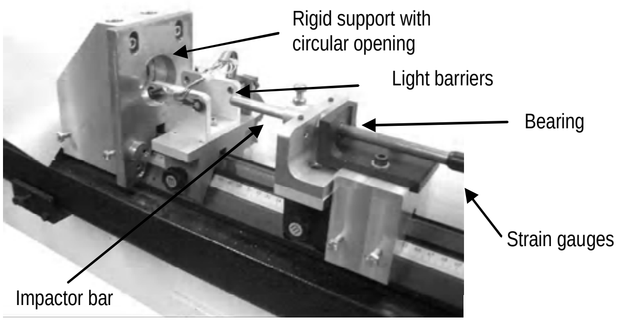

Fig. 1. Impact-bending-test device (IBT) with rigid support [3] (without specimen)

The hemispherical tip passes through two light barriers in order to determine the impact velocity. Additionally, the force in the impactor bar is being acquired by strain gauges with a resolution of 1 MHz. With this information about the elastic deformation and velocity, the stress wave propagation, caused by the impact in the impactor bar, can be fully reconstructed by applying the 1D wave theory

$$\frac{\partial^2 u(x,t)}{\partial t^2} = c^2 \frac{\partial^2 u(x,t)}{\partial x^2} \text{ with the sound speed } c = \sqrt{\frac{E}{\rho}} \quad (1)$$

where D'Alembert's solution

$$u(x,t) = f(x-ct) + g(x+ct) \quad (2)$$

gives the displacement, force, stress and velocity for every section of the thin rod for any time in the recorded interval. In (1) u denotes the displacement, x the position of the cross section, t the time, ρ the density and E the Young's modulus of the material. The obtained information thus enable the calculation of the energy balance for the whole system. For the purposes of the experiments discussed here, the IBT as proposed in [4] has been modified insofar that the formerly used support tube was replaced by a rigid support (Fig. 1). The energy balance simplifies from

$$\begin{aligned} \Delta E(t) = E^{P}_{kin0}(t) - E^{P}_{kin(t)}(t) - E^{S}_{kin(t)}(t) - \\ - E^{P}_{pot(t)}(t) - E^{S}_{pot(t)}(t) \end{aligned} \quad (3)$$

under consideration of the support tube to

$$\Delta E(t) = E^P_{kin0}(t) - E^P_{kin(t)}(t) - E^P_{pot(t)}(t) \tag{4}$$

for the rigid support setup [3]. In (3) and (4) the superscripts P and S indicate the energy components for the impactor bar and support tube. $\Delta E(t)$ is the value for all kinds of released energy of the system and is assumed to be the energy dissipated by the specimen during the impact. Thus, the dissipated energy ratio r can be calculated as

$$r = \frac{E^P_{kin0} - \Delta E(t)}{E^P_{kin0}} \tag{5}$$

where E^P_{kin0} is the kinetic energy of the impactor bar before the impact.

In addition, a velocity acquisition system has been installed which allows to record the impact velocity as well as the velocity of the rebounding impactor bar after the impact. In combination with the rigid support solution, it's now possible to determine the dissipated energy ratio r independently from the calculations using the 1D wave theory in order to verify the results. With E^P_{kin1} denoting the kinetic energy of the impactor bar after the impact

$$r = \frac{E^P_{kin1}}{E^P_{kin0}} \tag{6}$$

Besides the possibility of verifying the modified test setup by additional velocity measurements, experiments with rigid targets and a finite element analysis (FEA) of the impact between projectile and impactor bar have been performed. The comparison of the momentum is presented in Fig. 2. The results of the FEA concerning the wave propagation and elastic deformations correlate appropriately with the experimental data. The FEA software LS DYNA© 970, MAT1 has been used.

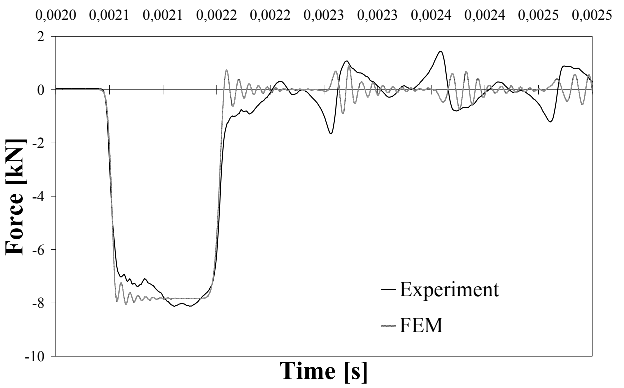

Fig. 2. Comparison between experimental and FEA results of the impact: projectile - impactor bar

MATERIAL CONFIGURATION

Since the complex shapes of composites for many light weight structures prevent the application of preforms made of one piece, several pieces of textile reinforcements need to be joined. Therefore, stitching technology can be applied. A special and commonly used type of this kind of local 3D reinforcement is the double locked stitch technology. The variation of the yarn tension enables to shift the yarn plaiting from the conventionally used position in the materials middle plane to the upper or bottom side (Fig. 3). Thus, the position of the seams weakest point can be chosen. This is highly relevant especially under bending loading conditions. In this case it is reasonable to eliminate the strength reducing yarn plaiting from the area where shear stresses affect failure due to delamination.

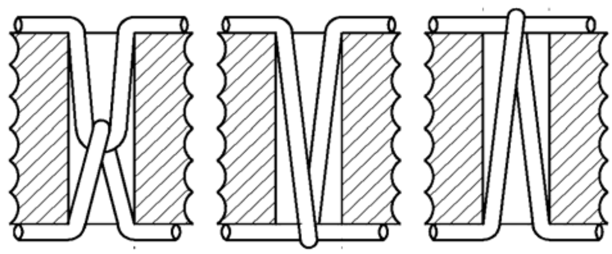

Fig. 3. Variation of the yarn tension with the double locked stitch technology [2]

For the accomplished test series either aramid or glass stitching yarns were used, while the stitching pattern varies with 1.0, 2.2, 4.8 st/10 mm for the stitch length, and with 5 and 10 mm for the stitch distance (Fig. 4).

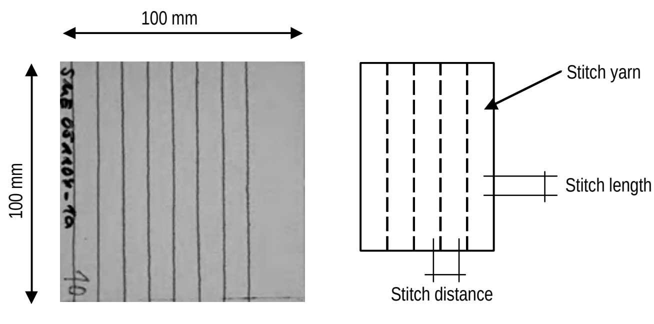

Fig. 4. Specimen configuration (stitch yarn: aramid, stitch length 4.8 st/10 mm, stitch distance 10 mm)

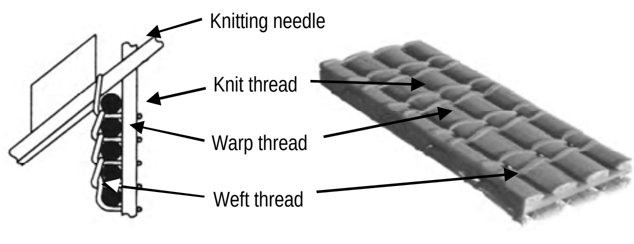

Fig. 5. MKF type 1, left: basic architecture (schematic) [6], right: CT-scan [3]

A globally 3D reinforced material, the multi-layered weft knitted fabrics (MKF) made by the Institut für Textil- und Bekleidungstechnik (ITB), TU Dresden, was applied. The used MKF type 1 specimen with the textile architecture, as illustrated in Figure 5, are based on glass fibres and were infiltrated with an epoxy resin (Bakelite L1000) by the resin transfer moulding (RTM) process. It is composed of weft (1200 tex) and warp yarn (2400 tex) layers which are held together by a stitching yarn (137 tex) system, respectively. The lay-up corresponds to 2 layers of symmetrically arranged MKF type 1 with a specimen size of 100×100 mm (Fig. 4) and 2 mm thickness.

IMPACT EXPERIMENTS

With the introduced experimental setup of the IBT the tests with the stitched specimen have been performed at an impact velocity of v_{imp} = 8 m/s. Beside the analysis of the data obtained by the data acquisition system of the test rig, like maximal plate deflections and dissipated energy ratios (Fig. 6), non-destructive inspections of the damaged specimen (Fig. 7) have been performed.

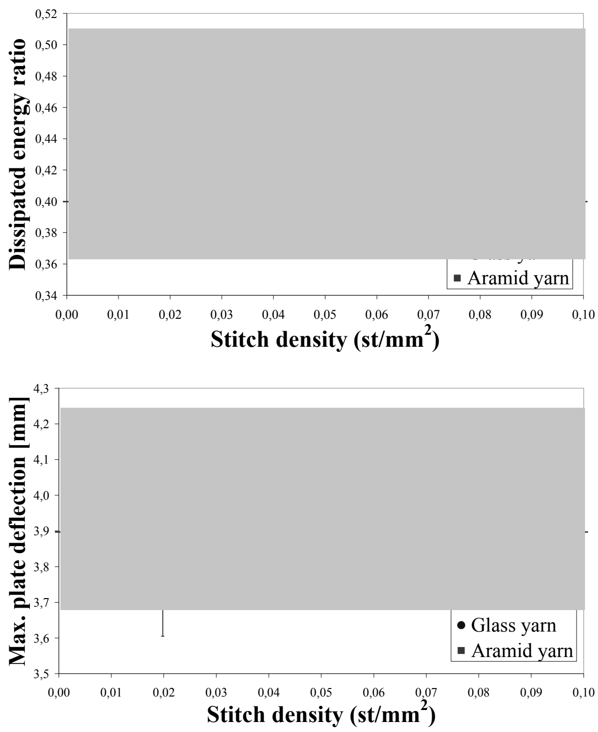

Fig. 6. Exemplary results of impact experiments at v_{imp} = 8 m/s based on recorded data [3]

The analysis showed, that the results of optical and computer tomography (CT) inspections contain less instructive information compared to ultrasonic and x-ray observations. The inter fibre damage mode matrix cracking and delamination (interlaminar damage) turned out to be the dominant fracture modes under impact bending conditions. In this respect optical analysis is qualified to identify the failure area, where the lacteal area indicates delaminated zones, whereas the CT-scans enabled the identification of the fracture depth (Fig. 7).

As shown in Figure 8, stitched materials lead over all to a reduction of the delaminated area. In the range of lower stitch densities the glass yarn shows an advantage compared to the aramid yarn, which can be explained with its bad fibre matrix adhesion capabilities and consequentially a reduced interlaminar strength. At higher stitch densities this trend inverts and aramid reveals its excellent energy absorption performance.

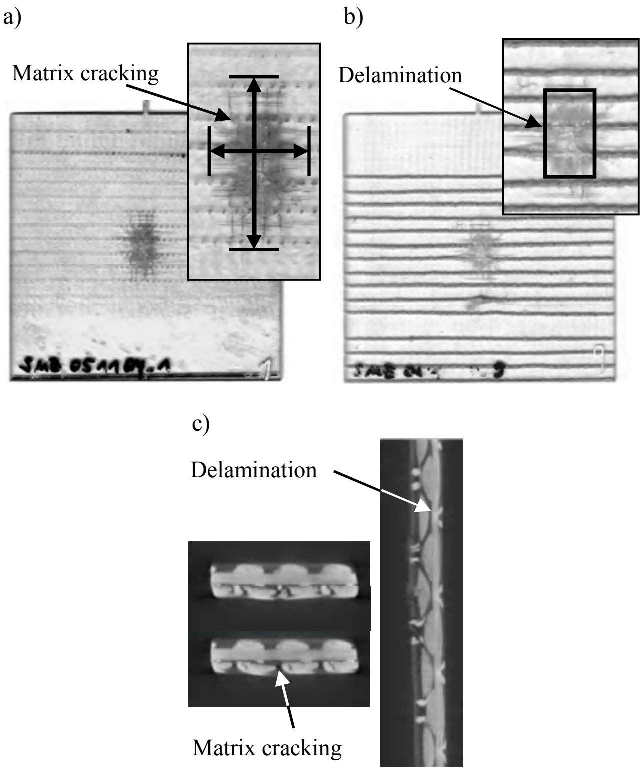

Fig. 7. Specimen damaged due to impact: a) glass stitching, b) aramid stitching, c) CT-scan [3]

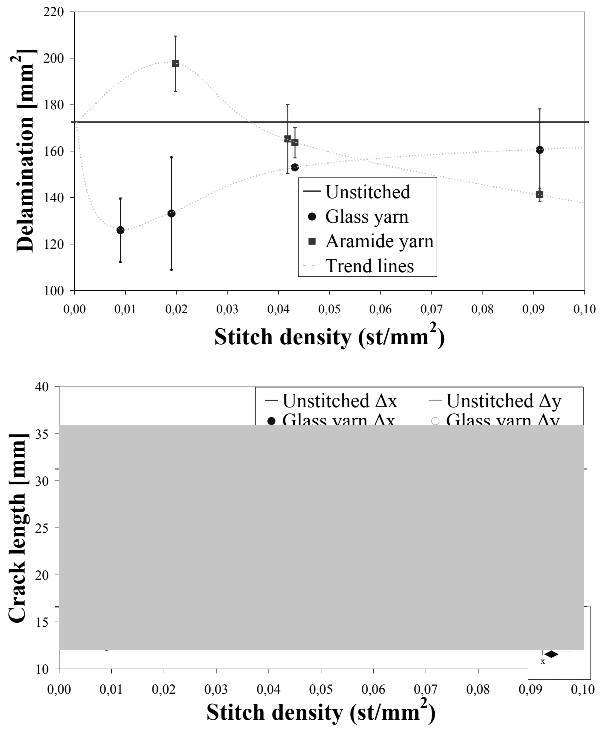

Fig. 8. Exemplary results of impact experiments at v_{imp} = 8 m/s based on non-destructive inspections [3]

The reason for the initial difference of the crack lengths in *x* and *y* direction of the unstitched material lies in the fibre architecture of MKF type 1 (Fig. 5). The crack evolution length of different stitching configurations can be seen as almost independent from stitching material with the tendency to converge caused by the raising perforation density due to the stitching process.

An increasing stitch density causes the tendency concerning rising dissipated energies and deflections thus decreasing flexural stiffness's (Fig. 6). Exceptionally, glass yarn is able to reduce the dissipated energy. The dissipated energy and the plate defections are expected to correlate. This assumption can be confirmed by comparing the trends of both, but with closer examinations the values don't correspond with each other. The reason can be found in different micro-kinematical effects due to varying stitching conditions. Additionally, those obvious trends don't correspond as noticeable as expected with the results of the observations concerning the inter fibre failure (Fig. 7). Hence, apart from the already discussed fracture phenomenology, a considerable amount of energy is being dissipated by mechanisms which can not be traced in details yet.

CONCLUSION

The paper focuses on an experimental approach for the characterisation of 3D reinforced composite materials under crash and impact loading conditions. The impact-bending-test device is qualified to characterise the composite materials performance for structural lightweight components in aircraft engine applications under highly dynamic loadings. Due to a modified experimental setup an easier and more accurate assessment of the material response was identified. It has been shown that impact experiments at subcritical impact velocities (no break through of projectile) causing a fracture behaviour where delamination and matrix cracking dominantly occurred. 3D fibre placement in 2D textile reinforced composites is able to raise the materials applicability in terms of their delamination resistance. Additionally, higher energy dissipation can be denoted and, with respect to the used flat bed weft knitted textile performs, stitching caused the approximation of the matrix cracking pattern in both main reinforcement directions. In comparison to unreinforced structures load adapted 3D reinforcement is able to enhance the materials property profile.

An efficient usage of materials with this kind of 3D reinforced materials, especially for crash and impact loadings, is strongly dependent on the fundamental understanding of its structural and failure behaviour to evaluate and describe the materials response and phenomenology under complex loading situations. Especially in terms of numerical modelling by FEM, further effort has to be put in future investigations in order to establish 3D reinforced structures in the design and development process of broad applications. The results of the proposed experimental studies were used to find numerical approaches for a simulation of the delamination behaviour in particular [3].

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Tomasz Sterzyński

Recenzent