DELAMINATION BEHAVIOUR OF 3D-TEXTILE REINFORCED COMPOSITES – EXPERIMENTAL AND NUMERICAL APPROACHES

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ABSTRACT

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. However, the insufficient delamination behaviour of 2D-reinforced composites is often opposed to a broad application in impact resistant lightweight structures. In this respect, through thickness reinforcements, e.g. by stitching, are 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 the experimental results. The focus of the experimental investigation was set on the examination of damage due to delamination failure depending on various stitching configurations using a multi-layered weft knitted fabrics (MKF). Concerning the implementation of the 3D-reinforcement by stitching with the double locked stitch technology, two different stitching thread materials, glass and aramid, were used. In order to compare the stitching configuration effects, different stitch lengths and stitch distances have been investigated as well as unstitched specimens. The laminate specimen plates were subjected to sub-critical impact velocities at an impact-bending-test device. The gained information has been used for numerical investigations to evaluate possibilities of simulating delamination damage in 3D-reinforced structures by the FEM.

KEYWORDS: 3D reinforcement, crash and impact test, stitching, composites, numerical modelling, delamination, LS-DYNA

INTRODUCTION

Fibre and textile reinforced composites have firmed their position as lightweight materials for structural aircraft components like wings and fuselage. Unlike the conventionally used isotropic materials, fibre and textile reinforced composites can be specifically customised in terms of their material properties for particular loading situations by modifying the fibre architecture and material combinations. In this field, two dimensional textile preforms are predominantly used. Those 2D-composites have excellent in-plane properties due to the fibre arrangement whereas the laminate properties in through thickness direction are dominated by its matrix and fibre-matrix strengths. Especially for applications with dynamic crash and impact loading conditions, increasing the inter fibre strengths by modifying the matrix or the fibre-matrix-interface often does not lead to a considerable improvement of the materials through-thickness-properties. A spatial fibre fraction seems to be capable to reduce this drawback. Recent developments in the field of 3D-reinforced high performance composite materials are considered as a very promising alternative to the conventional in-plane

reinforced 2D structures. Additionally, the advantages from the viewpoint of increasing manufacture efficiency put these materials in a main focus of today's interest.
3D textile preforms are commonly considered to enhance the through-the-thickness properties, such as interlaminar shear and normal strength, damage tolerance and fracture toughness. Particularly relevant in the structural design process is to enhance the delamination resistance. The recently invented flat bed weft knitting technique [1] is a well suited possibility to realise 3D textile reinforcement with global uniformly distributed 3D-reinforcements. Furthermore, local 3D reinforcements confectioning technologies like stitching and tufting can be applied.
The efficient usage of such 3D reinforced composite structures for crash and impact relevant applications strongly depends on the fundamental understanding of its structural failure behaviour. This article focuses on the experimental and numerical investigation of locally 3D reinforced composite structures and has been elaborated in a cooperation of the DEPARTMENT OF ENGINEERING SCIENCE, UNIVERSITY OF OXFORD and the INSTITUTE OF LIGHTWEIGHT STRUCTURES AND POLYMER TECHNOLOGY, TU DRESDEN. For the development of realistic simulation models for textile reinforced lightweight structures under dynamic loading, basic experimental investigations of textile reinforced composites are necessary in order to gain an indepth knowledge about their material behaviour and failure mechanisms [2].
Specimens were tested under impact loading conditions with the focus on its delamination resistance and energy dissipation. As shown in previous studies [3], the impact-bending-test device (IBT) is capable to evaluate the materials impact resistance. This device was used to investigate the effects of different stitching configurations to the delamination behaviour (varying stitch density and thread material).
The Finite Element Analysis (FEA) plays a key role in the design process. Qualified tools for a structural modelling as well as for a failure analysis are essential for industrial applications to establish 3D reinforced structures in the design and development process. Concerning the simulation of delamination initiation and propagation, much effort is put on investigational work. Based on phenomenological knowledge gained by the experimental work, numerical approaches for the simulation of the executed experiments are presented in this article. The implementation of the 3D-reinforcements and the failure due to delamination are the main subjects of interest.

EXPERIMENTAL SETUP

The impact experiments with the IBT (Fig. 1) are based on a modified Split-Hopkinson-Bar apparatus which enables impact velocities up to 15 m/s [4, 5]. 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 until the impact. The target is a specimen plate of 100 x 100 mm which is positioned free to move in front of a support with a circular opening.

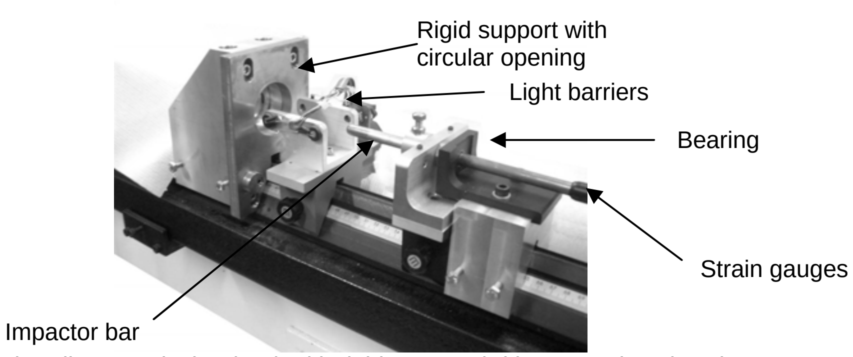

Fig. 1 Impact-bending-test device (IBT) with rigid support (without specimen) at the Department of Engineering Science, Oxford University [6]

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 deformations and the velocity, the stress wave propagation, initiated by the impact in the impactor bar, can be fully reconstructed by applying the 1D wave theory

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

where D'Alembert's solution

$$u(x,t) = f(x-ct) + g(x+ct) \tag{2}$$

gives the displacement, force, stress and velocity for every section of the thin rod for any time in the recorded interval. In Eq. (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. Thus, the obtained information enables the calculation of the energy balance for the whole system. For the purposes of the experiments discussed here, the IPB as proposed in [4, 7 has been modified insofar that the formerly used support tube was replaced by a rigid support (Fig. 1). The energy balance simplifies from

$$\Delta E(t) = E^P_{kin0}(t) - E^P_{kin(t)}(t) - E^S_{kin(t)}(t) - E^P_{pot(t)}(t) - E^S_{pot(t)}(t) \tag{3}$$

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 [6]. In Eq. (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 by

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

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 is 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

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

MATERIAL CONFIGURATION

Since the complex shapes of composites for many lightweight structures prevent the application of preforms made of one piece, the 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. 2). 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.

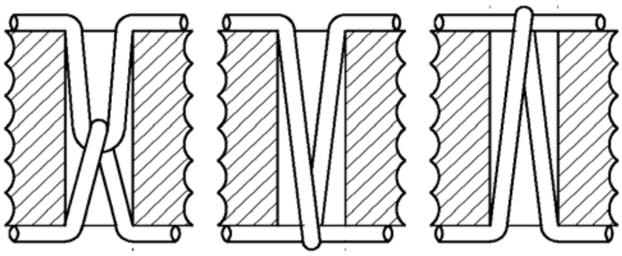

Fig. 2 Variation of the yarn tension with the double locked stitch technology [8]

Two layers of the globally 3D-reinforced material, the multi-layered weft knitted fabrics (MKF) made by the Institute of Textile and Clothing Technology, TU Dresden, have been joined by stitching. The MKF type 1 (MKF 1) specimen with the textile architecture, as illustrated in Fig. 3, use 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 of the MKF 1 is arranged symmetrically with a specimen size of 100 mm × 100 mm (Fig. 4) and 2 mm thickness.

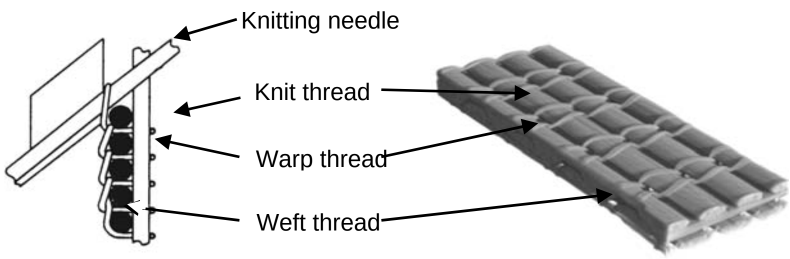

Fig. 3 MKF type 1, left: basic architecture (schematic) [1], right: CT-scan [9]

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 mm and 10 mm for the stitch distance (Fig. 4).

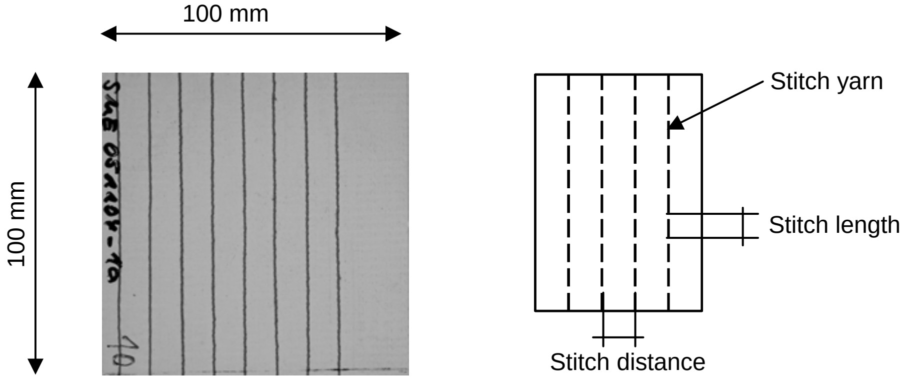

Fig. 4 Configuration of the stitched specimens

IMPACT EXPERIMENTS AND ANALYSIS

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. Besides the non-destructive inspections of the damaged specimen (Fig. 5), the analysis of the data obtained by the data acquisition system of the testing rig like maximal plate deflections and dissipated energy ratios (Fig. 7) has been performed.

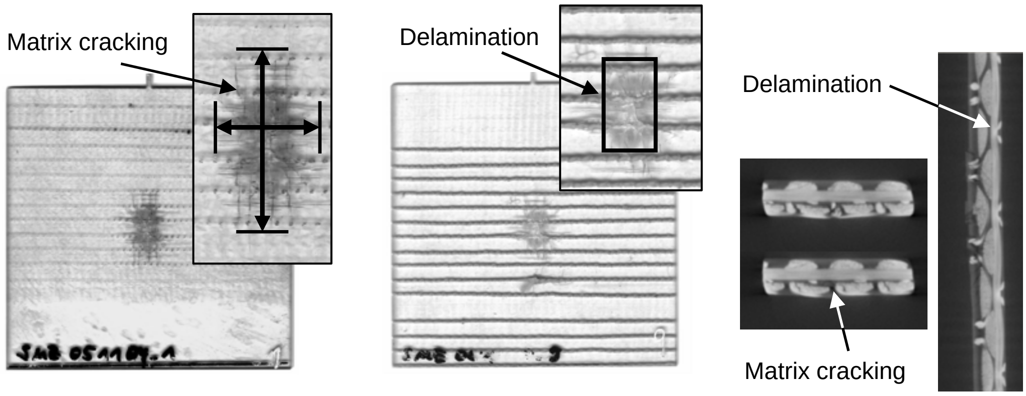

Fig. 5 Damage events and failure modes after impact (left: glass stitching; middle: aramid stitching, right: CT-scan) [9]

The analysis showed, that the results of the ultrasonic and x-ray observations contain less instructive information compared to optical and computer tomography (CT) inspections. 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 enables the identification of the fracture depth (Fig. 5).

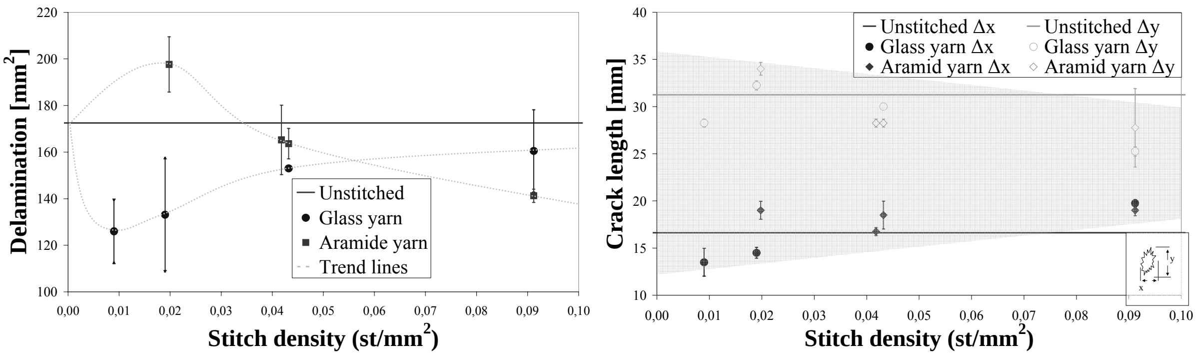

Fig. 6 Exemplary results of impact experiments at v_{imp}= 8 m/s based on non-destructive inspections [9]

As shown in Fig. 6 stitched materials tend to have less delaminated area after impact. In the range of lower stitch densities the glass yarn shows an advantage compared to the aramid yarn. This 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. The initial difference of the crack lengths in x and y direction of the unstitched material is reasonable by the fibre architecture of MKF type 1 (Fig. 3). The crack evolution length for different stitching configurations can be seen as almost independent from the stitching material with the tendency to converge caused by the raising perforation density due to the stitching process.

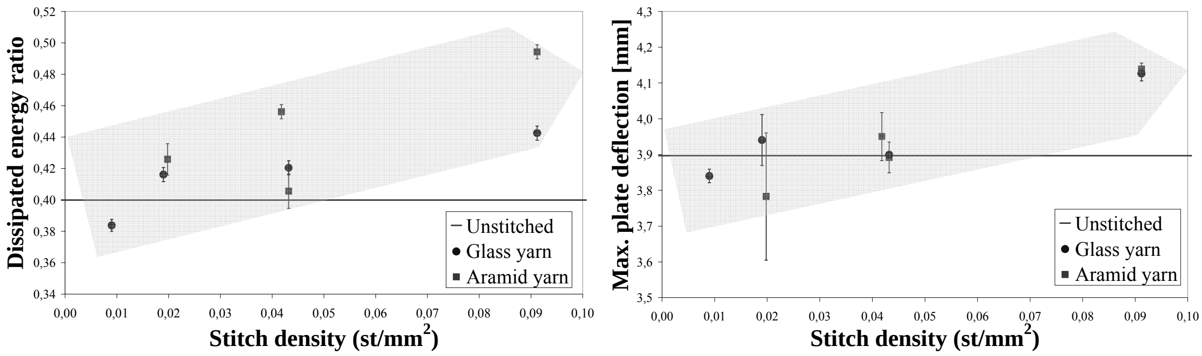

Fig. 7 Exemplary results of impact experiments at v_{imp}=8 m/s based on recorded data [9]

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

NUMERICAL APPROACHES

The influence of the through thickness reinforcements on the delamination resistance has been shown in the previous chapter. The purposeful usage of locally 3D-reinforced materials can be accelerated by the use of numerical analysing tools like the Finite Element Analysis (FEA). Since analytical approaches are not capable to represent satisfying results yet, the aim is to develop FE simulation approaches to enable the structural evaluation of 3D-textile composites under crash and impact conditions. Two main issues were aimed at: the implementation of the locally stitched 3D-reinforcements and the representation of correct delamination behaviour. The structural model has to provide sufficiently enough possibilities to study both problems (Fig. 8). In this objective, one specific MKF 1 configuration was chosen in order to simulate the impact tests.

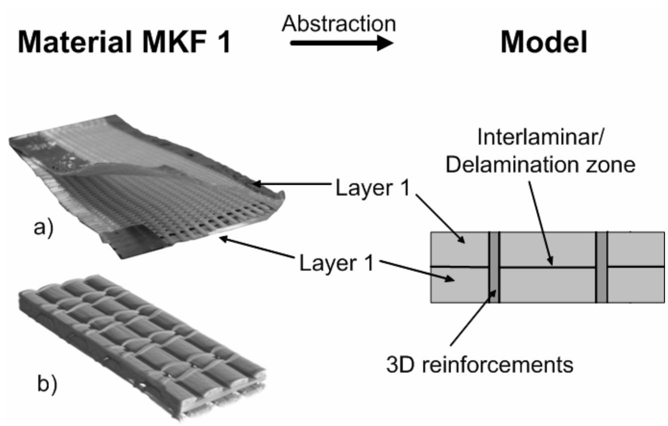

Fig. 8 (a) Material structure photo of unconsolidated knitted MKF 1, (b) CT-scan of the material and mesoscopic model [6]

The key issue is to identify whether the phenomenological problem of delamination in combination with the 3D-reinforcement should be handled in terms of fracture or continuum mechanics [6]. Three dimensional modelling and analysis of every single composite layer connected by an appropriate bonding condition can be seen as the most accurate way of treating this problem [6]. From the viewpoint of the changing geometric conditions while impact, a fracture mechanical approach for the failure due to delamination is adequate following the damage mesomodel approach for laminates (see LADEVEZE, ALLIX et al. e.g. [11]). Only interlaminar delamination is considered. The following three main approaches for delamination modelling can be taken into account:

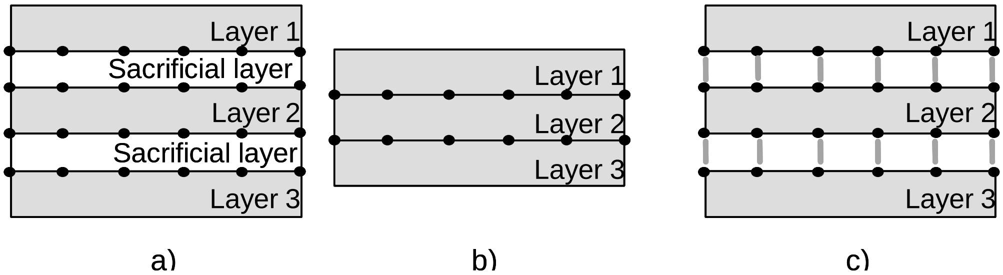

Fig. 9 Basic approaches for delamination modelling: (a) sacrificial layer, (b) implemented in material model, (c) contact definition

Including an additional unreinforced layer, situated between the material layers (Fig. 9a) and representing a continuum for the resin rich interface is called forming a sacrificial layer. Therefore, the failure parameters can easily be adapted to the actual behaviour by choosing an appropriate material model in order to separate the neighbouring fibre reinforced layers and create delamination. Reaching the failure threshold, the elements are being deleted which tends to cause numerical instabilities because of the complex internal energy algorithms of FE codes and a loss of mass. This effect is even more intensified dealing with the localised application of energy during impacts. Besides this, another drawback is the dramatic increase of the number of elements. According to microanalytic observations, the resin rich layer is very thin. In order to prevent poor aspect ratios in the sacrificial layer, the element size drops in the whole model. The calculation time rises extensively.
An implemented delamination criteria within the material model (Fig. 9b) is also known as the smeared approach. The zones which are likely to delaminate are not specified explicitly. The composite layers are not treated individually but all together as a continuum. Potential delamination zones are not specifiable, witch causes inaccuracies in geometric and structure mechanical respects. Additionally, element deletion is unpreventable. A significant feature of this method is the low modelling effort.
Finally, a so called tied contact definition can be used (Fig. 9c) to model the delamination process. This approach has the advantage that the choice of the material model and its failure modes is completely independent from the delamination criteria. Furthermore, different element sizes can be connected. That often eases modelling and provides more freedom from the structural modelling point of view. Increasing number of contact definitions always raise the calculation effort.
The previous observations showed that due to its double layered knitted structure, delaminations occur in the resin richer zone between only. It is also called the interlaminar zone. Based on investigations in terms of the calculational effort, the accuracy and numerical stability as well as the modelling effort, a tied contact definition has been used to simulate the delamination. Within the FE software LS-DYNA, a various initially connected contact definitions are available like the group *TIED or *TIEBREAK CONTACT. Most of those provide a separation of the contact partners at certain shear or normal stresses. Debonding criteria like

$$\left(\frac{\sigma_n}{R_n}\right)^2 + \left(\frac{\sigma_s}{R_s}\right)^2 = 1 \quad \text{for} \quad \sigma_n > 0 \tag{7}$$

or

$$\frac{\sqrt{\sigma_n^2 + 3|\sigma_s|^2}}{R_n} = 1 \qquad \text{for} \quad \sigma_n > 0 \ , \tag{8}$$

$$\frac{\sqrt{3|\sigma_s|^2}}{R_n} = 1 \qquad \text{for} \quad \sigma_n < 0 \tag{9}$$

can be applied, where σ_n and σ_s denote the normal and shear stresses components and R_n and R_s the corresponding failure stresses respectively [12]. In contrast to the stress based failure criteria, force based formulations are practically irrelevant.

The contact models also differ in their post failure treatment concerning the definition, numerical stability and accuracy. In general, linear post failure behaviour is available as for example shown in Fig. 10 for mode I loading. But also a non-linear response is possible, following a predefined characteristic by applying i.e. progressive or regressive behaviour.

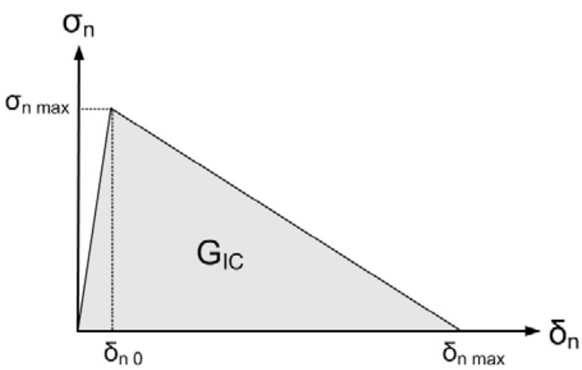

Fig. 10 Bilinear stress-gap opening behaviour (linear post failure response) for interlaminar mode I fracture with σ_n and δ_n the normal stress and the gap opening

For locally 3D-reinforced composites, a modelling approach based on a representative volume element can be seen as the most promising one. With the focus on the delamination occurrence and its strong interaction with 3D-reinforcements, this method has its drawbacks due to the fracture mechanical background of the problem. Furthermore standardised tools provided by LS-DYNA were ought to be used. Therefore the aim was to identify a suitable mesoscopic representative model of the material structure (Fig. 8). Additionally, the necessary level of abstraction in combination with a reasonable modelling and calculation effort can be stated as limiting conditions.

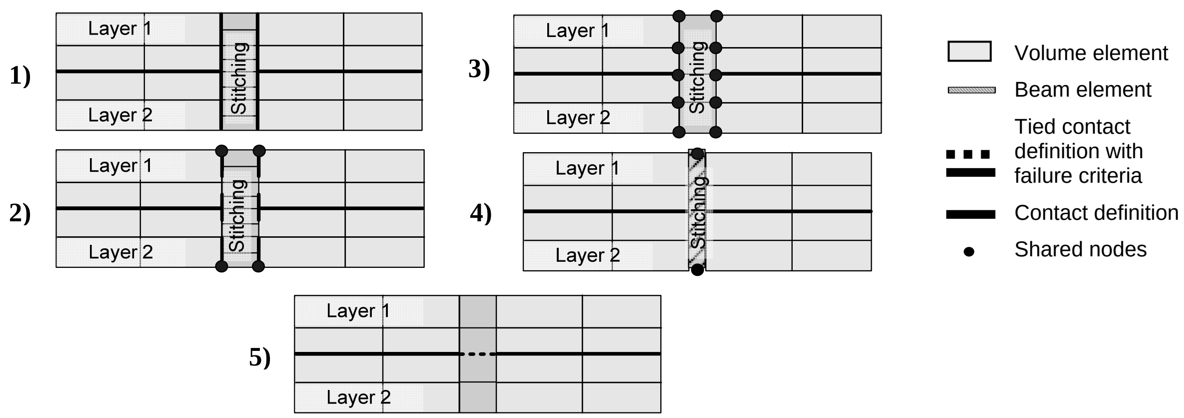

Fig. 11 Modelling concepts for the 3D-reinforcememtns: 1) tied contact of volume elements, 2) contact of volume elements, 3) classification by material model, 4) beam element, 5) contact [6]

As displayed in Fig. 11, five basic approaches were identified. The 3D-reinforcing stitching fibres are considered as independent structural unit in each concept. Detailed studies regarding the numerical stability, accuracy and the modelling effort have been performed on a Double Cantilever Beam model. In this study, concept 4 – inserting beam elements – and 5 – connecting the layers by tied contacts – qualified for further usage in more complex applications like the simulation of the impact experiments. The modelling effort was reasonable compared to the other concepts with volume element solutions, whereas the calculation effort drops significantly. A big advantage of the beam elements is the adaptability by modifying the underlying beam theory or the parameters like the diameter and material model. In this work, tross elements have been used. Concerning the governing shear failure stresses under impact loadings, concept 5 has to be considered as well, due to the limited capability of the beam elements to represent shear failure. The good compatibility to the contact definition used to represent the delamination is an additional advantage.
Based on the investigations, the impact experiment of the two layered MKF 1 structure has been simulated. One point integrated eight node brick elements and the Material model *MAT_COMPOSITE_DMG_MSC (*MAT 162) of the explicit FE-software LS-DYNA have been used in a quarter model (Fig. 12). A good agreement in the theoretically predicted and experimentally determined delaminated area (Fig. 12) has been achieved by using *CONTACT_AUTOMATIC_SURFACE_TO_SURFACE_TIEBREAK for the delamination simulations and the same contact algorithm to represent the 3D-reinforcements (concept 5, Fig. 11).

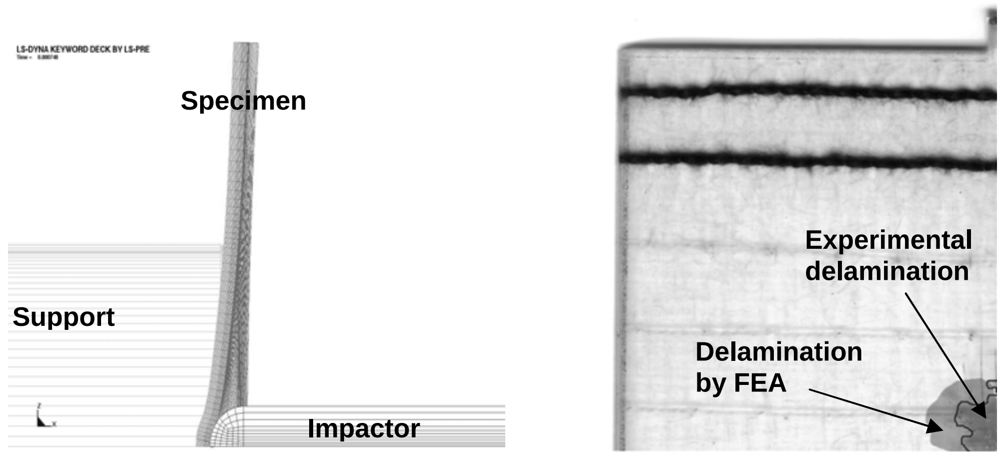

Fig. 12 Impact simulation (left), delaminated area calculation vs. experimental result (right, quarter of specimen) [6]

CONCLUSION

The paper focuses on an experimental approach for the characterisation of 3D-reinforced composite materials under 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 on GFRP consisting of flat bed weft knitted textile performs at subcritical impact velocities (no breakthrough of the projectile) dominantly causes the fracture modes delamination and matrix cracking. 3D fibre reinforcement in laminated composites achieved by stitching is capable of raising the materials applicability in terms of their delamination resistance. Additionally, higher energy dissipation can be denoted.
An efficient usage of 3D-reinforced 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 FEA, the gained knowledge from the proposed experimental studies was used to show and investigate approaches to implement the local 3D-reinforcements into a numerical model. The representation by beam elements and contact definitions respectively showed satisfying results. The implementation of the correct delamination behaviour in the mesoscopic model was investigated in particular. Applying a contact definition to represent the interlaminar zone in which delamination occurs turned out to be adequate.

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