Structural Stitching as a Method to design High-Performance Composites in Future

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Abstract: *With the realisation of modern and cost-effective high performance fibre composite structures, the significance of textile technologies is constantly increasing. In addition to being a very reliable process and to providing a high degree of automatisation, the possibility of a targeted and defined influence on process parameters offers a great potential when dealing with local problems such as notches and locations of load application. Stitching methods can assume a significant position in the process chain and can play an important role in the future during the realisation of large structures in fibre composite technology. They provide the potential to structurally link different textile technologies with another and thus represent an essential part of the process chain in addition to a qualified injection method and preform technologies. Stitching methods can be used as a means of fixation or as a fibre-suited bonding process. In addition, they provide the possibility of specifically producing local three-dimensional stiffness and strengths in laminate-shaped fibre composite structures. Here, the improvement of the out-of-plane properties are compared with a degradation of the in-plane properties. The question of optimal stitching revolves around the issue of how much must be stitched in order to achieve a certain benefit without decisively weakening the composite's real structural mechanical tasks.*

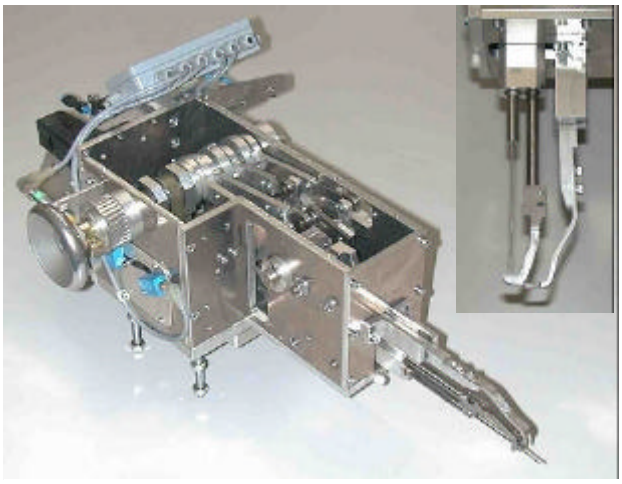

Fig.1: Development of a "tufting head" for operation on conventional CNC machines. KSL GmbH, Lorsch and DLR, Institute of Structural Mechanics, Brunswick.

1. Introduction and Motivation

Fibre composite technology plays an important role in the realisation of lightweight construction projects, especially in the field of aerospace. Future areas of application for this technology call for a considerable reduction in costs while maintaining the structural properties. In contrast to the conventional construction methods, a weight reduction of 30%, for example, is being planned in the HGF[2] research project "Black Fuselage" while simultaneously reducing 40% of the costs. However, these goals cannot be met with the presently available fibre composite technologies ("prepreg methods").

Cost-efficient and high-performance fibre composite structures can be realised in the future with the aid of the resin injection technologies. A manufacturing concept based on these technologies essentially consists of the following components [40]:

- **textile preform technologies:** highly-automated methods for the manufacture of qualified textile preforms, e.g. multi-axial warp knits and TFPs (Tailored Fibre Placement), etc.
- **structural stitching techniques:** influence on the mechanical properties in the 3D direction as well as the development of fibre-suited bonding methods is possible. Preform fixation is an additional technological aspect.

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- **injection method:** Qualified and cost-effective resin injection method, e.g. SLI technology (Single Line Injection).

In the recent past, great success and progress could be achieved in the area of textile preform technologies and injection methods. Yet the promising first steps of the "structural stitching method" still require further development. Only when a bonding and fixation technique is available that is able to structurally link different textile preform technologies with each other and that offers the possibility of creating local three-dimensional stiffness and strengths will the potential of this new concept be fully exhausted.

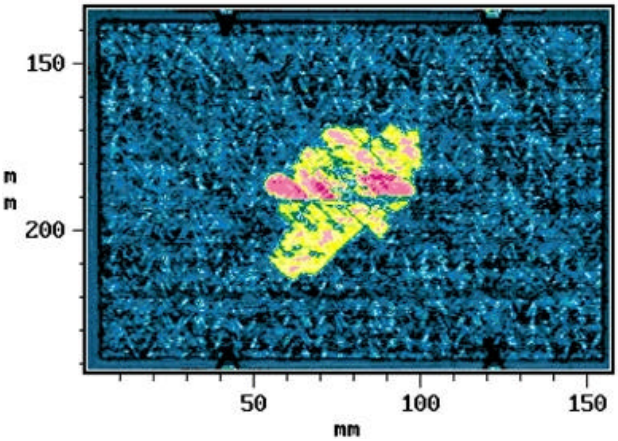


Fig. 2: Ultrasonic scan of a laminate with impact damage. Delamination endangers the mechanical properties of the composite.

Conventional prepreg fibre composite components are usually manufactured by a laminate-shaped layering of single fibre plies. The attainable specific in-plane stiffness and strengths have helped make the fibre composite technologies successful in the present and in the past. However, a disadvantage has become evident: The out-of-plane stiffness and strengths are determined by the matrix and show a considerable loss compared to the in-plane properties which are greatly influenced by the fibre properties. The significance of three-dimensional stress conditions, e.g. at locations of joints or load application or in areas prone to notches are increasing with the realisation of complex, modern, highly-stressed structural components made with fibre reinforced composites. Delamination damage due to impact can greatly affect the composite to the extent that a considerable loss in compression strength must be expected (Fig. 2).

In the future increasingly complex and highly stressed fibre composite structures will require a technology which allows for specific and local influence on the three-dimensional properties of a material without extensively damaging the excellent structural in-plane properties. The "Structural Stitching Technologies" and especially the "Single-Sided Tufting Method" (Fig. 1) developed at the DLR Institute of Structural Mechanics in Brunswick have the potential of meeting the structural as well as cost-efficiency demands. Thus it is possible to significantly improve the damage tolerance, energy absorption behaviour, esp. the energy release rates, crack propagation and crash behaviour of conventional fibre composite structures by means of appropriate structural stitching [7,8,9,14,21,22,23,25,27,30,31,35,36,38,39].

Several methods have been developed in order to produce stiffness and strength in the 3D direction [10,40]. One of these is primarily the use of three-dimensional weaving and braiding techniques. The many years of experience in the textile industry could be very useful here. However, the developed machines are very expensive and complex. An additional disadvantage is the lack of flexibility of the semi-finished products: A local adaptation to certain stress conditions is possible only with a considerable amount of difficulty because of the inflexible machine parameters. In this case, stitching methods prove to be much better.

Since the stitching process becomes effective as a further step in the process chain only after the actual manufacture of the semi-finished fibre product, stitching is generally considered damaging to the in-plane properties despite the improved out-of-plane properties. The undulation of the fibre material as a result of the damage has a negative effect on the in-plane properties of the stitching material. For this reason, a basis must be created in which the stitching process is included as a quantifying and reproducible process of the design of an actual component. The multitude of possible stitching parameters (i.e. stitching threads, stitching density, stitching pattern, type of stitch, stitching method, type of needle, thread tension, stitching speed, type of laminate, machine parameters, etc.) as a special advantage of this technology provide a high amount of flexibility but make the quantification of the stitching as a design parameter particularly difficult.

2. Development of a Structural Tufting Method

The "tufting method" developed at the DLR Institute of Structural Mechanics is very different from conventional stitching technologies (Fig. 1,3). When "larger" fibre composite preforms are sewn, the stitching machine is actively operated instead of the stitching material. The "tufting head" developed in cooperation with KSL GmbH (Lorsch) is operated on a conventional CNC unit at the DLR. However, applications such as portal systems, handling machines or robots are also possible (Fig. 3).

Conventional stitching technologies use a dual-threading system (upper and lower threads) which make the seam by forming loops and knots (e.g. chainstitch or lockstitch). The formation of knots and the resulting tensioning of the thread can considerably weaken the mechanical properties, especially the compression and bending properties, due to undulation and constrictions [11,12]. In contrast, “tufting” is a single-thread method in which the formation of loops is possible with a loose and almost tension-free introduction of the threading system that does not adversely affect the material. The actual reinforcement comes from the bonding between the matrix and stitching thread which is present only after injection. Steps were taken from the very beginning during the development of the “tufting head” at the DLR and at KSL GmbH to ensure a flexible application. A 60 mm lift of the crankshaft also allows for the stitching of particularly thick materials. A large application area can be covered by controlling the needle position in a bandwidth of 0 to 40 mm. A particularly small “hold-down” device also allows for inaccessible areas such as the notches of mounted stringers on a wing shell to be stitched. The lack of thread tension makes it possible to make oblique stitches as well. Up to 1000 stitches per minute are possible even without oiling the unit. An additional advantage of this method in contrast to conventional ones [6,28,29] is that the material to be sewn only has to be accessible from one side which eliminates the need for complex and particularly costly constructions with lift tables [6]. In the ideal case, it is possible to make stitches directly into the SLI injection mould.

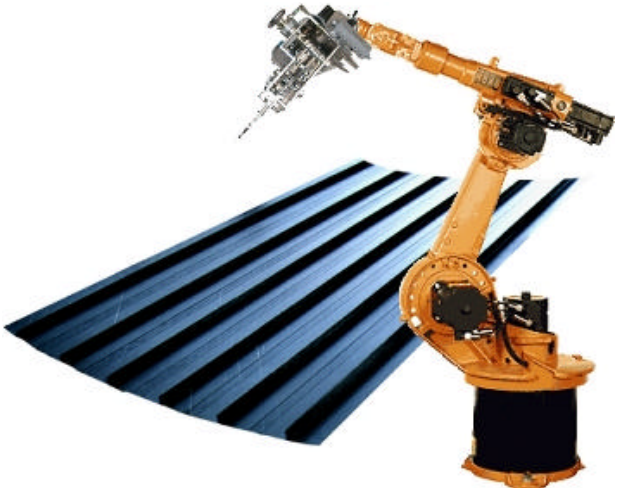


Fig. 3: Industrial application with a stitching-robot to bond stringer on a CFRP-panel which is endangered by impact (schematic).

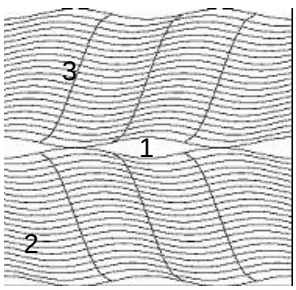
The singe-sided stitching method such as the “tufting” method presented here or the “dual-needle single-sided stitching” technology [16] developed at ALTIN Nähtechnik GmbH offers the possibility of reinforcing fibre composite structures with highly stiff and strong stitching threads where it is necessary. In addition, the development of a more cost-efficient and more reliable method will pave the way from the laboratory to an application ready for a series.

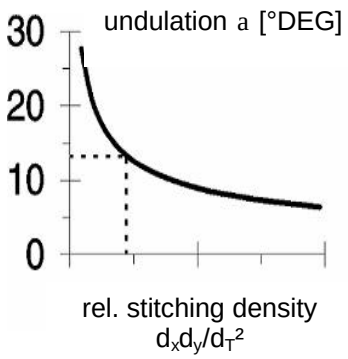
3. Computational Approaches

Conventional fibre composite computations are usually based on transversal isotropic, unidirectional single layers (CLT, FSDT, etc.). Properly aligned prepreg laminates and fibre composite structures developed with the filament winding method correspond to this idea from a technological point of view. In contrast, all textile processes have in common that the semi-finished products are more or less developed from the twisting and linkage of individual threading systems and thus the idea of a directional strand of threads homogeneously embedded in a matrix is no longer valid. Even stitching creates undulations in the laminate which influences the mechanical properties at the micro and macro-mechanical level.

Geometric models make it possible to get a good overview on the typical problems posed by textile preforms. Compared to prepregs, a degradation in stiffness and strength must be taken into account.

1. disturbance (stitching thread)
2. undulated laminae
3. lines of maximum undulation





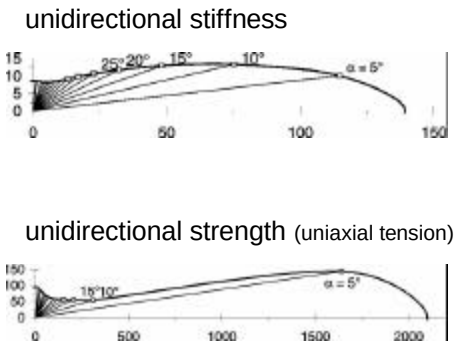


Fig. 4: Unidirectional undulation model. Polar computation with *LamTech*© (CLT). Parameters: T300, Ciba 6376, j =60%, failure criteria TsaiWu

There are two main reasons for this:

- a fibre-breakage caused by penetration due to the sewing process,
- fibre undulations which can lead to an in-homogenous distribution of the stresses.

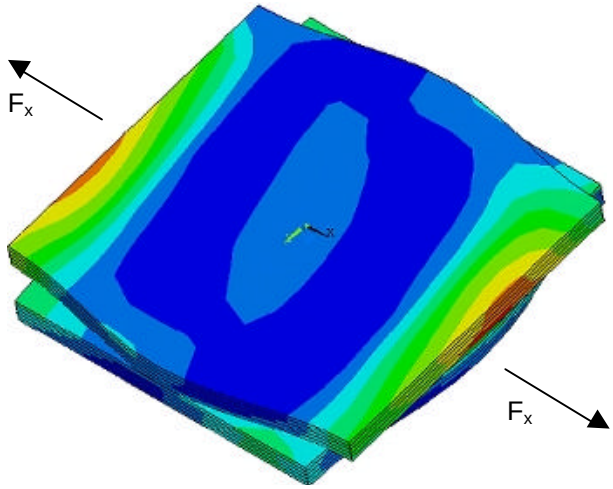


Fig. 5: Finite element analysis of a stitched $[0°/90]_s$ laminate unit cell (disturbance is not shown here). Estimation of the TsaiWu failure criterion due to uniaxial tension.

Although the fibre-breakage caused by the sewing process cannot be ignored, the fibre undulation is mainly responsible for a degradation of the in-plane properties.

It is necessary to develop an appropriate computation method to determine the order of magnitude of the in-plane degradation. The basis of all computation models is a possibly realistic geometrical formulation of a so-called unit cell. Fig. 4 depicts a simple, two-dimensional undulation model which is able to point out general problems found in textile processes and in stitching technologies in particular. The model is based on a undisturbed, unidirectional laminate. The stitching thread causes a disturbance which is practically "surrounded" by the fibre strands. As a consequence, the fibre strands result in an out-of-phase sinus curve. An estimate of the influence of the undulation becomes possible when the local undulation angle in the y-direction is integrally averaged and then the maximum along the x-axis is determined. With this, the maximum mean undulation angle results as

(3-1) $$\hat{a}_{\max} = \arctan\left(\frac{p^2}{8}\frac{d_T}{d_x}\right)$$

If the usual geometry dimensions for the diameter of the disturbance due to the stitching thread d_T and the stitching distance d_x are taken as the basis for the geometry values for the stitching, then a middle undulation angle of up to 15° seems to be quite realistic. A disadvantage of the model formation becomes immediately apparent: Equation 3-1 does not depend on the stitching distance d_y transverse to the fibre orientation. Experience, however, has shown that the influence diminishes with increasing distance from the disturbance and thus this becomes an issue for only relatively "narrow" stitching distances. The UD-polars for the stiffness and strength of a unidirectional laminate under uniaxial tension shown in Fig. 4 make clear that minimal deviations from the optimum 0° orientation of the fibres can already have a considerable effect on the mechanical properties of the laminate. Therefore, the improvement of the out-of-plane properties has to be compared with a degradation of the in-plane properties. Stitching as a means of improving the 3D properties of the composite is presented as an optimisation:

"How much must be stitched in order to improve the out-of-plane properties while minimally degrading the in-plane properties?"

Series/parallel or parallel/series models can be used to obtain an answer for the changes in the stiffness properties. A simple rule which bears a good relation to more elaborate models links the two-dimensional undulation model (Fig. 4) with a one-dimensional correlation [2,3] by definition of a fictive geometry. The Young's modulus in the longitudinal direction of the fibres of an undulated, unidirectional laminate *E_»,||* dependent on the value for a non-undulated laminate ($E_{\|}$, $G_{\#}$, $v_{\|\perp}$) then results as

(3-2) $$E_{\approx,\|} = \frac{E_{\|}}{1+\frac{p^4}{128}\left[\frac{E_{\|}}{G_{\#}} - 2*(1+n_{\|\perp})\right]\left(\frac{d_T}{d_x}\right)^2}.$$

For an undulated CFRP/T300-UD, knock-down factors for typical stitching widths and thread diameters[3] can be given as opposed to the ideal and perfectly aligned UD laminate from 0.54 to 0.93.

It is more difficult to make a statement on the strength behaviour. However, at least areas can be defined in which the undulation angle reaches its maximum and where the greatest risk of in-plane degradation can be expected. Corresponding to the sinusoidal distribution of the fibre strands, the areas of maximum deflection are found between the individual disturbances as well as in areas where the undulation starts. Since not only the fibre angles but also the fibre volume content j and thus the local strengths are inhomogeneously distributed, the stress/strain distribution of the unit cell must be known in order to evaluate the global strength. The application described in Fig. 4 of the undulation model within the analysis of a three-dimensional unit cell is shown in Fig. 5. The evaluation of the TsaiWu failure criterion with uniaxial tension in the x-direction of an undulated $[0°/90°]_s$ laminate is depicted. In contrast to elementary stress conditions of the classical laminate theory, the distribution of the failure criterion is an indication of clearly inhomogeneous stresses. If the geometry values for an estimation of the "middle" undulation angle according to equation 3-1 are taken and a knock-down of the UD strength is determined by means of the strength polarities shown in Fig. 4, an angle of a_{max}»10.5° and a strength of approx. 300 N/mm^2 is the result. If a balance of this value is made up on the critical strain of the fibres, a critical intermediate fibre maximum elongation of $e_{x,ZFB}$»0.22% can be concluded. This value agrees well with the result of the FE analysis: $e_{x,ZFB}$»0.17%. This comparably low value, however, should not be interpreted as a strength limit in the original sense. Instead, reaching the failure criterion early on is an indication of a local concentration of stresses which primarily affects the matrix. In practice, these stress peaks are locally reduced by plastification and "bridging" so that it becomes necessary to make a non-linear assessment of the material behaviour while taking into consideration the non-linear material laws [24]. If the maximum safety factor, which is given by the fibre strength, is consulted for a rough assessment of the ultimate strength limit, then a critical strain of $e_{x,kr}$»1.51% is the result.

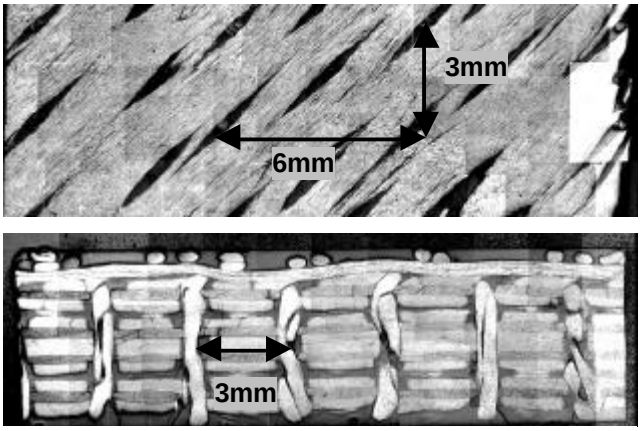


Fig. 6: Micrographs. Above: 45° layer of a stitched composite made of CFRP warp knitted fabrics, RTM6 matrix, Single Line Injection (SLI). Below: Cross-section of a symmetrically layered, stitched composite.

The compression strength is affected by the undulations in that a local buckling failure of a deflected fibre occurs at the micromechanical level in the elastic bedding [13,17,18,41]. Thus an further degradation of the in-plane compression strength can generally be expected with an increasing degree of undulation or stitching density. However, there are also indications that the stitching threads can have a supportive effect which, by forcing a certain half wave buckling length, help positively influence the stability behaviour [39]. This, for example, can be used to improve the energy absorption behaviour of sandwich panels by stitching the skin to the core [34].

Every result from the computation model greatly depends on whether it is possible to appropriately map the geometry of the examined section. As long as these are textile processes whose machine parameters lay down and wrap individual fibre strands in a defined and reproducible manner, it can be assumed that an accurate modelling is possible (e.g. fabrics, weaves, non-crimp fabrics, etc.). In contrast, the stitching process becomes effective only after the actual production of the textile semi-finished product as a further step in the process chain, so that it is very difficult to develop a generally applicable geometrical model. Every stitch has a different micro-mechanical appearance! Micrographs of a 45°-layer, a cross-section of a symmetrically stacked composite and the detailed image of a resin-rich volume nearby a stitch are shown in Figures 6 and 7.

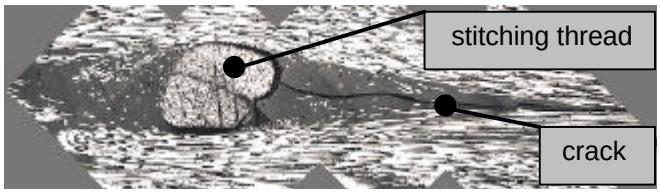


Fig. 7: Stitching threads cause disturbance which can start cracks. Warp-knitted fabrics, matrix Blendur®.

[3]The basis for computation is stitching widths of 3mm to 10mm as well as Torayca T900 stitching threads with 80 tex

Although the tendency of the model formation from Fig. 4 and 5 can be confirmed, a statement on the macro-mechanical strength, which can be considerably affected by micro-mechanical events, can only be made with precaution. The homogenisation of strength is always problematic! In contrast, a fairly precise homogenisation of the stiffness is possible even without knowing the precise stress/strain distribution in the continuum.

There are additional technological influences in addition to the basic computational problems of a stitching. Research has shown that the disturbance caused by the stitching threads are responsible for the development of cracks (Fig. 7). Resin-rich volumes and the concentration of stress can be the cause of this problem. In addition, the choice of a matrix system and curing cycle have an influence on the thermal stresses in the cured composite as well as on the chemical reactions. Tension tests on stitched warp-knitted fabrics, on the other hand, show that the expected loss in strength and stiffness in relation to the unstitched reference is considerably less that would have been expected from the results of the computation and estimation models in section 3. An indication could be that the undulations caused by stitching only minimally exceed the disturbances which already occur in the unstitched warp-knitted fabric due to the knitting thread. The undulations seen in the upper part of Fig. 6 are not only due to the stitching (3x6 mm²) but are also clearly caused by the knitting thread!

The order of magnitude of the influence of the stitching and knitting thread is easy to see in Figure 8. Because of the lack of thread tension in the "tufting method", no constrictions are expected in the thickness direction ("funnel formation"). However, constrictions and inhomogeneity clearly occur in-plane which are caused by the knitting and stitching threads.

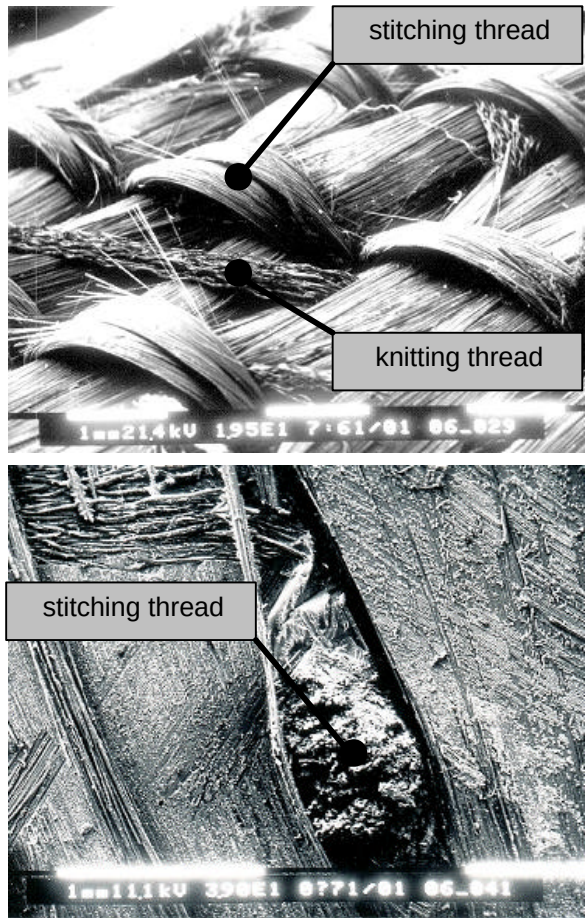


Fig. 8: Images from scanning electron microscope. Above: 3x3mm² stitched CFRP warp knitted fabric. T900 stitching thread. Below: Top view of a sheared stitching thread (experiments on stitched joint bonding [43]).

Figures 7 and 8 clearly show how hard it is to achieve a sensible geometric modelling of a unit cell. Stitching is a highly stochastic process which makes it basically impossible to make a general statement dependent on the stitching parameters. One possibility could be to achieve a statistical selection of real unit cells with the aid of a micro image processor (e.g. microtomography (µCT)) and, based on this selection, to determine the filament and resin distribution [2,33]. The ensuing analysis at the micro-mechanical level then provides the statistical data.

4. Experiments

Three-dimensional reinforcements always make sense when the goal is to counteract three-dimensional stress conditions. It is not important how the loads occur: either as direct result of a real 3D load (e.g. impact) or indirectly i.e. as a result of the development of interlaminar 3D stresses which is the result of intralaminar membrane stresses. The equilibrium of the three-dimensional inhomogeneous continuum show that the interlaminar stresses s_z, t_{xz} and t_{yz} always play a role when gradients of the membrane loads s_x, s_y and t_{xy} are expected. The integration with *z* delivers e.g. an interlaminar shear stress t_{zx} as the result of the normal load s_x changeable over *x* and an in-plane shear stress t_{yx} changeable over *y* as found in wing shells. The interlaminar stress in thin-walled shells — which are almost always present in the structure — can usually be neglected. The point of load application and force deflections or the "free" edges of structures which tend to be thick-walled (and which will play an increasingly important role in the future) can cause an increase in interlaminar stresses. Structural stitching can be used here directly as a means of reinforcement.

The results which were determined within the framework of the 1+ project sponsored by BMBF for the compilation of design rules for the CFRP outer wing of the 2010 Megaliner [20] are shown in Fig. 9.

The goal is to improve the notch sensitivity of a tension test by inserting a local reinforcement plaster. A simple material reinforcement of additional fabric plasters, a plaster reinforcement made of TFP preforms (Tailored Fibre Placement) as well as a stitched fabric plaster (= variant 1 + stitching) are also available for comparison.

The candidates have a thickness of 3.2 mm, a width of 400 mm and a length of 1600 mm. The basis laminate is made of CFRP warp knitted fabrics with a [50/40/10] lay-up. The injection is carried out at the DLR Institute of Structural Mechanics using the SLI method (RTM6). The TFP reinforcements [15] applied by the Institute of Polymer Research in Dresden on the uppermost and lowest CFRP warp knitted fabrics are totally symmetric and are not "over-pressed". The fabric plaster reinforcements have a type [33/67/0] laminate construction. They were symmetrically stacked from the outside to the basis laminate of the stitched samples and to two of the unstitched test candidates. In this "tufting" process which takes place at the DLR Institute of Structural Mechanics a Torayca T900 stitching thread is used with a stitching distance of 3x3mm^2. The stitching thread was inserted through the entire material (i.e. through two plasters and the basis laminate). During test runs (static tension, room temperature, dry) a "free length" of 800mm was realised [32].

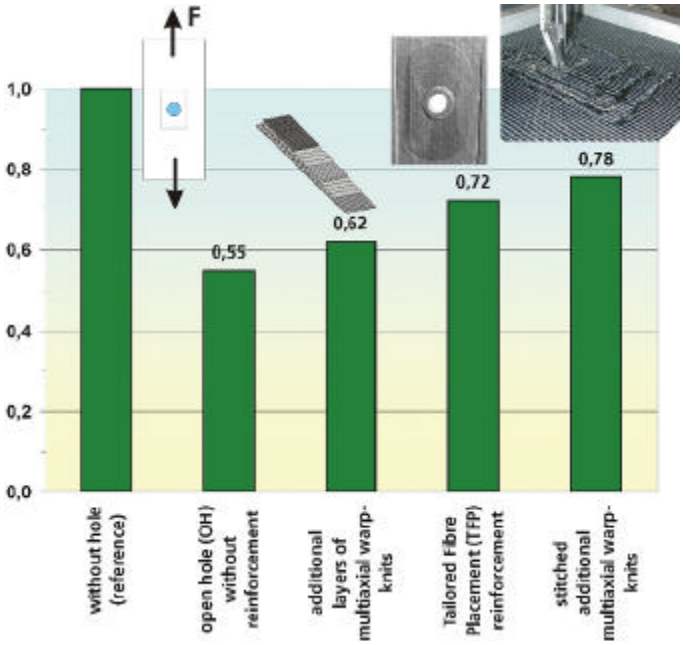


Fig. 9: Tension test on notched CFRP samples. Comparison between simple fabric plaster reinforcements, reinforcements with TFP (Tailored Fibre Placement) and stitched fabric plasters. Results are from the 1+ Project sponsored by BMBF.

At first, a TFP plaster seems to be a more appropriate method compared to a simple fabric plaster reinforcement but it is possible to considerably increase the failure potential by an additional stitching of the fabric plaster. The notched reference samples show an fracture load of 55% of the failure load with respect to the unnotched reference. This result can be increased to 62% of the reference failure load by means of a simple fabric plaster reinforcement. During the test run, a deterioration mechanism was observed in which the whole fabric plaster cracks and falls off. Although the local thickness in the area of the cut-out is three times thicker than the basis laminate, the expected load level cannot be reached because of the plaster burst. The probes reinforced with the TFP technology show an increase in the load level to 72% of the reference failure load. The result of the evaluation of the 3D grid measurements [1] are interesting: a shift of stress and strain takes place which can be responsible for the considerable increase in the fracture load. During the fracture, the whole TFP plaster – similar to the fabric plaster – cracked and broke off of the basis laminate although it had been applied to the outer fabric plies by the TFP process.

The burst of the reinforcement plaster leads to the assumption that the failure mechanism is primarily influenced by the interlaminar stresses. For this reason, an additional variant with the goal of the realisation of a real "3D plaster reinforcement" was manufactured and tested. "Tufting" as a means of three-dimensional reinforcement could increase the load level to 78% of the unnotched reference in this case, thus considerably exceeding the researched alternatives. The influence of stitching in comparison to simple, unstitched fabric plaster reinforcements shows an improvement of 42%. In addition, a completely different patter of the failure mechanism can be observed: In two of three experiments, the plaster did not burst and break off which is an indication that the 3D reinforcement was successful. The breakage, however, occurs in a much more classical way.

The object of the research results shown in Fig. 10 is the use of the structural stitching method as a means of a textile bonding, i.e. as a substitute for an adhesive or bolt connection [26,37,43]. In a coupon test programme, which is part of a work package within the framework of the LuFo2 aerospace research project, double-lap joint connections are also being researched. The "tufting method" and SLI technology were used during the manufacture of the samples. A Schappe Techniques Modelite/Carbone-PVA and a Toray T900 were used as the stitching threads. A considerable improvement of the bonding grade could be achieved with stitching. In comparison to the unstitched samples an improvement of 112% could be reached with a stitching density of 2x2 mm² in case of the Schappe thread and 65% with a stitch spacing of 1.5x1.5 mm² in case of the Toray thread. At 82% and 64% respectively, the bonding grade of such a

connection attains an order of magnitude that cannot be realised with conventional bolting methods. Realistic assumptions for bolt connections are around 50% depending on the estimated stacking sequence. Until the maximum occurs the failure mechanism corresponds to a classical shear failure behaviour between the basic laminate and the joint: The stitching threads have been sheared off together with the matrix (Fig. 8). However, excessive stitching can lead to a decrease of the applicable load which can be explained by an extreme damage of the basic laminate and its degradation of the in-plane strength. During the test procedure this behaviour was accompanied by a change of the failure mode (breakage of the whole cross-section). The differences of the results caused by the use of different investigated stitching threads can be explained by their distinguishing Tex-values which are indicators of the amount of the stitching. It is interesting to note that the failure propagation of the stitched samples, in addition, proves to be much more tolerant than the crack mechanism of the unstitched samples which usually abruptly fail. It was therefore possible after the primary damage occurred (stress peaks at the edges of the plaster) to realise a further load increase with all stitched samples beyond the level of the initial damage.

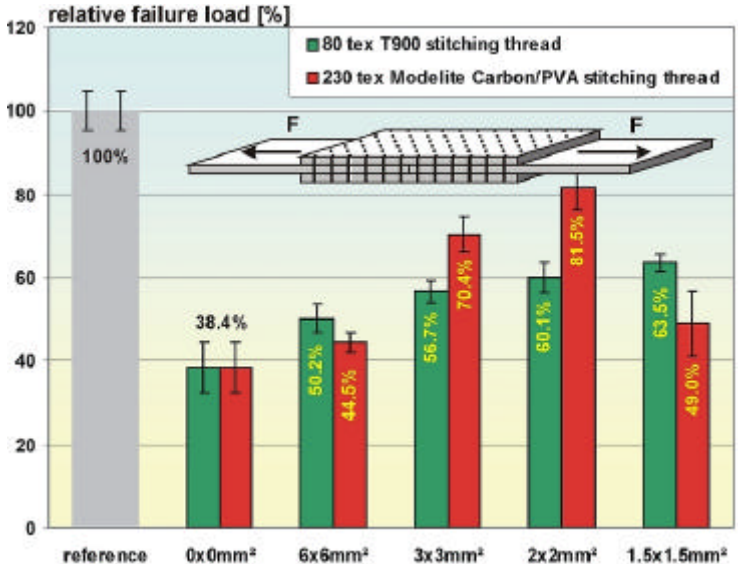


Fig. 10: Innovative joining methods [43]. Static tension tests on symmetrically stacked CFRP's bonded by a stitching joint.

5. Summary and Prospects

Structural stitching methods are currently paving the way from research in the laboratory to an applicable technology ready for the industry. In order to exhaust the entire potential of the method, it is necessary to create a dimensioning basis (design rules) for which the first steps have already been taken. Selected examples of experimental research have shown that structural stitching as a possibility of three-dimensional reinforcement is particularly useful when having to react to specific and local requirements. The great number of different stitching parameters can enable a high degree of flexibility. In addition to the technological aspect of preform fixation, typical areas of application are particularly found in cases where three-dimensional stress conditions must be expected: point of load applications as well as shells endangered by impact (e.g. wing leading edge). These types of problems are increasingly coming to the fore in present and future complex components.

During the assessment of the damage-tolerant fracture behaviour of a stitched composite, additional potentials were found while taking into consideration the presently applied conception criteria for CFRP structures. Since the fracture mechanisms between unstitched and stitched structures greatly differ, the application of an adapted design philosophy seems to be the best step. The effect of primary damage can be locally limited by using three-dimensional reinforcement techniques. A typical example is when stringers break off of a shell prone to buckling after impact has occurred. Stitched stringers provide a connection between the skin and shell so that the stringer can carry out its structural task of supporting the skin area that is prone to buckling even after primary damage has occurred. If this behaviour is consistently put into practice in a new conception philosophy then an additional weight-reduction potential can be expected.

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