Assessing the structural response of automated fibre placement composite structures with gaps and overlaps by means of numerical approaches

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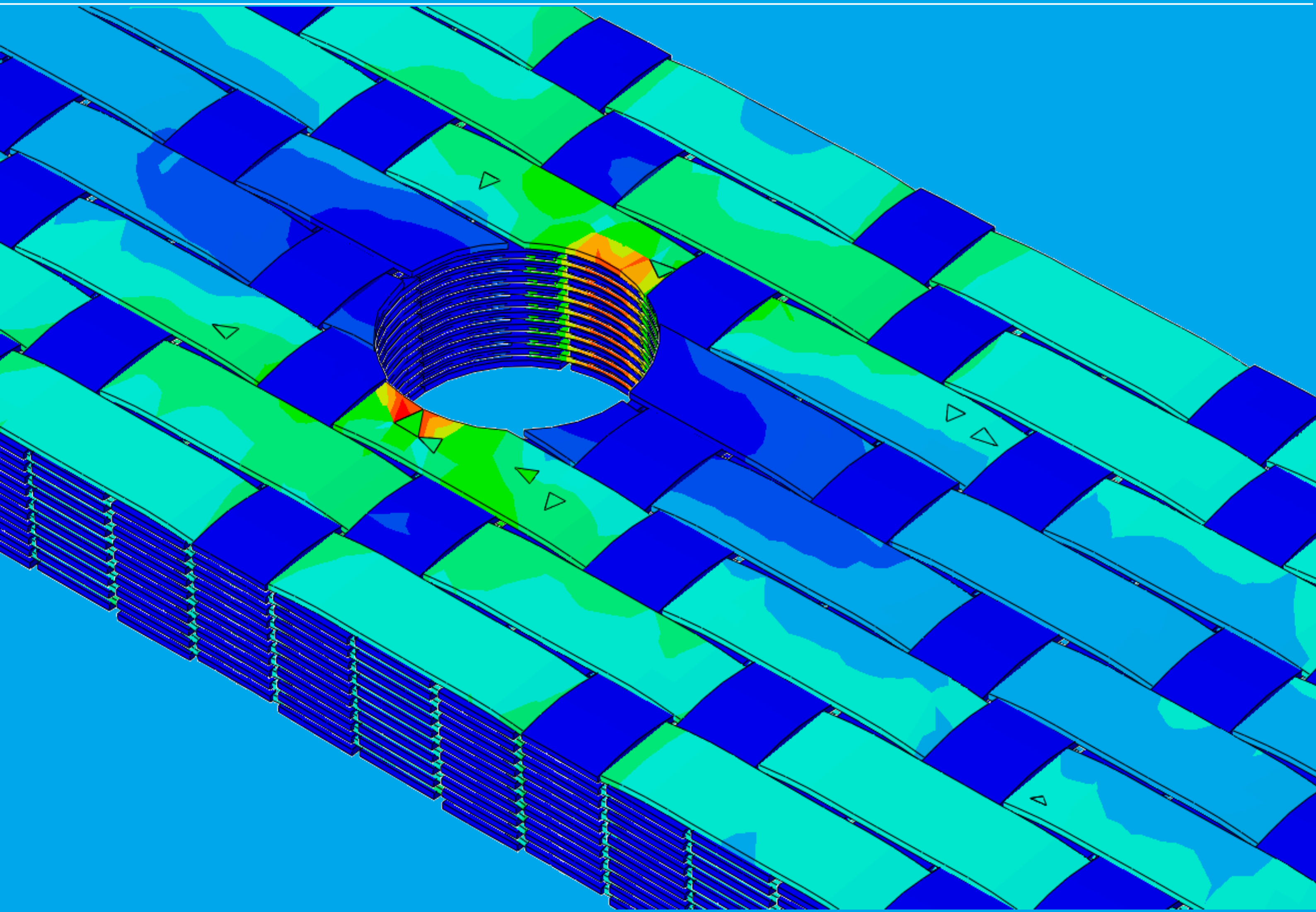

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EXECUTIVE SUMMARY

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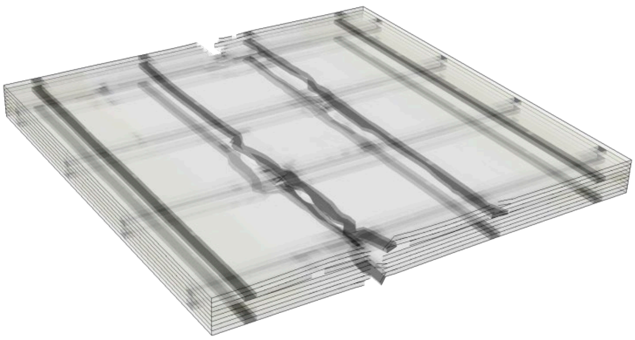

Finite element model of a composite laminate with local gaps indicated in black. After loading of the laminate damage develops originating from the gaps

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Author(s)
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Problem area

Automated production technologies for composite materials are being used in today's industry and will be used more in the future. Also the Dutch industry is interested in these technologies to streamline the production process. The automated fibre placement technology allows to place composite strips or tows using a robot arm as manipulator. However during design and manufacturing small deviations can occur due to material differences that can cause gaps and overlaps in the composite laminate. The definite influence of these gaps and overlaps in the final composite product needs to be investigated.

Description of work

Within the EU ECOMISE project the effect of gaps and overlaps in composite laminates is investigated together with DLR as partner in the project. Three different approaches are presented that include an analytical approach for rapid calculations, a virtual

This report is based on a presentation held at the ICCM20, Copenhagen, 2015.

coupon test approach using advanced damage mechanics methods and a multiscale approach. The multiscale approach tries to combine the small scale at which gaps occur (sub-millimetre) and the macro scale of the composite product (meters). In the project several test cases are defined for the fibre placement deviations such as small gaps, large gaps and large overlaps. The effects of the deviations is investigated for these cases with the three methods. Further research should also provide test data for validation of the developed methods.

Results and conclusions

The results of the calculation on the deviation for composite laminates show that there is a clear effect of the gaps and overlaps. The investigation reveals that there is a considerable effect on stiffness and strength caused by the investigated deviations. It is further found that depending on the modelling approach and the applied failure criterion (e.g. first ply failure, progressive damage) the resulting stiffness and strength properties are quite diverse. The decrease in strength is mainly caused by a local increase in stress in the laminate which triggers damage growth up to final failure. This shows that including these local effects in the laminate is important to improve the confidence in the final product. The designer can compensate for this strength reduction by further optimization and/or reducing the number of tow boundaries where gaps and overlaps form.

Applicability

The research is applicable to the automated fibre placement and tape laying composite production facilities. This is currently the most common production method for high-end CFRP products such as aircraft components.

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Summary

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Within the EU ECOMISE project the effect of gaps and overlaps in composite laminates is investigated together with DLR as partner in the project. Three different approaches are presented that include an analytical approach for rapid calculations, a virtual coupon test approach using advanced damage mechanics methods and a multiscale approach. The multiscale approach tries to combine the small scale at which gaps occur (sub-millimetre) and the macro scale of the composite product (meters). In the project several test cases are defined for the fibre placement deviations such as small gaps, large gaps and large overlaps. The effects of the deviations is investigated for these cases with the three methods. Further research should also provide test data for validation of the developed methods.

The results of the calculation on the deviation for composite laminates show that there is a clear effect of the gaps and overlaps. The investigation reveals that there is a considerable effect on stiffness and strength caused by the investigated deviations. It is further found that depending on the modelling approach and the applied failure criterion (e.g. first ply failure, progressive damage) the resulting stiffness and strength properties are quite diverse. The decrease in strength shows that including these local effects in the laminate is important to improve the confidence in the final product. The designer can compensate for this strength reduction by further optimization and/or reducing the number of tow boundaries where gaps and overlaps form.

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Content

ABBREVIATIONS

Acronym	Description
DLR	German Aerospace Centre
NLR	National Aerospace Laboratory NLR
RTM	Resin Transfer Moulding
RTI	Resin Transfer Infusion
AFP	Automated Fibre Production
ECOMISE	EU project Enabling Next Generation Composite Manufacturing
FEM	Finite Element Method
MSA	Multi Scale Approach

ASSESSING THE STRUCTURAL RESPONSE OF AUTOMATED FIBRE PLACEMENT COMPOSITE STRUCTURES WITH GAPS AND OVERLAPS BY MEANS OF NUMERICAL APPROACHES

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Keywords: Virtual testing, Multi-scale, AFP, Gap, Overlap

ABSTRACT

Ecomise is a European funded project enhancing process and evaluation techniques for automated dry fibre placement (AFP), infusion/ injection (RTI/ RTM) and curing for the purpose of achieving less energy and material consumption, higher reproducibility, reduction waste and rework. The paper focuses on the automated dry fibre placement technique (AFP), in particular on the assessment of manufacturing induced gaps and overlaps within the composite laminate. The goal is to determine the effect of these manufacturing deviations on the material behaviour in terms of stiffness and strength in order to enable a so called "as-built" analysis. Three different approaches are investigated, an analytical (comparable to a rule of mixtures) and two numerical based approaches ("virtual test" and multi-scale analysis), which are applied to two different types of deviations, long narrow gaps and long wide gaps/ overlaps. The investigation reveals that there is a considerable effect on stiffness and strength caused by the investigated deviations. It is further found that depending on the modelling approach and the applied failure criterion (e.g. first ply failure, progressive damage) the resulting stiffness and strength properties are quite diverse. This study is not exhaustive, further investigations and validation with experimental data is to be done.

1 Introduction

Within current composite part development and manufacturing processes a disproportional high effort is implied in order to find optimal process parameters and to meet required qualities and tolerances of high performance light weight structures. The necessity of new approaches and methodologies in order to improve and consolidate, respectively, these currently still disjoint processes was pointed out by Wille [5]. Within the ECOMISE project high precision process and evaluation techniques for automated dry fibre placement (AFP), infusion/ injection (RTI/ RTM) and curing will be developed in order to maximize process efficiency at reduced costs and production time due to less material consumption, higher reproducibility, less energy, less waste and less rework.

For the presented work the focus lies on the AFP composite manufacturing process where common manufacturing deviations are investigated for their influence on the mechanical performance. These effects are caused by machine deviations, material variation and laminate designs that require ply angle transitions and consequently cutting of tows. The gap and the overlap effects in composite laminates are investigated using numerical methods. In particular long narrow (less or equal 10% of a tow width) and long wide (exceeding 10% of a tow width) deviations in the laminate are addressed in this research (cf. Figure 1) with the goal to establish proper criteria on the coupon level.

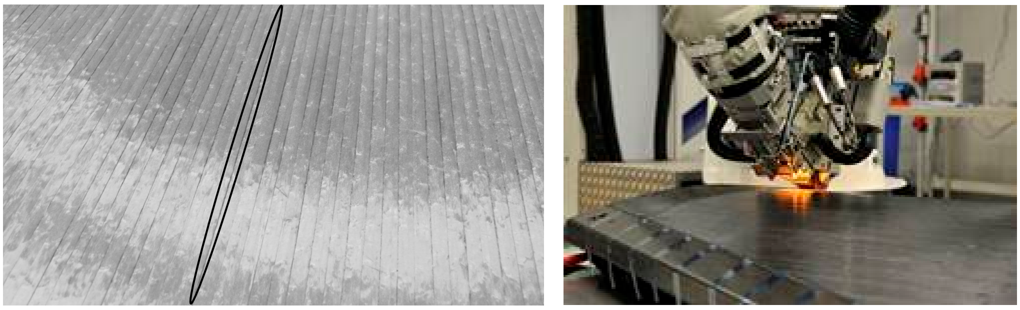


Figure 1: Composite laminate manufactured using the AFP technique (right) with long narrow gaps between the tows (indicated by the black ellipsoid)

This in-situ evaluation process aims to correlate data measured (e.g. optical fibre monitoring) and/ or simulated (e.g. draping simulation) for the actual manufacturing process to the corresponding "as-design" analysis model (in this case an FE model of the structure to be manufactured). By means of this correlation relevant manufacturing deviations can be evaluated and assessed w.r.t. their influence on the structural response in terms of stiffness and strength. Since the addressed structures have very large dimensions compared to the actual defect size a strategy is needed to efficiently incorporate manufacturing deviations into the structural analysis. A schematic of such a process is illustrated in

Figure 2, which was further developed by Kärger and Kling [4]. The aim is to predict the quality of the product during manufacturing by on-line measurement of manufacturing deviations. For this the finite element results will be used to create parameter curves that can be interpolated for in-situ evaluation of the knock-down factor (cf. Figure 1).

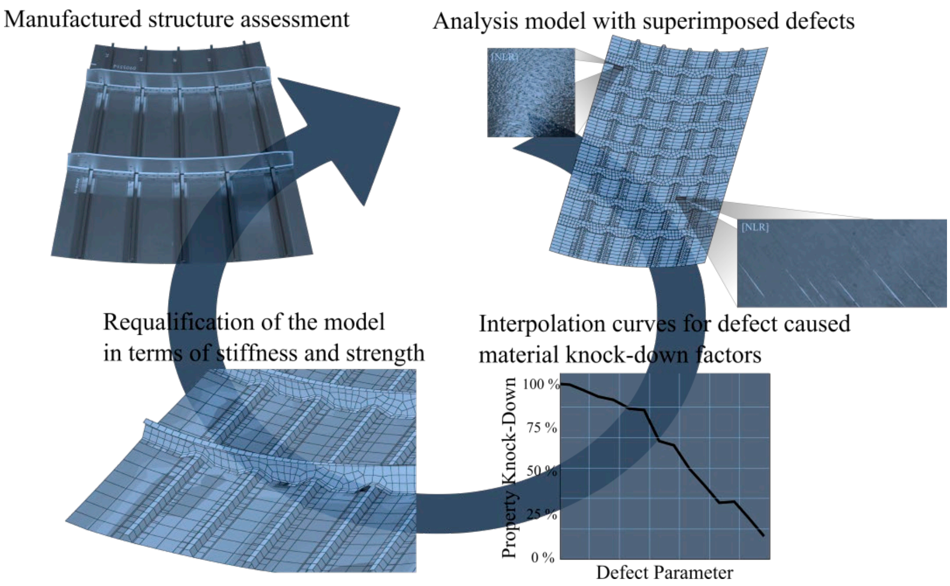


Figure 2: Schematic of process to capture manufacturing defects by means of the FEM

Starting point for the process is an “as-design” analysis model, which is subsequently adjusted considering the manufacturing data, simulated and measured, respectively. Depending on the characteristic of the manufacturing deviation, the effective (“as-built”) material properties might deviate from the original (“as-design”) properties. Thus, a key aspect within this process is the derivation of interpolation curves, which relate the defect characteristics to respective knock-down factors of the material properties. Based on the location and the characteristic of the manufacturing deviation these interpolation curves are exploited in order to adjust the material properties of the analysis model accordingly. Using this strategy a fast re-evaluation and re-qualification of the structural response is enabled, in order to assess final part performance.

The first method to derive an interpolation curve for manufacturing deviations is the so-called “Virtual Test”. As the name already implies, this method is based on numerical simulations representing the actual test as close as possible, e.g. correct boundary conditions. This approach uses progressive damage methods with in-plane damage mechanics and cohesive elements for prediction of the composite laminate strength and comparison of “as-designed” and “as-built”.

The second method is the multi-scale analysis, which considers local ply discontinuities and provides a suitable macroscopic resolution of composite ply deviations like gaps and overlaps. The effective stiffness and strength on the macroscopic level is calculated by numerical analysis on the local level in conjunction with a homogenization. This way the structural response on macroscopic level can be calculated computationally efficient.

2 Literature

The research dealing with the influence of fibre placement manufacturing deviations on the mechanical properties has received attention from various research groups. Often this research is performed as a direct consequence of fibre steering with variable stiffness laminates which require tow cutting. Subsequently, research relevant for the current topic will be briefly introduced.

In work by Fayazbakhsh [1] the triangular gaps created by fibre steering and tow cutting is investigated. A detailed FEM approach with local degradation on the material properties is performed on a flat plate structure. This approach revealed a considerably high influence of gaps and overlaps onto the stiffness of the structure. Another study was performed by Falcó [6]. The effect of triangular shaped manufacturing deviations on the tensile strength of un-notched specimen as well as open-hole specimen. It was found that depending on the layup design strength reductions up to 20% are observed. The gap defect without staggering was identified to be the most critical laminate design in terms of ultimate strength.

Fundamental investigations by Sawicki [2] showed that the effect of gaps and overlaps on the compression strength is mainly driven by the associated fibre waviness within the laminate. Depending on the layup and material specimens with a gap/overlap larger than 0.03 inch a reduction in compression strength of 27% was observed. This effect stabilized when the gap/overlap was larger than 0.10 inch. Further experimental results on the effect of gaps and overlaps were provided by Croft [3]. This study also considers twisted tows. The experiments are performed on standard coupons including notched and open-hole coupons in tension and compression. The results show a very small effect on tension and compression loading for the standard uniform coupons, but due to fibre waviness effects strengths can be reduced up to 12%.

From the literature it is concluded that there is an effect on the strength and also on the stiffness of the composite laminate induced by gaps and overlaps. Furthermore the literature review indicates that stiffness effects of manufacturing deviations can be represented rather accurate using contemporary numerical approaches. However, the determination and prediction of failure poses the analysts to several challenges. A clear approach or indication for knock-down factors for laminates containing gaps and overlaps is currently not present. There is also a need for efficient models and analysis methods enabling the in-situ evaluation of manufacturing deviations and a concurrent engineering within the overall composite design process.

3 Methods

This section is dedicated to explain three different methods used in this work for deriving interpolation curves for defect caused material knock-down factors (cf.

Figure 2). These three methods are:

Method	Approach	Basis
1. Analytical	Laminate	Rules of Mixture formulae
2. Virtual testing	Laminate	FEM
3. Multi-scale	Lamina	FEM

For the finite element approaches parametric models are created with the focus on stiffness and strength prediction. These models use a lamina based ("ply-by-ply") approach including in-plane damage mechanics. For the virtual testing approach out of plane delamination is additionally considered using fracture mechanics.

3.1 Model Set-up

Without limiting the generality of applicability, the proposed methods are demonstrated for two different types of manufacturing deviations. The corresponding laminate configurations are depicted in Figure 3 and consist of 16 layer $[0/90]_s$ lay-ups. Introduced deviations are indicated in dark grey. All methods are applied to a square shaped plate with 0.025m in each dimension. The long narrow (less or equal 10% of a tow width) configuration displays a kind of grid pattern in the combined 0° (loading direction) and 90° layers. The long wide (exceeding 10% of a tow width) deviations are located in the 2^{nd}, 4^{th}, 13^{th} and 15^{th} layer (90° layers) in the centre of the plate.

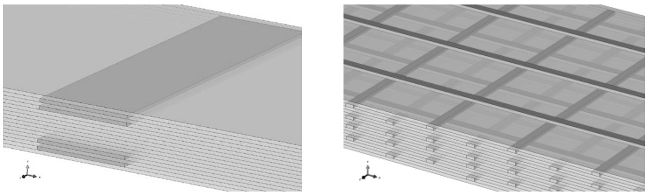


Figure 3: Model of the coupons investigated. The light grey indicates the normal tows in the laminate per layer and the dark grey indicates the location of gaps. (left) Long wide deviation configuration shows four layers in which an entire tow is missing, hence a large gap. (right) Shows a long narrow gap representing small offsets between tows which for the 0/90 lay-up results in a grid like pattern

Parameter studies are performed for both configurations by varying the width of the deviation. Table 1 lists the different parameter variations:

Table 1: Parameters used for parameter studies

Laminate Configuration	Deviation Type	Deviation Width $[10^{-3}m]$
Long Narrow	Gap	0.1905
	Gap	0.3810
	Gap	0.6350
Long Wide	Gap/Lap	3.1750
	Gap/Lap	6.350
	Gap/Lap	9.525

The material properties used within the analyses are typical composite properties. Gaps are considered as resin filled ("fibre free" areas). The corresponding area is assigned to resin properties. In case of overlaps ("additional fibres" areas) the nominal stiffness of the material within the affected areas is increased.

3.2 Analytical method

For the investigated manufacturing deviations a first rough estimate on the effect on the lamina stiffness can be made analytically. Due to a repeating pattern of the deviations and the simple geometry of the deviations rule of mixtures and the classical lamination theory can be used for the calculation. The ratio α (see Equation 1) of the deviation width with the lamina width is used to calculate the effective stiffness. It represents the percentage of length containing deviations from the initial pristine length.

$$\alpha = \frac{width_{deviation}}{width_{la\min a}} \tag{1}$$

Figure 4 illustrates the geometric parameters used to determine α for the long narrow deviations in a 0° lamina.

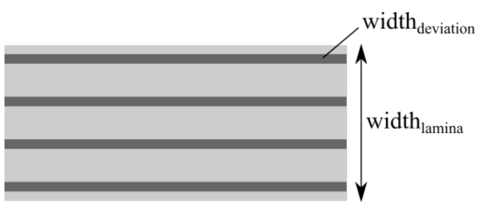


Figure 4: Long narrow deviations (top view of laminate) in a 0° lamina indicated with dark grey lines

When determining the stiffness in a lamina by lamina manner the total knock-down on stiffness of the laminate can be calculated. This is shown exemplarily by Equation 2 and Equation 3 for the long narrow gaps. The stiffness properties E_1, E_2 and E_{resin} are defined with respect to the loading direction parallel to the 0° lamina.

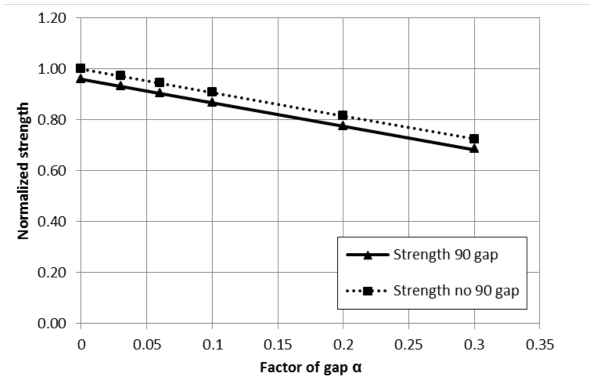
$$E_{0-layers} = E_1(1-\alpha) + E_{resin}(\alpha) \tag{2}$$

$$E_{90-layers} = \left(\frac{1-\alpha}{E_2} + \frac{\alpha}{E_{resin}}\right)^{-1} \tag{3}$$

When looking at these stiffness values as function of α, it shows that the stiffness of the 0°-lamina decreases linearly as expected. The strength of the laminate is mainly dominated by the stress/ strain in the 0°-lamina. In this calculation the effects such as stress concentration caused by the gaps and overlaps are not considered. By introducing the deviations the lamina stiffness is locally affected. It has to be noted that all deviations in one lamina are parallel to the fibre direction. By calculating the maximum strain in the laminate and comparing with the failure strain of the fibres, the strength can be calculated analytically. In this case no staggering is assumed.

$$S_{0-layers} = S_1(1-\alpha) + S_{resin}(\alpha) \tag{4}$$

The effect of different α values is depicted in Figure 5.



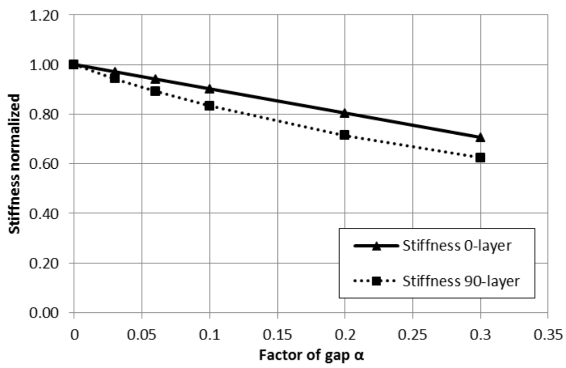


Figure 5: Stiffness and strength dependency for gap as a factor of the entire ply surface from 0 – 35%)

For the long wide gaps manufacturing deviation the effect for the cases investigated is isolated to the 90° laminae. This gives two variations in laminate, one at a gap and one without gaps. In case of a gap it is filled with resin material and therefore the 0° laminae attract more load. For all cases the expected reduction in strength in case of wide gaps is around 4.2%.

For the overlaps the strength is dominated by the laminate around the manufacturing defect, which is limiting in this case, hence same strength as the baseline. Possibly the out-of-plane effect on the overlap interface can lead to a lower strength than the baseline reference.

3.3 Virtual Testing

In this section the virtual test approach and results are discussed for the manufacturing deviations described earlier. The main purpose of using the virtual testing approach is to gather insight in the knock-down factors caused by local effect near the manufacturing defects. Therefore the focus is on relative values of strength instead of absolute values. A principle work flow of the virtual test approach is shown in Figure 6.

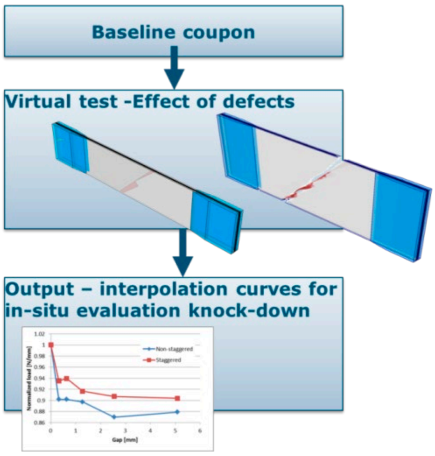


Figure 6 : Work flow virtual test approach

The inputs for the material model are elastic material properties, material strength for the fibre directions and the shear nonlinear behaviour. This model includes the important failure modes as observed during experiments such as fibre failure and shear matrix failure. The in-plane strain terms in their respective directions are calculated using the materials elasticity moduli and damage variables d_{1+}, d_{1-}, d_{2+}, d_{2-} and d_{12} [7] using the elastic stress-strain relations, shown in Equation 5, where ε is the strain, E the stiffness and σ the stress in the respective laminate direction.

$$\begin{pmatrix} \varepsilon_{11} \\ \varepsilon_{22} \\ \varepsilon_{12}^{el} \end{pmatrix} = \begin{pmatrix} \dfrac{1}{(1-d_1)E_1} & \dfrac{-\nu_{12}}{E_1} & 0 \\ \dfrac{-\nu_{21}}{E_2} & \dfrac{1}{(1-d_2)E_2} & 0 \\ 0 & 0 & \dfrac{1}{(1-d_{12})2G_{12}} \end{pmatrix} \begin{pmatrix} \sigma_{11} \\ \sigma_{22} \\ \sigma_{12} \end{pmatrix} \tag{5}$$

Damage variables are d_1 and d_2 for damage in fibre and perpendicular to fibre direction as well as d_{12}, which is related to the shear damage. The model determines the tensile or compressive fibre failure mode by activating the damage variable related to the stress state, depending on the trace value of the ε_{11} and ε_{22} strains. The fibre damage variables d_1 and d_2 as stated are used to determine the effective stress in the corresponding laminate directions.

Besides the in-plane damage mechanics material model, also the delamination is simulated in the model using cohesive surface definitions. Cohesive interaction is based on traction separation laws that describe the relative displacement Δ of two connected surfaces and depending on the element stiffness determine the internal traction. The damage modes that are assumed are Mode I (peel), and Mode II, III (shear), see [7]. The approach allows a linear softening of the interface when the damage is initiated.

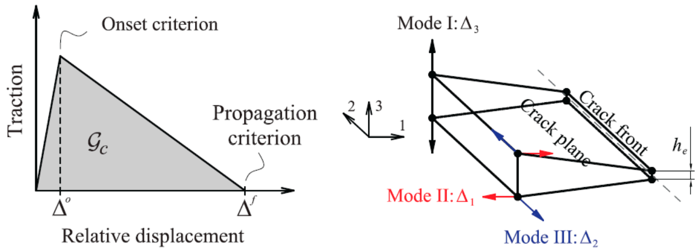


Figure 7: Traction separation graph depending on the relative displacement of the two connection surfaces and the mode discrimination in the cohesive model [7]

The inputs needed for the cohesive surfaces are the stress value for the damage initiation and the fracture toughness G_{Ic}, G_{IIc}, G_{IIIc} for the three modes. The interaction between the modes is determined using the BK-law shown in Equation 6 [8], where the *Gc* is the total mixed mode fracture energy, G_{Ic}, G_{IIc}, G_{IIIc} the critical fracture toughness energy and G_I, G_{II} and G_{III} the fracture toughness values during the simulation..

$$G_c = G_{Ic} + (G_{IIc} - G_{Ic}) {\frac{G_{II} + G_{III}}{G_I + G_{II} + G_{III}}}^{\alpha} \tag{6}$$

The critical fracture toughness values have to be determined experimentally with DCB or ENF testing. The interface between the individual laminae (ply-by-ply approach) is modelled using cohesive surface properties with damage growth, see Figure 8.

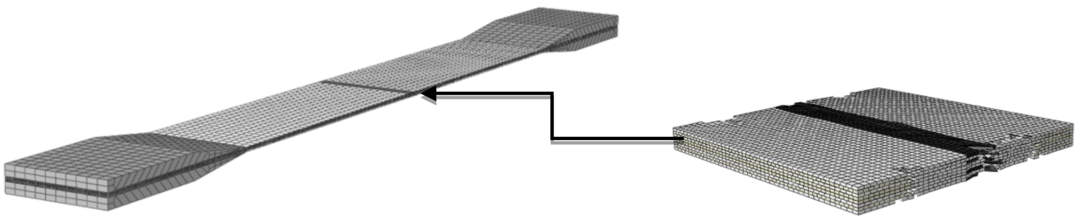


Figure 8: Model of the composite coupon with local gaps. On the right a detailed view of the mesh with the gaps indicated. This finite element model is used to calculate the stiffness and strength of the laminate with defects

The numerical investigation for the small gaps showed that the gap in the 90° lamina has an effect on the local strains in the 0° lamina. Out-of-plane deformation is not observed.

Failure was observed initiating from the gap location in the model as expected, shown in Figure 9. Here the loading is applied in horizontal direction.

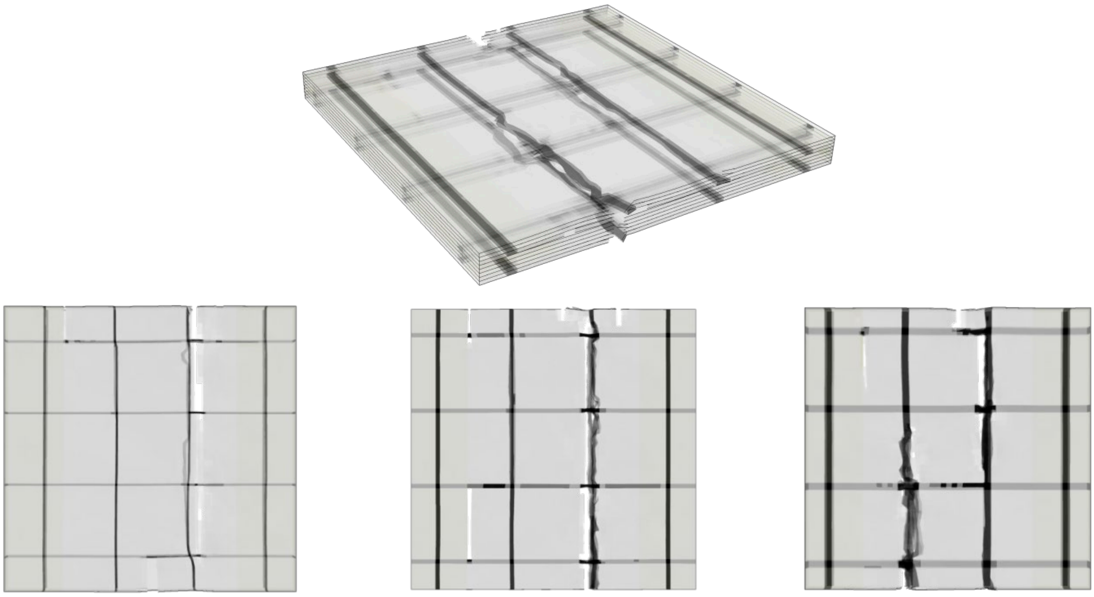


Figure 9: Overview of different coupons with gap percentages, from left to right with 3%, 6% and 10% gaps. Failure modes in the centre section of coupons with gaps (indicated by black) can be observed. Loading is applied in horizontal direction

The simulation results of the long narrow gaps show a failure near the gap locations. However there is some uncertainty about the simulation method input parameters such as the interface stiffness which can have an influence on the strength. In Figure 10 a comparison is shown of the strength as function of the gap as factor of the total ply between the analytical results (cf. Section 3.2) and the FEM results with tab-boundary conditions and simplified boundary conditions. On the right the strength as function of absolute gap width in [mm] for the wide gap and overlap are shown.

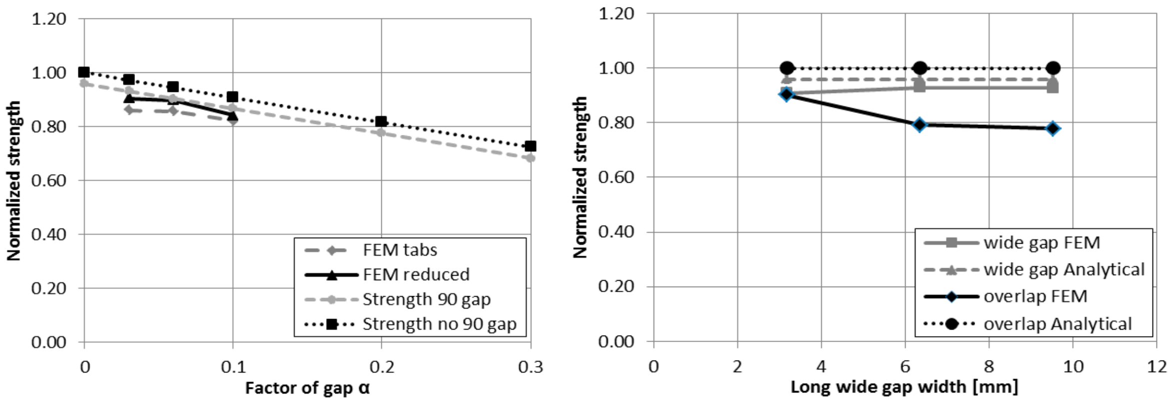


Figure 10: Comparison of analytical predictions and FEM calculations for different small and wide gap sizes, and overlaps. The FEM predictions are in the same region but show a larger reduction in strength already for small gaps

The FE model gives a good indication of the strength reduction when compared to the analytical model. In general the FEM predicts a lower strength of the coupon, hence larger knock-down factor. For the long narrow gap manufacturing deviation the knock-down is at 10 – 20%. This is expressed as factor of the gap compared to the ply size between 3% and 10%.

For the long wide gaps it can be concluded that the FEM calculation also predicts a lower strength. The knock-down is around 10% for this type of manufacturing deviation. For the overlap results, surprisingly this manufacturing effect gives a large reduction in strength. It appears that due to the overlapped region, the centre section of the 0° lamina is unloaded, and at the sides of the overlap again introduced in the 0° lamina. This gives higher stress values at the sides of the overlap and failure at these locations.

3.4 Multi-scale Analysis (msa) Method

Material particularities like gaps and overlaps on the meso-scale (lamina level) or imperfections on an even smaller material scale co-determine the structural response on the macro-scale (laminate/ structure level). The MSA exploits a so called homogenization approach to efficiently capture the effects on material level by means of effective properties on the structure level. Such a homogenization can be performed empirically, by using rules of mixture or numerically. Garnich and Karami [11] present a numerical homogenization approach to consider the effect of localized fibre waviness in unidirectional composites.

In order to perform any numerical homogenization, periodic boundary conditions have to be applied by definition. For the purpose of determining the effective material properties different types of boundary conditions can be used [10]. In this work periodic displacement boundary conditions are applied to the local FE model. Additionally, the approaches proposed in [1] and [9] are adopted in order to generate parameterized local FE models suitable for the evaluation of the effective material properties on the lamina level. Correspondingly, the following assumptions and simplifications were made:

- Ideal fibre distribution,
- Gaps are assumed as zones having the resin material properties,
- Overlaps are assumed as zones having an increased fibre volume content,
- The simulation model is shell based (using layered elements),
- The finite element mesh is regular and structured discretized.

The multi-scale approach is composed of different steps. A principle workflow of the applied method describing the determination of the effective properties is depicted in Figure 11.

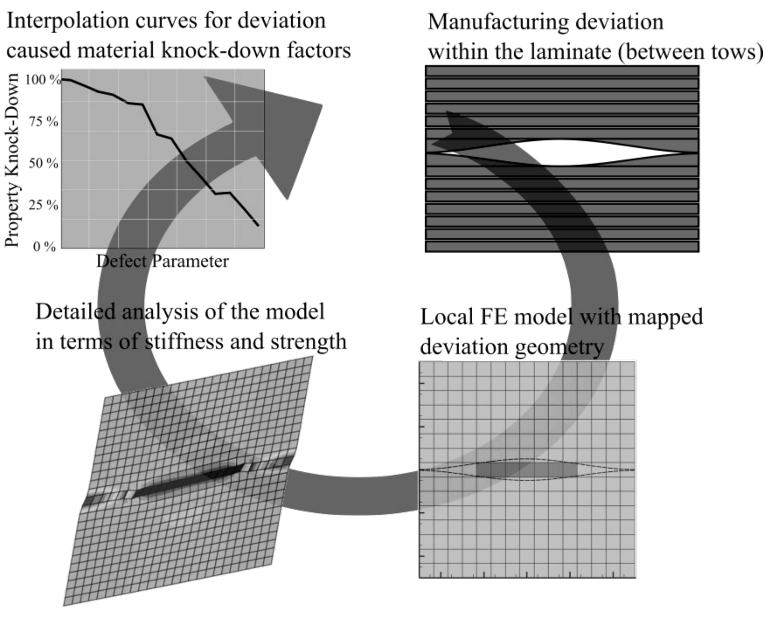


Figure 11: MSA - Principle workflow of applied method

In order to perform the MSA a local FE model is to be generated. For this purpose the information about manufacturing deviations (e.g. deviation width and deviation length – cf. Figure 11 upper right) are mapped onto a high density structured and regular finite element mesh. Within this context the finite elements belonging to the deviation affected domain are assigned to the respective properties (e.g. resin properties for a gap – cf. Figure 11 lower right). Finally, unidirectional unit-strains are sequentially applied, which is exemplarily by applied shear in Figure 11 lower left. The effective stiffness can be computed by averaging the stresses occurring in the local model for each applied deformation.

Almost the same approach is used to determine the effective strength. Any failure criterion can be evaluated to compute the effective strength. In this work the Tsai-Wu criterion is applied to the local model to retrieve the failure indexes of each finite element. The maximal failure index determines the residual strength of the material.

The MSA is applied for the manufacturing deviations described in section 3.1 on lamina level. The effect of these deviations on the material properties is illustrated in Figure 12. The normalized stiffness related properties (E_1, E_2, G_{12}, η_{12}) as well as the normalized strength related properties (X_T, Y_T, S) are plotted for different ratios α (see Equation 1).

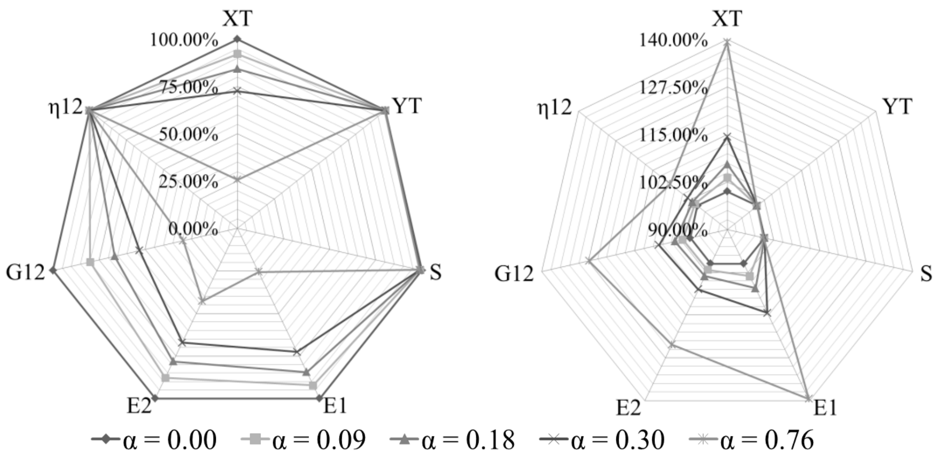


Figure 12: Effect of deviations with varying width on material properties for gap (left) and overlap (right)

It is found that neither the gap nor the overlap has any influence onto the shear strength (S) or the strength perpendicular to the fibre direction (Y_T). The investigation further reveals that the structural response in terms of stiffness is almost the same for the gap and the overlap. This is related to the modelling approaches used for the gap, as domain with pure resin properties, and the overlap, as domain with increased fibre volume content. As expected stiffness and strength components are decreased for the gap and increased for the overlap, respectively. For the gap the highest decrease in stiffness and strength is determined to be in fibre direction, with approximately 75%. The overlap causes an increase of stiffness and strength in fibre direction up to 40%.

4 Conclusions

The work presented in this paper has been performed within the project ECOMISE. Three approaches (analytical, virtual test, MSA) have been used to investigate the effect of common manufacturing deviations in fibre placement laminates. The focus of the research has been on long narrow gaps, long wide gaps and long wide overlaps under tensile loading. The results give evidence that the manufacturing deviations investigated have a significant effect on the stiffness and the strength. A decrease in strength for the gap has been observed from the finite element analyses using progressive damage methods. For the overlap cases also a strength decrease has been observed.

Method	Approach	Basis	Efficiency
1. Analytical	Laminate	Rules of Mixture formulae	Fast but limited application, no stress concentration effects
2. Virtual testing	Laminate	FEM	Relative slow approach, but more accurate and realistic results
3. Multi-scale	Lamina	FEM	Limited applicability because of lamina approach. Will be extended to laminate in the future by DLR.

It can be concluded that the virtual test model on laminate level gives a good indication of the strength reduction when compared to the analytical model. In general the FEM predicts a lower strength of the coupon, hence larger knock-down factor. For the long narrow gap manufacturing deviation the knock-down is at 10 – 20%for realistic gap sizes. For a long wide overlap the knock-down is in the range of 10%. For overlaps a reduction in strength up to 22% was observed.

However, in contrast to the virtual test approach the MSA predicts a greater influence of manufacturing deviations, but on lamina level. It is expected that on laminate level the influence of these effects will be rebalanced. Validation tests are planned for the coupons investigated which should give additional insight in the manufactured laminates with misalignments.

To summarize, more research for these types of deviations is needed to proof the findings. The investigation reveals that there is a considerable effect on stiffness and strength caused by the investigated deviations gaps/overlaps. It is further found that depending on the modelling approach and the applied failure criterion (e.g. first ply failure, progressive damage) the resulting stiffness and strength properties are quite diverse. According to the findings the disregard of geometric out-of-plane effects like fibre waviness might not be justified. Since fibre waviness leads to stress concentrations and out-of-plane loading/ instability it will most certainly become eminent for other loading conditions like compression or shear.

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