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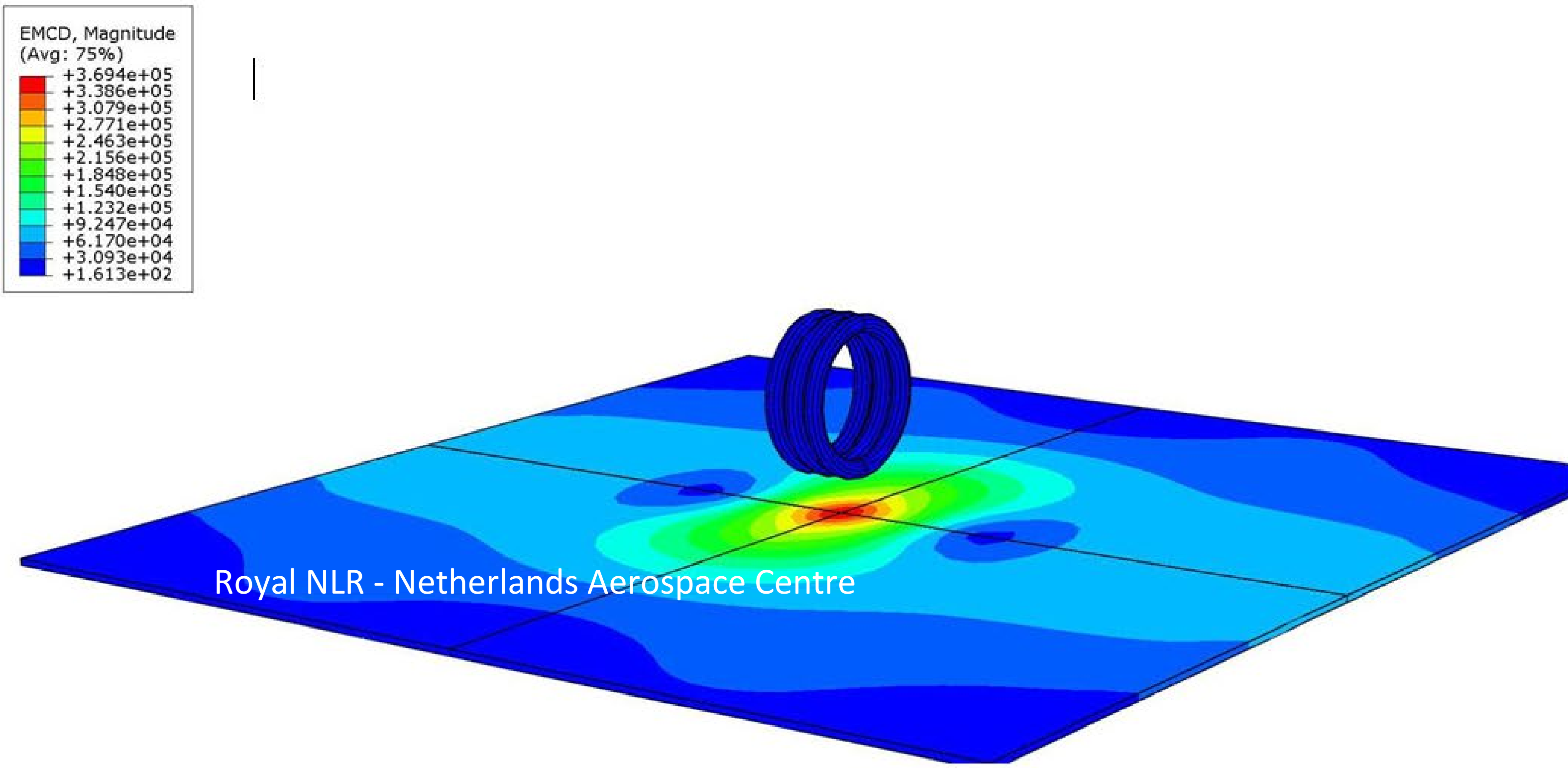
NLR-TP-2021-491 | August 2022

Prediction of thermo-mechanic effects through numerical simulation of induction heating of thermoplastic composites

CUSTOMER: Clean Sky 2 Joint Undertaking



Royal NLR - Netherlands Aerospace Centre

EXECUTIVE SUMMARY

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Prediction of thermo-mechanic effects through numerical simulation of induction heating of thermoplastic composites

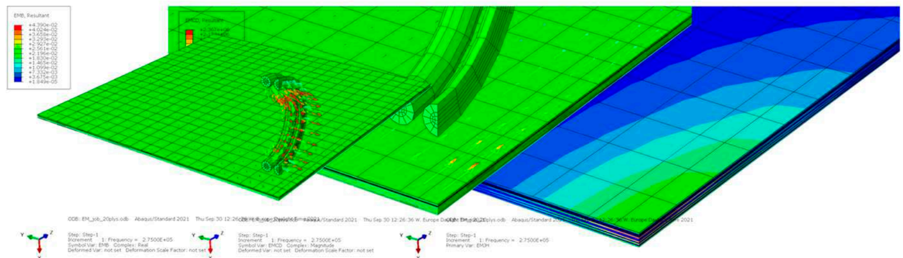

Figure 1 Numerical model to compute Inductive heating. Left real part of the magnetic flux density vector. Middle induced Eddy Currents. Right Joule heating due to the induced eddy currents.

Problem area

In the European R&D program Clean Sky 2, Large Passenger Aircraft Platform 2, a MultiFunctional Fuselage Demonstrator (MFFD) for single aisle aircraft is developed that serves as a platform for examining the full potential of thermoplastic (TP) composites. This MFFD consists of an assembly of building blocks for which novel assembly techniques need to be developed. One such novel assembly technique is welding. This paper is focused more specifically on induction welding of thermoplastic unidirectional (UD) carbon fiber reinforced polymer (CFRP) materials.

Induction welding makes use of the fact that the thermoplastic matrix of TP composites can be re-melted by inductive heating, allowing TP composite adherends to be joined via welding. At present, the inductive heating of woven fabric composites is well documented and understood. However, inductive heating of UD CFRP laminates is not well understood and therefore this work focusses on modelling and simulation of the induction heating process of UD CFRP Laminates, see Figure 1.

REPORT NUMBER
NLR-TP-2021-491

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REPORT CLASSIFICATION
UNCLASSIFIED

DATE
August 2022

KNOWLEDGE AREA(S)
Computational Mechanics and Simulation Technology
Aerospace Collaborative Engineering and Design
Structures and Manufacturing Technology

DESCRIPTOR(S)
Electro-magnetic
Inductive heating
Finite Element Analysis
thermoplastic composites
numerical simulation

Description of work

The influence of material properties and ply layup on the generation and distribution of eddy currents inside the TP composite laminate is investigated via a study of the open literature. Furthermore, a measurement technique to obtain electric conductive parameters necessary for the electromagnetic modelling is developed. To improve the electromagnetic modelling of inductive heating of UD laminates, special attention is paid to the cross-ply interfaces in the laminate. A specific interface model is derived that takes into account the heating effects that occur in the cross-ply interfaces of the UD plies in the laminate. The interface model is implemented in an electromagnetic finite element (FE) model that is applied to an inductive heating study of a cross-ply laminate taken from the literature.

Results and conclusions

The numerical results of the model with interface represent the measured surface temperature of a UD laminate that is inductively heated more accurately than the numerical results of a model without interface. Electric properties of a single UD ply that were derived with the measurement techniques were in agreement with values from literature.

Applicability

The developed electromagnetic FE model building block for TP composite UD material can be used to predict the required power and frequency settings of an induction heating setup for UD laminates. Together with thermal and mechanical building blocks this allows for the numerical simulation of induction welding of laminates. Via simulation of the induction welding process an operator of an induction welding setup can better determine the correct induction heating settings for a given laminate to arrive at a successful weld. Furthermore, the measurement technique developed can be used to measure the anisotropic electric properties of individual plies.

GENERAL NOTE
This report is based on a presentation held at the 11th EASN Virtual International Conference on Innovation in Aviation & Space to the Satisfaction of the European Citizens, Salerno, 1-3 September 2021.

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CUSTOMER	Clean Sky 2 Joint Undertaking
CONTRACT NUMBER	945583
OWNER	NLR
DIVISION NLR	Aerospace Vehicles
DISTRIBUTION	Unlimited
CLASSIFICATION OF TITLE	UNCLASSIFIED

APPROVED BY:		Date
AUTHOR	A.J. de Wit	10-05-2022
REVIEWER	B. Noordman	10-05-2022
MANAGING DEPARTMENT	A.A. Ten Dam	17-08-2022

Summary

Several heating mechanisms take place in the induction heating of thermoplastic CFRP. The extent in which each mechanism contributes to the heating process, depends on the material that is heated and the process parameters that are applied. In this work we focus on modelling and simulation of the induction heating process of unidirectional (UD) CFRP material. In particular the influence of material properties and ply layup on the generation and distribution of eddy currents inside the composite laminate is investigated. A measurement technique to determine the electrical conductivity properties is presented. The experimentally obtained values are in agreement with literature values. A finite element simulation of a UD CFRP material shows the positive effect of modelling electromagnetic ply properties with interface modelling with respect to the calculated surface temperature.

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Abbreviations

ACRONYM	DESCRIPTION
AC	Alternating Current
DC	Direct Current
EMF	Electro Magnetic Field
FEA	Electro Magnetic Field
MFFD	MultiFunctional Fuselage Demonstrator
NLR	Royal NLR - Netherlands Aerospace Centre
TPCs	Thermoplastic Composites
UD	Uni-Directional

1 Introduction

In the European R&D program Clean Sky 2, Large Passenger Aircraft Platform 2, a MultiFunctional Fuselage Demonstrator (MFFD) for single aisle aircraft is developed. This MFFD shall validate high potential combinations of airframe structures, cabin/cargo, and system elements. The MFFD consists of an assembly of multi-functional building blocks for the next generation fuselage and cabin. Such an assembly requires the development of advanced joining technologies together with materials that take advantage of them.
One example of such advanced joining techniques is induction welding. Thermoplastic Composites (TPCs) can be re-melted allowing them to be joined via welding. This is an attractive alternative to conventional methods that are used to join thermoset composite parts such as mechanical fastening and adhesive bonding. The joining of TPCs is established via heat and melting of the polymer matrix on the weld surfaces. In addition, both surfaces of the weld need to be pressed together for polymer solidification and consolidation (Yousefpour, Hojjati, & Immarigeon, 2004).
Composite heating can be established in several ways each having their advantages and disadvantages (Yousefpour, Hojjati, & Immarigeon, 2004). In the present work the focus is on electromagnetic heating and more specific on induction heating for which the equipment is available at NLR. Induction heating offers the advantage of rapid heating of the laminate to its melting temperature within seconds. The heat input is directly into the laminate and the heating is contact free, but it does require inductive electromagnetic characteristics of the material as existent in TPCs. Induction heating of a composite is accomplished via through-the-thickness heating of the laminate.
To summarize, induction heating relies on several processing parameters that depend on the material electromagnetic characteristics, thermal characteristics and mechanical characteristics of the heating setup. These processing parameters need fine tuning to not overheat a laminate. Because it is complex and expensive to identify experimentally the right processing parameters a simulation model is desired to predict the influence of altering parameters to the heating process.
The objective of our work is to develop 3D simulation models that provide the required insight into inductive heating for different material and geometric configurations. Because of the complexity of the underlying physics, our primary focus in this document is the electromagnetic characterization of a composite UD laminate. First the basic processes involved in inductive heating are addressed. Second, the measurement techniques to obtain electromagnetic properties for the UD laminate and cross-ply interfaces are presented. The electromagnetic parameters are temperature dependent, however at present initial measurements have been conducted for a constant temperature. Third, a numerical simulation model based on Electromagnetic FEA is introduced. This model is then extended via an interface model as reported by (Xu, et al., 2018) to illustrate the effect of such a detailed modelling on computed eddy current distribution. Finally, the main conclusions and directions for further research are given.

1.1 Inductive heating background

In this work we focus on induction heating because from all heating mechanisms to heat a composite, induction heating has the potential of transferring the most heat and no contact between workpiece and equipment is necessary (Mitschang, Neitzel, & Rudolf, 2000). Induction heating is accomplished by making use of the fact that the fibres in composite material are electrical conductors. By placing an electromagnetic coil close to a workpiece a magnetic field is created and this magnetic field induces eddy currents within the composite. The heating occurs by electric properties of the fibre material and the micromechanical structure of the laminate. The increase in temperature of the fibres brings the surrounding polymer to the melting temperature. The complete physics behind induction heating is covered in e.g. (Christopoulos, 1990). In the present work the aspects considered relevant for the inductive heating process at NLR are highlighted.

1.2 Eddy currents

Induction heating is accomplished via Eddy currents that are generated in the carbon fibres through the magnetic field from the coil, see Figure 2.

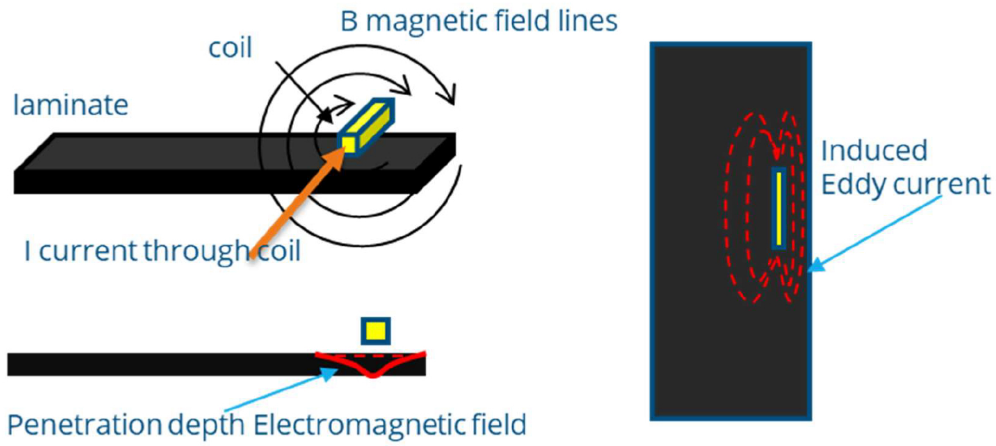


Figure 2 Eddy currents in a composite laminate due to external coil (Ahmed, Stavrov, Bersee, & Beukers, 2006).

For Eddy currents to occur, closed loops of electrically conductive paths are necessary. Hence, current flowing along the fibres has to be able to return back along another set of fibres. If there is sufficient galvanic connection a conductive loop is created. Typically, in woven fabrics this is easily established as the fibres make contact in the weave. For Uni-Directional (UD) material this contact is not evident. Hence, UD material is typically more difficult to weld.

If insufficient contact between fibres is present such as in UD material, the only way for current to flow in a closed loop is via capacitive coupling through the polymer matrix. For most polymers this can only occur at very high frequencies (several MHz). In such cases additional heat is generated via dielectric losses in the polymer. Since equipment that can operate at frequencies of several MHz is not applicable in our setup this form of heating is not considered.

For UD material another option remains to create electrical closed loops. When UD material is stacked at different angles with respect to each other so-called junction heating is present between fibres that are in contact. The conductive loop that arises is typically a rectangle (cross-ply) or a parallelogram (angle-ply), see Figure 3.

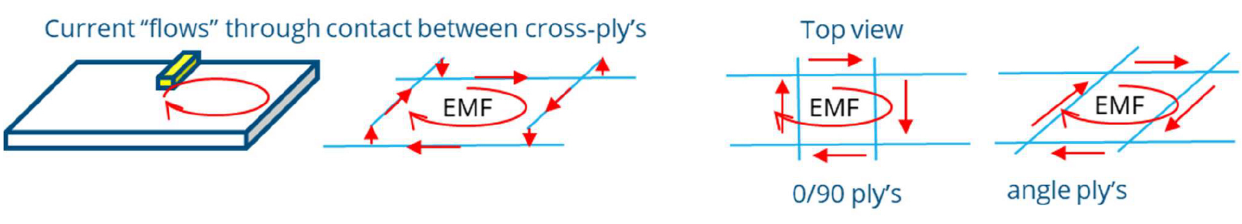


Figure 3 Cross-plies necessary for closed loop such that current can 'flow' through the plies. EMF is electromagnetic field (Kim, Yarlagadda, Shevchenko, Fink, & Gillespie Jr., 2000).

Along the global loop, heat generation occurs if a voltage drop due to electrical impedance is present. The heat that is generated depends typically on the fibre volume fraction as more plies imply more voltage drops. The heating takes place throughout the entire thickness of the part to be heated. Since the electromagnetic field is much stronger near the coil, it is expected that the laminate will heat up quicker at the surface than further down through the thickness. However, recent research suggests that for UD material this may not be entirely correct (Cheng, Wang, Xu, Qiu, & Takagi, 2021).

1.3 Heating mechanisms

Materials that heat up under induction are magnetic, conductive or both. An alternating current in a coil generates an alternating magnetic field inducing eddy currents in the conductive materials that are present within this field. Eddy current generation is possible when closed electrical loops can be formed. Electrical losses of the eddy currents result in heating of the material. Since the induced currents act as a volumetric heat source, the process does not rely on heat conduction to transport the heat from the boundaries to the inside of the material. Thus, concentrated and fast heating is possible.

For the applied frequency range that is of interest in this work (0.1~1 MHz)[1] there are two heating mechanisms in the conductive loop.

1. Fibre heating due to electrical resistance
2. Junction heating where cross-fibres from adjacent plies overlap.

When a current is applied to a fibre, heat is generated due to electrical resistance. Junctions can generate heat due to contact resistance in case fibres are in direct contact. If fibres are separated by a small gap of dielectric polymer matrix, heating may occur at very high frequencies due to dielectric hysteresis.

For frequencies that are of interest in this work contact resistance heating is the dominant heating mechanism for fibre-based prepregs that exhibit substantial fibre-fibre contact before and during consolidation (Kim, Yarlagadda, Shevchenko, Fink, & Gillespie Jr., 2000). According to literature (Kim, Yarlagadda, Shevchenko, Fink, & Gillespie Jr., 2000) the contact resistance and dielectric junction resistance can be simplified as a ‘generic junction resistance’ since the junction resistance between these two mechanisms is distinguished only by the resistance value in the electric current model. Hence, this could simplify the modelling significantly as resistance values, that are measured for a certain ply layup, can be used directly. Alternatively, electric resistance values could be adjusted by multiplying them by a single parameter for alternative ply layup. However, as argued in (Cheng, Wang, Xu, Qiu, & Takagi, 2021) this assumption may not be valid for UD material due to two mechanisms that are discussed in the next two sections.

1.4 Directional dependent skin depth

In addition to contact between adjacent plies playing a role in the formation of eddy currents and being a heating source, an important factor to estimate the success of inductive heating is the so called skin effect (Haimbaugh, 2015). This effect describes how the electric current applied to the coil distributes itself within the conductor (laminate). For homogenous materials the current density is largest near the surface of the conductor and decreases through-thickness according to the relation.

$$I = I_s e^{-d/\delta}$$

The parameter δ is called the skin depth. The parameter d corresponds to the depth below the surface of the conductor at which the current density decays to 1/e (roughly 0.37) of the current density I_s at the surface. But for UD laminates the strong directional dependence of electrical conductance in UD laminates has a

[1] For frequencies above 1 Mhz dielectric heating is a third heating mechanism that could take place.

negative effect on the penetration depth of eddy currents, see (Cheng, Wang, Xu, Qiu, & Takagi, 2021). Therefore, the assumption of bulk conductivity of the through-thickness direction may not be sufficient to accurately compute the eddy current field in a UD laminate since the penetration depth depends on the orientation of plies with respect to the coil.

1.5 Interlaminar contact resistivity

The strong directional dependence of electrical conductance in UD laminates and the effect it has on the penetration depth also necessitates a closer look at the interlaminar contact resistivity. Hence, the electrical "properties" of the interface between two adjacent plies. Accounting for interlaminar contact resistivity is necessary to obtain a better insight into the forming of eddy currents for ply layup with different anisotropy and a necessity if plies are modelled without the use of through-thickness bulk properties as junction heating is not accounted for in the modelling. In (Xu, et al., 2018) a procedure is presented to measure anisotropic conductivity and contact resistivity for single plies and cross-plies. Such measurements can be used to explain the eddy current decay in thickness direction as was shown in (Cheng, Wang, Xu, Qiu, & Takagi, 2021) and improve the heating that is predicted by the FEA model.

2 Experimental measurements

Numerical FEA relies on availability of accurate measured material properties that are applicable to the model. Although material data sheets include recognized standards for mechanical and thermal material properties, electrical properties are less common to be included. As previously stated, for UD material an additional property involving the cross-ply electrical properties are application specific.

The ply electrical conductivity measurement setup is first discussed. Second, the cross-ply measurement setup is discussed. Finally, measurement results are presented.

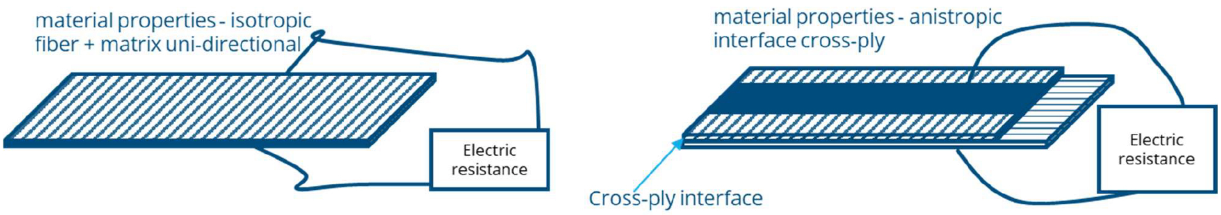


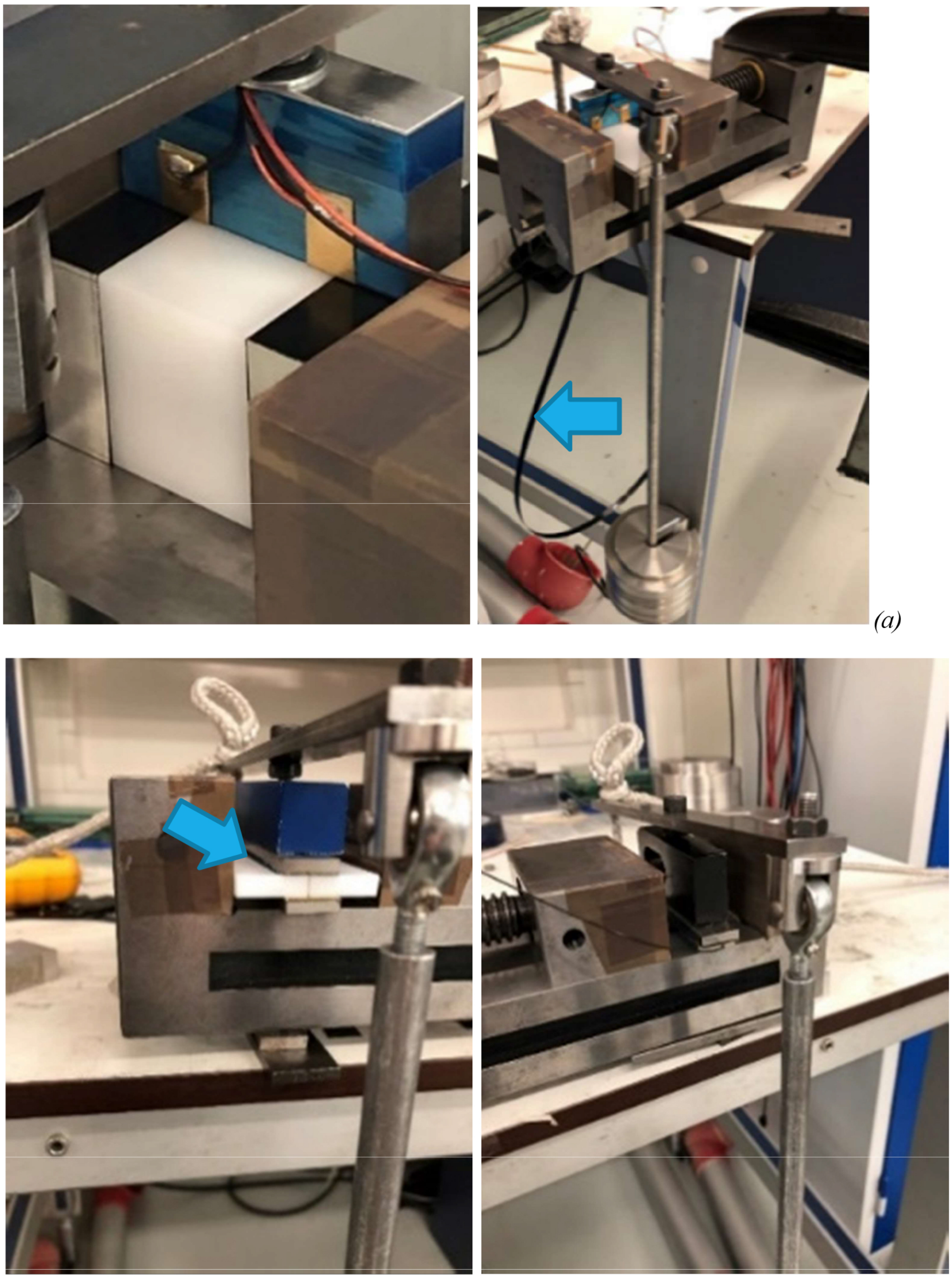
Figure 4 UD ply conductivity measurements.

2.1 UD ply electrical conductivity measurements

The anisotropic electrical conductivity of a single ply is characterised by measuring the resistance. This includes a measurement in the longitudinal, transverse, and through-thickness direction.

2.2 Experimental setup

Unconsolidated strips of UD tape material with a thickness of 0.21 mm are clamped between electrodes. Minimising the contact area is essential to assure maximum contact between fibres/resin and the electrode. In addition, to increase the measurement accuracy a low resistance should be avoided. Therefore, for the resistance measurements in longitudinal direction (i.e., fibre direction) a 6.35 mm wide and 1000 mm long specimen is used, see Figure 5. For the resistance measurement in the transverse and through-thickness direction shorter specimens of 20 mm are used and the clamping devices are adjusted, see Figure 5.



(a)

(b)

Figure 5 (a) Illustration of the test setup for the resistance measurement in longitudinal direction. (b) Illustration of the test setup for the resistance measurement in transverse and through-thickness direction. Blue pointer indicates the coupon.

2.2.1 Measurement results.

Five samples are used for each measurement and the Direct-Current (DC) resistance, as well as, the Alternating-Current (AC) impedance measurement method. The impedance is measured at several frequencies, that is: 50 Hz, 25 kHz, 50 kHz, 75 kHz, and 100 kHz. Each specimen is measured at two instances to exclude the influence of the test setup and clamping procedure. By using the specimen dimensions the resistance in Ohm is transformed to conductivity in S/m. The AC conductivity measurements are extrapolated to the frequency of the induction welding simulation (i.e., 384 kHz). The results are given in Table 1 .

Table 1 Measured anisotropic UD ply electrical conductivity.

Longitudinal conductivity [S/m]	31307 ± 581
Transverse conductivity [S/m]	0.865 ± 0.260
Through-thickness conductivity [S/m]	0.055 ± 0.018

2.2.2 Cross-ply electrical conductivity measurements

For the interface modelling described in Section 1.5 electrical conductivity properties have to be assigned to the interface elements. Such values can be determined via a similar measuring approach as described in the previous section. The specimen dimensions and test setup are identical to the measurements in Section 2.2. Unfortunately, there was little consistency in the measured electrical conductivity properties. A possible cause could be delamination or fiber breakage of the specimens but this has not been further investigated. It is the intention of the authors to repeat the measurements on new specimens in future works.

2.3 Discussion on the results of the measurements and how to apply them in the FEA model

The values that were obtained for the first experiment are close to values reported in the literature (Xu, et al., 2018). A relatively high error in transverse and through-thickness measurements is observed due to the fact that current has to travel through the resin. In addition, the amount of contact between individual fibers significantly influences the measurement results. However, the resulting conductivities are several orders of magnitude lower than the conductivity in longitudinal direction. For the purpose of modelling in an FEA model the accuracy is considered sufficient.

3 Numerical simulation model

In this work the Finite Element package Abaqus (Simulia, 2021) is used for the electromagnetic modelling. A complete derivation of the underlying equations can be found in the theory manual (Simulia, 2021). Here we address the relevant steps to build the analysis model.

3.1 Model geometry and boundary conditions

The FEA model setup is extracted from (Grouvea, Vrugginka, Sacchetti, & Akkerman, 2020) and the relevant geometry is shown in Figure 6.

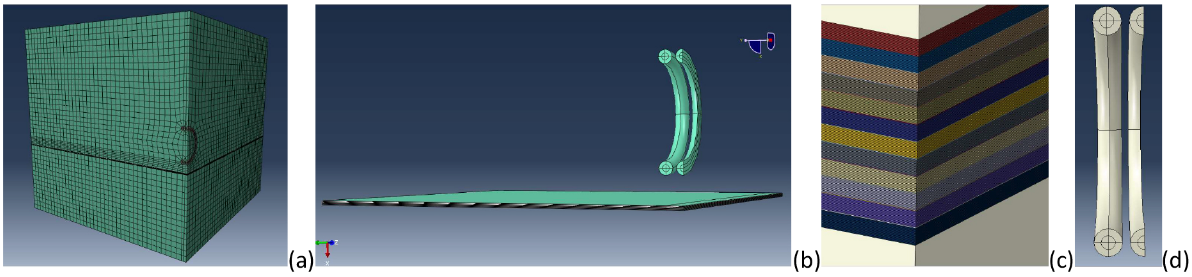


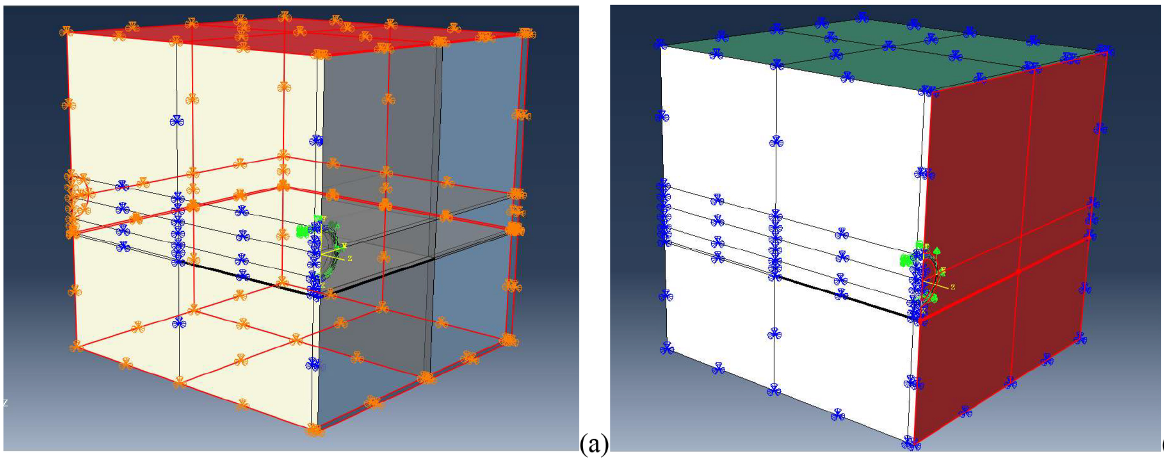
Figure 6 Quarter of the model showing (a) air, coil and laminate, (b) coil and laminate, (c) the plys coloured per ply. In between each 2 plies an interface is assigned, (d) The coil consists of one and a half circle in the model.

The composite laminate 145[mm]x145[mm] comprises 12 plies with a thickness of 0.137mm per ply. The stacking corresponds to $[0/90]_{3S}$. A coil as shown in Figure 6 is modelled. The coil is assumed to have homogenous properties. A current of 350 [A] is applied in the circumferential direction of the coil at a frequency of 275kHz. The distance between the coil external surface and top of the laminate is 10 [mm]. The coil has an inner radius of 32.5 [mm] and outer radius of 42.1 [mm] and a coil pitch of 6.1[mm] and 3 windings. Furthermore, the air, coil and laminate material properties are taken as in Table 2.

Table 2 Material properties applied to the electromagnetic simulation model. Note that in Abaqus the coil electrical conductance is set to a small value to avoid computing eddy currents in the coil that counteract the current density that is applied as a load on the coil geometry.

	Electric conductivity	Magnetic permeability	Magnetic permittivity
Air, Coil	1 [S/m]	$4\pi/1E7$ [H/m]	8.85E-12 [F/m]
Laminate $[0/90]_{3s}$	In-plane 23e3 [S/m] Transverse in-plane 3.4 [S/m] Through-thickness 0.6 [S/m]	$4\pi/1E7$ [H/m]	8.85E-12 [F/m]

A boundary condition is set on external domain where the magnetic flux is set to equal zero. Dirichlet boundary conditions and Neumann boundary conditions are set on the symmetry and anti-symmetry surfaces respectively, see Figure 7 (a).



(a) (b)

Figure 7 (a) Boundary conditions on the externals of the air domain (in red). (b) the Dirichlet boundary conditions are set on the white surface and Neumann boundary conditions on the red surface.

Dirichlet boundary conditions and Neumann boundary conditions are set on the symmetry and anti-symmetry surfaces respectively, see Figure 7 (b). Furthermore, the air surrounding the workpiece is a box of 275[mm] x 275[mm] x 275[mm]. Each ply is modeled separately and considered an homogenous anisotropic sheet. For meshing 20 elements are used in thickness direction for each ply. The whole model comprises 460.000 EMC3D8 elements which proved sufficient for this case.

3.2 Interface modelling

The interface electric conductivity is computed using in-plane and transverse electrical resistance properties of ply measurements. Resistance $R_{0\ UD}$ (0-direction) and $R_{90\ UD}$ (90-direction) is computed via the inverse of the conductivity ($c_{ply,i}$) adjusting for ply thickness (spt), specimen length (spL) and specimen width (spW) via (Fowle, 1919)

$R_{0\ UD} = \frac{spL}{(spW*spt)} * \frac{1}{c_{ply,x}}$ and $R_{90\ UD} = \frac{spW}{(spL*spt)} * \frac{1}{c_{ply,y}}$.

The total resistance is then computed via $R_T = \frac{1}{\left(\frac{1}{R_{0\ UD}}+\frac{1}{R_{90\ UD}}\right)}$.

For the interface thickness of the FEA model the ply resistances have to be adjusted for via

$R_{f,1} = \frac{R_{0\ UD}}{(0.5-0.5*t_{int})}$, $R_{f,2} = \frac{R_{90\ UD}}{(0.5-0.5*t_{int})}$.

The in-plane resistance of a [0,90] interface (i.e., in 1- and 2-direction) is then determined using,

$R_{0,90}{}^{1,2} = \frac{R_{f,1}{}^{1} R_{f,2}{}^{2} R_T}{\left(R_{f,1}{}^{1} R_{f,2}{}^{2} - R_T\left(R_{f,1}{}^{1} + R_{f,2}{}^{2}\right)\right)}$

where, $R_{f,1}{}^{1}$ and $R_{f,2}{}^{2}$ are the resistance values of a single ply in longitudinal and transverse direction adjusted for the interface thickness, respectively. For the through-thickness resistance of the interface $R_{f1,f2}{}^{3}$ the rule of resistances in series is used,

$$R_{f1,f2}{}^{3} = R_T - R_{f,1} - R_{f,2}$$

The interface conductivities are then calculated as:

$$c_0 = \frac{sp_l}{R_{0,90}{}^{1,2} * \left(sp_w * t_{int} * 2 * t_{ply}\right)}, c_{90} = \frac{sp_w}{R_{0,90}{}^{1,2} * \left(sp_w * t_{int} * t_{ply}\right)}$$

3.3 Electromagnetic simulation results

The effect on computed eddy currents in the laminate when modelling the ply layup separately is shown in Figure 8. The computed current is plotted from top surface to bottom surface in thickness direction and ply orientation is clearly visible. Eddy currents are mainly generated in the 0 plies.

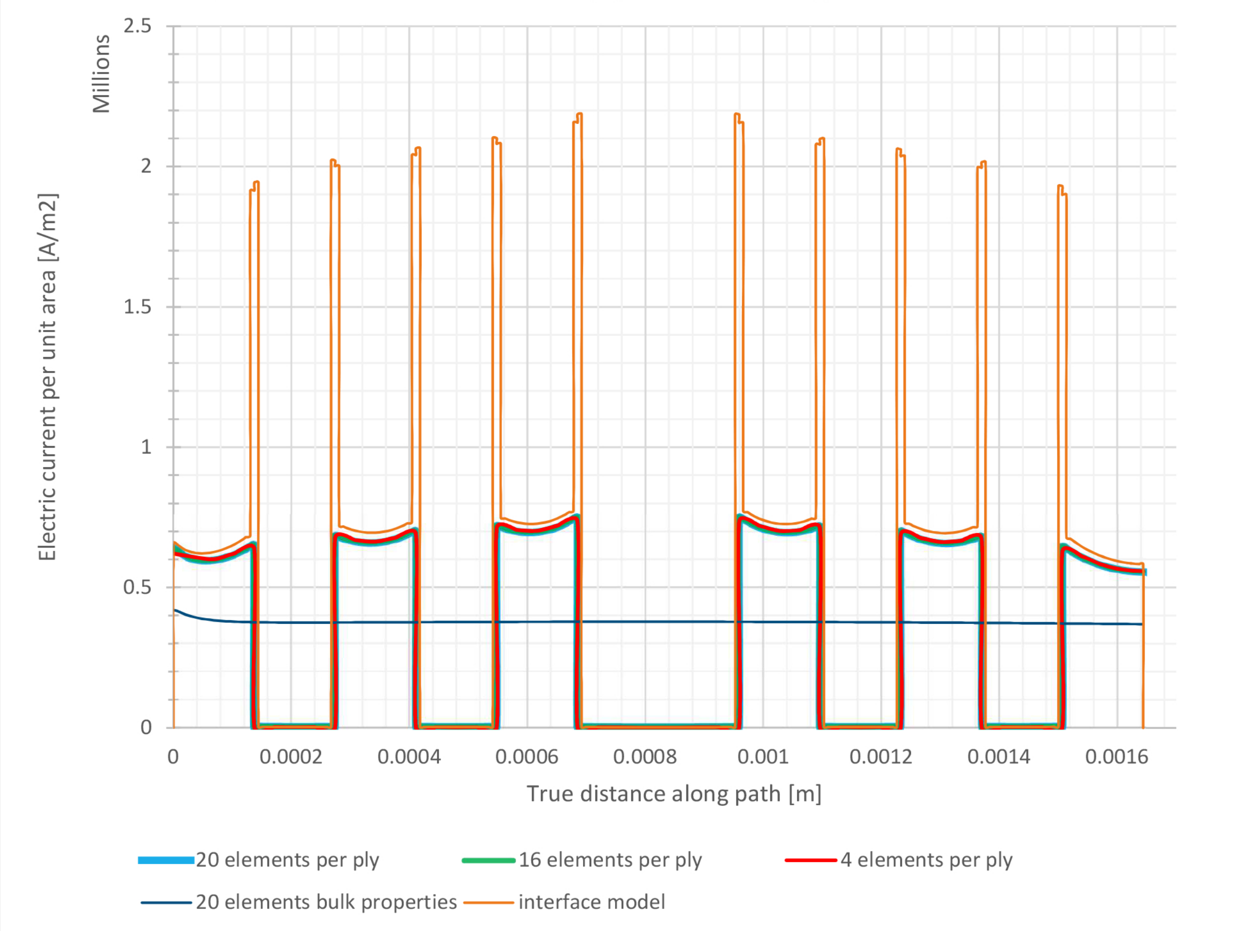


Figure 8 Eddy current distribution in thickness direction from top to bottom for several element partitioning in thickness direction. Furthermore, the effect of adding an interface model to the calculated electric current per unit area is shown.

Furthermore, Figure 8 shows the difference between modelling bulk properties(i.e. collecting the properties of plies in different orientation into a single property for the entire thickness) and per ply properties.
When adding the interface properties to the FEA model a small peak in the computed values is present as shown in Figure 8. The effect of the interface properties is that the computed eddy currents are slightly higher than without the interface model. Hence, it is expected that in the simulation the laminate will heat up faster than without the interface modelling.

To show the effect that different modelling approaches have on the top surface temperature the computed values are compared with the measurements reported in the literature (Grouvea, Vrugginka, Sacchetti, & Akkerman, 2020). The model using bulk properties, per ply modelling and per ply modelling with interface properties is compared in Figure 9.

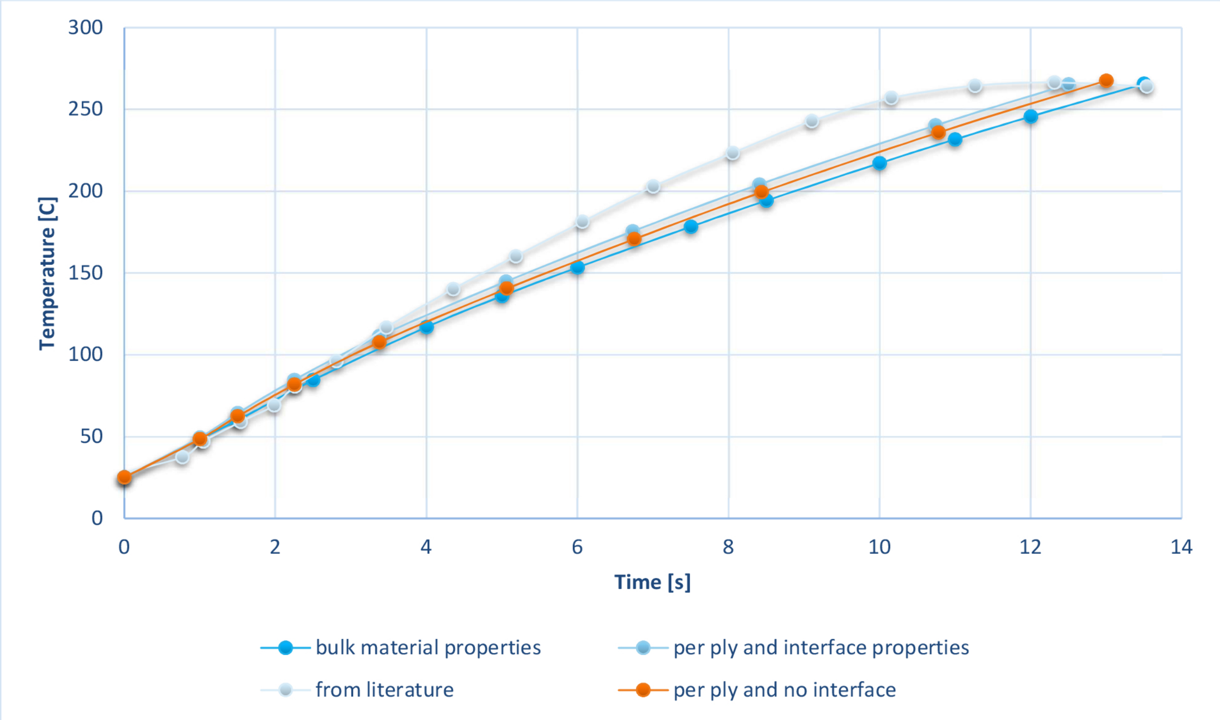


Figure 9 Temperature of the top of the laminate with respect to time. Several modelling approaches are compared to measured values taken from literature.

Figure 9 shows that the difference in calculated top surface temperature is small. Between bulk properties and the per ply modelling with interfaces the difference in reaching the maximum temperature of the laminate is 0.5 [s]. The larger difference between the modelling results and the data taken from literature at higher temperature is expected to be due to the electric conductivity depending on temperature. For higher temperatures the electric conductivity decreases, see e.g. (O'Shaughnessey, Dubé, & Villegas, 2016). However this was not further investigated.

4 Results conclusions/further work

A modelling approach for UD tape material using an interface model was presented. The results show that this interface model has a positive effect on the temperatures that are calculated with respect to experimental results from the literature. Furthermore, an experimental approach was setup to determine electrical properties for UD tape material. In future work the cross-ply measurements will be repeated to compare experimentally determined conductivity values with the computed values.

Acknowledgement

This project has received funding from the Clean Sky 2 Joint Undertaking (JU) under grant agreement No 945583. The JU receives support from the European Union's Horizon 2020 research and innovation programme and the Clean Sky 2 JU members other than the Union.

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