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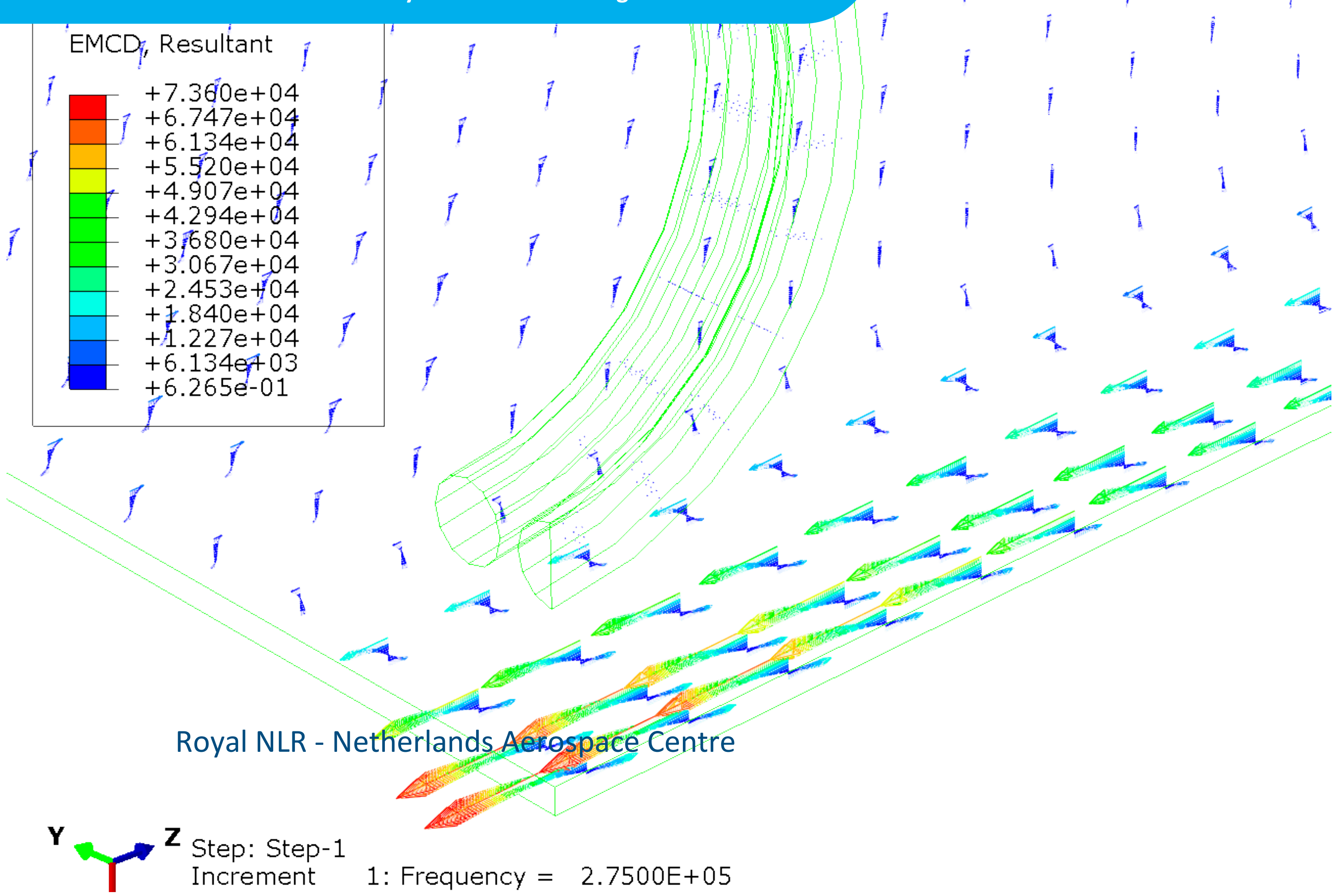
Numerical simulation of eddy current generation in uni-directional thermoplastic composites

CUSTOMER: Clean Sky 2 Joint Undertaking



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EXECUTIVE SUMMARY

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Numerical simulation of eddy current generation in uni-directional thermoplastic composites

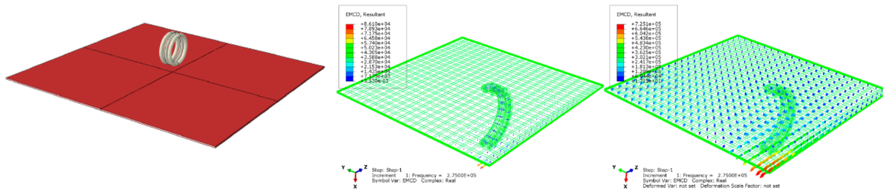

Figure 1: When an electrically conductive composite laminate is placed near an alternating current carrying coil, eddy currents are induced inside the composite laminate. These eddy currents are generated due to the presence of an electromagnetic field surrounding the coil. Via finite element analysis these eddy currents can be computed and visualized

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 uni-directional (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. According to literature this could be due to the absence of a current returning path in the UD laminate where this is naturally embedded in the weave. The objective of this work is to develop 3D electromagnetic simulation models that can provide insight into the influence of ply interfaces on the eddy currents that are generated inside a UD CFRP laminate when placed inside an electromagnetic field that is induced by a coil, see Figure 1.

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Computational Mechanics and Simulation Technology
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Description of work

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 that was developed in previous work by the authors is improved that takes into account the through the thickness resistance 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 cross-ply laminate taken from literature. To obtain electrical conductivity properties for the laminate that are not readily available a measurement technique developed in previous work is improved.

Results and conclusions

The numerical results of the model with interface modelling show the effect of different stacking sequences on the eddy currents that are generated in the laminate. The stacking has to be chosen carefully such that current return paths are present in the laminate so to form a closed current loop. 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 Composites Meet Sustainability – 20th European Conference on Composite Materials, ECCM20. 26-30 June, 2022, Lausanne, Switzerland.

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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 uni-directional (UD) CFRP material. In particular the influence of material properties and ply layup interfaces on the generation and distribution of eddy currents inside the composite laminate is investigated. An improved interface model that models the through the thickness electrical resistance is developed and 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 effect of different ply stackings and different cross-ply interfaces on the formation of eddy currents inside the laminate when placed near a coil.

Contents

Abbreviations

ACRONYM	DESCRIPTION
AC	Alternating Current
CFRP	Carbon fiber reinforced polymer
DC	Direct Current
EMCD	Electromagnetic current density
FE	Finite Element
JU	Joint Undertaking
MFFD	Multi-functional fuselage demonstrator
NLR	Royal NLR - Netherlands Aerospace Centre
R&D	Research and development
TP	Thermoplastic
UD	Uni-directional

Numerical simulation of eddy current generation in uni-directional thermoplastic composites

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Abstract: *In this work the generation of eddy currents in uni-directional (UD) plies of thermoplastic carbon fiber reinforced polymer (CFRP) laminates is investigated. The focus is on developing a numerical electromagnetic simulation model that captures the main processes involved in eddy current generation, in particular in the UD plies interface areas. To simulate this eddy current generation an interface model is introduced that represents the mixed electrical properties in the ply interface areas and a measurement technique is presented to measure the necessary material properties. Finally, the effects on the eddy current generation of the positioning of plies with different orientation within the stacking order is shown. Adjacent, different oriented plies increase the eddy current density through the laminate thickness.*

Keywords: eddy currents; thermoplastic composites; numerical simulation; electromagnetic

1 Introduction

In the Large Passenger Aircraft Platform 2 of the European R&D program Clean Sky 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 TP composite MFFD shall demonstrate the benefits of integrating various functionalities and help future European airliner production to become faster, greener, and more competitive. Significant weight reduction and thus environmental improvements of aircraft are expected as a result of innovative manufacturing, assembly, and installation processes. These innovations in turn will drive down costs and improve product competitiveness to European aeronautics. The TP composite MFFD consists of an assembly of multi-functional building blocks for the next generation fuselage and cabin. Development of advanced joining technologies and effective use of materials is necessary to enable a competitive assembly.

One example of such advanced joining techniques is induction welding. TP composites can be re-melted allowing them to be joined via welding. At present, the inductive heating of woven fabric composites is well documented and understood (Yousefpour, Hojjati, & Immarigeon, 2004). Several heating mechanisms take place in the induction heating of TP carbon fiber reinforced polymer (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. However, a Uni-Directional (UD) CFRP material is more difficult to heat than a weave CFRP material. According to literature (Ahmed, Stavrov, Bersee, & Beukers, 2006) this could be due to the absence of a current returning path that is naturally embedded in the weave.

The objective of this work is to develop 3D electromagnetic simulation models that can provide insight into the influence of ply interfaces on the eddy currents that are generated inside a UD CFRP laminate when placed inside an electromagnetic field that is induced by a coil. First, basic steps involving eddy current generation in a CFRP laminate are introduced. Second, a numerical simulation model based on electromagnetic Finite Element (FE) analysis is introduced. This model is extended with an updated version of an interface model (Wit, Hoorn, Nahuis, & Vankan, 2021) previously developed by the authors. The updated interface model is constructed analogous to a surface implementation (Cheng, Wang, Xu, Qiu, & Takagi, 2021) but is extended to a volumetric implementation in this work. Third, the effect of 0/90 cross-ply interfaces on a laminate stacking is shown. Finally, the main conclusions and steps for further research are presented.

2 Electromagnetic modelling

For IW of TP CFRP, the electromagnetic properties of the plies and the laminate layup are of key importance for the behavior of the electromagnetic eddy currents that emerge in the CFRP composite laminate. Besides the magnetic permeability and magnetic permittivity, the electric conductivity of the material is a key determinant for the eddy current density distribution in the laminate. Although these properties depend on temperature and frequency, in the current study these properties are kept constant.

2.1 Cross-ply laminates and ply interfaces

In cross-ply laminates there are specific areas of increased eddy current density that are located at the interfaces of the cross-plies (Ahmed, et al., 2006) (O'Shaughnessey, et al., 2016) (Yousefpour, et al., 2004). Therefore, these cross-ply interfaces play an important role in the eddy current density distribution in the laminate under inductive electromagnetic loading. The background of this phenomenon is the increased occurrence of contacts between fibers in this interface layer and the opportunity for current to form a closed circuit. This is shown in Figure 2.

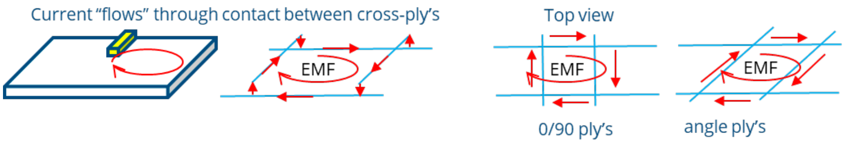


Figure 2: Cross-plies form a closed loop such that current can 'flow' through the plies. EMF stands for electro magnetic field

These cross-fiber contacts result in a more isotropic in-plane conductivity and increased out-of-plane conductivity in this interface layer. To incorporate this important effect, the augmented electric conductivity properties in the cross-ply interfaces must be included in the FE model.

2.2 Cross-ply interface definition

In this work we develop an approach for solid FE modelling of electromagnetic eddy currents in cross-ply laminates including their cross-ply interfaces. To develop the interface concept, we consider a small two-ply laminate sample with arbitrary thickness, width and length. Furthermore, two interface cases are considered. The first consists of a [0,0] UD laminate and the second of a [0,90] cross-ply laminate. The cross-section is sketched in Figure 3.

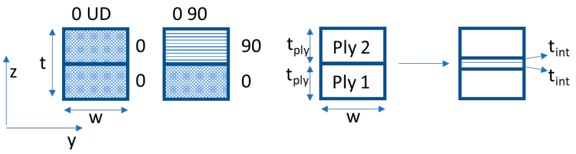


Figure 3: Front view of the small 2-ply laminate sample. A [0,0] and a [0,90] cross-ply laminate. The 0 fibers are oriented in x-direction. The cross-ply interface layer of arbitrary finite thickness t_{int} per ply is considered in between the ply. Hence, interface layer thickness is $2t_{int}$.

In the region around the interface between the plies, a cross-ply interface layer of arbitrary but finite thickness t_{int} per ply is introduced, see Figure 3. This interface layer is considered to have the augmented an-isotropic electric conductivity properties. Furthermore, these properties are taken homogeneous throughout the whole interface. The in-plane conductivities in the interface layer are assumed to result from the combination or mixture of the conductivities of the two plies. The out-of-plane conductivity in the interface layer is taken equal to the out-of-plane conductivity (or resistivity) of the considered cross-ply.

2.3 Electric resistances of plies and interface

The an-isotropic resistance tensor for each of the two plies (ply1 and ply2) in the small laminate sample (recall Figure 3) contains the resistances of each of the two plies in the three directions x,y,z, see Figure 4.

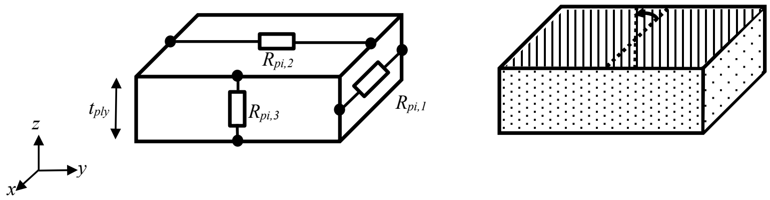


Figure 4: illustration of the an-isotropic resistances (left) and fiber orientation expressed by ply angle (right) for a single ply in the small laminate sample

Hence, the resistances are written as:

$$\boldsymbol{R}_{pi} = [R_{pi,1}, R_{pi,2}, R_{pi,3}] \; ; i \; = \; 1,2; \tag{2}$$

In Eq. (2), i is de ply index and each ply can have arbitrary ply orientation, expressed by a ply angle ϕ_i. The resistances of a ply in the small laminate sample at an arbitrary ply angle ϕ_i can be determined by assuming a linear relation between the resistance in fibre direction (R_11) and the resistance in transverse direction (R_22) of a single ply, see (Cheng, et al., 2021).

Since the interface layer has finite thickness (recall Figure 3 right), the total resistance in each direction x,y,z of the small two-ply laminate sample must be equal to the total resistance of the sample without the interface layer Figure 3 left). This yields that the resistance of the whole interface is equal to the combined resistance of its components. Hence, the lower half of the interface that contains the Ply1 properties and the upper half of the interface that contains the Ply2 properties.

Consequently, the in-plane resistances of the interface, i.e. in x,y directions, are composed from the parallel resistances of the interface components:

$$R_{i,j} = \frac{R_{i1,j}R_{i2,j}}{R_{i1,j}+R_{i2,j}} \; ; \mathrm{j} = 1,2 \; ; \tag{5}$$

Here $R_{i,j}$ is the resistance of the whole interface in direction j, and $R_{i1,j}$ is the lower interface component resistance and $R_{i2,j}$ is the upper interface component resistance, in direction j, with j=1,2,3 that refers to the x,y,z directions.

The out-of-plane resistance of the interface, i.e.in z direction, is composed from the serial interface component resistances, and an additional ply-contact resistance. In (Xu, et al., 2018) this ply-contact resistivity ρ_c is determined experimentally for two-ply laminate samples.

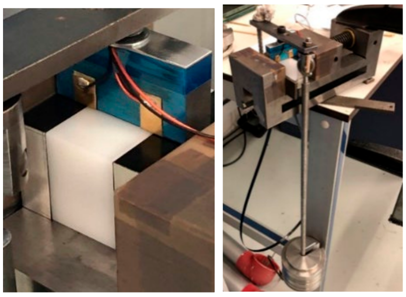
3 Electrical characterization of (UD) CFRP

Although material data sheets include recognized standards for mechanical and thermal material properties, electrical properties are less common to be included. For UD material, an additional property involving the cross-ply electrical properties is application specific.

3.1 UD ply electrical conductivity measurements

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

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 specimens shorter specimens of 20 [mm] are used and the clamping devices are adjusted, see Figure 5.


(a)

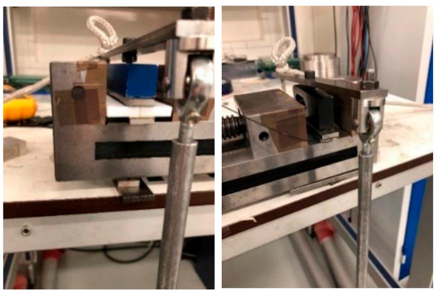

(b)

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

Measurement results. Five samples are used for each measurement and the Direct-Current (DC) resistance, as well as, the Alternating-Current (AC) impedance. 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 (for this measurement, 384 [kHz]). The results are given in Table 1.

Table 1: Measured anisotropic UD ply electrical conductivity

σ_{11} **[S/m]**	**31307 ± 581**	σ_{22} **[S/m]**	**0.865 ± 0.260**	σ_{33} **[S/m]**	**0.055 ± 0.018**

3.2 Cross-ply electrical conductivity measurements

For the interface modelling 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 3.1. 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.

4 Numerical simulation model

The electromagnetic simulations are carried out in the Finite element package Abaqus (Simulia, 2021). The theoretical manual provides a complete derivation of the underlying equations. In this work we address the relevant steps to build the analysis model.

4.1 Model geometry and boundary conditions

The FEA Model is constructed according to the information provided in (Grouve, et al., 2020). The model consists of a three circular coil, a laminate and a volume of air surrounding the coil and laminate. In Figure 6 the geometry is shown. By making use of symmetry conditions only quart of the geometry is modelled.

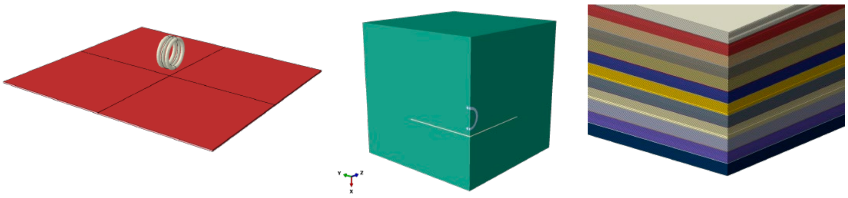


Figure 6: Model geometry. (left) The laminate and coil. (middle) Quarter model of the coil, laminate and air surrounding the workpiece. (right) The laminate stacking highlighted with coloring

The one quarter model consists of a composite laminate with dimensions 145[mm]x145[mm] and 12 plies, see Figure 6. Each ply has a thickness of 0.137[mm]. Hence, the laminate thickness equals 1.644[mm]. The coil consists of three circles with a pitch of 6.1[mm] of which one quarter is modelled. The distance between coil and laminate is 10[mm]. The coil cross section has a radius of 2.4[mm] and the coil turn has a radius of 18.6[mm]. Hence, the coil outer radius is 41.1[mm]. The coil is assumed to have homogenous material properties. A current of 350[A] is applied in circumferential direction of the coil at a frequency of 275kHz. The composite material is C/PEKK corresponding to (Grouve, Vruggink, Sacchetti, & Akkerman, 2020). For completeness, the material properties that are used in the present model for the air, coil and laminate are listed in Table 2.

Table 2: Material properties taken from (Grouve, Vruggink, Sacchetti, & Akkerman, 2020) *for the air, coil and plies*

	Electric conductivity	**Magnetic permeability**	**Magnetic permittivity**
Air, Coil	1 [S/m]	$4\pi/1E7$ [H/m]	8.85E-12 [F/m]
Laminate $[0]_{12}$	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]
0/90 interface	In-plane and transverse 11451 [S/m] Through-thickness 0.2694 [S/m]	$4\pi/1E7$ [H/m]	8.85E-12 [F/m]

A boundary condition is set on the 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.

The air surrounding the coil and laminate is a box of 275 [mm]x275 [mm]x275 [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 460.183 EMC3D8 elements which proved sufficient for this case. The interfaces between plies are taken as 10% of ply thickness. Hence, the interfaces consume 2 elements in thickness direction from each ply except for top and bottom ply that only assign one element to the interface.

4.2 Number and position of interfaces within the laminate stacking

To show the effect of adding ply interfaces, several non-standard stackings are considered to emphasize the difference in induced current density. Hence, a uniform zero stacking is considered and as opposite a uniform $[0/90]_6$ stacking that most closely resembles a weave. To obtain an idea of how interfaces improve the eddy current generation through the thickness both the number of cross-ply interfaces is changed as well as the position of the cross-ply interface. In Table 3 the different stackings considered are summarized.

Table 3: Cross-ply orientations considered in the modelling. Each stacking consists of 12 plies

Ply stacking	0/90 interfaces	Ply stacking	0/90 interfaces	Ply stacking	0/90 interfaces
$[0]_{12}$	0	$[0_{11}/90]$	1	$[0_2/90_2]_3$	5
		$[90/0_{11}]$	1	$[0/90]_6$	11

4.3 Results for different stacking sequences

UD ply interfaces are considered to be the main mechanism to allow eddy currents to form in a UD laminate. A laminate that has no UD ply interfaces is a 0_{12} layup where all plies are oriented in the direction of the coil. Since the plies in the simulation model are assumed to perfectly align, the only means of generating an induced current is in thickness and out-of-plane direction. The computed current densities are an order of magnitude lower in the 0_{12} layup as compared to the $[0/90]_6$ layup, see Figure 7.

Abaqus uses the absolute value of the magnitude of the EMCD vector to calculate the Joule Heating. Hence, when plotting the complex magnitude of the EMCD in through the thickness direction an idea of how the heat generation is taking place in the laminate is obtained. Hence, for a 0_{12} laminate the induced heating will mainly occur at the surface, see purple line Figure 8.

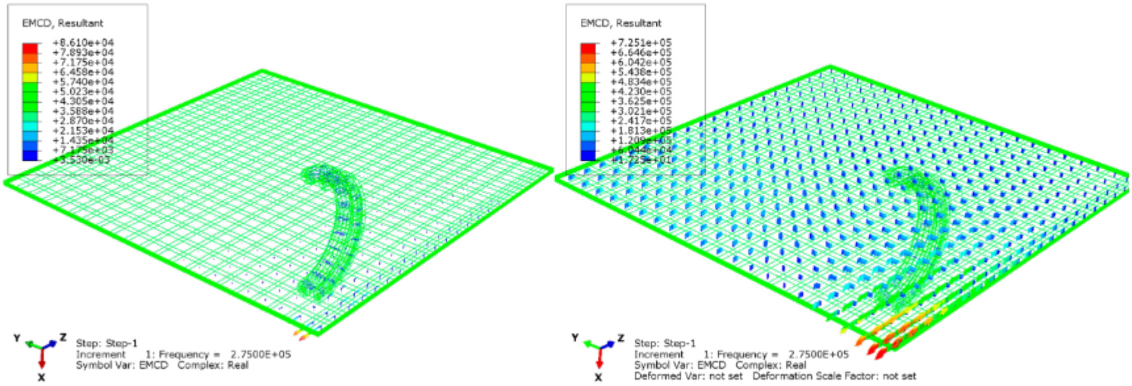


Figure 7: Real part of the eddy current density vector in the laminate. Left is the eddy current generated in the 0_{12} laminate and right is the eddy generated in the $[0/90]_6$ laminate

Figure 8 shows that increasing the number of UD ply interfaces has the effect of increased current density. Hence, the peak values are higher as well as the part of the thickness in which the high currents are generated. Furthermore, the results show that the current density is not the highest at the top surface. Hence, inside the laminate the heating can be higher than at the surface depending on the stacking. However, this is not further investigated in this study.

Increasing the number of cross plies has the effect that multiple current returning paths are present in the laminate. Hence, the calculated eddy current increases through the thickness. This is shown for a $[0_2 90_2]3$ (five cross ply interfaces) and a $[0_1 90_1]_6$ (eleven cross ply interfaces) stacking. The resulting EMCD through the thickness is shown in Figure 8.

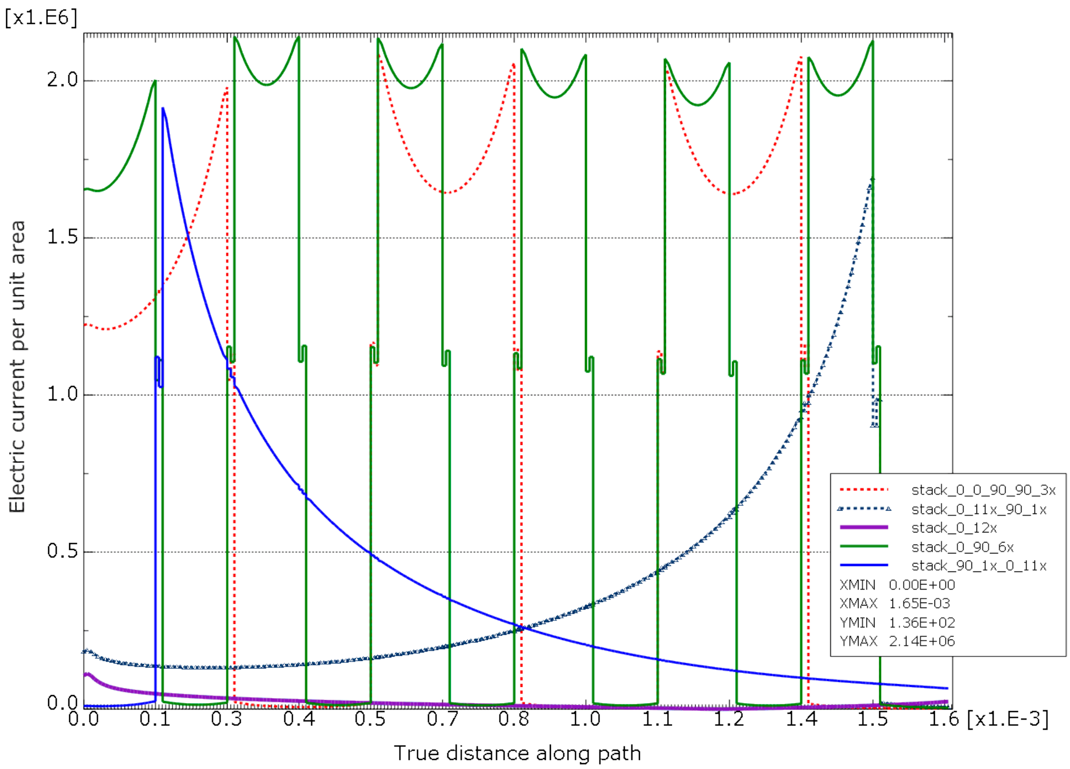


Figure 8: EMCD through the thickness for different ply stackings. Adding ply interfaces to the stacking increases the EMCD value calculated. Furthermore, a ply interface closer to the surface below the coil increases the current density through the laminate thickness

5 Conclusions and further work

An increased number of cross-ply interfaces inside a UD CFRP laminate has a positive effect on the current density distribution inside the laminate which is important for inductive heating of UD CFRP. The measurement of anisotropic electric material properties was successful in determining electrical properties of the plies with respect to values recorded in literature. In future work we will examine the effect of cross-ply interfaces on thermal behavior of the inductive heating both via numerical simulation as well as thermal imaging of an inductive heating setup with UD CFRP laminate.

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Disclaimer

The results, opinions, conclusions, etc. presented in this work are those of the author(s) only and do not necessarily represent the position of the JU; the JU is not responsible for any use made of the information contained herein.

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