THERMAL HOMOGENIZATION OF PERFORATED SANDWICH STRUCTURES FOR SPACE ANTENNAS

T. Sproewitz[1], J. Tessmer[2], R. Rolfes[3]

[1,2] *DLR, Institute of Composite Structures and Adaptive Systems*
Lilienthalplatz 7, 38122 Braunschweig, Germany
Phone: +49 531 295 2343, FAX: +49 531 295 2232

[3] *University of Hannover, Institute for Static and Dynamics*
Appelstraße 9A, 30167 Hannover, Germany
Phone: +49 511 762 3867, FAX: +49 511 762 2236

In this paper a strategy is presented to characterize the thermal behavior and to determine effective thermal parameters of a new sandwich concept made from tri-axial single-ply face sheets and a Korex honeycomb core. The characterization is conducted by means of the FEM (Finite Element Method) using the MSC/NASTRAN software code applied to a detailed 3D modelization of a representative Unit Cell. Based on the gained results a homogenization will be performed leading to effective conductivities and effective thermal loads. They allow for an application to a simplified FE model where the honeycomb core will be resembled by a conventional solid finite element and the face sheets by shell elements. It therefore enables the thermal analysis of large structures made from this specific material. The applicability and capability of this approach is proofed by thermal investigations of a real antenna reflector, which is to be operated on a satellite in GEO (geosynchronous orbit).

Keywords: *thermal homogenization, antenna reflector, thermal analysis, sandwich structures, FEM*

1 Introduction

In order to steadily increase the capacity of satellite telecommunication, it is of great importance to continuously improve the effectiveness and to broaden the areas of application (e.g. frequency ranges). Thus, the securing of sending and receiving quality and especially the trend to higher radio frequencies claim extreme requirements on thermal stability of satellite antenna reflectors. These demands have to be fulfilled in compliance with a minimum allowable structural mass and the stringent stiffness constraints. Only the intelligent application of advanced materials allows for meeting all these requirements.

Depending on the field of application the sandwich of the reflector is composed of tri-axial single-ply CFRP (Carbon Fiber Reinforced Plastic) face sheets and Korex honeycomb core. The "holes" in the face sheets caused by the tri-axial lay-up as well as the transmissivity of the Korex material can lead to an increase of thermo-elastic stability due to a reduction of the transverse temperature gradient.

As can be seen in Fig. 1 the artificial transmissivity of the sandwich is highly dependent on the angle of incidence b of the radiation source. Hence, the thermal characteristic varies as the location of the heat source changes. Furthermore, the position of the face sheet relative to each other influences the overall thermal behavior.

The closer investigation of the thermal properties of the sandwich wrt. angle of incidence and the derivation of a homogenization strategy to enable the calculation of a whole antenna structure with reasonable computational effort will be presented in the next paragraphs.

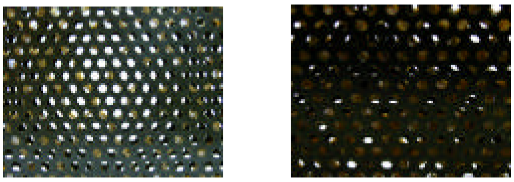

Figure 1: Sandwich Structure for different View Angles

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[1] Research Scientist, tom.sproewitz@dlr.de
[2] Dr.-Ing., jan.tessmer@dlr.de
[3] Professor, r.rolfes@isd.uni-hannover.de

2 Unit Cell Approach

In order to describe the thermal behaviour of the sandwich material accurately the creation of a 3D FE model is mandatory. The necessary high level of geometrical accuracy and also the required fine discretization to properly account for boundary conditions would lead to a rather large FE model and would subsequently result in a tremendous computational time. To keep the effort within a reasonable frame, the investigation of the overall thermal behaviour will be conducted on a representative part of a sandwich probe. This part will be chosen such that it may recur regularly and therefore forms a **Unit Cell**. Its size will be determined by geometrical constraints and in a convergence study.

To assure the correctness and applicability of the FE modelization and the assumed boundary conditions all computational results will be correlated against available test results.

2.1 General Remarks

The geometrical dimensions of the sandwich structure are decisive for its overall thermal behavior. Only one specific configuration has been investigated. All values are displayed in terms of ratios wrt. honeycomb height *h* in Table 1. Furthermore, the position of the face sheets relative to each other is assumed to be congruent.

Table 1: Honeycomb Geometrical Dimensions

honeycomb height *h*	1
honeycomb diameter *d*	1
CFRP face sheet roving width *l*	≈1/7
CFRP face sheet thickness t_{CFRP}	≈1/32
Korex honeycomb foil thickness t_{Honey}	≈1/160

Conductivities and thermo-optical properties of face sheets and honeycomb core were experimentally determined.

In preliminary considerations it could be shown that the transverse temperature gradients in the thin walled face sheets and honeycomb foils can be neglected. This allows for the usage of merely shell elements for the modelization of the detailed unit cell FE model.

2.2 Finite Element Model

2.2.1 General FE Model Description

A FE model as shown in Fig. 2 was created consisting of 2D FE elements only. The face sheets' location relative to the honeycomb was chosen such that the whole model fulfills the geometrical constraints and that it forms a unit cell that regularly recurs. The model shown resembles the smallest unit cell, with three closed honeycomb cells.

2.2.2 Application of Boundary Conditions

All boundary conditions applied to the FE model have radiative character. They are applied be means of differing thermo-optical properties depending on the material and the magnitude of the present heat fluxes.

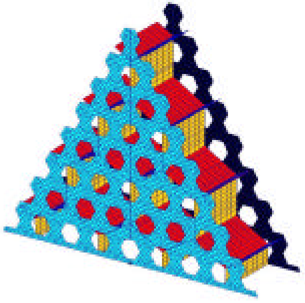

Figure 2: Unit Cell with three closed Cavities

Since the angle of incidence varies from $0° \le b \le 90°$, where $b = 0°$ is normal to the sandwich surface, the front skin will be illuminated by solar radiation for all *b*. Parts of the interior of the back skin and honeycomb foils can be irradiated depending on the angle of incidence (conf. Fig. 3). The application of the solar heat loads is realized by an ambient node definition for all elements which are visible to the heat source. The node temperature is defined as $T_\infty = 396.5K$ which is equivalent to a black body emitting $1400\,W/m^2$. Infra-red radiation of all external surfaces is defined using an ambient node with $T_\infty = 77K$, which is the temperature of liquid nitrogen as used throughout all tests. To account for internal infra-red heat exchange every honeycomb cell is considered as an open cavity against $T_\infty = 77K$. At the outside edges of the sandwich adiabatic boundary conditions were assumed. No radiation enclosures are defined in the open cells on the unit cell edges, since the energy loss about these cells would then be unrealistically high. In order to keep the subsequent error on the global temperature field as small as possible a convergence study was conducted leading to a unit cell with 37 honeycomb cells.

Since it is not possible to account for transmissivities within the applied FE code an adjusted emissivity for infra-red radiation for the honeycomb foils is introduced. Assuming the total heat load on a single foil to be 100% leads for Korex material to an absorption of 80% of which 20% will be transmitted (conf. Fig. 3). Under the consideration that the transmitted heat illuminates the next cell wall and the assumption of an infinite number of cell walls the absorbed heat adds up to 100% which leads to an emissivity of $e_{honey} = 1$.

In case of solar radiation the transmitted heat is computed according to the illuminated honeycomb area and subsequently applied as heat load to the interior of the back skin.

2.3 Parameter Study and Test Correlation

2.3.1 Parameter Study

Aim of the parameter study is to analyze the thermal behavior of the sandwich for an arbitrary configuration of face sheets and honeycomb core as well as a variable angle of incidence. Furthermore it shall provide data for a correlation against test results.

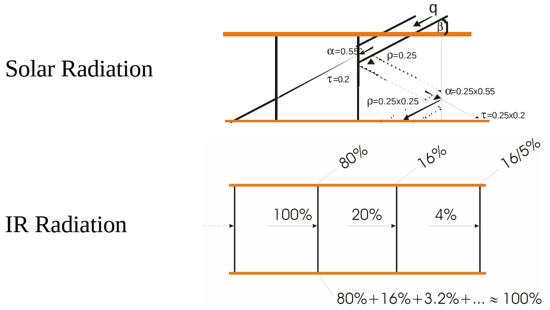

Figure 3: Unit Cell Radiation Boundary Conditions

A sandwich configuration (congruent face sheets) was analyzed by rotating about the x- and y-axis of the FE model resembling a real configuration under different angles of incidence. Furthermore, upper and lower temperature boundaries are assessed by assuming worst load cases. In Fig. 4 there are displayed the load conditions for the cold and hot configuration, where in case of the cold configuration no solar radiation illuminates the interior of the back skin at any angle of incidence. In contrary to that, the whole possibly visible area of the interior of the back skin will be illuminated.

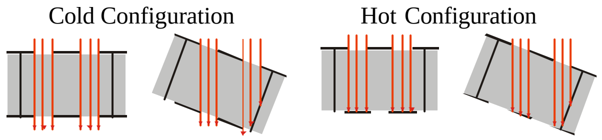

Figure 4: Loading for Worst Case Configurations

As can be seen in Fig. 5 the thermal behavior is strongly dependent on the face sheet configuration and the angle of incidence. Due to the specific tri-axial lay-up different maxima and minima can be found for rotation about x- and y-axis. Both are enveloped by the assumed cold and hot configurations. Comparing the worst cases at $b = 0°$, high temperature variations can be found. Depending on the thermo-optical properties of the front skin ($0.17 \le a \le 0.92$), the back skin temperature variations are 4-6 times higher than for the front skin.

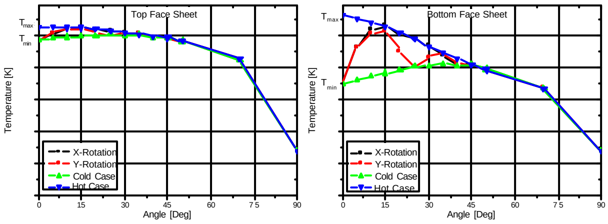

Figure 5: Face Sheet Temperatures

2.3.2 Test Correlation

Due to the manufacturing process the sandwich configuration is random. For this reason a probabilistic approach was chosen to account for all heat that will illuminate the back skin. Since the total area of the skins consists of 66% CRFP and 33% holes there is an assumed 2/3 possibility of illumination of the interior of the back skin.

With this approach a very good agreement between experimental and analysis data could be achieved for specimens with different front face absorptivities and varying heat power. In Fig. 6 there are shown the max. errors wrt. the experimental front skin temperature for one configuration. For all investigated cases the error does not exceed 5.5%.

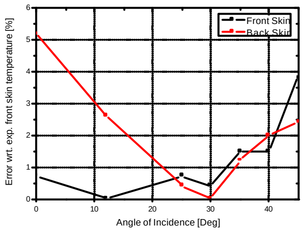

Figure 6: Correlation Temperature Error

3 Homogenization of Honeycomb Core Thermal Properties

3.1 General Remarks

Homogenization in the existing problem will be the representation of complex heat transport of the honeycomb by means of a single, homogenous material. Main output is an effective conductivity and apparent boundary conditions as input for a simplified FE model. The homogenization is conducted under the assumption that all heat gains and losses due to the open sandwich design are taken into account in the transverse homogenization.

This approach allows for a good representation of the thermal behavior of the sandwich by using solid elements for the sandwich core and shell elements for the skins.

3.2 In-plane Homogenization for the Sandwich Core

A FE model with a quasi-rectangular cross section was created resembling a honeycomb with 17 closed cells. All boundaries are adiabatic, except for 2 surfaces in order to introduce and remove heat, which leads to a conservative heat flux. The heat flux density is assumed to be constant. By giving the skins a very low conductivity all heat will be transferred via the honeycomb foils (conduction) and cells (radiation). The introduced heat loads are chosen such that a temperature range up to 500K is covered.

Following the homogenization strategy as depicted in Fig. 7 and assuming a 1D heat conduction element Fourier's Law (Eq.1) can straightforward by applied to determine the in-plane conductivities:

$$l_{eff_x} = \dot{q}_x \frac{\Delta x}{\Delta T}\ ,\ l_{eff_y} = \dot{q}_y \frac{\Delta y}{\Delta T} \text{ at } T_m = \frac{T_1 + T_2}{2} \qquad (1)$$

All conductivities will be related to a mean temperature T_m leading to temperature dependent material properties as depicted in Fig. 8.

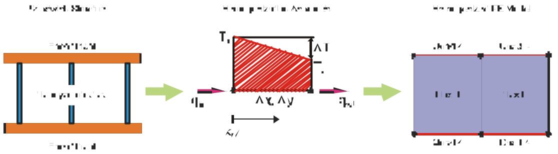

Figure 7: In-plane Homogenization Strategy

The application of the conductivities to a simplified FE model will be realized by means of an average conductivity since the differences in ~~x~~ and y-direction are very small and the honeycomb orientation in the real configuration is not exactly known.

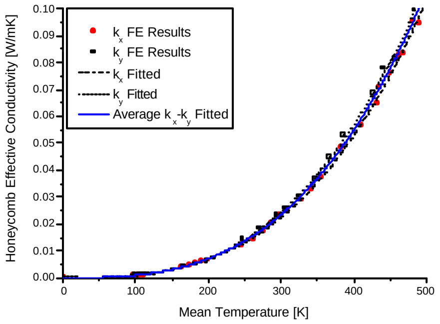

Figure 8: Honeycomb in-plane Effective Conductivity

3.3 Out-of-plane Homogenization of Sandwich Core

To describe the transverse sandwich thermal properties wrt. the angle of incidence *b* a 1D heat conduction element as shown in Fig. 9 is considered. Energy balances are drawn at the nodes, where a corrective heat flux $q_{corrective}$ is introduced. It is applied to the front and back node in equal shares and accounts for heat gains and losses which are not directly considered in this approach. Necessary input is:

- face sheet temperatures T_{top}, T_{bot} gained from unit cell investigations
- solar heat fluxes q_{top}, q_{bot} derived from geometrical information of FE model
- ambient loads given by ambient temperature and thermo-optical properties

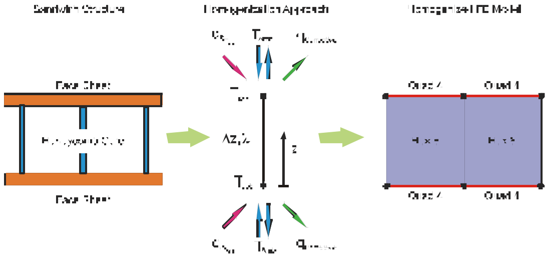

Figure 9: Out-of-plane Homogenization Strategy

$$\dot{q}_{corrective} = \frac{1}{2}\left[\dot{q}_{S_{top}} + \dot{q}_{S_{bot}} - es\left(T_{top}^4 + T_{bot}^4\right)\right] + es\,T_\infty^4 \qquad (2)$$

$$l_{eff} = \frac{h}{2\left(T_{top} - T_{bot}\right)}\left[\dot{q}_{S_{top}} - \dot{q}_{S_{bot}} + es\left(T_{top}^4 - T_{bot}^4\right)\right] \qquad (3)$$

Based on Equations (2) and (3) a corrective heat flux and an effective honeycomb conductivity can be determined in dependency on the angle of incidence. In Fig. 10 there are shown the corrective heat flux and effective conductivity for the investigated sandwich configuration.

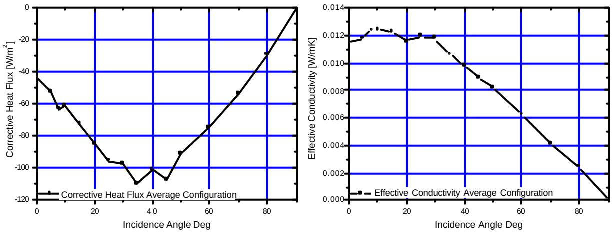

Figure 10: Corrective Heat Flux and Effective Conductivity

When analyzing a sandwich structure by means of a simplified FE model solar and corrective heat loads, effective transverse conductivities and ambient boundary conditions have to be applied depending on the angle of incidence. For every sandwich build-up and varying boundary conditions a single homogenization loop will be necessary.

4 Conclusions and Summary

The investigation of the thermal behavior of a "perforated" sandwich structure based on a unit cell approach is described. A test correlation was conducted which under consideration of the transmissivity of the honeycomb material led to a good agreement.

Homogenized material properties for the in-plane conductivity of the honeycomb were analyzed. Effective conductivities and corrective heat fluxes in transverse direction were determined such that the thermal behavior, which is highly dependent on the heat source angle of incidence, will accurately be represented.

All data gained within this study are necessary input for the thermal investigation of a reflector antenna mounted on a spacecraft structure.

5 References

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