THERMAL ANALYSIS OF HYBRID COMPOSITE STRUCTURES

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Abstract

A strategy for accurate, efficient and economic thermal investigation of hybrid composite structures by means of the Finite Element Method (FEM) will be presented. It includes test prediction, validation tests, validation analysis, and an industrial application. Drawbacks of commercial software codes are identified and current research work for the solving of these disadvantages are presented.

Nomenclature

a	diffusity coefficient $[m^2/s]$
c	heat capacity $[J/kgK]$
h	convection $[W/m^2K]$
q	heat flux $[W/m^2]$
t	layer thickness $[m]$
v	fluid velocity $[m/s]$
A	cross section $[m^2]$
H	height $[ft]$
L	characteristic length $[m]$
P	Power $[W/s]$
T	temperature $[K]$ or $[^\circ C]$
α	convection heat transfer $[W/m^2K]$
ε	infrared emissivity $[-]$
λ	thermal conductivity $[W/mK]$
η	efficieny $[-]$
ρ	density $[kg/m^3]$
σ	Boltzman constant $5.67 \cdot 10^{-8} W/m^2K^4$
Λ	solid heat transfer coefficient $[W/mK]$

1 Introduction

In design and development of aircraft structures requirements like enhancement of safety, cleanliness and stiffness as well as reduction of mass, fuel consumption, production and manufacturing costs, to name a view, are major issues for basic conceptual decisions. Though the ways to cope with these problems can be manyfold there are two specific topics that are pursued in industry which are also subject to resent research work at the German Aerospace Center (DLR) Institute of Composite Structures and Adaptive Systems. These are:

1. **increased usage of composite materials** in a wide range of structural parts of airframe structures for weight reduction

2. **reduction of development costs** by minimizing the amount of experimental testing –especially for large scale structures– based on reliable simulation abilities.

In this context the meaning of composite material must not only be understood as common fibre reinforced epoxy but also as hybrid materials like sandwich constructions with different face sheet and core materials or fibre-metal-laminates (FML) as glas fibre-aluminum reinforced epoxy (GLARE). In general these materials are characterized by superior stiffness properties in conjunction with a lower specific density compared to conventional isotropic materials. They furthermore allow for a design of stiffness properties depending on their specific field of application. Together with these favourable mechanical material properties under normal environmental conditions comes their strong dependence on the existing temperature niveaus, which can range from $-50°C \leq T \leq 100°C$ or worse. At low temperatures the matrix systems may become brittle and as temperatures rise near transition temperature the mechanical properties are deteriorating notably. Critical thermal loadcases which may have major influence on the mechanical performance of an aircraft structure are e.g.:

- aircraft parking and taxiing in hot ambient environment and under sun illumination prior to take-off,
- warming near air conditioning system heat exchangers in the center wing box,
- failure of pneumatic or hydraulic systems,
- fire events.

The temperature field is also very important for the evaluation of stresses induced by thermal expansion. This concerns not only hybrid structures as such but also the complete airframe structure as common aircrafts are made of a mixture of both conventional isotropic and composite materials. To ensure a safe operation of airframe structures in service thermal issues must be addressed. Hence, it is mandatory to know the temperature fields that are likely to occure throughout the different missions as accurate as possible. In the early design process the only way to gain necessary thermal data is by analytical or numerical simulations of the different missions that are required for the certification of airframe structures.

Numerical simulation techniques are also key components for a reduction of development costs. So far a high amount of expensive tests and numerical validation analyses was neccesary from small material specimens to full scale structures. But as computer resources and simulation techniques are improving it is possible to simulate a great variaty of scenarios –which classically were subject to testing– with such an accuracy and speed that cost and time expensive tests can be saved. In Fig. 1 there is shown the future tendency of effort put to testing and simulation in dependence on the specimen size and complexity.

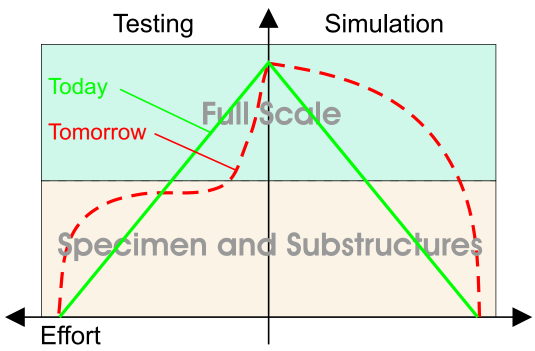

Fig. 1 Test and simulation effort vs. structure size

In order to save development costs by favouring simulation tools instead of testing it is envisaged to validate the numerical methods by means of small scale material or substructure tests for parameter identification. Therefore high effort shall be put to both experimental testing and validation analyses. As the size of structures increases the amount of tests shall be reduced and the structural behavior will mainly be analyzed by means of reliable simulation techniques. The future aim shall be the radical reduction of expensive full-scale experimental testing by simulation called **virtual testing**. The whole process must be reliable and standardized in a way that it will get agreement from the certification authorities and can be introduced as standard procedure in the design and development process. Fig. 2 shows a principle procedure for validation of simulation tools to predict the behavior of the structure to be designed. To allow for a broad field of safe application using the above mentioned materials and to ensure the abidance to the high aircraft safety standards an accurate an effective thermal analysis and thermal loads prediction is mandatory [1].

2 Procedure for reliable application of virtual testing

As mentioned above the general procedure starts with investigations on material specimen or substructure level. Necessary modelling assump-

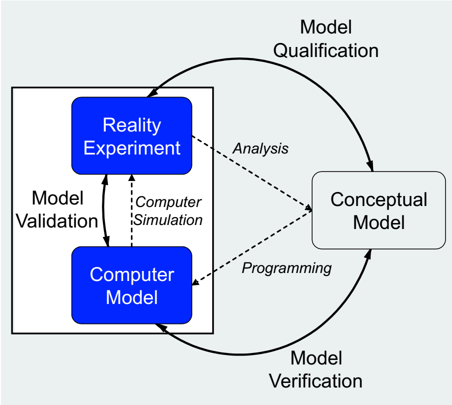

Fig. 2 Simulation tools validation procedure

tions and parameters will be identified and verified by test correlation analyses. On basis of the determined information the simulation of the next lower dicretization level can be conducted. A principle procedure for the evaluation of makro scale behavior by means of micro scale results is depicted in the flow chart in Fig. 3. The thermal investigation of a FML fuselage section will be given as a practical example in the following section.

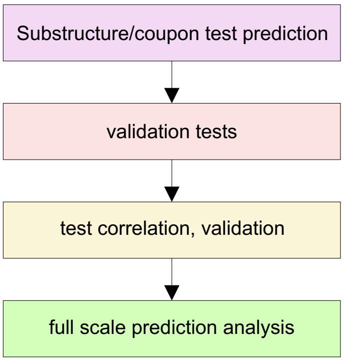

Fig. 3 Virtual testing process flow-chart

First step in a general procedure is to define the lowest unit which has to be investigated to be able of simulating the structure of interest. In many cases this part can also be called **unit cell** since mostly it resembles a regularly or periodically recuring part. A test prediction analysis on this unit gives necessary information for the design of an adequate test set-up for the subsequent verification tests. Based on the results gained from the experiments, test correlation analyses will be performed in order to get a parameter set that allows for an exact reproduction of the structural behavior. This step can be realized with different approaches which can also be based on homogenization strategies. The following three possible strategies are common in thermal engineering but do not cover all possibilities:

(a) **geometrically and physically unchanged**
Verification analyses are conducted on a geometrically and physically detailed unit cell model under consideration of possible symmetric boundary conditions. Unchanged usage in the global analysis where the global model is mainly composed from duplicated unit cells.

(b) **geometrically unchanged, physically homogenized**
Verifcation analyses are conducted on a geometrically detailed unit cell model. Physical properties are homogenized like equivalent thermal properties of laminated composites. The global model will be modelized from duplicated unit cells [2].

(c) **geometrically and physically homogenized**
Verification analyses are conducted on a geometrically and physically detailed unit cell model. After homogenization of geometrical (e.g. modelling of pourous media as solids) and physical properties application to a simplified global model by duplicating the unit cells. Ideally the results from the homogenized model should be equal to the detailed analysis. [3]

From the list above it becomes already clear how the results from the unit cell investigation can be used for the analysis of a global structure. The choise of the applied procedures and the accuracy of the verification analysis are decisive for the quality of the global results. Especially the application of a homogenization requires a good knowing about the structural characteristics and in most cases it also requires a high number of parameter studies and validation tests. However it enables the thermal analysis of full scale structures with reasonable effort in modelling and computational resources.

The necessity of using homogenization techniques in thermal analysis is caused by a great variety of different problems. It can be performed to simplify certain heat transfer mechanisms but it can also be done to use specific simulation tools. Throughout the present work the thermal analysis is conducted by using the FEM. Therefore all problems concerning simulation matters will be related to this method. Some homogenization applications and the origin of their necessity will be described hereafter.

Considering the combination of mechanical and thermal analysis in the design process by means of the FEM, it would be very helpfull to use only one FE model for both. For thin-walled structures the mechanical analysis is usually performed using 2D shell elements. In thermal analysis however these elements do not allow to calculate the transverse temperature gradient. This can be a fatal neglection especially when applied to thermally bad conductors or sandwich structures. Therefore solid elements are normally used for such applications where every single layer has to be dicretized by at least one element. This necessarily leads to very large numerical models and hence requires very much computational time. By applying a homogenization to the thermal material properties it is possible to predict the temperature profile of such a structure with only one or two solid elements in thickness direction as will be shown in the industrial application example. This corresponds to point (b) of the list above. The explained problem can also be overcome by using new FE formulations where shell elements can predict the transverse heat conduction problem as will be shown in section 4.

Another field of application is the homogenization of geometrically complex structures which regularly or periodically recure. They need a high modelling and computational effort when applied to large structures. In order to reduce necessary resources the structure can be homogenized in a way that it can be resembled by simple formulations whithout loosing to much information. This corresponds to point (c) of the list above.

At last it shall be mentioned that for specific applications, like aircrafts which have tremendous amounts of rivited joints, the joints can be treated best when homogenized. This field can of course be enlarge to spot welded or glued joints or other kinds of thermal contact zones.

Having dealt with all these problems the validation of the simplified model can be conducted and the results can directly be applied to a structure of the next higher or even full scale level.

3 Industrial application example

3.1 Basic concept for thermal analysis of fuselage structures

This work aimed at the predicition of temperature fields in the skin-stringer-frame system of an aircraft fuselage section made from FML (GLARE). Herein the take-off with its high mechanical loads after a heating phase (parking, taxiing, and hold) is considered to be a critical mission part. For an exact prediction it will be focused on heat transfer between skin, stringer and frames which have a crucial influence on the global thermal behavior. These parameters have so far been treated very conservatively and may give opportunities for a further structural optimization. All investigations to gain knowledge about the thermal behavior will be performed on panel level and will subsequently be applied to a fuselage section under take-off environmental conditions.

3.2 Test prediction and homogenization

Based on the test panel geometry, thermal loads, and the way of the load application, test prediction analyses were performed by means of the FEM. The results are important input for the final design of the test facility e.g. position of thermocouples. In Fig. 4 there is shown an illustration of a typical aircraft panel which is to be investigated. It consists of a GLARE skin as well as aluminum frames and stringers. All interfaces are glued and the frames are connected to the skin using binders and rivited joints. The GLARE skin itself is composed of 5 layers of aluminum and 4 layers of glas-fibre reinforced polymer (GFRP) in an alternating lay-up. Each GFRP layer consists of a 0° and 90° sublayer, forming an orthotropic material.

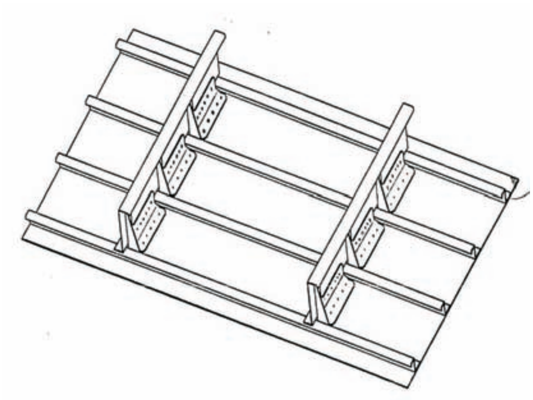

Fig. 4 Test panel

In order to keep the modelling effort as small as possible symmetry characteristics were considered. The smalest unit from geometrical point of view as shown in Fig. 4 is an eighth of the panel. Taking into account the relative size of test specimen and infrared radiator, as can be seen in Fig. 5, it could be proven by means of FE analyses that the panel is not homogeneously illuminated on its complete surface. This is due to the finite dimensions of the radiator leading to differing heat flux densities which decrease from the center to the outside edges of the test specimen. Therefore a quarter panel was used for all subsequent analyses.

Convergence studies wrt. the discretization level were conducted aiming on a further reduction of the model size. At this instance simplified boundary conditions were applied to the structure. They merely consist of radiation exchange between the panel exterior and radiator as well as the environment and forced convection due to the convectional cooling of the radiator bulbs. The radiator is modelled as an ideal black emitter with $\varepsilon = 1$, which emits $1000\,W/m^2$. This is an approximate heat flux q on zero altitude near the equator [4]. From this the radiator temperature can be calculated using the Stefan-Boltzman-Law as follows:

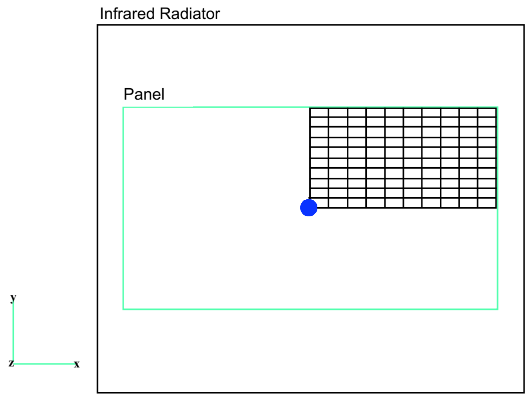

Fig. 5 Test panel unit structure

$$T_{radiator} = \sqrt[4]{q/\sigma\cdot\varepsilon} \tag{1}$$

For the consideration of the convection a frictionless fluid on a parallel blown plate is taken into account. With Equ. (2) it is possible to roughly estimate the forced convection coefficient [4].

$$\alpha = 2\cdot\lambda\sqrt{\frac{v}{\pi\cdot a\cdot L}} \tag{2}$$

Since the fluid stream impinges the specimen on the whole surface and flows off to all four edges the characteristic length L is chosen to be half the total specimen length. All remaining surfaces on the test specimen are considered to be adiabatic.

The discretization level in transversal and lateral direction of the skin, which is composed of layered material, was closely investigated on a strip model of a part of the panel. In lateral direction three exact 3D models with either 1, 2 or 4 solid elements per layer were compared to three homogenized models with either 4, 2 or 1 element over the whole laminate thickness in order to enable a reduction of elements in material thickness direction. Aim of the lateral discretization investigation is the reduction of elements in radiation exchange analysis which is in general a very time-consuming process. In this case the finest 3D model with 9 elements per layer was compared to two reduced models with 4 or 2 elements over the whole laminate thickness. In order to do so a homogenization of material properties was necessary. The conductivity in transversal direction is dealt as a series connection as shown in Equ. (3) and in lateral direction as parallel connection which can be seen in Equ. (4).

$$\lambda_{transvers} = \sum_{i=1}^{n} t_i \Bigg/ \sum_{i=1}^{n} t_i/\lambda_{i,tansvers} \quad (3)$$

$$\lambda_{lateral} = \sum_{i=1}^{n} \lambda_{i,lateral} \cdot t_i \Bigg/ \sum_{i=1}^{n} t_i \quad (4)$$

Additionally for transient studies the density and the heat capacity have to be homogenized. In case of the density the averaging is made in dependence on the layer thicknesses:

$$\rho = \sum_{i=1}^{n} \rho_i \cdot t_i \Bigg/ \sum_{i=1}^{n} t_i \quad (5)$$

and in case of capacity in dependence on areal masses:

$$c = \sum_{i=1}^{n} c_i \cdot \rho_i \cdot t_i \Bigg/ \sum_{i=1}^{n} \rho_i \cdot t_i \quad (6)$$

where i is a control variable and n is the number of layers in the material. As a result Fig. 6 shows the transversal temperature distributions in the skin for the finest 3D model with 4 elements per single layer and the homogeneous model with 2 elements over the laminate thickness. This homogeneous model still shows slight deviations to the exact panel. The accuracy is in the same order of magnitude as for the model with 4 elements over the laminate thickness. The maximum error can be estimated to be in the range of $3-4K$ in the most critical part near the stringer foot. By using only one element over the laminate thickness the accuracy is not satisfactory so that for all further analysis the skin is modelled with 2 elements over the thickness. The results in lateral direction do not show a high dependence on the discretization level such that it can be varied slightly around the once investigated in this study.

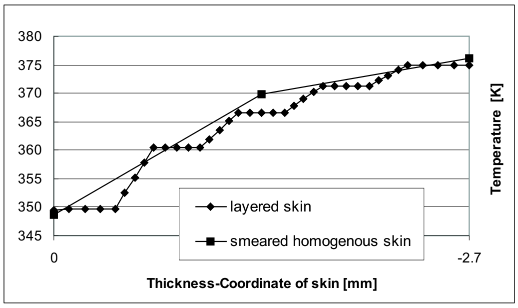

Fig. 6 Transversal temperature profile for different discretization levels

Based on all the above mentioned studies stationary and transient thermal analyses were performed on the quarter panel in order to understand the thermal behavior of the panel while testing. Hereby the calculations were conducted with all variations of the following parameter values:

$\varepsilon = 0.7,\ 0.85,\ 0.99,$

$T_{radiator} = 370K,\ 390K,\ 410K$ and

$\alpha = (0.0,\ 5.0,\ 10,\ 100)W/m^2K.$

3.3 Experimental testing

All validation tests were conducted on the thermo-mechanical test facility THERMEX of the Institute of Composite Structures and Adaptive Systems of the DLR in Braunschweig. In principle it allows for a simultaneous application of thermal and mechanical loads. It is therefore well suited for investigations of thermally induced stresses with or without additional mechanical load cases. Even thermal buckling phenomena are a field of application for this kind of test facility. Fig. 7 gives an impression of a THERMEX test set-up as used for the FML panel experiments. In this case the heater is mounted above the test specimen and a water basin for the application of boundary conditions is located below the panel. For better understanding a drawing of the principle test set-up is depicted in Fig. 8. On the left side the two different investigated boundary conditions on the back side of the panel are shown. One is completely insulated

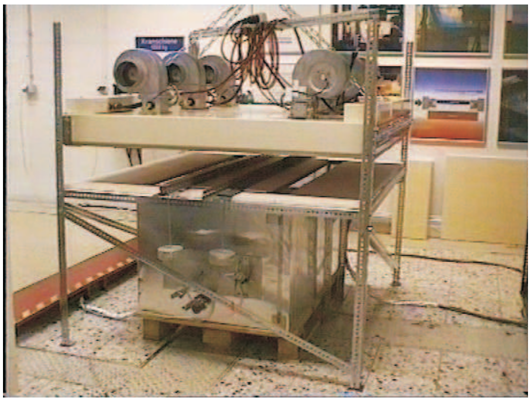

Fig. 7 THERMEX - thermo-mechanical test facility

leading to almost adiabatic conditions. In the second set-up the ends of the frames are in contact with permanently stirred water. In this way it represents a very good conductor and a high thermal capacity. The right side of Fig. 8 shows the four investigated different illumination schemes, which are realized by covering the to be protected areas with insulation plates.

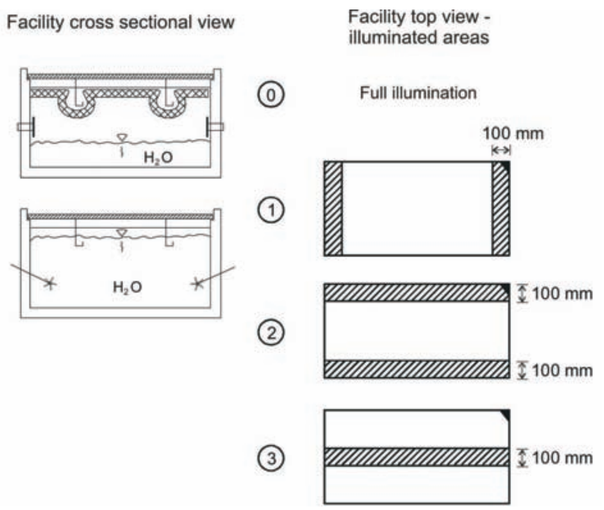

Fig. 8 Test set-up and illumination scheme

In order to investigate the heat transfer through the panel and heat transfer resistances at contact zones between FML and aluminum parts the full illuminated test specimen would be appropriate. For the investigation of inplane heat transfer of the panel, the partially heated surfaces are better suited. A test panel without insulation blankets is shown in Fig. 9. All test data are recorded with the DIADEM 10.0 data acquisition software. It includes 39 thermocouples on skin, stringer and frames as well as 1 heat flux sensor on the skin.

Fig. 9 Glare test panel with stringers and frames

3.4 Test correlation analysis

Based on the test prediction with its convergence studies and test results a validation is conducted in order to validate the panel FE model for a global analysis on fuselage level. For this reason the so far used model needs to be refined. The discretization itself will be unchanged but in the contact zones between skin-stringer, skin-binder and frame-binder additional solid elements were introduced to account for the adhesive layer between these structural parts. This layer resembles a thermal insulator and must therefore be taken into account. From experience it can be said that such contact zones are decisive for the global thermal behavior of such structures. Depending on the adhesive layer and the existence of rivets at the connections different heat transfer coefficients Λ were derived for a constant adhesive element thickness of $0.5mm$. They are in the range of $2.0W/mK \leq \Lambda \leq 12.3W/mK$.

The validation analysis was conducted using one specific test which gives best opportunities for a proper derivation of all crucial parameters. Boundary conditions to be considered were chosen as in the test:

1. radiation heat flux between radiator and test specimen is estimated from the electrical power of the radiator:

$$T_{radiator} = \sqrt[4]{\frac{\eta \cdot P_{el}}{\varepsilon \cdot \sigma \cdot A_{radiator}}} \qquad (7)$$

2. measured heat flux through insulation panels for illumination control

3. radiation heat flux between specimen back side and water surface by using an effective emissivity of the back surface:

$$1/\varepsilon_{eff} = 1/\varepsilon_{water} + 1/\varepsilon_{back} \qquad (8)$$

4. fixed temperature boundary conditions on the contact between stringer ends and water surface

In the validation analyses the following parameters have been varried: contact resistances, thermo-optical properties of the test panel, radiator heat flux and homogenized thermal conductivity of the skin. At the end a set of parameters was determined that in global gives very promissing results. The deviations to the measured results are $\approx 6K$ at maximum. For three measurement points the corralation curves are shown in Fig. 10. Attention was paid that all results in hot areas are conservative in the sence that they overpredict the measured data. The influence of the contact resistances was checked by varying their values by one order of magnitude. This showed moderate changes in the overall thermal behavior. However the neglection of the contact zones would lead to temperature deviations of more than $40K$.

3.5 Full scale analysis

After having developed a validated FE model on a representative FML panel, the aim of this task was to analyse the thermal characteristics of a complete fuselage section during parking, taxiing and take-off. Since the heat fluxes within the structure along the airplane longitudinal axis are

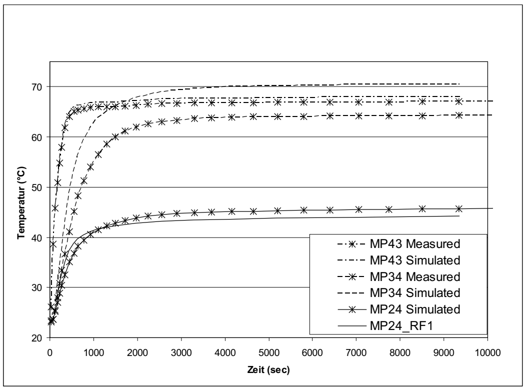

Fig. 10 Comparison of validation tests against test correlation results

considered to be negligible the problem can be reduced to a representative sector. This sector consists of one frame with the two half corresponding skin sections and the stringers over the full circumference. The boundary conditions on the sector edges are adiabatic.

To create this section, 128 panel models have to be connected. The size of a single panel, although reduced, is still high and would lead to a very big global model. Therefore a further model reduction is necessary. Since the top parts of the fuselage, which are under direct sun illumination, are in the focus of the study all other parts are again simplified. They incorporate skin and stringer conductivity in one effective conductivity such that the panels in the bottom section consist only of the frame and a homogenized skin definition. Furthermore all relevant boundary conditions for such a mission were taken into account. There are:

- direct solar heat flux
- convection heat exchange with air
- heat exchange with hot runway
- reflected solar heat flux from runway
- heat flux through insulation into the aircraft interior

In Fig. 11 there are shown the given profiles of velocity, temperature, altitude and convection coefficient during parking, taxiing and take-off for the first 480 seconds of a flight mission. Based on this input a transient thermal analysis was conducted and the temperature histories in the FML panels were determined. A typical temperature

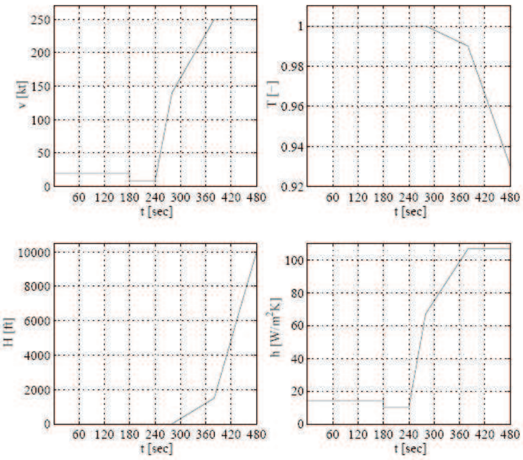

Fig. 11 Take-off profiles of velocity v, Temperature T, Altitude H and Convection h

distribution in skin, stringer and frame right before take-off can be seen in Fig. 12. In this context it should be noted that the temperatures are decreasing from the middle of the skin field over the binder to the top of the frames. After take

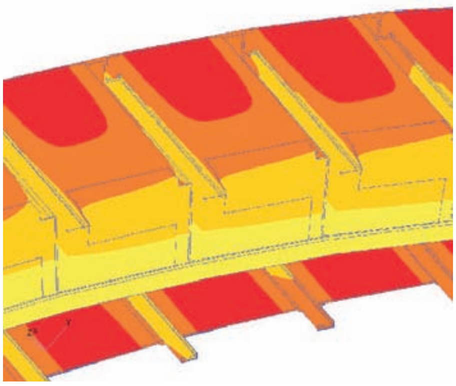

Fig. 12 Fuselage temperature profile accross one frame

off the skin fields are cooled down very rapidly by forced convection such that the temperature distributions will qualitatively be inverted. This becomes clear when looking at the temperature-time history in Fig. 13. The numbering of the nodes in the diagram is in a straight line from the skin field center over the binder to the frame as already considered this way above. It should also be noticed that the decrease of the temperature in the panel already starts 60 *sec* before take-off. Here the change of the airplane orientation between taxiing and take-off has also been considered.

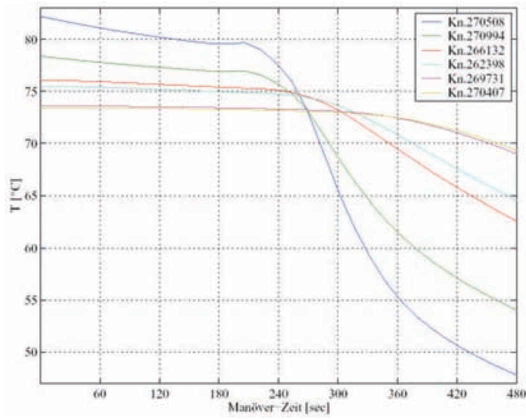

Fig. 13 Temperature distribution in take-off environment

These predictions are valuable input for the designers work. They are enabled by the validation of the simulation tools on small scaled structures. By means of this example a conceivable procedure for virtual testing can be demonstrated.

4 Approaches for effective thermal modeling and analysis

4.1 Efficient thermal analysis

At the present time mechanical FE simulations of thin walled structures are conducted by means of 2D elements, which are suitable for most applications. To gain a fully 3D temperature field however a 3D discretization is necessary so far. This poses one main problem in simulation:
The usage of only one FE model for both analysis tasks mechanical and thermal is not operable. Very often it demands the modification of the mechanical mesh and a geometrical and physical homogenization of the model parameters. Furthermore an increase of the model size and computational time is often a direct result of these model

changes. Up to now this is not automated to an extent that is adequate for current design tasks and needs further development.

With the thermal lamination theory (TLT) one approach has been presented by Rolfes [5] with further developments by Noack [6, 7]. Applied to the FEM it allows to analyse hybrid composite structures as FMLs with layerwize varying thermal conductivities.

By assuming a perfect thermal contact at the layer interfaces the TLT describes a linear or quadratic temperature distribution in each single layer depending on the approach. Nonlinear temperature distributions are likely to occur in transient problems with rapid heating or cooling, under concentrated thermal loads or for large temperature gradients in conjunction with temperature dependent material properties.

The application of equilibrium conditions at the layer interfaces for temperature and heat flux in transverse direction for linear TLT and additionally the change of heat flux for quadratic TLT makes the number of functional degrees of freedom independent of the number of layers. The temperature of layer k, $T^{(k)}$, can then be expressed by means of the temperature of a reference layer b, $T^{(b)}$, as shown in Equ. (9) for linear and Equ. (10) for quadratic TLT where $\tilde{z}_k$ and $\tilde{\tilde{z}}_k$ are functions of the thickness coordinate z.

$$T^{(k)} = T_0^{(b)} + \tilde{z}_k(z) T_{0,z}^{(b)} \qquad (9)$$

$$T^{(k)} = T_0^{(b)} + \tilde{z}_k(z) T_{0,z}^{(b)} + \tilde{\tilde{z}}_k(z, z^2) T_{0,zz}^{b} \qquad (10)$$

Based on these theories, FE elements are developed using linear shape functions in lateral direction.

To demonstrate the performance of these elements they have been applied to the FML convergence studies from section 3.2 with slightly simplified boundary conditions. The exact 3D model with 4 elements per layer and the homogenized model with 2 elements over the material thickness are used for the comparison with one quadratic QLT element. Fig. 14 gives an impression of the effectiveness of this element formulation. Although there are slight differences, the results are in very good agreement and the computational effort can be reduced by orders of magnitude. Using these elements would also improve the mesh compatibility between mechanical and thermal analysis.

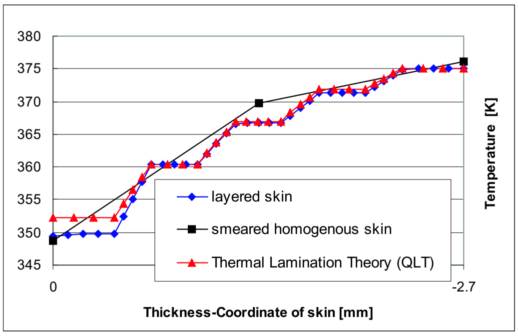

Fig. 14 Comparison of fully 3D and homogenized simulation with thermal lamination theory

4.2 Heat transfer in joints and interfaces

As already pointed out in the previous sections, thermal interface parameters (rivets, bolts, spot welds or adhesive) can be decisive for the quality of the analysis predictions. In many cases it is necessary to homogenize the thermal contact area since an exact modelling of these zones would be very complex and the model size would get out of limits very easily. In order to gain more knowledge, preliminary investigations were conducted on spot welded and/or glued connections as shown in Fig. 15. In order to limit the number of boundary conditions, namely convection, these tests were carried out in the thermal-vacuum investigation facility (see Fig. 16). It is suitable for thermal testing of structures under technical vacuum. In this specific case the test results were also used for the validation of the

Fig. 15 Thermal contact investigation examples

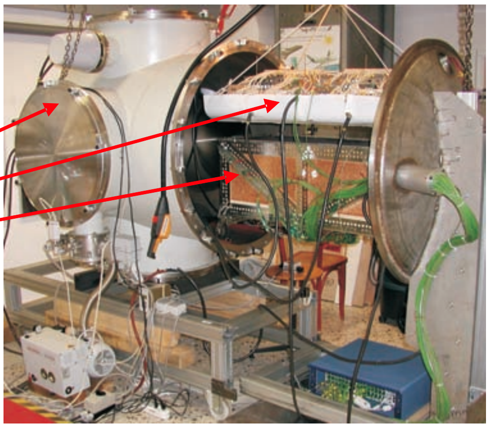

Fig. 16 Thermal radiation investigation chamber

numerical methods in order to simulate the transient temperature distribution in manufacturing processes of hybrid sheet metal structures.

5 Conclusions and outlook

The paper outlines a general procedure for the establishment of virtual testing in thermal analysis of composite and hybrid structures. It is made clear by an industrial application example; the analysis of a fuselage section made from FML, based on experimental testing on panel level. In the course of this presentation problems of numerical simulation like the necessity of homogenization, the modelling of interface zones or the transferability of mechanical and thermal FE meshes are discussed. An approach for the solving of the latter problem was explained. It is based on the development of new 2D finite elements which allow the calculation of a 3D temperature distribution. Furthermore the work gives an outline on the used test facilities which enable the investigation of a wide range of thermal transfer phenomena.

In the presently used FE software for thermal analysis the consideration of free and forced convection is very rudimentary. Here it should be focused on multi-disziplinary solving of design tasks by incorporating fluid-dynamics solvers. For a better application of the above described extented 2D finite elements, interface elements shall be developed in order to easily connect thin-walled structures to geometrically complex structures.

It seems that although more and more composite and hybrid materials are used in aircraft structures, the dependence of the mechanical behavior on thermal loadcases is still underestimated. A higher sensitivity to the thermal analysis problems is recommended in the early design phase.

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