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# NUMERICAL MODELLING OF NOMEX HONEYCOMB CORES FOR DETAILED ANALYSES OF SANDWICH PANEL JOINTS

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**Abstract.** Detailed numerical analyses of honeycomb sandwich cores, where the core cell wall geometry is modelled accurately (meso-scale), have found increasing applications in the recent past. However, such simulations require additional material properties as well as model validation. Based on a literature review, the present contribution identifies three prevailing approaches for numerically modelling Nomex honeycomb core materials on meso-scale level. In an experimental study, the stress-strain curves of a common Nomex honeycomb core are determined from standard compressive and shear tests. In a preliminary numerical study, two of the identified approaches are then implemented in a virtual testing environment using an explicit FE-solver. The model performance of both approaches is evaluated by matching the simulated stress-strain curves with the experimental data. The fitted material properties of the investigated material are provided for future use.

## 1 INTRODUCTION

Over the last decades, composite honeycomb sandwich structures have established themselves as standard material in many lightweight design applications such as aerospace and mass transportation in general. This is largely due to their excellent weight specific stiffness and strength as well as the large variety of available base materials for core and face sheets allowing tailor made properties for a wide range of requirements, including not only mechanical but also acoustic and thermodynamic aspects. However, one of the major short comings of sandwich structures in general is their inability to bear localized loads [1]. This weakness is due to the inherent functional principle of two stiff face skins separated and supported by a relatively weak core structure. As a result, sandwich structures need to be locally reinforced in order to withstand local load introductions for instance at joints of sandwich panels. Such reinforcements naturally lead to stress concentrations and therefore require particular attention when designing and dimensioning sandwich structures. Furthermore, the combination of thin-walled composite face sheets and core cell walls as well as local reinforcements such as resin and metal components leads to a generally complex failure behaviour of the multi-material sandwich panel joints and inserts [2].

In order to determine the strength and failure behaviour of a particular sandwich panel joint, manufacturers of honeycomb sandwich structures currently still depend on extensive testing. During the last few years, first attempts have been made to virtually test panel joints using advanced non-linear Finite Element Methods with the objective of creating a better understanding of the prevailing failure mechanisms [2, 3]. This objective could be achieved, however, it is not reported that these first studies have concluded numerical models that are actually applied to reduce the current high testing effort for characterizing sandwich panel joints. It is therefore assumed that further research on the validation of numerical models of sandwich panel joints is needed, in order to successfully perform virtual tests on them.

One of the crucial issues when developing a detailed numerical model of sandwich panels in general is the correct representation of the weak core structure. This particularly applies for the inhomogeneous honeycomb cores, since their thin walled cells easily buckle when locally loaded, thus initiating the failure of a panel. Such initial failure quickly leads to complete failure of the entire structure due to propagating debonding of core and face skin. In order to correctly represent the cell wall deformation during buckling in a numerical model, it has become increasingly common to model the cell walls accurately using two-dimensional or even three-dimensional elements. This level of model detail is often referred to as meso-scale and is regarded necessary for the proposed application, since local cell wall buckling is a common first failure in many sandwich panel joint configurations. Meso-scale honeycomb models naturally require basic mechanical properties of the applied cell wall material. However, manufacturers of honeycomb cores generally only provide the homogenized properties of the core, as this is sufficient for most design purposes. Therefore, performing meso-scale numerical studies often requires additional component tests for the mechanical characterization of the cell wall material. This especially applies for Nomex honeycomb cores, which are widely used in aerospace applications. The literature only provides a few references on the Nomex cell wall material properties as well as on the material model definition for the use in numerical meso-scale models. In addition, these references partly differ significantly with regards to both mechanical properties and applied material model.

The present contribution reviews and compares the different material property data and material models found in the literature in order to eventually recommend a suitable approach for the detailed numerical analysis of sandwich panel joints. As benchmark serve proprietary test results from standard flatwise compression and transverse shear tests of honeycomb Nomex sandwich specimens. These tests are remodelled in a virtual testing environment using the commercial explicit FE-solver RADIOSS. A selection of the reviewed approaches is implemented in this virtual test environment and the model performance is evaluated by matching the stress-strain curves of simulation and test results.

## 2 NOMEX HONEYCOMB MATERIALS

Nomex is a trademarked non-metallic paper material, which is well known for its excellent fire-resistant properties. It consists of two forms of aramid polymer, the fibrids (small fibrous binder particles) and the floc (short fibres). These two components are mixed in a water-based slurry and machined to a continuous sheet. Subsequent high-temperature calendering leads to a dense and mechanically strong paper material. During this manufacturing process, the longer floc fibres align themselves in direction of the paper coming off the machine. This leads to orthotropic mechanical properties of the paper, with the machine direction being stiffer and stronger than the cross direction ($E1 > E2$ in Figure 1) [4].

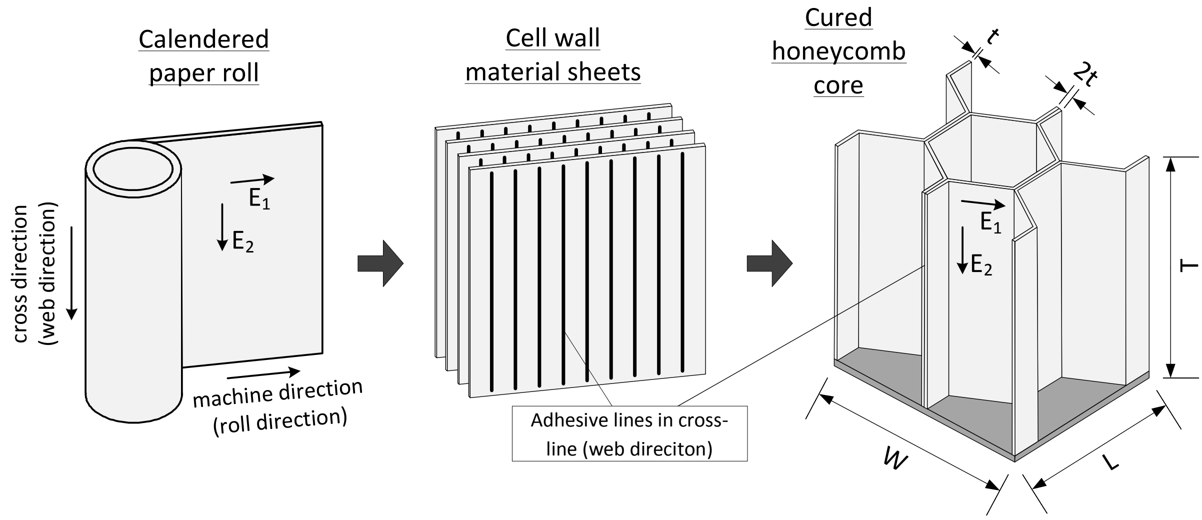



**Figure 1:** Manufacturing of Nomex honeycombs and display of the terminology on a final honeycomb section

There are many different types of Nomex papers, each tailor made for its specific application range. In honeycomb fabrication, Type 412 is generally used. Further processing of this paper material to form hexagonal cells is commonly carried out using the adhesive bonding method, meaning that the bonded portion of two adjacent paper sheets is held together by adhesive [5]. This method inevitably leads to double the wall thickness of the bonded cell walls if compared to the unbonded “free” cell walls. After the paper sheets are bonded and shaped to hexagonal cells, the resulting Nomex honeycomb block is dipped in liquid phenolic resin and subsequently oven cured. This dipping-curing process is repeated until the desired density of the core is achieved. The resulting phenolic resin coating of the Nomex paper leads to a layered material with an orthotropic ductile center layer (Nomex aramid paper) and two isotropic very brittle outer layers (phenolic resin). This layered composite retains the orthotropic behavior from the Nomex paper, which is why it is important to determine the alignment of the Nomex in the final honeycomb core. This alignment essentially depends on the direction of the adhesive lines on the paper sheets during the honeycomb fabrication. It is generally more practical to apply the adhesive lines in cross direction of the paper (see Figure 1). This ensures that the dimension of the final honeycomb block in L-direction is not limited by the width of the initial paper roll. Therefore, the less stiff material axis (E2) can be generally assumed to be in T-direction. This is also assumed in previous publications [21], [19].

There are several manufacturers that fabricate the Type 412 Nomex paper into honeycomb cores. Table 1 summarizes the homogenized mechanical properties of the core material that is investigated in the present study based on the data sheets of different manufacturers (the manufacturer of the tested specimens is highlighted). Table 1 reveals small differences in the mechanical performance of Nomex honeycomb cores with the same geometry and density coming from different manufacturers. These variations might be attributed to slightly differing fabrication processes as well as materials (i.e. phenolic resin). Yet, considering the general uncertainties in the process of determining material properties, the observed differences are considered negligible leading to a comparable mechanical performance of Nomex honeycombs across different manufacturers. Hence, it could be assumed that previous studies on meso-scale modelling of Nomex honeycomb applied comparable material properties and models. However, in the following literature survey it is shown that this assumption is not quite met.

**Table 1:** Mechanical properties of the investigated Nomex honeycomb (cell size 3.2mm, density 48kg/m³) based on the data sheets of different manufacturers

| | **Compressive** | | | **Shear** | | | |
|---|---|---|---|---|---|---|---|
| | Bare | Stabilized | | L-Direction | | W-Direction | |
| | Strength [MPa] | Strength [MPa] | Modulus [MPa] | Strength [MPa] | Modulus [MPa] | Strength [MPa] | Modulus [MPa] |
| HRH-10-1/8-3.0 [7] | 2.07 | 2.24 | 138 | 1.21 | 41 | 0.69 | 24 |
| ECA-3.2-48 [8] | 2.10 | - | - | 1.32 | 48 | 0.72 | 30 |
| C1-3.2-48 [6] | 1.80 | 2.10 | - | 1.35 | 42 | 0.80 | 25 |
| ANA-3.2-48 [9] | - | 2.40 | 138 | 1.25 | 40 | 0.73 | 25 |

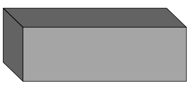
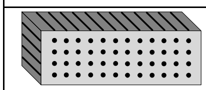
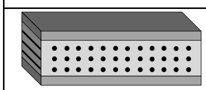
## 3 LITERATURE SURVEY ON NOMEX MESO-SCALE MODELLING

Despite its wide distribution as well as the increasing interest in meso-scale modelling, there are only a few studies that provide references for the mechanical properties of Nomex paper as base material for honeycomb cores. Tsujii et al. [10] determined the compressive and shear properties of different aramid paper samples with varying thickness of the phenolic coating as well as the homogenized honeycomb core properties for the investigated paper materials (cell size 3.2mm). The elastic moduli of Type 412 aramid paper dipped twice in phenolic resin are here determined as follows: $E_1$=5276 MPa, $E_2$=4048 MPa. However, the corresponding homogenized honeycomb properties with this paper exceed the values given in Table 1, leading to the assumption that these moduli are too high. The moduli of an additionally studied alternative aramid paper, which was tested with homogenized core properties in the range of Table 1, are determined as $E_1$=3667 MPa, $E_2$=2317 MPa. Similarly to Tsujii et al., Hähnel and Wolf [11] performed an extensive test program on Nomex papers with varying paper thickness and phenolic resin fraction. They particularly point out that the stress-strain relation of impregnated Nomex strongly depends on the phenolic resin fraction, with a twice impregnated Nomex already showing an almost pure brittle failure. Foo et al. [12] determined the linear elastic properties of Nomex paper in material tests ($E_1$=3400 MPa, $E_2$=2460 MPa) and performed numerical and experimental studies on the in-plane as well as out-of-plane behavior of Nomex honeycombs using the determined paper properties. They report good correlation between numerical and experimental results. Fischer et al. [13] determined the mechanical material properties of a phenolic impregnated aramid paper similar to Nomex for an application in foldcore sandwich structures. Although their material properties cannot be transferred to the here investigated Nomex paper, they give a good overview over the qualitative mechanical behaviour of phenolic impregnated aramid paper. For instance, they point out that this material has a non-uniform stress strain behaviour not only in transverse and longitudinal but also in tensile and compressive direction. They furthermore confirm the assumption that the layered composition of the material strongly influences its bending behaviour, leading to a lower bending modulus if compared to the tensile modulus.

In addition to the above reviewed studies with emphasis on the determination of the mechanical properties of Nomex paper, there are some works on the numerical meso-scale modelling of Nomex honeycomb cores. Many of these studies focus on the prediction of the low velocity impact and out-of-plane behaviour of honeycombs, while some also apply meso-scale models for broader virtual testing of honeycombs. The vast majority of the reviewed studies apply two-dimensional elements to represent the cell wall material. Giglio et al. [14] have done a comparative study on the out-of plane crushing of Nomex honeycomb cores using two-dimensional and three-dimensional elements. They conclude that both, 2D and 3D elements are able to predict the first failure of the structure reasonably well, while 3D elements perform better especially in the following plateau of the stress-strain curve. However, they also point out the very high computational effort needed when using 3D elements. Regardless the applied element type, three prevailing approaches to modelling the Nomex cell wall paper material can be found in the literature.

The first and most simplistic approach uses an isotropic linearly elasto-plastic material model in a single layer, thus neglecting not only the orthotropy of the Nomex paper but also its layered structure. This approach has proven to be sufficient for predicting the out-plane crushing of aramid cellular sandwich structures [14]-[18]. Secondly, the Nomex paper is modelled using a single layer orthotropic linearly elasto-plastic material model, which is more difficult to implement but at the same time gives more freedom in modelling the directional mechanical behaviour [19]-[21]. However, due to its single layered nature, this approach has its limitation with regards to the correct representation of bending behavior as well as initial failure of the phenolic coating. Lastly, there is the approach of considering the multi-layer structure of the material by implementing a three-layered property set with an isotropic material model that allows brittle failure for the phenolic resin coating and either an orthotropic material model as described in the second approach or a another isotropic material model for the inner aramid paper [13], [22], [23].

**Table 2** Summary of the modelling of honeycomb Nomex paper as found in the literature

| | Reference | Core type | $E_1$ [MPa] | $E_2$ [MPa] | $G_{12}$ [MPa] | $\vartheta$ | $\sigma_{yield}$ [MPa] |
|---|---|---|---|---|---|---|---|
|  Single layer isotropic | Giglio et al. [14] | 4.8mm – 32kg/m³ | 1878 | - | - | - | 40 |
| | Aktay et al. [15] | 4.8mm – 48kg/m³ | - | - | - | - | - |
| | Heimbs et al. [16] | fold core | - | - | - | - | - |
| | Asprone et al. [17] | 3.2mm – 48kg/m³ | 3500 | - | - | - | 60 |
| | Foo et al. [18] | 13mm – 64kg/m³ | 2000 | - | - | 0.4 | 30 |
|  Single layer orthotropic | Roy et al. [19] | 3.2mm – 48kg/m³ | 4570 | 3520 | 1680 | 0.2 | - |
| | Heimbs et al.[20] | 3.2mm – 48kg/m³ | 5276 | 4048 | - | - | 66/40 |
| | Aminanda et al. [21] | honeycomb | 3065 | 2341 | 800 | 0.4 | - |
| | Foo et al. [12] | honeycomb | 3400 | 2460 | - | - | - |
|  Multi layer | Barranger [23] | fold core | - | - | - | - | - |
| | Fischer [13] | fold core | - | - | - | - | - |
| | Kilchert [22] | fold core | - | - | - | - | - |

It therefore, is the most complicated approach and promises the best performance. However, in the reviewed literature, this multi-layered approach has only been applied for fold core aramid paper sandwich structures. In this context, it is worth mentioning that Giglio et al. [14] attempted to place additional shell elements on their isotropic single layer honeycomb cell walls to model the phenolic coating and its initial failure. However, they report little impact on the results using this method. Table 2 summarizes the reviewed literature, indicating the applied modelling approach as well as the mechanical properties if provided. Those references that study the same material as in this work are highlighted. It becomes apparent that a comparison between the references is difficult, since different honeycomb geometries are investigated and the eventually applied material properties are only partially given. In fact, most reviewed publications do not mention the applied cell wall thickness, making it impossible to reconstruct the results. However, the given material properties serve as rough references for the present study.

## 4 EXPERIMENTAL STUDIES

### 4.1 Flatwise compression tests

Flatwise compression is a standard test for determining the out of plane behavior of sandwich structures. In the reviewed studies, it serves as primary source of experimental data for the validation of low velocity impact models of honeycombs. The flatwise compression tests in the present study are performed on the basis of the ASTM standard C363, using a universal Shimadzu material testing machine (Figure 2a). The tested specimen have been cut to dimensions of 60x60x19mm directly from a cured sandwich panel comprising 3.2mm honeycomb cells with a density of 48kg/m³ and glass fiber fabric reinforced phenolic resin face skins (cured ply thickness of 0.28mm). The tested honeycomb specimens can thus be considered stabilized. The tests have been performed with a constant cross head velocity of 0.75 mm/min, while the internal load cell and displacement measurement of the material testing machine have been used to derive the compressive stress-strain curve of the honeycomb. The observed scatter of the tested specimens has been small (< 2%), while the manufacturer specifications as indicated in Table 1 have been achieved.

### 4.2 Transverse shear tests

In addition to the compression experiments, the transverse shear behavior of the investigated honeycomb material has been characterized through shear tests in accordance with the ASTM standard C273. The tests have been performed in both material directions (L and W) using a universal testing machine where the relative displacement of the loading plates has been measured using an external laser sensor (Figure 2b). The specimens have dimensions of 150x50x19mm and originate from the same sandwich panel as the compression specimens. The bonding between specimen and loading plates has been carried out using high strength 2-component epoxy resin. The tests have been conducted with a constant cross head velocity of 2 mm/s and the stress-strain curve has been derived from the external displacement data as well as the internal load cell data. Similarly to the compressive tests, the observed scatter of the test data has been small at about 3%, however the manufacturer specifications (Table 1) have been underachieved by about 10%.

a) b)

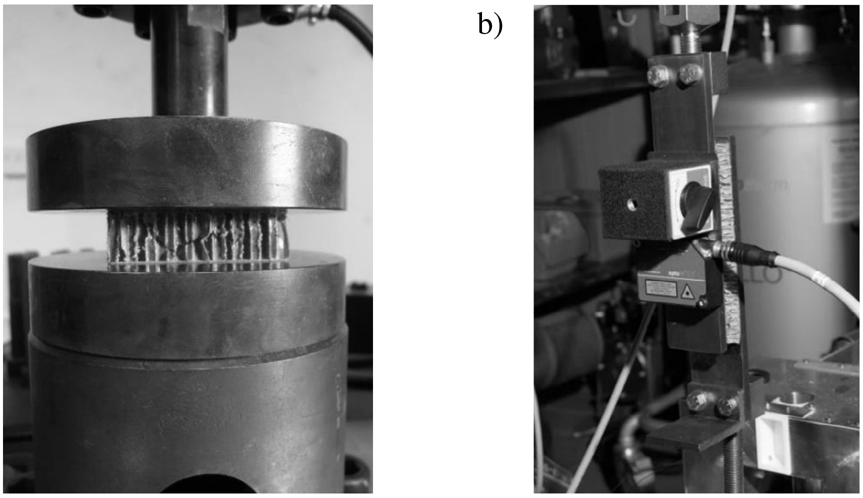


**Figure 2** a) Compressive test setup, b) Transverse shear test setup

## 5 NUMERICAL STUDIES

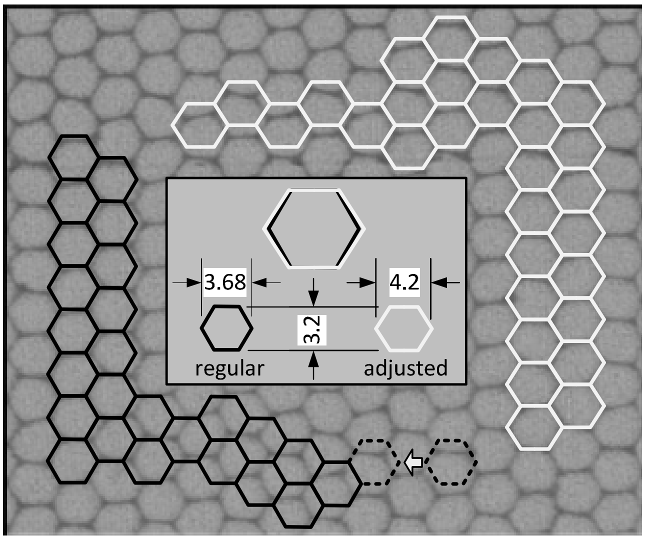
The numerical studies of the present work focus on investigating the two more common single layer approaches to modelling Nomex honeycomb (see section 3). Before the performed numerical studies are presented, the investigated Nomex material is analyzed and it is discussed how imperfections have been accounted for. The numerical computations are performed using the explicit commercial FE-solver RADIOSS.

### 5.1 Optical analysis of the specimens and consideration of imperfections

It is well known that honeycomb cores are characterized by global geometric imperfections, such as irregular geometry as well as uneven surfaces. Figure 3a displays a section of the investigated honeycomb core material illuminated via transmitted light. The photo is overlaid with two patterns of correctly scaled honeycomb cells of regular shape as well as adjusted shape. It can be seen, that regular shaped hexagons with a cell size of 3.2mm lead to a poor representation of the actual honeycomb pattern. In case of the here investigated honeycomb, an adjustment of the L-dimension of the unit cell leads to a great improvement in overall representation of the actual global geometry. Figure 3b illustrates local geometric imperfections such as varying cell wall thickness and resin accumulations using a microscopic image of a polished honeycomb section. The average wall thicknesses of the studied specimens have been determined to 0.055mm and 0.11mm for single and double cell walls respectively. This value is somewhat lower than in previous publications that investigate the same material [17], [20]. Furthermore, there are several micro mechanical material imperfections such as cracks and pores, which can be made visible through CT-scan images.

The literature provides comprehensive general studies on the representation of structural sandwich core imperfections in numerical models. Many methods are based on altering the ideal hexagon cell geometry for instance through random node shaking, pre-buckling of the cell walls or importing the real cellular geometry from 3D-scans, the latter being the most comprehensive method. In addition, random assignment of different properties to individual elements as well as uniformly reducing the cell wall material properties can be found in previous studies. In reality both, geometric imperfections and variations in the material properties occur, which would require a simultaneous application of the presented approaches. However, Heimbs [20] concludes that reducing the material properties is an effective method for compensating the different sources of imperfections. Due to its simple implementation, this method is also used in the present preliminary numerical study along with an adjusted unit cell geometry as indicated in Figure 3a.

a)




b)

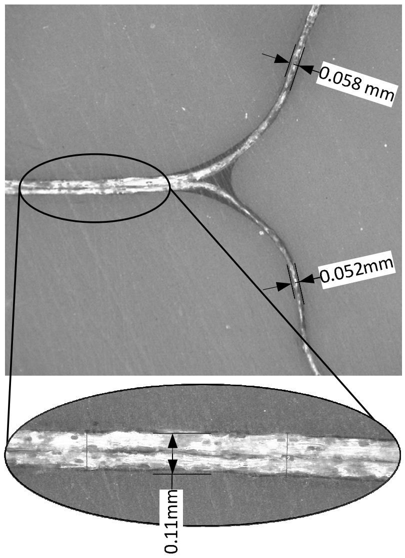



**Figure 3** a) Photo of investigated honeycomb illuminated via transmitted light and overlaid with regular and adjusted hexagon patterns b) Microscopic image of a polished honeycomb section

### 5.2 Preliminary numerical studies

The investigated honeycomb specimens can be regarded as periodic structures. As a result, they do not necessarily have to be numerically modeled in full scale. If appropriate boundary conditions are applied, the model scale can be reduced significantly without compromising the accuracy of the simulation, thus saving computational effort. In previous works on virtual tests of honeycomb structures, both symmetry- and periodic boundary conditions (PBC) are evident. Wilbert et al. [24] investigated this issue for aluminum honeycomb under lateral compressive crushing. They find that despite the application of PBC, the number of considered unit cells and thus the model scale still considerbaly influences the stress-strain behavior. They furthermore show that a model domain without PBC (free edges) leads to similar results as the domain with PBC already for moderate total model sizes.

In the present work the issue of finding an appropriate model size for the investigated material is addressed by a scale analysis for the flatwise compression load case. In addition, a mesh convergence study is performed based on the findings of the scale analysis. For the scale analysis, a parametric FE-model was developed using the script language of the pre-processor HyperMesh. The parametric model enables a quick generation of honeycomb core sections with variable hexagon geometry, number of cells, mesh size and core height. Figure 4 shows the results of the performed scale analysis using the example of four investigated scales. All simulations were performed with a mesh size of 0.4mm and had the same set of boundary conditions, where the bottom nodes are rigidly clamped in all six degrees of freedom, while the top plane nodes are guided allowing only a displacement in vertical direction. Constant displacement velocity is applied to the top end nodes. The multiple cell models have free edges (i.e. "cell-008"). The model "cell-01s" is a unit cell where symmetry boundary conditions are applied to the outer edges of the free standing cell walls. This set of boundary conditions represents an approach to defining PBC and has been applied previously by Asprone et. al [17]. All models in the present study use under integrated 4-nodes elements. For the plots in Figure 4 an orthotropic elasto-plastic material model in a single layer propertiy has been defined. In plot a), only multiple cell models are compared. It can be seen that at about 300 cells a wide and smooth peak develops, which can be regarded as convergence. However, the buckling stress does converge already at about 40 cells. Plot b) compares the results of the 314cell model with the PBC unit cell and the averaged test data. It becomes apparent, that the actual peak is much narrower followed by a sharper drop, if compared to the simulation. This can be attributed to the applied material model that does not consider the brittle failure of the phenolic resin coating at the onset of buckling. During the tests, this brittle failure has been evident through clearly visible dust particles around the specimens during failure. However, it can also be seen that the PBC unit cell does represent a good first approximation of compressive modulus, plateau stress and peak stress while it generally over estimates the latter. Due to its good performance, the PBC unit cell has been applied for a mesh convergence analysis, which is illustrated in Figure 5. Convergence is achieved at a cell size of 0.2 mm, while an element size of 0.4 mm represents a good trade-off between convergence and computational effort, which confirms the findings of previous studies [14], [20]. Therefore, an element size of 0.4 mm is used in the following studies.

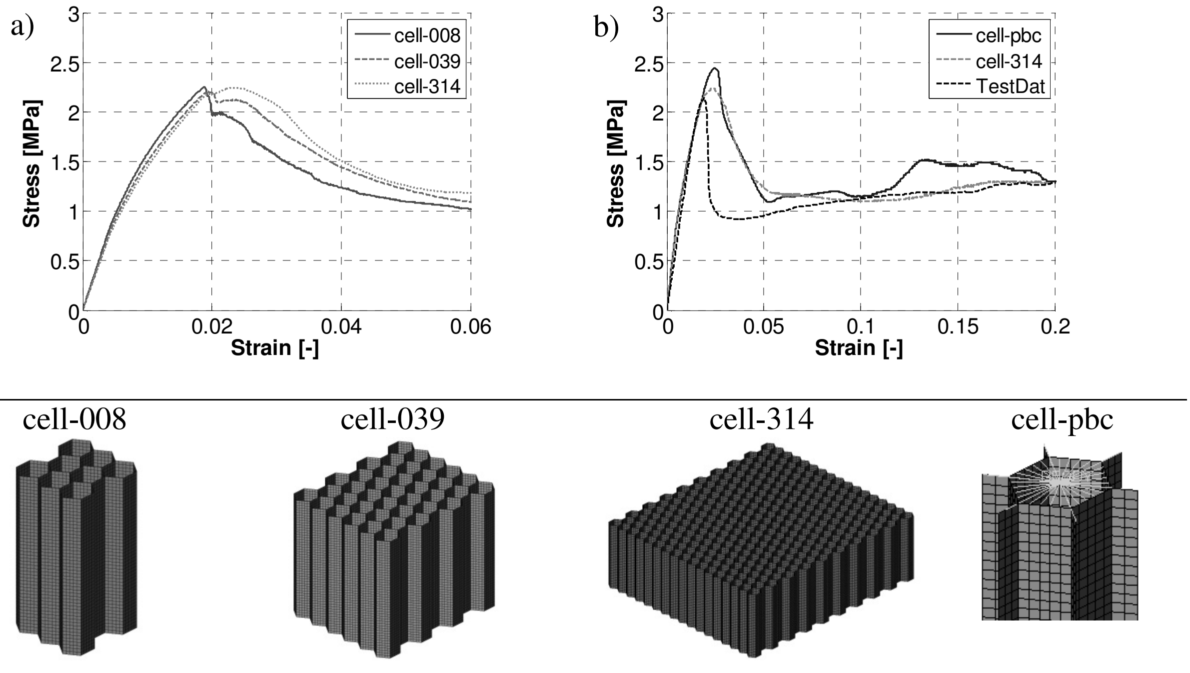



**Figure 4** Comparison of stress-strain plots for different model scales, a) multiple cell models with free edges, b) PBC cell, 314 cell model and test data

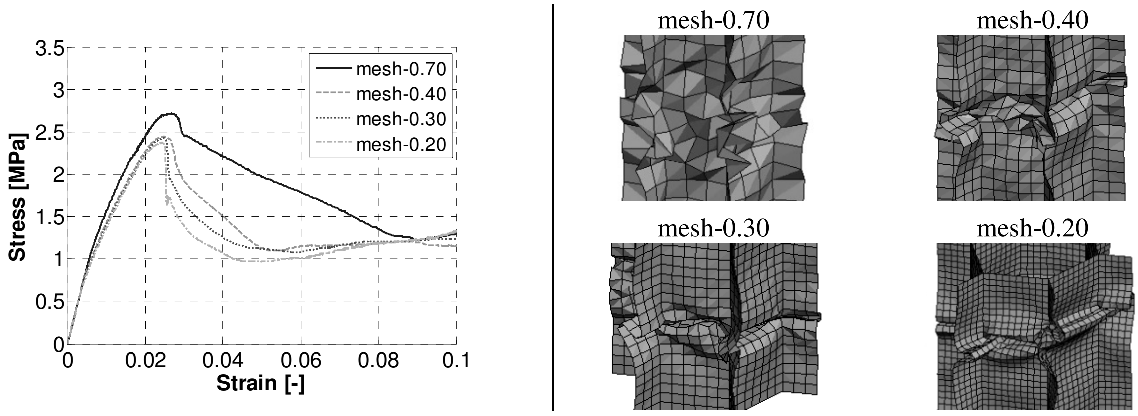



**Figure 5** Mesh convergence analysis for the unit cell with periodic boundary conditions

### 5.3 Comparison of virtual tests with experimental data

In the preliminary study of the present work only the isotropic and orthotropic elasto-plastic material models are fitted to the experimental data. As region of interest a strain between 0-0.15 has been defined. This is regarded as sufficient for the intended application in virtual test methods of sandwich panel joints, where the first failure is of primary interest. The results of this first fitting are summarized in Figure 6. The eventually applied scale is indicated for each load case in the right column, where the deformation of simulation and experiments are comparatively illustrated. It can be seen that both material models allow an equally good representation of the compressive loading, with regards to compressive modulus, peak stress and pleateau stress. Fitting the transverse shear tests has turned out to be more complicated. In general both implemented approaches are capable of predicting the shear modulus as well as the peak stress. However, it has not been possible to fit the progressive failure behavior accurately. This is attributed to the limitations of the fracture consideration of the applied material models. In reality, the Nomex paper does tear already at low strains, which is currently not implemented. The orthotropic material has slight advantages since it allows to adjust the directional mechancial behavior more freely.

## 6 CONCLUSIONS AND OUTLOOK

Based on a literature review, the present study has compared the two most common approaches to modeling Nomex honeycomb material on meso scale for the three main sandwich panel load cases, compression in T-direction, shear in LT and shear in LW. Generally both, the single layer isotropic and orthotropic material model are capable of representing the experimental data reasonably well. The orthotropic material model enables more freedom in defining the directional mechanical properies and is therefore to be favored. However, for a first approximation the isotropic material is considerably easier to fit as it only has three decisive material parameters. The fitted material parameters for the determined cell wall thicknesses (0.055 and 0.11mm) are as follows.

**Isotropic material model:** E =4000 MPa, possion r. = 0.25, yield strength = 100 MPa. **Orthotropic material model:** $E_1$=3950 MPa, $E_2$=5050 MPa, $G_{12}$=1600 MPa, possion r. = 0.20, compressive yield strength = 105 MPa, shear yield strength = 45 MPa. These values lie generally in the range of the reviewed literature.

In a following more comprehensive study the remaining modelling approach using a multilayered property set that enables brittle frailure of the outer thin layers is to be studied. It is expected that this approach will lead to a more accurate representation of the experimental data. In addition it is to be investigated whether implicit time integration will lead to considerable savings in computational time.

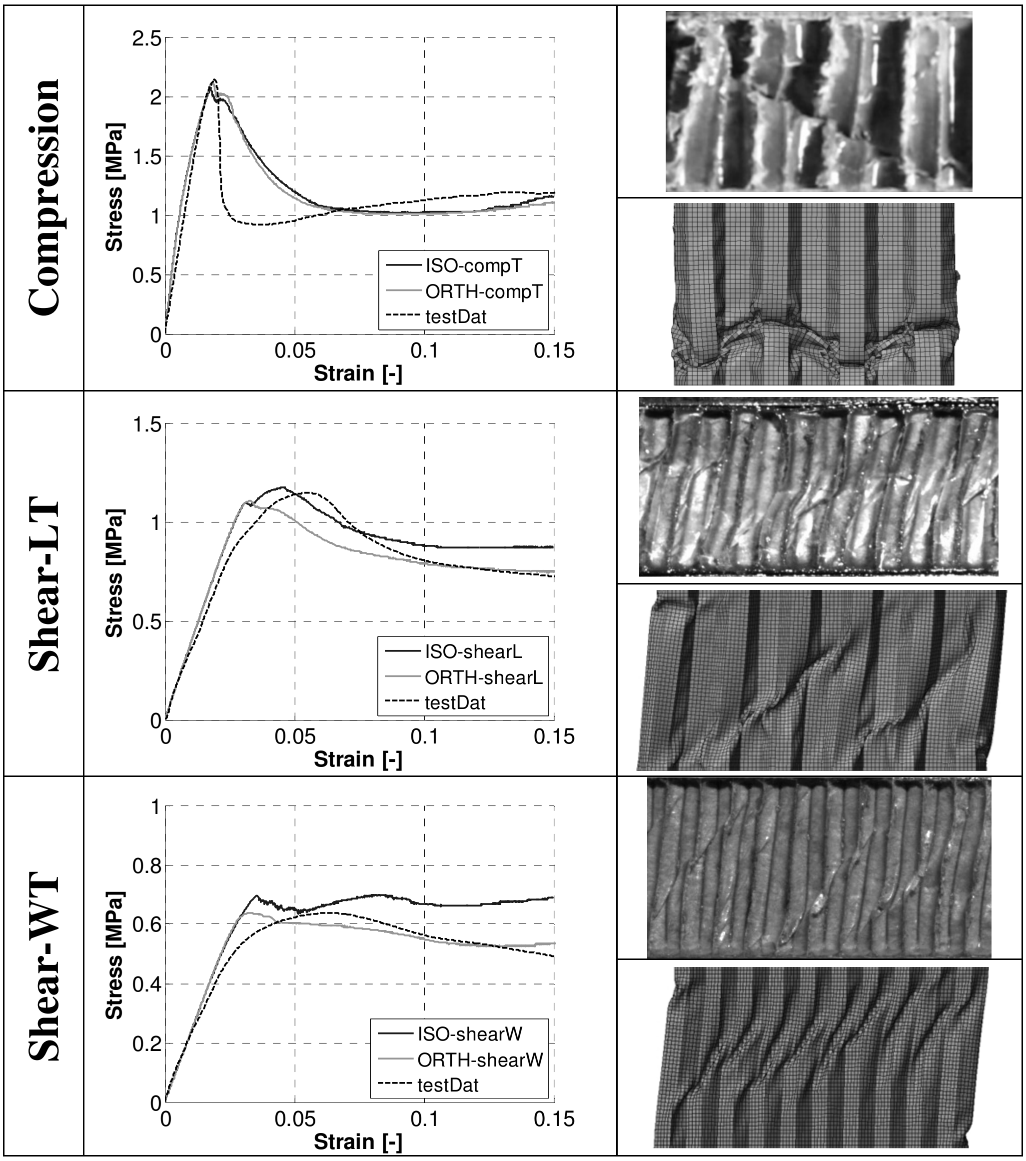



**Figure 6** Comparison of isotropic and orthotropic elasto-plastic material models under compression and shear loading after a preliminary fitting to the experimental data (element size 0.4 mm)

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