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COMPOSITE PLATES WITH NOMEX HONEYCOMB CORE MODELLING FOR DYNAMIC INTEGRITY AT THE MESOSCALE LEVEL

MODELIRANJE KOMPOZITNIH PLOČA SA NOMEX SAĆASTOM ISPUNOM ZA DINAMIČKI INTEGRITET NA MEZO NIVOU

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Abstract

In the present work the methodology for a composite plate with Nomex core material modelling is presented at the mesoscale level. The structure investigated consists of face sheet carbon composite plates (2D), mainly for normal stress load, a Nomex honeycomb core (T412 paper with chopped aramid fibres in phenolic matrix, manufactured using expansion process), and carbon composite leading and trailing edges (3D orthotropic composite). It is assumed that the Nomex core mainly carries shear stresses. This material model is further used to perform dynamic (modal) analysis on a composite structure with complex geometry. Comparing the results obtained (for simply supported beam and tested as per ASTM standards) and reported in literature, a good agreement between the proposed material model and experimental results is noted. However, material modelling and geometry modelling using the FEA approach is very tedious and requires relatively demanding computing resources.

Ključne reči
- kompozitna ploča
- Nomex ispuna
- dinamička analiza
- mezo nivo
- dinamički integritet

Izvod

U ovom radu je prikazana metodologija za modeliranje kompozitne ploče sa Nomex materijalom jezgra na mezo nivou. Ispitana struktura se sastoji od karbonskih kompozitnih ploča (2D), uglavnom za normalno opterećenje, Nomex saćastog jezgra (T412 papir sa iseckanim aramidnim vlaknima u fenolnoj matrici, proizveden ekspanzionim postupkom), i prednje i zadnje ivice od karbonskog kompozita (3D ortotropni kompozit). Pretpostavlja se da Nomex jezgro uglavnom nosi napone na smicanje. Ovaj model materijala se dalje koristi za obavljanje dinamičke (modalne) analize na kompozitnoj strukturi složene geometrije. Upoređivanjem dobijenih rezultata (za jednostavnu oslonjenu gredu i testiranu prema ASTM standardima) i objavljenih u literaturi, dobija se dobra saglasnost predloženog modela materijala i eksperimentalnih rezultata. Međutim, modeliranje materijala i geometrija korišćenjem FEA pristupa je veoma zamorno i zahteva relativno zahtevne računarske resurse.

INTRODUCTION

Composite plates with Nomex core are widely used in aerospace and other high-performance applications due to their excellent strength-to-weight ratio, stiffness, and fatigue resistance. Dynamic modelling of composite plates with Nomex core is crucial in predicting and optimising their behaviour under various loading conditions, including vibration and impact.

Dynamic modelling of composite plates with Nomex core can be accomplished through finite element analysis (FEA). FEA is a numerical method used to solve complex engineering problems. It involves dividing a complex structure into small, manageable parts or elements, and applying mathematical equations to each element to determine its behaviour in response to external forces.

In the case of composite plates with Nomex core, FEA can be used to predict structural behaviour under different loading conditions. This includes static and dynamic loading conditions, as well as vibration and impact. By analysing the results of FEA simulations, engineers can determine the natural frequencies of the structure which can be used to predict the likelihood of resonance and potential failure modes.

Another approach to dynamic modelling of composite plates with Nomex core is through experimental methods such as modal analysis or impact testing. Modal analysis involves exciting the structure at different frequencies and measuring its response which can be used to determine the natural frequencies and mode shapes of the structure.

Impact testing involves subjecting the structure to a known force or impact, and measuring its response, which can be used to determine the dynamic behaviour and failure modes of the structure. Both modal analysis and impact testing can be used to validate the FEA models of composite plates with Nomex core and to optimise their design for specific applications.

One of the advantages of composite plates with Nomex core is their ability to dampen vibrations, making them ideal for use in aircraft and other high-stress applications. Dynamic modelling can help to optimise the design of these plates to ensure that they have the necessary stiffness and damping properties required for specific applications.

Moreover, composite plates with Nomex cores are also excellent at absorbing energy during impact events, making them an ideal material for the design of crash-resistant structures. By using dynamic modelling techniques, engineers can optimise the design of composite plates with Nomex core to ensure that they have the required energy-absorbing properties to withstand impact events.

In conclusion, dynamic modelling of composite plates with Nomex core is critical to predicting and optimising the behaviour of these structures under different loading conditions. Through FEA and experimental methods, engineers can validate models and optimise the design of composite plates with Nomex core for specific applications. By doing so, they can ensure that these structures have the necessary stiffness, damping properties, and energy-absorbing properties required for high-performance applications, including aerospace and defense.

MATERIAL MODEL - COMPOSITE PLATES WITH NOMEX CORES

The material model of composite plates with Nomex cores is crucial to accurately predict the behaviour of these structures under various loading conditions. The material model defines the mechanical properties of the composite material, including stiffness, strength, and failure modes, as well as the properties of the Nomex core, such as its compressive and shear strength, and the core's density.

A typical material model for composite plates with Nomex cores includes a combination of elasticity and failure criteria. The elasticity criteria define linear elastic behaviour of the composite material, while the failure criteria define the maximal stresses that the material can withstand before failure.

The elasticity criteria for the composite material are typically defined by the stiffness matrix which includes the elastic moduli and Poisson's ratios. The elastic moduli include the longitudinal modulus, transverse modulus, and shear modulus, which determine the stiffness of the composite material in different directions. Poisson's ratios define the material's tendency to contract or expand in response to an applied force.

The failure criteria for composite plates with Nomex cores can include various failure modes, such as fibre failure, matrix failure, and interlaminar failure. These failure modes are often defined using maximum stress criteria, such as the Tsai-Wu failure criterion which considers the effects of both longitudinal and transverse stresses on the composite material.

The Nomex core also plays a critical role in the mechanical behaviour of composite plates with Nomex cores. The compressive and shear strength of the Nomex core, as well as the density of the core, are important parameters to consider in the material model.

The compressive and shear strength of the Nomex core can be defined using standard material testing methods, such as ASTM C364, which measures the compressive strength of honeycomb core materials. The density of the Nomex core can also be determined using standard material testing methods, such as ASTM D1622 which measures the density of cellular plastics.

In addition to the elasticity and failure criteria, the material model for composite plates with Nomex cores may also include damping properties. The Nomex core has a unique honeycomb structure that can dampen vibrations and provide excellent energy absorption during impact events. The damping properties of the composite material can be determined experimentally using modal analysis techniques.

Equivalent honeycomb models

When analysing sandwich structures, an accurate prediction of the equivalent orthotropic core material properties is of utmost importance. The nine necessary core material characteristics are the three Poisson ratios ν_{12}, ν_{13}, ν_{23}, the two in-plane Young's moduli E_1, E_2, the out-of-plane Young's modulus E_3, the in-plane shear modulus G_{12}, the out-of-plane shear moduli G_{13}, G_{23}. Hence, the stress-strain relation, as a function of these elastic coefficients can be written in the following matrix form:

$$\begin{bmatrix}\varepsilon_1\\ \varepsilon_2\\ \varepsilon_3\\ \gamma_4\\ \gamma_5\\ \gamma_6\end{bmatrix}=\begin{bmatrix}\frac{1}{E_1} & -\frac{\nu_{21}}{E_2} & -\frac{\nu_{31}}{E_3} & 0 & 0 & 0\\ -\frac{\nu_{12}}{E_1} & \frac{1}{E_2} & -\frac{\nu_{32}}{E_3} & 0 & 0 & 0\\ -\frac{\nu_{13}}{E_1} & -\frac{\nu_{23}}{E_2} & \frac{1}{E_3} & 0 & 0 & 0\\ 0 & 0 & 0 & \frac{1}{G_{23}} & 0 & 0\\ 0 & 0 & 0 & 0 & \frac{1}{G_{13}} & 0\\ 0 & 0 & 0 & 0 & 0 & \frac{1}{G_{12}}\end{bmatrix}\begin{bmatrix}\sigma_1\\ \sigma_2\\ \sigma_3\\ \tau_4\\ \tau_5\\ \tau_6\end{bmatrix}. \quad (1)$$

Analysing the Eq.(1) it can be observed that a total of 9 elastic coefficients have to be known to fully qualify the elastic behaviour of the core in 3D space. The equivalent model approach represents one of the very effective techniques to calculate the required coefficients required by Eq. (1) stiffness matrix. Many models exist, and a very comprehensive review of equivalent models applicable to the elastic coefficient calculation, based on the cell geometry and core material characteristics, is given in /1/.

Widely used equivalent models are the sandwich theory equivalent honeycomb model, the honeycomb plate theory model, and equivalent plate theory model. These models are presented in /2/. The analysis of these equivalent models reveals several facts that require further investigation. First, not all models give the equations for all the nine elastic coefficients required by the stiffness matrix given in Eq.(1). Theoretical material properties, derived by Gibson and Ashby (1988) and Burton and Noor (1997), give relations for all elastic coefficients required and are expressed as a function of cell geometry and cell material properties, /1/. Furthermore, these two models give similar results (reported for Hex Web 5.2-1/4-25 3003) for all coefficients except for ν_{12} (1 vs 0.44) Poisson coefficient and G_{23} (2.6E8 vs 22.6E8) for shear modulus in the '23' plane. The impact of these differences on the final results is not investigated. Experimental data, usually reported by the OEM manufacturer, based on ASTM standards usually reports values for E_3, G_{13}, and G_{23}. Second, all of these models assume isotropic material properties for cell wall material, whereas, for the cell wall made of aramid/phenolic components, the isotropy assumption is not valid. Thirdly, when dynamic analyses of honeycomb structures are sought, the effects of mass distribution have to be taken into account. The natural frequencies of a composite structure are affected by the mass distribution of the structure. In general, the natual frequencies of a structure decrease as its mass increases.

When the mass of a composite structure is distributed in a way that is not uniform, the natural frequencies of the structure can be affected in different ways. For example, if there is more mass in one region of the structure than in another region, the natural frequency of the structure in the region with more mass will be lower than in the region with less mass.

Additionally, the location of the mass can also affect the natural frequencies of the structure. If the mass is concentrated in a certain area of the structure, the natural frequency in that area will be lower than in areas where the mass is not concentrated.

In summary, the mass distribution of a composite structure plays a critical role in determining its natural frequencies, and designers need to carefully consider mass distribution in the design process to achieve desired performance characteristics.

Honeycomb model for dynamic structural analysis at the mesoscale level

Material modelling at the mesoscale level involves studying the properties and behaviour of materials at the scale between the atomic and macroscopic levels. This level of analysis can provide valuable insights into the microstructural features that influence material performance and behaviour.

In the present study, the focus is given to developing the material model for honeycomb cells based on cell materials that are manufactured from NomexTM/phenolic phases.

Type 412 paper is mostly used in honeycomb structures. Nomex 412 is a type of aramid paper made primarily from meta-aramid fibres. It is a high-performance insulation material widely used in electrical applications where high-temperature resistance, mechanical strength, and durability are required.

The primary component of Nomex 412 aramid paper are meta-aramid fibres which are a class of synthetic fibres made from polyamide materials. Meta-aramid fibres are known for their high strength, flame resistance, and excellent thermal stability which makes them ideal for use in high-temperature applications.

In addition to meta-aramid fibres, Nomex 412 aramid paper may also contain small amounts of other materials such as binders and fillers to improve its properties. However, the exact composition of Nomex 412 can vary depending on the specific manufacturer and application requirements.

The components of aramid paper are flocs and fibrids, both of which have the same composition. Aramid flocs are brief areas of long aramid filaments that are around 6 mm in length and 10 μm in breadth and have an unbending tube shape. Aramid fibrids have an adaptable, unpredictable fibre-film shape and are 0.2-1 mm long and less than 1 μm thick. Fibrids act as folios, keeping the aramid filaments together. They moreover work as fillers in aramid paper. Hydrogen and van der Waals bonds are shaped among aramid filaments (interfibre) and between aramid fibrids and aramid filaments. The cement constraints between strands and fibroids are five times weaker than the fibrid-fibrid constraint. Typically, due to the bigger contact zone within the case of fibroids.

Phenolic resin is a type of thermosetting polymer widely used in various industrial applications due to its excellent chemical resistance, high-temperature stability, and low smoke and flame properties. Phenolic resins are formed by the reaction between phenol and formaldehyde in the presence of a catalyst and can be tailored to have a wide range of properties by adjusting the ratio of phenol to formaldehyde and the degree of cross-linking. Phenolic resins are commonly used in the manufacture of composites, adhesives, coatings, and moulded products. They are particularly well-suited for applications that require high strength, durability, and resistance to chemicals and high temperatures, such as in the aerospace, automotive, and construction industries. Phenolic resins can be reinforced with various materials, such as fibres or particles, to improve their mechanical properties. For example, phenolic resin composites are used to manufacture lightweight and high-strength components for aerospace and automotive applications. However, phenolic resins also have some limitations, such as their brittleness and low-impact resistance, which can make them unsuitable for certain applications. Additionally, the formaldehyde used in their production is a known carcinogen which has led to increased research into alternative production methods that minimize the release of formaldehyde. This multiphase material system is presented in the following figure (Fig. 1).

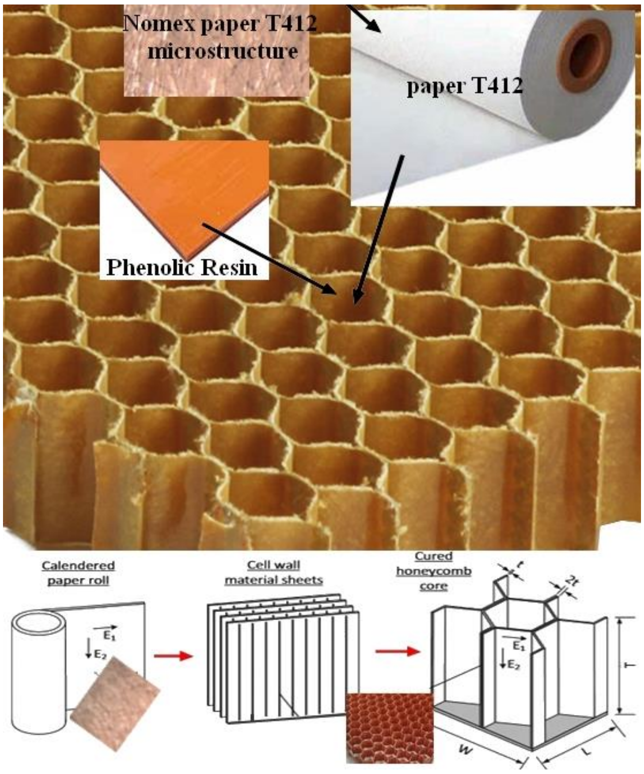

Figure 1. Honeycomb structure.

Honeycomb cell geometry can have a significant influence on honeycomb structural analysis. Honeycomb structures are widely used in aerospace, automotive, and other applications where high strength-to-weight ratios are required. The mechanical properties of honeycomb structures depend on various factors, such as material properties, cell size, cell shape, and cell orientation.

The geometry of honeycomb cells can affect mechanical properties of the structure in several ways:

Strength: the strength of a honeycomb structure is proportional to the thickness of cell walls. Therefore, a change in cell geometry can lead to a change in the strength of the structure. For example, increasing the cell wall thickness can increase the strength of the structure.

Stiffness: the stiffness of a honeycomb structure is affected by cell geometry. A change in the geometry of the cells can lead to a change in bending- and shear stiffness of the structure. For example, a hexagonal shape cell can result in higher bending stiffness compared to a square cell shape.

Buckling: the geometry of the cells can also affect the buckling behaviour of the structure. Buckling is a failure mode that occurs when the structure undergoes compressive loading. For example, cells with smaller diameters are more prone to buckling than cells with larger diameters.

Weight: the weight of the structure is directly related to cell geometry. Therefore, a change in cell geometry can lead to a change in the weight of the structure. For example, cells with smaller diameters are generally lighter than cells with larger diameters.

In summary, the geometry of the honeycomb cells can have a significant impact on the structural analysis of honeycomb structures. Therefore, it is important to carefully consider the cell geometry when designing honeycomb structures for specific applications.

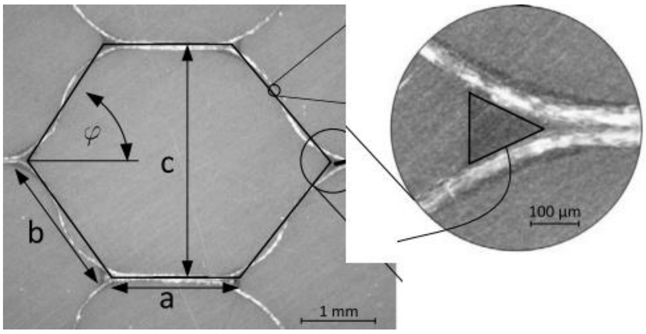

Figure 2. Cell geometry, /3/.

In the present study experimentally obtained results (by Roy et al.) /4/ are used to define the material of the honeycomb cell. It is assumed that the cell is layered, T 410 Nomex paper, coated with phenolic resin on both sides. Based on the results /4/ it can be seen that the Nomex paper, when subjected to tension behaves in a nonlinear manner. Furthermore, it has orthotropic material characteristics. The Young's moduli (linear domain) in directions 0°, 45° and 90° are 3.18 GPa, 2.36 GPa, and 1.96 GPa, respectively.

Assuming plane stress, the stiffness matrix for honeycomb cell wall can be presented in the form as in Eq.(2).

Young's moduli for Nomex T-type paper are obtained experimentally, as stated previously. The material nonlinear effects are included in the material model, based on experimental data /5,/ and stress-strain curves are presented in Fig. 3.

$$\begin{bmatrix} \frac{1}{E_1} & -\frac{\nu_{12}}{E_2} & 0 \\ -\frac{\nu_{21}}{E_1} & \frac{1}{E_1} & 0 \\ 0 & 0 & \frac{1}{G_{12}} \end{bmatrix} . \quad (2)$$

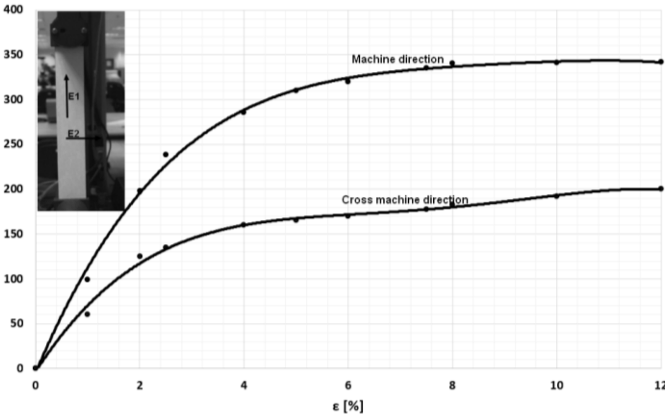

Figure 3. Nomex paper stress-strain data.

The required shear modulus G_{12} is calculated using the following approach, /6/:

$$G_{12} = \left[(E_1 + E_2)/2 \right] / 2(1+\nu_{12}) . \quad (3)$$

This assumption is verified by performing sensitivity analyses using the FEA approach. It was found that the shear modulus has an impact on the overall results. However, Young's moduli are more influential when axial loading is predominant, on the other hand when the structure twisting is extensive the impact of G_{12} values becomes more dominant (Fig. 4).

Poisson's ratio is a measure of the deformation in a material when subjected to an applied load. Poisson's ratio is constant for isotropic materials which have the same properties in all directions. However, for orthotropic materials, with different properties in different directions, Poisson's ratio can vary depending on the orientation of the applied load. In the present study, the major Poisson ratio is assumed to be 0.28, as suggested in /4/. Using stiffness matrix symmetry Eq.(2), minor Poisson ratio ν_{21} is calculated using previously obtained values for elastic coefficients as:

$$\nu_{21} = \frac{E_1}{E_2} \nu_{12} . \quad (3)$$

During the manufacturing process of Nomex cores the phenolic resin is used for T-type paper coating. Phenolic resin is a type of thermosetting polymer that is widely used in various industrial applications due to its excellent chemical resistance, high-temperature stability, and low smoke and flame properties. Phenolic resins are formed by the reaction between phenol and formaldehyde in the presence of a catalyst and can be tailored to have a wide range of properties by adjusting the ratio of phenol to formaldehyde and the degree of cross-linking.

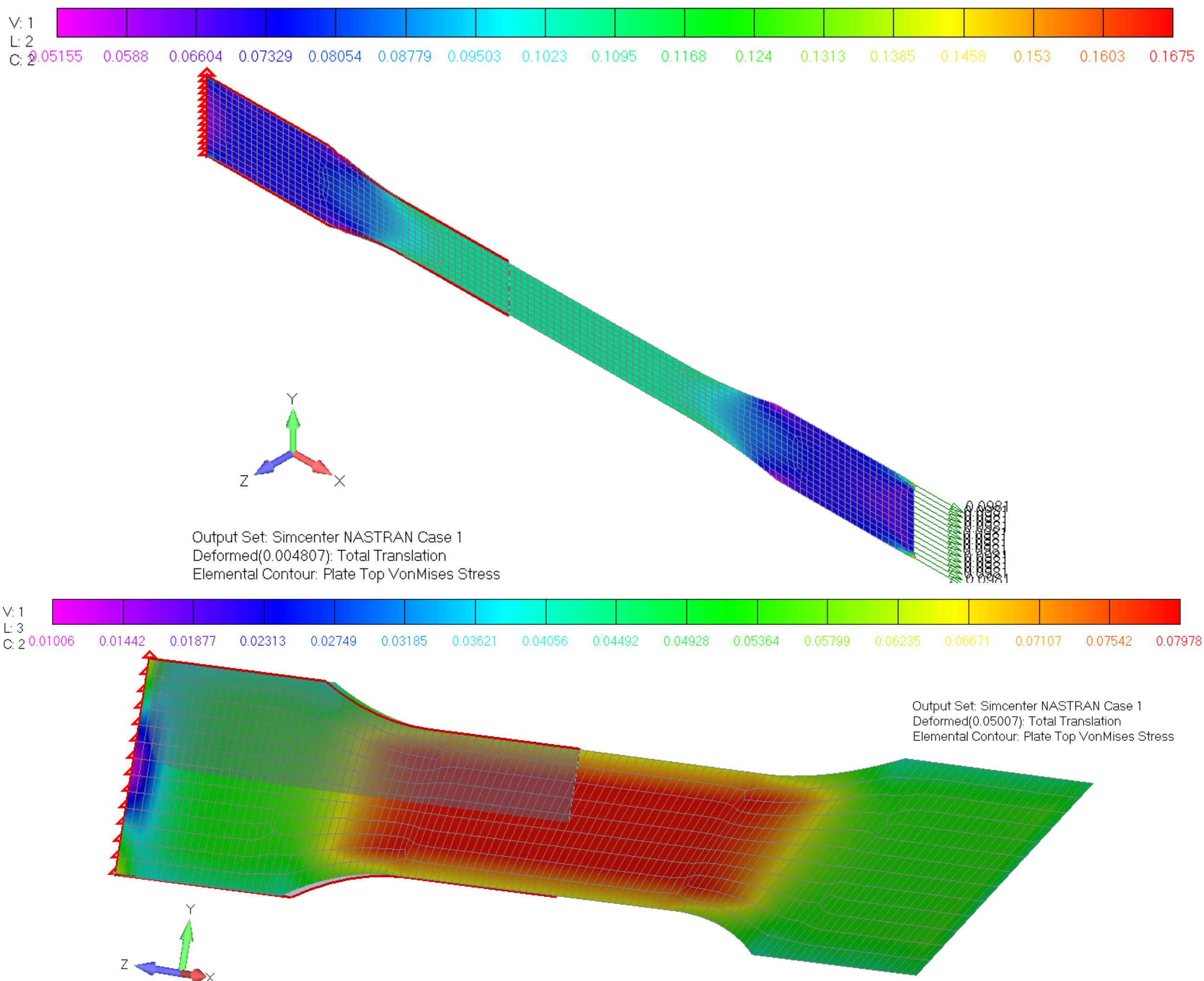

Figure 4. Nomex paper G12 virtual testing.

Phenolic resins are commonly used for manufacturing of composites, adhesives, coatings, and moulded products. They are particularly well-suited for applications requiring high strength, durability, resistance to chemicals and high temperatures, such as aerospace, automotive, and construction industries. Phenolic resins can be reinforced with various materials, such as fibres or particles, to improve their mechanical properties. For example, phenolic resin composites are used to manufacture lightweight and high-strength components for aerospace and automotive applications. However, phenolic resins also have some limitations, such as their brittleness and low-impact resistance, which can make them unsuitable for certain applications. Additionally, the formaldehyde used in their production is a known carcinogen which has led to increased research into alternative production methods that minimize the release of formaldehyde.

In the present study, phenolic resin is considered to be isotropic and is included as such in a Nomex material model. At present, the literature provides only a few experimental references for phenolic resin mechanical properties. Phenolic resin experimentally obtained mechanical properties found in literature are summarized in Table 1.

Table 1. Phenolic resin material data.

	E [MPa]	Poisson’s ratio [-]
Redjel /7/	5160	.36
Roy /4/	4940	.389
Liu /8/	5800	.389

Material components, described in the RVE material model of the Nomex core cell, are presented in Fig. 5, /3/.

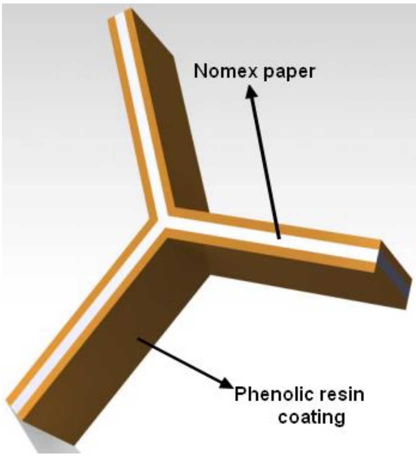

Figure 5. Nomex core RVE.

EXAMPLE

Based on the material model, for the presented Nomex core, the application of the modelling approach is used for a complex aileron structural dynamics analysis. The structure consists of a Nomex core, thin composite face sheet plates (2D carbon), and leading and trailing edges (3D composite carbon) with wing aluminium attachments. The FEA model is presented in Fig. 6.

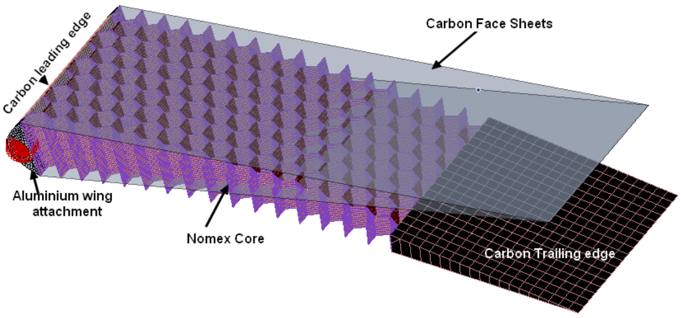

Figure 6. Example aileron model for dynamic analysis.

Direct Transient Dynamic Analysis is a computational technique used in structural engineering to simulate the behaviour of structures subjected to dynamic loads, such as earthquakes, wind, and blasts. It is a numerical method that solves the equations of motion of the structure over time, taking into account the damping, stiffness, and mass properties of the structure.

The analysis is called 'direct' because it directly solves the equations of motion without the need for any simplifying assumptions or linearization. In this method, the structure is modelled as a system of interconnected mass, stiffness, and damping elements. The equations of motion are then derived based on Newton's second law and solved numerically using techniques such as the Newmark method, which is commonly used for direct transient dynamic analysis.

During the analysis, the time-history of the dynamic load is applied to the structure and the response of the structure is calculated over time. This allows engineers to predict the behaviour of the structure under different types of dynamic loads and evaluate its safety and performance.

Direct transient dynamic analysis is commonly used in the design and evaluation of structures such as bridges, buildings, dams, and other critical infrastructures subjected to dynamic loads. The results of the analysis can be used to optimise structural design, assess its response to dynamic loads, and evaluate its safety under extreme conditions.

The Newmark method used is a numerical technique in dynamic analysis for solving equations of motion for a system subject to time-varying loads or excitations. It is commonly used in the analysis of structures under earthquake or wind loading, Fig. 7.

The Newmark method is a time integration technique that involves dividing the time interval of interest into small time steps. At each time step, the displacement, velocity, and acceleration of the system are updated based on the loads and equations of motion. The method is an implicit method, which means that the equations of motion are solved at each time step, taking into account the displacements and velocities from the previous time step.

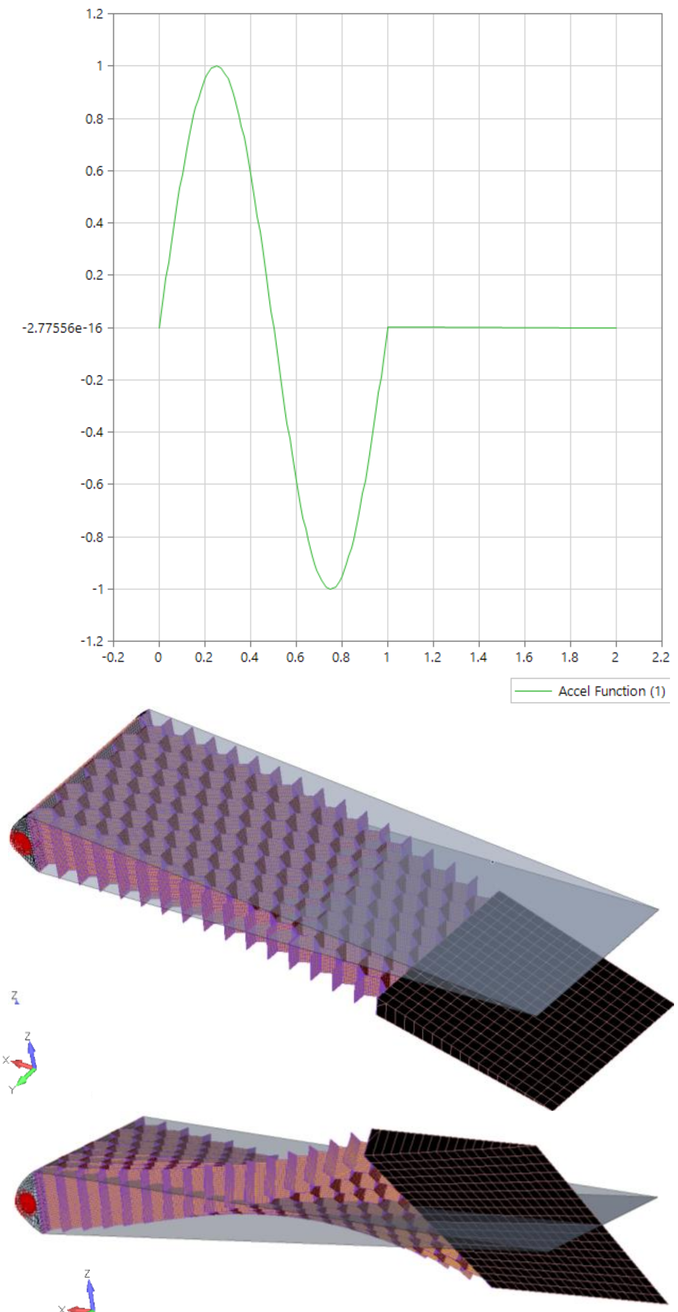

Figure 7. Dynamic response

The Newmark method uses a two-parameter family of algorithms to compute the response of a system. The two parameters are the numerical damping and the time step size. Numerical damping is a parameter that is introduced to prevent the simulation from diverging due to numerical errors. The time step size is the size of the time interval between successive time steps. A smaller time step size will result in more accurate results but at the cost of increased computational time.

The Newmark method is a widely used numerical method for solving dynamic problems in civil engineering, including earthquake engineering, wind engineering, and structural dynamics. It has been implemented in many software packages used by engineers and researchers in these fields.

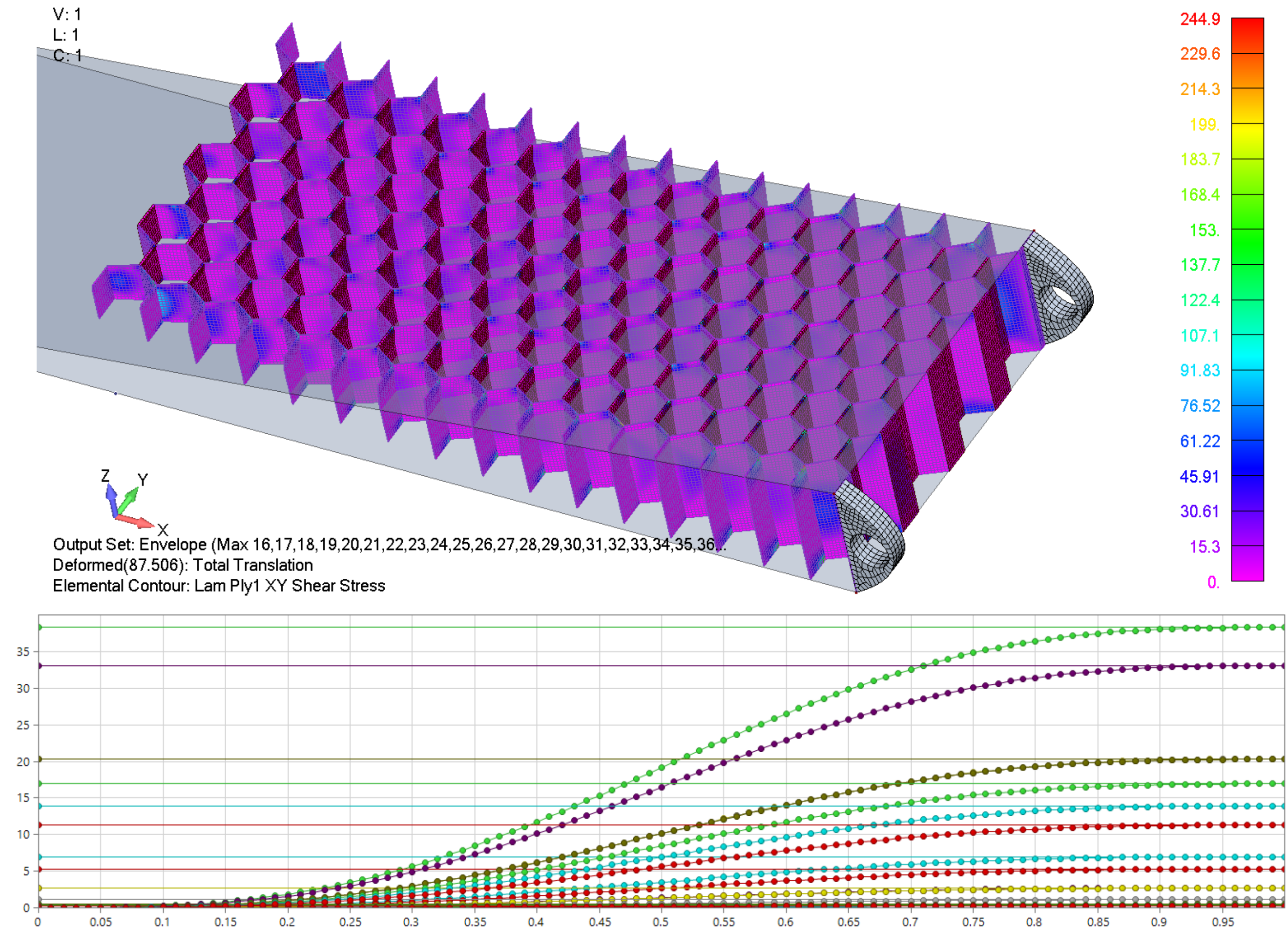

Figure 8. Example aileron model, displacement of control model modes and core shear stress.

CONCLUSION

In the present paper, the Nomex core material model with nonlinear effects at the meso scale level is presented. It is found that this model can be used for different types of dynamic analyses, rendering acceptable results, especially in the early stages of design, for complex structures with honeycomb cores. Comparing the results with widely accepted honeycomb equivalent material models it can be concluded that the results obtained using mesoscale approach are more accurate. However, they require very large computing resources coupled with long modelling times.

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