Accounting for glue and temperature effects in Nomex based honeycomb models

C. Florens, E. Balmes, F. Clero, M. Corus
Onera, Structural Dynamics and Coupled Systems Department, Chatillon, France
Ecole Centrale Paris, Soil Structure and Material Mechanics Laboratory, Chatenay Malabry, France
e-mail: **corine.florens@onera.fr**

Abstract

To predict the effect of active control on aircraft or helicopter trim panels, made with honeycomb sandwich composite, one approach consists in modeling the panel by Finite Element Method. FEM with shell elements for the laminate and volume elements for the core is classically used in industry. The aim of the present study is to determine the limits of the Shell-Volume-Shell model, in case of honeycomb core, through numerical correlation with a very detailed three dimensional model. More precisely, the influence of glue stiffness by numerical simulation has been considered, and the temperature influence has been observed through modal tests inside a controlled environment chamber.

1 Introduction

Reducing noise transmission inside cabins is an important concern for the aircraft industry, to improve the comfort of passengers. Usually trim panels are made of honeycomb sandwich composite. This material has a high strength to weight ratio, but acoustical properties have to be improved by acoustic treatments. Passive treatments are efficient for high frequencies, active sound and vibration control is a solution to reduce residual noise for low and medium frequencies. To predict the effect of active control on the trim panel, made with sandwich composite, one approach consists in modeling the panel by Finite Element Method (FEM).

In the case of a honeycomb sandwich panel, building a proper FEM representation for material and geometric properties is itself a difficulty. The section 2 presents two FEM, with different levels of detail, built with the Structural Dynamics Toolbox (SDT [1]) of Matlab software. Detailed 3D model that accounts for the actual cell geometry (see *Figure 1 (left)*) has been considered, but it reaches rapidly very high DOF numbers. This is acceptable for sample validations but could not be used for full panel predictions. Classically honeycomb panels are thus represented using a shell, orthotropic volume, shell model (SVS). The properties of the orthotropic volume used to represent the honeycomb are classically derived from mathematical manipulations of a detailed 3D model [2] (section 2.1). To allow for a more detailed representation of glue effects, a numerical procedure to derive equivalent orthotropic properties is introduced, section 2.2. The interest of this approach is that it allows for arbitrary levels of detail in the 3D model of the honeycomb. It can thus be used to extend classical homogenization methods to models with more details.

Core properties in the case of Nomex honeycomb are not well known and need to be derived from sample tests. Through shape correlation of free-free beam modes, parameters of SVS, accounting for the glue, or detailed 3D models can be updated by optimization of parameters which minimize the error between analysis and test frequencies. The experimental setup is presented in section 3, and some partial results with the most important conclusions, concerning the frequency dependence of material parameters, are given in section 4.2.

The physical geometry and materials of the honeycomb structure are represented with what is deemed sufficient accuracy, in the 3D FEM, to represent all physical phenomena of interest, in particular the stiffness properties of glue. Section 4.1 shows that, within reasonable margins, glue properties have a visible impact on the dynamics of the considered honeycomb and thus cannot be neglected. Many types of glue are also known to be viscoelastic.

Tests, whose conclusions are detailed in sections 4.2 and 4.3, will demonstrate that viscoelastic effects are indeed important for Nomex based samples that were considered. The dependence on frequency and temperature cannot be neglected in the FEM for active control application.

In the future, the work presented here will be extended to applications with piezoelectric patches placed on skins, the local 3D model will thus be used to validate the ability to represent local property transitions in a SVS model.

2 Finite Element Model (FEM) of honeycomb sandwich accounting for the glue

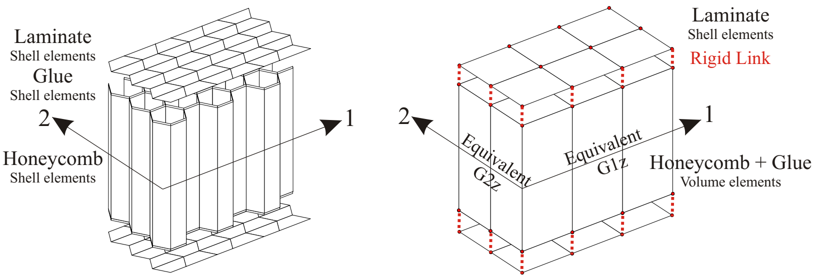
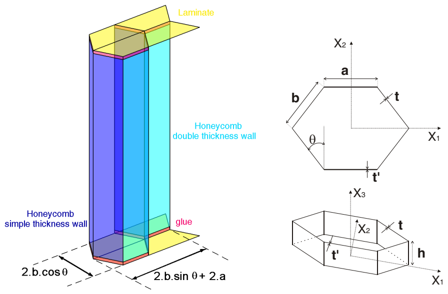


Figure 1: 3D and SVS models - exploded views.

The prediction of honeycomb sandwich behavior, through FEM that fit with reality, presents some difficulties because of the complex core geometry and the unknown composite material properties. Indeed, honeycomb core is strongly heterogeneous, but orthotropic due to the manufacturing process. However its modeling by equivalent homogeneous layer in Shell-Volume-Shell (SVS) model (*Figure 1, right*), gives good results for specific applications [3, 4]. The equivalent core properties for the FEM derive from analytical estimations, first assessed by Kelsey [5] in 1958, and enriched by numerous researchers [6]. Regarding the Sound and Vibration Active Control application, one wants to investigate the reliability of the SVS FEM. With this intention, a very detailed three dimension (3D) FEM has been developed (*Figure 1, left*), to do predict which effect are not represented by the classical SVS approach.

The proposed estimation, by numerical homogenization from basic material properties, includes the glue, frequency, and temperature effects, to evaluate their influence on core parameters estimation. The numerical approach consists in comparing arbitrary dynamic behaviors of SVS model to 3D model (section 2.2) and in extracting the best equivalent homogeneous parameters.
Nevertheless, the basic material properties are rarely well known, and the material parameters have been updated through tests (section 3).



Geometric parameters	
a	length of alveole side (x dir.)
b	length of alveole side
θ	angle of alveole
t	thickness of simple wall
t'	thickness of double wall

Figure 2: Definition of geometric parameters.

2.1 Existing methods for honeycomb properties estimation

With the objective of model parameters estimation for SVS FEM, one considers here the pure honeycomb core material and not the entire sandwich structure. Fifteen existing theories for the material properties of honeycomb estimation are reviewed and compared by Schwingshackl [6], based on Energy Method [2, 5], on homogenization theory [7], and on Finite Element Method with ANSYS [8] or NASTRAN [4].

The expressions of the honeycomb material properties chosen as reference are Gibson and Ashby's ones [2], with the hypothesis of linear, elastic and isotropic constitutive material. The Nomex paper, basis of honeycomb Nomex core, is a non woven sheet made of short aramid fibers (Nomex). It is calandrered before being impregnated with phenolic resin, its isotropy is assumed because of the arbitrary distribution of short fibers.

The orthotropic material law depends on 9 independent material parameters E_{c_x},E_{c_y},E_{c_z}, $\nu_{c_{yx}}$,$\nu_{c_{zx}}$, $\nu_{c_{zy}}$, $G_{c_{xy}}$, $G_{c_{xz}}$, $G_{c_{yz}}$. The orthotropic law [9] is given by:

$$\left\{\begin{array}{c}\epsilon_x\\ \epsilon_y\\ \epsilon_z\\ \gamma_{yz}\\ \gamma_{xz}\\ \gamma_{xy}\end{array}\right\} = \left[\begin{array}{cccccc} 1/E_{c_x} & -\nu_{c_{yx}}/E_{c_y} & -\nu_{c_{zx}}/E_{c_z} & 0 & 0 & 0\\ -\nu_{c_{xy}}/E_{c_x} & 1/E_{c_y} & -\nu_{c_{zy}}/E_{c_z} & 0 & 0 & 0\\ -\nu_{c_{xz}}/E_{c_x} & -\nu_{c_{yz}}/E_{c_y} & 1/E_{c_z} & 0 & 0 & 0\\ 0 & 0 & 0 & 1/G_{c_{yz}} & 0 & 0\\ 0 & 0 & 0 & 0 & 1/G_{c_{xz}} & 0\\ 0 & 0 & 0 & 0 & 0 & 1/G_{c_{xy}} \end{array}\right] \left\{\begin{array}{c}\sigma_x\\ \sigma_y\\ \sigma_z\\ \tau_{yz}\\ \tau_{xz}\\ \tau_{xy}\end{array}\right\} \tag{1}$$

The four in-plane moduli are calculated by causing the hexagonal cell wall to bend under loads in x and y directions [2]. The Young's moduli, E_{c_x}, E_{c_y}, and shear modulus, $G_{c_{xy}}$, are calculated by standard beam theory, as the ratio of strain to stress. The Poisson's ratio, $\nu_{c_{yx}}$, is deduced by the negative ratio of the strains normal to, and parallel to, the loading direction.
The $\nu_{c_{zx}}$, $\nu_{c_{zy}}$, Poisson's ratio are equal to the constitutive material one. And the out of plane Young's modulus, E_{c_z}, is the constitutive material Young's modulus referred to the effective area which support the normal loading in z direction.

It has been shown [6], and confirmed by the present FEM approach, that the most influent material parameters on the dynamic behavior are $G_{c_{xz}}$ and $G_{c_{yz}}$ for the core, and E_l for the laminate. Hence, only the out of plane shear moduli expressions are presented here.
Exact analytical calculation of $G_{c_{xz}}$ or $G_{c_{yz}}$ is not possible due to the complexity of stress distribution in a sheared honeycomb. Theorems of minimum potential energy and minimum complementary energy are used to estimate the lower and upper bounds of the out-of-plane shear moduli, $G_{c_{xz}}$ and $G_{c_{yz}}$. For the $G_{c_{yz}}$

modulus, lower and upper bounds are equal, therefore, the value of $G_{c_{yz}}$ is known:

$$G_{c_{yz}} = G\frac{t}{b}\frac{cos\theta}{\frac{a}{b}+sin\theta},$$
$$G_{c_{2z}} = G_{c_{yz}}. \tag{2}$$

However, for $G_{c_{xz}}$ modulus, energy methods only give a range as function of constitutive material shear modulus G and geometric parameters,

$$G\frac{(at'+btsin\theta)^2}{bcos\theta(a+bsin\theta)(2at'+bt)} \leq G_{c_{xz}} \leq G\frac{at'+2btsin^2\theta}{2bcos\theta(a+bsin\theta)},$$
$$G_{c_{1z}} = G_{c_{xz}}. \tag{3}$$

The estimated core parameters by energy methods depend, only, on constitutive material parameters and cell geometry. First, the basic material of honeycomb layer is considered as linear, elastic and isotropic, which has not been confirmed by test/analysis correlation (section 4.2). Then, the glue layer is not represented by the existing analytical approaches.

2.2 Finite Element Models developed with SDT

The use of the Structural Dynamic Toolbox of Matlab, to build the classical SVS and the very detailed 3D FEM, makes the parametric studies easy to implement. The FEM approach with detailed geometry, (*Figure 1 (left)*), allows to evaluate the influence of geometric and constitutive material parameters, but also the influence of the glue stiffness. Indeed the observation of honeycomb sample (*Figure 3*) shows that the glue layer may not be neglected in the honeycomb modeling to represent well the reality.

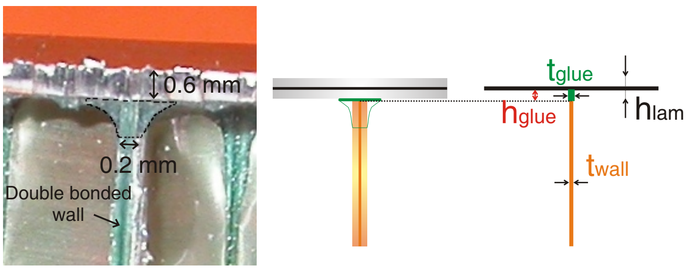


Figure 3: Modeling of glue joint.

The classical Shell, orthotropic Volume, Shell (SVS) representation (*Figure 1 (right)*) is more reasonably used for full panel predictions. Volume and Shell elements are connected by rigid links.
The core material parameters estimation assessed by Gibson and Ashby is enriched by numerical homogenization, based on periodic modes. The numerical homogenization of the core, honeycomb with glue, is performed by non-linear optimization with objective function to match with the 3D detailed FEM dynamic behavior with periodic boundary conditions, that means same DOF values at the beginning and the end of the period (4). It amounts to releasing oneself from boundary conditions by considering an infinite beam.

$$\begin{aligned} \phi(0, L_y) &= \phi(L_x, L_y), \\ \phi(L_x, 0) &= \phi(L_x, L_y). \end{aligned} \tag{4}$$

One has to notice that the periodic boundary conditions have no physical sense for the trim panels' application, but it allows to simulate the models for every wished frequency.

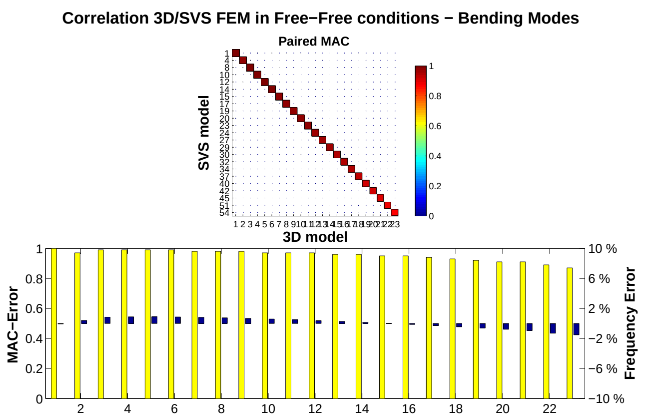
Due to the periodicity, modal shapes are pure sine curve, and the two models, 3D and SVS, can be compared on arbitrary configurations that cannot be tested. The modal analyses are projected on a common wireframe to compare the mode shape of the two models. Then, a mode shape correlation is performed between SVS ad 3D FEM for the first "mode" of different wavelength beams, to compare the mode frequencies, and the equivalent shear modulus of honeycomb core $G_{c_{1z}}$ and $G_{c_{2z}}$ are updated.
The 3D/SVS models correlation has shown that, whatever the wavelength, that means whatever the frequency, only one optimized equivalent core shear modulus G_{1z} assumes the good correlation with less than 1% of error. The numerical homogenization allows to build a SVS model which matches to 3D modeling for every frequency.

As a conclusion, the SVS FEM has been validated for periodic analysis. For the 3D model parameters, E_{Nomex}, E_{Glue} and t_{Glue}, fixed to reference values, Gibson and Ashby and numerical homogenization estimation of G_{1z} are different:

$$G_{1z_{Gibson\&Ashby}} = 30,8 \text{ MPa},$$
$$G_{1z_{numhomogenization}} = 29 \text{ MPa}.$$

That was to be expected since the glue is included in core homogenization. This estimation has been validated in other configurations, and compared with experiments (section 4.2).

The comparisons of 3D and SVS models, in free-free conditions and for out of plane bending solicitations, are presented on *Figure 4*, for the estimated homogenized parameter, $G_{1z_{NumHomog.}}$ = 29 MPa, and on *Figure 5*, for Gibson & Ashby's parameter G_{1z}.
The 3D FEM and SVS FEM out of plane bending modes are almost perfectly correlated for $G_{1z_{NumHomog.}}$ (*Figure 4*), the MAC [10] is higher than 0.87 for the 23 first bending modes with a frequency error lower than 1.5 $\%$.
In comparison with the same 3D/SVS FEM correlation, for the value of G_{1z} given by Gibson $\&$ Ashby (*Figure 5*) the reduction of frequency error is visible.



3D FEM freq. Hz		SVS FEM freq. Hz		Δ f/f_{3d} %	MAC *100
1	196.34	1	196.22	-0.1	100
2	437.54	4	439.28	0.4	97
3	944.09	8	952	0.8	99
4	1189.4	10	1199.9	0.9	99
5	1429.2	12	1441.9	0.9	99
6	1666.1	14	1680.4	0.9	99
7	1900	15	1915.4	0.8	98
8	2132.4	17	2148.4	0.7	98
9	2363.2	19	2379.1	0.7	98
10	2593.3	20	2608.5	0.6	97
11	2822.4	23	2836.1	0.5	97
12	3051.4	24	3062.9	0.4	97
13	3279.6	27	3288.2	0.3	96
14	3508.1	29	3512.9	0.1	96
15	3735.9	30	3736.1	0.0	95
16	3964.4	32	3958.9	-0.1	95
17	4192.1	34	4180	-0.3	94
18	4420.8	37	4401.1	-0.4	93
19	4648.2	40	4620.1	-0.6	92
20	4877.6	42	4839.4	-0.8	91
21	5104.3	45	5055.6	-1.0	91
22	5557.5	51	5485.1	-1.3	89
23	5790.2	54	5702.1	-1.5	87

Figure 4: Correlation 3D/SVS FEM in free-free conditions - Bending modes - $G_{1z_{NumHomog.}}$ = 29 MPa.

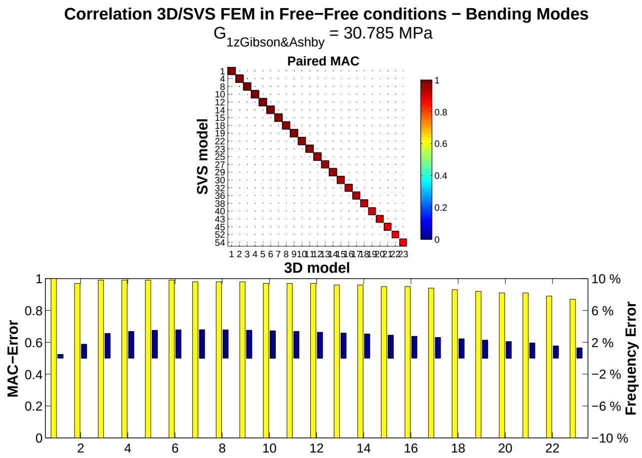


Figure 5: Correlation 3D/SVS FEM in free-free conditions with Gibson & Ashby G_{1z} = 30.785 MPa.

With one value of equivalent shear modulus G_{1z}, of the Nomex based honeycomb included the glue, by numerical homogenization, the SVS model is well correlated with the 3D model. The quality of the correlation is good for periodic boundary conditions and for free-free boundary conditions. Therefore, the numerical procedure is validated in the frequency range between 100 Hz and 6 kHz.

What about the correlation with experiments? Is the equivalent shear modulus, found by taking into account the glue, a good parameter to describe the real dynamic behavior of honeycomb sandwich beam?
Modal tests on Aluminum/Nomex honeycomb beam have been carried out to answer to this question (section 3).

3 Honeycomb beam tests

Figure 6: Experimental setup and sensor on beam modeling.

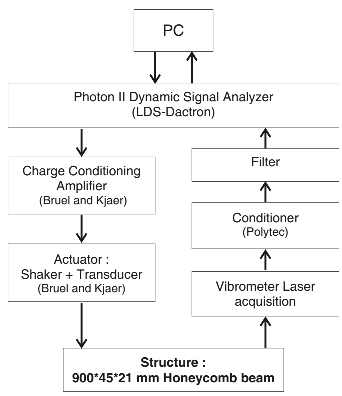


Figure 7: Acquisition chain.

	Geometric parameters		Material parameters	
Laminate (Aluminum)	h_{lam}	0.6 mm	ρ_{lam} E_{lam}	2.8 $10^3 kg/m^3$ 72.5 GPa
Honeycomb core (Nomex)	h_h t (t'=2.t) a, b, θ	20 mm 2.54 10^{-2} mm (5.08 10^{-2} mm) 2.75 mm, 2.75 mm, $\pi/6$ rad	ρ_h $E_{h_{ref}}$	1.38 10^3 kg/m^3 9 GPa
Glue (Hypothesis: epoxy)	$h_{glue} = h_{lam}/2$ $t_{glue_{ref}}$	0.3 mm 0.1 mm	ρ_{glue} $E_{glue_{ref}}$	10^3 kg/m^3 5 GPa

Table 1: Definition of Aluminum-Nomex test beam parameters.

Modal tests on honeycomb beams have been carried out at the Soil, Structure and Material Mechanics Laboratory (MSSMat) of Ecole Centrale Paris. 900mm long, 45mm large and 21mm thick honeycomb sandwich beams have been tested in free-free conditions, inside a controlled environment chamber (5°C, 25°C, 45°C) and for the 0 - 4.5 kHz frequency band. The quality of measurements is good enough to be used for the modal analysis to 3 kHz.

A shaker causes the beam to vibrate, using a force transducer screwed through the sandwich beam. The signal sent to the structure is a white noise created by the analyzer (Photon by LDS-Dactron), amplified, finally transformed and transmitted to the structure by the shaker (Bruel and Kjaer). The measure acquisition is made with a laser vibrometer (Polytec) which measures the velocity of the beam at different reflecting points in the direction of the laser.
To assure the free-free conditions, the beam is suspended by 3 elastic strings (*Figure 6*). In the fourth corner the shaker rod crosses the honeycomb sandwich through a really fine hole.

Tests campaign have been carried out for different temperatures on Aluminum/Nomex beam, whose properties are given in *Table 1*, in both orthotropic directions.
The results and conclusions concerning the material properties correlation and the influence of temperature are presented in sections 4.2 and 4.3.

4 Results

4.1 Prediction of the glue parameters influence

The 3D model has been built to find the limits of SVS model. Therefore a specific study of 3D model has been made to simulate the behaviors that are not taken into account in the SVS representation. More precisely, the influence of glue on honeycomb modeling has been evaluated through 3D FEM simulations and is presented in this section.

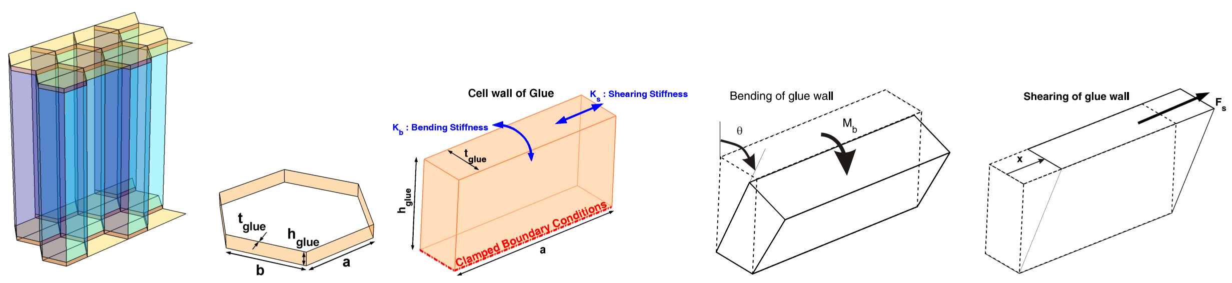


Figure 8: parameterization and stress on glue element definition.

Both E_{Glue} and t_{Glue} are influent parameters. The relevant parameters are the shear and bending stiffness of the glue, which depend on E_{Glue} and t_{Glue} according to formulations (5) and (6). The stiffness is calculated for clamped beam and depends on geometric parameters, defined on *Figure 8*. K_{shear} and K_{bend} are respectively stiffness on displacement x and angle θ :

$$M_b = K_{bend}.\theta \text{ with } K_{bend} = \frac{E_{glue} a t_{glue}^3}{12 h_{glue}}, \tag{5}$$

$$F_s = K_{shear}.x \text{ with } K_{shear} = \frac{E_{glue} a^3 t_{glue}}{4 h_{glue}^3}. \tag{6}$$

The meshing procedure imposes h_{glue} as equal to the half-thickness of the skin, and *a* as length honeycomb cell side. The variable parameters are the Young's modulus E_{glue} and the thickness of the wall of glue t_{glue} (*Figure 8*). K_{bend} and K_{shear} parameters are fixed to assume the real behavior of the glue. That means the glue modeling has the same stiffness as the real glue volume (*Figure 3*).

As the geometry of the real glue volume is not regular, only plausible limits of stiffness can be given. K_{bend} and K_{shear} ranges are evaluated by surrounding the real glue volume by parallelepipedic element. A typical value of glue Young's modulus is E_{glue}= 2 GPa. According to manufacturers data, epoxy adhesive Young's modulus E_{glue} is included in,

$$\begin{aligned} E_{glue_{min}} &= 20MPa, \\ E_{glue_{max}} &= 5GPa. \end{aligned} \tag{7}$$

The glue thickness must be higher than $t_{cell-wall}$ = 0.0254 mm (t' on *Figure 8*) for our test beam. Concerning $t_{glue_{max}}$, it is chosen by observing the picture of glue joint (see *Figure 3*). The thickness of the skin is 0.6 mm, it is assumed to be a reasonable value for the upper bound of glue volume thickness,

$$\begin{aligned} t_{glue_{min}} &= 0.0254mm, \\ t_{glue_{max}} &= 0.6mm. \end{aligned} \tag{8}$$

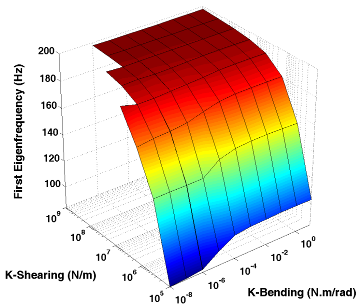
The height h_{glue} of the glue volume is lower than laminate thickness, 0.6 mm and higher than 0.2 mm.

With this approximate data, a realistic stiffness range of the glue can be determinated (*Figure 10*),

$$\begin{aligned} K_{shear_{min}} &= 3.30.10^5 N/m, \\ K_{shear_{max}} &= 7.22.10^7 N/m, \end{aligned} \tag{9}$$

$$\begin{aligned} K_{bend_{min}} &= 3.75.10^{-7} N.m/rad, \\ K_{bend_{max}} &= 4.12.10^{-1} N.m/rad. \end{aligned} \tag{10}$$

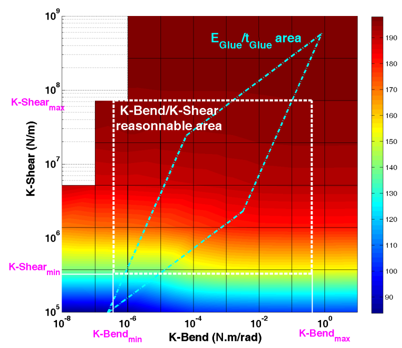
Figure 9 presents the result of the numerical study on the 900 millimeter-long sample beam, in free-free conditions. The first eigenfrequency has been calculated for several values of shear and bending stiffness.



K_{Shear} (N/m)	$K_{Bend}(N.m/rad)$									
	10^{-8}	10^{-7}	10^{-6}	10^{-5}	10^{-4}	10^{-3}	10^{-2}	10^{-1}	1	10
10^5	83.87	84.47	85.9	94.35	101.4	102.9	103.5	103.7	103.7	103.4
$3.7\ 10^5$	140.2	140.2	140.4	140.5	149.8	153.1	154.0	154.1	154.1	153.8
$1.4\ 10^6$	169	170.7	171.4	173.1	176.6	179.7	180.9	181.1	181.1	180.9
$5.2\ 10^6$	190.5	187.6	187.6	188.4	189.0	190.1	191.0	191.3	191.3	191.3
$1.9\ 10^7$		193.5	194.1	193.5	193.9	194.1	194.5	194.7	194.7	194.7
$7.2\ 10^7$		196.5	195.9	196	196.0	196.0	196.1	196.2	196.3	196.3
$2.7\ 10^8$			197.1	197.1	197.1	197.1	197.1	197.2	197.3	197.3
$1\ 10^9$			198.0	197.8	197.7	197.7	197.7	197.8	198.0	198.0
	Frequency (Hz)									

Figure 9: First eigenfrequency (Hz) for Aluminum-Nomex 900mm beam in free-free conditions as function of K_{Bend} and K_{Shear}.

The reasonable areas for K_{bend} (10), K_{shear} (9) and E_{glue} (7), t_{glue} (8) are plotted on *Figure 10*, respectively in white and blue. Even in the restricted area, the glue has a big influence of the value of eigenfrequency. Indeed for a K_{bend} fixed, the error on the frequency relative to experimental value $\Delta f/f_{Test}$ is varying between -42.2 and +12.7 %. Thus, it is important to take into account the glue layer in honeycomb sandwich and to know the glue material values to have an accurate modeling approach.



Error on Frequency for $K_{Bend} = 10^{-4}$ N.m/rad		
K_{Shear} N/m	$\Delta f/f_{Test}$ %	Δ f/mean(f) %
10^5	-42.2	-42.1
$3.7\ 10^5$	-14.6	-14.5
$1.4\ 10^6$	0.66	0.81
$5.2\ 10^6$	7.72	7.87
$1.9\ 10^7$	10.5	10.7
$7.2\ 10^7$	11.7	11.9
$2.7\ 10^8$	12.4	12.5
$1\ 10^9$	12.7	12.9

Figure 10: Influence of Glue stiffness, K_{Bend} and K_{Shear}, on the first eigenfrequency in free-free conditions.

Due to the parametric study of honeycomb, the unknown FEM parameters can be found by test/analysis correlation.

4.2 Updating and frequency dependence of models parameters

For a first approximation, and to start the homogenization of honeycomb core, reference value of E_{Nomex} has been chosen, based on manufacturer database. But the Test/analysis correlation has proved that this value is not the best for all modes, it turns out that minimizing the frequency error between 3D FEM modal analysis and test for the all bending modes together is difficult for this Aluminum/Nomex honeycomb beam. The same applies to Test/SVS FEM correlation. One value of G_{1z} does not allow a good correlation of the SVS FEM with test on beam for all frequencies.

Thus, the constitutive material parameter E_{Nomex} and the equivalent homogeneous core parameters G_{1z} and G_{2z} have been updated frequency by frequency (Figure 11).

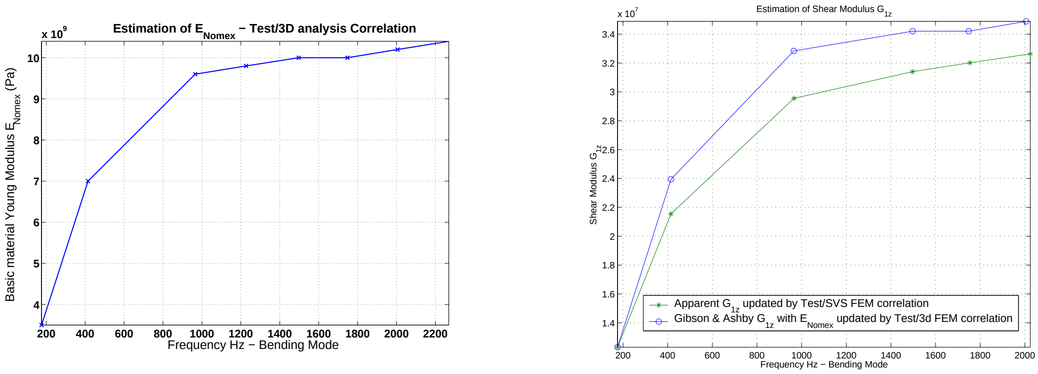


Figure 11: Updated E_{Nomex} and equivalent shear modulus G_{1z} for each Bending modes by Test/analysis correlation.

The Test/Analysis correlation for each bending frequency, shows the dependence of E_{Nomex} and G_{1z} (respectively G_{2z}) with the frequency. Both 3D and SVS models have the same frequency dependence behavior.

The equivalent shear modulus G_{1z} of the homogenized honeycomb layer has been evaluated in to ways (*Figure 11, right*). First, by Gibson and Ashby's method using the updated value of E_{Nomex}, which depends on frequency, then, directly by Test/SVS model analysis correlation. The first method considers only the frequency dependence of Nomex, constitutive material of the honeycomb, thus the glue parameters are fixed and not taken into account. The second approach, by direct updating of the Honeycomb + Glue core, includes the frequency dependence of both Nomex and Glue. The glue parameters have been, previously, updated for the first mode (section 4.1), thus the values of G_{1z}, estimated by the two methods, are the same for the first eigenfrequency. However, for the next modes the estimated G_{1z} curves are shifted, it is the result of the glue effect.

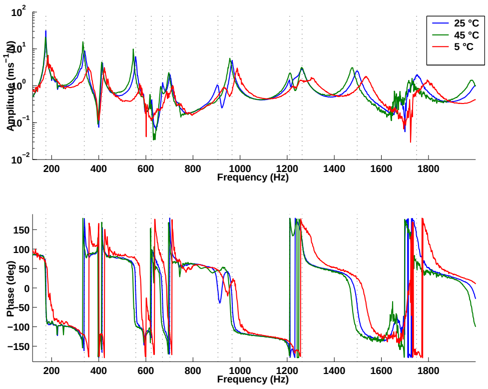
Test/analysis correlations show the frequency dependence of the material parameters, but also the importance of the glue layer in the modeling approach.

The frequency influence on updated parameters points out the fact that viscoelasticity of Nomex based honeycomb cannot be neglected and a single set of parameters does not allow a correct fit for the whole range. In the section 4.3, the viscoelastic behavior of the Nomex based honeycomb sandwich is proved by vibrating experiments for different temperatures.

4.3 Influence of temperature of Nomex based honeycomb sandwich

Test/analysis correlations for 3D and SVS FEM have shown the frequency dependence of the material parameters; it is typical of viscoelastic behavior. Experiments in a controlled environment chamber have been carried out by changing the temperature of the test.

The Frequency Responses plotted for three different temperatures, represented on *Figure 12*, are the result of observations.



Bending Modes	T=5°C order	T=5°C ω Hz	T=5°C ζ %	T=25°C order	T=25°C ω Hz	T=25°C ζ %	T=45°C order	T=45°C ω Hz	T=45°C ζ %
1	1	185	*4.58**	1	175.5	0.49	1	174.3	0.84
2	3	423.3	0.99	3	414.8	0.47	3	412.8	0.56
3**	5	689.6	0.82	5	670.8	0.53	5	663.1	0.49
4	8	985.3	0.79	8	965.7	0.52	7	957.9	0.51
6	11	1536	1.09	10	1497	0.75	10	1477	0.72
7**	12	1793	0.73	11	1754	0.87	11	1726	0.22
8**	13	2062	1.08	12	2024	0.87	12	1987	0.82

* *The error on measurement cannot assure the reliability of this value.*
** *Mixed bending and torsion modes.*

Figure 12: Frequency Response and bending eigenfrequencies for 5°C, 25°C, 45°C temperatures.

The temperature is really influential on the modes, which confirms the viscoelastic behavior of the honeycomb sandwich beam. Both Nomex core or glue layers may have viscoelastic properties. The error in terms of frequencies between the 45°C test and the 5°C test is around 2-6 %. This observation shows that it will be necessary to take into account the viscoelasticity behavior of the core to estimate the equivalent core properties, and in the end to simulate the effect of active control on Nomex based honeycomb sandwich, with sufficient accuracy.

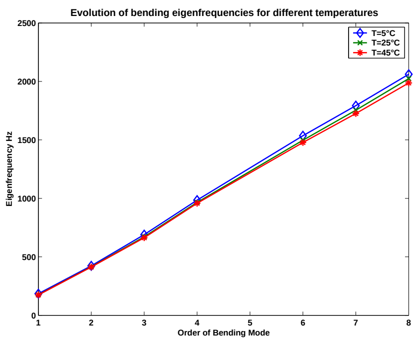


Figure 13: Evolution of bending eigenfrequencies for different temperatures.

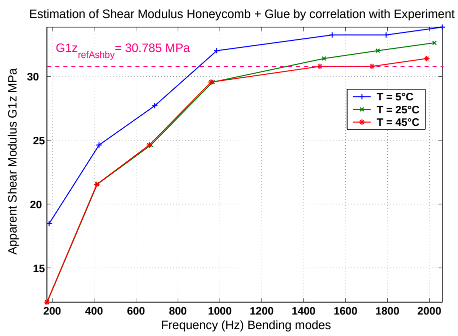


Figure 14: Equivalent shear modulus G1z of honeycomb+glue core as a function of frequency and temperature.

The study has been focused on the bending. The deviation of the bending eigenfrequencies increases with the frequency and inversely with the temperature (*Figure 13*). The estimation of homogenized core shear modulus by test/analysis correlation and updating for each temperature, gives an idea of the viscoelastic behavior of the Aluminum/Nomex honeycomb sandwich. The evolution of the equivalent shear modulus G_{1z} (*Figure 14*) looks like typical curves of viscoelastic materials [11]. No conclusion can be drawn about the modal damping. Indeed, the modal damping presents such error (Table of *Figure 12*) that comes from experiment and modal identification, that there is no need trying to compare with viscoelastic law.

5 Conclusion

The three dimensions Finite Elements Model built with the Structural Dynamics Toolbox of Matlab allows to simulate the influence of different parameters, such as the glue stiffness presented in this paper. The equivalent material parameters of the classical Shell-Volume-Shell model can be derived from numerical homogenization, by taking into account, in addition and in comparison with the existing method [6], for glue and frequency effects.

The numerical analysis has predicted the influence of glue stiffness, and it turns out that the effects could be important in the reasonable range of glue parameters. The numerical predictions have been validated by test/analysis correlation. As a conclusion, to model properly honeycomb sandwich structures, it is necessary to take into account the glue stiffness effect.

To update the models parameters, modal tests of honeycomb beams have been carried out. The test/analysis correlation has pointed out the viscoelastic effects of Nomex and Glue. Indeed, the equivalent out of plane shear moduli of the core, honeycomb and glue, depend on frequency and on temperature. To match with the observed dynamic behaviors, the parameters updating must be made frequency by frequency. Moreover, tests in a controlled environment chamber have proved the influence of the temperature, its effect is appreciable between 5°C, 25°C, so that the temperature is a parameter to consider in order to minimize the error between active control simulation in laboratory and active control application on helicopter and aircraft.

The procedure of comparison between the detailed 3D and the classical SVS models set up to estimate the core parameters will be extended to beam with piezoelectric patches bonded on the skin. The final aim being to predict, as well as possible, the behavior of smart panel equipped with piezoelectric patches for active control application.

References

[1] E. Balmes and J.-M. Leclere. *Structural Dynamics Toolbox - FEMLink*. User's Guide Version 5.2, May 2005.

[2] L. J. Gibson and M. F. Ashby. *Cellular Solids Structure and Properties, Second Edition*. Cambridge University Press, 1997.

[3] R. D. Buehrle, J. H. Robinson, and F. W. Grosveld. Vibroacoustic model validation for a curved honeycomb composite panel. In *7th AIAA/CEAS Aeroacoustics Conference and Exhibit*, AIAA, 2001-2277.

[4] J. Klos, J. H. Robinson, and R. D. Buehrle. Sound transmission through a curved honeycomb composite panel. AIAA, 2003-3157.

[5] S. Kelsey, R. A. Gellatly, and B. W. Clark. The shear modulus of foil honeycomb cores. *Aircraft Engineering*, 30:294302, 1958.

[6] C. W. Schwingshackl, P. R. Cunningham, and G. S. Aglietti. Honeycomb elastic material properties: A review of existing theories and a new dynamic approach. In *International Conference on Noise and Vibration Engineering*, ISMA, 2004.

[7] G. Shi and P. Tong. Equivalent tranverse shear stiffness of honeycomb cores. *International Journal of Solids and Structures*, 32:1383–1393, 1995.

[8] P. R. Cunningham, R. G. White, and G. S. Aglietti. The effects of various design parameters on the free vibration of doubly curved composite sandwich beams. *Journal of Sound and Vibration*, 230:617–648, 2000.

[9] J.-M. Berthelot. *Materiaux composites - Comportement mecanique et analyse des structures*. Masson, 1992.

[10] N. Lieven and D. Ewins. Spatial correlation of modeshapes, the coordinate modal assurance criterion (comac). International Modal Analysis Conference, 1988.

[11] G. Kergourlay. *Mesure et prediction vibroacoustique de structures viscoelastiques - Application a une enceinte acoustique*. PhD thesis, Ecole Centrale Paris, France, 2004.