

Full 3D Effective Properties of Piezoelectric d_{31} MFC: Validation by Detailed Finite Element Analyses of Experimented Free Smart Hybrid Honeycomb Sandwich

Ayech Benjeddou, Marcelo A. Trindade

Abstract. The purpose of this contribution is to provide a *validation* of the recently proposed *full* 3D effective *Electro-Mechanical* (EM) dataset of the *Piezo-Electric* (PE) *transverse mode* (d_{31}) *Macro-Fiber Composite* (MFC) transducer through *detailed* finite element analyses of an *experimented* free *smart hybrid honeycomb* sandwich with a *surface-bonded* PE d_{31} MFC patch. Depending on the faces and core *quadrangular* or *triangular* meshes, less than 6% deviation was found for *short-circuit* and *open-circuit* frequencies of the first three EM *coupled* modes.

Key words: Full 3D electromechanical properties, PE d_{31} MFC, Detailed FE analysis, Modal analysis, Smart hybrid honeycomb sandwich.

1 INTRODUCTION

Thanks to their main feature, the conformability, *transverse mode* (d_{31}) *Piezo-Electric* (PE) *Macro-Fiber Composites* (MFC) are nowadays popularly used for sensing [1], actuation [2], control [3,4], health monitoring [1] and energy harvesting [5]. While their multilayer *hybrid* (multi-materials) construction does not pose particular difficulty in experimental applications, their use for 3-Dimensional (3D) simulations is rather challenging. Indeed, only *partial* 3D electromechanical (EM) properties of the *multilayer* d_{31} MFC were available [2,3,5,6] until the recent *extension* [7] of the *Average Quantities-based Homogenization* (AQH) *Finite Element*

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(FE) procedure [6] for computing the *full 3D dataset* that includes the earlier missing *transverse shear* EM properties. The latter were formerly completed using either the values of the piezoceramic (PZT) fiber material [5] or those of the active layer (PZT fibers + Epoxy matrix) [8]. However, due to the *anisotropy* of the MFC material *effective behavior*, using nil missing values in 3D FE simulation leads to very poorly predicted zeros of the smart structure (MFC + host) application's frequency response function (FRF), as shown in [8].

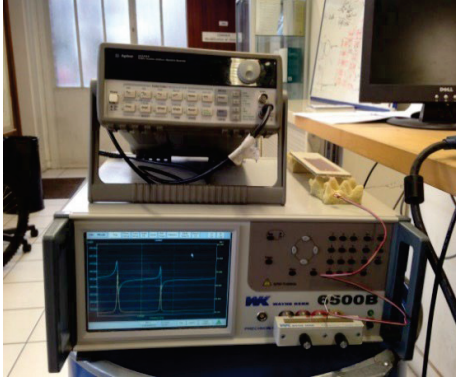
On the other hand, while MFC combination with metallic, mainly Aluminum (Al) [2], or laminated composite, often Carbon Fiber Reinforced Polymer (CFRP) [8], hosts is common, that with *honeycomb* sandwiches is scarce. Indeed, a careful literature search has led to only two references [1,4]: One [1] has experimented a d_{31} MFC patch on a honeycomb sandwich made of CFRP [1] (no further details were given on the skins/core construction). The other [4] experimented *longitudinal* response mode (d_{33}) MFC patches on a *hybrid* honeycomb sandwich made of [0/90] CFRP laminated skins and Aramid (Nomex[®]) core. Here, for the patches' maximum/minimum strain-based locations, the host structure was modelled as a laminate for which the skins and core were considered as a *transversely equivalent isotropic* material with no variation along the thickness. No material dataset was given for the used d_{33} MFC patches.

Due to its *multilayer* construction, the d_{31} MFC is homogenized using FE approaches that exploit its constituents' material EM properties for computing its effective ones. As the multilayer construction, material and geometric details are mostly not known, generic material data and construction dimensions reverse engineering are used for the FE computations. Therefore, it is necessary to validate the reached effective dataset. The most followed approach is to compare to the manufacturer data and literature-homogenized ones. However, the former are incomplete and the latter use different computation inputs, such as the material and geometric data, representative volume element (RVE), FE mesh, software, etc..., hence not comparable. Consequently, there is a need to validate the homogenized data through test-model correlation of a smart structure application's measured outputs. Examples are: cantilever aluminum beam *actuation* using a d_{31} MFC patch [2], *active elasticity control* of a d_{31} MFC patch using a negative capacitance shunt [3], strain *energy harvesting* from a substrate (not defined) on which is bonded a d_{31} MFC patch [5], and *active vibration control* of a composite boom using a d_{31} MFC actuator/sensor pair [8].

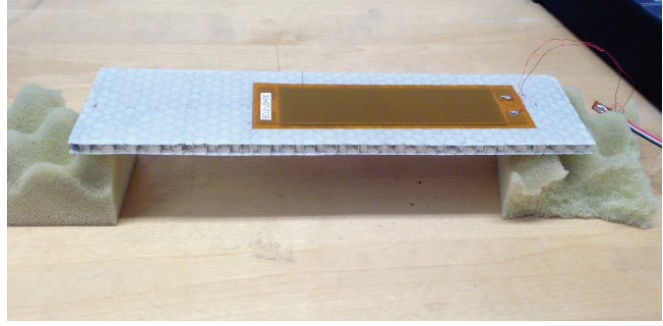
Therefore, this contribution has the main aim to complement originally the above-analyzed literature by investigating the validation of the presently *unique 3D full* material dataset of the multilayer PE d_{31} MFC [7]. For this purpose, *detailed* FE approach [9]-based *short-circuit* (SC) and *open-circuit* (OC) *modal* analyses, using ANSYS[®] Mechanical APDL via a developed C⁺⁺ application, are correlated for their SC/OC frequency outputs with those from earlier *experimental impedance analyses* (EIA) of a free *smart hybrid honeycomb sandwich* [10]. The latter is made of an Al core and *woven* Glass Fiber Reinforced Plastic (GFRP) skins on which a PE d_{31} MFC patch is bonded. Hence, in the following section 2, the SC/OC frequencies extracted from the EIA of the smart hybrid honeycomb sandwich and the FE AQH-induced 3D *full* dataset of the multilayer PE d_{31} MFC are first recalled from [10] and [7], respectively. Then, inspired from [9], section 3 presents the *detailed* FE models, simulations and test-model correlation of the host and smart hybrid honeycomb sandwich, leading to the validation of the 3D *full* material dataset of the PE d_{31} MFC. Finally, conclusions are given as a closure.

2 SMART HYBRID HONEYCOMB SANDWICH BENCHMARK

The smart structure application, used here as a benchmark for the validation of the FE AQH-induced full 3D material dataset, is a free smart *hybrid* honeycomb sandwich, typically used as a trim panel in aircraft interiors. It is composed of an Al regular *hexagonal* honeycomb core sandwiched between *woven* GFRP skins on which a PE d_{31} MFC large patch is surface-bonded. This benchmark was used earlier [10] for the EIA-based evaluation of the related effective EM coupling coefficient. Here, the resonant/anti-resonant frequencies, used for the EMCC evaluation, are considered as experimental references for, respectively, the SC/OC natural frequencies computed using the FE AQH-induced full 3D material dataset as input to the later described detailed FE approach for modelling the bare and smart sandwich panels. Figure 1 shows (a) EIA test setup and (b) a zoom on the *free* boundary conditions (BCs) realization.



(a) EIA test setup



(b) Zoom on the free BCs

Figure 1: EIA test setup (a) and free BCs realization (b) [10].

2.1 EIA-extracted SC/OC frequencies of the smart hybrid honeycomb sandwich

The SC (f_{sc}) and OC (f_{oc}) natural frequencies of the free smart hybrid honeycomb sandwich were extracted (Table 1) from the surface-bonded PE d_{31} MFC patch's *capacitance module* and *phase* of the *voltage-to-current ratio* (FRF), displayed on a WK 6500B *impedance analyzer* (Figure 1a). They approximate, respectively, the resonant (f_r) and anti-resonant (f_a) frequencies.

Table 1: EIA-extracted SC/OC frequencies (Hz) of the free smart hybrid honeycomb sandwich.

EM coupled Mode	f_r, f_{sc}	f_a, f_{oc}
1	600.00	618.07
2	1502.92	1523.39
3	2751.82	2788.52
4	4184.76	4242.32
5	6981.76	7089.31
6	7722.69	7850.82
7	7988.71	8061.02
8	8170.71	8319.28

It is worthy to mention that the EIA-displayed FRFs can show only the EM *coupled* modes. As the *in-plane bending* and *torsion* modes are EM *uncoupled*, only the FE computed SC/OC frequencies associated to the *transverse bending* modes-type can be compared to the extracted experimental SC/OC values shown in Table 1. This requires not only to consider the FE modal analyses SC/OC frequency outputs but also to check the *type* (transverse bending, in plane bending or torsion) of their corresponding modes.

2.2 FE AQH-induced 3D full EM dataset of the multilayer d_{31} MFC

The 3D *full* EM material properties of the *multilayer* d_{31} MFC were obtained by extending the FE AQH approach [6] to consider the *missing transverse shear* PE and dielectric (DE) coefficients [7]. The same 5-layer construction (Figure 2a) and RVE (Figure 2b), were used.

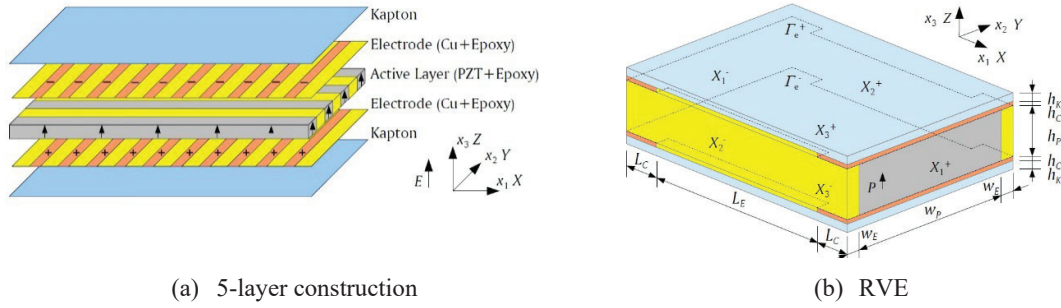


Figure 2: d_{31} MFC 5-layer construction (a) and RVE (b) used in the extended [7] FE AQH approach [6].

However, few *additional local problems* were introduced to cover the missing coefficients, namely the shear response mode-related PE and DE ones, which are e_{15} , e_{24} , ϵ_{11}^S , ϵ_{22}^S , in the e-form, or d_{15} , d_{24} , ϵ_{11}^T , ϵ_{22}^T , in the d-form. Table 2 lists the resulting *engineering* 3D full EM dataset in both e-form and d-form, since either of them can be used as material inputs to an FE software, such as the ANSYS[®] Mechanical APDL used here for implementing the FE AQH. Nevertheless, only the e-form dataset will be used in the later-presented detailed FE approach for its validation via the modal analyses of above-presented smart hybrid honeycomb sandwich.

Table 2: e-form and d-form full 3D material dataset of multilayer PE d_{31} MFC.

SC elastic coefficients		e-form PE & DE coefficients		e-form PE & DE coefficients	
Y_1^E (GPa)	31.37	e_{31} (C/m ²)	-6.03	d_{31} (pC/N)	-172.3
Y_2^E (GPa)	19.69	e_{32} (C/m ²)	-3.44	d_{32} (pC/N)	-133.2
Y_3^E (GPa)	9.02	e_{33} (C/m ²)	1.48	d_{33} (pC/N)	308.9
G_{23}^E (GPa)	2.16	e_{15} (C/m ²)	0.81	d_{15} (pC/N)	334.9
G_{31}^E (GPa)	2.42	e_{24} (C/m ²)	0.47	d_{24} (pC/N)	219.3
G_{12}^E (GPa)	5.33	$\epsilon_{11}^S/\epsilon_0$	988.6	$\epsilon_{11}^T/\epsilon_0$	1019.3
ν_{12}^E (-)	0.36	$\epsilon_{22}^S/\epsilon_0$	24.1	$\epsilon_{22}^T/\epsilon_0$	24.1
ν_{23}^E (-)	0.37	$\epsilon_{33}^S/\epsilon_0$	1181.7	$\epsilon_{33}^T/\epsilon_0$	1573.3
ν_{13}^E (-)	0.42	ϵ_0 (pF/m)	8.854	ϵ_0 (pF/m)	8.854

3 DETAILED FE MODELS, SIMULATIONS AND CORRELATIONS

3.1 Hybrid honeycomb sandwich host structure

The honeycomb sandwich panel, having the geometric and material properties shown in Table 3, is modelled using a similar methodology to the practical detailed FE approach [9]. The latter is based on a *Graphical User Interface* (GUI) that generates a *commands script* for a FE software (ANSYS[®] Mechanical APDL). Beside the main characteristic of the skins and core cell walls *individual meshes*, the generated script contains all other data and commands for the pre-processing, solution (modal) and post-processing (outputs) steps needed by a FE analysis.

Table 3: Hybrid honeycomb sandwich panel geometric and materials properties [9]

Sandwich*	Length (L)	Width (I)	Thickness (H)	Length cells (N_L)	Width cells (N_I)
	18.3 cm	5.2 cm	4.6 mm	25 (<i>counted</i>)	10 (<i>counted</i>)
Core	Cell length (A)	Cell width (B)	Cell wall thickness (t)	Double wall thickness (2t)	Cell side (a)
	*6 mm	*5.2 mm	*45 μm	*90 μm	*3 mm
	Material	Thickness (h)	Young's (E_c)	Poisson's (ν_c)	Density (ρ_c)
	Aluminum	*4.2 mm	**70 GPa	**0.3	**2815 Kg/m ³
Faces	Material	Thickness (t_f)	Young's (E_f)	Poisson's (ν_f)	Density (ρ_f)
	Composite	*155 μm	***19 GPa	**0.17	***2200 Kg/m ³

* *Measured*. ** *Assumed* as generic data. *** *Identified* via test-FE correlation.

The main new features of the present detailed FE approach are: (i) a specifically developed C⁺⁺ *application* (Visual Studio 2022), instead of the earlier Matlab[®] GUIDE function-based GUI for generating the commands script; (ii) the skins and core cell walls are *automatically meshed* in ANSYS[®] while, earlier, each core cell wall was meshed prior to ANSYS[®] by a single element and those of the skins use a minimum number of elements that cover top and bottom areas of the core hexagonal cells; (iii) the geometric models of the skins are defined by only their corner nodes while, formerly, their geometries were extruded from the top and bottom geometric nodes of the core, prior to meshing the three layers (skins and core). Here, the core in-plane geometry (Figure 3a) is obtained by repeating the elementary cell shown in Figure 3b.

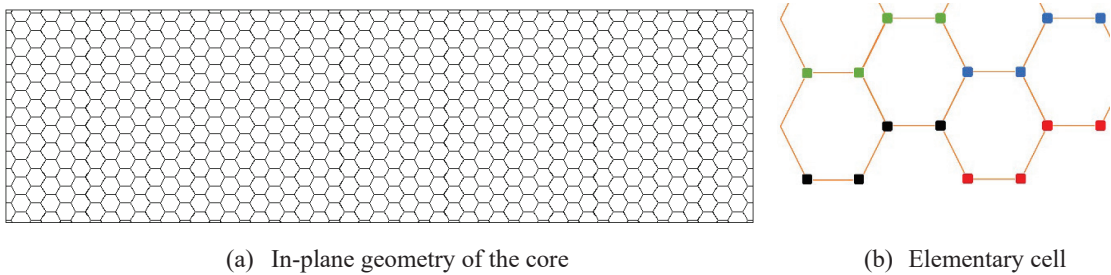


Figure 3: The core in-plane geometry (a) created by repeating an elementary cell (b).

Noticeably, as ANSYS[®] has archived its SHELL63 element used in [9], it is replaced here

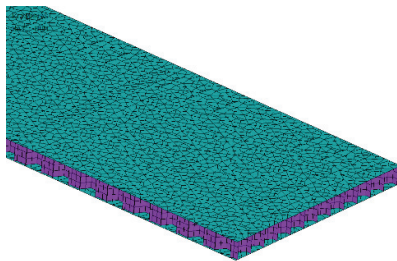
by SHELL181 element, as recommended in ANSYS® documentation. Besides, the geometries induced by the detailed FE approach [9] led to *saw teeth-like lateral edges* of the sandwich that were necessary to make straight as are the actual ones while here, by the new design approach, there is no need for this meshing complexity, as the edges are ‘naturally’ straight. Moreover, due to manufacturing geometric defaults of the sandwich panel assembly, the use of the counted 25 hexagonal cells of 3 mm radius in the length leads to a longer panel, while using the latter radius value leads to 21 cells only along the length. For this reason, to use the 25 cells as a dimension input, a homothetic factor of 4/5 was used in [9] to cover a closer value to the actual length. Here, 2.44 mm hexagonal cell radius is used to cover the counted 25 cells. Table 4, comparing the two cell radii-induced fundamental mode frequency with the measured one, via a drop test, of the sandwich panel, shows clearly the very good accuracy (0.56 % error) of the reduced radius. It can be also noticed that using a homothetic factor with the length actual cells number (25) recovers the results of the saw teeth edges with a length of reduced 21 cells. The closest (0.07 % error) value to the experiment is obtained using the latter cell number and 3-node triangular (T3) FE for closing the saw teeth-like lateral edges.

Table 4: Fundamental frequency variation with the sandwich panel modelling method.

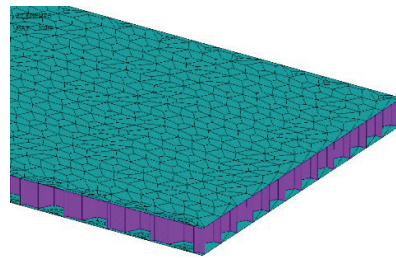
Method	Model	Frequency (Hz)	Error* (%)
Test		560.00	reference
Present (SHELL181)	21 cells (3 mm)	576.73	2.99
	25 cells (2.44mm)	563.13	0.56
[9] (SHELL63)	21 cells (3 mm, <i>saw teeth</i> -like lateral edges)	567.52	1.34
	21 cells (3 mm, added T3 FE- <i>straight</i> lateral edges)	560.40	0.07
	25 cells (3 mm, added T3 FE- <i>straight</i> lateral edges & homothetic factor)	567.61	1.36

* Error (%) = 100*(FE-test)/test

The results from [9] in Table 4 were obtained using a *mapped* mesh as described above. However, the present ones were obtained using an *automatic* mesh with a 4-node quadrangular (Q4) element size of 2 mm, shown in Figure 4a in comparison to that of 5 mm (Figure 4b). It corresponds to the minimum error (0.56%) with the drop test fundamental frequency (Figure 5a) in the cost of a dense mesh of 20496 elements (Figure 5b). Nevertheless, it is retained for the next sub-section and its validation results with the present methodology.



(a) Element size 2 mm (20496 FE)



(b) Element size 5 mm (7570 FE)

Figure 4: Hybrid honeycomb sandwich Q4 FE mesh with element size 2 mm (a) and 5 mm (b).

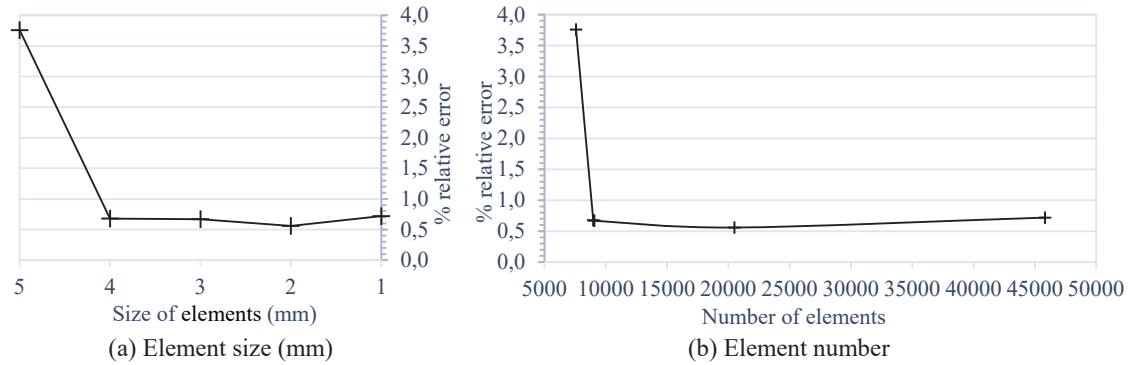


Figure 5: Element size (a) and number (b) of the mesh *convergence* analysis.

Besides, all results of Table 4 were obtained using Q4 FE-based meshes. The use of a T3 FE-based mesh for all layers, within the present methodology, led to a much less accurate (5.26 % error) fundamental frequency (589.48 Hz) as can be seen in Table 5. This may be because T3 *option* is a *degeneration* of the Q4 SHELL181, which is ‘*not recommended*’ by ANSYS®. Table 5 shows other combinations of skin/core/skin Q4- and T3-based meshes, but clearly, the most accurate (0.56 % error) mesh is the Q4/Q4/Q4 followed by the T3/Q4/T3 (1.57 % error).

Table 5: Fundamental frequency variation with the skin/core/skin FE mesh.

Method	Skin/core/skin FE mesh (2 mm)	Frequency (Hz)	Error* (%)
Test		560.00	reference
Present (SHELL181, 25 cells, 2.44 mm)	Q4/Q4/Q4	563.13	0.56
	T3/T3/T3	589.48	5.26
	T3/Q4/T3	568.78	1.57
	Q4/T3/Q4	578.23	3.25

* Error (%) = 100*(FE- test)/test

The fundamental mode, superposed to the non-deformed honeycomb sandwich, is illustrated in Figure 6 with the Q4/Q4/Q4 most accurate mesh, hence *retained* for the next sub-section.

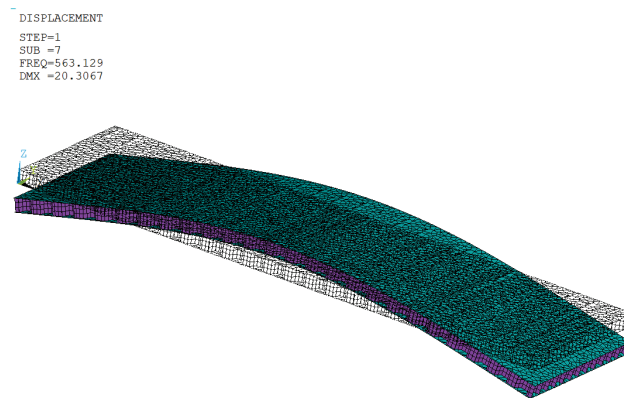


Figure 6: Superposed fundamental mode shape and non-deformed honeycomb sandwich (Q4/Q4/Q4 mesh).

3.2 Hybrid honeycomb sandwich smart structure

In the C⁺⁺ application, first, the four corners model the geometry of d₃₁ MFC patch (having an active area of 85 x 28 mm² and thickness of 0.3 mm) and its bottom-left node defines its location (30 mm from an edge of the sandwich and *width-centered*) on the sandwich top skin. Then, in replacement of SOLID5 used in [9], which was archived, the d₃₁ MFC patch mesh in ANSYS[®] uses the 6-node *prismatic* (P6) FE *option* of the 8-node hexahedral (H8) SOLID225 one, which cannot be used for an *automatic* mesh. Thanks to its three quadrangular and two triangular faces, the prismatic FE can be *automatically* compatible with Q4 and T3 meshes of the top skin. The other two options of 4-node *tetrahedral* and 5-node *pyramid* FEs are ‘*not recommended*’ by ANSYS[®]. Figure 7 shows one of the smart hybrid honeycomb sandwich meshes used in the hereafter validation results.

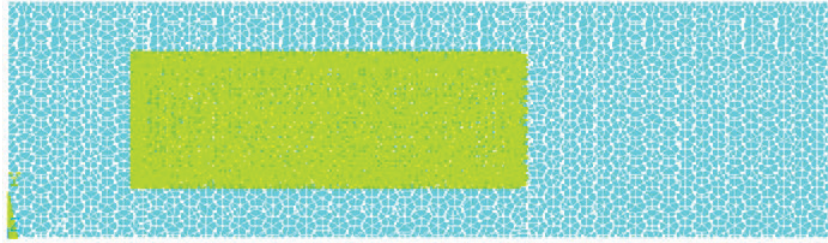


Figure 7: Top view of the free smart hybrid honeycomb sandwich Q4/Q4/Q4/P6 2mm-size mesh.

First, Table 6 shows a comparison of the first three EM *coupled* modes’ frequencies and their variations with those of the EIA test (Table 1), obtained with the C⁺⁺ application four-mesh options of the smart hybrid honeycomb sandwich when the d₃₁ MFC patch electrodes are in SC electric connection. The most accurate mesh is that with Q4/Q4/Q4, except for the fundamental mode where Q4/T3/Q4 performs better. The second most accurate mesh is the T3/Q4/T3, which also performs less than Q4/T3/Q4 for the fundamental mode.

Table 6: EM coupled FE SC frequencies and variations with EIA test (Table 1) and skin/core/skin FE mesh.

Skin/core/skin FE mesh (2 mm)	Order of EM coupled mode	7		9		11	
		Freq. (Hz)	Error (%)	Freq. (Hz)	Error (%)	Freq. (Hz)	Error (%)
Q4/Q4/Q4		587.44	-2.09	1501.62	-0.03	2796.23	1.61
T3/T3/T3		611.95	1.99	1565.09	4.19	2912.24	5.83
T3/Q4/T3		592.21	1.30	1514.36	0.82	2820.16	2.48
Q4/T3/Q4		602.26	0.38	1539.98	2.52	2866.55	4.17

* Error (%) = 100*(FE- test)/test

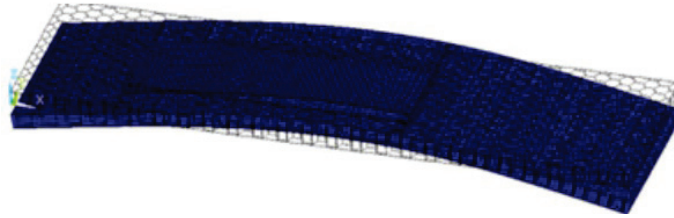
Then, Table 7 shows the comparison of the first three EM *coupled* modes’ frequencies and their variations with those of the EIA test (Table 1), obtained with the C⁺⁺ application four-mesh options of the smart hybrid honeycomb sandwich when the d₃₁ MFC patch electrodes are in OC electric connection with enforced *equipotential* (EP) constraints. Here, Q4/Q4/Q4 and T3/Q4/T3 behave similarly in the sense that each one is the most accurate for one mode, performs secondly for another mode and less than T3/T3/T3 for the fundamental mode.

Table 7: EM coupled FE OC frequencies and variations with EIA test (Table 1) and skin/core/skin FE mesh.

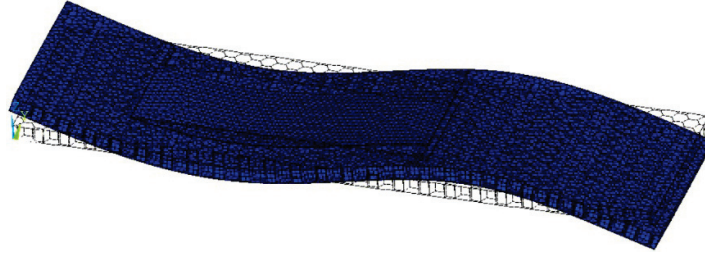
Skin/core/skin FE mesh (2 mm)	Order of EM coupled mode	7		9		11	
		Freq. (Hz)	Error (%)	Freq. (Hz)	Error (%)	Freq. (Hz)	Error (%)
Q4/Q4/Q4		590.01	-4.54	1506.82	-1.09	2805.44	0.61
T3/T3/T3		614.70	-0.54	1570.65	3.10	2922.11	4.79
T3/Q4/T3		594.82	-3.76	1519.64	-0.25	2829.54	1.47
Q4/T3/Q4		604.91	2.13	1545.35	1.44	2876.08	3.14

* Error (%) = 100*(FE- test)/test

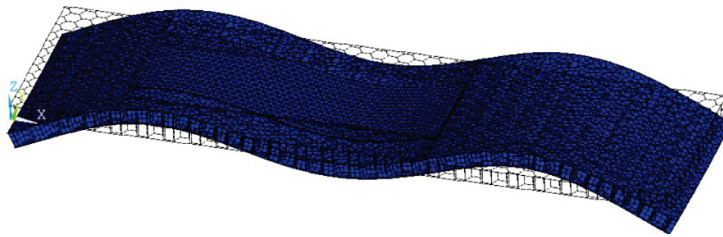
As guessed earlier, on one hand, the FE EM *coupled* modes are transverse (x-z) ones. For confirmation, those (of order 7, 9, 11) compared in Tables 6 and 7 are shown in Figure 8.



(a) First (FE order 7) transverse (x-z) mode.



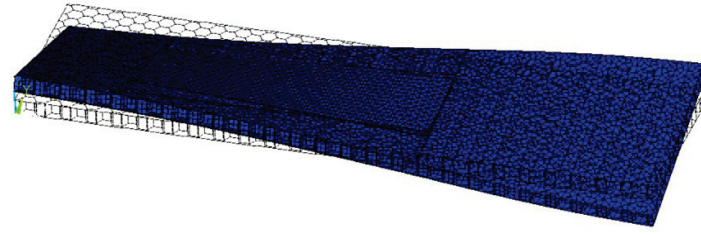
(b) Second (FE order 9) transverse (x-z) mode.



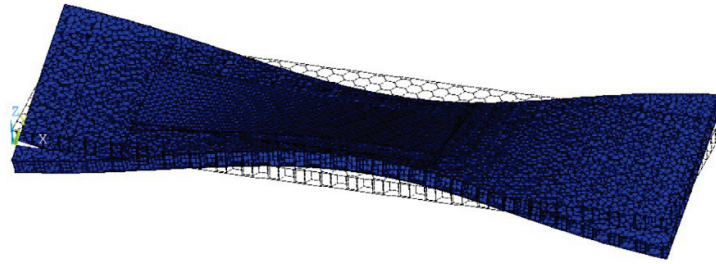
(c) Third (FE order 11) transverse (x-z) mode.

Figure 8: First three FE EM *coupled* modes of the free *smart* hybrid honeycomb sandwich.

On the other hand, the FE EM *uncoupled* modes are *torsion* ones and are shown in Figure 9 for those (of order 8 and 10) not appearing in Tables 6 and 7.



(a) First (FE order 8) *torsion* mode.



(b) Second (FE order 10) *torsion* mode.

Figure 9: First two FE EM *uncoupled* modes of the free *smart* hybrid honeycomb sandwich.

4 CONCLUSIONS

The presently *unique* 3D *full* EM material properties dataset of the *multilayer* (5-layer) d_{31} MFC [7] has been validated against drop test [9] and EIA tests (Table 1) [10] of a *free* hybrid honeycomb sandwich, as a *host* structure and *smart* (with surface-bonded d_{31} MFC) one. Both structures were modelled by a detailed FE approach [9]-like *new* methodology, which was implemented via a C^{++} *application* new GUI that generates *commands* scripts, as input files for ANSYS® Mechanical APDL FE *modal* analyses. It was found that, for the *host* structure, the comparison of the only experimentally available *fundamental* mode frequency, a maximum 5.26 % error was obtained for the four configurations of Q4 and T3 *automatically* meshed skin/core/skin sandwich. Besides, for the *smart* structure with the same four mesh configurations of the host while the d_{31} MFC patch always meshed with P6 FEs, maximum errors of 5.83 % and 4.79 % were obtained, respectively, for the SC and OC (with EP constraints) MFC patch electrodes. Therefore, these good results clearly validate the presently *unique* 3D *full* EM material properties dataset of the *multilayer* (5-layer) d_{31} MFC [7].

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REFERENCES

- [1] M. Rebillat, M. Guskov, E. Balmès, and N. Mechbal, “Simultaneous influence of static load and temperature on the electromechanical signature of piezoelectric elements bonded to composite aeronautic structures,” *ASME Journal of Vibration and Acoustics*, vol. 138, art. no. 064504, 2016.
- [2] M. P. Saravanan, K. Marimuthu, and K. Jayabal, “Characteristic investigation of macro fiber composite structure using FE model,” *Archives of Metallurgy and Materials*, vol. 66, no. 4, pp. 1059-1066, 2021.
- [3] K. Steiger, and P. Mokry, “Finite element analysis of the macro fiber composite actuator: macroscopic elastic and piezoelectric properties and active control thereof by means of negative capacitance shunt circuit,” *Smart Materials and Structures*, vol. 24, art. no. 025026, 2015.
- [4] A. Zippo, G. Ferrari, M. Amabili, M. Barbieri, and F. Pellicano, “Active vibration control of a composite sandwich plate,” *Composite Structures*, vol. 128, pp. 100–114, 2015.
- [5] Y. Kuang, and M. Zhu, “Evaluation and validation of equivalent properties of macro fibre composites for piezoelectric transducer modelling,” *Composites Part B*, vol. 158, pp. 189-197, 2019.
- [6] M. A. Trindade, and A. Benjeddou, “Finite element characterisation of multilayer d_{31} piezoelectric macro-fibre composites,” *Composite Structures*, vol. 151, pp. 47-57, 2016.
- [7] M. A. Trindade, and A. Benjeddou, “Finite element evaluation of full 3D effective properties of d_{31} piezoelectric macro-fibre composites,” In *Proceedings of the Eighth International Conference on Smart Materials and Nanotechnology in Engineering*, M. Ghommam, A. Benjeddou, J. Leng and A. Abdelkefi (eds.), pp. 52-61, 2024.
- [8] A. Deraemaeker, S. Benelechi, A. Benjeddou, and A. Preumont, “Analytical and numerical computation of homogenized properties of MFCs : application to a composite boom with MFC actuators and sensors,” In *Proceedings of the III ECCOMAS Thematic Conference on Smart Structures and Materials*, W. Ostachowicz, J. Holnicki-Szulc, C. Mota Soares et al. (eds.), CD-ROM, 2007.
- [9] A. Benjeddou, and M. Guerich, “Free-vibration of actual aircraft and spacecraft hexagonal honeycomb sandwich panels: a practical detailed FE approach,” *Advances in Aircraft and Spacecraft Science*, vol. 6, no. 2, pp. 169-187, 2019.
- [10] A. Benjeddou, “Experimental evaluation of the effective electromechanical coupling of a vibrating aircraft-type hybrid honeycomb sandwich panel with bonded piezoelectric d_{31} macro-fibre composite (MFC) patch,” In *Proceedings of the Eighth International Conference on Smart Materials and Nanotechnology in Engineering*, M. Ghommam, A. Benjeddou, J. Leng and A. Abdelkefi (eds.), pp. 62-69, 2024.