ESA STUDY CONTRACT REPORT –

Deliverable D 2.1

Numerical and analytical sandwich structure analysis-technical note

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<tr><td>ESA Contract No:
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numerical and analytical sandwich structure analysis-technical note</td><td>CONTRACTOR:
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ABSTRACT:

The main emphasis of current interim report is focused on development steps towards numerical and analytical methods for simulation of CFRP/Al honeycomb sandwich structures under compressive loading with introduction of barely visible damage (BVID). As input parameters from specimen prototyping and physical testing was pending, initial effort was given for finite element model verification with physical tests obtained from non-destructive evaluation tests reported in WP-3. Therefore current report summarise results of sandwich equivalent stiffness identification by methodology described in ASTM E1876. Furthermore verification of detailed FEM model developed in commercial code ANSYS have been performed. All those verification cases have been provided in line with actual prototyping and NDE effort, thus detailed BVID and CAI simulations was shifted to next reporting period when models could be validated with physical tests.

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1 Introduction

The current deliverable summarise and address the analytical and numerical analysis. As input parameters from specimen prototyping and physical testing was pending during this period, all initial effort was given for finite element model verification with physical tests obtained from non-destructive evaluation tests reported in WP-3. Therefore current report summarise results of sandwich equivalent stiffness identification by analytical methodology described in ASTM E1876. Furthermore verification of detailed FEM model versus NDE by commercial FE code ANSYS have been performed. Such an approach brought more emphasis on prototyping part and assurance of specimen quality than focusing on residual load carrying capacity.

2 Analytical analysis based ASTM E 1876 methodology

A four step procedure have been elaborated based on ASTM E1876 methodology. This methodology provides an equivalent material property identification from physical self-frequency tests and simple weight measurements identifying the mechanical stiffness of tested specimen. It should be noted that methodology is primary developed for beams nevertheless it may be extended and updated for identification of plate stiffness as well. Therefore a dedicated tool for analysis was developed. A flow chart of test procedure is depicted in Figure 2.1

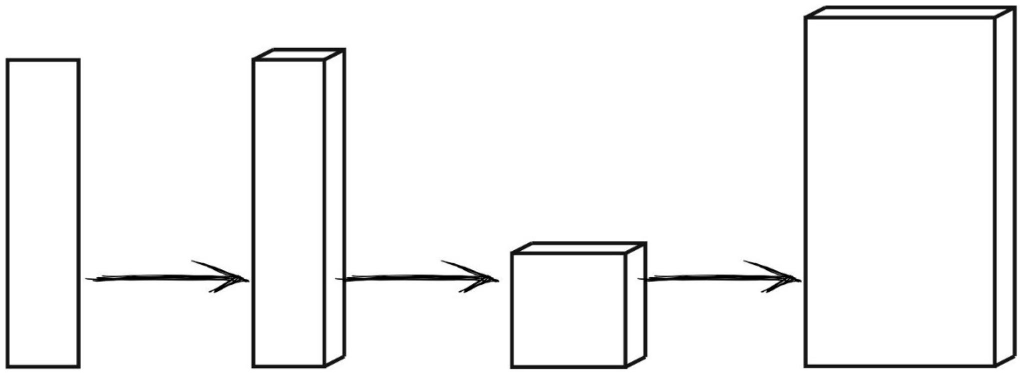


Figure 2.1. Flow chart of verification procedure

Initially, while mechanical property characterization was expected from WP-4 and only first steps in prototyping was done. Therefore a swift method for identifying realized mechanical properties were required. According to ASTM E 1876 standard the methodology requires – input parameters as *m* - mass; *b* – width; *l* - free span and *t* – thickness. Furthermore first few natural frequencies f_1 and f_2, which determine *Ex*, *G* and Poisson ratio *v*.

The natural frequencies and vibration modes were scanned using Polytec laser vibrometer (shown in figure 2.2). For structural excitation a loudspeaker placed 180° opposite the measured area. Measurement conducted in range from 0 to 600

Hz for skin plate and for sandwich beam/panel with “Free Free” boundary conditions (the specimens were hanged to tiny ropes). As there was non-contact measurement and excitation, the additional mass is not considered to influence the physical experiment.

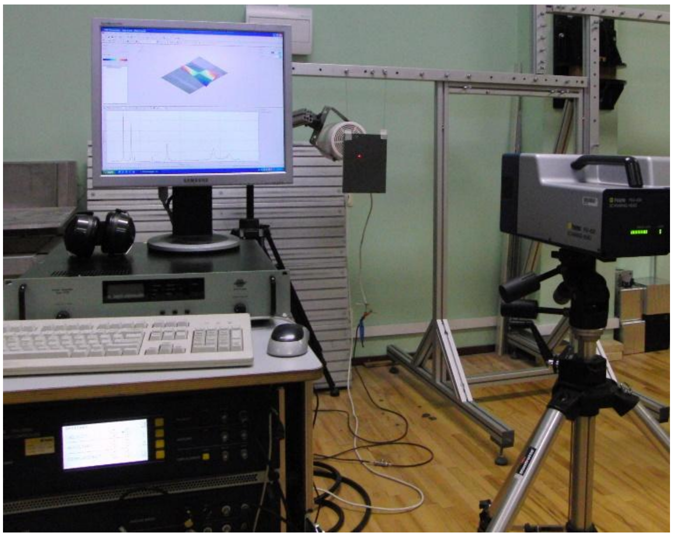


Figure 2.2. Physical testing procedure of beam/plate specimens

To begin with CFRP beams/strips was analysed in order to identify the mechanical properties. It should be noted that originally method considers isotropic material properties thus a special attention should be given to mode shape – half wave’s longitudinal and transverse direction. Based on this both Ex and Ey could be identified along with Gxy. It should be noted that Poison ratio showed no sensitivity and was neglected. Obtained results are more described in detail in following chapter of Specime#1. A following steps were similar for CFRP/Al honeycomb beam – Specimen #2 and small size panel Specimen series #3. And finally validated with actual size preliminary Specimens series #4 and final Specimens series #5 produced according to technical excellence. Summarised results are only partial effort, however highlights the principle and main challenges.

3 Finite element analysis

Sandwich honeycomb construction is modelled and analysed by ANSYS [1]. Model consists of components shown in Figure 3.1. Numerical analyses was carried out as Modal analyses and Block Lanzos method. Numerical model represents finite element model composed of SHELL281 shell elements used for sandwich structure Figure 3.2. The material properties of the sandwich components are:

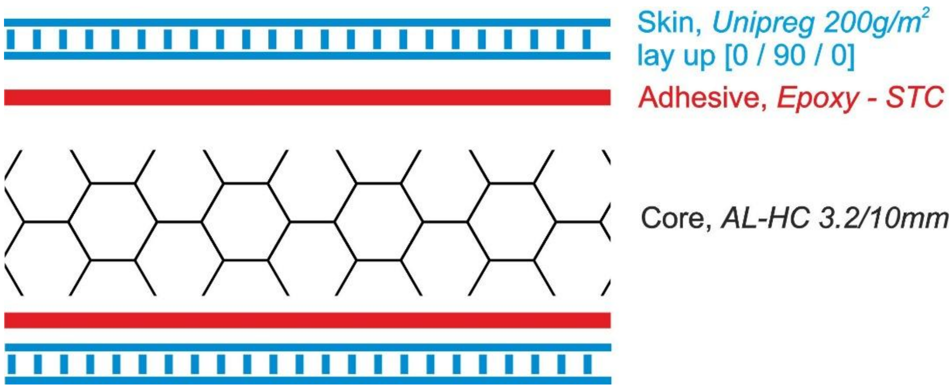


Figure 3.1. Schematic structure of sandwich panel.

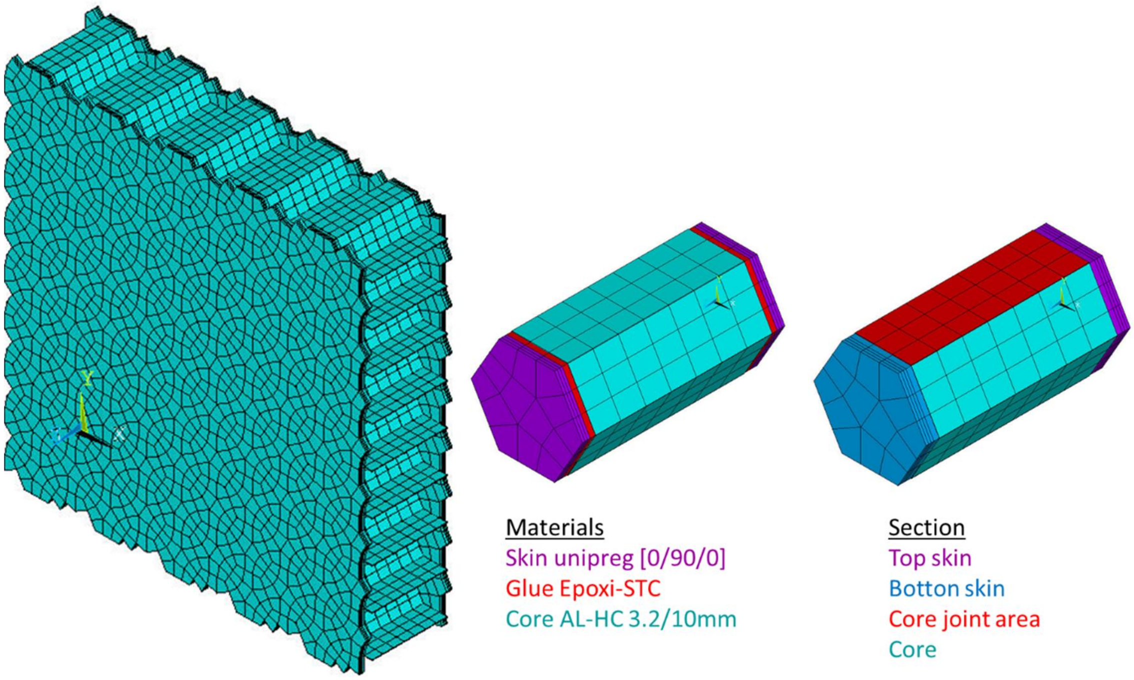


Figure 3.2. Finite element model of sandwich panel

During creation of model is necessary to consider coordinate system in which element is created, because in the case if whole model is built in global coordinate system the local orientation of model will be created toward to one side of area, which will lead to a lack of one direction in element (
Figure 3.3. Coordinate system in element.
Figure 3.3.a). Creating elements in new local coordinate system, which is matching to global one, the problem will be solved (
Figure 3.3.b).

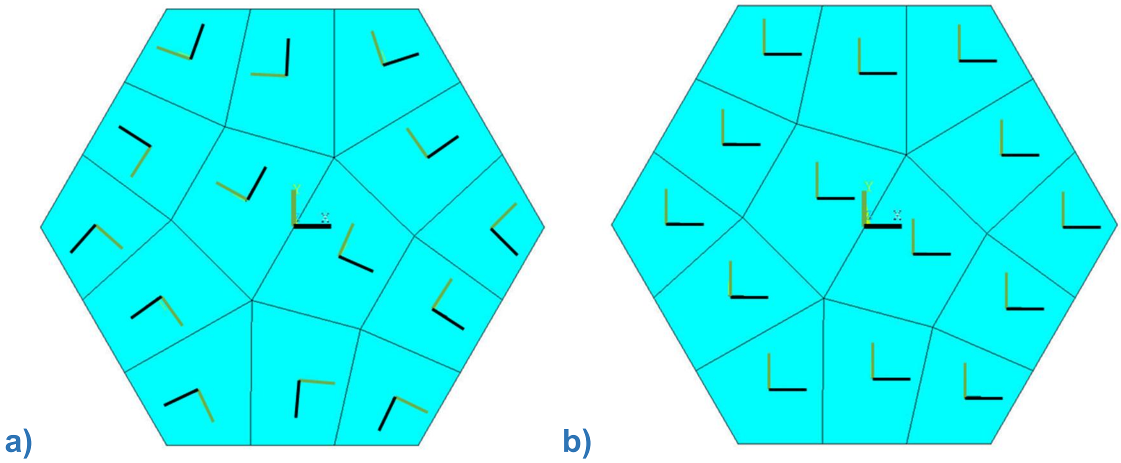


Figure 3.3. Coordinate system in element.
a) disorderly elements; b) ordered elements

A finite element mesh correlation have been performed and graphically presented in Figure 2.4, where one can outline that between 3 and 2 mm element mesh size is most appropriate for numerical simulation.

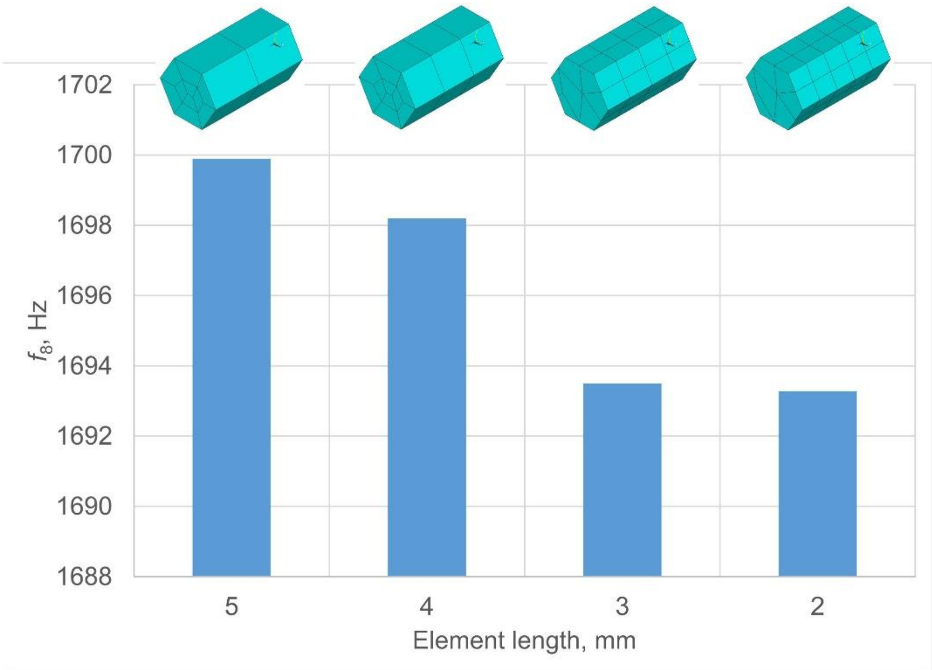


Figure 3.4. Correlation of FEM element mesh size

4 Result synopsis

4.1.1 Sample #1 (RTU code 905)

Initially produced scratch CFRP beams/strips was analysed in order to identify the mechanical properties as early as possible in project implementation phase. A dedicated numerical tool have been programmed. It should be noted that originally ASTME E1876 analysis method considers isotropic material properties thus a special attention should be given to mode shape forming half wave's longitudinal and transverse direction. Therefore first beam/strip specimen was manufactured from the UNIPREG pre-preg (200 g/m^2) considering 16 plies. Geometrical dimensions was 254.5 x 259.5 x 1.47 mm.

Experimental natural frequencies presented in Table 4.15. For dynamic Young's modulus, shear modulus and Poisson's ratio estimation by the ASTM E1876 [2]. Obtained equivalent mechanical properties are summarised in Figure 4.1. An alternative method for determination of material properties was carried out by Response surface method and design of experiment (DoE) [3]. Results obtained by using of two methods are collected in Table 4.1.

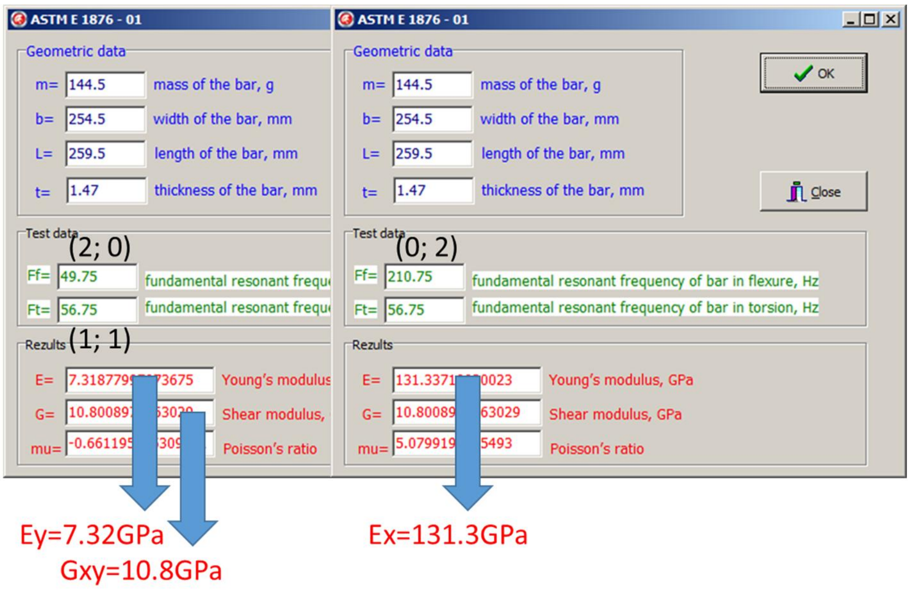


Figure 4.5 Standard ASTM E1876 by material properties determination by sample #1

Table 4.1. Material properties by sample#1

Parameters	ASMT	RSM/DoE
Young's modulus *E*x, GPa	131.3	132.6
Young's modulus *E*y, GPa	7.3	6.64
Shear modulus *G*xy, GPa	10.8	7.6

Sensitivity analysis of experimental results versus numerical calculations with finite element method is summarised in Table 4.2.

Table 4.2. Comparison Experimental Eigen-frequencies vs. FEM solution with data from ASTM and RSM/DoE by Sample #1

	(m; n)	f_{EXP} [Hz]	$f_{FEM, ASTM}$	Δ, %	$f_{FEM, DoE}$	Δ, %
1	(2; 0)	49.75	51.79	-4.10	49.41	0.68
2	(1; 1)	56.75	61.75	-8.81	52.25	7.93
3	(2; 1)	106.75	135.60	-27.03	117.36	-9.94
4	(3; 0)	142.25	143.63	-0.97	137.04	3.66
5	(3; 1)	200.75	211.23	-5.22	210.09	-4.65
6	(0; 2)	210.75	236.16	-12.06	212.28	-0.73
7	(1; 2)	236.50	244.68	-3.46	236.47	0.01
8	(4; 0)	271.25	284.32	-4.82	271.25	0.00
9	(2; 2)	290.00	330.85	-14.09	303.63	-4.70
10	(4; 1)	331.00	376.65	-13.79	342.74	-3.55
11	(3; 2)	371.50	451.01	-21.40	407.11	-9.59
12	(5; 0)	459.75	476.32	-3.60	454.41	1.16

*with red marked frequencies for which modes are shifted

4.1.2 Sample #2 (RTU code 920 SP-X)

As next step a sandwich beam/strip with honeycomb core was manufactured from the UNIPREG Pre-preg (200g/m^2) and three layers layup [0/90/0], core material AL-HC 3.2 height 10mm and adhesive material Epoxy – STC thickness approximately 0.3 mm. Dimensions sample are length 233mm, width 17.18, thickness 11.3 mm and total weight of 11g.

A frequency response graph and modes summarised in Figure 4.6. Also Eigen- frequency value are

$$f(2;0) = 1507.8Hz; \quad f(3;0) = 3656.3Hz;$$
$$f(4;0) = 6161.7Hz; \quad f(5;0) = 8851.6Hz;$$

By using 1st bending frequency $f(2;0) = 1507.8Hz$ obtained from experiment, specimen dimensions and ASTM E1876 methodology it is possible to determine equivalent properties of the specimen, specifically Young's modulus which was determined at level of 12.3 GPa –depicted in Figure 4.. Furthermore Sample #2 was physically tested in 4-point bending test obtaining Young's modulus much lower - 9.08 GPa value.

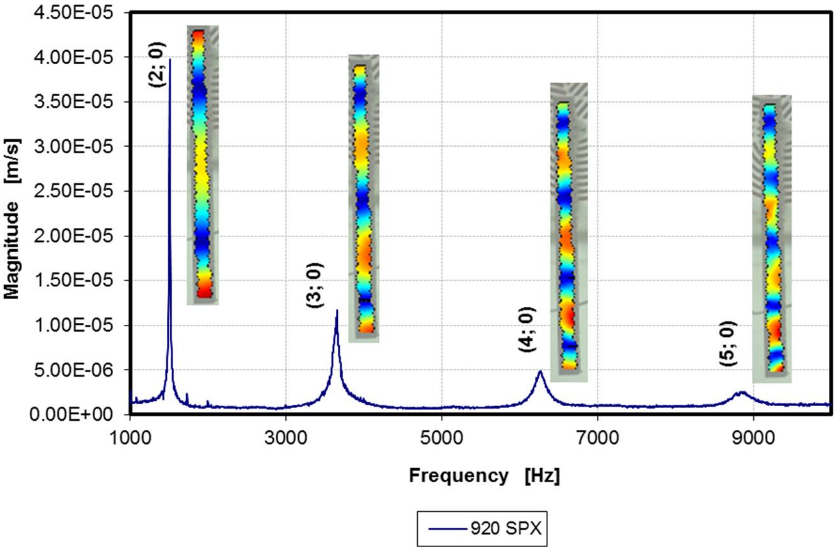
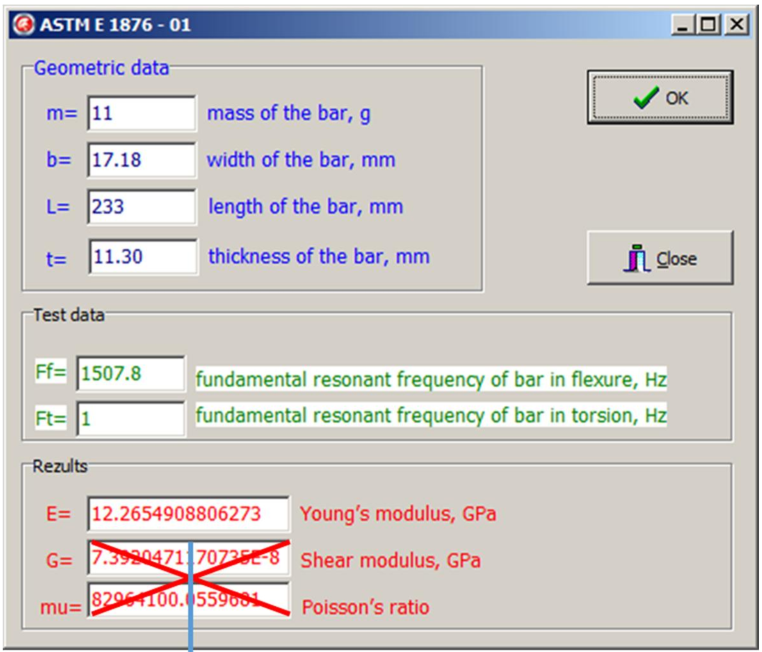


Figure 4.6. Eigen frequency response and modes by sample#2

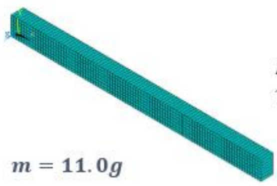


$$E = 12.3GPa$$

Figure 4.7. Standard ASTM E1876 by material properties determination by sample #2

Obtained properties were used to compare the equivalent model with physical experiment. Furthermore a detailed element mesh size correlation calculation was performed where Eigen-frequency served as reference response value. The model, influence of element size and self-modes presented in Figure 4.8.

Equivalent model shown very high convergence for first frequency, deviation is 0.2%. Increase of frequency leads to increase of deviation from experimental results, where deviation exceeds 10%.



$m = 11.0g$

$E = 12.3GPa$
$v = 0.3$

Modes (m; n)	Elements sizy 5mm	Elements sizy 2.5mm
(2; 0)	1509	1509
(3; 0)	4097	4097
(4; 0)	7865	7865
(5; 0)	12662	12662

Equivalent material properties

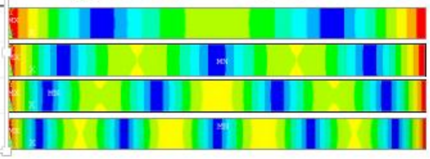


Figure 4.8. Equivalent model, effect of FE size, Eigen-modes

Actual detailed model was elaborated for studying of sensitivity of the cover panel Young’s modulus. It was confirmed that by increasing of Young’s modulus in X direction from 132.6 to 152.6 GPa led to decrease of an average deviation of calculated results from experimental results: 6.5% to 1.5%. Moreover it also decreased absolute value of deviation from 11.8% to 6.2%. Comparison of two models (equivalent model`s and actual models`s) with experiment results are shown in
Table 4.3

Table 4.3. Comparison Experimental Eigen-frequencies vs. FEM solution equivalent model and real model by Sample #2

Modes (m; n)	EXP	FEM EM	Δ, %	FEM RM Ex=132.6	Δ, %	FEM RM Ex=152.6	Δ, %
(2; 0)	1507	1509	-0.13	1330	11.75	1414	6.17
(3; 0)	3656	4097	-12.1	3365	7.96	3566	2.46
(4; 0)	6262	7865	-25.6	5932	5.27	6266	-0.06
(5; 0)	8851	12662	-43.1	8739	1.27	9201	-3.95

4.1.3 Sample series #3 (RTU code 920 SP-1, 2, 3, 4)

Initial coupon scale sandwich panels assembled from UNIPREG 200g/m^2 pre-preg skins with layup of three layers [0/90/0] and 10 mm thick aluminium honeycomb core with cell size of 3.2 mm and STC epoxy adhesive with thickness approximately 0.3 mm was produced and tested. Dimensions of each specimen was 50 x 50 x 11.3 mm and average weight 6.93g. A frequency response graphs and modes summarized in Figure 4.9. Also Eigen-frequency value are presented in
Table 4.4.

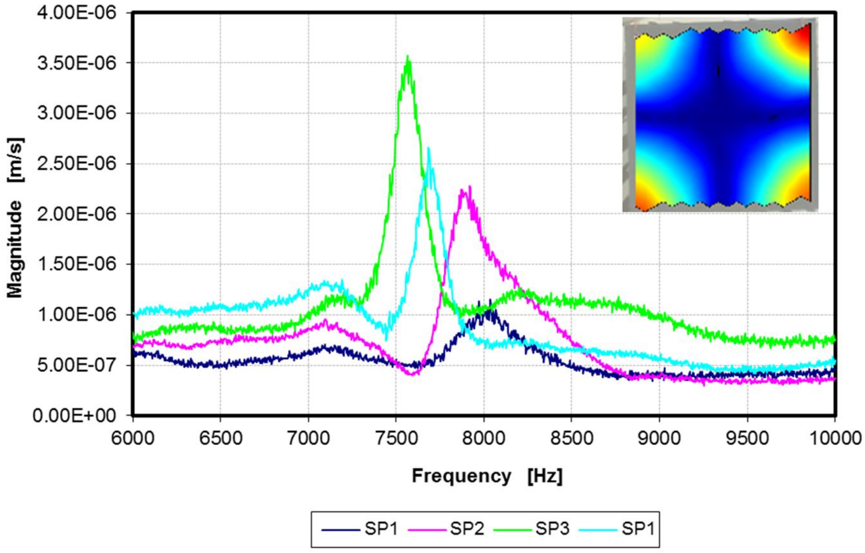


Figure 4.9 Eigen frequency response and mode by samples #3

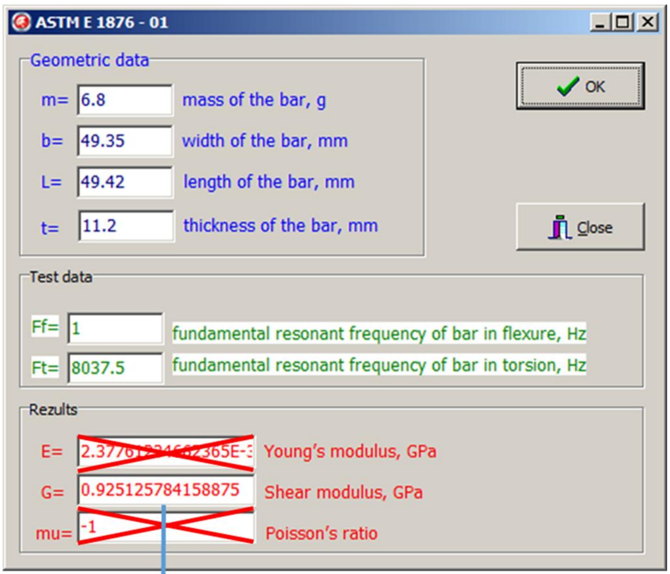
Table 4.4 Eigen frequency and weight value by samples series #3

Frequency	SP1	SP2	SP3	SP4	AVE
(1; 1)	8037.5	7918.8	7562.5	7684.4	7800.8
%	3.03	1.51	-3.05	-1.49	
m, g.	6.8	6.45	7.35	7.10	6.93

By using value of 1st torsion frequency $f(1;1) = 8037.5Hz$ which is obtained from experiment, specimen dimension values and ASTM E1876 methodology it is possible to calculate equivalent shear modulus Figure 4.10.

Using real model and chancing skin's shear modulus value, which is influencing torsion frequency it is possible to find optimal shear modulus of skin. For example, at *G*=7.62 GPa frequency is $f(1;1) = 8886Hz$, changing *G* to 5.62 GPa, frequency changes to $f(1;1) = 8058Hz$. If shear modulus is decreased to 3.62 GPa frequency is $f(1;1) = 6949Hz$. From reviewed data it can be concluded that for future calculations will be used shear modulus with value 5.62 GPa (Figure 4.11.).

Comparison of real model and model constructed in ANSYS also is possible to carry out by using specimen mass $m_{Real,\ avg}$=6.93g. and m_{FEM}=6.87g.



	SP1	SP2	SP3	SP4	AVE
G, GPa	0.925	0.857	0.888	0.886	0.89

Figure 4.10. Standard ASTM E1876 by material properties determination by sample series #3

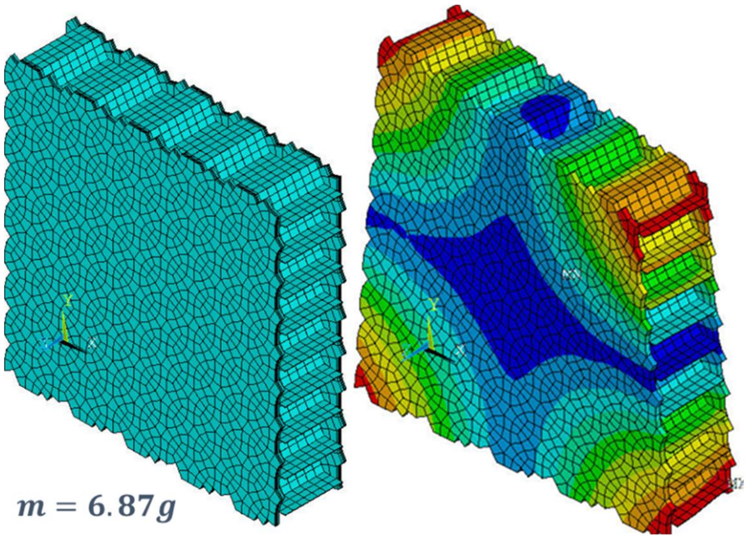


Figure 4.11 FE model and Eigen-mode (1; 1)

4.1.4 Sample series #4 (RTU code 919 SP-1, 2)

A specimens with dimensions corresponding to 150 x 100 compression after impact standard were manufactured from the UNIPREG 200g/m^2 pre-preg. Consisting of three layers CFRP laminate [0/90/0], aluminium honeycomb core (thickness 10 mm, cell size 3.2 mm) and STC epoxy adhesive with thickness approximately 0.3 mm. Dimensions of specimens are presented in Table 4.5. A frequency response graph summarized in Figure 4.22.

Table 4.5 Dimension of sample series #4

SP name		Geometry				
		A, mm	B, mm	t, mm	mass, g	Ro, kg/m3
919	SP1	153.7	98.8	11.27	39.55	231.16
	SP2	157	97.7	11.11	43.35	254.34

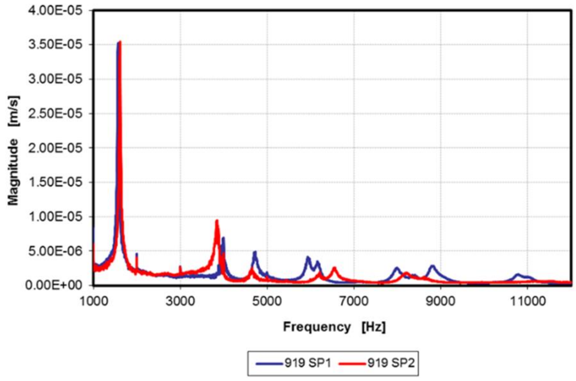
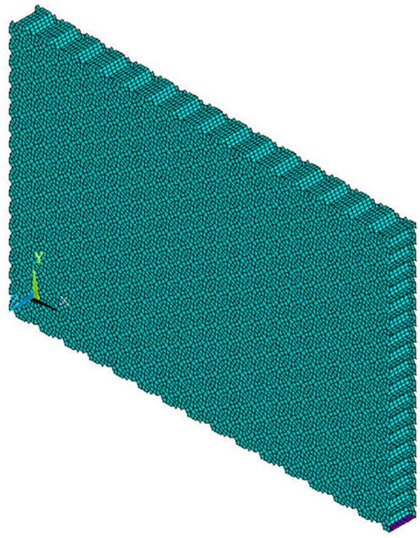


Figure 4.22 Eigen frequency response by samples series #4

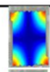
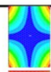
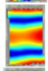
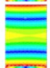
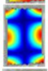
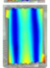
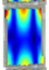
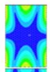
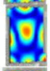
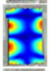
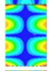
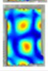
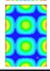
Analysis of actual detailed model was carried out by using corrections in mechanical properties of skin plates obtained by improved calculations in § 4.1.2 and § 4.1.3 (shown in Figure 4.33). Comparison of real and calculated values is shown in Table 2.6.



$$E_{Al} = 68.9GPa$$
$$E_{gl} = 2.5GPa$$
$$E_{X,skin} = 152.6GPa$$
$$E_{Y,skin} = 6.64GPa$$
$$G_{XY,skin} = 5.62GPa$$

Figure 4.33 Real model and mechanical properties

Table 4.6 Eigen frequency and Eigen-modes by sample series #4

Modes (m; n)	919 SP1	Δ, %	919 SP2	Δ, %	Modes	ANSYS	Modes
(1;1)	1566.4	7.51	1613.3	-4.38		1684.0	
(0;2)	3984.4	1.59	3853.5	-1.75		3921.1	
(1;2)	4727.9	-0.30	4650.0	-1.98		4742.2	
(2;0)	5937.5	-16.88	6210.0	-11.75		6939.7	
(2;1)	6160.2	-19.35	6552.3	-12.21		7352.4	
(2;2)	7996.1	-11.62	8212.9	-8.68		8925.4	
(1;3)	8402.3	1.93				8239.8	
(2;3)	8826.2	-29.07	8648.4	-31.72		11391.7	

4.1.5 Sample series #5 (RTU code ESA 001, ESA 002, ESA 003, ESA 004)

Finally several proper size sandwich panels was manufactured and delivered for identification purposes. They been labelled ESA 001, ESA 002, ESA 003, and ESA 004. Furthermore an appropriate mechanical characteristics done within WP - 4. For each component of panel (skins, adhesive and core) has properties as listed below.

- Properties for unidirectional carbon fibre pre-preg laminate (Unipreg 100g/m^2)
  $$E_x = 122.69GPa, E_y = E_z = 8.39GPa \;\; G_{xy} = G_{xz} = G_{yz} = 6.07GPa \;\; v_{xy} = v_{xz} = v_{yz} = 0.27 \;\; \rho = 1560kg/m^3$$
  The thickness of skin in sandwich panel is 0.261mm (1 layer-0.087mm) and layup – [+60/0/-60].
- Adhesive. Trade name Permabond ET538. Adhesive layer thickness is 0.37mm. $E = 2.5GPa \;\; v = 0.3 \;\; \rho = 1250kg/m^3$
- Aluminium honeycomb has thickness 10mm, cell size 3.2mm and foil thickness 0.035mm. $E = 70GPa \;\; v = 0.33 \;\; \rho = 2700kg/m^3$

Table 4.7. Dimension of sample series #5

SP name		Geometry: Length, mm	Width, mm	Thickness, mm	Mass, g	Density, kg/m^3
ESA	001			11.28	237.1	217.6
ESA	002	460	210	11.27	240.2	220.7
ESA	003			11.14	225.7	209.7

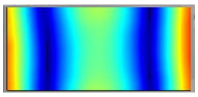
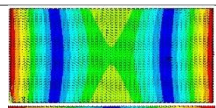
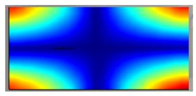
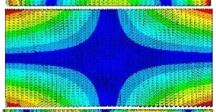
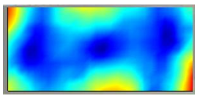
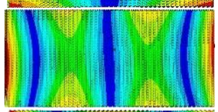
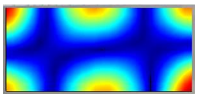
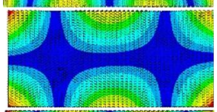
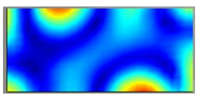
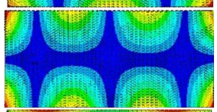
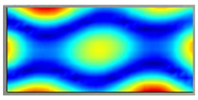
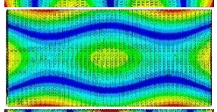
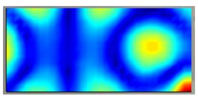
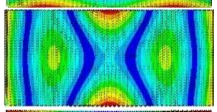
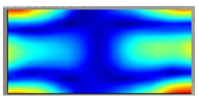
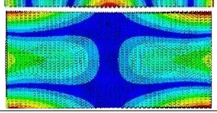
ESA	004	11.11	221.0	205.9

The special attention was given for verification of proper scale panel FEM mesh element size correlation. The convergence of the finite element method is presented in Table 4.8. Comparison of real and calculated values is shown in Table 4.9.

Table 4.8. Convergence of finite element method

Frequency, Hz (m; n)	Elements size, 2 mm	Elements size, 3 mm	Elements size, 4 mm
1 (0; 2)	320.13	320.15	320.98
2 (1; 1)	405.97	406.01	406.98
3 (1; 2)	868.99	869.02	871.62
4 (0; 3)	870.23	870.30	872.66
5 (2; 0)	1439.8	1439.9	1443.5
6 (1; 3)	1455.0	1455.5	1460.3
7 (2; 1)	1634.0	1634.5	1639.6
8 (0; 4)	1693.3	1693.5	1698.2

Table 4.9. Comparison of experimental frequencies and waveforms with frequencies from ANSYS

f **Hz (m; n)**	**EXP**		**FEM**		**Δ, %**
1 (0; 2)	301.25		320.15		-6.27
2 (1; 1)	393.13		406.01		-3.28
3 (1; 2)	811.25		869.02		-7.12
4 (0; 3)	832.50		870.30		-4.54
5 (2; 0)	1388.75		1439.9		-3.68
6 (1; 3)	1410.63		1455.5		-3.18
7 (2; 1)	1573.75		1634.5		-3.86
8 (0; 4)	1615.00		1693.5		-4.86

A frequency response graph summarized in Figure 4.24. Also Eigen-frequency value are presented in Table 4.610 and Eigen modes are presented in Table 4.611.

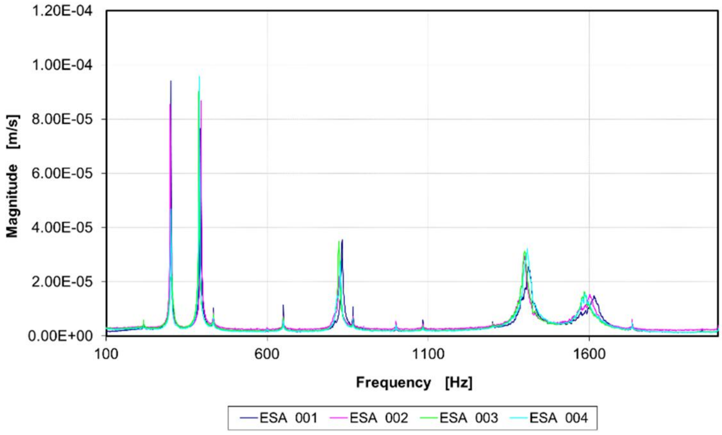
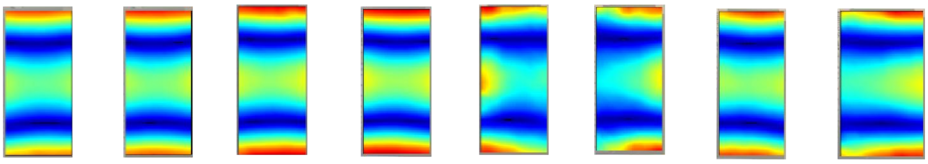
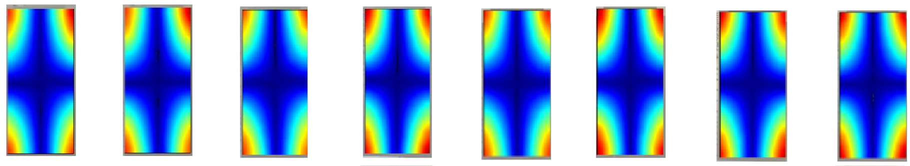
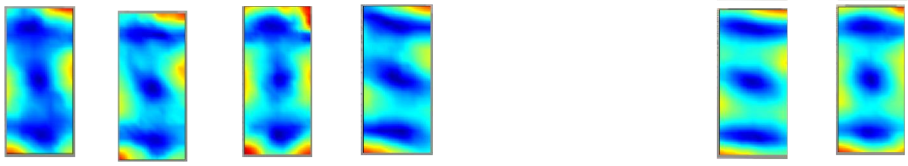
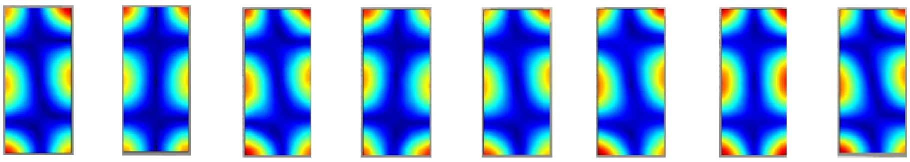
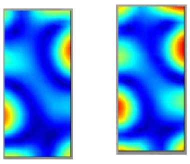
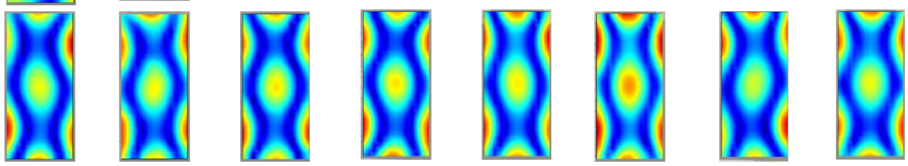
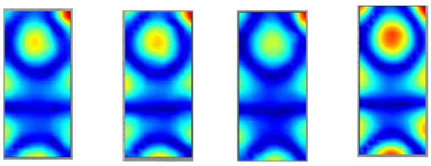
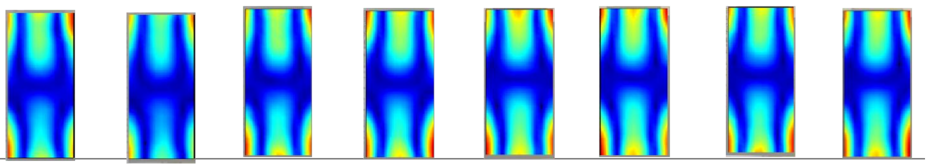


Figure 4.44 Eigen frequency response by samples series #5

Table 4.10 Eigen-frequency by sample series #5

#	mode	ESA 001		ESA 002		ESA 003		ESA 004	
	(m; n)	**view A**	**view B**	**view A**	**view B**	**view A**	**view B**	**view A**	**view B**
1	**(0; 2)**	301.25	301.25	299.38	299.38	303.13	298.75	301.25	298.75
2	**(1; 1)**	393.13	393.13	395.00	395.00	388.13	388.75	390.00	390.00
3	**(0; 3)**	811.25	810.63	810.00	806.25			818.13	818.13
4	**(1; 2)**	832.50	831.88	824.38	824.38	822.50	823.13	827.50	827.50
5	**(1; 3)**	1388.75	1388.13						
6	**(2; 0)**	1410.63	1410.63	1397.50	1398.13	1398.75	1398.13	1407.50	1407.50
7	**(0; 4)**	1573.75	1574.38	1575.00	1574.38				
8	**(2; 1)**	1615.00	1615.00	1601.25	1601.25	1585.00	1585.63	1586.25	1586.25

Table 4.11. Eigen-modes for sample series #5

mode	ESA 001		ESA 002		ESA 003		ESA 004	
(m; n)	view A	view B	view A	view B	view A	view B	view A	view B
(0; 2)								
(1; 1)								
(0; 3)								
(1; 2)								
(1; 3)								
(2; 0)								
(0; 4)								
(2; 1)								

5 Conclusions

Currently based on ASTM E1876 methodology the determination of specimen equivalent stiffness have been analysed. Such swift approach provided necessary – preliminary mechanical properties for more detailed FEM analysis. Furthermore a detailed FEM model in commercially available code ANSYS have been developed and verified with physical experiments of initial CFRP/Al-honeycomb sandwich panels.