UNIVERSITY OF MISKOLC
FACULTY OF MECHANICAL ENGINEERING AND INFORMATICS

MINIMUM WEIGHT AND COST DESIGN OPTIMIZATION OF HONEYCOMB SANDWICH STRUCTURES

Booklet of PhD Theses

PREPARED BY:
ALAA ABDULZAHRA DELI AL-FATLAWI

ISTVÁN SÁLYI DOCTORAL SCHOOL
TOPIC FIELD OF MECHANICAL ENGINEERING SCIENCES
TOPIC GROUP OF APPLIED MECHANICS

HEAD OF DOCTORAL SCHOOL
Dr. Gabriella Bognár
DSc, Full Professor

SCIENTIFIC SUPERVISOR
Dr. Károly Jármai
DSc, Full Professor

&

Dr. György Kovács
Dr. habil, Associate Professor

Miskolc
2021

JUDGING COMMITTEE

Chair:	Prof. Dr. Edgár Bertóti, DSc, University of Miskolc,
Secretary:	Dr. Tamás Szabó, PhD, University of Miskolc,
Members:	Dr. Balázs Pere, PhD, István Széchenyi University, Győr,
	Dr. Zoltán Virág, PhD, University of Miskolc,
	Prof. Dr. János Égert, István Széchenyi University, Győr.

OFFICIAL REVIEWERS

Dr. Tamás Mankovics, PhD, University of Debrecen,

Dr. Ferenc J. Szabó, PhD, University of Miskolc.

1. INTRODUCTION

Sandwich plates, consisting of a core covered by face-sheets, are frequently used instead of solid plates because of their high bending stiffness-to-weight ratio. The high bending stiffness results from the distance between the face-sheets, which carry the load, and the lightweight is due to the lightweight of the core. The core may be foam or honeycomb and must have a material symmetry plane parallel to its midplane; its in-plane stiffnesses must be small compared with the in-plane stiffnesses of the face-sheets. The sandwich plates with face-sheets on both sides of the core. Each face-sheet may be anisotropic material like aluminum alloy or a fiber-reinforced composite laminate like epoxy woven glass fiber, epoxy woven carbon fiber, and hybrid composite layers (a combination of epoxy woven glass fiber layers and epoxy woven carbon fiber layers) but must be thin compared with the core. The honeycomb sandwich structure provides low density and relative out-of-plane compression and shear properties. Honeycomb structures are natural or human-made structures with the honeycomb architecture to reduce the amount of materials used in industrial applications to achieve minimum weight and minimum cost. Honeycomb sandwich structures have made a remarkable development in engineering applications over the past 40 years. The application of honeycomb structures ranges from the aerospace and automobile industry to structural application. Expanded honeycomb structure production reached an astonishing degree of automation in the first decade of the 20th century. There is interest in investigating these honeycomb structures' performance and efficiency in multi-disciplinary applications due to their high specific strength [1-3].

1.1. SANDWICH PANELS

Sandwich panels, a class of structural composites, are designed to be lightweight beams or panels having relatively high stiffnesses and strengths. A sandwich panel consists of two outer sheets, faces, or skins separated by an adhesively bonded to a thicker core. The outer sheets are a relatively stiff and strong material, typically aluminum alloys, steel, and stainless steel, fiber-reinforced plastics, and plywood; they carry bending loads applied to the panel. When a sandwich panel is bent, one face experiences compressive stresses, the other tensile stresses. The core material is lightweight and typically has a low modulus of elasticity. Structurally, it serves several functions. First, it provides continuous support for the faces and holds them together. It must also have sufficient shear strength to withstand transverse shear stresses and be thick enough to provide high shear stiffness (to resist buckling of the panel). Tensile and compressive stresses on the core are much lower than on the faces. Panel stiffness depends primarily on the core material's properties and core thickness; bending stiffness increases significantly with increasing core thickness. Furthermore, faces must be bonded firmly to the core. The sandwich panel is a cost-effective composite because core materials are less expensive than the faces' materials. Core materials typically fall within three categories: rigid polymeric foams, wood, and honeycombs. The widespread core consists of a honeycomb structure with thin foils formed into interlocking cells (having hexagonal and other configurations), with axes oriented perpendicular to the face planes; Figure 1 shows a cutaway view of a hexagonal honeycomb core sandwich panel.

Mechanical properties of honeycombs are anisotropic: Tensile and compressive strengths are most significant in a direction parallel to the cell axis; shear strength is highest in the panel's plane. The strength and stiffness of honeycomb structures depend on cell size, cell wall thickness, and the honeycomb material. Honeycomb structures also have excellent sound and vibration damping characteristics because of the high volume fraction of void space within each cell. Honeycombs are fabricated from thin sheets. Materials used for these core structures include metal alloys, aluminum, titanium, nickel-based, stainless steels, polymers, polypropylene, polyurethane, and kraft paper [4].

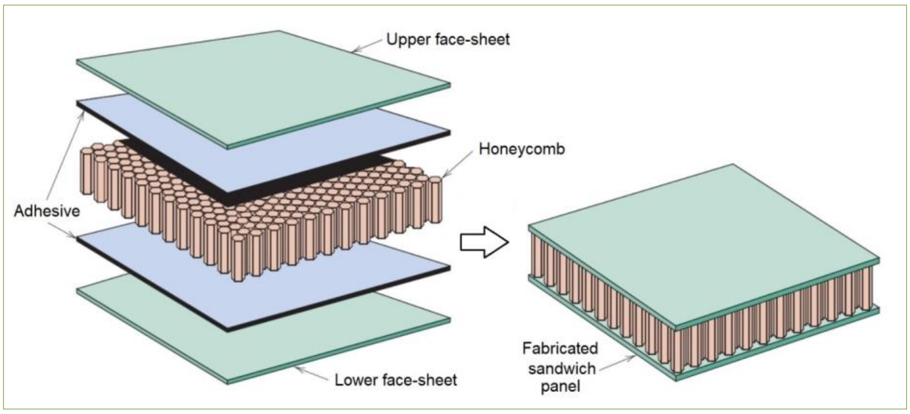

Figure 1: Schematic diagram showing the construction of a honeycomb sandwich panel.

1.2. Research Objectives

Several main goals of the covert research investigation have been identified to solve this problem:

- Identify the honeycomb sandwich structure's mechanical behavior through a series of static and dynamic tests to manufacture the required applications.
- Investigation how to optimize the honeycomb sandwich structure in terms of weight and/or cost both separately and simultaneously.
- We are exploring the hybrid composite material using high cost, high stiffness composites (carbon fiber) with low price, lower stiffness (glass fiber) in sandwich applications.
- Development methods to choose optimal solutions based on minimizing both weight and/or cost under require constraints.
- Identify the optimum face-sheets thickness and stacking angle of composite configuration in terms of minimum weight and minimum cost under certain load constraints.

1.3. Literature Review

This literature review provides motivations to the present dissertation on topics related to this thesis: optimization, analytical models, analysis methods, novel designs of composite sandwich structures due to the desired design requirements in some sandwich structure applications, composite material effects, and hybrid on the sandwich structure. In 2016, Liu et al. explored the characteristics of crashworthiness and mechanism of failure for square tubes of carbon fiber reinforced plastic (CFRP) filled with aluminum honeycomb subjected to quasi-static axial crushing [5].

In 2016, Karen et al. presented a hybrid evolutionary optimization technique based on the Multi-Island Genetic Algorithm [6]. In 2017, Yan et al. studied the effects of face-sheet materials on the mechanical properties of aluminum foam sandwich under three-point bending using a WDW-T100 electronic universal tensile testing machine [7]. In 2017, Adel & Steven presented a methodology for a combined weight and cost optimization for sandwich plates with composite face-sheets and foam core. The hybrid sandwich plates' weight and cost considered objective functions are subject to required equality constraints based on the bending and torsional stiffnesses [8]. In 2017, Arild optimized the wall of the shelters to reduce the weight. The shelters' deflection was calculated both analytical and numerical, with four random pressures to verify the inverse stiffness calculation [9]. In 2017, Ingrole et al. presented novel design and performance improvement of new auxetic-strut and hybrid honeycomb structures for in-plane property enhancement [10]. In 2017, Wu et al. identified the crash responses and crashworthiness characteristics of bio-inspired sandwich structures formed of carbon fiber reinforced plastic (CFRP) panels and aluminum honeycomb core [11]. In 2017, Liu et al. investigated the lateral planar crushing and bending responses of carbon fiber reinforced plastic (CFRP) square tube filled with an aluminum honeycomb core [12].

In 2017, Zaharia et al. analyzed and determined the CFRP-Nomex sandwich structures specimens' mechanical properties to different types of tests, such as three-point bending, compression, and impact [13]. In 2017, Kececi and Asmatulu investigated the hydrophobic barrier films utilized to prevent moisture ingression into honeycomb sandwich structures [14]. In 2017, Hambric et al. redesigned a rotorcraft roof composite sandwich panel to optimize the loss of sound power transmission and minimize the structure-borne sound. The gear meshing noise from the transmission has the most impact on speech intelligibility. The roof is framed by a grid of ribs constructed of honeycomb core and composite face-sheet [15]. In 2017, Wang et al. carried out comprehensive investigations of honeycomb structures embedded with the inclined cells to understand the mechanical behavior subjected to compression [16]. In 2017, Yalkin et al. improved the out-of-plane tensile and compressive performances of foam core composite sandwich structural regarding the simplicity of application and time consumption [17]. In 2018, Wang et al. studied the effects of aluminum honeycomb core thickness and density on the laminate material properties by three-point bending and panel peeling tests [18]. In 2018, Iyer et al. investigated a comparative study between three points and four points bending sandwich composites made of rigid foam core and glass epoxy skin [19]. In 2018, Chawa and Mukkamala optimized a shipping container made of sandwich panels to reduce tare weight and stresses [20]. In 2019, Florence & Jaswin investigated vibrational analysis and flexural behavior of hybrid honeycomb core sandwich panels filled with three different energy-absorbing materials experimentally [21]. In 2019, Teng et al. used the multi-objective optimization method to optimize compression strength, shear strength, and weight of the new type of solar panel structure [22]. In 2020, Zaharia et al. performed compression, three-point bending, and tensile tests to evaluate lightweight sandwich structures' performance with different core topologies [23]. In 2020, Yan B. et al. investigated the honeycomb sandwich structure's mechanical performance with face-sheet/core debonding under a compressive load by experimental and numerical methods [24]. In 2021, Aborehab et al. discussed the mechanical behavior of an aluminum honeycomb structure exposed to flat-wise compressive and flexural testing. They proposed finite element model based upon the sandwich theory to simulate the flexural testing's elastic behavior [25].

2. MECHANICAL TESTS ON PREPREG SANDWICH CONSTRUCTIONS

2.1. INTRODUCTION

Evaluating a sandwich panel's structural performance by conducting various mechanical tests consists of static and dynamic measurements such as four-point bending test, climbing drum peel test, forced vibration test, and damping test (Jones Measurement). The following tests are performed on sandwich panels.

2.2. MATERIALS AND METHODS

2.1.1. FOUR-POINT BENDING TEST OF HONEYCOMB SANDWICH PANELS

This test method is intended to determine the relationship between load and displacement as well as skin stress. The specimen lies on a span length, and the stress is uniformly distributed between the noses of loading. The sandwich panels' samples are made of an aluminum honeycomb core and orthotropic composite material face-sheets (see Figure 2). The composite face-sheets are made of phenolic woven glass fiber. The fiber orientation of the composite face-sheets was cross-ply. These specimens were made in the Kompozitor Ltd. Company. Numerical models are made for the same samples using the Digimat-HC modeling program to calculate the deflection, skin stress, and core shear stress to compare with the experimental results [26]. Table 1 represents the experimental and numerical results (four-point bending test) for the set of honeycomb sandwich specimens (see Figures 3 & 4).

Table 1: Technical data and experimental test results by applying the four-point bending test in the Kompozitor Company and numerical models using the Digimat-HC program for honeycomb sandwich specimens set.

Index	Length	Span	Width	Core thickness	Face-sheet thickness	Load	Skin stress	Core shear stress	Deflection		Differ-ence
	l	s	b	t_c	t_f (N_l)	P	σ_{skin}	τ_{core}	δ_{Exp}	δ_{Num}	
	mm	mm	mm	mm	mm (Layer)	N	MPa	MPa	mm	mm	%
1	460	400	100	15	1 (2-2)	1400	46.9	0.763	9	9.506	5.32
2					1 (2-2)	1500	50.3	0.818	10.2	10.185	0.15
3					1 (2-2)	1600	53.6	0.872	11	10.864	1.24
4				19	2 (4-4)	1650	44.8	0.675	5.7	5.345	6.23
5					2 (4-4)	1950	53	0.798	7	6.317	9.76
6					2 (4-4)	2000	54.4	0.818	6.5	6.479	0.32
7					2.5 (5-5)	1800	52.4	0.687	4.5	4.854	7.29
8					2.5 (5-5)	1900	50.5	0.74	5	5.357	6.66

Figure 2: Experimental specimens (four-point bending test) for the sandwich panels consisting of aluminum honeycomb core and phenolic woven glass fiber face-sheet.

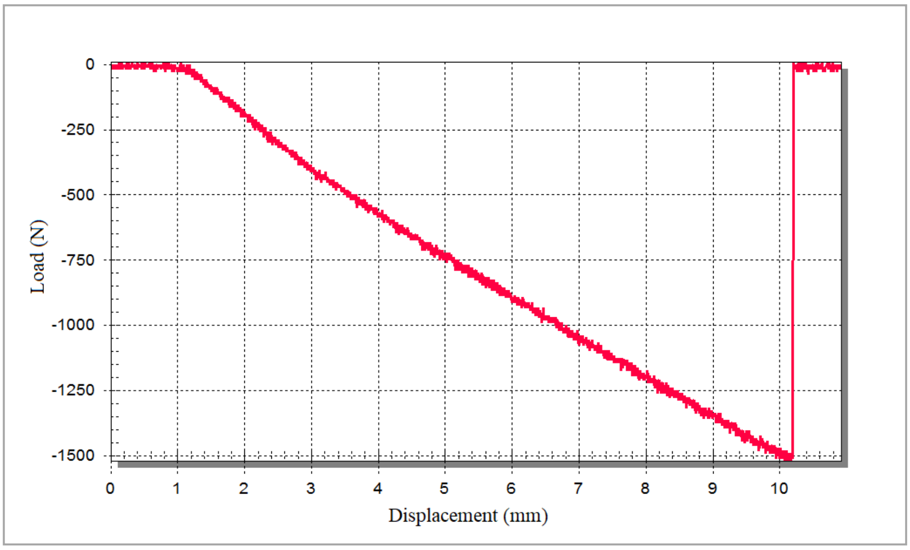

Figure 3: Experimental result (four-point bending test) for the specimen of the sandwich panel under applied load (P=1500 N) consisting of an aluminum honeycomb core (t_c=15 mm) and phenolic woven glass fiber face-sheets (t_f=1 mm).

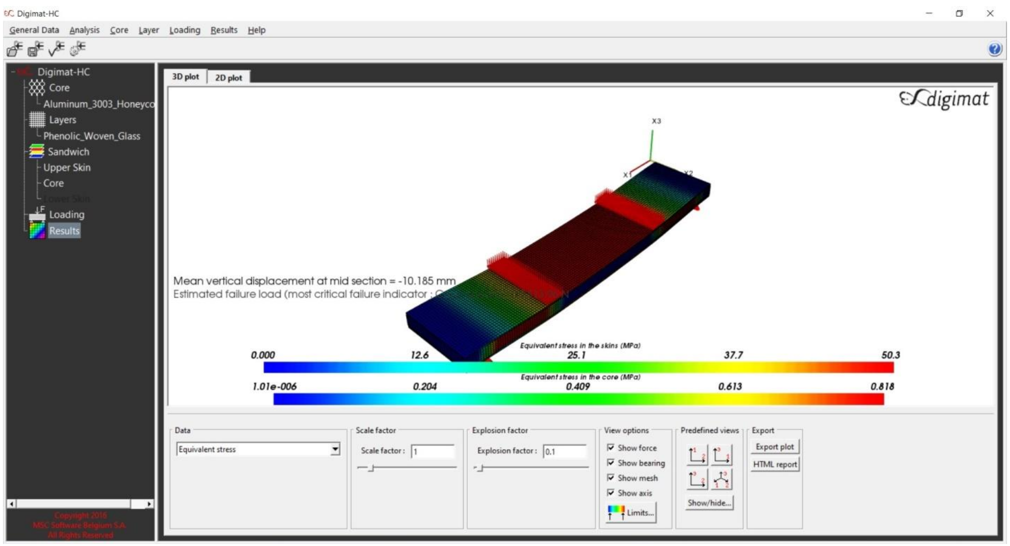

Figure 4: Numerical result (four-point bending test) for the specimen of the sandwich panel under applied load (P=1500 N) consisting of an aluminum honeycomb core (t_c=15 mm) and phenolic woven glass face-sheets (t_f=1 mm).

2.1.2. CLIMBING DRUM PEEL TEST

This test method is intended to determine the adhesive bonds' peel resistance between the facing skins and the sandwich panel's core (see Figure 5). As the test progresses, an average constant torque level necessary to peel the adhesive will be reached. However, this torque level will include the amount of torque required to roll the bare skin, so this level should be predetermined. That number can then be subtracted from the actual reading to arrive at a meaningful measure of the adhesive's peel strength. This test is referring to MIL-STD-401B Sec.5.2.6 or ASTM D-1781. The peel resistance force F_p and the average peel torque T can be calculated by the following equation [27]:

$$F_p(N) = F_r - F_i \tag{1}$$

$$T = \frac{F_p(R_o - R_i)}{b} \tag{2}$$

The specimens of sandwich panels are made of an aluminum honeycomb core and composite material face-sheets. The composite face-sheets are made of phenolic woven glass fiber. The fiber orientation of the composite face-sheets was cross-ply (0°, 90°). The specimens were manufactured and tested in the Kompozitor Ltd. Company. The honeycomb core thickness does not affect the adhesive's peeling resistance between the face-sheets and the sandwich structure's core, but the thickness of the face-sheets affects. Because the thicker face-sheets, the harder it bends on the drum. These results of peeling resistance and force are shown in Table 2 and Figure 6.

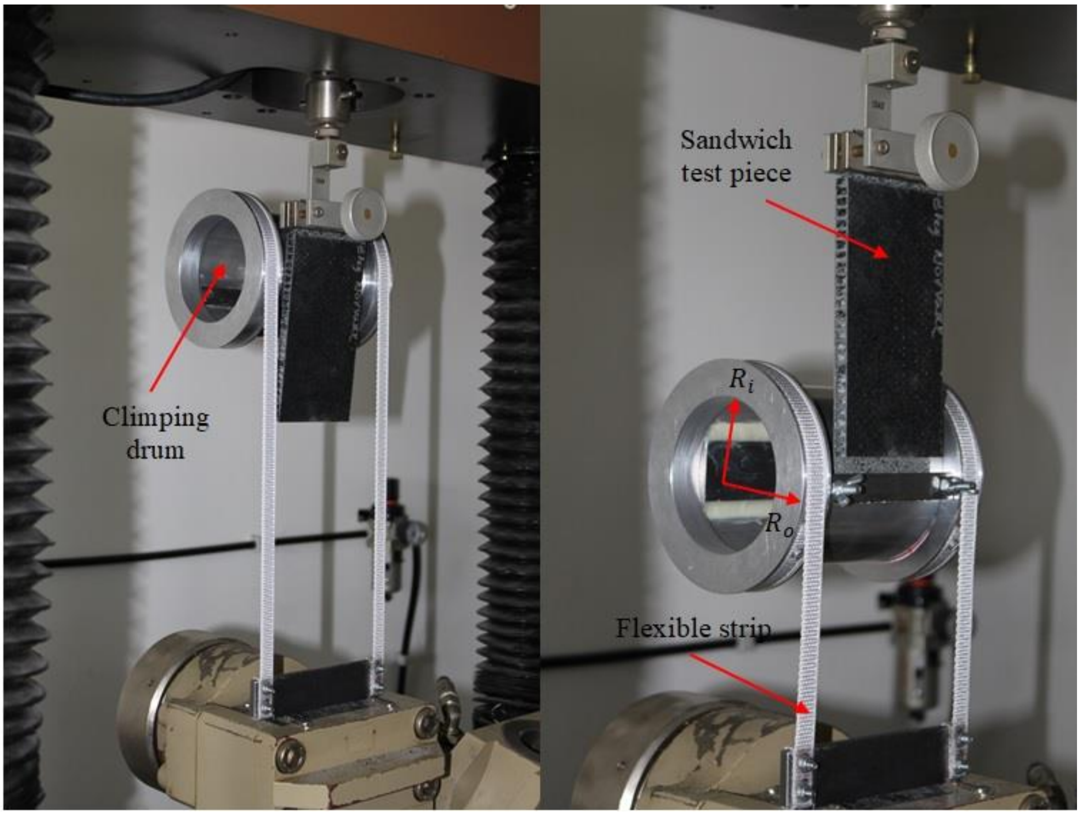

Figure 5: Climbing drum apparatus for the specimen of sandwich panels consisting of an aluminum honeycomb core and phenolic woven glass fiber face-sheets.

Table 2: Experimental result (Peeling test) for a set of sandwich panel specimens consisting of an aluminum honeycomb core and phenolic woven glass fiber face-sheets (2-2) layers / 0.5 mm.

Index	Peak force F_{max} [N]	Average force F_r [N]	Initial force F_i [N]	Peel strength F_p [N]	Peel length L_p [mm]
1	270	200	190	10	35
2	240	200	190	10	36
3	280	230	220	10	37
4	260	200	190	10	27
5	270	230	220	10	34
6	240	200	190	10	35
7	205	195	185	10	33
8	210	190	180	10	30

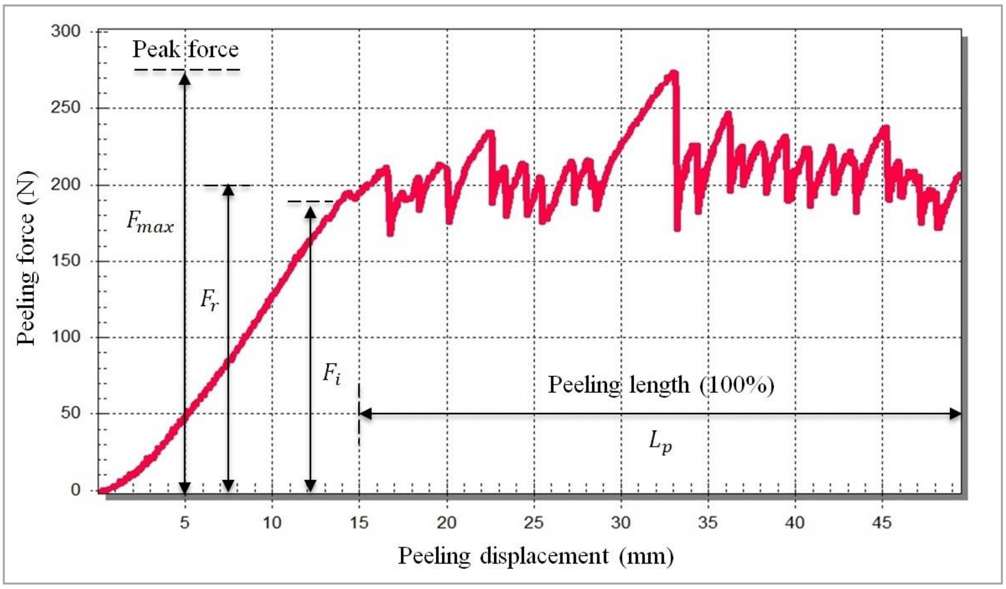

Figure 6: Experimental result (Peeling test) for specimen No.1 of sandwich panel consisting of an aluminum honeycomb core and phenolic woven glass fiber face-sheets (2-2) layers / 0.5 mm.

2.1.3. EXPERIMENTAL MODAL ANALYSIS (FORCED VIBRATION TEST AND DAMPING TEST)

It might be hard to improve the system's mathematical model in some practical situations and predict its vibration characteristics within an analytical study. Experimental methods can be applied to measure the sandwich structure's vibration response to a known input in such cases. This helps in identifying the system in terms of its mass, stiffness, and damping. This section shows the different aspects of vibration measurement for honeycomb sandwich structure application. An electrodynamic shaker's working principle, utilized to excite honeycomb sandwich specimens to study its dynamic characteristics, is presented. The signal analysis, which determines the system's response under known excitation and shows it in a suitable form, is summarized along with descriptions of the spectrum analyzer, bandpass filter, and bandwidth analyzers. The experimental modal analysis deals with determining natural frequencies and damping ratio by vibration testing [28].

- ***Results of Forced Vibration Test***

The experimental modal analysis deals with natural frequencies, stress, acceleration, and damping ratios through vibration testing [29]. The experimental tests included a forced vibration test to find natural frequencies, stress, and acceleration responses. The sandwich panels' specimens are made of an aluminum honeycomb core and phenolic woven glass fiber face-sheets in the Kompozitor Ltd. Company (see Figure 7). The dimensions of these specimens are shown in Table 3. The fiber orientation of the composite face-sheets was cross-ply. We can notice through the experimental results shown in Table 4 and Figure 8, the increase in the honeycomb core thickness will lead to a rise in the honeycomb sandwich panels' natural frequencies, a decrease in the stress response, and a reduction in the acceleration response due to the increase in stiffness-to-weight ratio.

Table 3: Dimensions of experimental tests by applying forced vibration test for honeycomb sandwich specimens set.

Specimens	Length	Width	Core thickness	Face-sheet thickness	Sandwich height
	l	b	t_c	$t_f(N_l)$	h
	mm	mm	mm	mm (Layers)	mm
S_1	1000	120	4	1 (2-2)	6
S_2	1000	120	20	1 (2-2)	22
S_3	1000	115	13	1 (2-2)	15
S_4	1130	54	18	1 (2-2)	20
S_5	710	43	16	1 (2-2)	18

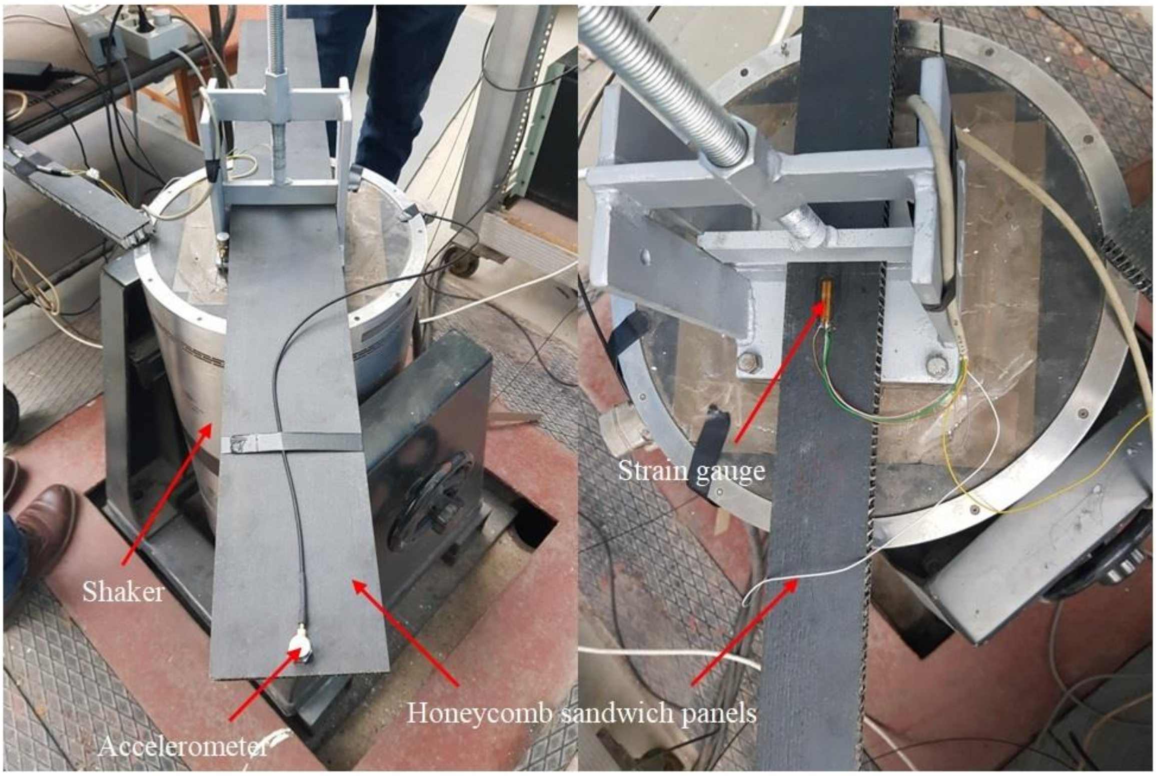

Figure 7: Experimental modal analysis (forced vibration test).

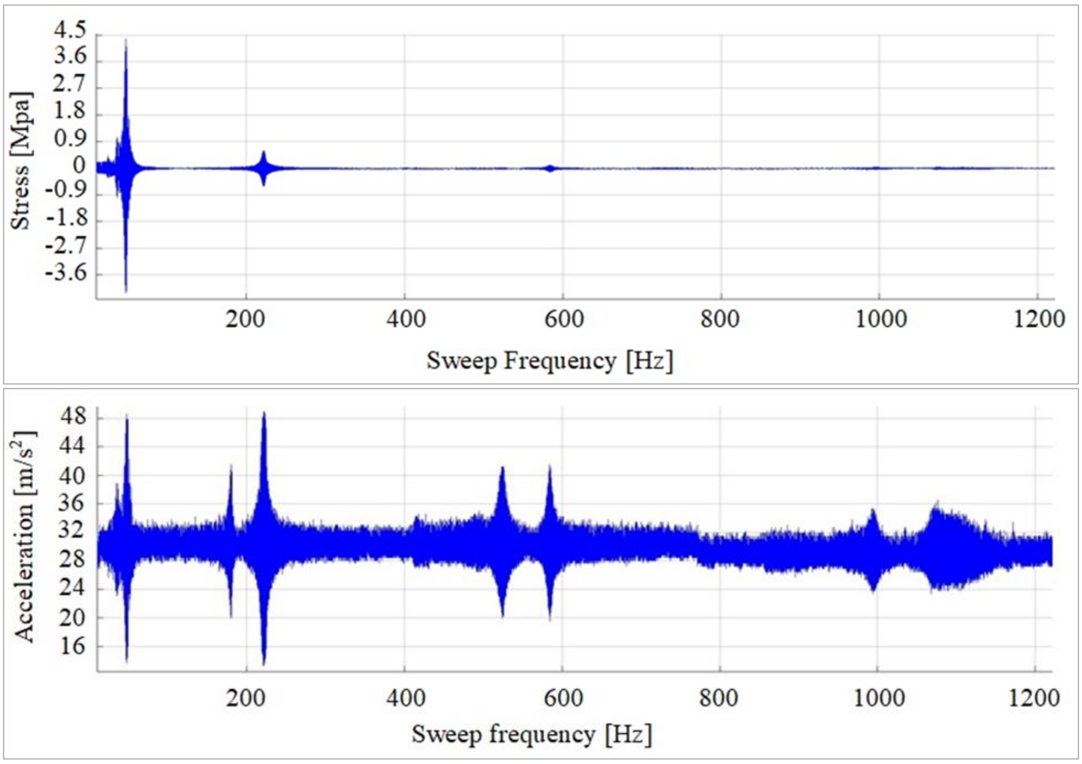

Figure 8: Experimental result (forced vibration test) for the specimen of sandwich panel consisting of an aluminum honeycomb core (t_c=18 mm) and phenolic woven glass fiber face-sheets (t_f=1 mm).

Table 4: Experimental results (forced vibration test) for the sandwich panel specimens, consisting of an aluminum honeycomb core and phenolic woven glass fiber face-sheets.

Range [Hz/sec]		(5-1200)	(10-1200)	(10-1200)	(10-1200)	(10-1200)
Gravity		2g	1g	1g	1g	1g
Specimens		S_1	S_2	S_3	S_4	S_5
Natural frequencies	f_1	14	56	38	34	50
	f_2	96	268	194	166	86
	f_3	254	350	244	210	408
	f_4	516	732	578	510	570
	f_5	812	826	666	572	1258
	f_6	1202	924	1086	980	1502
	f_7	1384	1434	1218	1060	
	f_8	1578	2192		1282	
	f_9		2728		1500	

- ***Results of Damping Test (Jones Measurement)***

This test method is intended to measure the damping; dynamic shear modulus, and acceleration of sandwich plate consisting of an aluminum honeycomb core and phenolic woven glass fiber face-sheets, thin rubber sandwich plate, and thick rubber sandwich plate with and without mass effect to compare between them (see Figures 9). The acceleration frequency response, acceleration response in time domain analysis, and response function for three types of specimens are calculated. Table 5 shows the experimental result calculations of damping test for the honeycomb sandwich plate, thin rubber plate, and thick rubber plate to compare. Considering dynamic loading, the structure's behavior can be different from the static one [30]. The damping ratio and the dynamic shear modulus are directly proportional to the mass. Figure 10 show the acceleration frequency response for the honeycomb sandwich plate. These responses decrease with an increase in the mass of the specimens.

Table 5: Experimental result calculations of damping test for specimens including: (A. Honeycomb sandwich plate consisting of an aluminum honeycomb core and phenolic woven glass fiber face-sheets, B. Thick rubber sandwich plate, and C. Thin rubber sandwich plate).

A. Honeycomb Sandwich Plate							
m	f_1	ω	$\ddot{x}_1$	$\ddot{x}_2$	T_R	η_d	G_d
kg	Hz	rad/sec	g	g	-	-	GPa
0.962	177.5	1115.055	2	40	20	0.0501	0.00332
2.036	164	1030.248	2	14	7	0.1443	0.00600
5.116	122	766.404	2	9	4.5	0.2279	0.00835
B. Thin Rubber Sandwich Plate							
m	f_1	ω	$\ddot{x}_1$	$\ddot{x}_2$	T_R	η_d	G_d
kg	Hz	rad/sec	g	g	-	-	GPa
0.962	173	1086.786	2	8	4	0.2582	0.00316
2.036	172	1080.504	2	9	4.5	0.2279	0.00660
5.116	126	791.532	2	4	2	0.5774	0.00890
C. Thick Rubber Sandwich Plate							
m	f_1	ω	$\ddot{x}_1$	$\ddot{x}_2$	T_R	η_d	G_d
kg	Hz	rad/sec	g	g	-	-	GPa
0.962	164	1030.248	2	17	8.5	0.1185	0.00284
2.036	156	979.992	2	12	6	0.1690	0.00543
5.116	115	722.430	2	10	5	0.2041	0.00742

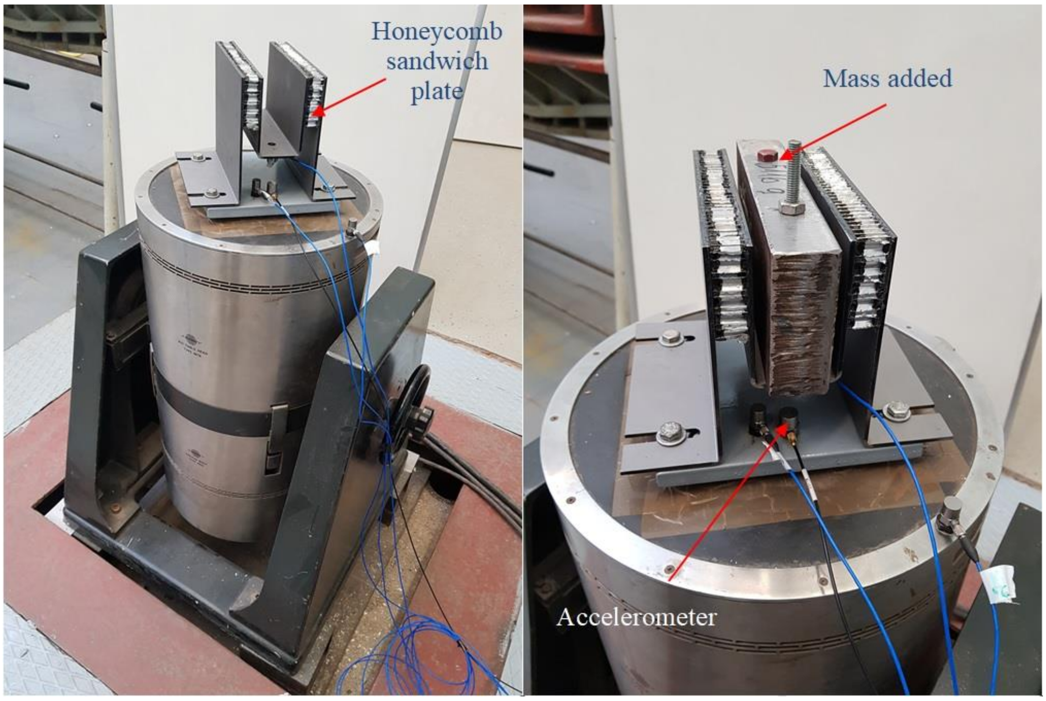

Figure 9: Damping test for the sandwich plate specimen consisting of an aluminum honeycomb core and phenolic woven glass fiber face-sheets, with and without mass effect.

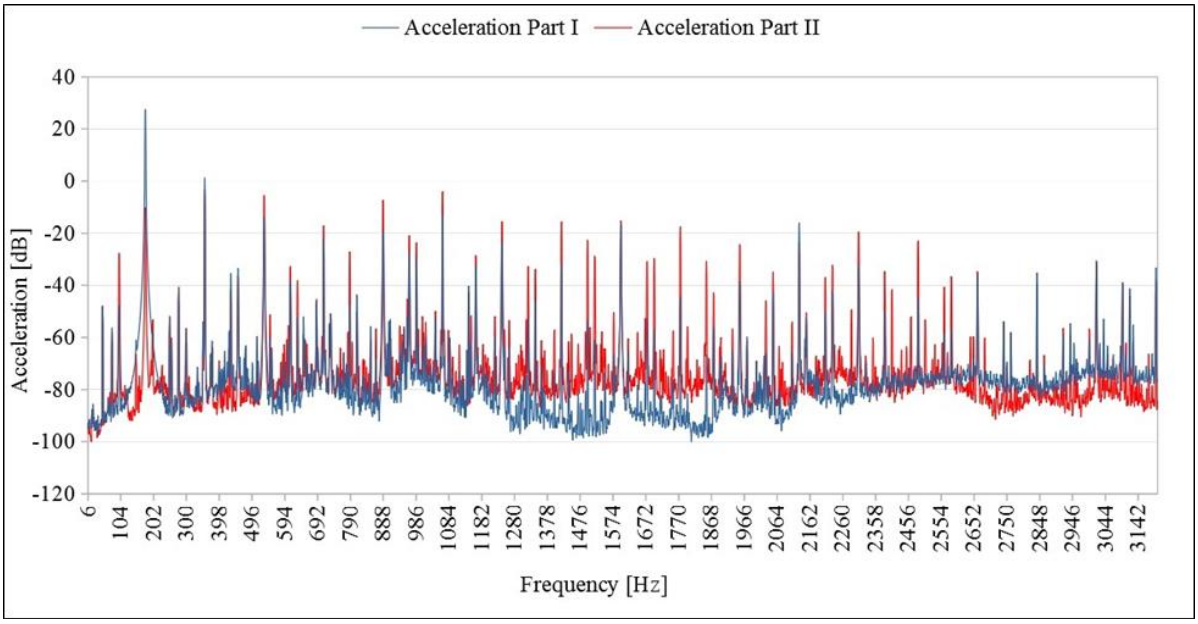

Figure 10: Jones measurement for honeycomb sandwich structure without weight, sine 177.5 Hz, 2g, shaker acceleration FFT.

2.3. SUMMARY

Four mechanical tests (static and dynamic measurements) were performed: four-point bending test, climbing drum peel test, forced vibration test, and damping test on a set of composite sandwich specimens. The specimens are made of an aluminum honeycomb core and phenolic woven glass fiber face-sheets with cross-ply fiber orientation. Concerning the four-point bending test, the relationship between load and displacement and skin stress was calculated. Simultaneously, the numerical models are made using the Digimat-HC program to get the deflection and skin stress for comparison. The honeycomb core thickness increase leads to decreased sandwich panels' deflection due to the increased stiffness-to-weight ratio. The peel test's adhesive bonds' peel resistance between face-sheets and honeycomb core of the sandwich specimens was determined. The honeycomb core thickness does not influence the adhesive's peeling resistance between the face-sheets and the sandwich structure's core. However, the thickness of the face sheets affects the difficulty of bending them on the drum.

The experimental tests included a forced vibration test to find natural frequencies, stress response, and acceleration response. When the honeycomb core thickness of the specimens increases, the natural frequency will increase and reduce stress response and acceleration response due to the rise in stiffness-to-weight ratio. The acceleration frequency response, acceleration time response, and response function for the honeycomb sandwich plate, thin rubber plate, and thick rubber plate are presented for comparison. These responses decrease with an increase in the mass of the specimens. According to the concepts of damping ratio, damping constant, Newton's second law of motion, and natural frequency, when the mass added on the sandwich structure specimen increases, the sandwich structure's acceleration will decrease. As the sandwich structure's natural frequency is inversely proportional to the mass, it will reduce, and thus the angular frequency will decrease. The damping ratio and the dynamic shear modulus are directly proportional to the mass.

3. OPTIMIZATION METHOD

The mathematical modeling for the optimization processes of the constructed honeycomb sandwich structures was presented. The sandwich structure is consisting of an aluminum honeycomb core and different types of face-sheets. The face-sheets are consisting of an aluminum alloy or composite material. The composite face-sheets included phenolic woven glass fiber, epoxy woven glass fiber, epoxy woven carbon fiber, and hybrid composite layers, which combined layers of epoxy woven glass fiber and epoxy woven carbon fiber. The mechanical properties of honeycomb core materials and face-sheet, as shown in Tables 6 and 7. The composite sandwich plates are considered thin layers, symmetric concerning the midplane of the sandwich plates and/or symmetric concerning the face-sheets' midplane. Every face-sheet is composed of (1, 2, 4, 6, and 8) layers. The layup of the fibers of the face-sheets was restricted to sets of plies having orientation angles of cross-ply (0°, 90°), angle-ply (±45°), and multidirectional (0°, 90°) & (±45°). The optimal design variables were honeycomb core thickness t_c and face-sheet thickness t_f for aluminum face-sheets or the number of layers for composite face-sheets N_l to minimize the weight and/or the cost of the sandwich structures. During the optimization techniques, nine design constraints were taken into consideration. The constraints of the optimization problem are the total stiffness (bending stiffness and shear stiffness), the full deflection (bending deflection and shear deflection), facing skin stress (bending load), core shear stress, facing skin stress (end loading), overall buckling (bending critical buckling load and shear critical buckling load), shear crimping load, skin wrinkling (critical stresses and load) and intracell buckling. These constraints were calculated to compare with yield stresses and applied loads of face-sheets and honeycomb core. The optimization procedure's flowchart is formulating the objective functions for the weight and/or the cost of the honeycomb sandwich structure. Formulate the constraints and defined the boundaries for the design variables; solve the single-objective optimization problem to minimize the total weight or the total material cost separately using the Matlab program (Interior Point Algorithm), and Excel Solver program (GRG Nonlinear Algorithm), where GRG stands for "Generalized Reduced Gradient". This solver method looks at the gradient or slope of the objective function as the input values (or decision variables) change in their most basic form. It determines that it has reached an optimum solution when the partial derivatives equal to zero. Solve the multi-objective optimization problem to minimize the weight and the cost simultaneously by applying the Matlab program (Genetic Algorithm Solver with Pareto Front) and Excel Solver program (Weighted Normalized Method). The strategies of composite face-sheets have been solved using the Laminator, an engineering program that analysis laminated composite material according to classical lamination theory and the ply failure calculation based on Tsai-Hill failure criteria.

Table 6: Engineering mechanical properties of aluminum honeycomb core materials [31].

Product construction		Compression		Plate shear			
Density	Cell size	Stabilized		L-direction		W-direction	
		Strength	Modulus	Strength	Modulus	Strength	Modulus
kg/m^3	mm	MPa	MPa	MPa	MPa	MPa	MPa
83	6	4.6	1000	2.4	440	1.5	220

Table 7: Engineering properties of facing materials for sandwich structure construction [31].

Facing Material	Typical Strength Tension/Compression [MPa]	Modulus of Elasticity Tension/Compression [GPa]	Poisson's Ratio (μ) [-]	Typical Cured Ply Thickness [mm]	Typical Weight Per Ply [kg/m^2]
Phenolic woven glass (7781-8hs) 50% volume fraction	400 / 360	20 / 17	0.13	0.25	0.47
Epoxy woven glass (7781-8hs) 50% volume fraction	600 / 550	20 / 17	0.13	0.25	0.47
Epoxy woven carbon (g793-5hs) 55% volume fraction	800 / 700	70 / 60	0.05	0.3	0.45
Aluminum Alloy (5251 H24)	150	70	0.33	0.5	1.35

3.1. Optimum Design for Honeycomb Sandwich Base Plate of Air Cargo Containers

In this study, the replacement of an existing aluminum base plate in air cargo containers with a honeycomb sandwich base plate was investigated. The conventional bottom base plate of the air cargo container has dimensions (1440 mm by 1412 mm) and consisting of a solid (2.5 mm) thick aluminum plate which weighs (14.1 kg) and costs (65 €) approximately. The value of (1 kg) of reduced weight is approximately (199 $ per year). The total load on the air cargo container's base plate is (1588 kg) uniformly distributed. The maximum deformation may not exceed (9.5 mm). The technical data and boundary conditions for the air cargo container's base plate were shown in Tables 8 and 9, respectively. The honeycomb sandwich plate is either clamped along all four edges. The sandwich plates' models consist of an aluminum honeycomb core, and different types of face-sheets, including aluminum alloy and composite material [32].

Table 8: Technical data for the conventional base plate of air freight container [32].

Length	Width	Thickness	Deflection	Payload			Weight	Cost
l	b	t	δ_{max}	W_{max}	P	p	W_t	C_t
mm	mm	mm	mm	kg	N	Pa	kg	€
1440	1412	2.5	9.5	1588	15578	7891	14.1	65

Table 9: Boundary conditions and constant design parameters for honeycomb sandwich base plate of air freight container [31].

Bending Deflection Coefficient	Shear Deflection Coefficient	Maximum Bending Moment	Maximum Shear Force	Buckling Factor
K_b	K_s	M	F	β
$\frac{1}{384}$	$\frac{1}{8}$	$\frac{Pl}{12}$	$\frac{P}{2}$	4

3.1.1. OPTIMIZATION RESULTS FOR SANDWICH BASE PLATE OF AIR CARGO CONTAINERS

The final optimization results of honeycomb sandwich base plate of air cargo container include minimum weight W_{min} and/or minimum cost C_{min} with optimum core thickness $t_{c,opt}$ and optimum face-sheet thickness $t_{f,opt}$ using the Excel Solver program and Matlab program for single-objective function and multi-objective functions.

– ***Minimizing the Single-objective Function for Honeycomb Sandwich Base Plate of Air Cargo Containers with Composite Material Face-sheets***

The optimum results of single-objective function (weight or cost) for composite material face-sheets of honeycomb sandwich base plate of air cargo container obtained by applying the Excel Solver program (GRG Nonlinear Algorithm) and the Matlab program (fmincon Solver Constrained Nonlinear Minimization / Interior Point Algorithm) as shown in Tables 10 & 11.

Table 10: Minimum weight objective function with optimum face-sheet thickness and optimum core thickness using the Matlab program (Interior Point Algorithm) for the sandwich base plate of air freight container consisting of an aluminum honeycomb core and orthotropic composite face-sheets are including (A. Epoxy woven glass fiber, B. Epoxy woven carbon fiber and C. Hybrid composite layers) with a different number of layers N_l and fiber orientation θ°.

Type	**A. Epoxy woven glass fiber face-sheets**	W_{min}	$t_{f,opt}$	$t_{c,opt}$
Number of layers N_l and fiber orientations θ°		kg	mm	mm
2 (+45°, -45°) Optimum value		11.435	0.5	45.111

Type	**B. Epoxy woven carbon fiber face-sheets**	W_{min}	$t_{f,opt}$	$t_{c,opt}$
Number of layers N_l and fiber orientations θ°		kg	mm	mm
1 (+45°) Optimum value		6.327	0.3	26.648

Type	**C. Hybrid composite face-sheets**	W_{min}	$t_{f,opt}$	$t_{c,opt}$
Number of layers N_l and fiber orientations θ°		kg	mm	mm
2 (+45°, -45°) Optimum value		8.572	0.55	28.625

Table 11: Minimum cost objective function with optimum face-sheet thickness and optimum core thickness using the Matlab program (Interior Point Algorithm) for the sandwich base plate of air freight container consisting of an aluminum honeycomb core and orthotropic composite face-sheets are including (A. Epoxy woven glass fiber, B. Epoxy woven carbon fiber and C. Hybrid composite layers) with a different number of layers N_l and fiber orientation θ°.

Type	**A. Epoxy woven glass fiber face-sheets**	C_{min}	$t_{f,opt}$	$t_{c,opt}$
Number of layers N_l and fiber orientations θ°		€	mm	mm
2 (+45°, -45°) Optimum value		121.075	0.5	45.131

Type	**B. Epoxy woven carbon fiber face-sheets**	C_{min}	$t_{f,opt}$	$t_{c,opt}$
Number of layers N_l and fiber orientations θ°		€	mm	mm
1 (+45°) Optimum value		133.397	0.3	26.646

Type	C. Hybrid composite layers face-sheets	C_{min}	$t_{f,opt}$	$t_{c,opt}$
Number of layers N_l and fiber orientations θ°		€	mm	mm
2 (+45°, -45°) Optimum value		147.452	0.55	28.637

– ***Minimizing Multi-objective Functions for Sandwich Base Plate of Air Cargo Containers with Composite Material Face-sheets***

The optimum results of multi-objective function (weight and cost) for composite material face-sheets of honeycomb sandwich base plate of air cargo container obtained by applying the Excel Solver program, and the Matlab program (Genetic Algorithm Solver) are shown in Table 12, and Figure 11.

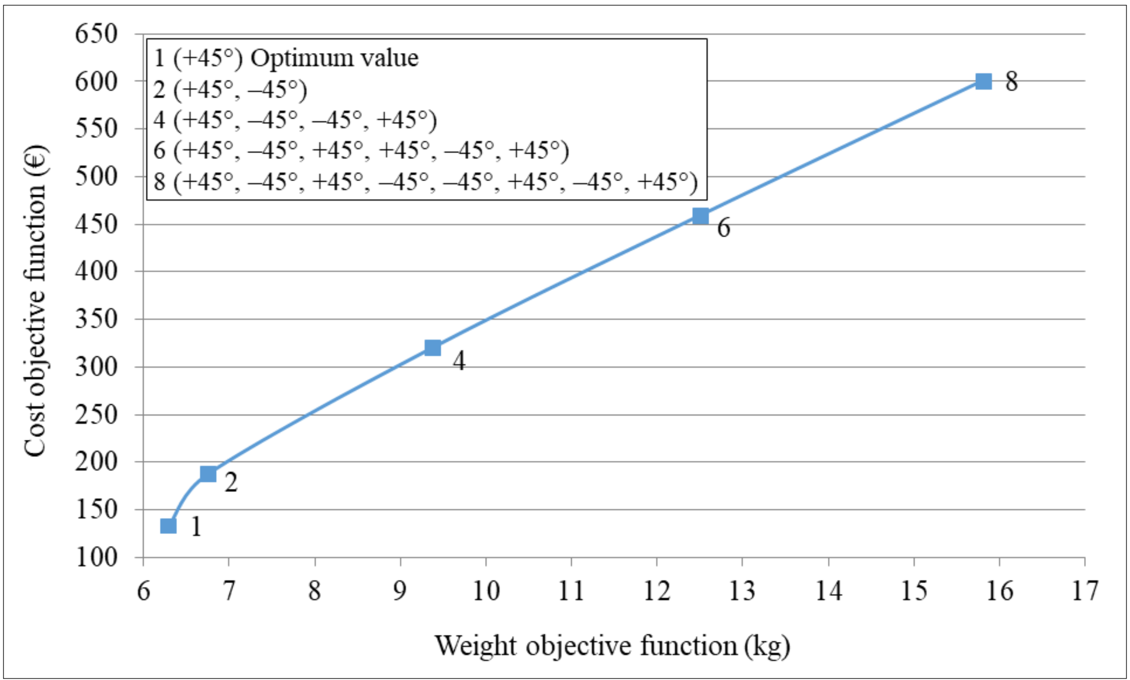

Figure 11: Minimum weight versus minimum cost objective function using the Matlab program (Genetic Algorithm Solver) for the sandwich base plate of air freight container consisting of an aluminum honeycomb core and epoxy woven carbon fiber composite face-sheets with a different number of layers N_l and angle-ply fiber orientation θ°.

Table 12: Minimum weight and minimum cost multi-objective function with optimum face-sheet thickness and optimum core thickness using the Matlab program (Genetic Algorithm Solver) for the sandwich base plate of the air freight container consisting of an aluminum honeycomb core and orthotropic composite face-sheets included (A. Epoxy woven glass fiber, B. Epoxy woven carbon fiber and C. Hybrid composite layers) with a different number of layers N_l and fiber orientation θ°.

Type	A. Epoxy woven glass fiber face-sheets	W_{min}	C_{min}	$t_{f,opt}$	$t_{c,opt}$
Number of layers N_l and fiber orientations θ°		kg	€	mm	mm
2 (+45°, -45°) Optimum value		11.394	120.475	0.5	44.866

Type	B. Epoxy woven carbon fiber face-sheets	W_{min}	C_{min}	$t_{f,opt}$	$t_{c,opt}$
Number of layers N_l and fiber orientations θ°		kg	€	mm	mm
1 (+45°) Optimum value		6.292	132.929	0.3	26.439

Type	**C. Hybrid composite face-sheets**	W_{min}	C_{min}	$t_{f,opt}$	$t_{c,opt}$
Number of layers N_l and fiber orientations θ°		kg	€	mm	mm
2 (+45°, -45°) Optimum value		8.573	147.44	0.55	28.632

3.1.2. SUMMARY

This study aimed to improve a novel honeycomb sandwich plate, which can be applied in manufacturing a lightweight base plate for air freight containers. In case of epoxy woven glass fiber face-sheets and hybrid composite layers face-sheets of honeycomb sandwich plates, the optimum face-sheet thickness and optimum core thickness which ensures the minimum weight and/or minimum cost are two layers with fiber orientation angle-ply (±45°). For epoxy woven carbon fiber face-sheets of the honeycomb sandwich plates, the optimum face-sheet thickness and optimum core thickness ensure the minimum weight and/or minimum cost are one layer with fiber orientation angle-ply (+45°). The best face-sheet according to minimum weight is epoxy woven carbon fiber, where the minimum weight, minimum cost, optimum face-sheet thickness, and optimum core thickness are (6.292 kg, 132.929 €, 0.3 mm, and 26.439 mm), respectively. This optimal sandwich plate provides (55.13 %) weight saving compared to the air cargo container's conventional aluminum base plate (14.1 kg). The epoxy woven carbon fiber having higher stiffness to weight ratio compared to epoxy woven glass fiber. The best face-sheet according to minimum cost is epoxy woven glass fiber, where the minimum weight, minimum cost, optimum face-sheet thickness, and optimum core thickness are (11.394 kg, 120.475 €, 0.5 mm, and 44.866 mm), respectively. The hybrid composite face-sheet is considered as a compromise between epoxy woven carbon fiber face-sheet and epoxy woven glass fiber face-sheet, where the minimum weight, minimum cost, optimum face-sheet thickness, and optimum core thickness are (8.573 kg, 147.44 €, 0.55 mm, and 28.632 mm), respectively. The epoxy woven glass fiber has a higher strength to weight ratio and more flexible than epoxy woven carbon fiber. In the aluminum face-sheets of the honeycomb sandwich plates, the optimum face-sheet thickness and optimum core thickness ensure the minimum weight and/or minimum cost are (9.0946 kg, 73.3321 €, 0.5024 mm, and 21.2029 mm), respectively.

3.2. OPTIMUM DESIGN OF HONEYCOMB SANDWICH STRUCTURE FOR A SINGLE BASE PLATE OF MILITARY AIRCRAFT PALLETS

This study aimed to replace the currently aluminum single base plate of military aircraft pallets with a sandwich plate. The pallets have dimensions (3175 mm by 2235 mm) and are supported by six frames (to distribute loads evenly over a larger area), which work in parallel inside the aircraft. Today's pallet design consists of a solid (4.2 mm) thick aluminum plate that weighs approximately (80 kg). The value of (1 kg) of reduced weight is approximately (USD 199 per year). The total load on the pallet is (6800 kg) uniformly distributed. The pallet should sustain an extra acceleration of (1.5 g), so the total load times (2.5 g). The maximum deformation may not exceed (50 mm). The loading system is approximated by studying the panels inscribed between the supports (with dimensions of 665 mm by 2235 mm). The plate's boundary conditions are simply supported along the long edges and free along the shorter edges (see Table 13). The design parameters of the conventional single base plate of the aircraft freight pallet are shown in Table 14.

Table 13: Boundary conditions and constant design parameters for the honeycomb sandwich panel [34].

Bending Deflection Coefficient	Shear Deflection Coefficient	Maximum Bending Moment	Maximum Shear Force	Buckling Factor
K_b	K_s	M	F	β
$\frac{5}{384}$	$\frac{1}{8}$	$\frac{Pl}{8}$	$\frac{P}{2}$	1

Table 14: Technical data for the conventional military pallet, aluminum alloy [2].

Length	Width	Thickness	Deflection	Payload			Weight
l	b	t	δ_{max}	W_{max}	P	p	W_t
mm	mm	mm	mm	kg	N	Pa	kg
3175	2235	4.2	50	6800	166770	23501.56	80

3.2.1. Optimization Results for a Single Base Plate of Military Aircraft Pallets

The final optimization results of military aircraft pallets are included minimum total weight $W_{min,t}$ and/or minimum total material cost $C_{min,t}$ with optimum core thickness $t_{c,opt}$ and optimum face-sheet thickness $t_{f,opt}$ using the Excel Solver program and Matlab program for single-objective function and multi-objective functions.

– ***Minimizing Single-objective Function for Honeycomb Sandwich Base Plate of Military Aircraft Pallets with Composite Material Face-sheets***

The optimum results of single-objective function (weight or cost) for composite material face-sheets, honeycomb sandwich base plate of military aircraft pallets, obtained by applying the Excel Solver program (GRG Nonlinear Algorithm), and Matlab program (fmincon Solver Constrained Nonlinear Minimization / Interior Point Algorithm) are shown in Tables 15 & 16.

Table 15: Minimum weight objective function with optimum face-sheet thickness and core thickness using the Matlab program (Interior Point Algorithm) for the honeycomb sandwich base plate of military aircraft pallets consists of an aluminum honeycomb core and orthotropic composite face-sheets are including (A. Epoxy woven glass fiber, B. Epoxy woven carbon fiber and C. Hybrid composite layers) with a different number of layers N_l and fiber orientation θ°.

Type	**A. Epoxy woven glass fiber face-sheets**	$W_{min,t}$	$t_{f,opt}$	$t_{c,opt}$
Number of layers N_l with fiber orientations θ°		kg	mm	mm
4 (0°, 90°, 90°, 0°) optimum value		40.742	1	23.872

Type	**B. Epoxy woven carbon fiber face-sheets**	$W_{min,t}$	$t_{f,opt}$	$t_{c,opt}$
Number of layers N_l with fiber orientations θ°		kg	mm	mm
2 (0°, 90°) optimum value		27.069	0.6	24.272

Type	**C. Hybrid composite face-sheets**	$W_{min,t}$	$t_{f,opt}$	$t_{c,opt}$
Number of layers N_l with fiber orientations θ°		kg	mm	mm
4 (0°, 90°, 90°, 0°) optimum value		40.115	1.1	23.772

Table 16: Minimum cost objective function with optimum face-sheet thickness and core thickness using the Matlab program (Interior Point Algorithm) for the honeycomb sandwich base plate of military aircraft pallets consists of an aluminum honeycomb core and orthotropic composite face-sheets are including (A. Epoxy woven glass fiber, B. Epoxy woven carbon fiber and C. Hybrid composite layers) with a different number of layers N_l and fiber orientation θ°.

Type	**A. Epoxy woven glass fiber face-sheets**	$C_{min,t}$	$t_{f,opt}$	$t_{c,opt}$
Number of layers N_l with fiber orientations θ°		€	mm	mm
4 (0°, 90°, 90°, 0°) optimum value		321.655	1	23.875

Type	**B. Epoxy woven carbon fiber face-sheets**	$C_{min,t}$	$t_{f,opt}$	$t_{c,opt}$
Number of layers N_l with fiber orientations θ°		€	mm	mm
2 (0°, 90°) optimum value		702.299	0.6	24.272

Type	**C. Hybrid composite face-sheets**	$C_{min,t}$	$t_{f,opt}$	$t_{c,opt}$
Number of layers N_l with fiber orientations θ°		€	mm	mm
4 (0°, 90°, 90°, 0°) optimum value		765.061	1.1	23.772

– ***Minimizing Multi-objective Functions for Honeycomb Sandwich Base Plate of Military Aircraft Pallets with Composite Material Face-sheets.***

The optimum results of multi-objective function (weight and cost) for composite material face-sheets, for honeycomb sandwich base plate of military aircraft pallets, obtained by applying the Excel Solver program, and the Matlab program (Genetic Algorithm Solver) are shown in Table 17 and Figure 12.

Table 17: Minimum weight and cost multi-objective function with optimum face-sheet thickness and core thickness using the Matlab program (Genetic Algorithm Solver) for the sandwich base plate of military aircraft pallets consists of an aluminum honeycomb core and orthotropic composite face-sheets included (A. Epoxy woven glass fiber, B. Epoxy woven carbon fiber and C. Hybrid composite layers) with a different number of layers N_l and fiber orientation θ°.

Type	**A. Epoxy woven glass fiber face-sheets**	$W_{min,t}$	$C_{min,t}$	$t_{f,opt}$	$t_{c,opt}$
Number of layers N_l with fiber orientations θ°		kg	€	mm	mm
4 (0°, 90°, 90°, 0°) optimum value		40.76	321.876	1	23.903

Type	**B. Epoxy woven carbon fiber face-sheets**	$W_{min,t}$	$C_{min,t}$	$t_{f,opt}$	$t_{c,opt}$
Number of layers N_l with fiber orientations θ°		kg	€	mm	mm
2 (0°, 90°) optimum value		27.127	703.074	0.6	24.371

Type	**C. Hybrid composite face-sheets**	$W_{min,t}$	$C_{min,t}$	$t_{f,opt}$	$t_{c,opt}$
Number of layers N_l with fiber orientations θ°		kg	€	mm	mm
4 (0°, 90°, 90°, 0°) optimum value		40.119	765.119	1.1	23.779

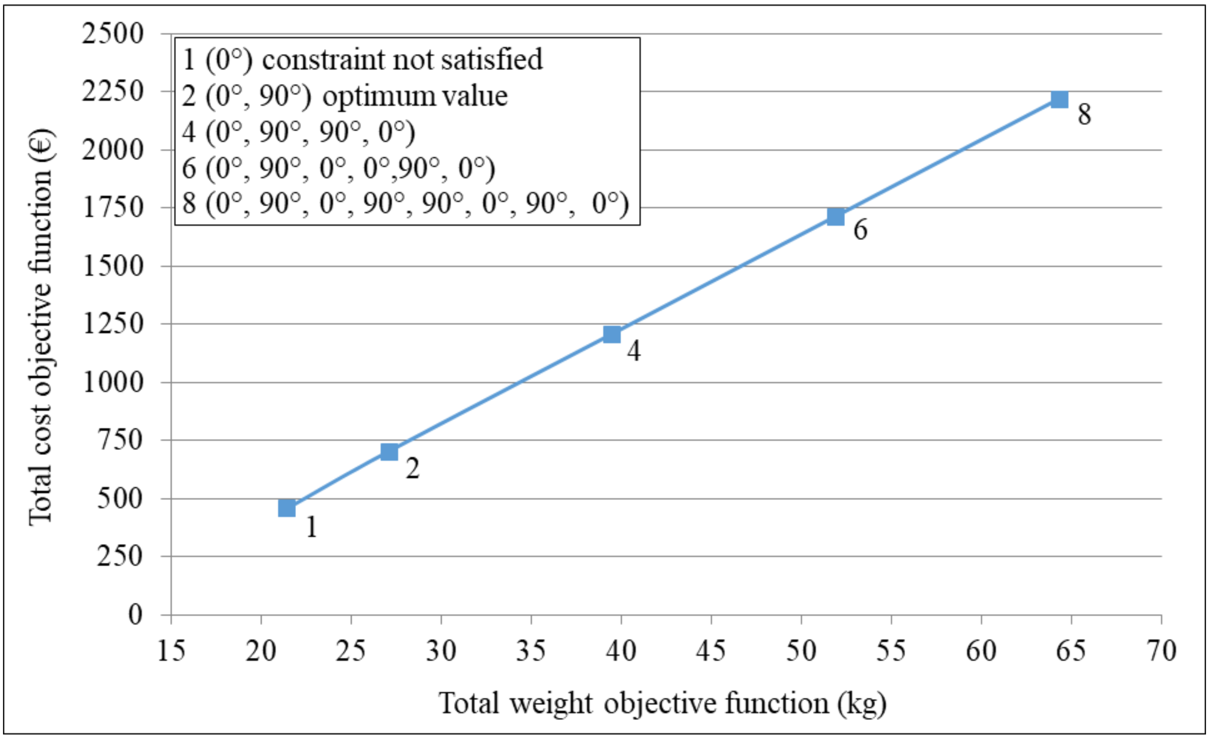

Figure 12: Minimum total weight versus minimum total material cost objective function using the Matlab program (Genetic Algorithm Solver) for honeycomb sandwich base plate of military aircraft pallets consisting of an aluminum honeycomb core and epoxy woven carbon fiber composite face-sheets with a different number of layers N_l and cross-ply fiber orientation θ°.

3.2.2. SUMMARY

This study aimed to replace the currently aluminum single base plate of military aircraft pallets with a honeycomb sandwich plate. For composite material face-sheets, in case of epoxy woven glass fiber face-sheet, and hybrid composite layers face-sheet for honeycomb sandwich base plate of pallets, the optimum face-sheet thickness and optimum core thickness which ensures the minimum weight and/or minimum cost are four layers with fiber orientation cross-ply (0°, 90°, 90°, 0°). As for epoxy woven carbon fiber face-sheets of the honeycomb sandwich plates, the optimum face-sheet thickness and optimum core thickness ensure the minimum weight and/or minimum cost are two layers with fiber orientation cross-ply (0°, 90°). The minimum weight, minimum cost, optimum face-sheet thickness, and optimum core thickness for epoxy woven carbon fiber face-sheet are (27.127 kg, 703.074 €, 0.6 mm and 24.371 mm), respectively. This optimal sandwich plate provides a (66.25 %) weight saving compared to the conventional aluminum single base plate pallet (80 kg). For aluminum alloy face-sheets for honeycomb sandwich base plate of pallets, the optimum face-sheet thickness and optimum core thickness ensure the minimum weight and/or the minimum cost are (0.8212 mm, 49.532 mm, 60.642 kg, and 535.612 €), respectively. This optimal sandwich plate provides (24.2 %) weight saving compared to the conventional aluminum single base plate pallet (80 kg).

4. NUMERICAL ANALYSIS OF HONEYCOMB SANDWICH STRUCTURES USING THE DIGIMAT-HC PROGRAM

The numerical models included a four-point bending test using the Digimat-HC program. In this study, the mean vertical displacement at mid-section δ_{Num}, equivalent stress in the face-sheets σ_{skin} and equivalent shear stress in the honeycomb core τ_{core} were calculated are shown in Table 18 and Figures 13-15. The numerical models of sandwich panels consisting of aluminum honeycomb core and different types of face-sheets, including aluminum alloy and composite material, the core and face-sheets mechanical properties, are shown in Tables 6 & 7. The composite face-sheets material included phenolic woven glass fiber, epoxy woven glass fiber, epoxy woven carbon fiber, and hybrid composite layers (a combination of epoxy woven glass fiber layers and epoxy woven carbon fiber layers). The face-sheets fiber orientations were restricted to groups of layers with directional angles to the cross-ply (0°, 90°), angle-ply (±45°) and multidirectional cross-ply (0°, 90°) and angle-ply (±45°). The honeycomb sandwich structure's numerical results with phenolic woven glass fiber face-sheets and epoxy woven glass fiber face-sheet are the same. Because the mechanical properties for phenolic woven glass fiber face-sheet and epoxy woven glass fiber face-sheet are very close. The graph lines for these types of face-sheets are identical, named as (phenolic/epoxy woven glass fiber face-sheet).

Table 18: Numerical results (four-point bending test) using the Digimat-HC program for sandwich panels consisting of an aluminum honeycomb core (t_c=15 mm) and composite material face-sheets of phenolic woven glass fiber (7781-8HS) 55% volume fraction.

Type	**Phenolic woven glass fiber face-sheet**	δ_{Num}	σ_{skin}	τ_{core}	t_f
No.	Number of layers N_l and fiber orientations θ°	mm	MPa	MPa	mm
1	1 (0°)	26.666	184	0.987	0.25
2	2 (0°, 90°)	15.977	97.1	0.864	0.5
3	4 (0°, 90°, 90°, 0°)	9.55	50	0.765	1
4	6 (0°, 90°, 0°, 0°,90°, 0°)	7.11	55.9	0.737	1.5
5	8 (0°, 90°, 0°, 90°, 90°, 0°, 90°, 0°)	5.894	54.4	0.704	2
6	1 (+45°)	42.982	185	1.49	0.25
7	2 (+45°, -45°)	23.058	91.5	0.991	0.5
8	4 (+45°, -45°, -45°, +45°)	12.868	44.4	0.816	1
9	6 (+45°, -45°, +45°, +45°, -45°, +45°)	9.292	44.4	0.774	1.5
10	8 (+45°, -45°, +45°, -45°, -45°, +45°, -45°, +45°)	7.385	43.6	0.738	2
11	4 (0°, 90°, +45°, -45°)	10.477	58.6	0.774	1
12	4 (+45°, -45°, 0°, 90°)	10.788	58.2	0.8	1
13	6 (0°, 90°, +45°, -45°, 0°, 90°)	7.593	58.4	0.743	1.5
14	6 (+45°, -45°, 0°, 90°, -45°, +45°)	8.229	41.4	0.756	1.5
15	8 (0°, 90°, +45°, -45°, -45°, +45°, 90°, 0°)	6.362	58.4	0.712	2
16	8 (+45°, -45°, 0°, 90°, 90°, 0°, -45°, +45°)	6.4	48.8	0.722	2

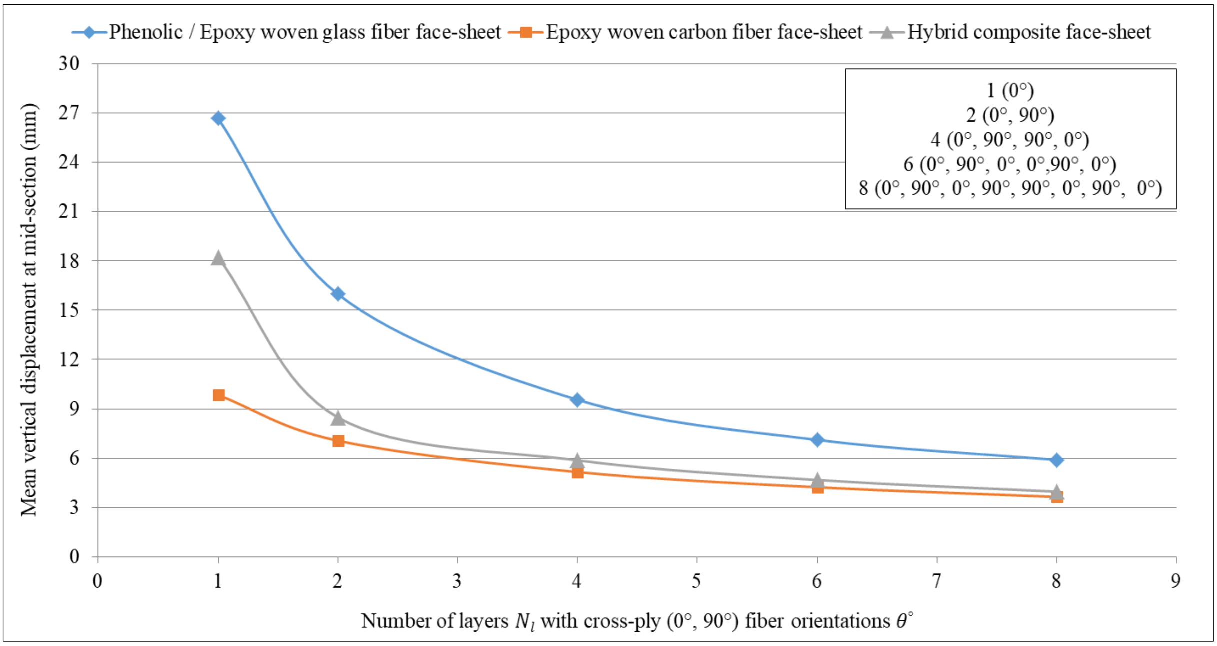

Figure 13: Comparison of deflection numerically using the Digimat-HC program (four-point bending test) for sandwich panels consisting of an aluminum honeycomb core (t_c=15 mm) and different composite material face-sheets of phenolic/epoxy woven glass fiber, epoxy woven carbon fiber, and hybrid composite layers with various numbers layers N_l and cross-ply (0°, 90°) fiber orientation θ°.

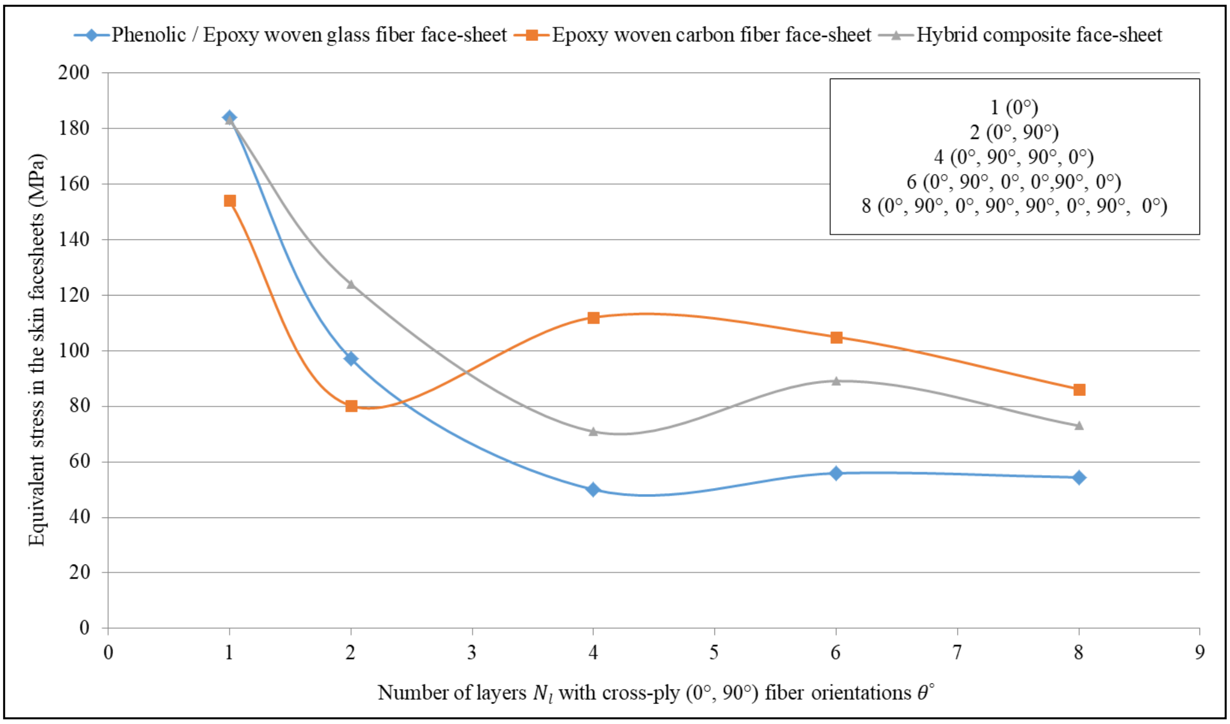

Figure 14: Comparison of face-sheet stress numerically using the Digimat-HC program (four-point bending test) for sandwich panels consisting of an aluminum honeycomb core (t_c=15 mm) and different composite material face-sheets of phenolic/epoxy woven glass fiber, epoxy woven carbon fiber, and hybrid composite layers with various numbers layers N_l and cross-ply (0°, 90°) fiber orientation θ°.

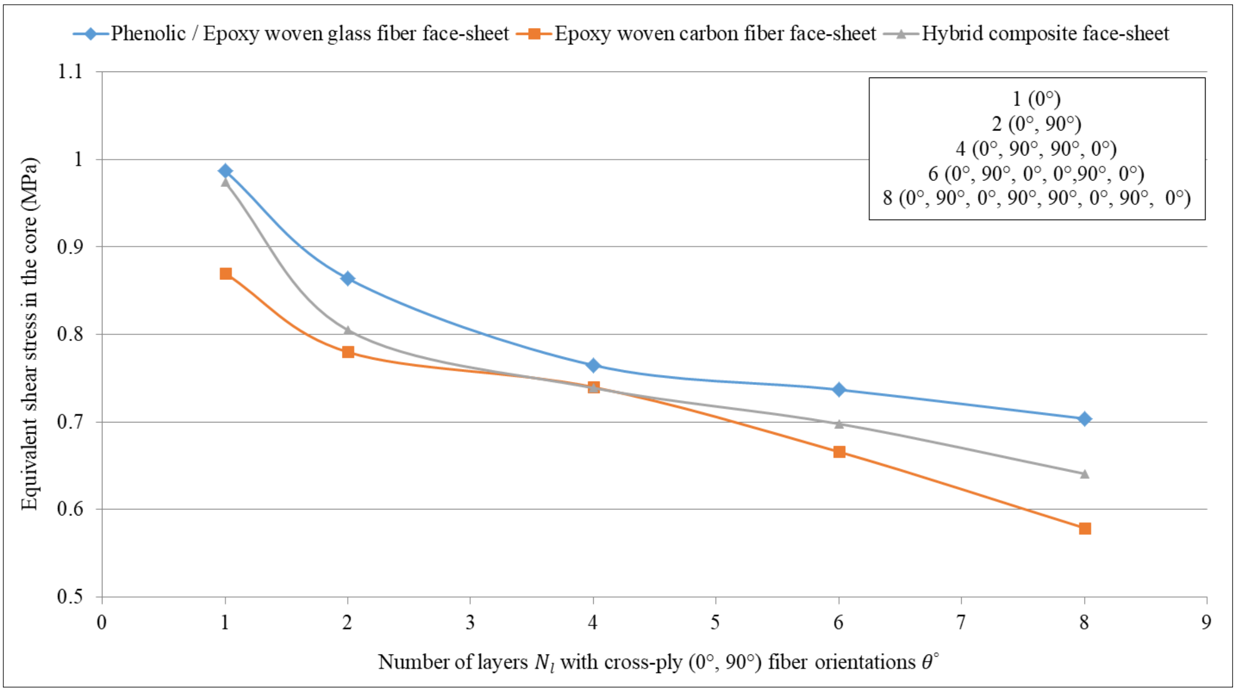

Figure 15: Comparison of core shear stress numerically using the Digimat-HC program (four-point bending test) for sandwich panels consisting of an aluminum honeycomb core (t_c=15 mm) and different composite material face-sheets of phenolic/epoxy woven glass fiber, epoxy woven carbon fiber, and hybrid composite layers with various numbers layers N_l and cross-ply (0°, 90°), fiber orientation θ°.

4.1. SUMMARY

The numerical models of sandwich panels consist of aluminum honeycomb core and different face-sheets, including aluminum alloy and composite material. The composite face-sheets included: phenolic woven glass fiber, epoxy woven glass fiber, epoxy woven carbon fiber, and hybrid composite layers. Every face-sheet is composed of (1, 2, 4, 6, and 8) layers with sets of fiber orientations, including cross-ply (0°, 90°) and/or angle-ply (±45°). The models are solved numerically using the Digimat-HC program (four-point bending test) to calculate the mean vertical displacement at mid-section, equivalent skin stress, and equivalent core shear stress. The numerical results consist of five main cases depending on the sandwich panels' face-sheets and every composite case study consisting of sixteen different fiber orientations. The numerical results, the mean vertical displacement at mid-section, equivalent stress in the face-sheets and equivalent shear stress in the honeycomb core in case of epoxy woven carbon fiber face-sheets of the honeycomb sandwich panels with fiber orientation cross-ply (0°, 90°) and angle-ply (±45°) are less than the aluminum alloy face-sheets, hybrid composite layers face-sheets, phenolic woven glass fiber, and epoxy woven glass fiber, respectively. While, the mean vertical displacement at mid-section and equivalent shear stress in the honeycomb core in case of cross-ply (0°, 90°) fiber orientation face-sheets are less than angle-ply (±45°) fiber orientation face-sheets of the honeycomb sandwich panels. But, the equivalent stress in the face-sheets in case of angle-ply (±45°) fiber orientation are less than cross-ply (0°, 90°) fiber orientation face-sheets of the honeycomb sandwich panels.

5. NEW SCIENTIFIC RESULTS – THESES

T1. The new scientific results extracted from the experimental tests of the thesis are summarized as follows:

1. The most efficient method to reduce the deflection of honeycomb sandwich panels is to increase the core thickness, thus increasing skin separation and lead to an increase in the stiffness-to-weight ratio; and increasing the face-sheets thickness is the most efficient way to reduce skin stress and core shear stress. This statement was proved by the 4-point bending tests carried out.
2. The honeycomb core thickness doesn't affect the adhesive's peeling resistance between the face-sheets and the sandwich structure's core, but the face-sheets thickness does. This statement was proved by the peeling tests carried out.
3. Increasing the honeycomb core thickness will increase the honeycomb sandwich panels' natural frequencies and reduce stress response and acceleration response due to increased stiffness-to-weight ratio. This statement was proved by the forced vibration tests carried out.
4. The acceleration frequency response, acceleration time response, and response function decrease with increasing the mass effect on the honeycomb sandwich plate, thin rubber plate, and thick rubber plate. The damping ratio and the dynamic shear modulus are directly proportional to the mass. This statement was proved by the damping test (Jones Measurement) carried out.

T2. A novel honeycomb sandwich structure has been optimized to manufacture a lightweight structure consisting of an aluminum honeycomb core and composite materials face-sheet. This statement was proved by theoretical analysis using the Matlab program and Excel Solver program carried out. It was applied to three studies:

1. Optimum design for honeycomb sandwich base plate of air cargo containers, the optimum face-sheet thickness and optimum core thickness ensure the minimum weight and minimum cost are 1-layer (+45°) of epoxy woven carbon fiber (0.3 mm, 26.439 mm, 6.292 kg, and 132.929 €), respectively. This optimal sandwich plate provides (55 %) weight saving compared to the air cargo container's conventional aluminum base plate (14.1 kg).
2. Optimum design of honeycomb sandwich structure for a single base plate of military aircraft pallets, the optimum face-sheet thickness and optimum core thickness ensure the minimum weight and minimum cost are two layers (0°, 90°) of epoxy woven carbon fiber (0.6 mm, 24.371 mm, 27.127 kg, and 703.074 €), respectively. This optimal sandwich plate provides (66 %) weight saving compared to the conventional aluminum single base plate of military aircraft pallet (80 kg).
3. Optimum design of solar sandwich panels for satellite applications, the optimum face-sheet thickness and optimum core thickness ensure the minimum weight and minimum cost are two layers (+45°, -45°) of epoxy woven carbon fiber (1.76 kg, 36.978 €, and 0.6 mm 54.058 mm), respectively.

T3. The mean vertical displacement at mid-section, equivalent skin stress, and equivalent core shear stress for epoxy woven carbon fiber face-sheets of the honeycomb sandwich structures with fiber orientation cross-ply (0°, 90°) and angle-ply (±45°) are less than the aluminum alloy face-sheets, hybrid composite face-sheets, phenolic woven glass fiber face-sheets, and epoxy woven glass fiber face-sheets, respectively. The mean vertical displacement at mid-section and equivalent core shear stress of cross-ply (0°, 90°) fiber orientation face-sheets are less than angle-ply (±45°) fiber orientation face-sheets of the honeycomb sandwich structures. While, the equivalent skin stress of angle-ply (±45°) fiber orientation is less than cross-ply (0°, 90°) fiber orientation face-sheets of the honeycomb sandwich structures. This statement was proved by Numerical analysis using the Digimat-HC program.

6. LIST OF PUBLICATIONS RELATED TO THE TOPIC OF THE RESEARCH FIELD

(1) Alaa, Al-Fatlawi; Károly, Jármai; György, Kovács. *Optimum Design of Honeycomb Sandwich Structure for a Single Base Plate of Military Aircraft Pallets*. Polymer, Vol. 13, No. 3, 834, 2021, ISSN 2073-4360. Doi: https://doi.org/10.3390/polym13050834; (Q1, IF: 3.426, WoS, Scopus)

(2) Alaa, Al-Fatlawi; Károly, Jármai; György, Kovács. *Optimum Design of Honeycomb Sandwich Plates used for Manufacturing of Air Cargo Containers*. Editura Politehnica, Academic Journal of Manufacturing Engineering, AJME, Romania, Vol. 18, No. 2, pp. 116-123, 2020, ISSN 1583-7904; (Q3, Scopus)

(3) Alaa, Al-Fatlawi; Károly, Jármai; György, Kovács. *Optimal Design of a Lightweight Composite Sandwich Plate used for Airplane Containers*. Techno-Press, Structural Engineering and Mechanics, an International Journal, South Korea, 2021, ISSN: 1598-6217; (Q1, IF: 2.984, WoS, Scopus), (under review – final review: "minor changes")

(4) Alaa, Al-Fatlawi; Károly, Jármai; György, Kovács. *Theoretical and Numerical Comparison Study of Aluminum Foam Sandwich Structure*. Pollack Periodica, an International Journal for Engineering and Information Sciences, Vol. 15, No. 3, pp. 113-124, 2020, Doi: https://doi.org/10.1556/606.2020.15.3.11; (Q3, Scopus)

(5) Alaa, Al-Fatlawi; Károly, Jármai; György, Kovács. *Minimum Mass Container Production for Ships and Airplanes, a Review*. Advances and Trends in Engineering Sciences and Technologies III: Proceedings of the 3rd International Conference on Engineering Sciences and Technologies (ESaT 2018), September, 12-14, 2018, High Tatras Mountains, Tatranské Matliare, Slovak Republic, CRC Press, Taylor and Francis Group, London, pp. 61-67, 2019, ISBN 978-0-367-07509-5, Doi: https://doi.org/10.1201/9780429021596; (Scopus index)

(6) Alaa, Al-Fatlawi; Károly, Jármai; György, Kovács. *Small and Full Scale Testing of Container Production for Ships and Airplanes, a Review*. CD proceedings of the 3rd International Conference on Engineering Sciences and Technologies (ESaT 2018), September 12-14, 2018, High Tatras Mountains, Tatranské Matliare, Košice, Slovak Republic, No. 18, 4 pages, 2019.

(7) Alaa, Al-Fatlawi; Károly, Jármai; György, Kovács. *Analytical and Numerical Study for Minimum Weight Sandwich Structures*. Proceedings of the 1st International Conference on Engineering Solutions for Sustainable Development (ICES^{2}D 2019), University of Miskolc, Hungary, 3-4 October, 2019, Taylor & Francis Group, London, pp. 3-11, 2020, ISBN: 9780367424251; (Q3, Scopus)

(8) Alaa, Al-Fatlawi; Károly, Jármai; György, Kovács. Structural Optimization of a Sandwich Panel Design for Minimum Weight Shipping and Airplane Containers. Proceedings of the MultiScience - XXXIII, microCAD, International Multidisciplinary Scientific Conference, 23-24 May, 2019, University of Miskolc, Egyetemváros, Hungary, 10 pages, 2019. Doi: https://doi.org/10.26649/musci.2019.036.

(9) Alaa, Al-Fatlawi; Károly, Jármai; György, Kovács. *Theoretical and Experimental Investigation of Aluminium Honeycomb Sandwich Structures*. Proceedings of the XIII, Hungarian Mechanical Conference on Theoretical and Applied Mechanics HCTAM, 27-29 August, 2019, University of Miskolc, Egyetemváros, Hungary, No. 463, pp. 1-8, ISBN: 978-963-358-181-0.

(10) Alaa, Al-Fatlawi; Károly, Jármai; György, Kovács. *Optimum Design of Solar Sandwich Panels for Satellites Applications*, Lecture Notes in Mechanical Engineering. Proceedings of the 3rd Vehicle and Automotive Engineering, University of Miskolc, Hungary, 2020, pp. 427-442, Springer, Singapore. Doi: https://doi.org/10.1007/978-981-15-9529-5_37; (Q3, Scopus)

(11) Alaa, Al-Fatlawi; Károly, Jármai; György, Kovács. *Theoretical and Numerical Comparison study of Aluminum Foam Sandwich Structure*. Abstract book of the 15th Miklós Iványi International PhD & DLA Symposium, University of Pécs, Faculty of Engineering and Information Technology, Pécs, Hungary, 28-29 October, 2019, No. 111, ISBN 978-963-429-449-8.

(12) Alaa, Al-Fatlawi; Jármai, Károly; Kovács, György. *Optimize Honeycomb Sandwich Design Technology in Shipping and Air Cargo Containers*. Doctoral students' forum, István Sályi Mechanical Sciences, 22-28 November, 2018, University of Miskolc, Egyetemváros, Hungary, pp. 1-6, ISBN: 978-963-358-194-0.

IN HUNGARIAN

(13) Alaa, Al-Fatlawi; Jármai, Károly; Kovács, György. *Méhsejtvázas kompozit panelek tervezése és mérése alkalmazással, Design and Measurement of Honeycomb Composite Panels with Application*. MACHINE-Technical Journal of the Mechanical Engineering Scientific Association, GÉP, Vol. 70, No. 2, pp. 36-39, 2019, ISSN: 0016-8572.

(14) Alaa, Al-Fatlawi; Jármai, Károly; Kovács, György. *Szendvicsszerkezet analítikus és numerikus vizsgálata alumíniumhab esetén, Analytical and Numerical Investigation of a Sandwich Beam with Aluminium Foam*. MACHINE-Technical Journal of the Mechanical Engineering Scientific Association, GÉP, Vol. 71, No. 2, pp. 40-47, 2020, ISSN: 0016-8572.

(15) Alaa, Al-Fatlawi; Jármai, Károly; Kovács, György. *Napelemes szendvics panelek optimális méretezése műholdas alkalmazásokhoz, Optimum Design of Solar Sandwich Panels for Satellites Applications*. MACHINE-Technical Journal of the Mechanical Engineering Scientific Association, GÉP, Vol. 72, No. 1-2, 5 p., 2021, ISSN: 0016-8572.

7. LITERATURE CITED IN THE THESES BOOKLET

[1] Bitzer, T.N. Honeycomb Technology: Materials, Design, Manufacturing. Applications and Testing, 1st edition, Chapman and Hall: London, UK; Dublin, Ireland; Dublin, CA, USA, 1997.

[2] Zenkert, D. An Introduction to Sandwich Construction, Student edition, Engineering Materials Advisory Services (EMAS): London, UK; Stockholm, Sweden, 1995.

[3] Zenkert, D. The Handbook of Sandwich Construction. Engineering Materials Advisory Services (EMAS): London, UK; Stockholm, Sweden, 1997.

[4] Callister, W.D.; Rethwisch, D.G. Materials Science and Engineering: An Introduction. 8th edition New York, John Wiley & Sons, Inc, 2018.

[5] Liu, Q.; Mo, Z.; Wu, Y.; Ma, J.; Pong, Tsui, G.C.; Hui, D. Crush Response of CFRP Square Tube Filled with Aluminum Honeycomb. Composites Part B: Engineering, Vol. 98, pp. 406-414, 2016.

[6] Karen, I.; Yazici, M.; Shukla, A. Designing Foam Filled Sandwich Panels for Blast Mitigation using a Hybrid Evolutionary Optimization Algorithm. Composite Structures, Vol. 158, pp. 72-82, 2016.

[7] Yan, C.; Song, X.D.; Feng, S. Aluminum Foam Sandwich with Different Face-sheet Materials under Three-point Bending. Applied Mechanics and Materials, Trans Tech Publications, Switzerland, Vol. 872, pp. 25-29, 2017.

[8] Adel I.S.; Steven, L.D. Weight and Cost Multi-objective Optimization of Hybrid Composite Sandwich Structures. International Journal of Computational Methods and Experimental Measurements, Vol. 5, No. 2, pp. 200-210, 2017.

[9] Arild, R. Analysis and Optimization of Sandwich Panels. Master Thesis in Engineering Design, the Arctic University of Norway, Faculty or Engineering Science and Technology, Norwegian, 2017.

[10] Ingrole, A.; Hao, A.; Liang, R. Design and Modeling of Auxetic and Hybrid Honeycomb Structures for In-plane Property Enhancement. Materials and Design, Vol. 117, pp. 72-83, 2017.

[11] Wu, Y.; Liu, Q.; Fu, J.; Li, Q.; Hui, D. Dynamic Crash Responses of Bio-inspired Aluminum Honeycomb Sandwich Structures with CFRP Panels. Composites Part B: Engineering, Vol. 121, pp. 122-33, 2017.

[12] Liu, Q.; Xu, X.; Ma, J.; Wang, J.; Shi, Y.; Hui, D. Lateral Crushing and Bending Responses of CFRP Square Tube Filled with Aluminum Honeycomb. Composites Part B: Engineering Vol. 118, pp. 104-115, 2017.

[13] Zaharia, S.M.; Pop, M.A.; Semenescu, A.; Florea, B.; Chivu, O.R. Mechanical Properties and Fatigue Performances on Sandwich Structures with CFRP Skin and Nomex Honeycomb Core. Materiale Plastice, Vol. 54, No. 1, pp. 67-72, 2017.

[14] Kececi, E.; Asmatulu, R. Effects of Moisture Ingressions on Mechanical Properties of Honeycomb-structured Fiber Composites for Aerospace Applications. The International Journal of Advanced Manufacturing Technology, Vol. 88, No. 1, pp. 459-70, 2017.

[15] Hambric, S.A.; Shepherd, M.R.; Schiller, N.H.; Snider, R.; May, C. Quieting a Rib-framed Honeycomb Core Sandwich Panel for a Rotorcraft Roof. Journal of the American Helicopter Society, Vol. 62, No. 1, pp. 1-10, 2017.

[16] Wang, Z.; Liu, J.; Hui, D. Mechanical Behaviors of Inclined Cell Honeycomb Structure Subjected to Compression. Composites Part B: Engineering, Vol. 110, pp. 307-314, 2017.

[17] Yalkin, H.E.; Icten, B.M.; Alpyildiz, T. Tensile and Compressive Performances of Foam Core Sandwich Composites with Various Core Modifications. Journal of Sandwich Structures and Materials, Vol. 19, No. 1, pp. 49-65, 2017.

[18] Wang, J.; Shi, C.; Yang, N.; Sun, H.; Liu, Y.; Song, B. Strength, Stiffness, and Panel Peeling Strength of Carbon Fiber-reinforced Composite Sandwich Structures with Aluminum Honeycomb Cores for Vehicle Body. Composite Structures, Vol. 184, No. 15, pp. 1189-1196, 2018.

[19] Iyer, S.V.; Chatterjee, R.; Ramya, M.; Suresh, E.; Padmanabhan, K. A Comparative Study of the Three Point And Four Point Bending Behaviour of Rigid Foam Core Glass/Epoxy Face Sheet Sandwich Composites. Materials Today: Proceedings, Vol. 5, No. 5, pp. 12083-12090, 2018.

[20] Chawa, P.K.; Mukkamala, S.K. Design and Analysis of Truck Container made of Honeycomb Sandwich Panels. Master Thesis, Blekinge Institute of Technology, Sweden, 2018.

[21] Florence, A.; Jaswin, M.A. Vibration and Flexural Characterization of Hybrid Honeycomb Core Sandwich Panels Filled with Different Energy Absorbing Materials. Materials Research Express, Vol. 6, No. 7, 32 pages, 2019.

[22] Teng, L.; Zheng, X.; Jin, H. Performance Optimization and Verification of a New Type of Solar Panel for Microsatellites. International Journal of Aerospace Engineering, Vol. 2019, 14 pages, 2019.

[23] Zaharia, S.M.; Enescu, L.A.; Pop, M.A. Mechanical Performances of Lightweight Sandwich Structures Produced by Material Extrusion-based Additive Manufacturing. Polymers, Vol. 12, No. 8, 1740, 2020.

[24] Yan, B.; Wang, X.; Pan, S.; Tong, M.; Yu, J.; Liu, F. Stability and Failure of the Edge-closed Honeycomb Sandwich Panels with Face/Core Debonding. Applied Sciences, Vol. 10, No. 21, 7457, 2020.

[25] Aborehab, A.; Kassem, M.; Nemnem, A.; Kamel, M. Mechanical Characterization and Static Validation of a Satellite Honeycomb Sandwich Structure. Engineering Solid Mechanics, Vol. 9, No. 1, pp. 55-70, 2021.

[26] Hexcel Composites Publication No. LTU035b, Mechanical Testing of Sandwich Panels, Technical Notes, 2007. Available online:
https://www.hexcel.com/user_area/content_media/raw/SandwichPanels_global.pdf.

[27] Hexcel Prepreg Publication No. FGU 017c, Prepreg Technology, 2013. Available online: https://www.hexcel.com/user_area/content_media/raw/Prepreg_Technology.pdf

[28] Singiresu R.S. Mechanical Vibrations. 6th edition in SI Units, Pearson Education Limited, 2017.

[29] De Silva, C.W.; Palusamy, S.S. Experimental Modal Analysis - a Modeling and Design Tool. Mechanical Engineering, ASME, Vol. 106, No. 6, pp. 56-65, 1984.

[30] Farkas, J.; Jármai, K. Analysis and Optimum Design of Metal Structures. CRC Press, 1997.

[31] Hexcel Composites Publication No. AGU 075b, Honeycomb Sandwich Design Technology, 2000. Available online:
https://www.hexcel.com/user_area/content_media/raw/Honeycomb_Sandwich_Design_Technology.pdf.

[32] Bode, W. Evaluation of a Lightweight Composite Bottom Plate for Air Freight Containers. Master Thesis, Faculty of Aerospace Engineering, Department of Aerospace Structures and Materials, Netherlands, 2016.