UNIVERSITY OF MISKOLC
FACULTY OF MECHANICAL ENGINEERING AND INFORMATICS

MINIMUM WEIGHT AND COST DESIGN OPTIMIZATION OF HONEYCOMB SANDWICH STRUCTURES WITH APPLICATIONS

PH.D. THESES

Prepared by

ALAA ABDULZAHRA DELI AL-FATLAWI

Engineering of Mechanics (BSc),
Applied Mechanical Engineering (MSc)

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

Head of Doctoral School

Dr. Gabriella Bognár
DSc, Full Professor

Scientific Supervisors

Dr. Károly Jármai
DSc, Full Professor
&
Dr. György Kovács
Ph.D., Associate Professor

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SUPERVISOR'S RECOMMENDATIONS

Alaa Abdulzahra Deli Al-Fatlawi was born in Al-Najaf city (Iraq) on April 2nd, 1980. His nationality is Iraqi. He is married since 2006 and has two children, a boy, and a girl.

He holds a bachelor's degree in Mechanical Engineering Sciences in 2002 and a master's degree in Applied Mechanical Engineering from the University of Kufa, Faculty of Engineering, and Department of Mechanical Engineering in 2006. He was a lecturer at his university from 2006 until now.

Miskolc, 10th January 2021

Prof. Dr. Károly Jármai & Dr. György Kovács
Supervisors

LIST OF SYMBOLS AND ABBREVIATIONS

GREEK LETTERS

η_d	Damping ratio	N/A
β	Buckling factor	N/A
δ	Deflection	mm
δ_b	Bending deflection	mm
δ_s	Shear deflection	mm
δ_{max}	Maximum deflection	mm
δ_{Exp}	Experimental deflection	mm
δ_{Num}	Numerical deflection	mm
σ_{Exp}	Experimental stress	MPa
σ_{Num}	Numerical stress	MPa
σ_{skin}	Skin stress	MPa
$\sigma_{f,x}$	Typical yield strength of the composite face-sheet in the x-direction	MPa
$\sigma_{f,y}$	Typical yield strength of the composite face-sheet in the y-direction	MPa
$\sigma_{f,y}$	Typical yield strength of face-sheet	MPa
σ_f	Face-sheet thickness	MPa
$\sigma_{wr,\,cr}$	Skin wrinkling critical stress	MPa
$\sigma_{f,\,cr}$	Intracell buckling critical stress	MPa
τ_c	Core shear stress	MPa
$\tau_{c,y}$	Typical shear stress of the core material in the transverse direction	MPa
ω	Angular frequency	rad/sec
ρ_f	Face-sheet density	kg/m^3
ρ_c	Core density	kg/m^3
ρ_g	Density of epoxy woven glass fiber	kg/m^3
ρ_{cr}	Density of epoxy woven carbon fiber	kg/m^3
µ	Poisson's ratio	N/A
ν_c	Core Poisson's ratio	N/A
ν_{12}^f, ν_{21}^f	Face-sheet Poisson's ratio	N/A
θ°	Fiber orientation angle	Degree
$\ddot{x}_1, \ddot{x}_2$	Acceleration	g

LATIN LETTERS

l	Length	mm
s	Span	mm
b	Width	mm
h	Total thickness	mm
t_f	Face-sheet thickness	mm
t_c	Core thickness	mm
N_l	Number of layers	layer
P	Applied load	N
p	Load per unit area	MPa
F_p	Peel resistance force or peel strength	N
F_r	Average force	N
F_i	Initial force	N
F_{max}	Peak force	N
T	Peel torque	mm
R_o	Flange radius	mm
R_i	Drum radius	N
L_p	Peel length	mm
R	Initial resistance	Ω
ΔR	Resistance change	Ω
K	Gauge factor	N/A
ΔL	Length change	mm
T_R	Transmissibility	N/A
G_d	Dynamic shear modulus	Pa
m	Mass	kg
f	Frequency	Hz
W_t	Total weight	kg
W_f	Face-sheets weight	kg
W_c	Core weight	kg
$W_{f,cr}$	Weight of epoxy woven carbon fiber face-sheets	kg
$W_{f,g}$	Weight of epoxy woven glass fiber face-sheets	kg
t_l	Lamina thickness	mm
t_f	Face-sheet thickness	mm
t_c	Core thickness	mm
t_g	Lamina thickness of epoxy woven glass fiber face-sheet	mm
t_{cr}	Lamina thickness of epoxy woven carbon fiber face-sheet	mm
$t_{c,opt}$	Optimum core thickness	mm
$t_{f,opt}$	Optimum face-sheet thickness	mm

N_g	Number of epoxy woven glass fiber laminates	layer
N_{cr}	Number of epoxy woven carbon fiber laminates	layer
$N_{l,opt}$	Optimum number of layers	layer
C_t	Total material cost	€
C_f	Cost of face-sheets	€/kg
C_c	Cost of honeycomb core	€/m^3
$C_{f,cr}$	Cost of epoxy woven carbon fiber face-sheets	€
$C_{f,g}$	Cost of epoxy woven glass fiber face-sheets	€
C_g	Cost of epoxy woven glass fiber material	€/kg
C_{cr}	Cost of epoxy woven carbon fiber material	€/kg
$[A]$	Extensional stiffness matrices	N/m
$[B]$	Coupling stiffness matrices	N
$[D]$	Bending stiffness matrices	N.m
A_{11}^{f}	Extensional stiffness matrices of the face-sheets	N/m
B_{11}^{f}	Coupling stiffness matrices of the face-sheets	N
D_{11}^{f}	Bending stiffness matrices of the face-sheets	N.m
$D_{11,x}$	Bending stiffness in global coordinate	N.m
$D_{f,x}$	Bending stiffness of the sandwich structure in global coordinate	N.m^2
D_{min}	Minimum stiffness of sandwich structure	N.m
$\tilde{S}_{11}$	Shear stiffness of composite sandwich structure	N/m
S	Shear stiffness of sandwich structure	N
K_b	Bending deflection coefficient	N/A
K_s	Shear deflection coefficient	N/A
d	Distance between facing skin centers	mm
G_c	Core shear modulus	GPa
G_W	Core shear modulus in W-direction (Transverse direction).	GPa
G_L	Core shear modulus in L-direction (Ribbon direction).	GPa
M	Maximum bending moment	N.m
F	Maximum shear force	N
$P_{b,cr}$	Overall critical buckling load	N
P_b	Bending buckling load	N
P_s	Shear buckling load	N
P_{cr}	Critical shear crimping load	N
$P_{wr,cr}$	Skin wrinkling critical load	N
$E_{f,x}$	Young's modulus elasticity of composite face-sheet in x-direction	GPa
$E_{f,y}$	Young's modulus elasticity of composite face-sheet in y-directions	GPa
E_f	Average modulus of elasticity	GPa
E_c	Young's modulus elasticity of core	GPa

SUBSCRIPTS

Exp	Experimental	N/A
Num	Numerical	N/A
cri	Critical value	N/A
max	Maximum	N/A
min	Minimum	N/A
x, y	Property refers to a Cartesian direction	N/A
c	Property refers to the core	N/A
f	Property refers to the face-sheet	N/A
y	Yield point	N/A
wr	Wrinkling	N/A

1. INTRODUCTION AND LITERATURE REVIEW

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 (see Figure 1.1) and must have a material symmetry plane parallel to its midplane; the core's 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 man-made structures that have architecture of a honeycomb to reduce the amount of materials used in industrial applications to achieve minimum weight and minimum cost of the material. 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.

The honeycomb sandwich panels are the lightest option for compressive or bending loads in specific applications. The honeycomb sandwich cores are manufactured using thin strips formed into honeycomb cells. The honeycomb geometry is nonisotropic, with greater stiffness in the longitudinal direction. However, the core acts nearly isotropically for in-plane loads when assembled in a sandwich configuration. The aluminum honeycomb core is used for several applications and in different sectors such as the public transport industry, nautical sector, building industry, etc. As core material, the aluminum honeycomb core is used in sandwich panels. It is utilized in floors, roofs, doors, partitions, facades, working surfaces for automatic machines, and all products requiring an optimal stiffness to weight ratio. The aluminum honeycomb as panels' core has several advantages: lightweight, stiffness, fire resistance, compression, shear, and corrosion resistance flatness. The aluminum honeycomb core can be used as a deflector for laminar flow ventilation and as a crash absorber for kinetic energy. The honeycomb core density depends on the thickness of the foil and the diameter of the cells. The engineering properties of the honeycomb core make it ideal for many applications like satellite sandwich panels. Aluminum alloys are the most commonly used metallic materials in spacecraft manufacturing. The advantages are high strength to weight ratios, high ductility, and ease of machining, weldability, and availability at low cost [1-3].

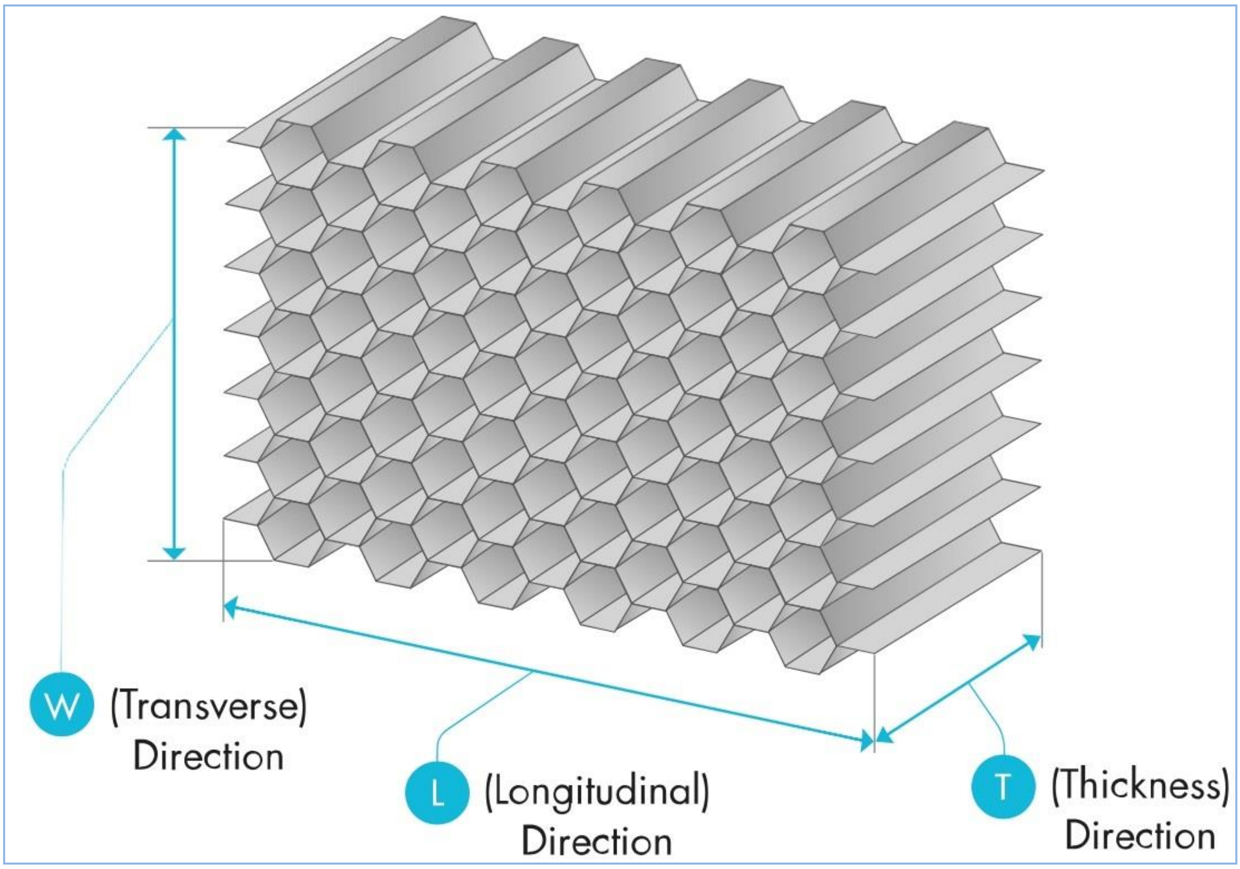


Figure 1.1: Illustration of the honeycomb core.

1.1. Background and Objectives of the Research

1.1.1. Fiber Reinforced Composites (FRC)

Technologically, the most important composites are those in which the dispersed phase is in the form of a fiber. The high strength and/or high stiffness on a weight basis are the purpose of design for fiber reinforced composites. These properties are expressed in terms of specific strength and specific modulus parameters, respectively, to the tensile strength ratios to specific gravity and modulus of elasticity to specific gravity. Fiber reinforced composites with high specific strengths and moduli have been produced using low-density fiber and matrix materials [4].

1.1.2. Polymer Matrix Composites (PMCs)

Composites of polymer matrix consist of a polymer resin as the matrix and fibers as the reinforcement medium. These materials are utilized in the greatest variety of composite applications, as well as in the largest amounts, in light of their room temperature properties, ease of manufacture, and cost. In this section, the different classifications of PMCs are discussed according to the type of reinforcement (i.e., glass and carbon fibers), along with their applications and the several polymer resins that are used (i.e., epoxy and phenolic resins).

Glass Fiber Reinforced Polymer (GFRP) Composites: Fiberglass is simply a composite consisting of glass fibers, either continuous or discontinuous, within a polymer matrix. This type of composite is manufactured in the largest quantities. Many fiberglass applications are familiar:

automotive and marine, pipes, containers, and industrial floorings. Transportation manufactures are utilizing increasing amounts of glass fiber-reinforced plastics in an attempt to decrease vehicle weight and increase fuel efficiencies.

Carbon Fiber Reinforced Polymer (CFRP) Composites: carbon fiber is a high-performance fiber material that is the most commonly utilized reinforcement in advanced (i.e., non-fiberglass) polymer matrix composites. Composites of the carbon-reinforced polymer are currently being used extensively in sports and recreational equipment, filament-wound rocket motor cases, pressure vessels, and aircraft structural components both military and commercial, both fixed-wing aircraft and helicopters (e.g., as a wing, body, stabilizer, and rudder components).

Hybrid Composites: The hybrid is a relatively new fiber-reinforced composite obtained by utilizing two or more different types of fibers in a single matrix. Hybrids have a better all-around combination of properties than those composites, containing only a single fiber type. A diversity of fiber combinations and matrix materials are utilized, but in the most common system, both carbon and glass fibers are inserted into a polymeric resin. The carbon fibers are strong and relatively stiff and provide low-density reinforcement. However, they are expensive. Glass fibers are inexpensive and lack the stiffness of carbon. The hybrid of glass carbon is more robust and tougher, has higher impact resistance, and may be produced at a lower cost than similar carbon or glass-reinforced plastics. The two different fibers may be combined in several ways, which will ultimately influence the overall properties. For example, the fibers may all be aligned and intimately mixed with one another, or laminations may be constructed consisting of layers, each of which consists of a single fiber type, alternating with one another. In virtually all hybrids, the properties are anisotropic. Principal applications for hybrid composites are lightweight land, water, air transport structural components, sporting goods, and lightweight orthopedic components [4].

1.1.3. Structural Composites

A structural composite is a multilayered and normally low-density composite utilized in applications requiring structural integrity, ordinarily high tensile, compressive, and torsional strengths and stiffnesses. These composites' properties depend not only on the constituent materials' properties but also on the geometrical design of the structural elements. Laminar composites and sandwich panels are two of the most common structural composites.

Laminar Composites: A laminar composite is composed of two-dimensional sheets or panels (plies or laminae) bonded to one another. Each ply has a preferred high strength direction, such as continuous and aligned fiber-reinforced polymers. A laminate is a multilayered structure. Laminate properties depend on several factors, including how the high strength direction varies from layer to layer. In this regard, there are four classes of laminar composites: unidirectional, cross-ply (0°, 90°), angle-ply (±45°), and multidirectional of cross-ply (0°, 90°) and angle-ply (±45°). For unidirectional, the orientation of the high strength direction for all laminae is the same (see Figure 1.2a); cross-ply laminates have alternating high strength layer orientations of 0° and 90° (see Figure 1.2b), and for angle-ply, successive layers alternate between $+\theta$ and $-\theta$ high strength orientations (e.g. ± 45°) (see Figure 1.2c). The multidirectional laminates have several high strength orientations (see Figure 1.2d). For virtually all laminates, layers are typically stacked such that fiber orientations are symmetric relative to the laminate midplane; this arrangement prevents any out-of-plane twisting or bending. Applications that use laminate composites are primarily in aircraft, automotive, and marine [4].

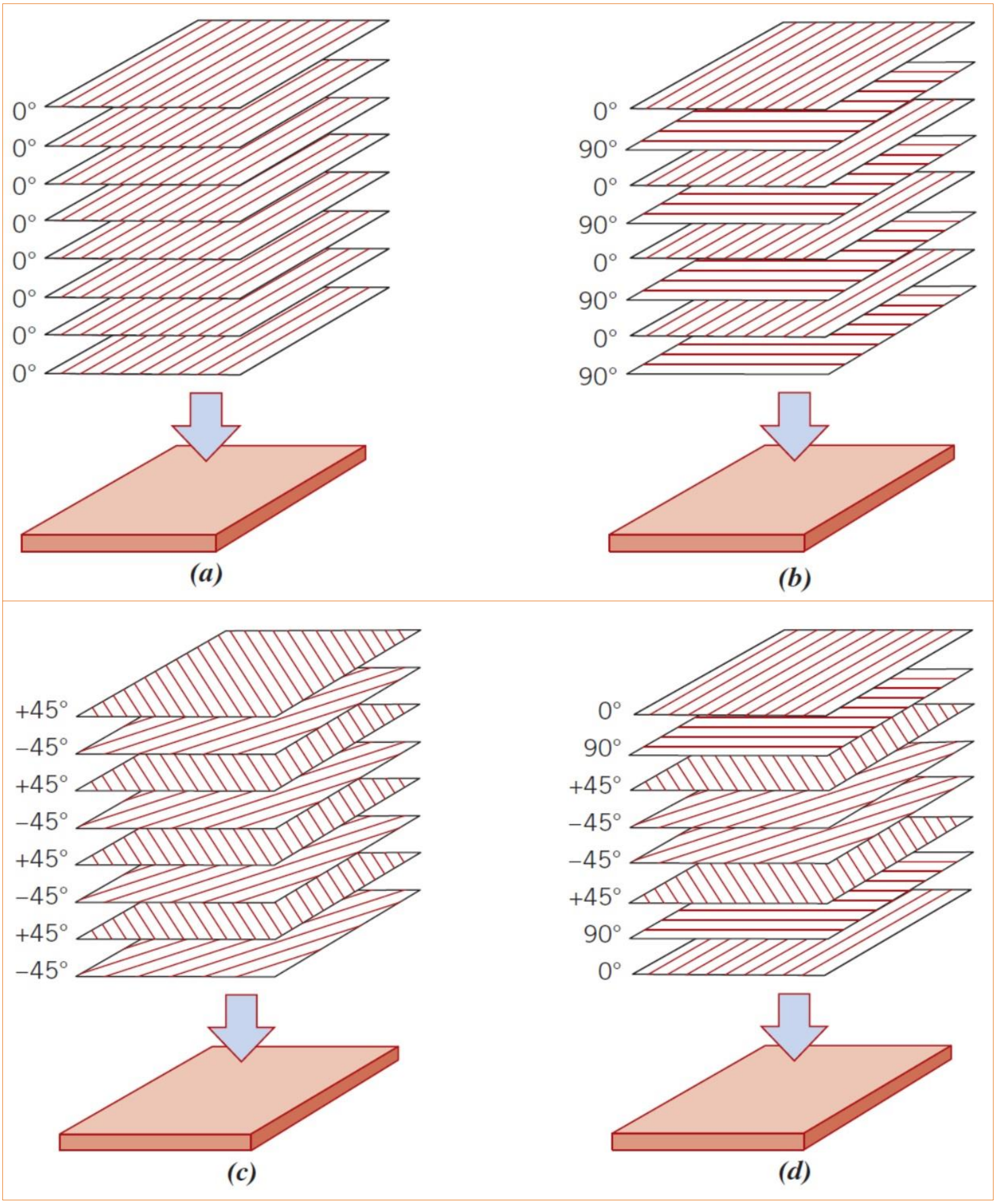


Figure 1.2: Lay-ups (schematics) for laminar composites. (*a*) Unidirectional; (*b*) cross-ply (0°, 90°); (*c*) angle-ply (±45°); and (*d*) multidirectional (cross-ply (0°, 90°) and angle-ply (±45°)) [4].

1.2. 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 made of 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 strongly 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 1.3 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, and stainless steels; and polymers polypropylene, polyurethane, kraft paper [4].

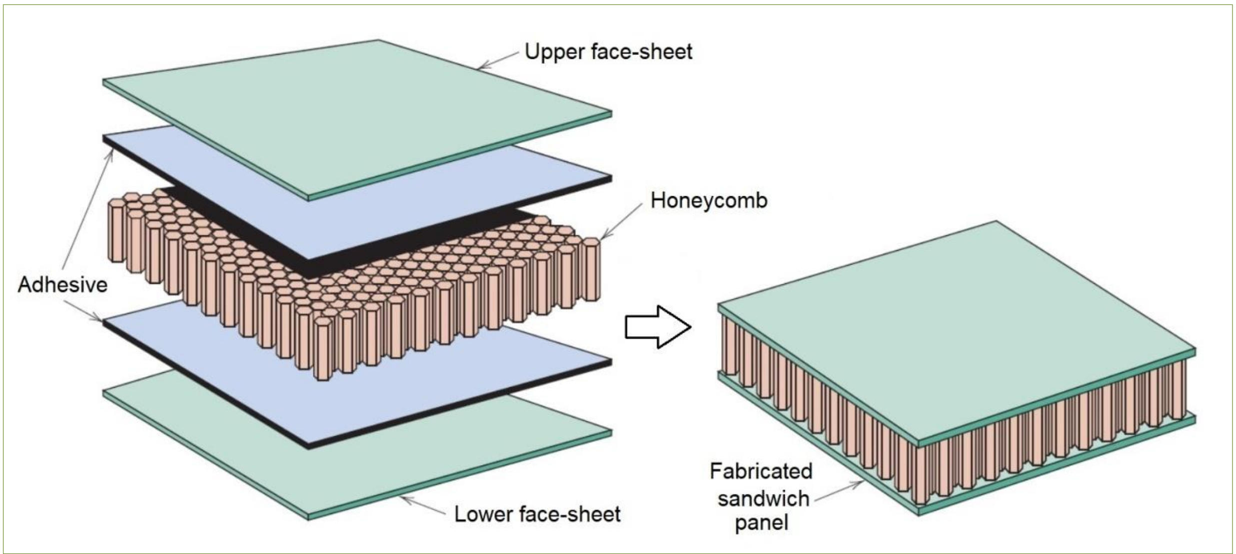


Figure 1.3: Schematic diagram showing the construction of a honeycomb core sandwich panel.

1.3. Composite Structural Optimization

In general, structural optimization is obtaining an assemblage of material and structure while ensuring that the assemblage maintains the applied loads efficiently. The most efficient method indicates designing the structure as lightweight as possible or to make the structure as rigid as possible. Other possibilities might be to make the structure as insensitive to buckling or instability as possible or the lowest possible cost. Therefore, it is evident such minimization or maximization cannot be performed or reached without any constraints. For example, suppose there is no limitation on the amount of material that can be utilized. In that case, the structure can be made stiff without limit, and we have an optimization problem without a well-defined solution. In the manufacture of high-performance structures, especially in weight critical applications, the sandwich structure with fiber-reinforced composite face-sheets is increasingly utilized due to its high performance (e.g. bending stiffness and strength to weight ratios).

Moreover, these advantages can be further improved by utilizing the available materials in an optimal method. The use of laminate composites for face-sheets allows the designer to vary ply material, ply orientation angles, and the layers sequence's stacking to achieve the desirable properties. Thus, when applying an optimization technique to the sandwich structure with composite material face-sheets, there are multiple design variables, include ply material, ply orientation angles, plies stacking sequence ply, and core thickness. Hence, this result is a complex design and analysis process in which several design parameters can be manipulated to modify the sandwich structure's final properties.

Implementing structural optimization techniques on the sandwich structure design process with fiber-reinforced composite face-sheets will provide the ability to make logical decisions on the design parameters that affect a sandwich structure's properties. Many different optimization methods and techniques have been proposed and developed to solve single and multi-objective problems of structural optimization. The very purpose of which is to find the best methodologies so that a designer can reach a maximum benefit from the available materials. The single-objective optimization problem is defined as minimizing or maximizing the objective function while satisfying a set of equality and inequality constraints. But in reality, in engineering design problems, the design is usually differentiated by more than one conflicting objective function, for example minimizing cost while maximizing the performance of a product or minimizing weight while maximizing the strength of a structure. Therefore, various solutions will produce trade-offs between different objectives, and a set of solutions is required to represent the optimal solutions of all conflicting objective functions.

In light of this, single and multi-objective optimization techniques were performed to obtain the optimum design values of honeycomb sandwich structure subject to required constraints based on 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, shear critical buckling load), shear crimping load, skin wrinkling (critical stresses and load) and intracell buckling. The honeycomb sandwich structures considered consisted of aluminum honeycomb core and different types of face-sheets. The face-sheets consisted of aluminum alloy, phenolic woven glass fiber, epoxy woven glass fiber, epoxy woven carbon, and hybrid composite layers. The face-sheets' fibers layups were restricted to discrete layup orientation angles of cross-ply and/or angle-ply. Epoxy resin is a polymer also known as polyepoxides containing at least two and more epoxide groups per monomer, which are also referred to as a glycidyl or oxirane groups. Phenol formaldehyde resins (PF) or phenolic resins are synthetic polymers obtained by the reaction of phenol or substituted phenol with formaldehyde.

Its versatile properties such as thermal stability, chemical resistance, fire resistance, and dimensional stability make it suitable for a wide range of applications [5]. Phenolic and Epoxy resins have been used in the composites industry as adhesives. The proposed sandwich structure's optimization methodology consisted of three stages: a weight objective optimization, cost objective optimization, and weight and cost multi-objective optimization of the honeycomb sandwich structure. The first stage of the optimization process started with a single-objective optimization technique to minimize the hybrid sandwich plate's weight for given data and calculated data. In the second stage of the optimization process, a single-objective optimization technique was applied to minimize the same honeycomb sandwich structure's cost subjected to the same constraints applied in weight minimization. Matlab program (fmincon Solver Constrained Nonlinear Minimization/ Interior Point Algorithm) and Excel solver program were used to minimize the single-objective optimization. The third stage for the optimization process explored the multi-objective optimization to minimize the weight and the cost simultaneously of the sandwich plate with different types of face-sheets and aluminum honeycomb core under design requirements of bending load and torsional load both separately and simultaneously. The Matlab program (Genetic Algorithm Solver) and Excel Solver program (Weighted Normalized Method) with Pareto filter were used to generate the Pareto front curve. The Pareto front curve was constructed by optimizing a sequence of combining weight and cost objective functions. The strategies of composite face-sheets were solved using the Laminator program, an engineering program that analysis laminated composite material according to classical lamination theory and the ply failure calculation based on Tsai-Hill failure criteria.

1.4. Research Objectives

To solve this problem, several main goals of the covert research investigation have been identified:

- Identify the mechanical behavior of the honeycomb sandwich structure through a series of static and dynamic tests to be used in manufacturing the required applications.
- Investigation how to optimize the honeycomb sandwich structure in terms of weight and/or cost both separately and simultaneously.
- Exploring the hybrid composite material using high cost, high stiffness composites (like carbon fiber) with low cost, lower stiffness composites (such as 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.

1.5. Research Significances

The importance of this research opens up new possibilities, including:

- Allow multi-objective structural design optimization on both weight and/or cost of the honeycomb sandwich structure.
- Use of composite and hybrid materials as a quantified and often preferred design option.
- Save on weight and cost of honeycomb sandwich structure.
- Practical design knowledge of high interest for many engineering applications like air cargo containers, military aircraft pallets, and solar panels of the satellite.

1.6. Literature Review

In order to provide motivations to the present dissertation, this chapter introduces a literature review on topics related to this thesis: optimization of composite sandwich structures due to the desired design requirements in some sandwich structure applications, effects of composite material, and hybrid on the sandwich structure.

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 weight and cost of the hybrid sandwich plates considered objective functions are subject to required equality constraints based on the bending and torsional stiffnesses [6]. In 2016, Bode investigated the replacement of the current aluminum floor with a lighter composite in Nordisk containers, and performed analytical and finite element calculations, and conducted small-scale and full-scale tests based on the calculation results and requirements [7]. 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 [8]. 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 [9].

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 [10]. In 2014, Rodrigues et al. optimized the material configuration of various composite plates and shells, subjected to different loading conditions, to maximize the structural stiffness with the possibility of having a weight constraint using an optimization model based on a discrete material optimization [11]. In 2018, Iyer et al. investigated a comparative study between three points and four points bending of sandwich composites made of rigid foam core and glass epoxy skin [12]. In 2016, Zhao et al. examined the lateral compressive buckling performance of the new long-span hollow core roof architecture with different length-to-thickness ratios by employed lateral compression tests and finite element analyses [13]. In 2009, Inés et al. studied the structural behavior of composite sandwich panels for construction industry applications [14].

In 1984, Gibson described a new method for maximizing stiffness per unit weight in sandwich beams with foam cores to obtain the optimum values of core thickness, face thickness, and core density [15]. In 2010, Manalo et al. investigated the flexural behavior of a new generation composite sandwich beams made up of glass fiber-reinforced polymer skins and modified phenolic core material using 4-point static bending test to determine their strength and failure mechanisms in the flatwise and the edgewise positions [16]. In 1999, Petras described theoretical models using honeycomb mechanics and classical beam theory and constructed a failure mode map for loading under 3-point bending to show the dependence of failure mode and load on the ratio of skin thickness to span length and honeycomb relative density [17]. In 2016, Mariana developed innovative, lightweight design and joining concepts for air cargo containers made of carbon fiber woven composite to reduce weight [18]. In 2014, Kovács and Farkas showed the optimization method for a new complex structural model consists of laminated carbon fiber-reinforced plastic deck plates with polystyrene foam core.

The objective functions are minimum weight and minimum cost and design constraints, including maximum deflection of the whole structure, stress in the composite plates, stress in the polystyrene foam core, eigenfrequency of the structure, thermal insulation of the structure, and size constraints for the design variables [19]. In 2015, Zhang studied an equivalent laminated model with three layers to simulate the aluminum honeycomb sandwich panel's behavior with a positive hexagon core [20]. In 2009, Wang conducted dynamic cushioning tests by free drop and shock absorption principle and analyzed the effect of paper honeycomb structure factors on the impact behavior [21]. In 2014, Joshi studied the impact of adding a mass on the composite beam at various locations on the damping loss factors for vibration modes present in the frequency range of interest [22]. In 2019, Florence & Jaswin investigated vibrational analysis and flexural behavior of hybrid honeycomb core sandwich panels filled with three different energy-absorbing materials experimentally [23].

In 2012, Aly et al. evaluated the sandwich specimens' impact properties produced from many types of woven fabrics using polyester fibers as warp threads with different structure parameters such as weft yarn material, picks densities, and weaving structures to be used as skin layers. The nonwoven fabric was used as a core layer to choose the best sample performance for automotive applications [24]. In 2009, Assarar et al. presented an analysis of damping for sandwich composites made of PVC foam cores and laminated skins using beam test specimens and an impulse technique [25]. In 2018, Chawa & Mukkamala optimized a shipping container made of sandwich panels to reduce tare weight and stresses [26]. In 2021, Aborehab et al. discussed the mechanical behavior of an aluminum honeycomb structure exposed to flat-wise compressive and flexural testing. They proposed an equivalent finite element model based upon the sandwich theory to simulate the flexural testing's elastic behavior and compare computational and experimental results [27]. In 2016, Yongha et al. used Lagrange's theorem, the Ritz method, and the mode shape function to define the dynamic model of a high-agility satellite considering the flexibility of composite solar panel and stiffness of a solar panel's hinge [28].

In 2013, Fajrin et al. presented the significance analysis of a new type of hybrid composite sandwich wall panel, which can be manufactured as a modular, panelized system [29]. In 2012, Xiang et al. develop a minimum weight optimization method for the sandwich structure under combined torsion and bending loads [30]. In 2020, Zaharia et al. performed compression, three-point bending, and tensile tests to evaluate lightweight sandwich structures' performance with different core topologies [31]. 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 [32]. In 2017, Yan J. et al. conducted a large experiment on three typical blade sandwich structures to simulate the natural lightning-induced arc effects [33]. In 2011, Jun & Dai developed a new lightweight sandwich structure by reinforcing the web of an insert with high strength carbon composite to increase the loading capability with reduced mass [34]. 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 [35]. In 2007, Boudjemai et al. proposed a genetic algorithm for structural optimization of satellite structural designs [36].

2. MECHANICAL TESTS ON PREPREG SANDWICH CONSTRUCTIONS

2.1. *Introduction*

To evaluate the structural performance of a sandwich panel by conducts various mechanical tests consist 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. *Four-Point Bending Test of Honeycomb Sandwich Panels*

This test method is intended to determine the relationship between load P and displacement δ_{Exp} 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' specimens are made of an aluminum honeycomb core and orthotropic composite material face-sheets (see Figure 2.1). The composite face-sheets are made of phenolic woven glass fiber. The fiber orientation of the composite face-sheets was cross-ply (0°, 90°). These specimens were made in the Kompozitor Company. Numerical models are made for the same specimens using the Digimat-HC modeling program to calculate the deflection, skin stress, and core shear stress to compare with the experimental results. The average skin stress and modulus can be determined [37]:

$$\sigma = \frac{Ps}{8dbt_f} \tag{2.1}$$

$$E = \frac{11}{384}\frac{P}{\delta}\frac{s^3}{bt_f d^2} \tag{2.2}$$

This test is referring to MIL-STD-401B Sec.5.2.4 or ASTM C-393. These equations are applicable for a symmetrical sandwich panel with thin face skins.

Figures 2.2-2.5 represents the experimental results (four-point bending test), including the deflection-load curve for the set of honeycomb sandwich specimens, and the numerical results (four-point bending test) including deflection, skin stress, and core shear stress for the set of honeycomb sandwich models to the comparison. Because the results have the same behavior, so I showed some of them.

According to the experimental and numerical results which are shown in Tables 2.1 & 2.2, the most efficient way to reduce the deflection of composite sandwich panels is to increase the honeycomb core thickness, thus increase the skin separation, and the most efficient way to reduce the skin stress and core shear stress is to increase the face-sheets thickness. Good agreement was found between experimental and numerical results.

Table 2.1: Dimensions and results of experimental tests by applying the four-point bending test in the university's laboratory and numerical models using the Digimat-HC program for honeycomb sandwich specimens set.

Index	Span	Width	Core thickness	Face-sheet thickness	Load	Deflection		Stress		Shear	Difference	
	s	b	t_c	$t_f\ (N_l)$	P	δ_{Exp}	δ_{Num}	σ_{Exp}	σ_{Num}	τ_{core}	δ	σ
	mm	mm	mm	mm (Layer)	N	mm	mm	MPa	MPa	MPa	%	%
1	840	120	4	1 (2-2)	101	24.875	25.047	11.834	12.9	0.112	0.7	8
2	840	120	20	1 (2-2)	1053	24.565	26.156	39.144	40.4	0.370	6	3
3	840	115	13	1 (2-2)	467	25.106	24.128	26.854	27.1	0.232	3.9	1
4	840	54	18	1 (2-2)	363	24.543	25.201	35.165	36.0	0.337	2.6	2.3
5	840	118	20	1 (2-2)	619	17.74	15.704	23.366	24.2	0.226	11	3.4

Table 2.2: 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	Stress	Shear	Deflection		Difference
	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	5.3224
2					1 (2-2)	1500	50.3	0.818	10.2	10.185	0.1479
3					1 (2-2)	1600	53.6	0.872	11	10.864	1.2364
4				19	2 (4-4)	1650	44.8	0.675	5.7	5.345	6.2287
5					2 (4-4)	1950	53	0.798	7	6.317	9.7573
6					2 (4-4)	2000	54.4	0.818	6.5	6.479	0.3237
7					2.5 (5-5)	1800	52.4	0.687	4.5	4.854	7.2924
8					2.5 (5-5)	1900	50.5	0.74	5	5.357	6.6648

Figure 2.1: Experimental specimens (four-point bending test) for the sandwich panels consisting of an aluminum honeycomb core and phenolic woven glass fiber face-sheet.

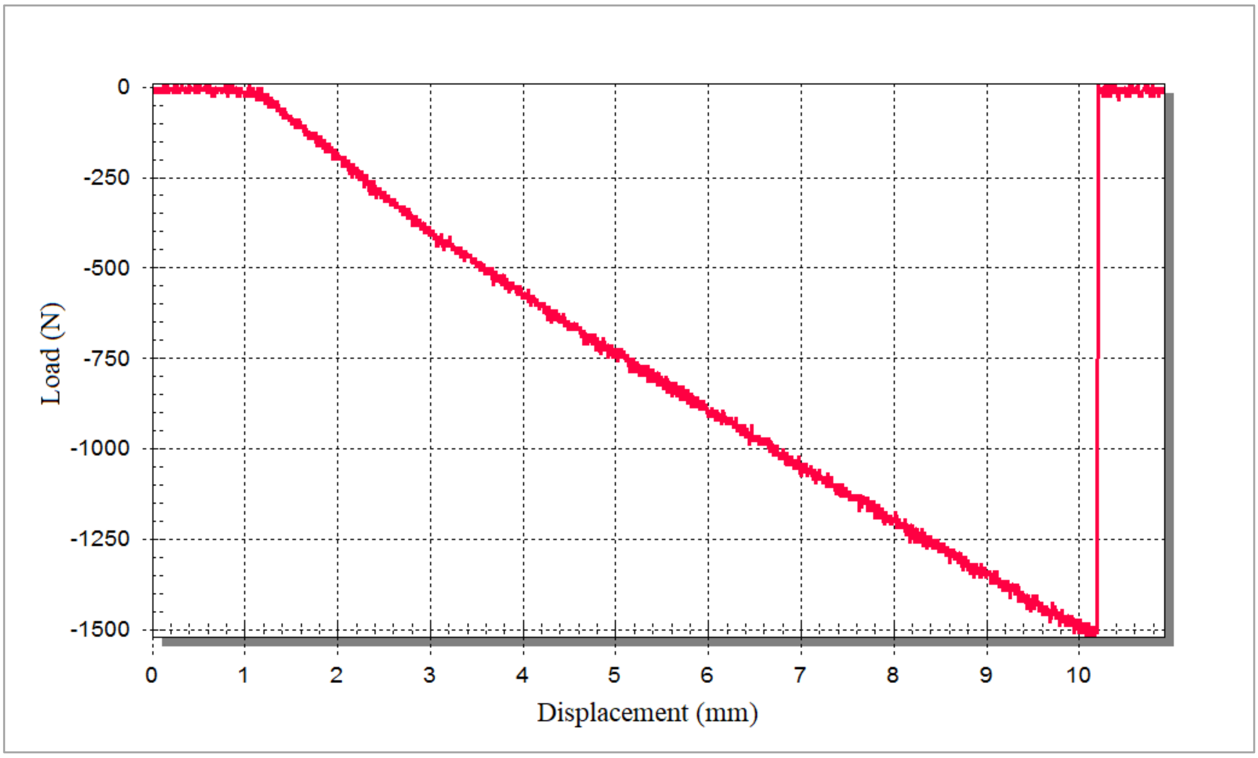


Figure 2.2: Experimental result (four-point bending test) for the specimen of the sandwich panel under applied load (P=1500 N) consisting of an aluminum honeycomb core (t_c=15 mm) and phenolic woven glass fiber face-sheets (t_f=1 mm).

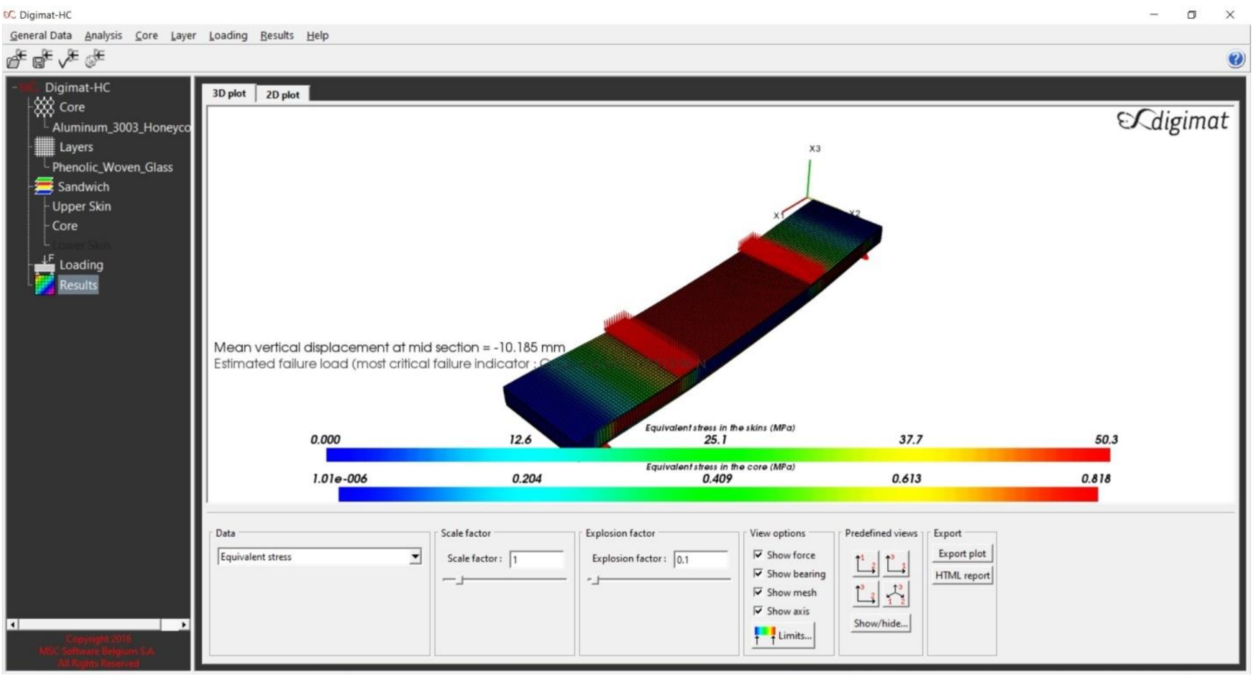


Figure 2.3: Numerical result (four-point bending test) for the specimen of the sandwich panel under applied load (P=1500 N) consisting of an aluminum honeycomb core (t_c=15 mm) and phenolic woven glass face-sheets (t_f=1 mm).

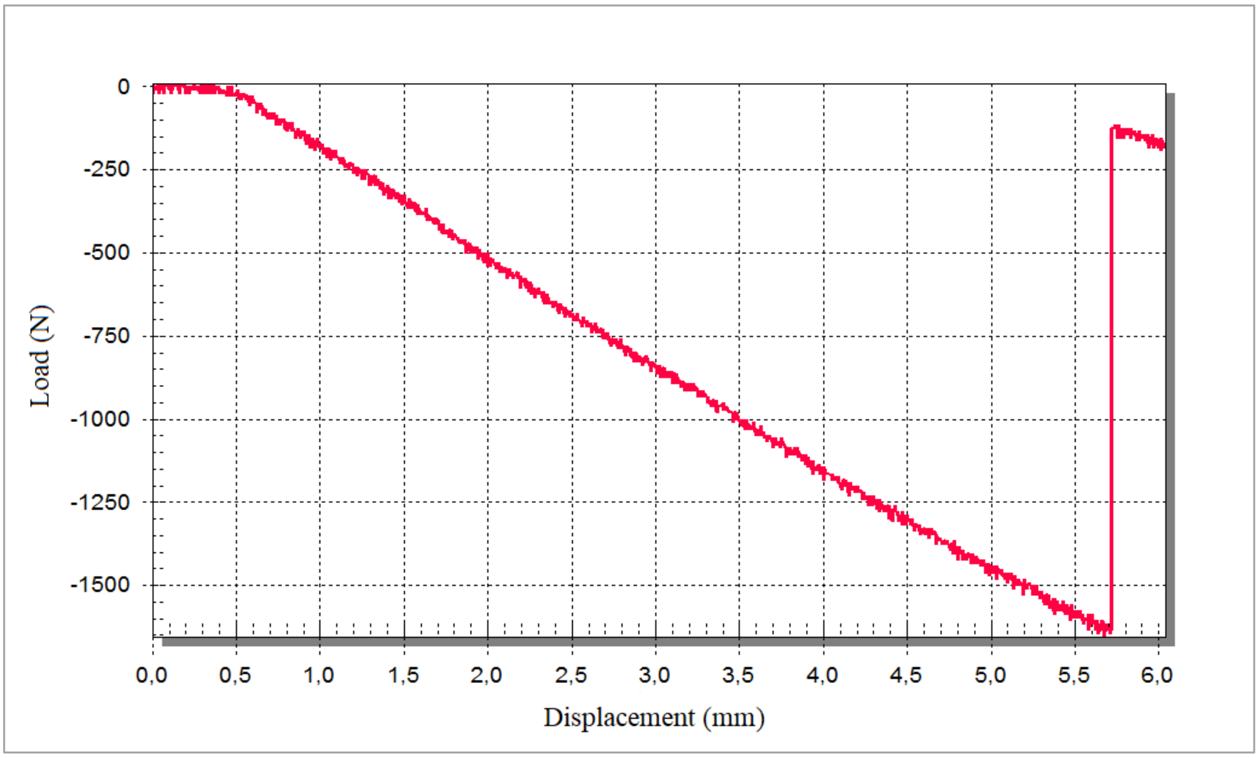


Figure 2.4: Experimental result (four-point bending test) for the specimen of the sandwich panel under applied load (P=1650 N) consisting of an aluminum honeycomb core (t_c=19 mm) and phenolic woven glass face-sheets (t_f=2 mm).

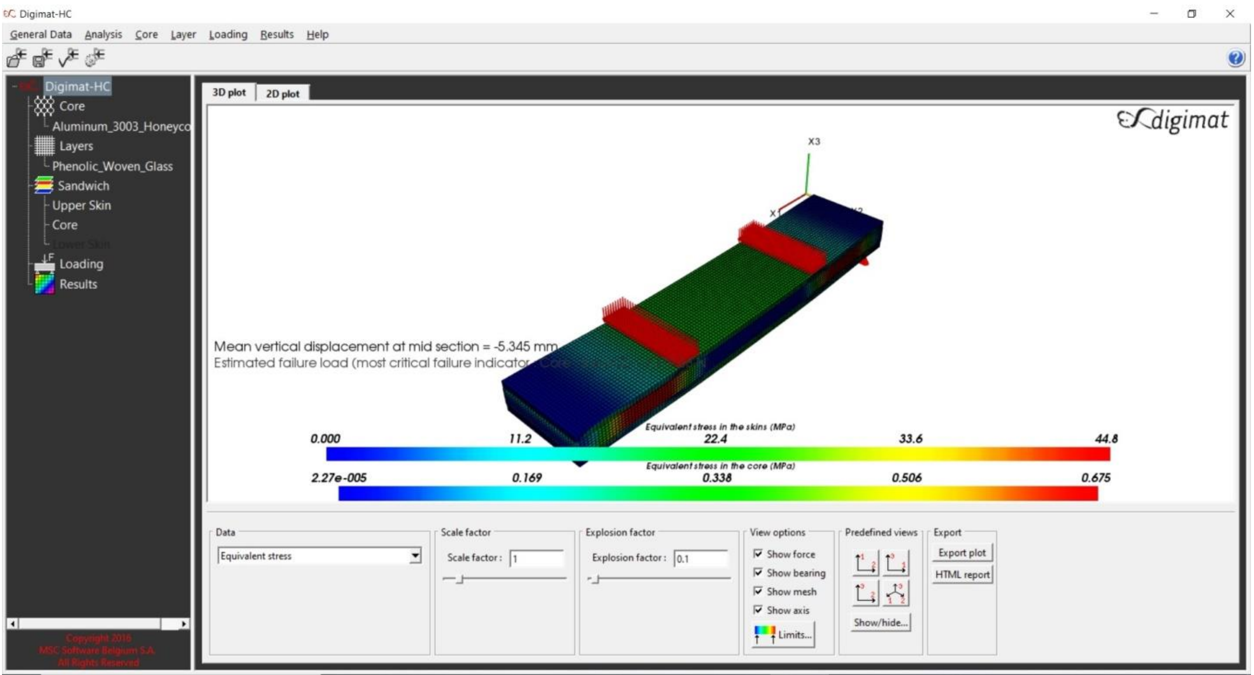


Figure 2.5: Numerical result (four-point bending test) for the specimen of the sandwich panel under applied load (P=1650 N) consisting of an aluminum honeycomb core (t_c=19 mm) and phenolic woven glass face-sheets (t_f=2 mm).

2.3. 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 2.6). 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 [38]:

$$F_p(N) = F_r - F_i \quad (2.3)$$

$$T = \frac{F_p(R_o - R_i)}{b} \quad (2.4)$$

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 Company. The thickness of the honeycomb core does not affect the adhesive's peeling resistance between the face-sheets and the core of the sandwich structure, but the thickness of the face-sheets affects. Because the thicker face-sheets, the harder it bends on the drum. These results in increased peeling resistance and force are shown in Table 2.3 and Figure 2.7. Because the results of the Peeling test have the same behavior, so I showed one of them.

Table 2.3: Experimental result (Peeling test) for 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	Average force	Initial force	Peel strength	Peel length
	F_{max} [N]	F_r [N]	F_i [N]	F_p [N]	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

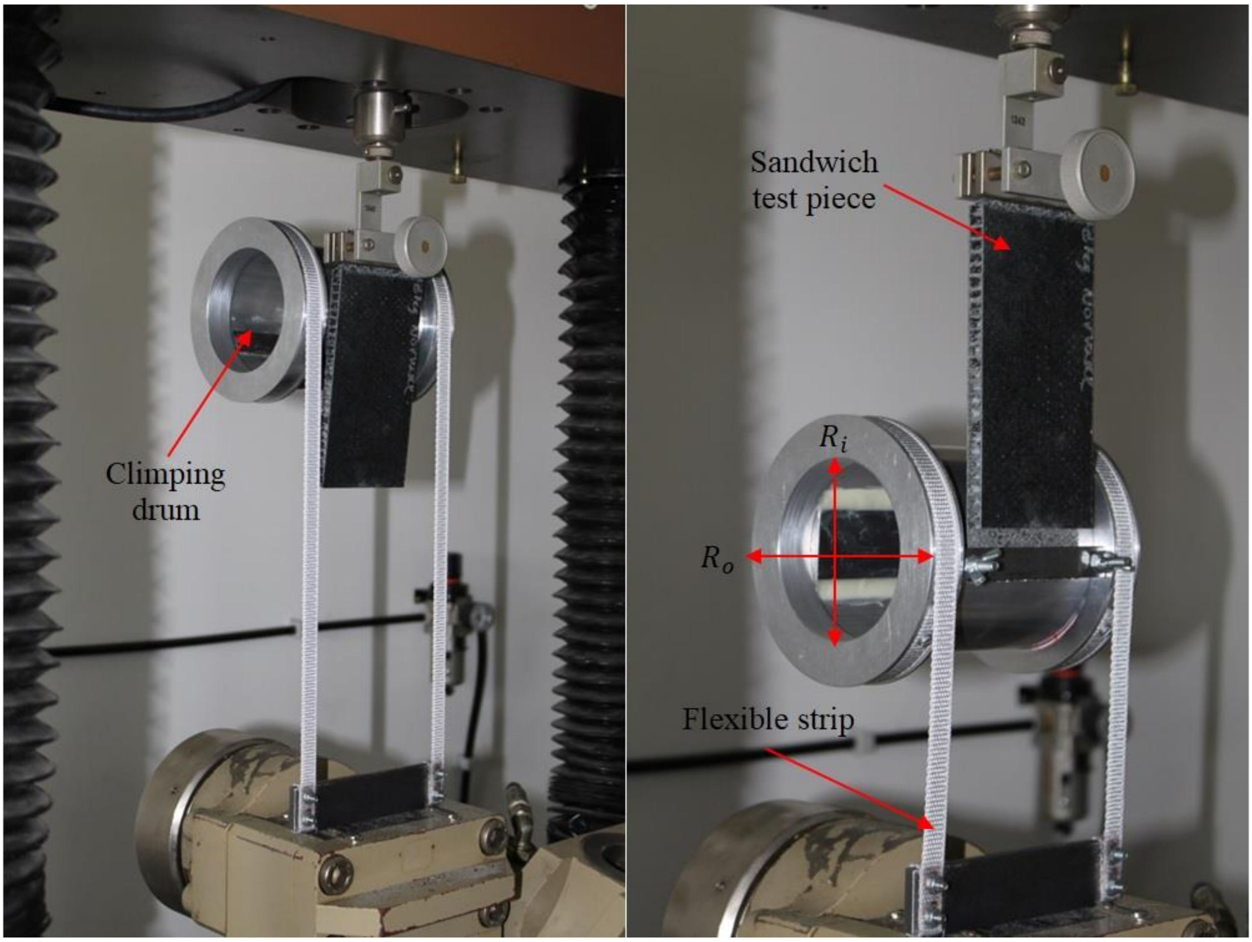


Figure 2.6: Climbing drum apparatus for the specimen of sandwich panels consisting of an aluminum honeycomb core and phenolic woven glass fiber face-sheets.

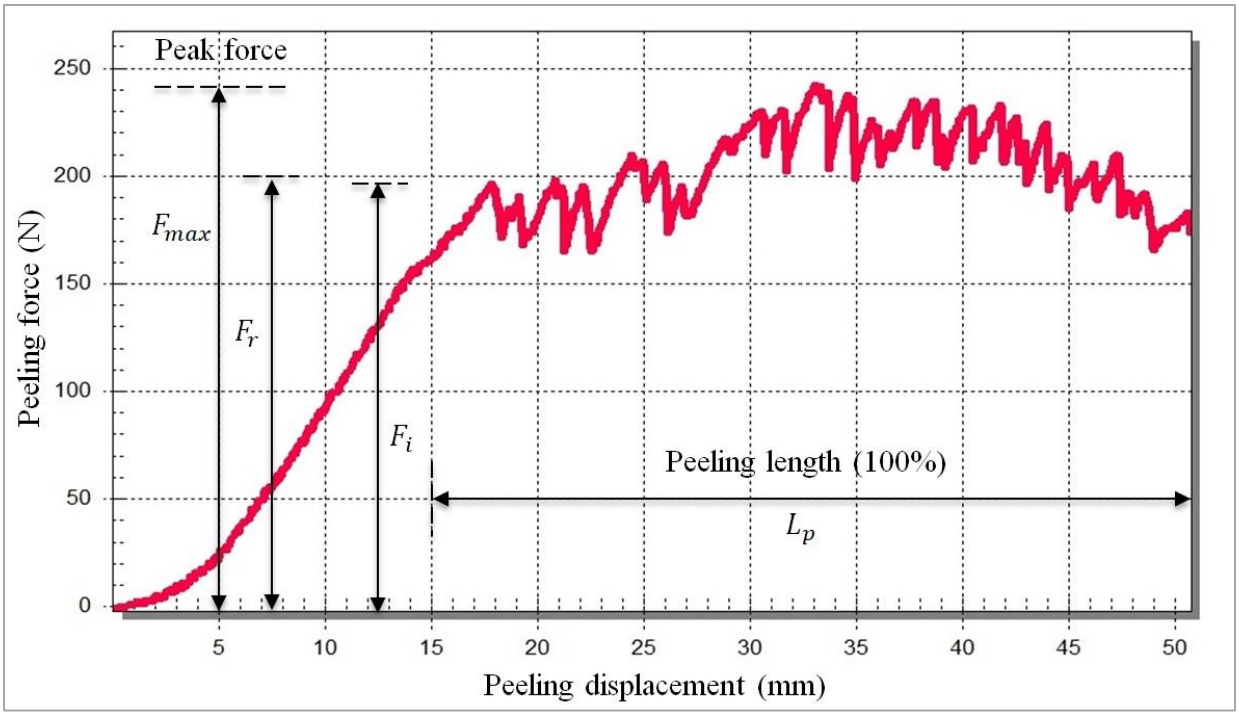


Figure 2.7: Experimental result (Peel test) for specimen No.2 of sandwich panel consisting of an aluminum honeycomb core and phenolic woven glass fiber face-sheets (2-2) layers / 0.5 mm.

2.4. Experimental Modal Analysis (Forced Vibration Test)

The experimental modal test deals with the determination of natural frequencies, stress, and acceleration through vibration testing. Measuring the natural frequencies of the structure helps avoid resonant conditions; it is also necessary for designing vibration isolation systems. Sweep frequency response analysis is a powerful and sensitive method to evaluate the mechanical integrity of structures. The vibration exciters or shakers can be used in several applications, such as determining the dynamic characteristics of structures and fatigue testing of materials. The electrodynamics exciters are used to generate forces up to 30,000 N, displacements up to 25 mm, and frequencies in the range of 5 Hz to 20 kHz (see Figure 2.8). An accelerometer is an instrument that measures the acceleration of a vibrating structure. An electrical resistance strain gauge consists of a fine wire whose resistance changes when subjected to mechanical deformation. When the strain gauge is bonded to a structure, it experiences the same motion (strain) as the structure, and hence its resistance change gives the strain applied to the structure. The manufacturer of the strain gauge gives the value of gauge factor K; hence the value of ε can be determined, once $\Delta R/R$ are measured, as R is the initial resistance, K is the gauge factor for the wire, ΔR is the change in resistance, L is the initial length of the wire and ΔL is the change in length of the wire [39]:

$$\epsilon = \frac{\Delta L}{L} = \frac{\Delta R}{RK} \tag{2.5}$$

Table 2.4: 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	

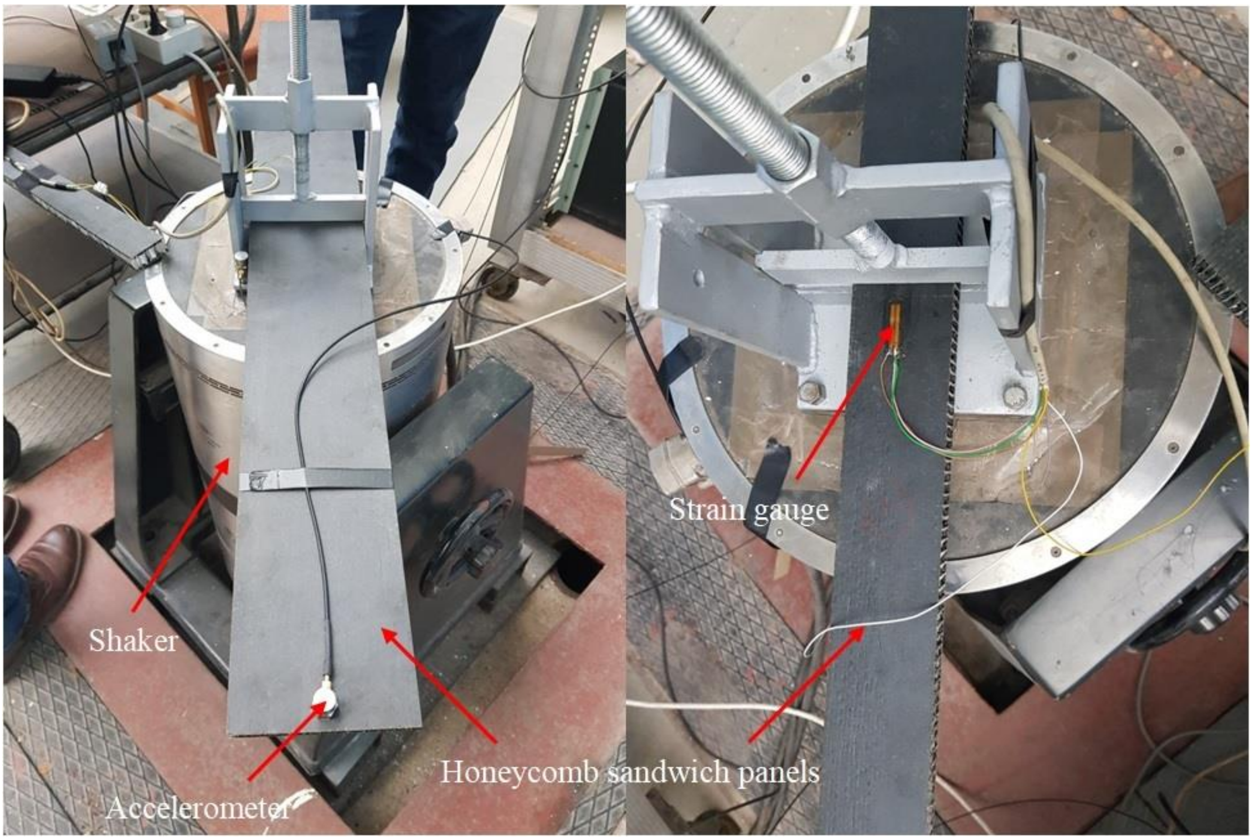
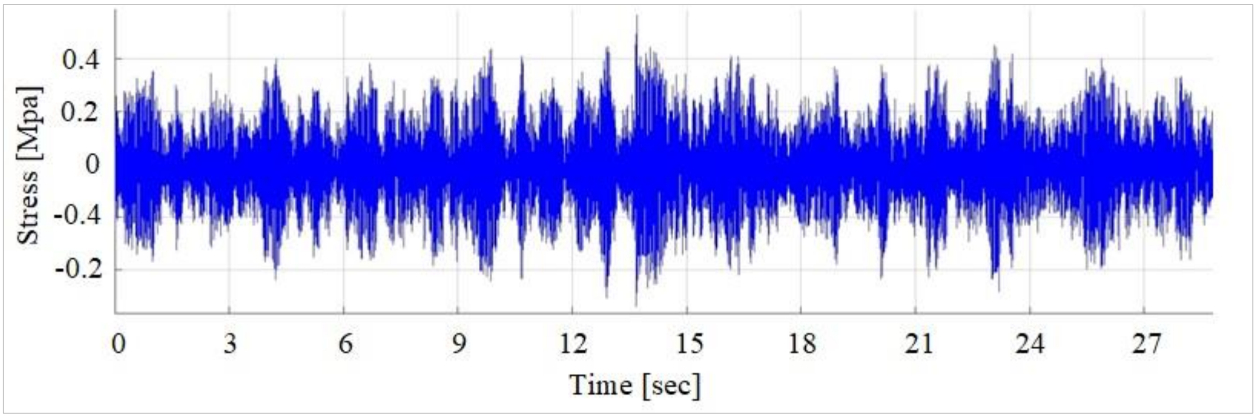


Figure 2.8: Experimental modal analysis (forced vibration test).

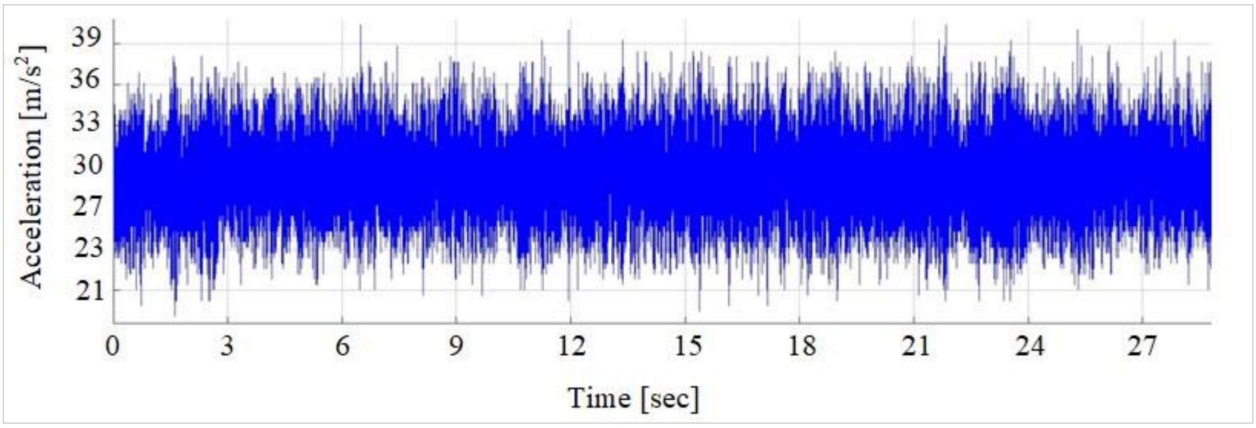
The experimental tests included forced vibration test to find natural frequencies are shown in Table 2.4, stress and acceleration responses (see Figures 2.9 & 2.10). The specimens of sandwich panels are made of an aluminum honeycomb core, and composite material face-sheets in the Kompozitor Company, the dimensions of these specimens are shown in Table 2.5. The composite face-sheets are made of phenolic woven glass fiber. The fiber orientation of the composite face-sheets was cross-ply (0°, 90°). We can notice through the experimental results shown in Table 2.4 and Figures 2.9 & 2.10, which the increase in the honeycomb core thickness will lead to a rise in the natural frequencies of the honeycomb sandwich panels and a decrease in the stress response, and a decrease in the acceleration response.

Table 2.5: Dimensions of experimental tests by applying forced vibration test for honeycomb sandwich specimens set.

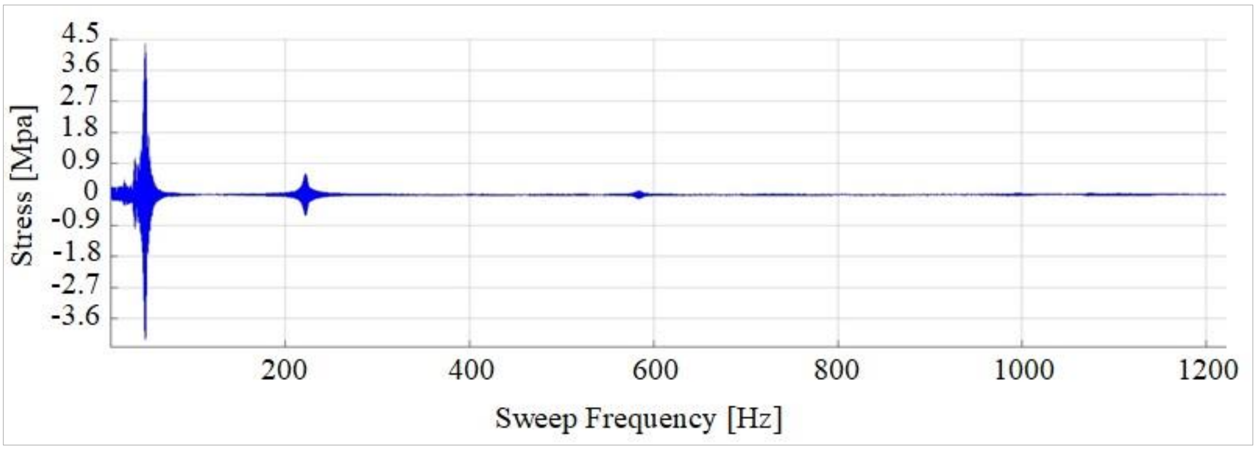
Specimens	Length	Width	Core thickness	Face-sheet thickness	Sandwich height
	l	b	t_c	t_f	h
	mm	mm	mm	mm (Layers)	mm
S_1	1000	120	4	1 (2-2)	6
S_2	1000	120	20	1 (2-2)	22
S_3	1000	115	13	1 (2-2)	15
S_4	1130	54	18	1 (2-2)	20
S_5	710	43	16	1 (2-2)	18



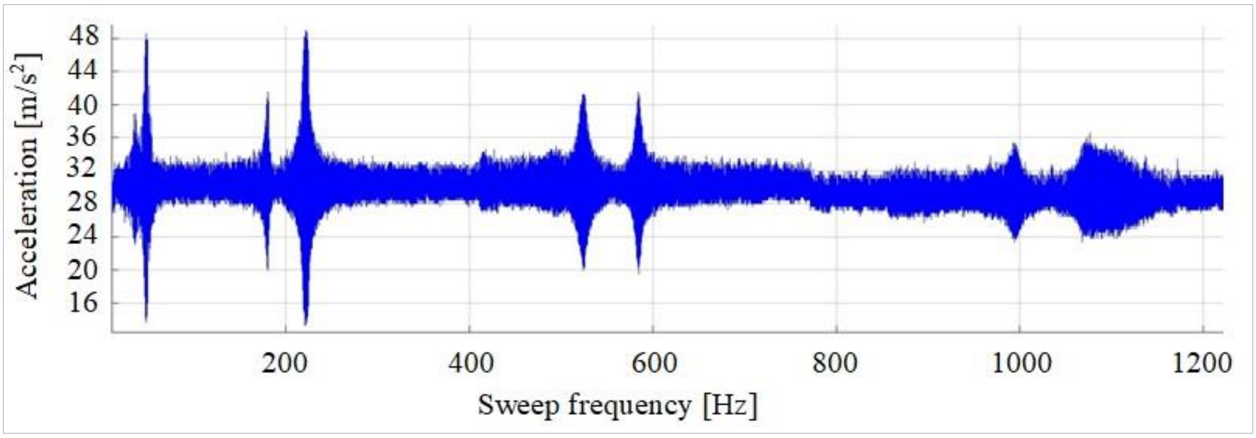
A. Stress response (white noise 10 – 1200 Hz).



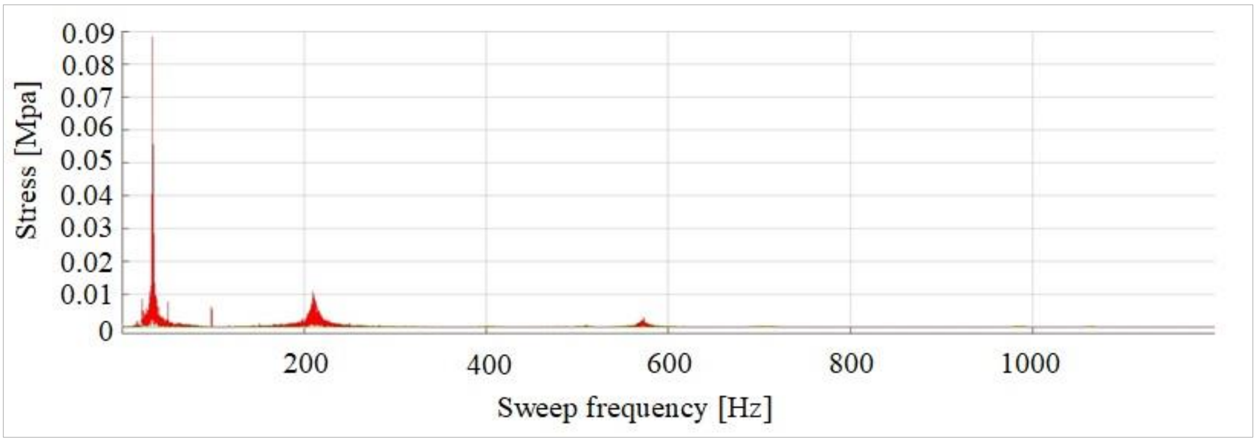
B. Acceleration response (white noise 10 – 1200 Hz).



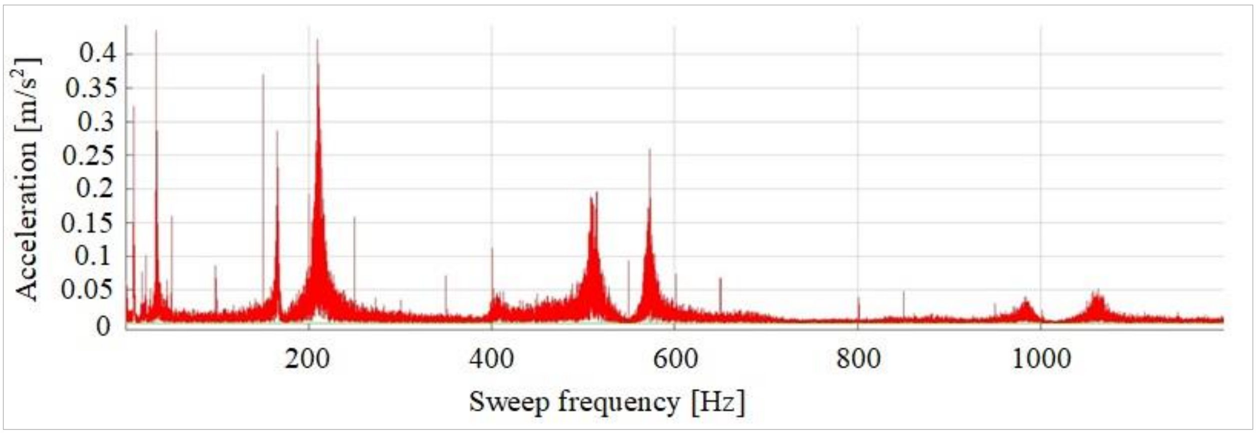
C. Stress vs. sweep frequency response (10 – 1200 Hz).



D. Acceleration vs. sweep frequency response (10 – 1200 Hz).

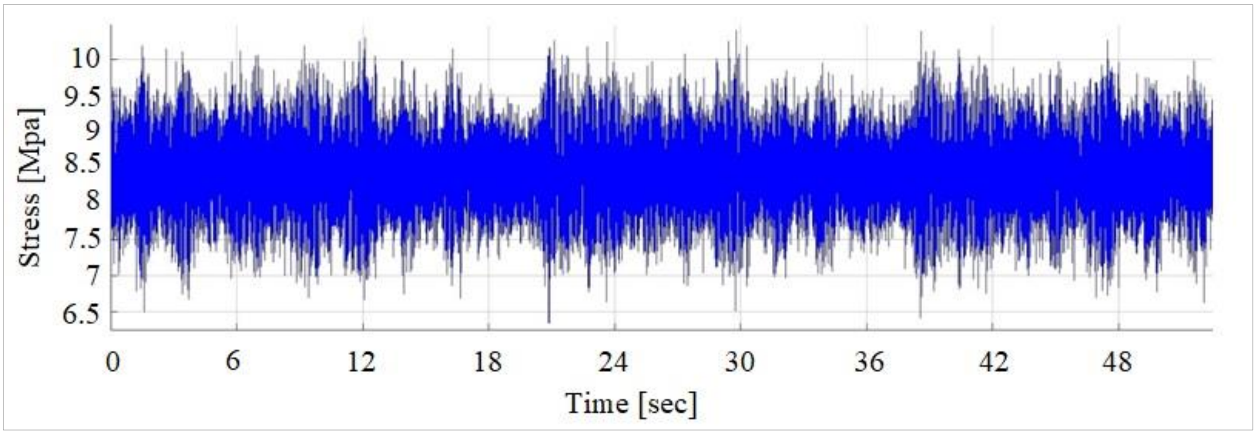


E. Stresses in frequency domain analysis by fast Fourier transform method (FFT).

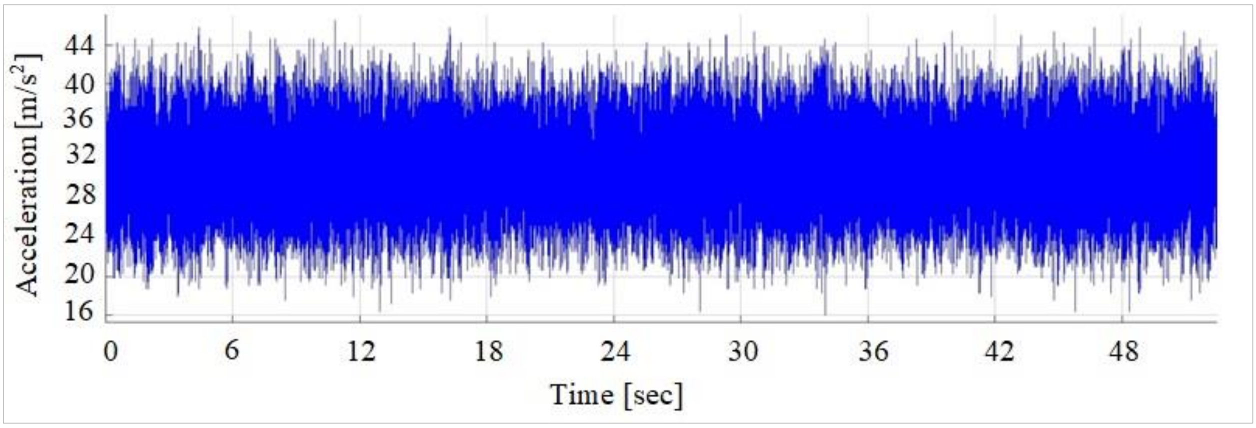


F. Acceleration in frequency domain analysis by fast Fourier transforms method (FFT).

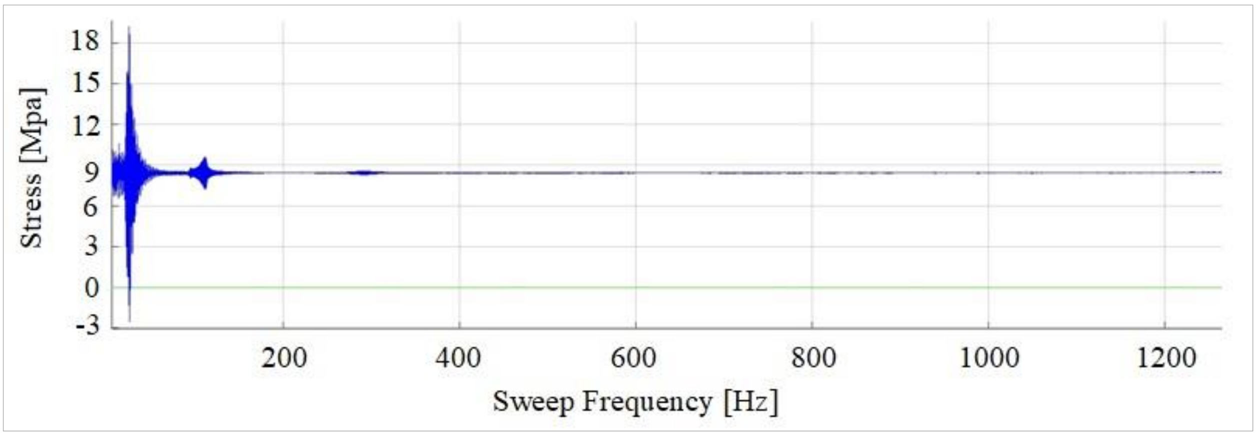
Figure 2.9 (A-F): Experimental result (forced vibration test) for the specimen of sandwich panel consisting of an aluminum honeycomb core (t_c=18 mm) and phenolic woven glass fiber face-sheets (t_f=1 mm).



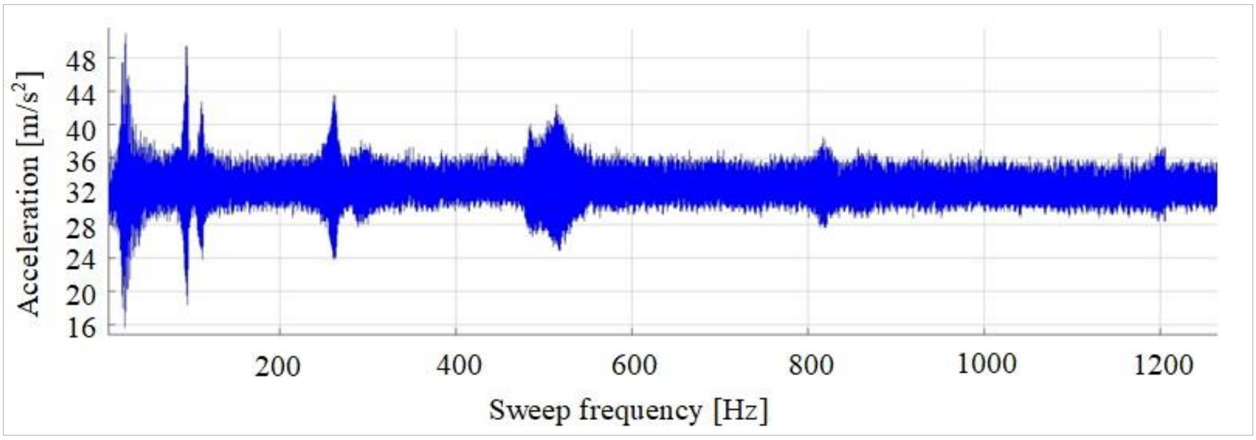
A. Stress response (white noise 10 – 1200 Hz).



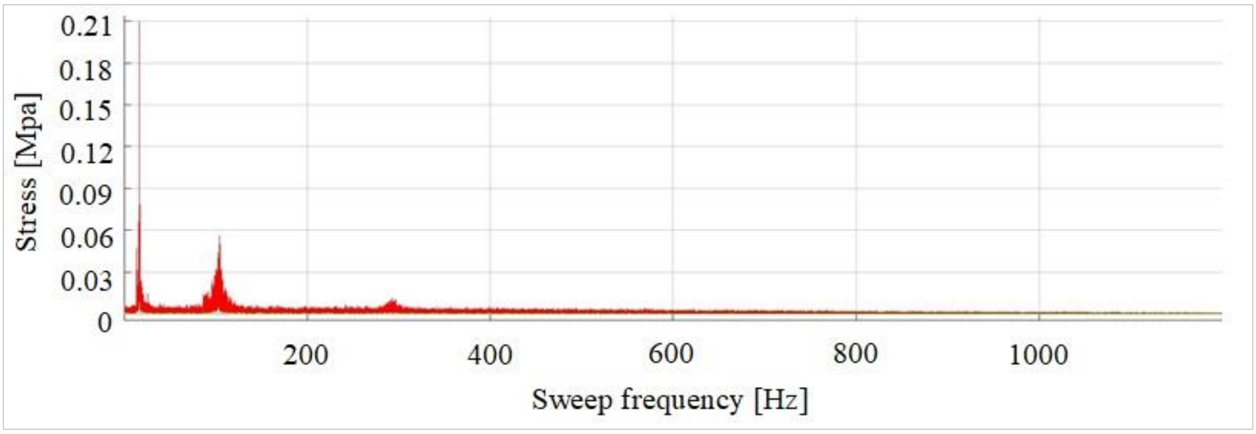
B. Acceleration response (white noise 10 – 1200 Hz).



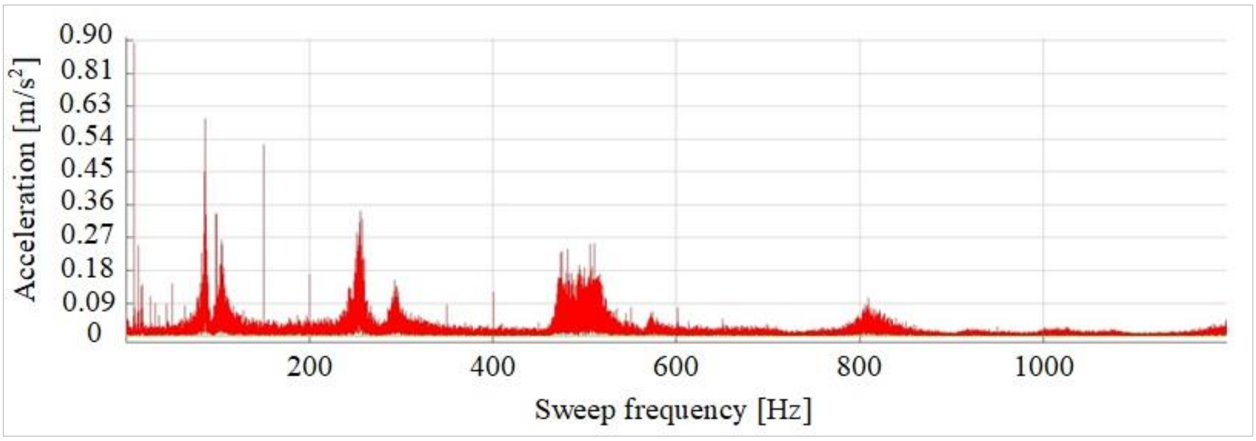
C. Stress vs. sweep frequency response (10 – 1200 Hz).



D. Acceleration vs. sweep frequency response (10 – 1200 Hz).



E. Stresses in frequency domain analysis by fast Fourier transform method (FFT).



F. Acceleration in frequency domain analysis by fast Fourier transforms method (FFT).

Figure 2.10 (A-F): Experimental result (forced vibration test) for the specimen of sandwich panel consisting of an aluminum honeycomb core (t_c=4 mm) and phenolic woven glass fiber face-sheets (t_f=1 mm).

2.5. Jones Measurement (Damping Test)

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 are shown in Tables 2.6 & 2.7 and Figures 2.11 & 2.12. The acceleration frequency response, acceleration response in time domain analysis, and response function for three types of specimens (see Figures 2.13-2.18) [40]. Considering dynamic loading the behavior of the structure can be totally different from the static one [41].

The damping ratio is inversely proportional to acceleration, and the dynamic shear modulus is directly proportional to frequency. Figures 2.13-2.18 show the mass effect on the acceleration frequency response, acceleration time response, and response function for the honeycomb sandwich plate, thin rubber plate, and thick rubber plate to compare. These responses decrease with an increase in the mass of the specimens. The damping test results have the same behavior for honeycomb, thin rubber, and thick rubber, so I showed one of them.

Table 2.6: 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	1	10	10	0.1005	0.00284
2.036	156	979.992	1	7.5	7.5	0.1345	0.00543
5.116	115	722.430	1	9	9	0.1118	0.00742
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

Table 2.7: Specimens sizes of Jones measurements 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).

Dimensions	Width	Length	Thickness
Symbols	b	s	h
Type of specimen	mm	mm	mm
A. Honeycomb Sandwich Plate	180	50	10.8
B. Thin Rubber Sandwich Plate	180	50	5
C. Thick Rubber Sandwich Plate	180	50	10

The sandwich plate damping η_d can be defined:

$$\eta_d = \frac{1}{\sqrt{T_R^2 - 1}} \tag{2.5}$$

Where the transmissibility T_R is:

$$T_R = \left|\frac{\ddot{x}_2}{\ddot{x}_1}\right| \tag{2.4}$$

And, the dynamic shear modulus G_d can be defined:

$$G_d = \frac{m\omega^2}{2b} \tag{2.6}$$

Where the angular frequency ω is:

$$\omega = 2\pi f \tag{2.7}$$

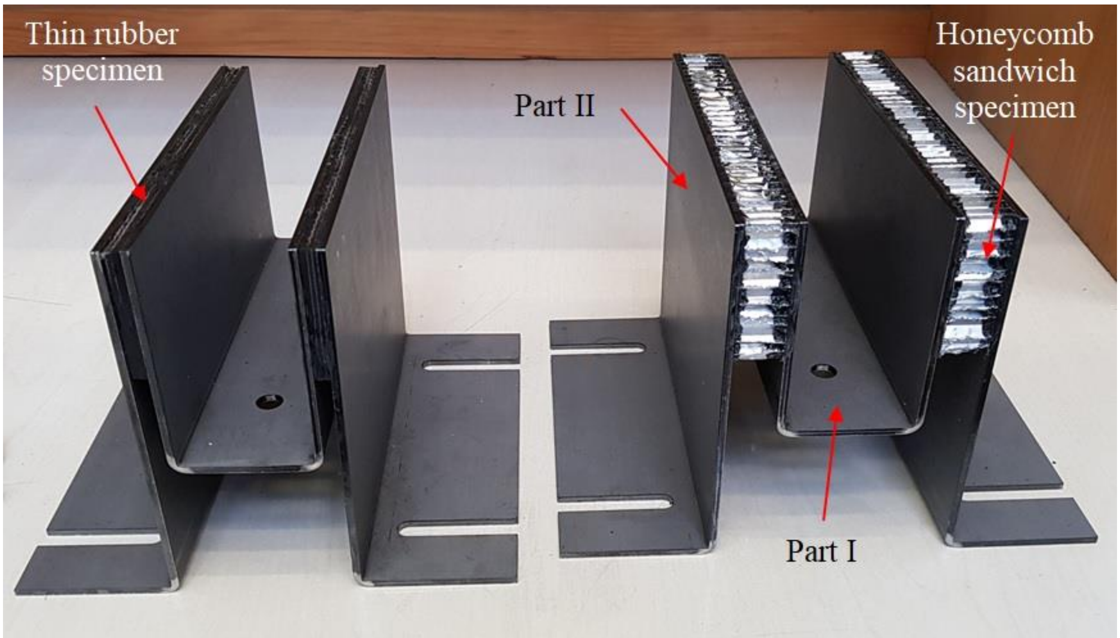


Figure 2.11: Jones measurement specimen's construction.

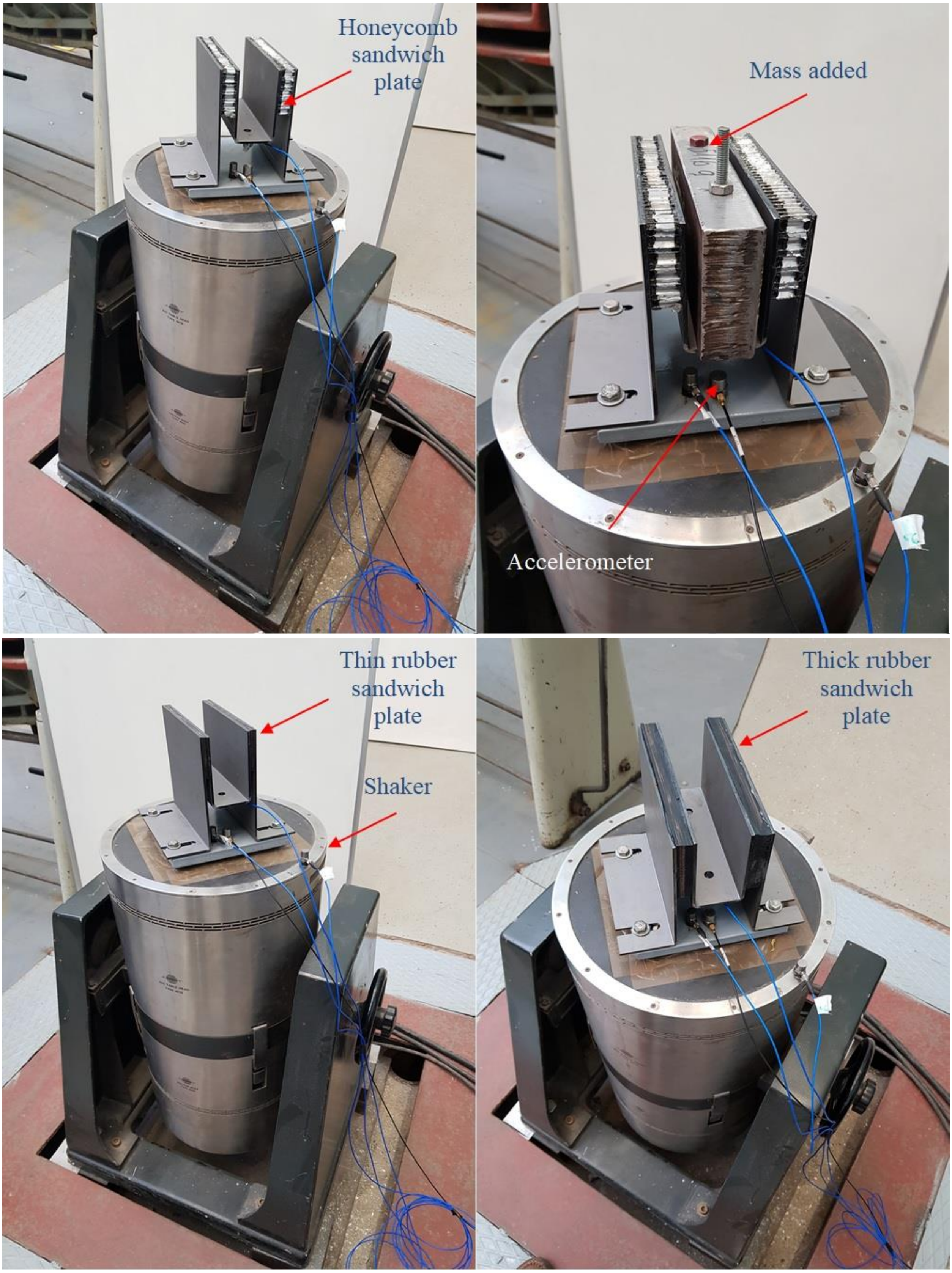


Figure 2.12: Jones measurement (damping test) for the specimen of sandwich plate consisting of an aluminum honeycomb core and phenolic woven glass fiber face-sheets, thin rubber sandwich plate and thick rubber sandwich plate with and without mass added effect.

Results of Jones measurement for honeycomb sandwich structure without weight

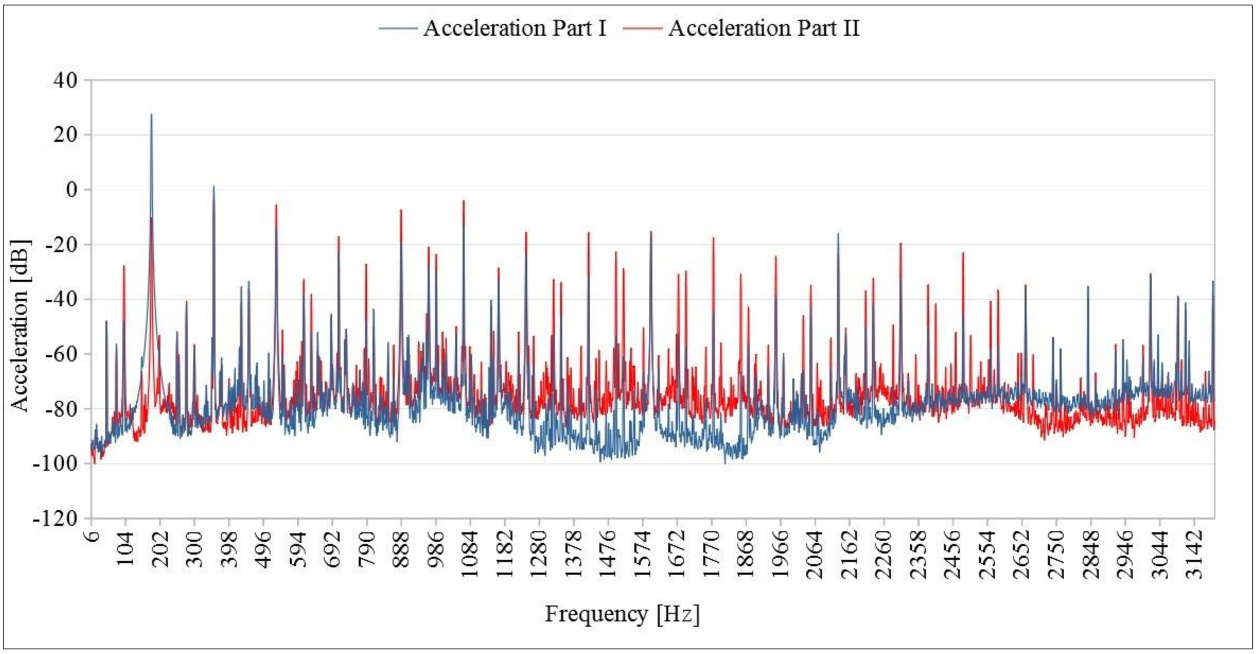


Figure 2.13: Jones measurement for honeycomb sandwich structure without weight, sine 177.5 Hz, 2g, shaker acceleration FFT.

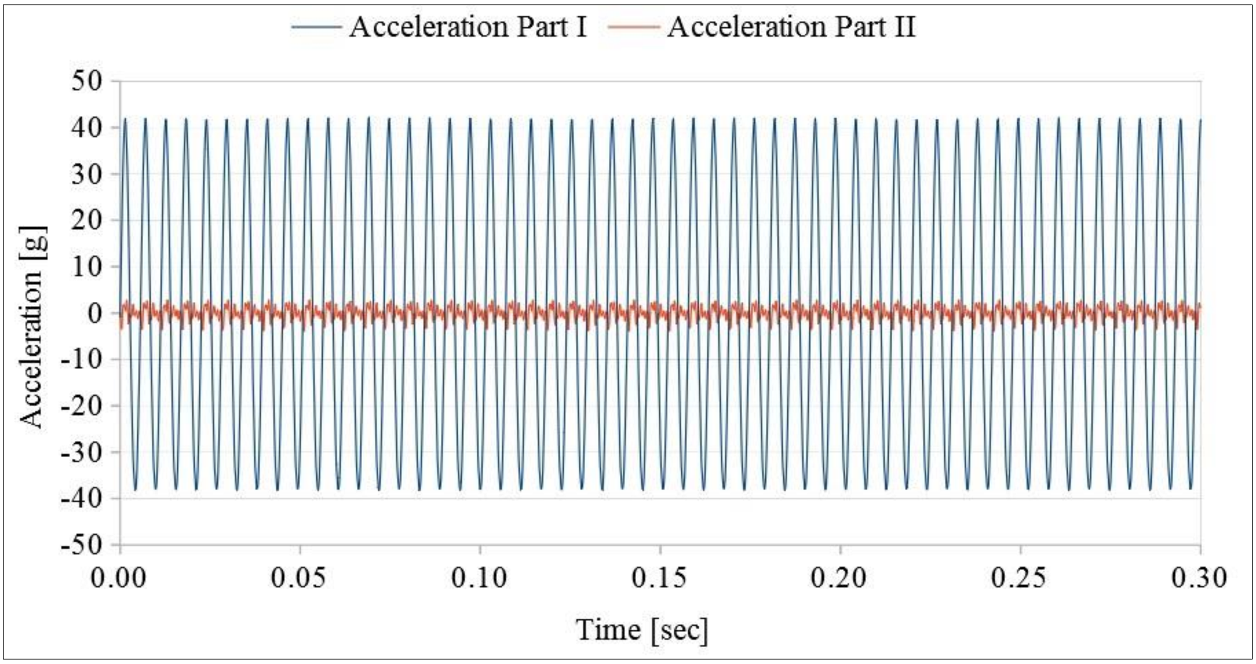


Figure 2.14: Jones measurement for honeycomb sandwich structure without weight, sine 177.5 Hz, 2g, shaker acceleration.

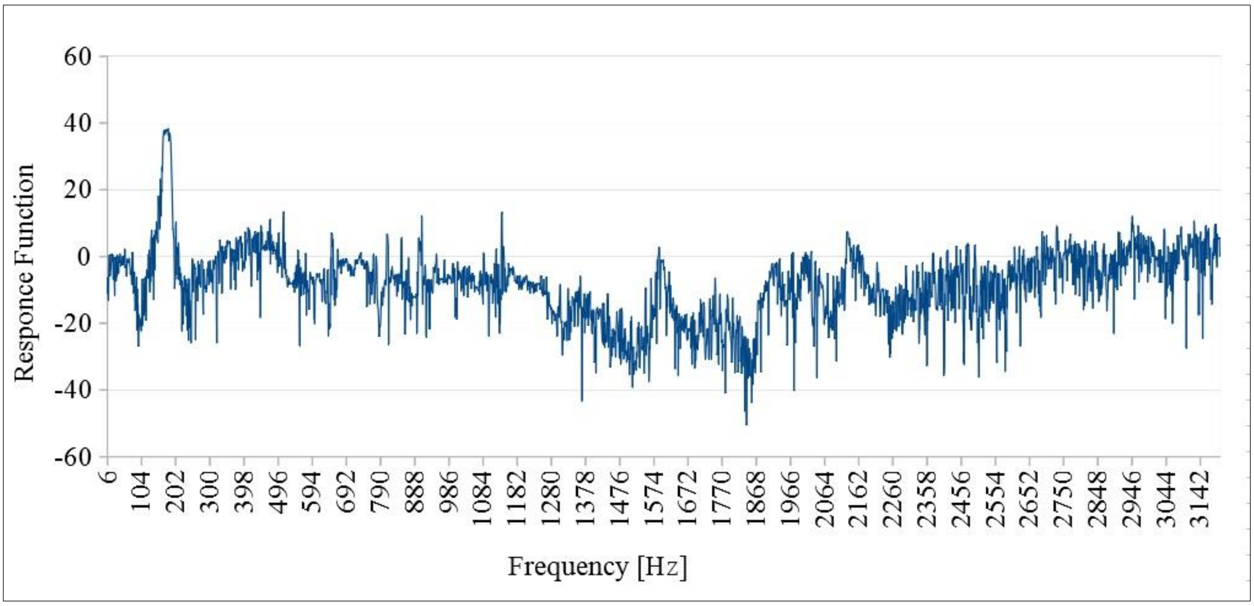


Figure 2.15: Jones measurement for honeycomb sandwich structure without weight, sine 177.5 Hz, 2g, shaker frequency response.

Results of Jones measurement for honeycomb sandwich structure with weight

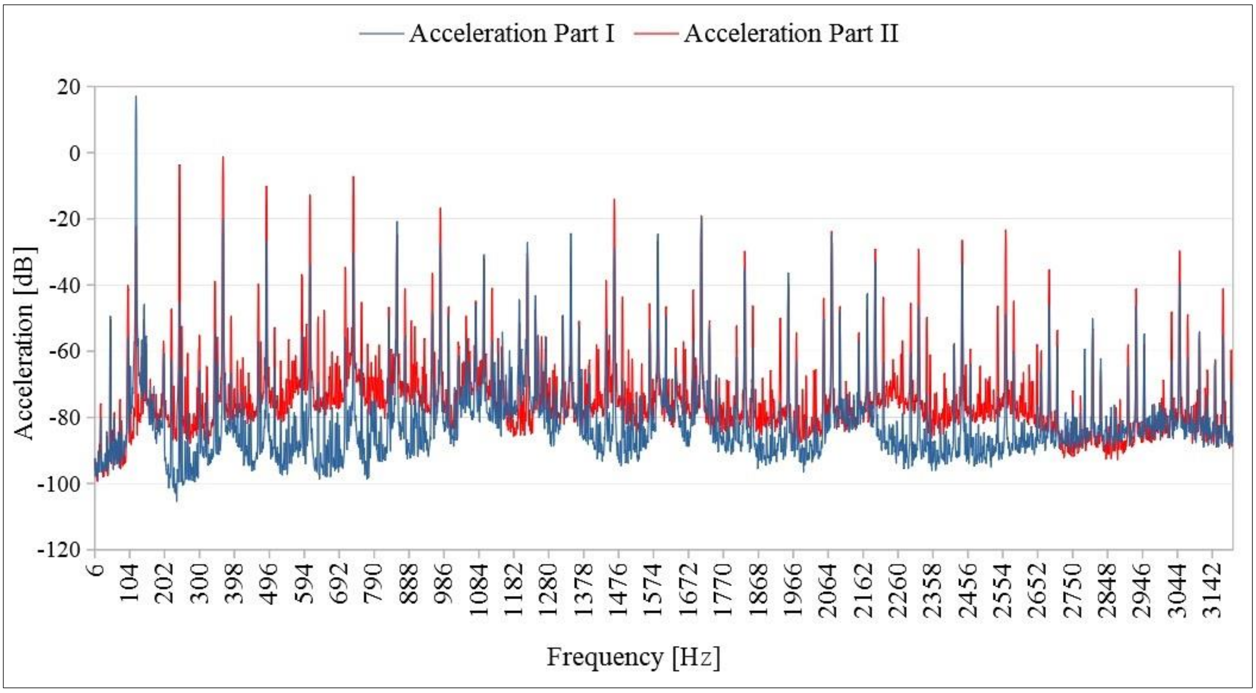


Figure 2.16: Jones measurement for honeycomb sandwich structure with added mass 5.116 kg, sine 122 Hz, 2g, shaker acceleration FFT.

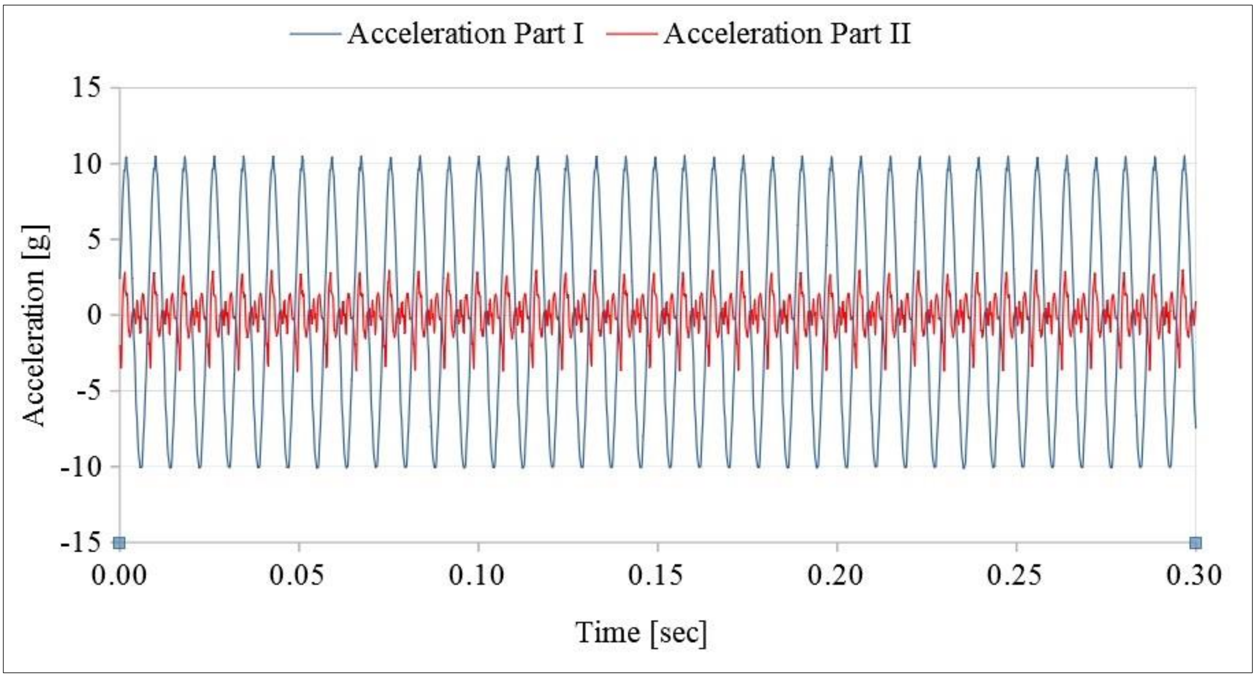


Figure 2.17: Jones measurement for honeycomb sandwich structure with added mass 5.116 kg, sine 122 Hz, 2g, shaker acceleration.

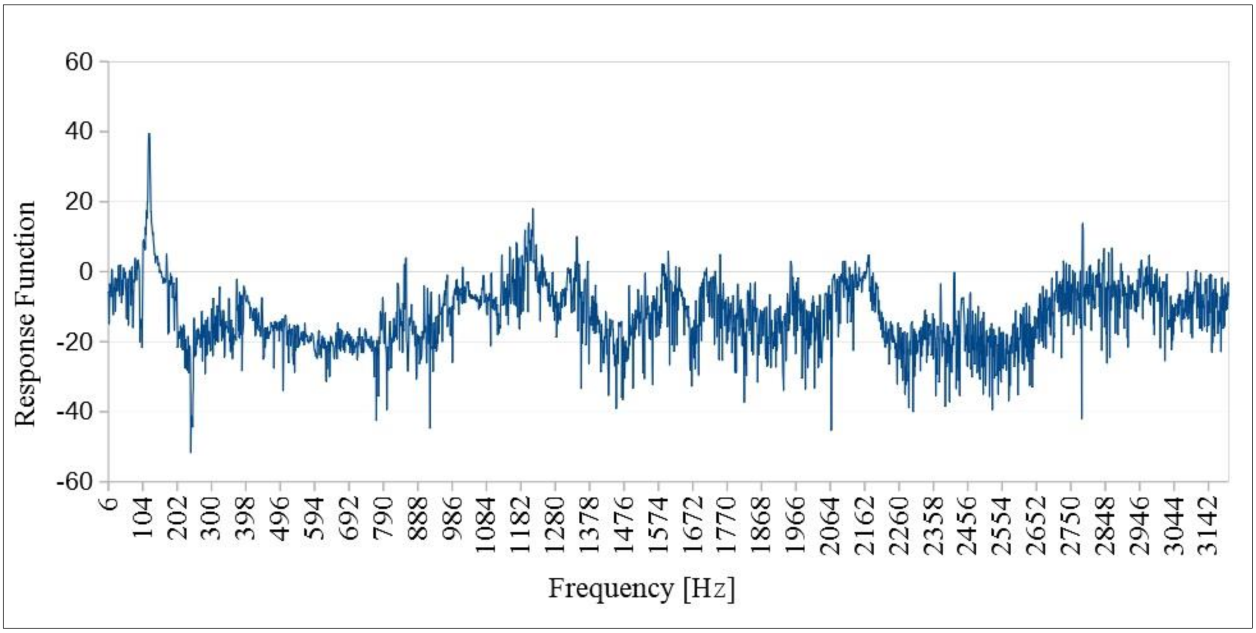


Figure 2.18: Jones measurement for honeycomb sandwich structure with added mass 5.116 kg, sine 122 Hz, 2g, shaker frequency response.

3. THEORETICAL WORKS (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 composite sandwich plates are considered to consist of thin layers, symmetric concerning the midplane of the sandwich plates and/or symmetric concerning the midplane of the face-sheets. 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". In its most basic form, this solver method looks at the gradient or slope of the objective function as the input values (or decision variables) change and determines that it has reached an optimum solution when the partial derivatives equal 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.

3.1. Single-objective Optimization

The single-objective function includes the weight or the cost of honeycomb sandwich structures was solved using the Matlab program (Interior Point Algorithm) and Excel Solver program (GRG Nonlinear Algorithm).

3.1.1. Weight Objective Function

The total weight of the sandwich structure includes the weight of upper and lower face-sheets (aluminum alloy, or composite material) and honeycomb core neglecting the weight of adhesive bond, was minimized using the Matlab program (Interior Point Algorithm) and Excel Solver program (GRG Nonlinear Algorithm).

For honeycomb sandwich structure, in which the face-sheets are of aluminum alloy or composite material, which are included epoxy woven glass fiber or epoxy woven carbon fiber, the equation of the total weight is:

$$W_t = W_f + W_c = 2\,\rho_f lbt_f + \rho_c lbt_c \quad \text{(for aluminum face-sheet)} \tag{3.1}$$

$$W_t = W_f + W_c = 2\,\rho_f lbN_l t_l + \rho_c lbt_c \quad \text{(for composite material)} \tag{3.2}$$

where: $t_f = N_l t_l$

For honeycomb sandwich structure, in which the face-sheets are of hybrid composite layers (a combination of epoxy woven glass fiber layers and epoxy woven carbon fiber layers), the equation of the total weight is:

$$W_t = W_f + W_c = 2(W_{f,g} + W_{f,cr}) + W_c = 2(\rho_g N_g t_g + \rho_{cr} N_{cr} t_{cr})lb + \rho_c lbt_c \tag{3.3}$$

Table 3.1: Engineering properties of facing materials for sandwich structure construction [42].

Facing Material	Typical Strength Tension/Compression [MPa]	Modulus of Elasticity Tension/Compression [GPa]	Poisson's Ratio [-]	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

Table 3.2: Engineering properties of an aluminum honeycomb core materials [42].

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

3.1.2. Cost Objective Function

The total material cost for the sandwich structure, including the cost of the upper and lower material face-sheets (aluminum alloy or composite material) and the cost of an aluminum honeycomb core were minimized using the Matlab program (Interior Point Algorithm) and Excel Solver program (GRG Nonlinear Algorithm).

For honeycomb sandwich structure, in which the face-sheets are of aluminum alloy or composite material, which are included epoxy woven glass fiber, or epoxy woven carbon fiber, the equation of the total material cost is:

$$C_t = 2\rho_f lbt_f C_f + lbt_c C_c \quad \text{(for aluminum face-sheet)} \tag{3.4}$$

$$C_t = 2\rho_f lbN_l t_l C_f + lbt_c C_c \quad \text{(for composite material)} \tag{3.5}$$

where: $t_f = N_l t_l$

For honeycomb sandwich structure, in which the face-sheets are of hybrid composite layers (a combination of epoxy woven glass fiber layers and epoxy woven carbon fiber layers), the equation of the total material cost is:

$$C_t = 2(C_{f,cr} + C_{f,g}) + lbt_c C_c = 2(\rho_g N_g t_g C_g + \rho_{cr} N_{cr} t_{cr} C_{cr})lb + lbt_c C_c \tag{3.6}$$

The cost of material for honeycomb core and face-sheets were considered only. The cost of an aluminum alloy face-sheet is 4.61 €/kg. The cost of epoxy woven glass fiber and epoxy woven carbon fiber material are 5 €/kg and 40 €/kg, respectively. The cost of an aluminum honeycomb core material is 20 €/m^2 (in the case of 18 mm core height).

3.2. Multi-objective Optimization

The multi-objective function includes the weight and the cost of honeycomb sandwich structures was solved using the Matlab program (Genetic Algorithm Solver) and Excel Solver program (Weighted Normalized Method).

3.2.1. Matlab Program (Genetic Algorithm Solver)

The gamultiobj function is compatible with Matlab's multi-objective Genetic Algorithm Solver tool. The gamultiobj Solver attempts to minimize multi-objective by creating a set of Pareto optimal [43].

3.2.2. Excel Solver Program (Weighted Normalized Method)

The weight and the cost of multi-objective optimization using the Excel Solver program (Weighted Normalized Method) were presented:

$$f(x) = \sum_{i=1}^{r} \frac{w_i\, f_i(x)}{f_i^{\circ}} \tag{3.7}$$

where: $w_i \geq 0$ and $\sum_{i=1}^{r} w_i = 1$. The condition $f_i^{\circ} \neq 0$ is assumed.

3.3. Design Variables

For honeycomb sandwich structure, in which the face-sheets are of aluminum alloy, core thickness t_c and face-sheets thickness t_f were modified to achieve the acceptable performance:

$$1\, mm \leq t_{c,opt} \leq 100\, mm \tag{3.8}$$

$$0.5\, mm \leq t_{f,opt} \leq 5\, mm \tag{3.9}$$

While, for honeycomb sandwich structure, in which the face-sheets are of composite material, include epoxy woven glass fiber, or epoxy woven carbon fiber, as well as hybrid composite layers, core thickness t_c and the number of face-sheets layers N_l were modified to achieve the acceptable performance:

$$1\, mm \leq t_{c,opt} \leq 100\, mm \tag{3.10}$$

$$1\, layer \leq N_{l,opt} \leq 8\, layers \tag{3.11}$$

3.4. Design Constraints

The design constraints of honeycomb sandwich structures include total stiffness (bending and shear stiffness), full deflection (bending and shear deflection), facing skin stress (bending load), core shear stress, facing skin stress (end loading), overall buckling (bending and shear critical buckling loads), shear crimping load, skin wrinkling (critical stress and critical load) and intracell buckling.

3.4.1. Total Stiffness (Bending Stiffness and Shear Stiffness)

The total stiffness constraint for the honeycomb sandwich structure, in which the face-sheets are of composite material, includes the bending stiffness and the shear stiffness:

When the top and bottom face-sheets are unsymmetrical concerning the midplane of the face-sheets but are symmetrical concerning the midplane of the sandwich structure, then:

$$[A]^t = [A]^b \,, \qquad [B]^t = -[B]^b, \qquad [D]^t = [D]^b \tag{3.12}$$

And, the $[A]$, $[B]$, $[D]$ matrices of the sandwich structure become [44]:

$$[A] = 2\,[A]^b, \qquad [B] = 0, \qquad [D]^t = 0.5\, d^2[A]^t + 2\,[D]^t + 2d[B]^t \tag{3.13}$$

So, the bending stiffness constraint for honeycomb sandwich structure, in which the face-sheets are of composite material, which is symmetrical concerning the midplane of the sandwich structure, is:

$$D_{11} = 0.5d^2A_{11}^f + 2D_{11}^f + 2dB_{11}^f \tag{3.14}$$

Also, the bending stiffness constraint for honeycomb sandwich structure in global coordinate is:

$$D_{11,x} = D_{11}/(1 - \nu_{12}^f\,\nu_{21}^f) \geq D_{min} = \frac{K_b p l^4}{\delta} \tag{3.15}$$

While the top and bottom face-sheets are symmetrical concerning the midplane of the face-sheets, then:

$$[A]^t = [A]^b, \qquad [B]^t = [B]^b = 0, \qquad [D]^t = [D]^b \tag{3.16}$$

And, the $[A]$, $[B]$, $[D]$ matrices of the sandwich structure become:

$$[A] = 2\,[A]^b, \qquad [B] = 0, \qquad [D]^t = 0.5\, d^2[A]^t + 2\,[D]^t \tag{3.17}$$

So, the bending stiffness constraint for honeycomb sandwich structure, in which the face-sheets are of composite material, which is symmetrical concerning the midplane of the face-sheets, is:

$$D_{11} = 0.5\, d^2\, A_{11}^f + 2\, D_{11}^f \tag{3.18}$$

Then, the bending stiffness constraint for symmetric honeycomb sandwich structure in global coordinate is:

$$D_{11,x} = D_{11}/(1 - \nu_{12}^f\,\nu_{21}^f)\; \geq D_{min} = \frac{K_b p\, l^4}{\delta} \tag{3.19}$$

where: $\nu_{12}^f = A_{12}^f/A_{22}^f$, $\nu_{21}^f = A_{12}^f/A_{11}^f$ and $d = t_f + t_c$ (3.20)

And, the shear stiffness for honeycomb sandwich structure, in which the face-sheets are of composite material, is:

$$\tilde{S}_{11} = \frac{d^2}{t_c} * \frac{E_c}{2\,(1+\nu_c)} \tag{3.21}$$

The calculated bending stiffness of the sandwich structure in the global coordinate $D_{11,x}$ must be higher than the minimum stiffness of the sandwich structure D_{min} was calculated using the given data ($\delta = \delta_{max}$ and $p = p_{max}$) [2].

While, the bending stiffness and shear stiffness for honeycomb sandwich structure, in which the face-sheets are of aluminum alloy, are:

$$D_{f,x} = \frac{E_f t_f d^2 b}{2(1-\nu_f^2)} \geq D_{min} = \frac{K_b P l^3}{\delta} \tag{3.22}$$

$$S = \, bhG_c \tag{3.23}$$

where: $G_c = G_w$

The calculated stiffness for the aluminum face-sheets sandwich structure in the global coordinate $D_{f,x}$ must be higher than the minimum stiffness of the sandwich structure D_{min} was calculated using the given data ($\delta = \delta_{max}$ & $P = P_{max}$).

3.4.2. Total Deflection

The total deflection constraint of the composite face-sheet sandwich structure includes the bending deflection and shear deflection:

$$\delta_{max} \geq \delta = \delta_b + \delta_s = \frac{K_b p l^4}{D_{11,x}} + \frac{K_s p l^2}{\tilde{S}_{11}} \tag{3.24}$$

While the total deflection constraint for the aluminum face-sheet sandwich structure includes the bending deflection and shear deflection:

$$\delta_{max} \geq \delta = \delta_b + \delta_s = \frac{K_b P l^3}{D_{f,x}} + \frac{K_s P l}{S} \tag{3.25}$$

The maximum deflection of the honeycomb sandwich structure δ_{max} has been given, must be greater than the total deflection calculated δ.

3.4.3. Skin stress (Bending Load)

The constraint of the facing skin stress for the honeycomb sandwich structure, in which the face-sheets are of composite material, is:

$$\sigma_{f,x} \geq \sigma_f = \frac{M}{dt_f b} \tag{3.26}$$

The typical yield strength of the composite material face-sheet in the x-direction $\sigma_{f,x}$ calculated using the Laminator program must be greater than the skin stress calculated σ_f, thus giving a factor of safety.

The constraint of the facing skin stress for the honeycomb sandwich structure, in which the face-sheets are of aluminum alloy, is:

$$\sigma_{f,y} \geq \sigma_f = \frac{M}{dt_f b} \tag{3.27}$$

The typical yield strength of the aluminum alloy face-sheet $\sigma_{f,y}$ given in Table 3.1 must be greater than the calculated skin stress σ_f.

3.4.4. Core Shear Stress

The core shear stress constraint of the honeycomb sandwich structure is:

$$\tau_{c,y} \geq \tau_c = \frac{F}{db} \tag{3.28}$$

The typical shear stress in the transverse direction of the core material $\tau_{c,y}$ given in Table 3.2 must be greater than the calculated core shear stress τ_c, giving a factor of safety, which could allow core density to be reduced.

3.4.5. Skin Facing Stress (End Loading)

The skin facing stress constraint of the composite sandwich structure is:

$$\sigma_{f,y} \geq \sigma_f = \frac{P}{2t_f b} \tag{3.29}$$

The typical yield strength of the composite face-sheet material $\sigma_{f,y}$ in the y-direction calculated using the Laminator program must be greater than the calculated skin facing stress σ_f.

While the typical yield strength of the aluminum alloy face-sheet $\sigma_{f,y}$ given in Table 3.1 must be greater than the calculated skin stress σ_f, thus giving a factor of safety.

$$\sigma_{f,y} \geq \sigma_f = \frac{P}{2t_f b} \tag{3.30}$$

3.4.6. Overall Buckling (Bending and Shear Buckling)

The overall critical buckling load of the sandwich structure, which includes the bending buckling load P_b and shear buckling load P_s, is:

$$\frac{1}{P_{b,cr}} = \frac{1}{P_b} + \frac{1}{P_s} \tag{3.31}$$

The bending buckling load P_b and shear buckling load P_s for the composite sandwich structure are:

$$P_b = \frac{\pi^2 D_{11,x}}{(\beta L)^2}, \qquad P_s = \widetilde{S}_{11} \tag{3.32}$$

Then, the overall buckling constraint for the composite sandwich structure is:

$$P_{b,\,cr} = \frac{\pi^2 D_{11,x}}{\beta l^2 + \frac{\pi^2 D_{11,x}}{\widetilde{S}_{11}}} \geq \frac{P}{b} \tag{3.33}$$

The calculated load at which overall critical buckling would occur is greater than the end load being applied per unit width, thus giving a factor of safety.

While the bending buckling load P_b and shear buckling load P_s for the aluminum face-sheets sandwich structure are:

$$P_b = \frac{\pi^2 D_{f,x}}{(\beta L)^2} \tag{3.34}$$

$$P_s = S = bhG_c \tag{3.35}$$

Then, the overall buckling constraint for the aluminum face-sheets sandwich structure is:

$$P_{b,\,cr} = \frac{\pi^2 D_{f,x}}{\beta l^2 + \frac{\pi^2 D_{f,x}}{S}} \geq P \tag{3.36}$$

The calculated load at which overall critical buckling would occur is greater than the end load P being applied is given in the Table of the application.

3.4.7. Shear Crimping

The shear crimping constraint of the honeycomb sandwich structure is:

$$P_{cr} = t_c G_c b \geq P \tag{3.37}$$

where: $G_c = G_w$

The calculated load at which shear crimping would occur is greater than the end load being applied P is given, thus giving a factor of safety.

3.4.8. Skin Wrinkling

The skin wrinkling constraints of the honeycomb sandwich structure, in which the face-sheets are of composite material, is:

$$\sigma_{wr,\,cr} = 0.5\sqrt[3]{E_{f,x}\,E_c\,G_c} \geq \sigma_{f,x} \tag{3.38}$$

where: $G_c = G_L$

$$\sigma_{wr,\,cr} = 0.5\sqrt[3]{E_{f,y}\,E_c\,G_c} \geq \sigma_{f,y} \tag{3.39}$$

where: $G_c = G_W$

$$P_{wr,cr} = 2\sqrt{D_{11}^{f} * \frac{E_c}{(t_c/2)}} \geq \frac{P}{b} \tag{3.40}$$

where:

$$E_{f,x} = A_{11}^{f}(1 - \nu_{12}^{f}\nu_{21}^{f})/t_f$$
$$E_{f,y} = A_{22}^{f}(1 - \nu_{12}^{f}\nu_{21}^{f})/t_f$$
$$E_f = \sqrt{E_{f,x}E_{f,y}}$$

All these parameters are calculated using the Laminator program.

The stress level at which skin wrinkling would occur $\sigma_{wr,\,cr}$ is well beyond the skin material typical yield strength in the x-direction $\sigma_{f,x}$ and in the y-direction $\sigma_{f,y}$ calculated using the Laminator program, so skin stress is more critical than skin wrinkling.

The calculated load $P_{wr,cr}$ at which skin wrinkling would occur is greater than the end load per unit width being applied (P/b).

The skin wrinkling constraint of the honeycomb sandwich structure, in which the face-sheets are of aluminum alloy, is:

$$\sigma_{wr,\,cr} = 0.5\sqrt[3]{E_f\,E_c\,G_c} \geq \sigma_{f,y} \tag{3.41}$$

where: $G_c = G_L$

$$\sigma_{wr,\,cr} = 0.5\sqrt[3]{E_f\,E_c\,G_c} \geq \sigma_{f,y} \tag{3.42}$$

where: $G_c = G_W$

$$P_{wr,cr} = t_f \sqrt{\frac{2}{3} \frac{t_f E_f E_c}{t_c (1 - \nu_f^2)}} \geq \frac{P}{b} \tag{3.43}$$

The stress level at which skin wrinkling would occur $\sigma_{wr,\,cr}$ is well beyond the skin material typical yield strength $\sigma_{f,y}$ given in Table 3.1, so skin stress is more critical than skin wrinkling.

3.4.9. Intracell Buckling (Face-sheet Dimpling)

The face-sheet dimpling constraint of the honeycomb sandwich structure, in which the face-sheets are of composite material, is:

$$\sigma_{f,\,cr} = \frac{2E_f}{(1 - \nu_{12}^f \nu_{21}^f)} \left[\frac{t_f}{s}\right]^2 \geq \sigma_{f,y} \tag{3.44}$$

where: $E_f = \sqrt{E_{f,x} E_{f,y}}$

The stress level at which intracell buckling would occur $\sigma_{f,\,cr}$ is well beyond the skin material typical yield strength $\sigma_{f,y}$, calculated using the Laminator program, so skin stress is more critical than intracell buckling.

The face dimpling constraint of the honeycomb sandwich structure, in which the face-sheets are of aluminum alloy, is:

$$\sigma_{f,\,cr} = \frac{2E_f}{(1 - \nu_f^2)} \left[\frac{t_f}{s}\right]^2 \geq \sigma_{f,y} \tag{3.45}$$

where: $E_f = \sqrt{E_{f,x} E_{f,y}}$

4. OPTIMUM DESIGN FOR HONEYCOMB SANDWICH BASE PLATE OF AIR CARGO CONTAINERS

4.1. Introduction (Air Cargo Container)

Manufacturing a high performance and lightweight structure with affordable cost without sacrificing strength has been a challenging task for design engineers. The air cargo containers are utilized to load baggage, freight, and mail on the aircraft. This study aimed to replace the conventional aluminum base plate of air cargo containers (see Figure 4.1) with a honeycomb sandwich plate. The honeycomb sandwich structures are widely applied in the field of industry of air cargo containers. The global manufacturing and development companies are competing to design a lightweight container to satisfy airline carriers' requirements.

The companies of development and manufacturing seek to produce a lightweight structure that can be used to manufacturing the walls, floor, and roof of containers. The structural core material finds applications in aerospace vehicles, automotive engineering applications, and containers due to its high performance, like bending stiffness and strength to weight ratios. The honeycomb core makes sandwich structures lighter, stiffer, and stronger than single sheet laminate. The core increases the sandwich panel's flexural stiffness by effectively increasing the distance between the two stress skins. The lightweight containers provide considerable savings in weight and thus reduce fuel consumption or increase aircraft turnover compared to conventional containers.

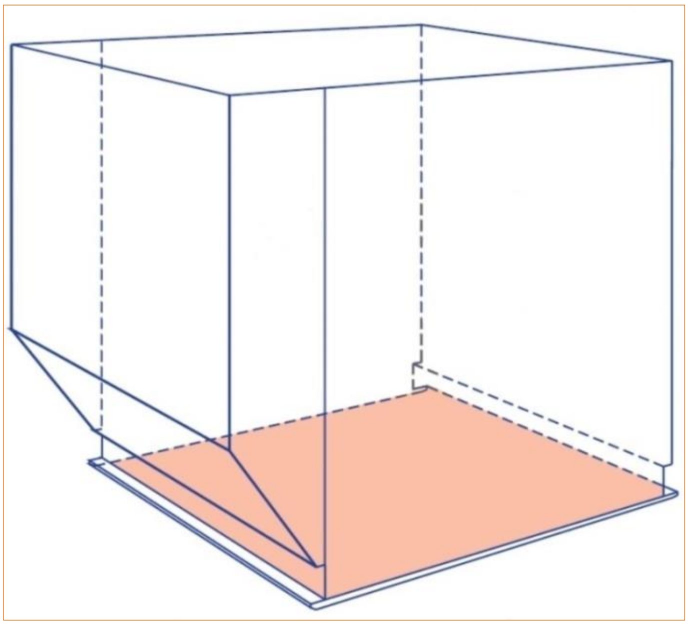


Figure 4.1: A base plate of an air cargo container.

4.2. Optimization Method (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 the 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 mathematical modeling for the optimization processes as described. The Equations (3.1-3.3) indicate weight objective function and cost objective function, Equations (3.4-3.6) indicate design variables of face-sheet thickness and honeycomb core thickness, and Equations (3.12-3.45) indicate design constraints. The technical data and boundary conditions for the air cargo container's base plate were shown in Tables 4.1 and 4.2, respectively. The honeycomb sandwich plate is either clamped along all four edges. The models of sandwich plates consisting of an aluminum honeycomb core and different types of face-sheets, including aluminum alloy and composite material, the face-sheets and honeycomb core's mechanical properties are shown in Tables 3.1 & 3.2, respectively [7].

Table 4.1: Technical data for the conventional base plate of air freight container [7].

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 4.2: Boundary conditions and constant design parameters for honeycomb sandwich base plate of air freight container [42].

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

4.3. 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.

4.3.1. Optimization of Single-objective Function (Air Cargo Containers)

The single-objective function was considered to minimize the weight objective function or cost objective function of honeycomb sandwich base plate of the air cargo container, separately, obtained by applying the Excel Solver program (GRG Nonlinear Algorithm) and the Matlab program (fmincon Solver Constrained Nonlinear Minimization / Interior Point Algorithm) for aluminum alloy face-sheets and composite material face-sheets.

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

The optimum results of single-objective function (weight or cost) for aluminum alloy face-sheets of honeycomb sandwich base plate of air cargo container obtained by applying the Excel Solver program (GRG Nonlinear Algorithm) are shown in Tables 4.3 & 4.4, and the Matlab program (Interior Point Algorithm) are shown in Tables 4.5 & 4.6.

Table 4.3: Minimize the weight objective function with disregard cost objective function using the Excel Solver program (GRG Nonlinear Algorithm) for the honeycomb sandwich base plate of the air cargo container, face-sheets are of aluminum alloy.

W_{min} [kg]	$t_{f,opt}$ [mm]	$t_{c,opt}$ [mm]
9.10545	0.5	21.424181

Table 4.4: Minimize the cost objective function with disregard weight objective function using the Excel Solver program (GRG Nonlinear Algorithm) for the honeycomb sandwich base plate of the air cargo container, face-sheets are of aluminum alloy.

C_{min} [€]	$t_{f,opt}$ [mm]	$t_{c,opt}$ [mm]
73.70975	0.50064552	21.4097224

Table 4.5: Minimize weight objective function with disregard cost objective function using the Matlab program (Interior Point Algorithm) for the honeycomb sandwich base plate of the air cargo container, face-sheets are of aluminum alloy.

W_{min} [kg]	$t_{f,opt}$ [mm]	$t_{c,opt}$ [mm]
9.134077	0.502825	21.41005

Table 4.6: Minimize cost objective function with disregard weight objective function using the Matlab program (Interior Point Algorithm) for the honeycomb sandwich base plate of the air cargo container, face-sheets are of aluminum alloy.

C_{min} [€]	$t_{f,opt}$ [mm]	$t_{c,opt}$ [mm]
73.75656	0.512037	21.17521

– ***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) are shown in Tables 4.7 & 4.8. The Matlab program (fmincon Solver Constrained Nonlinear Minimization / Interior Point Algorithm) are shown in Tables 4.9 & 4.10 (see Appendix A1).

Table 4.7: Minimum weight objective function with optimum face-sheet thickness and optimum core thickness using the Excel Solver program (GRG Nonlinear 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 with fiber orientations θ°		kg	mm	mm
2 (+45°, -45°) Optimum value		11.4355	0.5	45.11059

Type	**B. Epoxy woven carbon fiber face-sheets**	W_{min}	$t_{f,opt}$	$t_{c,opt}$
Number of layers N_l with fiber orientations θ°		kg	mm	mm
1 (+45°) Optimum value		6.3268	0.3	26.64614

Type	**C. Hybrid composite face-sheets**	W_{min}	$t_{f,opt}$	$t_{c,opt}$
Number of layers N_l with fiber orientations θ°		kg	mm	mm
2 (+45°, -45°) Optimum value		8.5719	0.55	28.62409

Table 4.8: Minimum cost objective function with optimum face-sheet thickness and optimum core thickness using the Excel Solver program (GRG Nonlinear 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 with fiber orientations θ°		€	mm	mm
2 (+45°, -45°) Optimum value		121.0267	0.5	45.11059

Type	**B. Epoxy woven carbon fiber face-sheets**	C_{min}	$t_{f,opt}$	$t_{c,opt}$
Number of layers N_l with fiber orientations θ°		€	mm	mm
1 (+45°) Optimum value		133.3970	0.3	26.64614

Type	**C. Hybrid composite face-sheets**	C_{min}	$t_{f,opt}$	$t_{c,opt}$
Number of layers N_l with fiber orientations θ°		€	mm	mm
2 (+45°, -45°) Optimum value		147.4220	0.55	28.62409

Table 4.9: 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		11.4357	0.5	45.11157

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		6.327142	0.3	26.64808

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		8.572076	0.55	28.62513

Table 4.10: 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		121.0746	0.5	45.13181

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		133.3972	0.3	26.64621

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		147.4526	0.55	28.63761

4.3.2. Optimization of Multi-objective Functions (Air Cargo Containers)

The multi-objective functions were considered to minimize the weight objective function and cost objective function of honeycomb sandwich base plate of air cargo container simultaneously obtained by applying the Excel Solver program (Weighted Normalized Method) and the Matlab program (Multi-objective Genetic Algorithm Solver) for aluminum alloy face-sheets and composite material face-sheets.

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

The optimum results of multi-objective function (weight and cost) for aluminum alloy face-sheets of honeycomb sandwich base plate of air cargo container obtained by applying the Matlab program (Multi-objective Genetic Algorithm Solver) are shown in Table 4.11 and Figure 4.2, and the Excel Solver program are shown in Table 4.12 and Figure 4.3. W_1 and W_2 are the weighted sum of weight objective function and cost objective function in percentage (%), respectively.

Table 4.11: Minimize the weight objective function and cost objective function simultaneously using Matlab program (Multi-objective Genetic Algorithm Solver) for honeycomb sandwich base plate of air cargo container consisting of aluminum honeycomb core and aluminum face-sheets.

Index	W_{min}	C_{min}	$t_{f,opt}$	$t_{c,opt}$
	kg	€	mm	mm
1	9.102777	73.3318681	0.5036	21.1774
2	9.109726	73.3317456	0.5045	21.1557
3	9.097997	73.3320637	0.5029	21.1924
4	9.110261	73.3316839	0.5046	21.1540
5	9.095993	73.3321282	0.5026	21.1987
6	9.098204	73.3320238	0.5029	21.1917
7	9.095993	73.3321282	0.5026	21.1987
8	9.110032	73.3317083	0.5046	21.1547
9	9.098196	73.3320528	0.5029	21.1918
10	9.109726	73.3317456	0.5045	21.1557
11	9.110261	73.3316839	0.5046	21.1540
12	9.094839	73.3321713	0.5024	21.2023
13	**9.094634**	**73.3321867**	**0.5024**	**21.2029**
14	9.095665	73.3321539	0.5026	21.1997
15	9.102777	73.3318681	0.5036	21.1774
16	9.097997	73.3320637	0.5029	21.1924
17	9.097997	73.3320637	0.5029	21.1924
18	9.094607	73.3321909	0.5024	21.2030

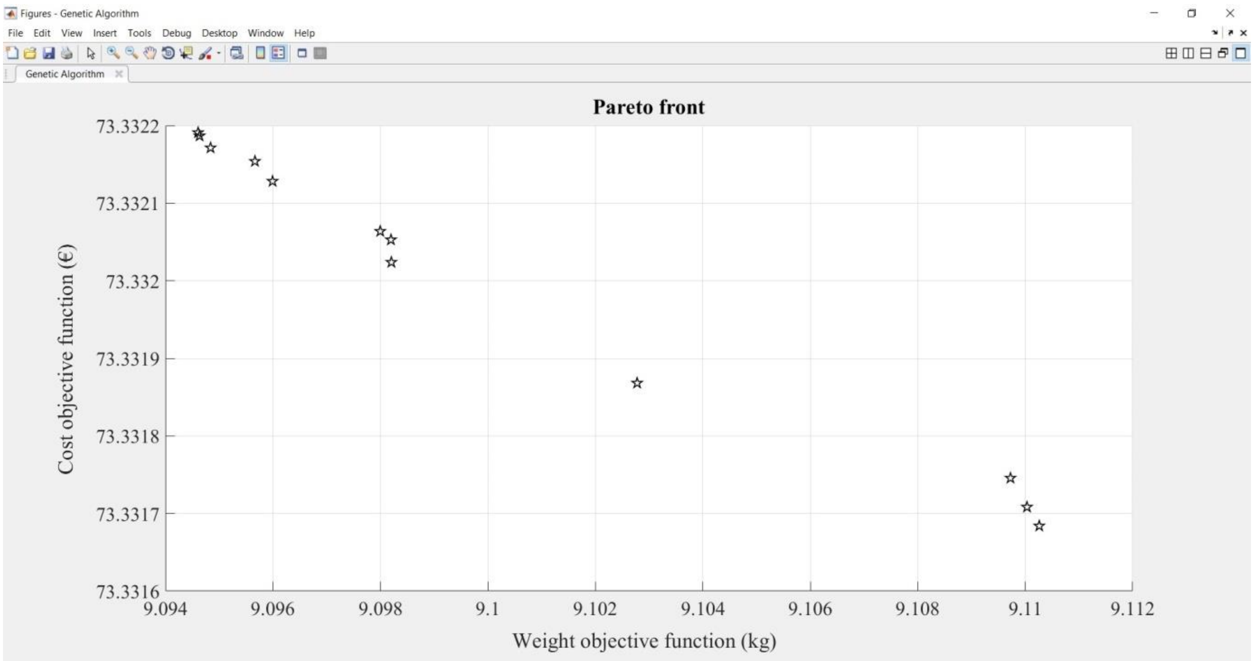


Figure 4.2: Pareto front curve for weight objective function and cost objective function simultaneously using the Matlab program (Multi-objective Genetic Algorithm Solver) for honeycomb sandwich base plate of an air cargo container.

Table 4.12: Minimize the weight and the cost of multi-objective functions using the Excel Solver program (Weighted Normalized Method) for honeycomb sandwich base plate of an air cargo container, face-sheets are of aluminum alloy.

Type	**Aluminum Alloy (5251 H24)**		W_{min}	C_{min}	$t_{f,opt}$	$t_{c,opt}$
No.	W_1 (%)	W_2 (%)	kg	€	mm	mm
1	50	50	9.1054473	73.709721	0.5	21.424172
2	60	40	9.1054476	73.709725	0.5	21.424174
3	70	30	9.1054479	73.709729	0.5	21.424176
4	80	20	9.1054482	73.709733	0.5	21.424178
5	90	10	9.1054485	73.709737	0.5	21.424179

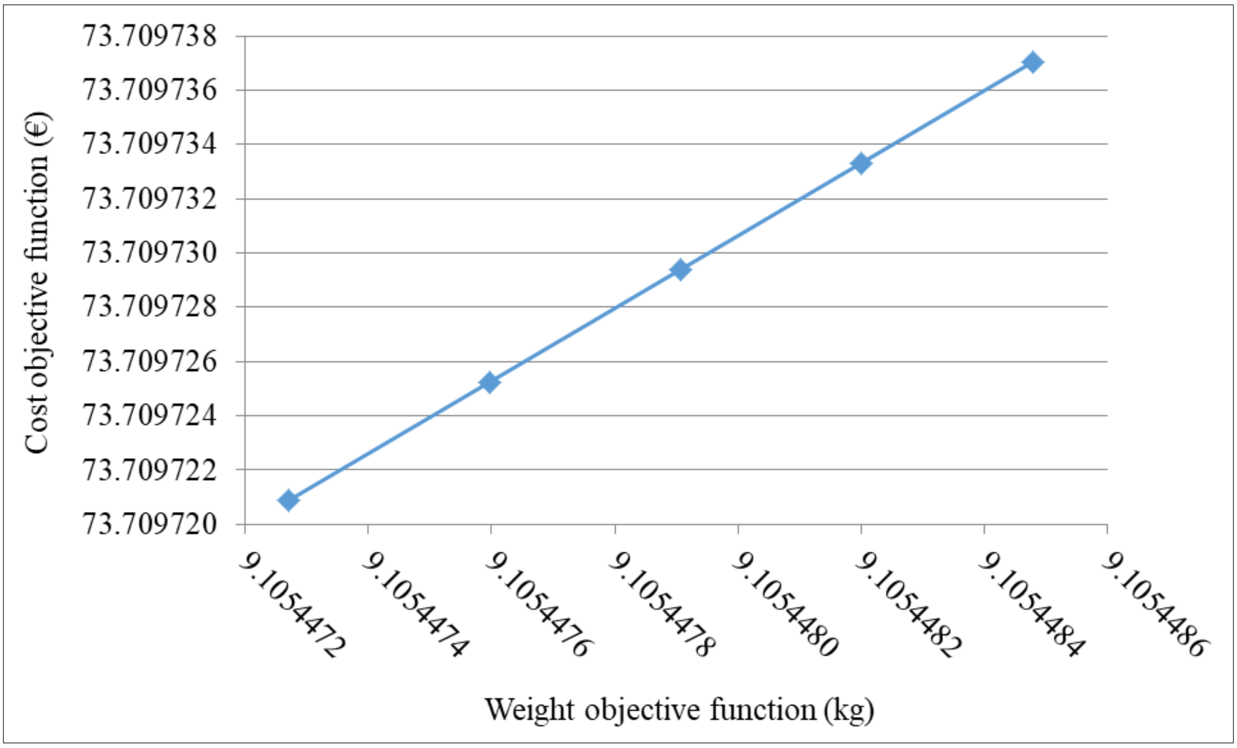


Figure 4.3: Compromise between multi-objective functions weight and cost using the Excel Solver program (Weighted Normalized Method) for honeycomb sandwich base plate of air cargo container, face-sheets are of aluminum alloy.

– ***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 are shown in Table 4.13, and the Matlab program (Multi-objective Genetic Algorithm Solver) are shown in Tables 4.14 (see Appendix A1), and Figure 4.4.

Table 4.13: Minimum weight and cost multi-objective functions with optimum face-sheet thickness and optimum core thickness using the Excel Solver program (Weighted Normalized Method) for the sandwich base plate of air freight container consisting of an aluminum honeycomb core and orthotropic composite face-sheets 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}	C_{min}	$t_{f,opt}$	$t_{c,opt}$
Number of layers N_l with fiber orientations θ°		kg	€	mm	mm
2 (+45°, -45°) Optimum value		11.4355	121.0267	0.5	45.11059

Type	**B. Epoxy woven carbon fiber face-sheets**	W_{min}	C_{min}	$t_{f,opt}$	$t_{c,opt}$
Number of layers N_l with fiber orientations θ°		kg	€	mm	mm
1 (+45°) Optimum value		6.3268	133.3970	0.3	26.64614

Type	**C. Hybrid composite face-sheets**	W_{min}	C_{min}	$t_{f,opt}$	$t_{c,opt}$
Number of layers N_l with fiber orientations θ°		kg	€	mm	mm
2 (+45°, -45°) Optimum value		8.5719	147.4220	0.55	28.62409

Table 4.14: 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		11.39432	120.4749	0.5	44.86638

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		6.2919	132.9296	0.3	26.43926

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		8.573244	147.44	0.55	28.63205

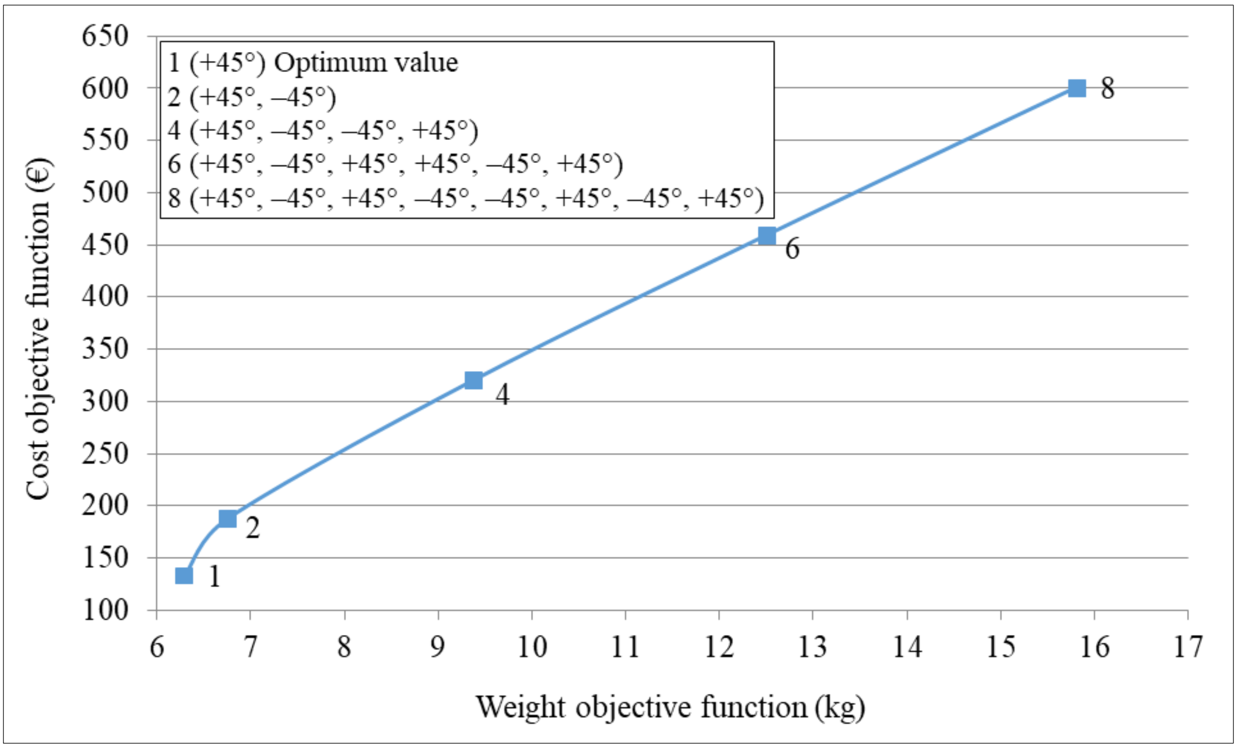


Figure 4.4(a): Minimum weight versus minimum cost objective function using the Matlab program (Genetic Algorithm Solver) for the sandwich base plate of air freight container consisting of an aluminum honeycomb core and epoxy woven carbon fiber composite face-sheets with a different number of layers N_l and angle-ply fiber orientation θ°.

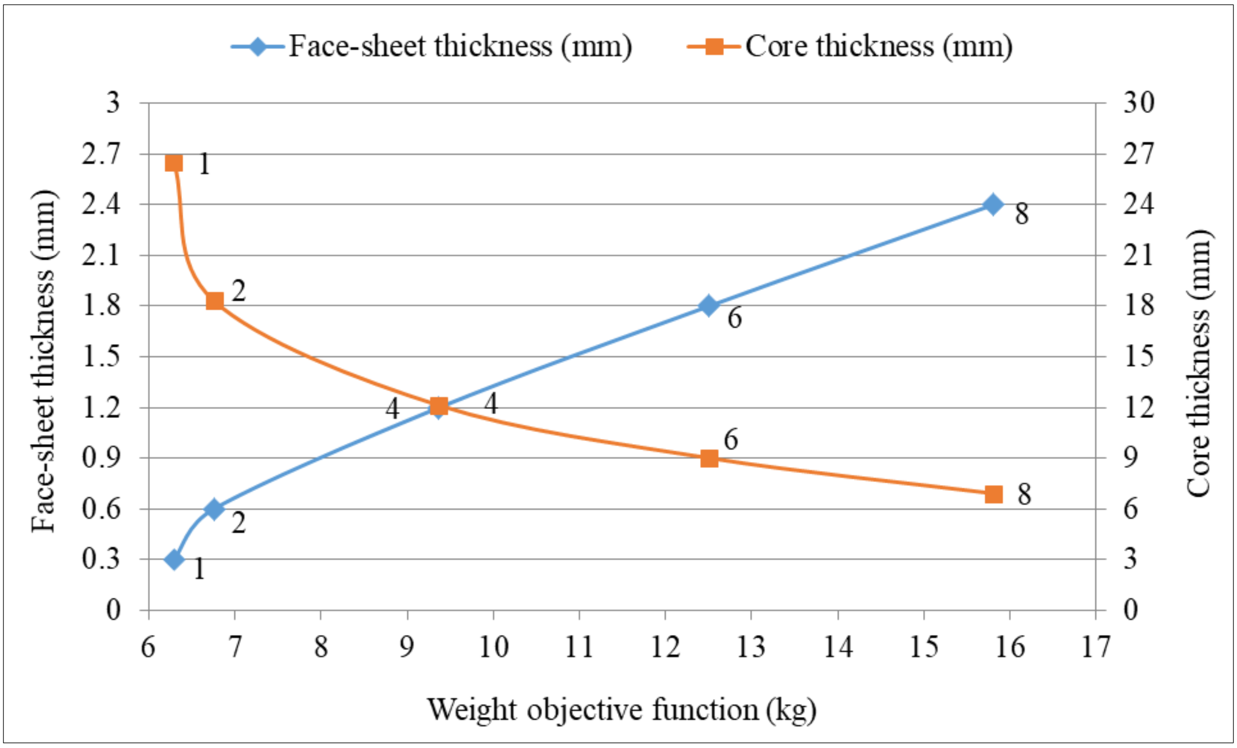


Figure 4.4(b): Minimum weight objective function versus optimum face-sheet and core thicknesses using the Matlab program (Genetic Algorithm Solver) for the sandwich base plate of air freight container consisting of an aluminum honeycomb core and epoxy woven carbon fiber face-sheets with a different number of layers N_l and angle-ply fiber orientation θ°.

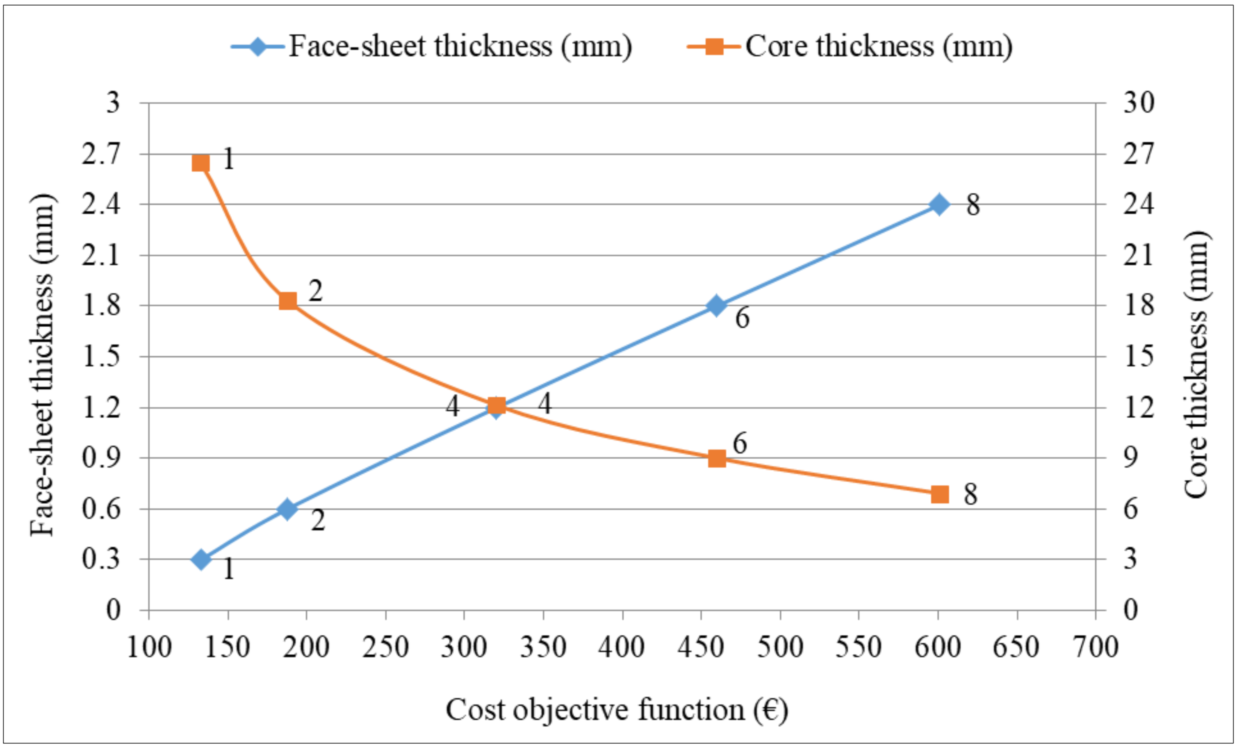


Figure 4.4(c): Minimum cost objective function versus optimum face-sheet and core thicknesses using the Matlab program (Genetic Algorithm Solver) for the sandwich base plate of air freight container consisting of an aluminum honeycomb core and epoxy woven carbon fiber face-sheets with a different number of layers N_l and angle-ply fiber orientation θ°.

4.4. *Factor of Safety (FoS)*

To designing an element or structure, the design engineers must consider many factors, such as safety factors. Safety is one of the most important qualities to be considered when creating parts or products. The term of "Factor of Safety" (FoS) or "Safety Factor (SF) is most commonly. A basic equation to calculate FoS is to divide the ultimate (or maximum) stress by the typical (or working) stress, and the same for the load. Table 4.15 shows the factors of safety for optimum design constrains for the base plate of an air cargo container.

Table 4.15: Safety factors for optimum design constrains for the base plate of an air cargo container.

Constraints		Factor of Safety (FoS)		
		Epoxy woven glass fiber face-sheet 2-layers (+45°, -45°)	Epoxy woven carbon fiber face-sheet 1-layer (+45°)	Hybrid composite face-sheet 2-layers (+45°, -45°)
Bending stiffness	$D_{11,x}$	1.013	1.021	1.114
Total deflection	δ	1	1	1.090
Skin stress (bending load)	σ_f	1.375	1.092	1
Core shear stress	τ_c	12.402	7.327	7.933

Facing stress (end loading)	σ_f	7.232	9.707	8.224
Overall buckling	$P_{b,\,cr}$	1.015	1.023	1.115
Shear crimping	P_{cr}	Not Active	Not Active	Not Active
Skin wrinkling critical stress in x-directions	$\sigma_{wr,\,cr}$	10.776	5.512	11.244
Skin wrinkling critical stress in y-directions	$\sigma_{wr,\,cr}$	8.556	4.384	8.927
Skin wrinkling critical load	$P_{wr,cr}$	14.837	14.726	29.208
Intracell buckling	$\sigma_{f,\,cr}$	2.513	1.087	4.728

4.5. *Weight Saving Calculator (Air Cargo Container)*

According to the International Air Transport Association (IATA), every dollar increase per barrel (42 gallons) drives an additional USD 415 million in yearly fuel costs for passengers and cargo airlines. Fuel expenses now range from 25% to 40% of the total airline operating expenses. The new lightweight freight containers offer an enormous saving possibility compared to the conventional aluminum containers. Data for calculating the fuel cost and discovering how much lightweight can be saved as well as carbon saving are shown in Table 4.16. Estimates from aircraft manufacturers and airlines vary greatly based on length of flight and type of aircraft but put operating costs at around 42 \$/kg per year [45].

Table 4.16: Annual fuel and carbon savings for the sandwich base plate of air cargo container compared to the air cargo container's conventional base plate.

- **Fuel savings**

Weight of fuel required to carry 1 kg additional weight per hour	0.04	kg
Expected annual hours flown	5,000	hours
Weight of fuel required to carry 1 kg weight for one year	200	kg
Current cost of fuel per 1000 kg (from Jet fuel price monitor)	993	US$
Annual cost to carry 1 kg additional weight for one year	199	US$
Quantity of units per aircraft	26	unit
Quantity of shipsets	4	set
Weight of existing base plate of fright container	14.1	kg
Number of units required	104	unit
Weight of lightweight base plate of air cargo container	6.3	kg
Weight reduction in one base plate of air cargo container	**7.8**	kg
Fuel cost saving per year for one base plate of air cargo container	**1,552**	US$

Weight reduction in one aircraft	202.8	kg
Fuel cost saving per year for one aircraft	40,276	US$

- **Carbon savings**

Carbon produced per kg of Fuel	3.1	kg
Total carbon produced to carry 1 kg for one year	620	kg
Total carbon saving	125,736	kg
Cost of carbon per Ton	40	US$
Annual carbon cost saved	5,029	US$

- **Total saved**

Combined effect of reduced fuel burn and carbon reduction	45,306	US$

4.6. Discussions (Air Cargo Container)

This study aimed to improve a novel honeycomb sandwich plate, which can be applied in manufacturing a lightweight base plate for air freight containers. The novel models of honeycomb sandwich base plate of air cargo container consisting of an aluminum honeycomb core and different types of face-sheets include aluminum alloy and composite material. The composite material face-sheets included 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 with sets of fiber orientations including cross-ply (0°, 90°) and/or angle-ply (±45°). The laminated composite plates were symmetric concerning the midplane of the sandwich plates and/or symmetric concerning the midplane of the face-sheets depending on the number of layers N_l and fiber orientation θ°. The models of sandwich plates were solved theoretically using the Excel Solver program and Matlab program to calculate the optimum face-sheet thickness $t_{f,opt}$, optimum core thickness $t_{c,opt}$, minimum weight W_{min} and/or minimum cost C_{min}. The objective functions were the total weight and/or the total material cost of the air cargo container's honeycomb sandwich base plate. The design constraints were taking into consideration were the following: total stiffness (bending stiffness and shear stiffness), full deflection (bending deflection and shear deflection), facing skin stress (bending load), core shear stress, facing skin stress (end loading), overall panel buckling (bending and shear critical buckling loads), shear crimping load, skin wrinkling (critical stresses and critical load) and intracell buckling as well as the size constraint for design variables. According to classical lamination plate theory and ply failure calculation, the mechanical properties of composite laminate face-sheets are calculated using the Laminator program dependent on Tsai-Hill failure criteria. Every face-sheet is composed of (1, 2, 4, 6, and 8) layers. The theoretical results consist of three main cases depending on face-sheets types of the honeycomb sandwich plates with a different number of layers N_l and fiber orientations θ°were presented.

In the case of epoxy woven glass fiber face-sheets, and hybrid composite layers face-sheets (a combination of epoxy woven glass fiber layers and epoxy woven carbon fiber layers) of the 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°). So, 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 (6.2919 kg, 132.9296 €, 0.3 mm, and 26.43926 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. While, 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 (11.39432 kg, 120.4749 €, 0.5 mm, and 44.86638 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 (8.573244 kg, 147.44 €, 0.55 mm, and 28.63205 mm), respectively. The epoxy woven glass fiber having higher strength to weight ratio and more flexible compared to epoxy woven carbon fiber. The case of aluminum face-sheets of the honeycomb sandwich plates, the optimum face-sheet thickness and optimum core thickness which ensures the minimum weight and/or minimum cost are (9.094607 kg, 73.3321909 €, 0.5024 mm, and 21.2030 mm), respectively. The results give good agreement between Excel Solver program and Matlab program as well as between methods of Interior Point Algorithm with GRG Nonlinear Algorithm for single-objective function, and Genetic Algorithm Solver with Weighted Normalized Method for multi-objective functions. The lightweight honeycomb sandwich plate containers provide huge savings in weight and thus decrease the fuel consumption or increase the airplane turning compared to the conventional aluminum plate containers.

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

5.1. Introduction (Military Aircraft Pallets)

The pallet is a durable and robust freight pallet for efficient and cost-effective cargo transportation. This case study aimed to design a lightweight sandwich plate consisting of an aluminum honeycomb core with different types of face-sheets. The elaborated structural model could be used to manufacture a single base plate of aircraft cargo pallets to fulfill the military air force requirements. The purpose of the application of lightweight pallets is to provide considerable savings in weight compared to the conventional aluminum sheet pallet (see Figure 5.1). The single base pallet (manufactured from a honeycomb sandwich structure for a cargo system) is a robust and durable cargo pallet that offers low-cost maintenance and (66.25 %) lower weight than the standard pallet. The pallet is the centrepiece of the materials handling support system, designed in the late 1950's to provide more efficient intermodal cargo transfer for the air force. Today the pallet is a common size platform for bundling and moving air cargo and serves as the primary air cargo pallet for the Air Forces and many civilian cargo transport aircraft worldwide.

Figure 5.1: Single base plate of the conventional aluminum sheet military aircraft pallet.

5.2. Optimization Method (Single Base Plate of Military Aircraft Pallet)

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 are shown in Figure 5.2. 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. Moreover, the pallet should be able to 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 5.1). The design parameters of the conventional single base plate of the aircraft freight pallet (Aluminum alloy – Al7021-T6) are shown in Table 5.2.

The mathematical modeling for the optimization processes as described in chapter 3. The Equations (3.1-3.3) indicate weight objective function and cost objective function, Equations (3.4-3.6) indicate design variables of face-sheet thickness and honeycomb core thickness, and Equations (3.12-3.45) indicate design constraints. The sandwich panel models consist of an aluminum honeycomb core and different types of face-sheets including aluminum alloy and composite material. The mechanical properties of the face-sheets and honeycomb core are shown in Tables 3.1 & 3.2, respectively.

Table 5.1: Boundary conditions and constant design parameters for the honeycomb sandwich panel [42].

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

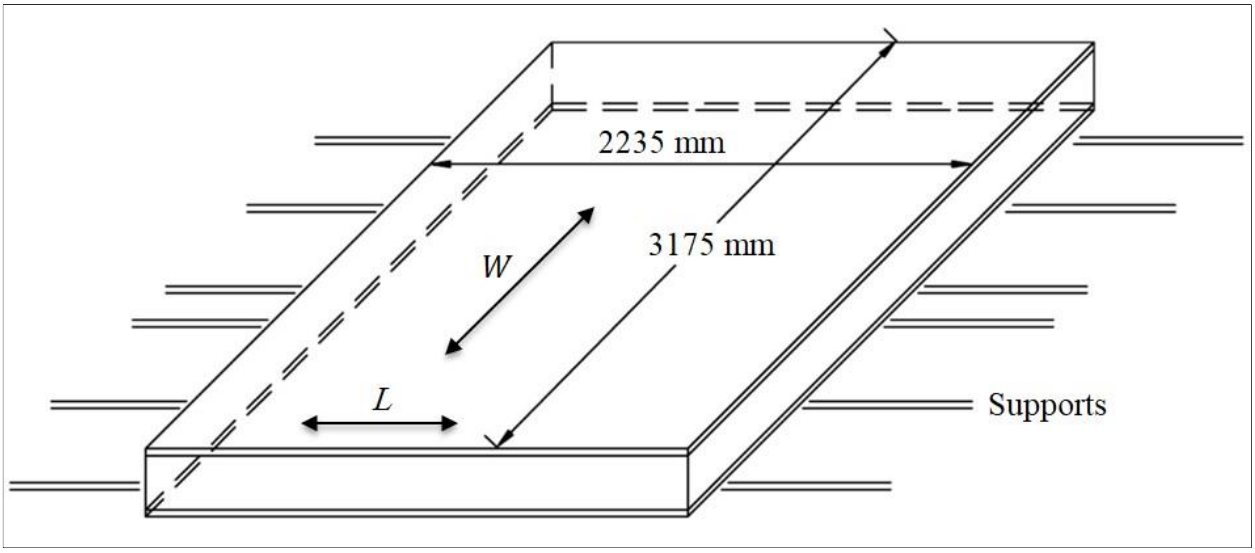


Figure 5.2: Dimensions of a base plate of military aircraft pallet with a supported beam [2].

Table 5.2: Technical data for the conventional military pallet, aluminum alloy–Al7021-T6 [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

5.3. 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.

5.3.1. Optimization of Single-objective Function (Military Aircraft Pallets)

The single-objective function was considered to minimize the weight objective function or cost objective function of military aircraft pallets separately obtained by applying the Excel Solver program (GRG Nonlinear Algorithm) and the Matlab program (fmincon Solver Constrained Nonlinear Minimization / Interior Point Algorithm).

– ***Minimizing the Single-objective Function for Single Base Plate of Military Aircraft Pallets with Aluminum Alloy Face-sheets***

The optimum results of single-objective function (weight or cost) for aluminum alloy face-sheets of military aircraft pallets obtained by applying the Excel Solver program (GRG Nonlinear Algorithm) are shown in Tables 5.3 & 5.4, and the Matlab program (fmincon Solver Constrained Nonlinear Minimization/ Interior Point Algorithm) are shown in Tables 5.5 & 5.6.

Table 5.3: Minimize the weight objective function with disregard cost objective function using the Excel Solver program (GRG Nonlinear Algorithm) for honeycomb sandwich base plate of military aircraft pallets, face-sheets are of aluminum alloy.

$W_{min,t}$	$t_{f,opt}$	$t_{c,opt}$
kg	mm	mm
60.62654	0.804558	50.59031

Table 5.4: Minimize the cost objective function with disregard weight objective function using the Excel Solver program (GRG Nonlinear Algorithm) for honeycomb sandwich base plate of military aircraft pallets, face-sheets are of aluminum alloy.

$C_{min,t}$	$t_{f,opt}$	$t_{c,opt}$
€	mm	mm
469.1386	1.390044	28.35738

Table 5.5: Minimize weight objective function with disregard cost objective function using the Matlab program (Interior Point Algorithm) for honeycomb sandwich base plate of military aircraft pallets, face-sheets are of aluminum alloy.

$W_{min,t}$	$t_{f,opt}$	$t_{c,opt}$
kg	mm	mm
63.15271	1.008813	41.59054

Table 5.6: Minimize cost objective function with disregard weight objective function using the Matlab program (Interior Point Algorithm) for honeycomb sandwich base plate of military aircraft pallets, face-sheets are of aluminum alloy.

$C_{min,t}$	$t_{f,opt}$	$t_{c,opt}$
€	mm	mm
469.1404	1.389901	28.36081

– *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) are shown in Tables 5.7 & 5.8 and Matlab program (fmincon Solver Constrained Nonlinear Minimization / Interior Point Algorithm) are shown in Tables 5.9 & 5.10 (see Appendix A2).

Table 5.7: Minimum weight objective function with optimum face-sheet thickness and core thickness using the Excel Solver program (GRG Nonlinear Algorithm) for the honeycomb sandwich base plate of military aircraft pallets consists of an aluminum honeycomb core and 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		40.741815	1	23.8725

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		27.06897	0.6	24.27243

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		40.11522	1.1	23.7725

Table 5.8: Minimum cost objective function with optimum face-sheet thickness and core thickness using the Excel Solver program (GRG Nonlinear Algorithm) for 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		321.6318	1	23.8725

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	24.27243

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		765.0608	1.1	23.7725

Table 5.9: 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		40.74181	1	23.87249

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		27.06899	0.6	24.27249

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		40.11522	1.1	23.77248

Table 5.10: 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		321.65588	1	23.87554

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		702.2996	0.6	24.27251

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		765.06088	1.1	23.77251

5.3.2. Optimization of Multi-objective Functions (Military Aircraft Pallets)

The multi-objective functions were considered to minimize the weight objective function and cost objective function for honeycomb sandwich base plate of military aircraft pallets simultaneously obtained by applying the Excel Solver program (Weighted Normalized Method) and Matlab program (Multi-objective Genetic Algorithm Solver) for aluminum alloy face-sheets and composite material face-sheets.

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

The optimum results of multi-objective function (weight and cost) for aluminum alloy face-sheets of honeycomb sandwich base plate of military aircraft pallets obtained by applying the Excel Solver program are shown in Table 5.11 and Figures 5.3, 5.4 & 5.5. W_1 and W_2 are the weighted sum of weight objective function and cost objective function in percentage (%), respectively, and the Matlab program (Multi-objective Genetic Algorithm Solver) are shown in Table 5.12 and Figure 5.6.

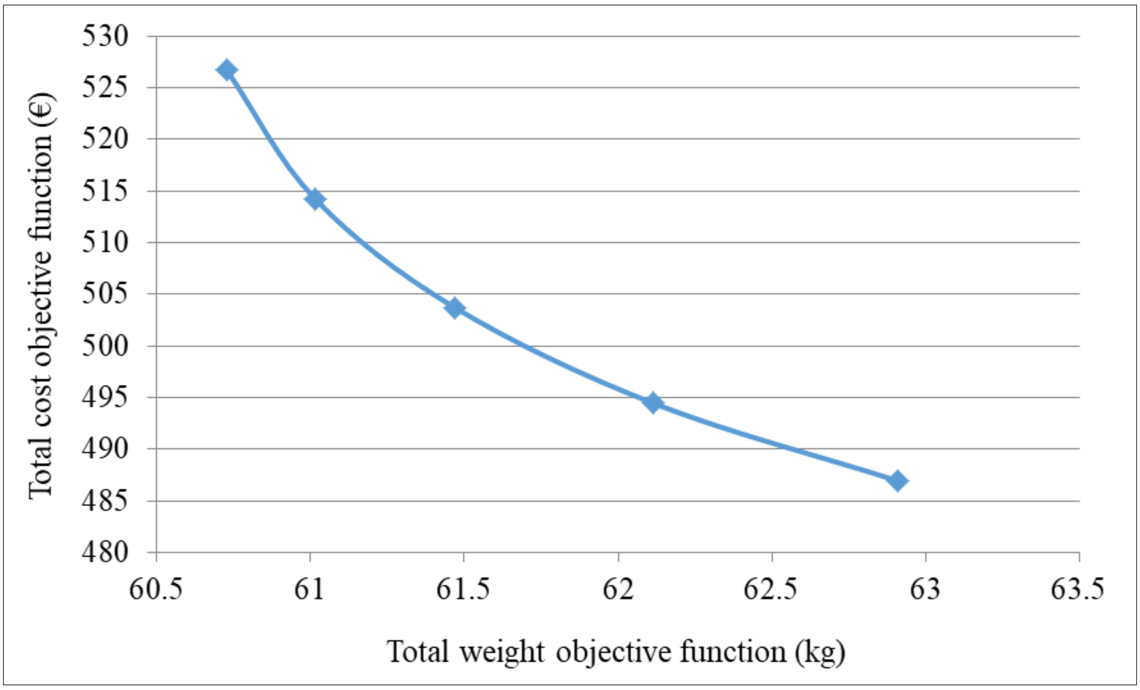


Figure 5.3: Compromise between multi-objective functions total weight and total material cost using the Excel Solver program (Weighted Normalized Method) for honeycomb sandwich base plate of military aircraft pallets, face-sheets are of aluminum alloy.

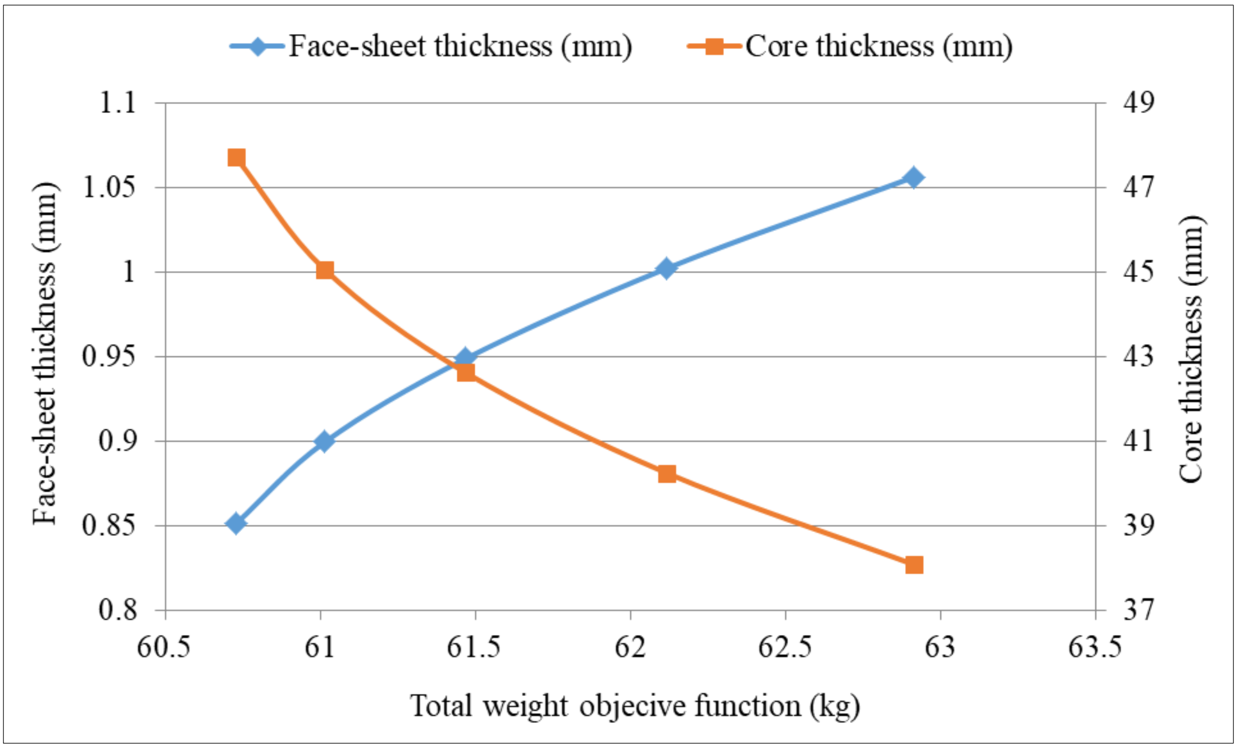


Figure 5.4: Minimum total weight objective function versus optimum face-sheet and core thicknesses using Excel Solver program (Weighted Normalized Method) for sandwich base plate of military aircraft pallets consist of an aluminum honeycomb core and aluminum face-sheets.

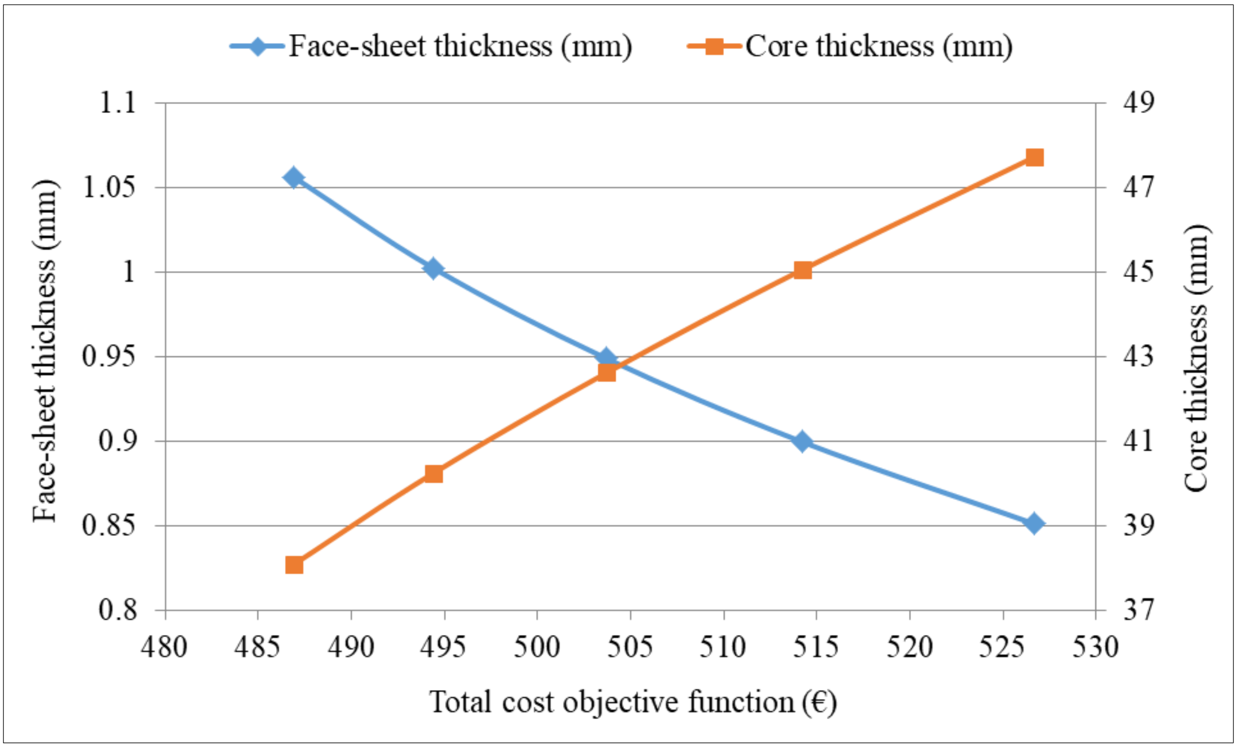


Figure 5.5: Minimum total material cost objective function versus optimum face-sheet and core thicknesses using Excel Solver program (Weighted Normalized Method) for sandwich base plate of military aircraft pallets consist of an aluminum honeycomb core and aluminum face-sheets.

Table 5.11: Minimize the total weight and the total material cost of multi-objective functions using the Excel Solver program (Weighted Normalized Method) for honeycomb sandwich base plate of military aircraft pallets, in which the face-sheets are of aluminum alloy.

Type	**Aluminum Alloy**		$W_{min,t}$	$C_{min,t}$	$t_{f,opt}$	$t_{c,opt}$
No.	W_1 (%)	W_2 (%)	kg	€	mm	mm
1	50	50	62.91129	486.9147	1.056343	38.08835
2	60	40	62.11550	494.4336	1.002311	40.25254
3	70	30	61.46809	503.7275	0.948907	42.62777
4	80	20	61.01494	514.2220	0.899667	45.06200
5	90	10	60.72751	526.6905	0.851153	47.73031

Table 5.12: Minimize total weight and total material cost objective functions simultaneously using the Matlab program (Multi-objective Genetic Algorithm Solver) for the sandwich base plate of military aircraft pallets consisting of aluminum honeycomb core and aluminum face-sheets.

Index	$W_{min,t}$	$C_{min,t}$	$t_{f,opt}$	$t_{c,opt}$
	kg	€	mm	mm
1	61.46027	504.8923	0.945133	42.86005
2	62.36408	491.8176	1.019984	39.5248
3	61.93097	496.8518	0.987776	40.88489
4	61.30941	507.0903	0.932593	43.41979
5	60.69463	532.34	0.833046	48.85252
6	61.58657	502.3664	0.95767	42.2588
7	**60.64256**	**535.6126**	**0.821243**	**49.53201**
8	61.77735	499.7452	0.973058	41.5816
9	61.07425	514.5953	0.900918	45.08132
10	60.94183	517.2846	0.887651	45.71965
11	60.71171	528.1774	0.846103	48.03203
12	62.17839	493.7488	1.00685	40.06397
13	62.008	496.0018	0.993369	40.65176
14	62.36408	491.8176	1.019984	39.5248
15	60.81731	522.8384	0.866181	46.90505
16	60.71171	528.1774	0.846103	48.03203
17	60.90846	520.5136	0.876721	46.37404
18	61.21983	509.7247	0.921194	44.00928

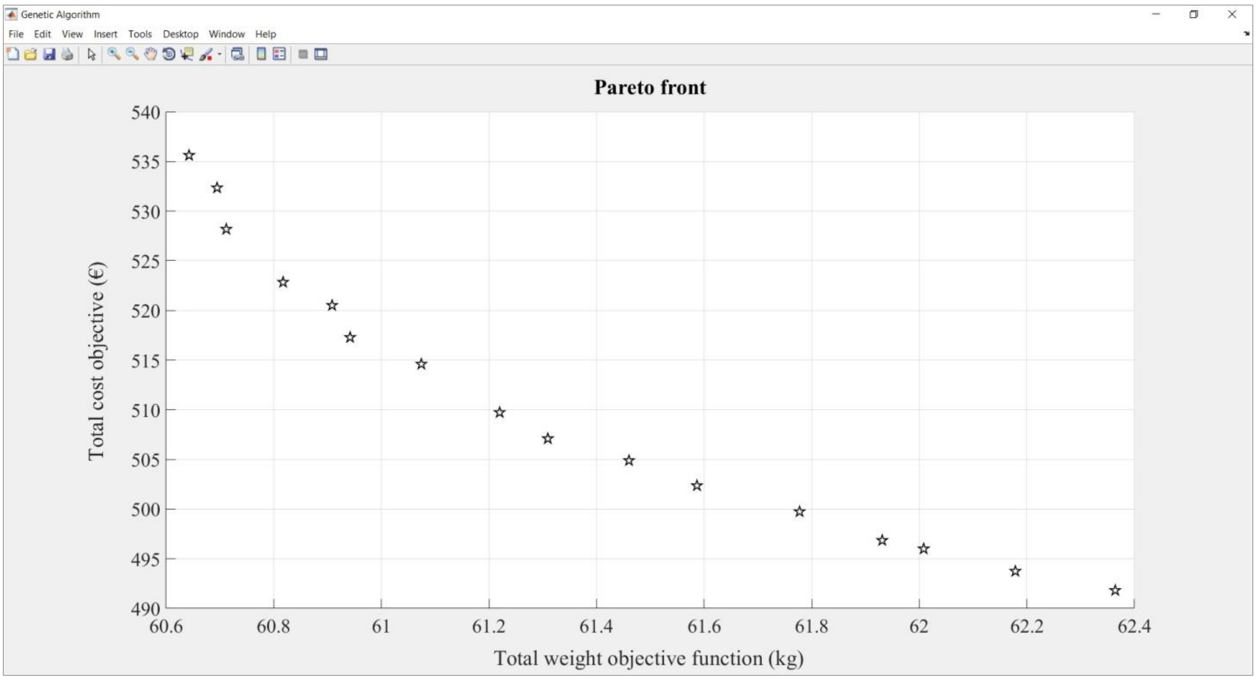


Figure 5.6: Pareto front set for multi-objective functions (total weight and total material cost) using the Matlab program (Genetic Algorithm Solver) for the sandwich base plate of military aircraft pallets consist of an aluminum honeycomb core and aluminum face-sheets.

– ***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 are shown in Table 5.13, and the Matlab program (Genetic Algorithm Solver) is shown in Table 5.14 (see Appendix A2), and Figure 5.7.

Table 5.13: Minimum weight and cost multi-objective functions with optimum face-sheet thickness and core thickness using the Excel Solver program (Weighted Normalized Method) for the sandwich base plate of military aircraft pallets consists of an aluminum honeycomb core and 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**	$W_{min,t}$	$C_{min,t}$	$t_{f,opt}$	$t_{c,opt}$
Number of layers N_l with fiber orientations θ°		kg	€	mm	mm
4 (0°, 90°, 90°, 0°) optimum value		40.7418	321.631	1	23.8725

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		27.0689	702.299	0.6	24.2724

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		40.1152	765.060	1.1	23.7725

Table 5.14: 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		40.7601	321.876	1	23.9034

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		27.1269	703.074	0.6	24.3707

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		40.1195	765.119	1.1	23.7798

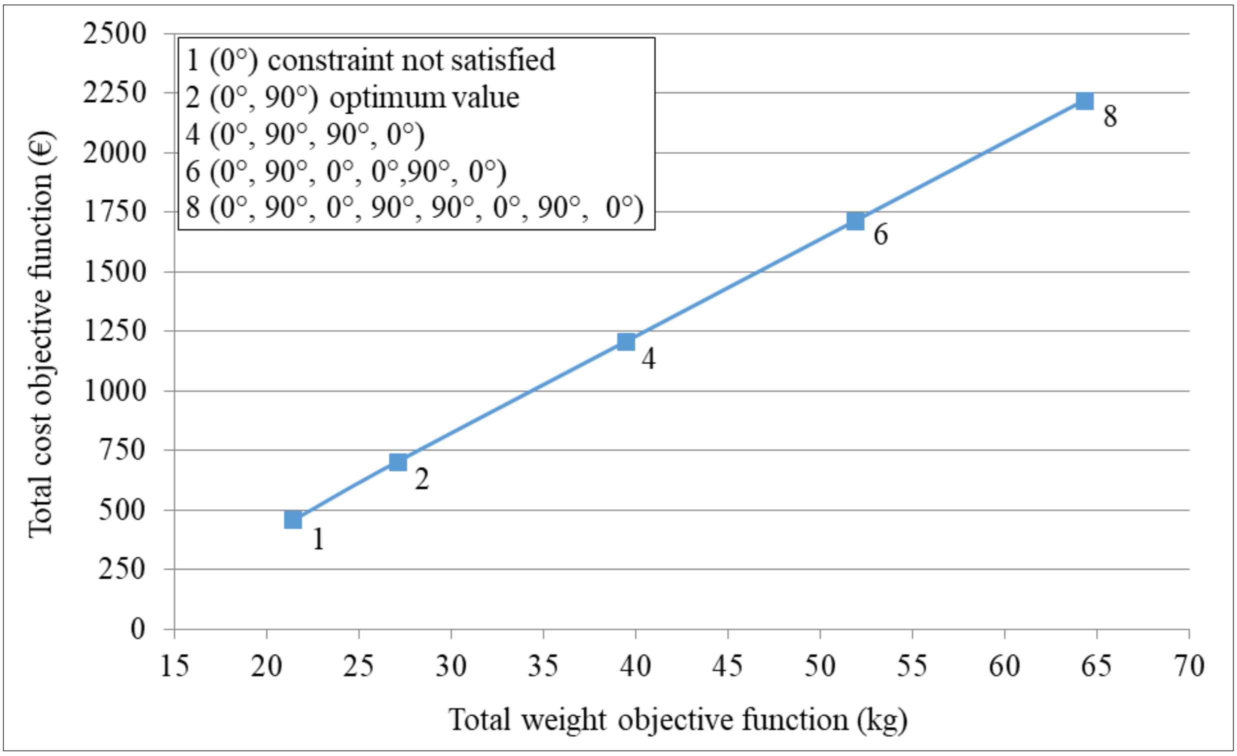


Figure 5.7(a): Minimum total weight versus minimum total material cost objective function using the Matlab program (Genetic Algorithm Solver) for honeycomb sandwich base plate of military aircraft pallets consisting of an aluminum honeycomb core and epoxy woven carbon fiber composite face-sheets with a different number of layers N_l and cross-ply fiber orientation θ°.

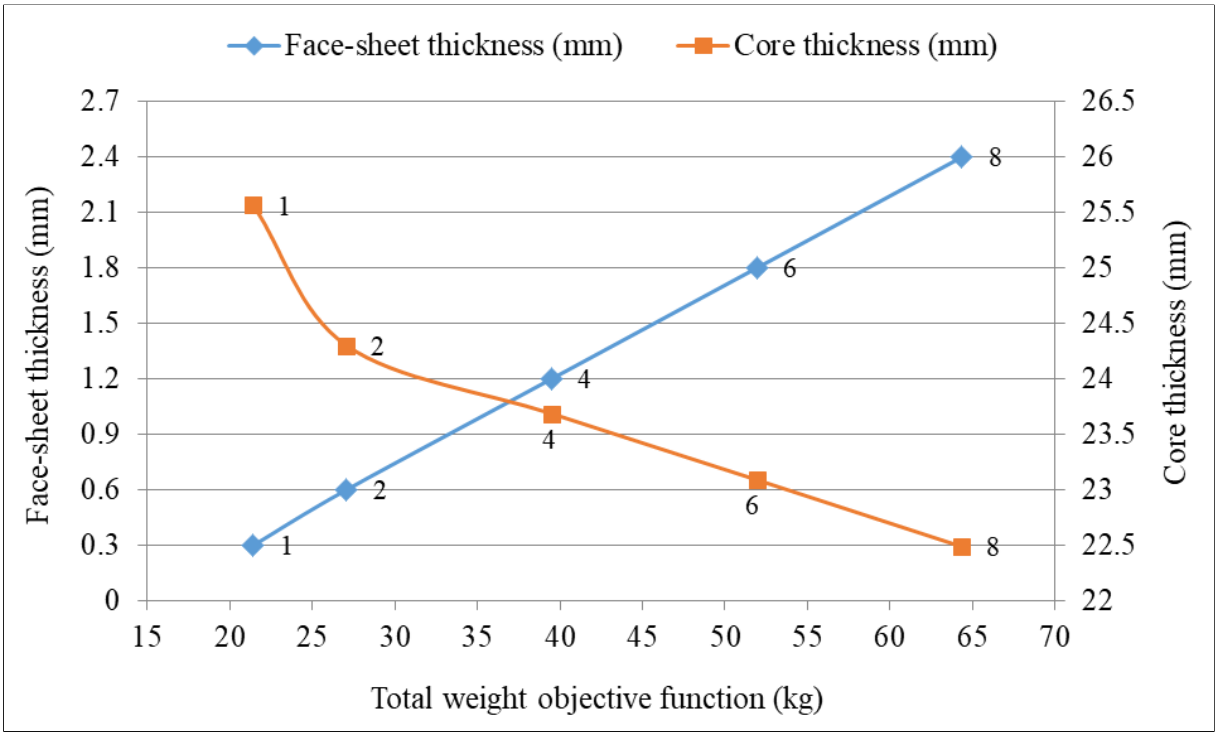


Figure 5.7(b): Minimum total weight objective function versus optimum face-sheet and core thicknesses using Matlab program (Genetic Algorithm Solver) for honeycomb sandwich base plate of military aircraft pallets consisting of an aluminum honeycomb core and epoxy woven carbon fiber face-sheets with a different number of layers N_l and cross-ply fiber orientation θ°.

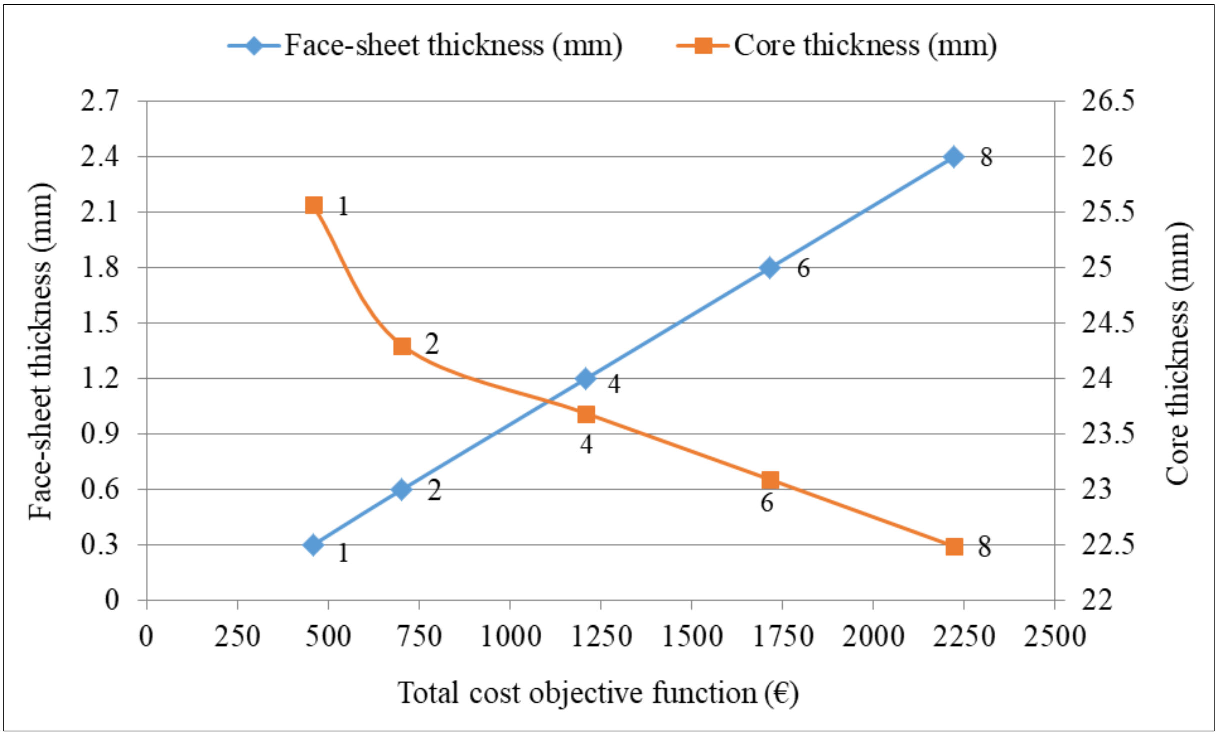


Figure 5.7(c): Minimum total material cost objective function versus optimum face-sheet and core thicknesses using Matlab program (Genetic Algorithm Solver) for honeycomb sandwich base plate of military aircraft pallets consisting of an aluminum honeycomb core and epoxy woven carbon fiber face-sheets with a different number of layers N_l and cross-ply fiber orientation θ°.

5.4. Saving Weight Calculator (Military Aircraft Pallets)

According to the International Air Transport Association (IATA), every dollar increase per barrel (42 gallons) drives an additional USD 415 million in yearly fuel costs for passengers and cargo airlines. Fuel expenses now range from 25% to 40% of the total airline operating expenses. The new lightweight freight pallets offer an enormous saving possibility compared to the conventional aluminum pallets. To calculate the fuel cost and the carbon saving, it is important to discover how much weight can be saved. It is shown in Table 5.15. Estimates from aircraft manufacturers and airlines vary greatly based on length of flight and type of aircraft but put operating costs at around 42 $/kg per year [45].

Table 5.15: Annual fuel and carbon savings for the sandwich base plate of military aircraft pallets compared to the conventional base plate of military aircraft pallets.

- **Fuel savings**

Weight of fuel required to carry 1 kg additional weight per hour	0.04	kg
Expected annual hours flown	5,000	hours
Weight of fuel required to carry 1 kg weight for one year	200	kg
Current cost of fuel per 1000 kg (from Jet fuel price monitor)	993	US$
Annual cost to carry 1 kg additional weight for one year	199	US$
Quantity of units per aircraft	26	unit
Quantity of shipsets	4	set
Weight of existing aluminum pallet	**80**	kg
Number of units required	104	unit
Weight of lightweight (FRP) pallet	**27**	kg
Weight reduction in one (FRP) pallet	**53**	kg
Fuel cost saving per year for one (FRP) pallet	**10,547**	US$
Weight reduction in one aircraft	1,378	kg
Fuel cost saving per year for one aircraft	27,3671	US$

- **Carbon savings**

Carbon produced per kg of Fuel	3.1	kg
Total carbon produced to carry 1 kg for one year	620	kg
Total carbon saving	854,360	kg
Cost of carbon per Ton	40	US$
Annual carbon cost saved	34,174	US$

- **Total saved**

Combined effect of reduced fuel burn and carbon reduction	307,845	US$

5.5. Discussions (Military Aircraft Pallets)

This study aimed to replace the currently aluminum single base plate of military aircraft pallets with a honeycomb sandwich plate. The novel sandwich plate consists of an aluminum honeycomb core and different face-sheets, including aluminum alloy and composite material. The composite material face-sheets included 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 with sets of fiber orientations including cross-ply (0°, 90°) and/or angle-ply (±45°). Every face-sheet is composed of (1, 2, 4, 6, and 8) layers. The laminated composite panels were symmetric concerning the midplane of the sandwich panels and/or symmetric concerning the midplane of the face-sheets depending on the number of layers N_l and fiber orientation θ°. The models of sandwich plates were solved theoretically using the Excel Solver program and Matlab program to calculate the optimum face-sheet thickness $t_{f,opt}$, optimum core thickness $t_{c,opt}$, minimum weight $W_{min,t}$ and/or minimum cost $C_{min,t}$. The objective functions were the total weight and/or the honeycomb sandwich panel's total material cost. The design constraints were taking into consideration as follows: total stiffness (bending and shear stiffnesses), full deflection (bending and shear deflections), facing skin stress (bending load), core shear stress, facing skin stress (end loading), overall panel buckling (critical bending buckling load and critical shear buckling load), shear crimping load, skin wrinkling (critical stress and critical load) and intracell buckling as well as the size constraint for design variables. According to classical lamination theory and ply failure calculation, the mechanical properties of composite laminate face-sheets are calculated using the Laminator program dependent on Tsai-Hill failure criteria. The theoretical results consist of three main cases depending on face-sheets types of the honeycomb sandwich plates with a different number of layers N_l and fiber orientations θ° were presented.

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 (27.0852 kg, 702.5157 €, and 0.6 mm 24.29992 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 core thickness ensure the minimum weight and/or cost are (0.8194 mm, 49.6609 mm, 60.64778 kg, and 536.303 €), respectively. This optimal sandwich plate provides (24.2 %) weight saving compared to the conventional aluminum single base plate pallet (80 kg). The epoxy woven carbon fiber having higher stiffness to weight ratio compared to epoxy woven glass fiber. The epoxy woven glass fiber has a higher strength to weight ratio and more flexible than epoxy woven carbon fiber. The results give good agreement between the Excel Solver program and Matlab program and between Interior Point Algorithm methods with GRG Nonlinear Algorithm and Genetic Algorithm Solver with Weighted Normalized Method.

6. OPTIMUM DESIGN FOR SOLAR SANDWICH PANELS OF SATELLITE

6.1. Introduction (Solar Sandwich Panel of Satellite)

The sandwich structures are often utilized in solar panel applications. A sandwich structure consists of two thin face-sheets bonded to both sides of a lightweight core. The sandwich structures' design allows the outer face-sheets to carry the axial loads, bending moments, and in-plane shears, while the honeycomb core carries the normal flexural shears. The sandwich structures are susceptible to failures due to large normal local stress concentrations because of the heterogeneous nature of the core/ face-sheet assembly. Therefore, component mounting must employ potted inserts to distribute the point loads from connections. The sandwich panel face-sheets are usually manufactured using aluminum alloy or composite material. The core is typically manufactured using a honeycomb or aluminum foam construction [1].

6.2. Optimization Method (Solar Sandwich Panel of Satellite)

In this study, the optimum design of solar sandwich panels for microsatellite applications was verified. The mathematical modeling for the optimization processes as described in chapter 3. The Equations (3.1-3.3) indicate weight objective function and cost objective function, Equations (3.4-3.6) indicate design variables of face-sheet thickness and honeycomb core thickness and Equations (3.12-3.45) indicate design constraints. The satellite sandwich panel is simply supported and has face-sheets from aluminum or composite material with an aluminum honeycomb core. The sandwich panel is subjected to a uniform pressure (p=50 kPa) and deforms (δ_{max}= 2 mm) at any point of the sandwich panel. The optimum face-sheet thickness and core thickness for a minimum weight and/or cost design are calculated. The upper and lower face-sheets are assumed to have the same thickness. The satellite sandwich panel's technical data and boundary conditions are shown in Table 6.1 & 6.2 and Figures 6.1 & 6.2 [2].

Table 6.1: Technical data of the satellite solar sandwich panels [2].

Length	Width	Deflection	Load	Pressure
l	b	δ_{max}	P	p
mm	mm	mm	kN	kPa
700	400	2	14	50

Table 6.2: Boundary conditions and constant design parameters for simply supported satellite solar sandwich panel [42].

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

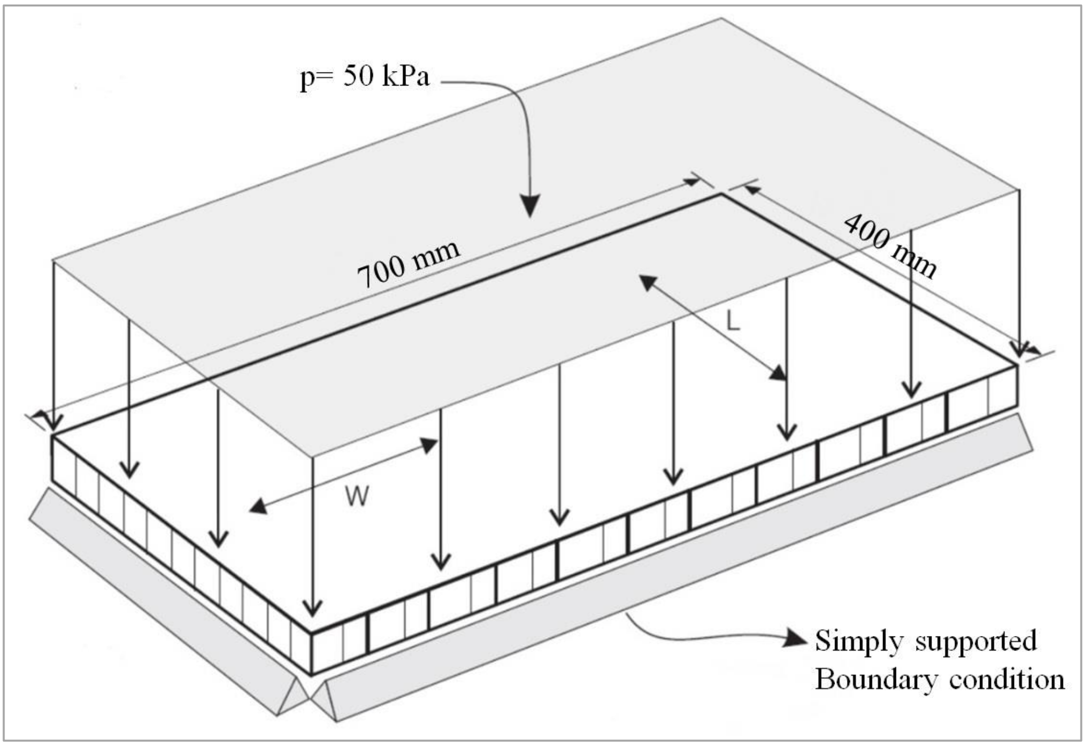


Figure 6.1: Honeycomb sandwich panel with simply supported boundary conditions on all four sides with a uniformly distributed load of (p =50 kPa) applied on the upper face-sheet.

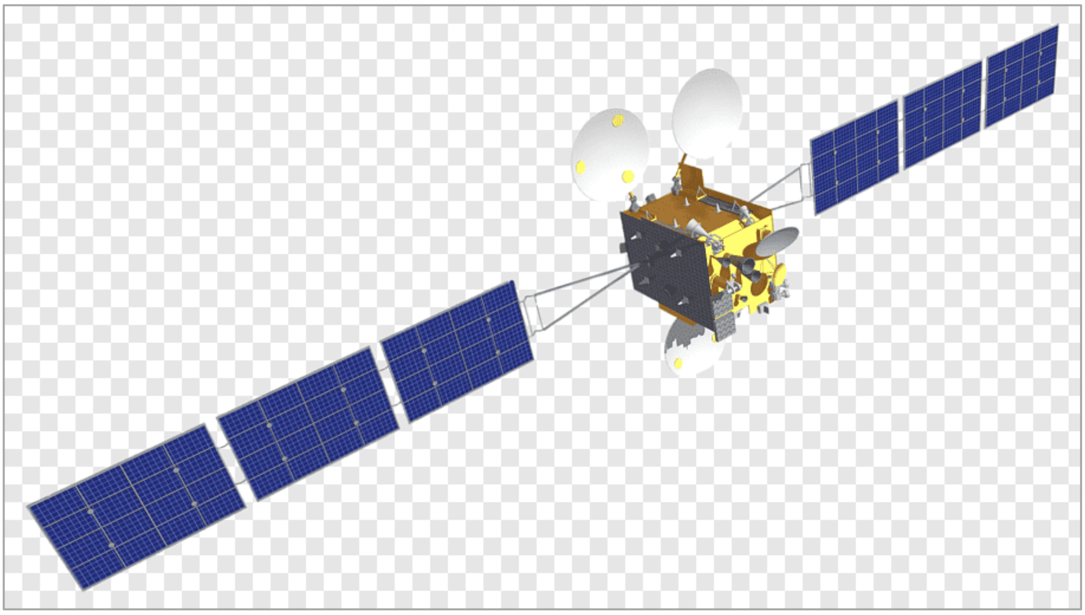


Figure 6.2: Satellite panels structure (ultra-high stiffness and strength per unit weight).

6.3. Optimization Results for Satellite Solar Sandwich Panels

The final optimization results of solar sandwich panels 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.

6.3.1. Optimization of Single-objective Function (Solar Sandwich Panels)

The single-objective function was considered to minimize the weight objective function or cost objective function of solar sandwich panels separately obtained by applying the Excel Solver program (GRG Nonlinear Algorithm) and the Matlab program (fmincon Solver Constrained Nonlinear Minimization / Interior Point Algorithm).

– ***Minimizing the Single-objective Function for Solar Sandwich Panels of Satellite with Aluminum Alloy Face-sheets***

The optimum results of single-objective function (weight or cost) for aluminum alloy face-sheets of solar sandwich panel obtained by applying the Excel Solver program (GRG Nonlinear Algorithm) are shown in Tables 6.3 & 6.4, and the Matlab program (Interior Point Algorithm) are shown in Tables 6.5 & 6.6.

Table 6.3: Minimize the weight objective function with disregard cost objective function using the Excel Solver program (GRG Nonlinear Algorithm) for honeycomb sandwich solar panels of satellite, in which the face-sheets are of aluminum alloy.

W_{min}	$t_{f,opt}$	$t_{c,opt}$
kg	mm	mm
2.293473661	0.487460114	66.97220177

Table 6.4: Minimize the cost objective function with disregard weight objective function using the Excel Solver program (GRG Nonlinear Algorithm) for honeycomb sandwich solar panels of satellite, in which the face-sheets are of aluminum alloy.

C_{min}	$t_{f,opt}$	$t_{c,opt}$
kg	mm	mm
21.65734	1.025124	46.64538

Table 6.5: Minimize weight objective function with disregard cost objective function using the Matlab program (Interior Point Algorithm) for honeycomb sandwich solar panels of satellite, in which the face-sheets are of aluminum alloy.

W_{min}	$t_{f,opt}$	$t_{c,opt}$
kg	mm	mm
2.23973	0.505007	63.51806

Table 6.6: Minimize cost objective function with disregard weight objective function using the Matlab program (Interior Point Algorithm) for honeycomb sandwich solar panels of satellite, in which the face-sheets are of aluminum alloy.

C_{min}	$t_{f,opt}$	$t_{c,opt}$
kg	mm	mm
21.6589	1.025687	46.63779

– ***Minimizing the Single-objective Function for Honeycomb Sandwich Solar Panels of Satellite with Composite Material Face-sheets***

The optimum results of single-objective function (weight or cost) for composite material face-sheets, honeycomb solar sandwich panels of satellite applying the Excel Solver program are shown in Tables 6.7 & 6.8, and the Matlab program (fmincon Solver Constrained Nonlinear Minimization/Interior Point Algorithm) are shown in Tables 6.9 & 6.10 (see Appendix A3).

Table 6.7: Minimum weight objective function with optimum face-sheet thickness and core thickness using the Excel Solver program for solar sandwich panels of satellite application consists of an aluminum honeycomb core and composite face-sheets 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 with fiber orientations θ°		kg	mm	mm
4 (0°, 90°, 90°, 0°) Optimum value		3.184675	1	91.73301

Type	**B. Epoxy woven carbon fiber face-sheets**	W_{min}	$t_{f,opt}$	$t_{c,opt}$
Number of layers N_l with fiber orientations θ°		kg	mm	mm
2 (+45°, -45°) Optimum value		1.807572	0.6	56.09174

Type	**C. Hybrid composite face-sheets**	W_{min}	$t_{f,opt}$	$t_{c,opt}$
Number of layers N_l with fiber orientations θ°		kg	mm	mm
4 (0°, 90°, +45°, -45°) Optimum value		2.364577	1.1	57.40863

Table 6.8: Minimum cost objective function with optimum face-sheet thickness and core thickness using the Excel Solver program (GRG Nonlinear Algorithm) for solar sandwich panels of satellite application consists of an aluminum honeycomb core and orthotropic composite face-sheets 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 with fiber orientations θ°		kg	mm	mm
4 (0°, 90°, 90°, 0°) Optimum value		33.80315	1	91.73301

Type	**B. Epoxy woven carbon fiber face-sheets**	C_{min}	$t_{f,opt}$	$t_{c,opt}$
Number of layers N_l with fiber orientations θ°		kg	mm	mm
2 (+45°, -45°) Optimum value		37.61076	0.6	56.09174

Type	C. Hybrid composite face-sheets	C_{min}	$t_{f,opt}$	$t_{c,opt}$
Number of layers N_l with fiber orientations θ°		kg	mm	mm
4 (0°, 90°, +45°, -45°) Optimum value		40.65246	1.1	57.40863

Table 6.9: Minimum weight objective function with optimum face-sheet thickness and core thickness using the Matlab program (Interior Point Algorithm) for solar sandwich panels of satellite application consists of an aluminum honeycomb core and orthotropic composite face-sheets 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 with fiber orientations θ°		kg	mm	mm
4 (0°, 90°, 90°, 0°) Optimum value		3.18261	1	91.64416

Type	B. Epoxy woven carbon fiber face-sheets	W_{min}	$t_{f,opt}$	$t_{c,opt}$
Number of layers N_l with fiber orientations θ°		kg	mm	mm
2 (+45°, -45°) Optimum value		1.776369	0.6	54.74912

Type	C. Hybrid composite face-sheets	W_{min}	$t_{f,opt}$	$t_{c,opt}$
Number of layers N_l with fiber orientations θ°		kg	mm	mm
4 (0°, 90°, +45°, -45°) Optimum value		2.338986	1.1	56.3075

Table 6.10: Minimum cost objective function with optimum face-sheet thickness and core thickness using the Matlab program (Interior Point Algorithm) for solar sandwich panels of satellite application 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	C_{min}	$t_{f,opt}$	$t_{c,opt}$
Number of layers N_l with fiber orientations θ°		kg	mm	mm
4 (0°, 90°, 90°, 0°) Optimum value		33.23378	1	89.90286

Type	B. Epoxy woven carbon fiber face-sheets	C_{min}	$t_{f,opt}$	$t_{c,opt}$
Number of layers N_l with fiber orientations θ°		kg	mm	mm
2 (+45°, -45°) Optimum value		37.02625	0.6	54.21296

Type	C. Hybrid composite face-sheets	C_{min}	$t_{f,opt}$	$t_{c,opt}$
Number of layers N_l with fiber orientations θ°		kg	mm	mm
4 (0°, 90°, +45°, -45°) Optimum value		40.18863	1.1	55.91774

6.3.2. Optimization of Multi-objective Functions (Solar Sandwich Panels)

The multi-objective functions were considered to minimize the weight objective function and cost objective function for honeycomb sandwich solar panels of satellite simultaneously obtained by applying the Excel Solver program (Weighted Normalized Method) and the Matlab program (Multi-objective Genetic Algorithm Solver) for aluminum alloy face-sheets and composite material face-sheets.

– ***Minimizing Multi-objective Functions for Solar Sandwich Panel of Satellite with Aluminum Alloy Face-sheets.***

The optimum results of multi-objective function (weight and cost) for aluminum alloy face-sheets of honeycomb sandwich solar panels of satellite obtained by applying the Excel Solver program (Weighted Normalized Method) are shown in Table 6.11 and Figures 6.3, 6.4 & 6.5 and the Matlab program (Multi-objective Genetic Algorithm Solver) are shown in Table 6.12 and Figure 6.6. W_1 and W_2 are the weights of weight objective function and cost objective function in percentage (%), respectively.

Table 6.11: Minimize the weight and the cost of multi-objective functions using the Excel Solver program (Weighted Normalized Method) for honeycomb sandwich solar panels of satellite, in which the face-sheets are of aluminum alloy.

Type	**Aluminum Alloy (5251 H24)**		W_{min}	C_{min}	$t_{f,opt}$	$t_{c,opt}$
No.	W_1 (%)	W_2 (%)	kg	€	mm	mm
1	50	50	2.3575184	22.428431	0.688089	56.675031
2	60	40	2.3335075	22.701801	0.643268	58.557914
3	70	30	2.3134871	23.055143	0.596447	60.742672
4	80	20	2.3030815	23.351422	0.563624	62.430378
5	90	10	2.2956145	23.740916	0.526742	64.508660

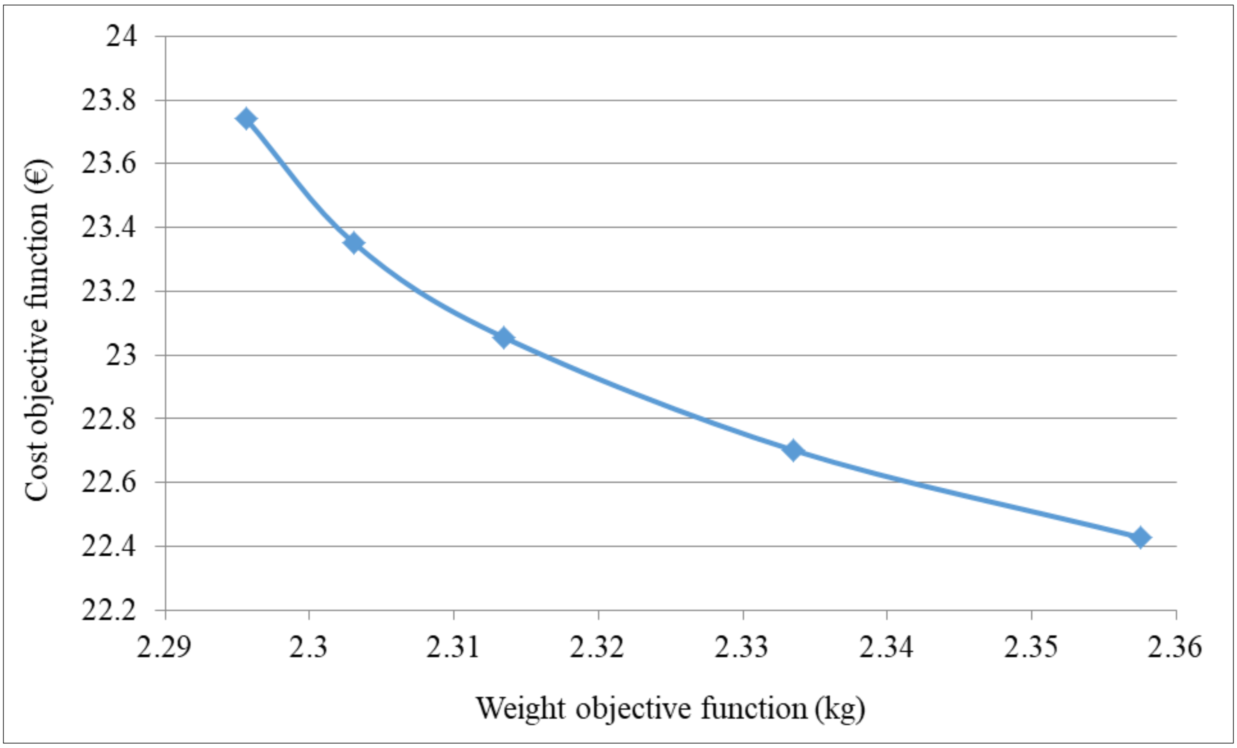


Figure 6.3: Compromise between multi-objective functions weight and cost using the Excel Solver program (Weighted Normalized Method) for honeycomb sandwich satellite panel, face-sheets are of aluminum alloy.

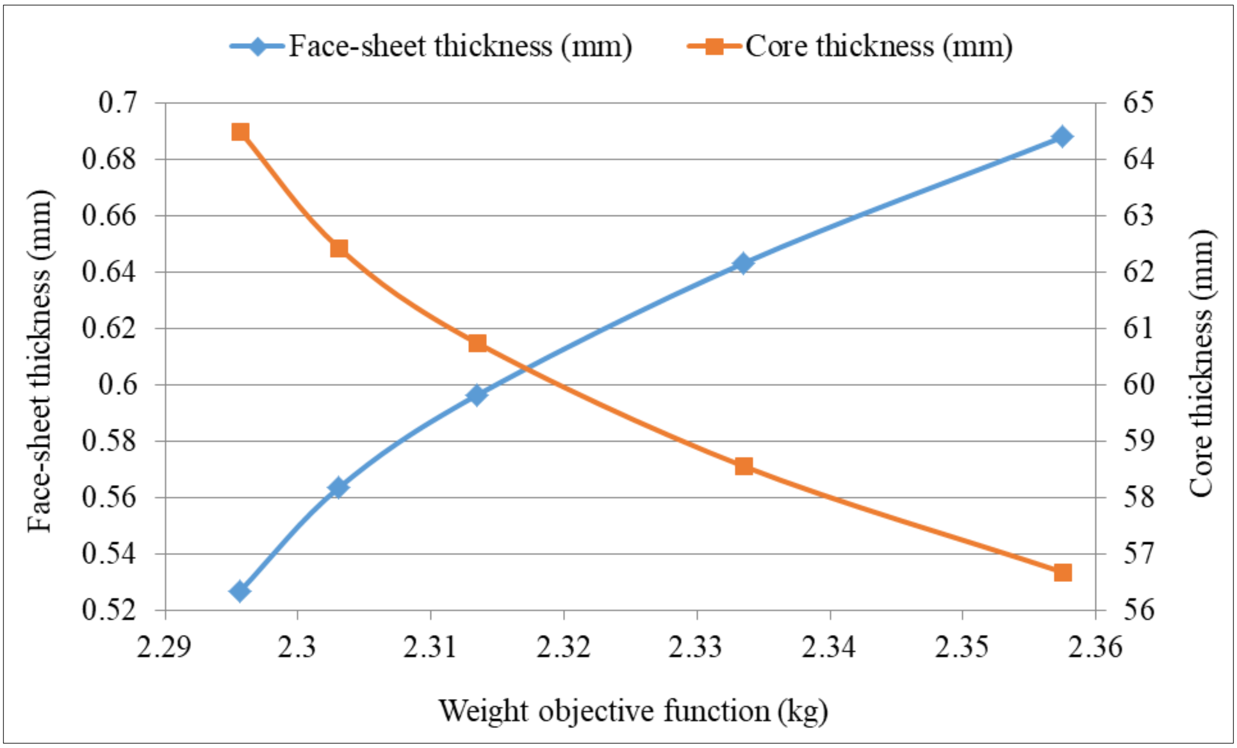


Figure 6.4: Minimum weight objective function versus optimum face-sheet and core thicknesses using the Excel Solver program (Weighted Normalized Method) for the sandwich panel of satellite consists of an aluminum honeycomb core and aluminum face-sheets.

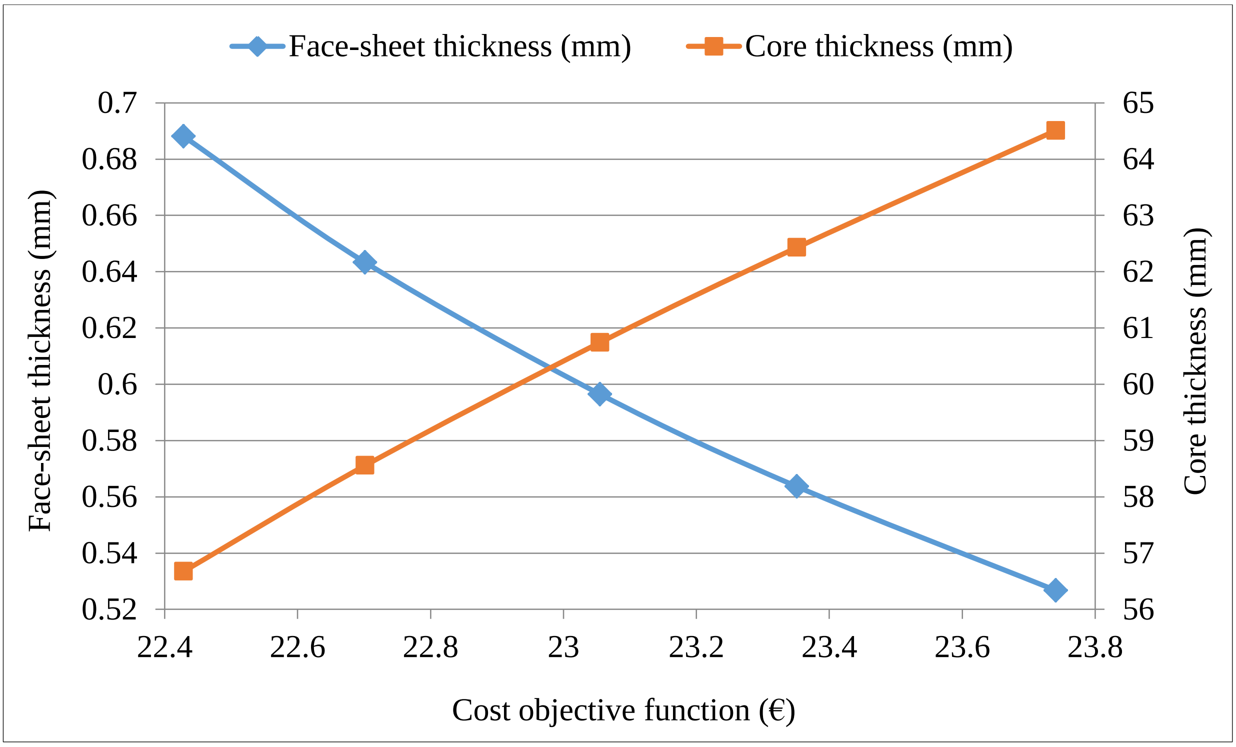


Figure 6.5: Minimum cost objective function versus optimum face-sheet and core thicknesses using the Excel Solver program (Weighted Normalized Method) for the sandwich panel of satellite consists of an aluminum honeycomb core and aluminum face-sheets.

Table 6.12: Minimize weight objective function and cost objective function simultaneously using Matlab program (Multi-objective Genetic Algorithm Solver) for honeycomb sandwich base plate of air cargo container consisting of aluminum honeycomb core and aluminum face-sheets.

Index	W_{min}	C_{min}	$t_{f,opt}$	$t_{c,opt}$
	kg	€	mm	mm
1	**2.213722**	22.561573	**0.5330**	60.5777
2	2.21767	22.5198278	0.5401	60.2838
3	2.225761	22.0990166	0.5800	58.0379
4	2.375451	**20.7545828**	0.8323	**48.0636**
5	2.243922	21.9433244	0.6101	56.8641
6	2.365845	20.8395664	0.8162	48.6973
7	2.281312	21.3681759	0.6911	53.1994
8	2.218824	22.3005114	0.5578	59.1825
9	2.308381	21.0991162	0.7387	51.2685
10	2.263419	21.4345405	0.6681	53.9291
11	2.3159	21.0257705	0.7518	50.7390
12	2.375451	20.7545828	0.8323	48.0636
13	2.251073	21.6858396	0.6367	55.4402
14	2.213722	22.561573	0.5330	60.5777
15	2.34405	20.8691365	0.7920	49.3349
16	2.257304	21.5090363	0.6563	54.4326
17	2.290992	21.178749	0.7151	52.0519
18	2.337654	20.9283943	0.7811	49.7700

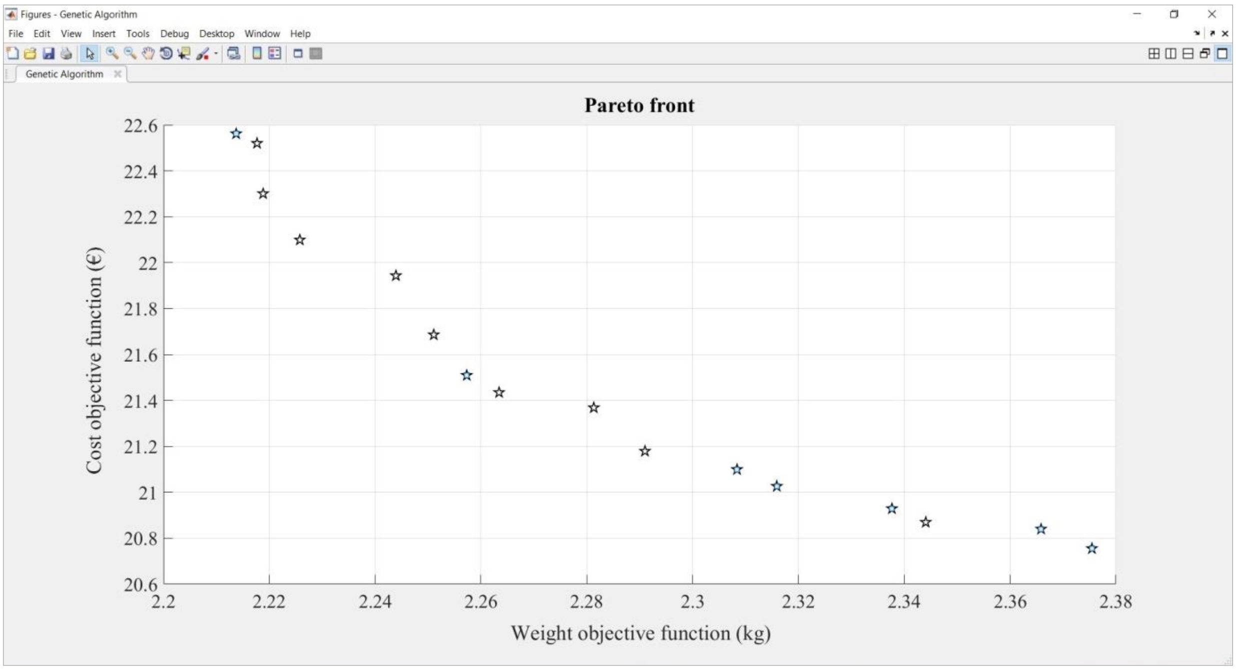


Figure 6.6: Pareto front set for multi-objective functions (weight and cost) using the Matlab program (Genetic Algorithm Solver) for solar sandwich panels of satellite consists of an aluminum honeycomb core and aluminum face-sheets.

– ***Minimizing Multi-objective Functions for Solar Sandwich Panel of Satellite with Composite Material Face-sheets.***

The optimum results of multi-objective function (weight and cost) for composite material face-sheets, honeycomb sandwich solar panel of satellite, obtained by applying the Excel Solver program are shown in Table 6.13, and the Matlab program (Multi-objective Genetic Algorithm Solver) are shown in Table 6.14 (see Appendix A3), and Figures 6.7 & 6.8.

Table 6.13: Minimum weight and cost multi-objective functions with optimum face-sheet thickness and core thickness using the Excel Solver program (Weighted Normalized Method) for solar sandwich panels of satellite application consists of an aluminum honeycomb core and orthotropic composite face-sheets 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}	C_{min}	$t_{f,opt}$	$t_{c,opt}$
Number of layers N_l with fiber orientations θ°		kg	€	mm	mm
4 (0°, 90°, 90°, 0°) Optimum value		3.184675	33.80315	1	91.73301

Type	**B. Epoxy woven carbon fiber face-sheets**	W_{min}	C_{min}	$t_{f,opt}$	$t_{c,opt}$
Number of layers N_l with fiber orientations θ°		kg	€	mm	mm
2 (+45°, -45°) Optimum value		1.807572	37.61076	0.6	56.09174

Type	**C. Hybrid composite face-sheets**	W_{min}	C_{min}	$t_{f,opt}$	$t_{c,opt}$
Number of layers N_l with fiber orientations θ°		kg	€	mm	mm
4 (0°, 90°, +45°, -45°) Optimum value		2.364577	40.65246	1.1	57.40863

Table 6.14: Minimum weight and cost multi-objective function with optimum face-sheet thickness and core thickness using the Matlab program (Genetic Algorithm Solver) for solar sandwich panels of satellite application 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}	C_{min}	$t_{f,opt}$	$t_{c,opt}$
Number of layers N_l with fiber orientations θ°		kg	€	mm	mm
4 (0°, 90°, 90°, 0°) Optimum value		3.13540	33.1435	1	89.61253

Type	**B. Epoxy woven carbon fiber face-sheets**	W_{min}	C_{min}	$t_{f,opt}$	$t_{c,opt}$
Number of layers N_l with fiber orientations θ°		kg	€	mm	mm
2 (+45°, -45°) Optimum value		1.760318	36.97817	0.6	54.05842

Type	**C. Hybrid composite face-sheets**	W_{min}	C_{min}	$t_{f,opt}$	$t_{c,opt}$
Number of layers N_l with fiber orientations θ°		kg	€	mm	mm
4 (0°, 90°, +45°, -45°) Optimum value		2.317042	40.01612	1.1	55.36324

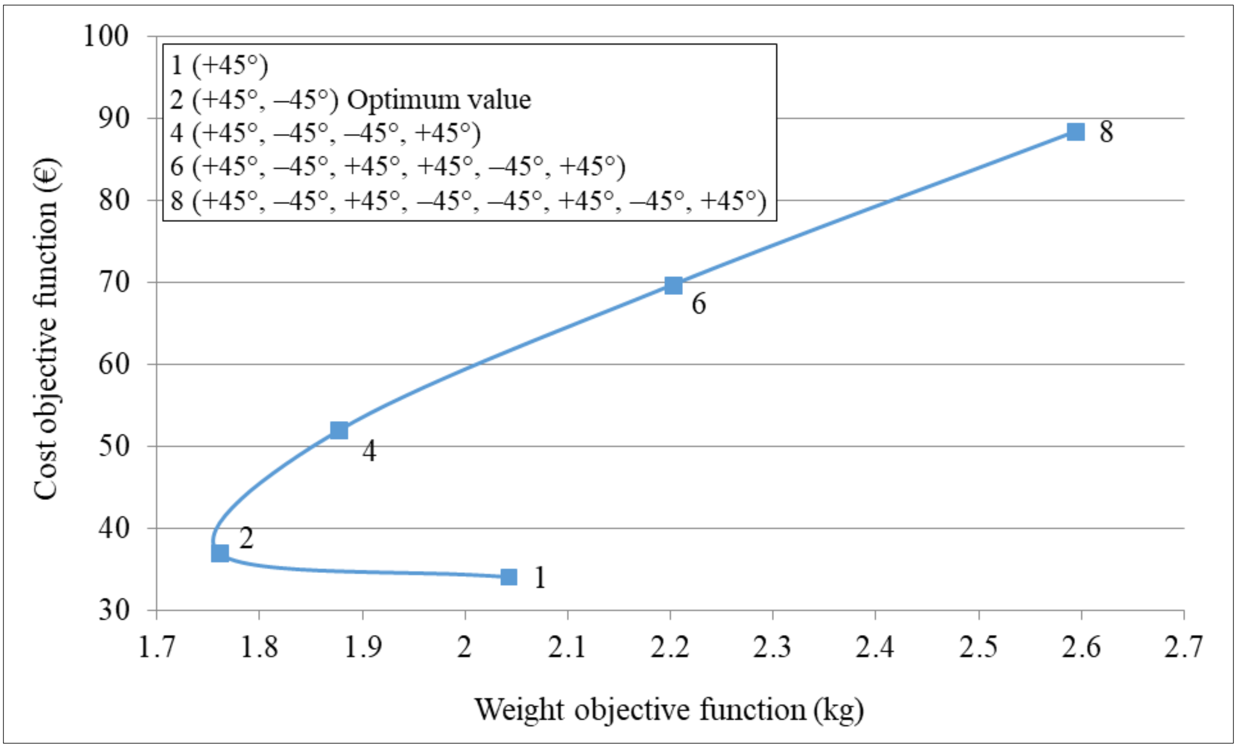


Figure 6.7(a): Minimum weight versus minimum cost objective function using the Matlab program (Genetic Algorithm Solver) for solar sandwich panels of satellite application consisting of an aluminum honeycomb core and epoxy woven carbon fiber composite face-sheets with a different number of layers N_l and angle-ply fiber orientation θ°.

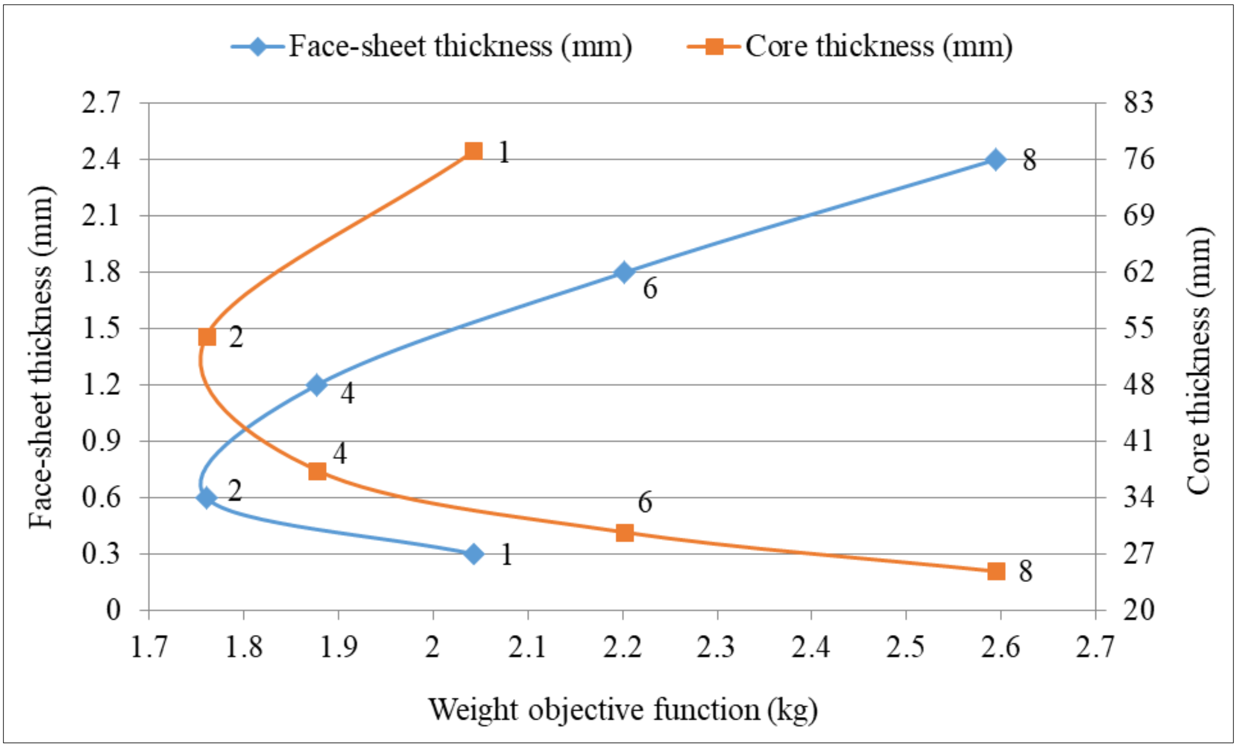


Figure 6.7(b): Minimum weight objective function versus optimum face-sheet and core thicknesses using the Matlab program (Genetic Algorithm Solver) for solar sandwich panels of satellite application consisting of an aluminum honeycomb core and epoxy woven carbon fiber face-sheets with a different number of layers N_l and angle-ply fiber orientation θ°.

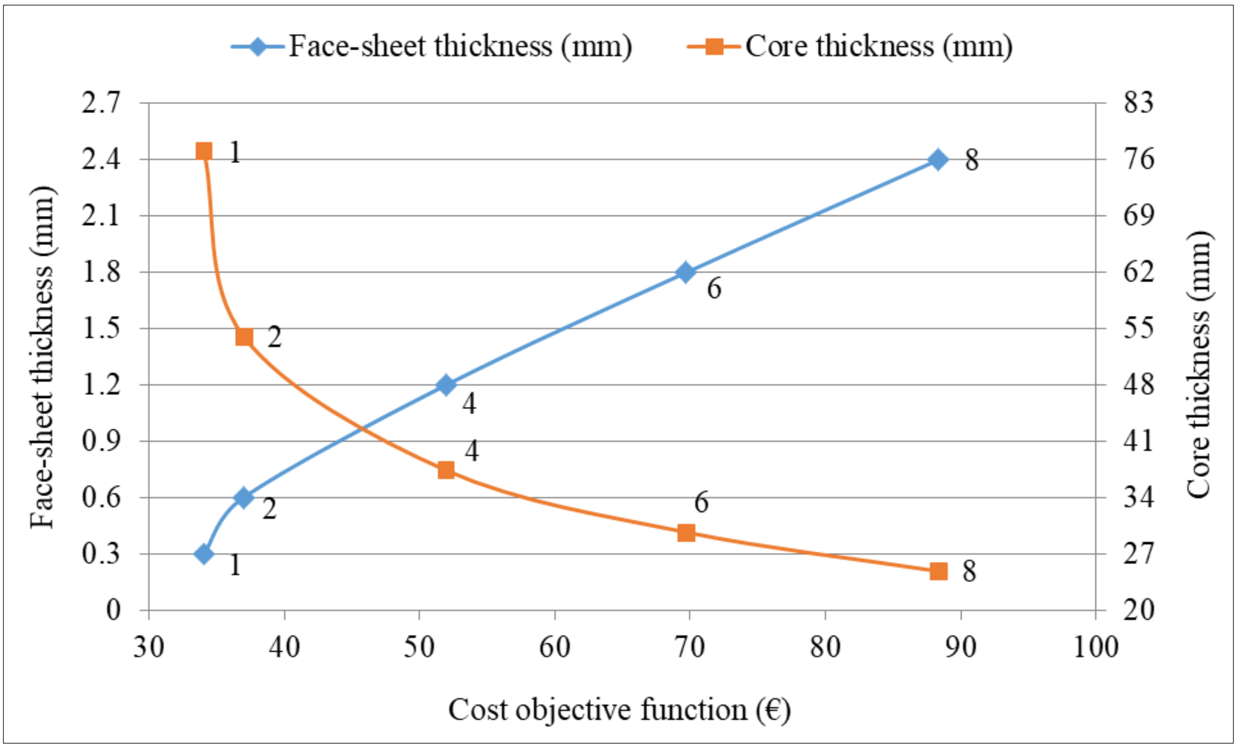


Figure 6.7(c): Minimum cost objective function versus optimum face-sheet and core thicknesses using the Matlab program (Genetic Algorithm Solver) for solar sandwich panels of satellite application consisting of an aluminum honeycomb core and epoxy woven carbon fiber face-sheets with a different number of layers N_l and angle-ply fiber orientation θ°.

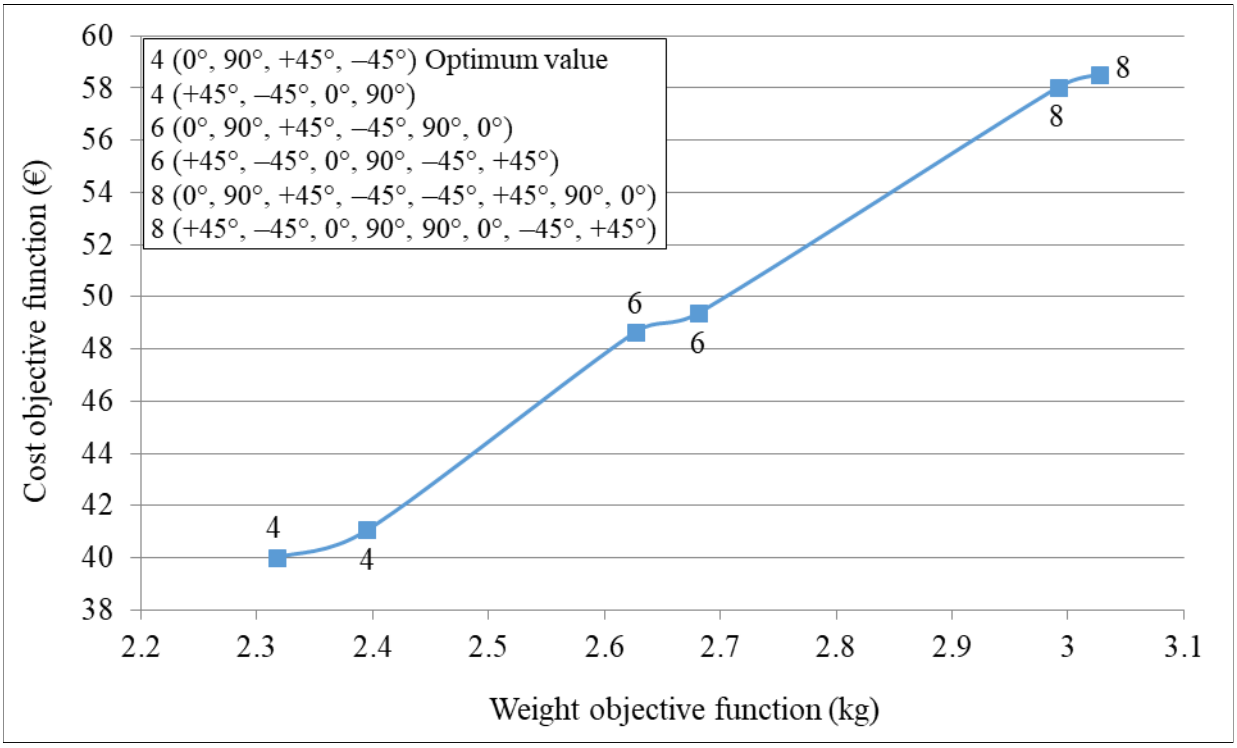


Figure 6.8(a): Minimum weight versus minimum cost objective function using Matlab program (Genetic Algorithm Solver) for solar sandwich panels of satellite application consisting of an aluminum honeycomb core and hybrid composite face-sheets with a different number of layers N_l and different fiber orientation θ° (multidirectional).

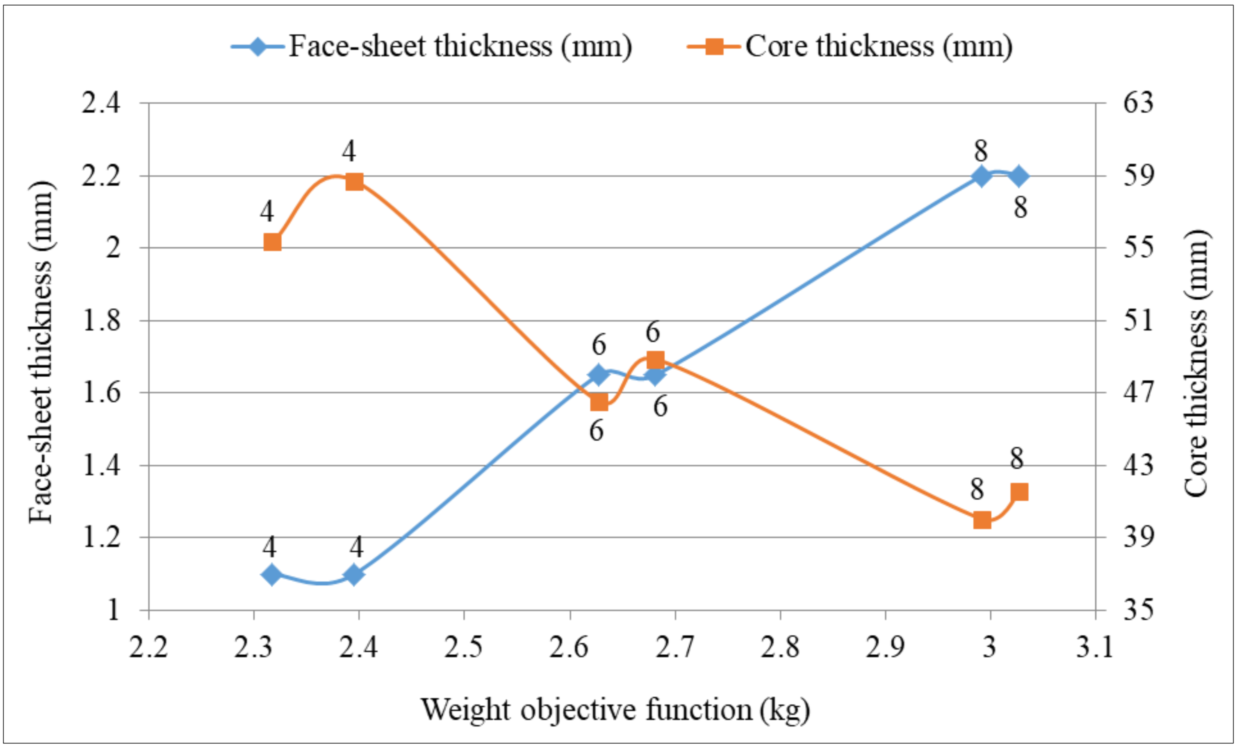


Figure 6.8(b): Minimum weight objective function versus optimum face-sheet and core thicknesses using the Matlab program (Genetic Algorithm Solver) for solar sandwich panels of satellite application consisting of an aluminum honeycomb core and hybrid composite face-sheets with a different number of layers N_l and different fiber orientation θ° (multidirectional).

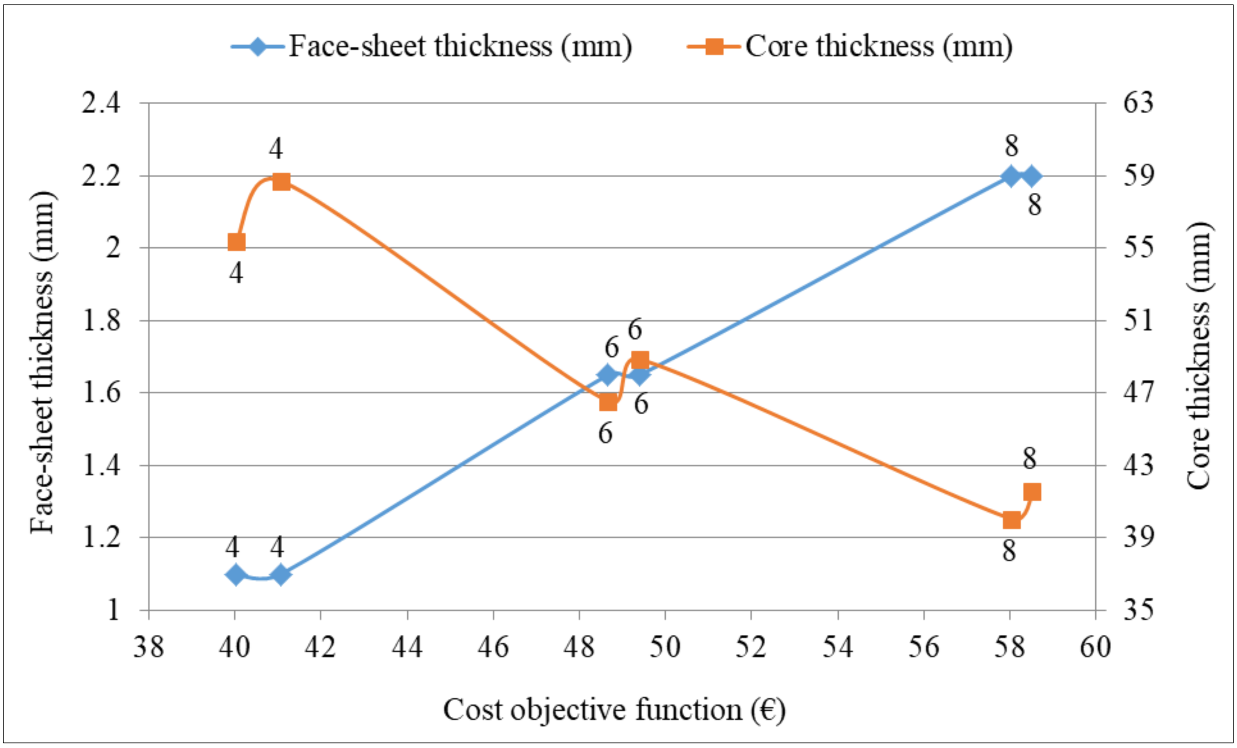


Figure 6.8(c): Minimum cost objective function versus optimum face-sheet and core thicknesses using the Matlab program (Genetic Algorithm Solver) for solar sandwich panels of satellite application consisting of an aluminum honeycomb core and hybrid composite face-sheets with a different number of layers N_l and different fiber orientation θ° (multidirectional).

6.4. Discussions (Solar Sandwich Panels)

This study aimed to design a lightweight sandwich panel, which can be applied in the industry of a satellite application because the solar panels of a satellite requires several holes for connection, installation, and fixing. The honeycomb sandwich panel model for satellite consists of an aluminum honeycomb core, and different types of face-sheets include aluminum alloy and composite material. The composite material face-sheets included 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 with sets of fiber orientations including cross-ply (0°, 90°) and/or angle-ply (±45°). The laminated composite panels were symmetric concerning the midplane of the sandwich panels and/or symmetric concerning the midplane of the face-sheets depending on the number of layers N_l and fiber orientation θ°.

The models of sandwich panels were solved theoretically using the Excel Solver program and Matlab program to calculate the optimum face-sheet thickness $t_{f,opt}$, optimum core thickness $t_{c,opt}$, minimum weight W_{min} and/or minimum cost C_{min}. The objective functions were the total weight and/or the honeycomb sandwich panel's total material cost. The design constraints were taking into consideration as follows: total stiffness (bending and shear stiffnesses), full deflection (bending and shear deflections), facing skin stress (bending load), core shear stress, facing skin stress (end loading), overall panel buckling (critical bending buckling load and critical shear buckling load), shear crimping load, skin wrinkling (critical stress and critical load) and intracell buckling as well as the size constraint for design variables. According to classical lamination theory and ply failure calculation, the mechanical properties of composite laminate face-sheets are calculated using the Laminator program dependent on Tsai-Hill failure criteria. Every face-sheet is composed of (1, 2, 4, 6, and 8) layers. The theoretical results consist of three main cases depending on face-sheets types of the honeycomb sandwich panels with a different number of layers N_l and fiber orientations θ° were presented.

In case of aluminum alloy face-sheets of honeycomb solar sandwich panels: for single-objective function using the Excel Solver program (GRG Nonlinear Algorithm), the optimum solar sandwich panels of a satellite which ensuring the minimum weight is (2.2934 kg), with optimum aluminum face-sheet thickness and optimum core thickness are (0.4874 mm, 66.9722 mm), respectively, as well as the optimum solar sandwich panels of a satellite which ensuring the minimum cost is (21.6573 €) with optimum aluminum face-sheet thickness and optimum core thickness are (1.0251 mm, 46.6453 mm), respectively.

Whereas, for single-objective function using the Matlab Program (fmincon Solver Constrained Nonlinear Minimization / Interior Point Algorithm), the optimum solar sandwich panels of a satellite which ensuring the minimum weight is (2.2397 kg) with optimal thickness of aluminum face-sheet and optimal honeycomb core thickness are (0.505 mm, 63.518 mm), respectively, as well as the optimum solar sandwich panels of satellite which ensuring the minimum cost is (21.6589 €) with an optimum thickness of aluminum face-sheet and optimum honeycomb core thickness are (1.02568 mm, 46.6377 mm), respectively.

As, for multi-objective functions using the Excel Solver Program (Weighted Normalized Method), the optimum solar sandwich panels of a satellite which ensuring the minimum weight and minimum cost are (2.3575 kg, 22.4284 €), respectively, with optimum thicknesses of aluminum face-sheet and optimum thicknesses of honeycomb core are (0.688 mm, 56.675 mm), respectively.

Whereas, for multi-objective functions using the Matlab Program (Multi-objective Genetic Algorithm Solver), the optimum solar sandwich panels of a satellite which ensuring the minimum weight is (2.2137 kg) with the cost is (22.5615 €), and the optimal thicknesses of aluminum face-sheet and honeycomb core are (0.533 mm, 60.5777 mm), respectively. The minimum cost is (20.7545 €) with weight is (2.37545 kg), and the optimal thickness of aluminum face-sheet and honeycomb core are (0.8323 mm and 48.0636 mm), respectively.

In case of composite material face-sheets of honeycomb solar sandwich panels, the optimum face-sheet thickness and core thickness which ensures the minimum weight and/or cost are four layers with cross-ply fiber orientation (0°, 90°, 90°, 0°) for epoxy woven glass fiber face-sheets, two layers with fiber orientation angle-ply (±45°) for epoxy woven carbon fiber face-sheets and four layers with fiber orientation multidirectioal cross-ply and angle-ply (0°, 90°, +45°, -45°) for hybrid composite layers face-sheets (a combination of epoxy woven glass fiber layers and epoxy woven carbon fiber layers). For single-objective function using the Excel Solver program (GRG Nonlinear Algorithm), the optimum solar sandwich panels of satellite with composite material face-sheet (epoxy woven carbon fiber) which ensuring the minimum weight are (1.807572 kg), with optimum face-sheet thickness and honeycomb core thickness are (0.6 mm, 56.09174 mm), respectively. The minimum cost is (37.61076 €) with optimum face-sheet thickness and honeycomb core thickness are (0.6 mm, 56.09174 mm), respectively. Whereas, for single-objective function using the Matlab Program (fmincon Solver Constrained Nonlinear Minimization/Interior Point Algorithm), the optimum solar sandwich panels of a satellite which ensuring the minimum weight is (1.776369 kg) with optimal thickness of composite face-sheet and thickness of honeycomb core are (0.6 mm, 54.74912 mm), respectively. The minimum cost is (37.02625 €) with an optimum thickness of composite face-sheet, and honeycomb core thickness are (0.6 mm, 54.21296 mm), respectively.

As for multi-objective functions using the Excel Solver Program (Weighted Normalized Method), the optimum solar sandwich panels of satellite with composite material face-sheet (epoxy woven carbon fiber), which ensures the minimum weight and cost are (1.807572 kg, 37.61076 €), respectively, with an optimum thickness of composite face-sheet and honeycomb core thickness are (0.6 mm, 56.09174 mm), respectively. Whereas, for multi-objective functions using the Matlab Program (Multi-objective Genetic Algorithm Solver), the optimum solar sandwich panels of satellite which ensuring the minimum weight and minimum cost are (1.760318 kg, 36.97817 €), respectively, with optimum face-sheet thickness and honeycomb core thickness are (0.6 mm, 54.05842 mm), respectively. The epoxy woven carbon fiber having higher stiffness to weight ratio compared to epoxy woven glass fiber. The epoxy woven glass fiber has a higher strength to weight ratio and more flexible than epoxy woven carbon fiber. The results give good agreement between Excel Solver program and Matlab program as well as between two methods (Interior Point Algorithm and Genetic Algorithm Solver) as well as (GRG Nonlinear Algorithm and Weighted Normalized Method), about (2.343%) for single-objective function and (6.1%) for multi-objective functions in case of aluminum face-sheets and (1.726%) for single-objective function and (2.614%) for multi-objective functions in case of composite face-sheets.

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

7.1. Introduction

The study aimed to make a comparison of mechanical behavior between numerical models for honeycomb sandwich panels. The numerical models included a four-point bending test using the Digimat-HC program to calculate the mean vertical displacement at mid-section, equivalent skin stress, and equivalent core shear stress. 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 symmetric concerning the midplane of the sandwich panels and/or symmetric concerning the midplane of the face-sheets. 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 of cross-ply (0°, 90°) and angle-ply (±45°).

7.2. Numerical Models of Honeycomb Sandwich Panels by Digimat-HC Program

The numerical models included a four-point bending test using the Digimat-HC program. The technical data and configuration of honeycomb sandwich panels are given and shown in Table 7.1 and Figure 7.1. 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 Tables 7.2-7.6, and Figures 7.2-7.9. 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 chapter 3, Tables 3.1 & 3.2. 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. So, the graph lines for these types of face-sheets are identical, named as (phenolic/epoxy woven glass fiber face-sheet).

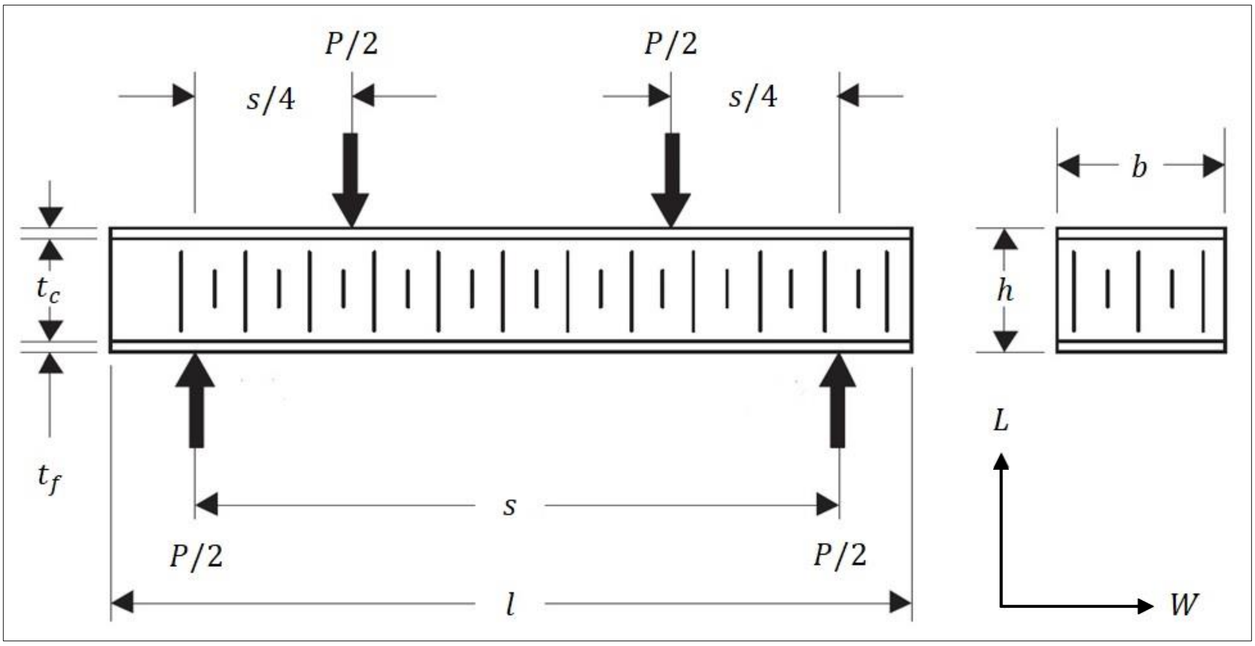


Figure 7.1: Set up and configuration of the honeycomb sandwich structure for a four-point bending test by applying the Digimat-HC program [42].

Table 7.1: Technical data of honeycomb sandwich models for Digimat-HC program.

Index	Length	Span	Width	Core thickness	Face-sheet thickness	Load
	l	s	b	t_c	t_f	P
	mm	mm	mm	mm	mm	N
1	460	400	100	15	1	1400
2				19	2	1950

Table 7.2: 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 t_c=19 mm) and aluminum alloy (5251 H24) face-sheets.

Type	**Aluminum Alloy (5251 H24) Face-sheets**	δ_{Num}	σ_{skin}	τ_{core}	t_f
No.		mm	MPa	MPa	mm
1	(t_c=15 mm)	7.515	91.3	0.8	0.5
2		5.481	44.1	0.765	1
3		4.562	28.3	0.715	1.5
4		3.958	20.5	0.642	2
5	(t_c=19 mm)	7.718	102	0.909	0.5
6		5.919	49.3	0.852	1
7		5.082	31.9	0.811	1.5
8		4.518	23.3	0.742	2

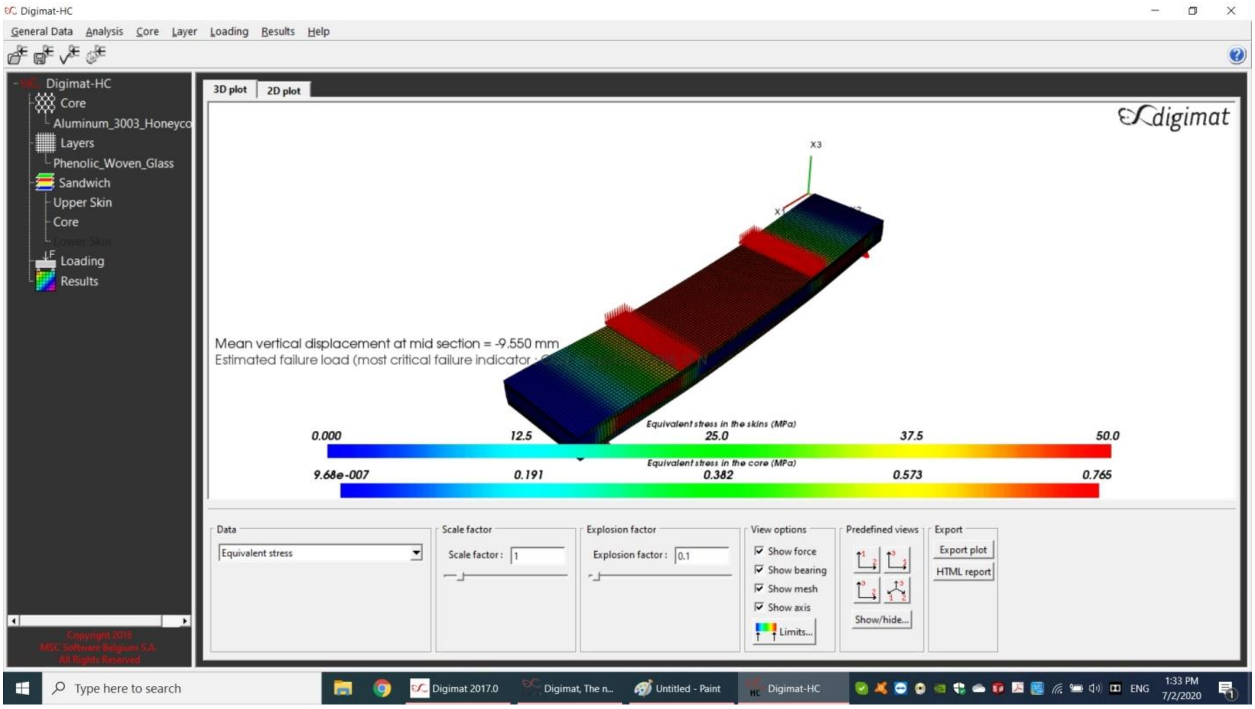


Figure 7.2: Numerical result (four-point bending test) for a model of the sandwich panel consists of an aluminum honeycomb core (t_c=15 mm) and phenolic woven glass face-sheets (t_f= 1 mm).

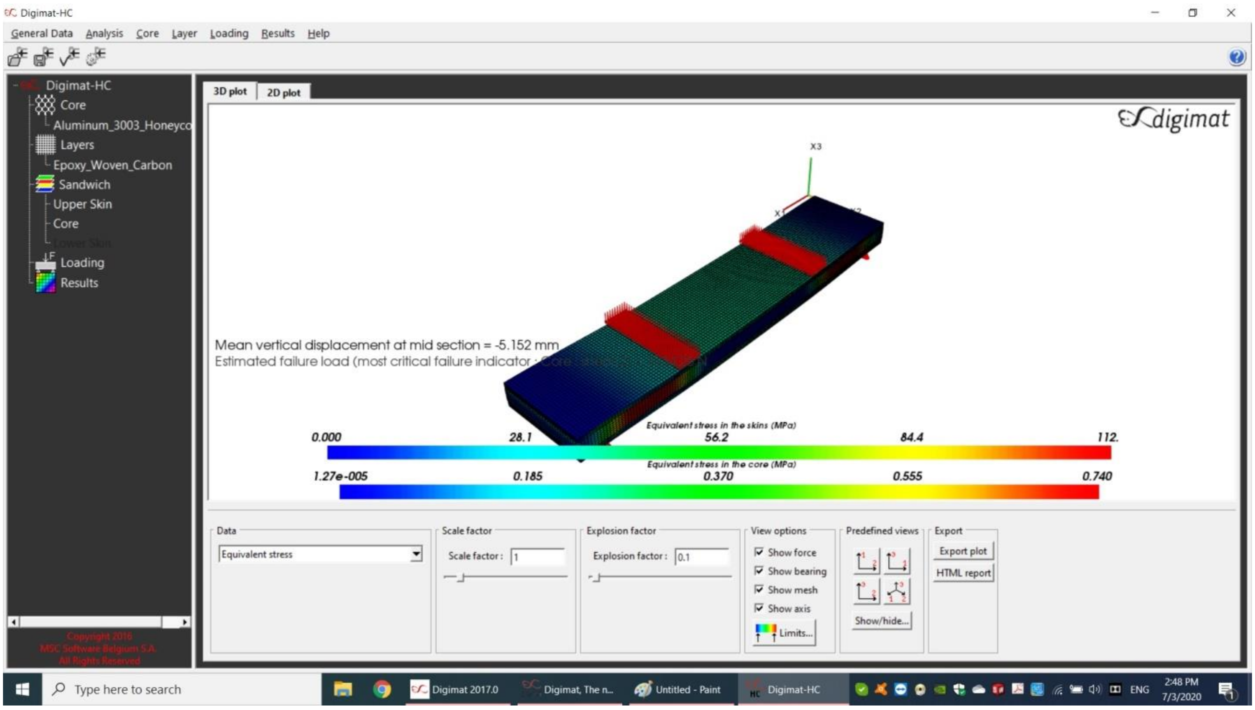


Figure 7.3: Numerical result (four-point bending test) for a model of the sandwich panel consists of an aluminum honeycomb core (t_c=15 mm) and epoxy woven carbon face-sheets (t_f= 1.2 mm).

Table 7.3: 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**	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

Table 7.4: 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 epoxy woven glass fiber (7781-8HS) 50% volume fraction.

Type	**Epoxy woven glass fiber**	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

Table 7.5: 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 epoxy woven carbon fiber (G793-5HS) 60% volume fraction.

Type	**Epoxy woven carbon fiber**	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°)	9.839	154	0.87	0.3
2	2 (0°, 90°)	7.062	80.2	0.78	0.6
3	4 (0°, 90°, 90°, 0°)	5.152	112	0.74	1.2
4	6 (0°, 90°, 0°, 0°,90°, 0°)	4.228	105	0.666	1.8
5	8 (0°, 90°, 0°, 90°, 90°, 0°, 90°, 0°)	3.638	86.2	0.579	2.4
6	1 (+45°)	25.66	157	1.28	0.3
7	2 (+45°, -45°)	14.526	77.5	0.908	0.6
8	4 (+45°, -45°, -45°, +45°)	8.652	78.5	0.807	1.2
9	6 (+45°, -45°, +45°, +45°, -45°, +45°)	6.461	82.3	0.753	1.8
10	8 (+45°, -45°, +45°, -45°, -45°, +45°, -45°, +45°)	5.234	77.6	0.683	2.4
11	4 (0°, 90°, +45°, -45°)	5.503	67.9	0.739	1.2
12	4 (+45°, -45°, 0°, 90°)	5.921	127	0.799	1.2
13	6 (0°, 90°, +45°, -45°, 0°, 90°)	4.402	109	0.67	1.8
14	6 (+45°, -45°, 0°, 90°, -45°, +45°)	4.854	95.3	0.728	1.8
15	8 (0°, 90°, +45°, -45°, -45°, +45°, 90°, 0°)	3.841	94.7	0.589	2.4
16	8 (+45°, -45°, 0°, 90°, 90°, 0°, -45°, +45°)	3.955	98.7	0.652	2.4

Table 7.6: 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 hybrid composite material face-sheets (a combination of epoxy woven carbon fiber layers (G793-5HS) 60% volume fraction and epoxy woven glass fiber layers (7781-8HS) 50% volume fraction).

Type	**Hybrid composite face-sheets**	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°)	18.217	183	0.974	0.3, 0.25
2	2 (0°, 90°)	8.471	124	0.805	0.55
3	4 (0°, 90°, 90°, 0°)	5.867	70.9	0.739	1.1
4	6 (0°, 90°, 0°, 0°,90°, 0°)	4.669	89.1	0.698	1.65
5	8 (0°, 90°, 0°, 90°, 90°, 0°, 90°, 0°)	3.959	73	0.641	2.2
6	1 (+45°)	34.284	184	1.45	0.3, 0.25
7	2 (+45°, -45°)	17.099	101	0.993	0.55
8	4 (+45°, -45°, -45°, +45°)	9.893	55.8	0.82	1.1
9	6 (+45°, -45°, +45°, +45°, -45°, +45°)	7.279	60.1	0.775	1.65
10	8 (+45°, -45°, +45°, -45°, -45°, +45°, -45°, +45°)	5.843	60.7	0.727	2.2
11	4 (0°, 90°, +45°, -45°)	5.95	83.5	0.737	1.1
12	4 (+45°, -45°, 0°, 90°)	8.571	58.8	0.825	1.1
13	6 (0°, 90°, +45°, -45°, 0°, 90°)	4.882	58.4	0.699	1.65
14	6 (+45°, -45°, 0°, 90°, -45°, +45°)	5.585	119	0.75	1.65
15	8 (0°, 90°, +45°, -45°, -45°, +45°, 90°, 0°)	4.193	47	0.644	2.2
16	8 (+45°, -45°, 0°, 90°, 90°, 0°, -45°, +45°)	4.435	95.8	0.698	2.2

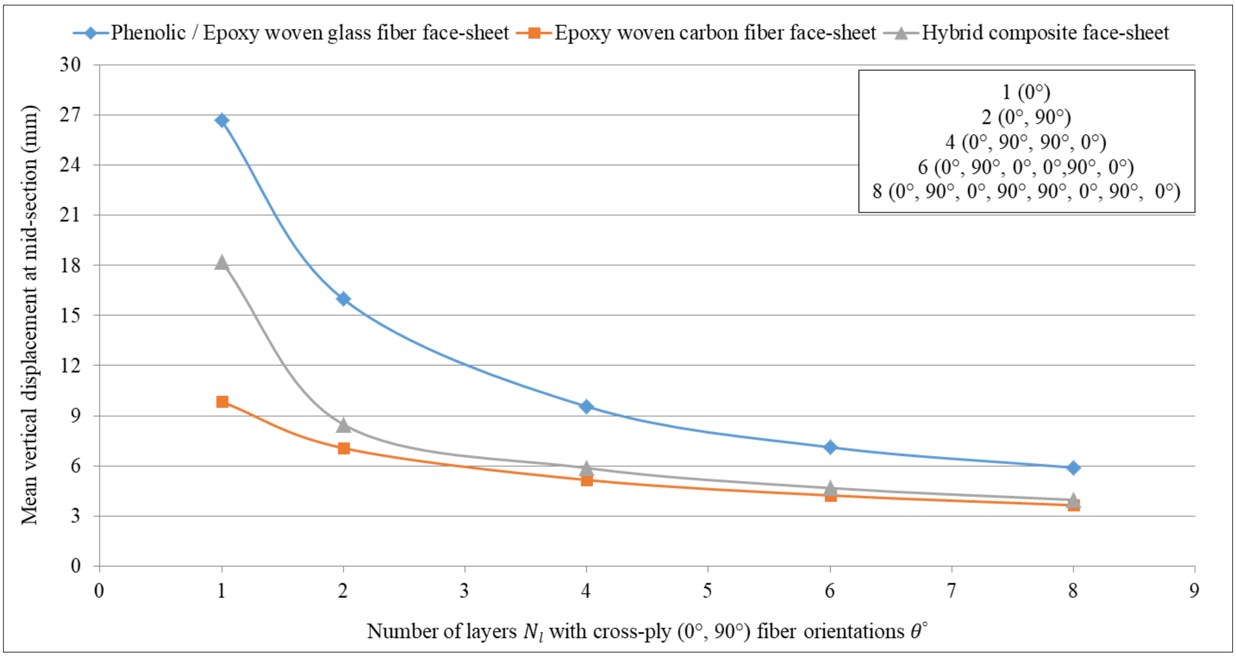


Figure 7.4(a): Comparison of deflection numerically using the Digimat-HC program (four-point bending test) for sandwich panels consisting of an aluminum honeycomb core (t_c=15 mm) and different composite material face-sheets of phenolic / epoxy woven glass fiber, epoxy woven carbon fiber, and hybrid composite layers with various numbers of layers N_l and cross-ply (0°, 90°) fiber orientation θ°.

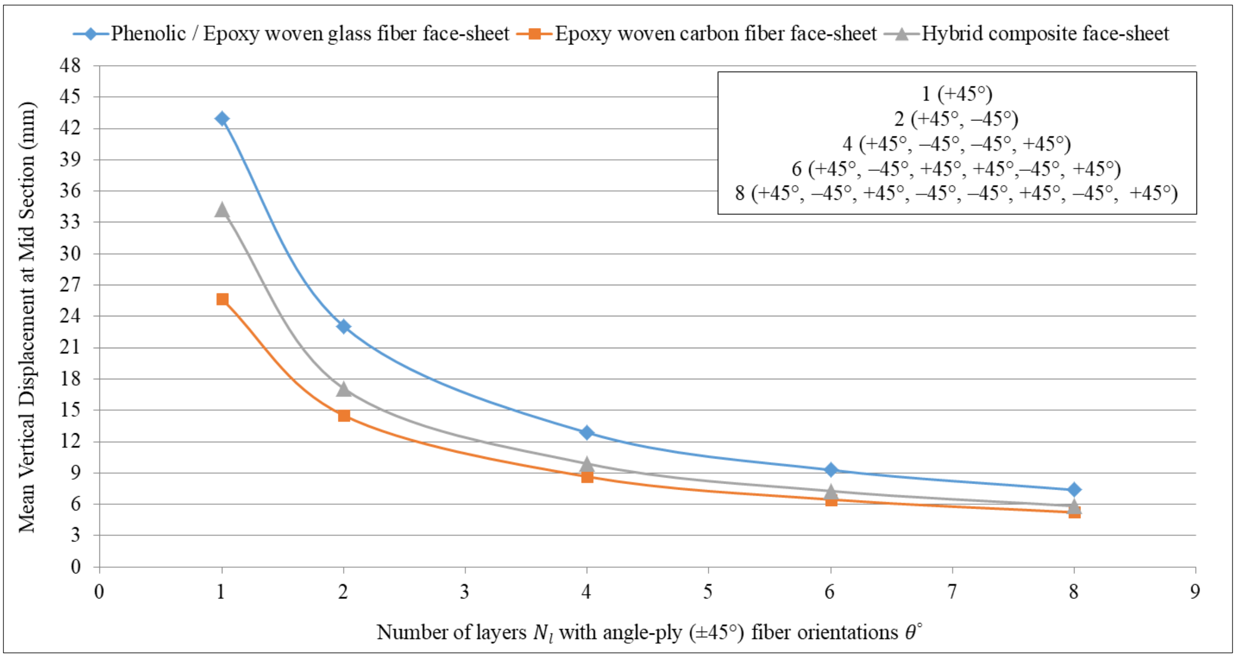


Figure 7.4(b): Comparison of deflection numerically using the Digimat-HC program (four-point bending test) for sandwich panels consisting of an aluminum honeycomb core (t_c=15 mm) and different composite material face-sheets of phenolic / epoxy woven glass fiber, epoxy woven carbon fiber, and hybrid composite layers with various numbers of layers N_l and angle-ply (±45°) fiber orientation θ°.

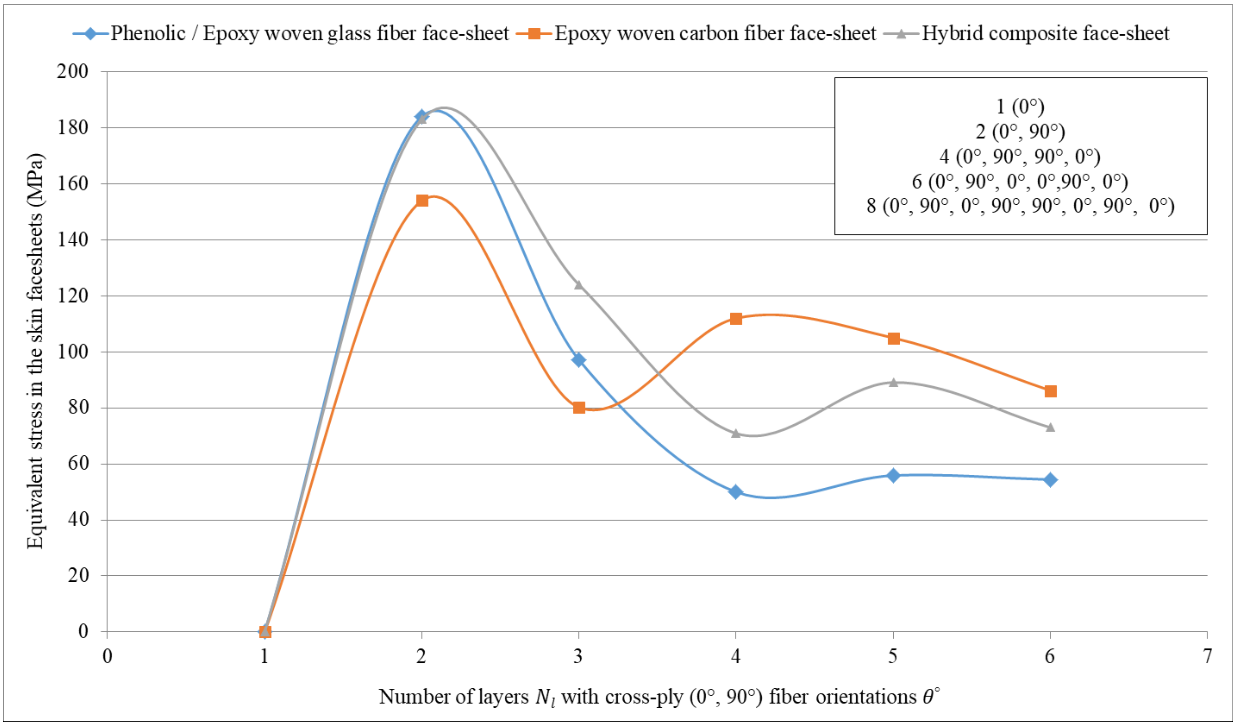


Figure 7.5(a): Comparison of face-sheet stress numerically using the Digimat-HC program (four-point bending test) for sandwich panels consisting of an aluminum honeycomb core (t_c=15 mm) and different composite material face-sheets of phenolic / epoxy woven glass fiber, epoxy woven carbon fiber, and hybrid composite layers with various numbers of layers N_l and cross-ply (0°, 90°) fiber orientation θ°.

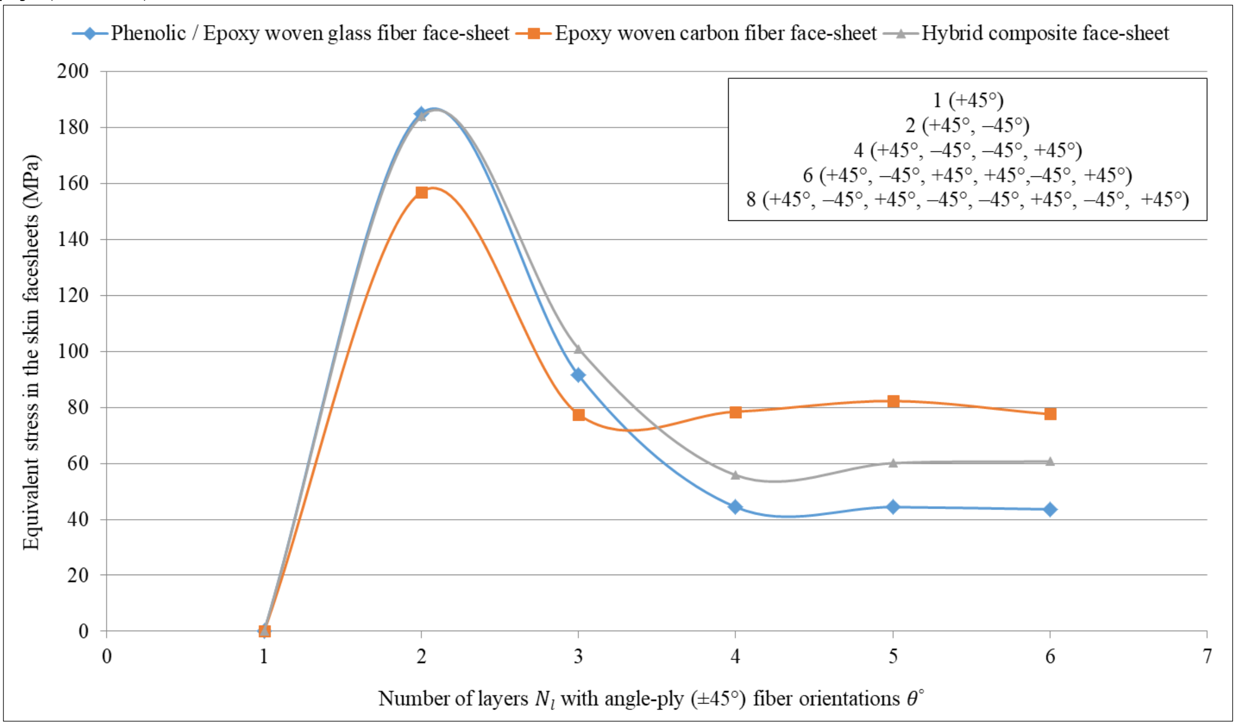


Figure 7.5(b): Comparison of face-sheet stress numerically using the Digimat-HC program (four-point bending test) for sandwich panels consisting of an aluminum honeycomb core (t_c=15 mm) and different composite material face-sheets of phenolic / epoxy woven glass fiber, epoxy woven carbon fiber, and hybrid composite layers with various numbers of layers N_l and angle-ply (±45°) fiber orientation θ°.

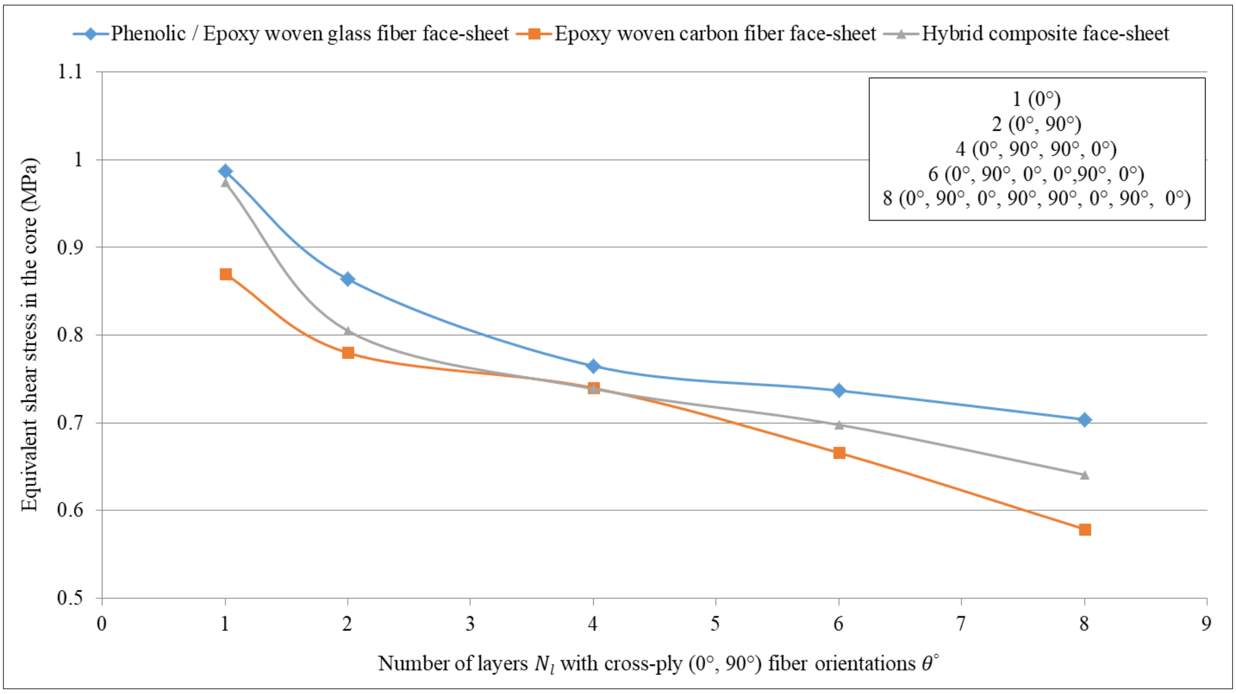


Figure 7.6(a): Comparison of core shear stress numerically using the Digimat-HC program (four-point bending test) for sandwich panels consisting of an aluminum honeycomb core (t_c=15 mm) and different composite material face-sheets of phenolic / epoxy woven glass fiber, epoxy woven carbon fiber, and hybrid composite layers with various numbers of layers N_l and cross-ply (0°, 90°), fiber orientation θ°.

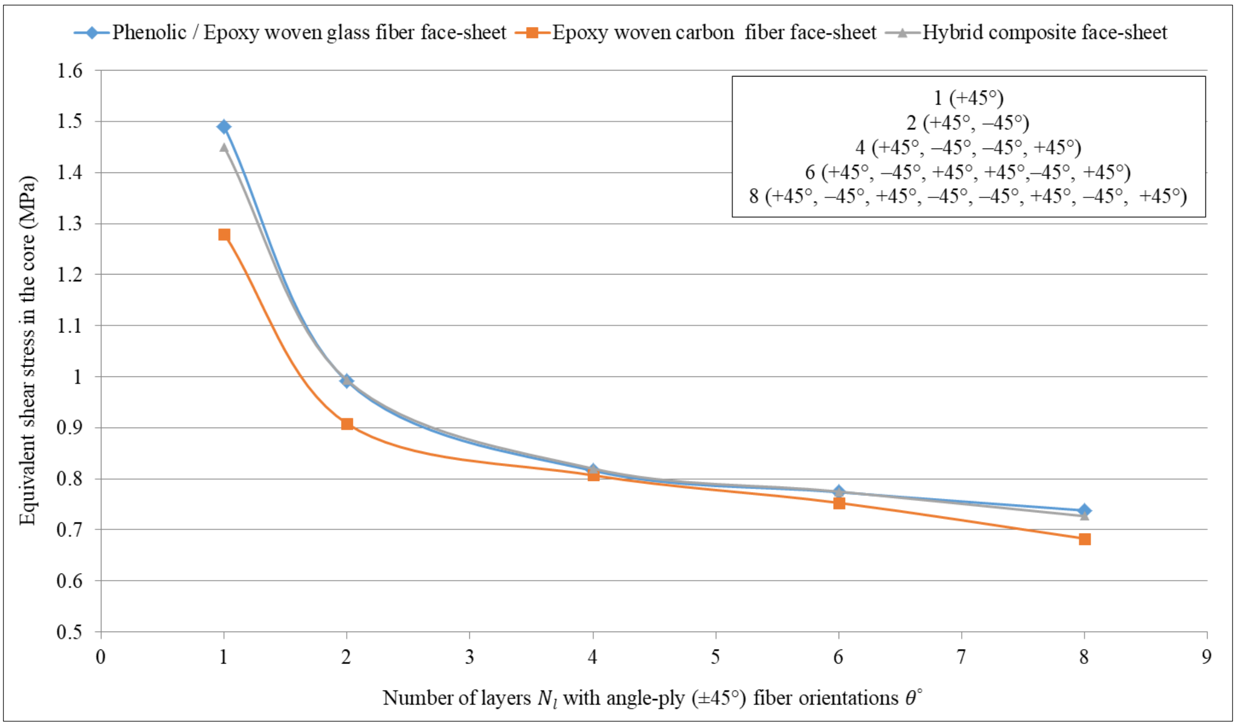


Figure 7.6(b): Comparison of core shear stress numerically using the Digimat-HC program (four-point bending test) for sandwich panels consisting of an aluminum honeycomb core (t_c=15 mm) and different composite material face-sheets of phenolic / epoxy woven glass fiber, epoxy woven carbon fiber, and hybrid composite layers with various numbers of layers N_l and angle-ply (±45°) fiber orientation θ°.

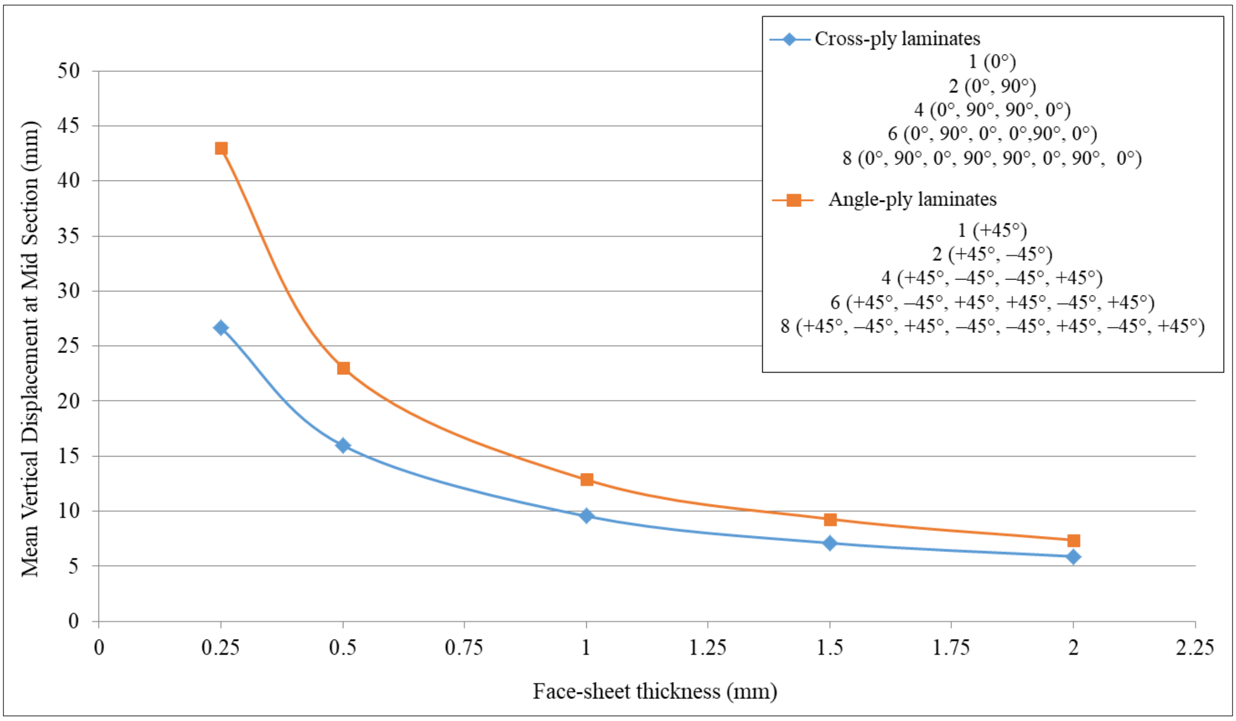


Figure 7.7: Comparison of deflection with face-sheet thickness and fiber orientation θ° numerically using the Digimat-HC program (four-point bending test) for sandwich panels consisting of an aluminum honeycomb core (t_c=15 mm) and composite material face-sheets of phenolic woven glass fiber.

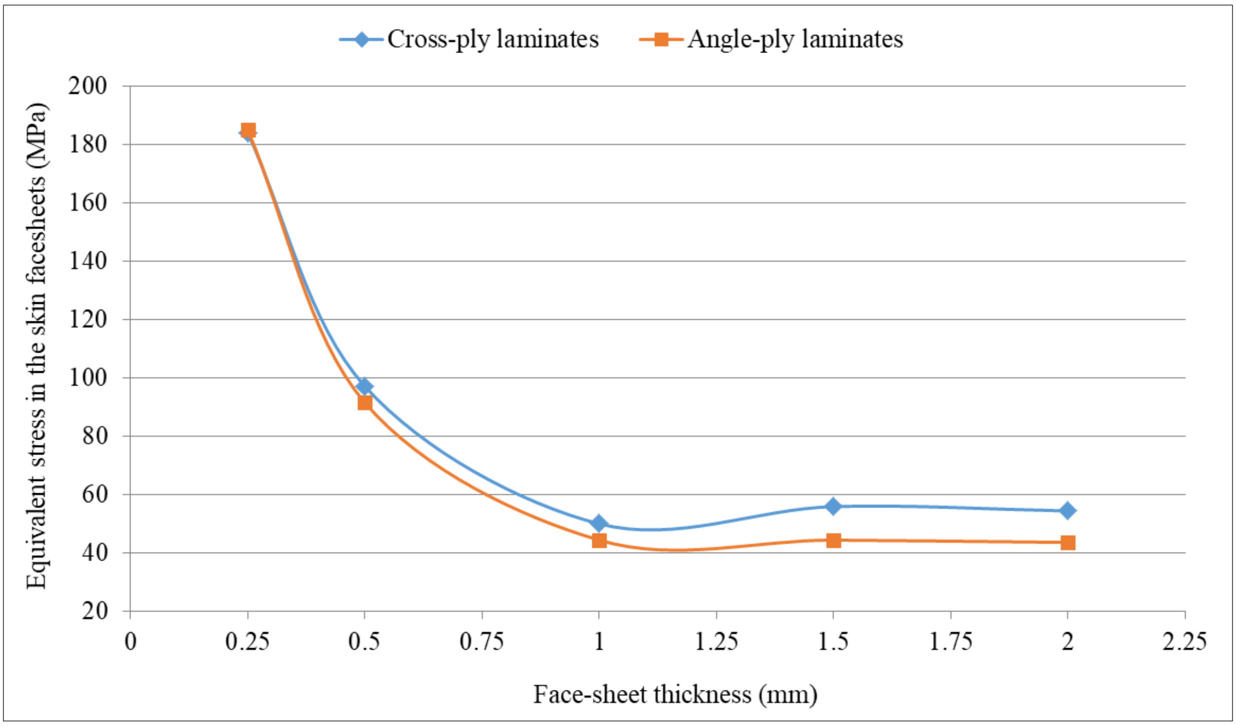


Figure 7.8: Comparison of face-sheet stress with face-sheet thickness and fiber orientation θ° numerically using the Digimat-HC program (four-point bending test) for sandwich panels consisting of an aluminum honeycomb core (t_c=15 mm) and composite material face-sheets of phenolic woven glass fiber.

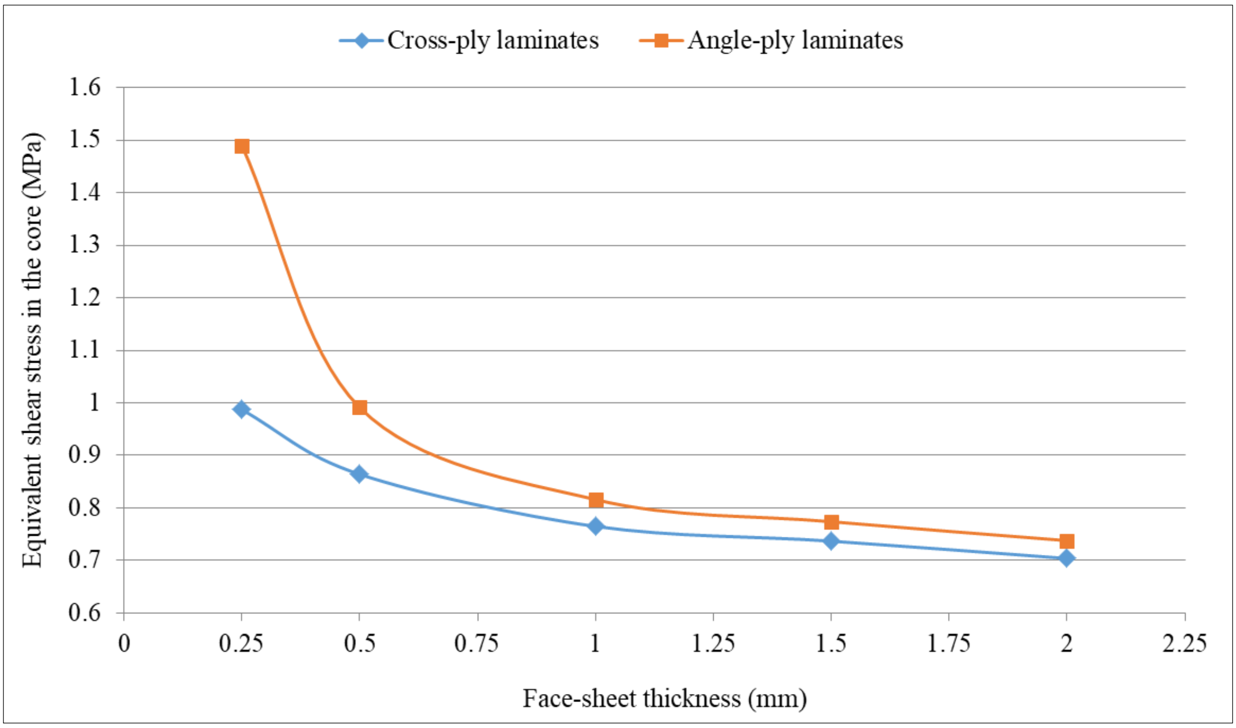


Figure 7.9: Comparison of core shear stress with face-sheet thickness and fiber orientation θ° numerically using the Digimat-HC program (four-point bending test) for sandwich panels consisting of an aluminum honeycomb core (t_c=15 mm) and composite material face-sheets of phenolic woven glass fiber.

7.3. Discussions

These studies aimed to make a comparison of mechanical behavior between numerical models for honeycomb sandwich panels. 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 laminated composite panels were symmetric concerning the midplane of the sandwich panels and/or symmetric concerning the midplane of the face-sheets depending on the number of layers N_l and fiber orientation θ°. 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 face-sheets types of the sandwich panels 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. The epoxy woven carbon fiber having a higher stiffness to weight ratio compared to epoxy woven glass fiber. The epoxy woven glass fiber has a higher strength to weight ratio and more flexible than epoxy woven carbon fiber. The difference between phenolic adhesive and epoxy is that the phenolic gives the best hostile environment resistance properties with temperature resistance up to 70°C, while epoxy gives higher strengths, toughness, and temperature resistance up to 200°C.

8. THESES – NEW SCIENTIFIC RESULTS

T1. The most efficient method to reduce the deflection of honeycomb sandwich panels is to increase the core thickness, thus increasing the skin separation and increasing the face-sheets thickness is the most efficient way to reduce the skin core shear stress. This statement was proved by the 4-point bending tests carried out.

T2. The thickness of the honeycomb core does not affect the adhesive's peeling resistance between the face-sheets and the core of the sandwich structure, but the thickness of the face-sheets does. This statement was proved by the peeling tests carried out.

T3. Increasing the honeycomb core thickness will increase the natural frequencies of the honeycomb sandwich panels, reduce the stress response, and decrease the acceleration response. This statement was proved by the forced vibration tests carried out.

T4. The acceleration frequency response, acceleration time response, and response function decreasing with increasing the mass on the specimens of honeycomb sandwich plate, thin rubber plate, and thick rubber plate. The damping ratio is inversely proportional to acceleration, and the dynamic shear modulus is directly proportional to frequency. This statement was proved by the damping test (Jones Measurement) carried out.

T5. A novel honeycomb sandwich plate was improved to manufacture a lightweight base plate of air cargo container consisting of an aluminum honeycomb core and FRP composite material face-sheets (1-layer (+45°) of epoxy woven carbon fiber). The optimum face-sheet thickness and optimum core thickness which ensures the minimum weight and/or minimum cost are (0.3 mm, 26.43926 mm, 6.2919 kg, and 132.9296 €), respectively. This optimal sandwich plate provides (55.13%) weight saving compared to the air cargo container's conventional aluminum base plate (14.1 kg). This statement was proved by theoretical analysis using the Matlab program and Excel Solver program.

T6. Replacing the currently aluminum single base plate of military aircraft pallets with a honeycomb sandwich plate, consisting of an aluminum honeycomb core and FRP composite material face-sheets (2-layers (0°, 90°) of epoxy woven carbon fiber). The optimum face-sheet thickness and optimum core thickness ensure the minimum weight and/or minimum cost are (0.6 mm, 24.29992 mm, 27.0852 kg, and 702.5157 €), respectively. This optimal sandwich plate provides (66.25 %) weight saving compared to the conventional aluminum single base plate of military aircraft pallet (80 kg). This statement was proved by theoretical analysis using the Matlab program and Excel Solver program.

T7. Design a lightweight sandwich panel, which can be applied in the industry of satellite application. The honeycomb sandwich panel model for satellite consists of an aluminum honeycomb core and FRP composite material face-sheets (2-layers (+45°, -45°) of epoxy woven carbon fiber). The optimum solar sandwich panels of a satellite that ensure the minimum weight and minimum cost with optimum face-sheet thickness and honeycomb core thickness are (1.760318 kg, 36.97817 €, and 0.6 mm 54.05842 mm), respectively. This statement was proved by theoretical analysis using the Matlab program (Interior Point Algorithm and Genetic Algorithm Solver) and Excel Solver program (GRG Nonlinear Algorithm and Weighted Normalized Method).

T8. 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. This statement was proved by Numerical analysis using the Digimat-HC program.

9. SUMMARY

Manufacturing a high performance and lightweight structure with affordable cost without sacrificing strength has been a challenging task for design engineers. The honeycomb sandwich structures are widely applied in the industry like air cargo containers, solar sandwich panels of satellite application and military aircraft pallets. The global manufacturing and development companies are competing to design lightweight structures to satisfy industrial requirements. This study aimed to make a comparison of mechanical behavior between experimental tests and numerical models, investigated the replacement of an existing aluminum base plate in the air cargo containers with a honeycomb sandwich plate, verify the optimum design of solar sandwich panels for satellite application and investigated the replacement of the current aluminum single base plate of military aircraft pallets with a honeycomb sandwich plate. In this dissertation static and dynamic measurements, numerical models, and theoretical solutions for honeycomb sandwich structures were presented.

The experimental tests included a four-point bending test to compute the skin stress and relationship between load and displacement curve, climbing peel test to determine the peel resistance of adhesive bonds between facing skins and core of sandwich panels, forced vibration test to find natural frequencies, stress and acceleration responses and Jones measurement (damping test) to calculate the damping ratio and dynamic shear modulus for thick rubber, thin rubber and honeycomb sandwich specimens. 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 with orientation cross-ply (0°, 90°). The numerical models included a four-point bending test using the Digimat-HC program to calculate the mean vertical displacement at mid-section, equivalent stress in the face-sheets and equivalent shear stress in the honeycomb core. A methodology of optimization techniques was presented to minimize the total weight and/or the total material cost of honeycomb sandwich structures. The total weight and/or the total material cost of honeycomb sandwich structures are the objective functions subjected to required constraints based on total stiffness (bending stiffness and shear stiffness), total deflection (bending deflection and shear deflection), facing skin stress (bending load), core shear stress, facing skin stress (end loading), overall panel buckling (bending and shear critical buckling loads), shear crimping load, skin wrinkling (critical stresses and critical load) and intracell buckling. The design variables are face-sheet thickness and honeycomb core thickness.

The single-objective function was solved using the Matlab program (fmincon Solver Constrained Nonlinear Minimization / Interior Point Algorithm) and Excel Solver program (GRG Nonlinear Algorithm) to compare between them, where GRG stands for “Generalized Reduced Gradient”. The multi-objective functions were solved using the Matlab program (Genetic Algorithm Solver) and Excel Solver program (Weighted Normalized Method). The strategies of composite face-sheets were solved using the Laminator program, an engineering program that analysis laminated composite material according to classical lamination theory and

the ply failure calculation based on Tsai-Hill failure criteria. The analytical and numerical models of honeycomb sandwich structures consist of an aluminum honeycomb core with different face-sheets, including aluminum alloy and composite material. The composite material 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 layup of the fibers of the face-sheets was restricted to sixteen discrete sets of plies having orientation angles of cross-ply (0°, 90°), angle-ply (±45°) and multidirectional of cross-ply (0°, 90°) and angle-ply (±45°). The composite sandwich plates considered consisted of thin layers, symmetric concerning the midplane of the sandwich plates and/or symmetric concerning the midplane of the face-sheets. Every face-sheet is composed of (1, 2, 4, 6, and 8) layers. The savings in weight are proportional to savings on annual fuel cost and/or increased payload, lower maintenance costs, less damage to bags and aircraft, and fewer freighters damage.

10. APPLICATION POSSIBILITIES OF THE RESULTS

Sandwich structure industry is evident in a wide range of honeycomb cores, composite panels and assemblies engineered to meet the unique demands of design and manufacturing engineers. Products of honeycomb sandwich structure offer superior strength-to-weight ratios, toughness, moisture and corrosion resistance for even the most demanding applications. These critical qualities are desirable for structural applications. Low-density options matched with superior mechanical properties make honeycomb products more desirable than traditional balsa and foam products. Providing high strength and stiffness characteristics during normal loading conditions, the shear failure mode of the honeycomb allows it to continue to function after its yield strength has been exceeded. In simple terms, the core increases the sandwich panel's flexural stiffness by effectively increasing the distance between the two stress skins. Honeycomb cores also effectively provide shear resistance, a key component to overall flexural stiffness. The stiffness of honeycomb laminations allows using less material, reduce weight while increasing speed and cargo capacity. Stiffness increases exponentially compared to single sheet material.

The use of honeycomb core creates a dramatic increase in stiffness with very little weight gain. Aluminum honeycomb core are not only lightweight cores, they are more cost-effective than balsa and foam and do not absorb water. Most core materials respond similarly to stress under normal operating loads. As loading increases, the core begins to flex to accommodate the increase in shear stress on the core. Unlike other core materials that reach ultimate yield stress and fail catastrophically, honeycomb, continues to respond and perform. This continued response indicates the honeycomb's ability to absorb energy even after the ultimate yield strength failure. Aluminum honeycomb core is used for several of applications and in different sectors such as: public transport industry, nautical sector, building industry, etc... As core material, aluminum honeycomb is used in sandwich panels and it is utilized in: floors, roofs, doors, and partitions, facades, working surfaces for automatic machines, and for all products which require an optimal stiffness-to-weight-ratio. Aluminum honeycomb as panels’ core has several advantages lightweight, stiffness, fire resistance, compression, and shear and corrosion resistance.

Miskolc, 10th January 2021

Alaa Abdulzahra Deli Al-Fatlawi
Engineering of Mechanics (BSc)
Applied Mechanical Engineering (MSc)

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I would like to utmost gratitude to my supervisors, Professor Károly Jármai and Professor György Kovács, for their precious guidance, advices, dynamism, and friendship. Without their help this research would never have come to fruition. I learned a lot from the regular discussion every week and their wisdom, insight, diligence and passion in research. It was an honor for me to work under their supervisions. Also, this dissertation would not have been possible unless the support from the Stipendium Hungaricum scholarship.

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IN ENGLISH

(1) 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.

(2) 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. (Accepted)

(3) 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.

(4) 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.

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APPENDICES

A1 Theoretical Results for Honeycomb Sandwich Base Plate of Air Cargo Containers.

A2 Theoretical Results for Honeycomb Sandwich Base Plate of Military Aircraft Pallets.

A3 Theoretical Results for Honeycomb Solar Sandwich Panels of Satellite Application.

Minimizing the Single-objective Function (Weight) for Honeycomb Sandwich Base Plate of Air Cargo Container Obtained by Applying the Matlab Program / Interior Point Algorithm

Table 4.9: 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 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}	$t_{f,opt}$	$t_{c,opt}$
No.	Number of layers N_l and fiber orientations θ°	kg	mm	mm
1	1 (0°) *	12.06271	0.25	60.15224
2	2 (0°, 90°) *	11.24972	0.5	44.00955
3	4 (0°, 90°, 90°, 0°)	12.79821	1	30.53453
4	6 (0°, 90°, 0°, 0°,90°, 0°)	15.50762	1.5	23.93852
5	8 (0°, 90°, 0°, 90°, 90°, 0°, 90°, 0°)	18.72217	2	20.33575
6	1 (+45°) *	13.06589	0.25	66.09657
7	2 (+45°, -45°) Optimum value	**11.4357**	**0.5**	**45.11157**
8	4 (+45°, -45°, -45°, +45°)	12.923	1	31.27396
9	6 (+45°, -45°, +45°, +45°, -45°, +45°)	15.66959	1.5	24.89826
10	8 (+45°, -45°, +45°, -45°, -45°, +45°, -45°, +45°)	18.81078	2	20.8608
11	4 (0°, 90°, +45°, -45°)	12.90739	1	31.18148
12	4 (+45°, -45°, 0°, 90°)	12.88657	1	31.05809
13	6 (0°, 90°, +45°, -45°, 0°, 90°)	15.66828	1.5	24.89052
14	6 (+45°, -45°, 0°, 90°, -45°, +45°)	15.72268	1.5	25.21287
15	8 (0°, 90°, +45°, -45°, -45°, +45°, 90°, 0°)	18.8414	2	21.04323
16	8 (+45°, -45°, 0°, 90°, 90°, 0°, -45°, +45°)	18.84258	2	21.04924

Type	**B. Epoxy woven carbon fiber face-sheets**	W_{min}	$t_{f,opt}$	$t_{c,opt}$
No.	Number of layers N_l and fiber orientations θ°	kg	mm	mm
1	1 (0°) *	6.844219	0.3	29.71202
2	2 (0°, 90°)	7.287207	0.6	21.49357
3	4 (0°, 90°, 90°, 0°)	9.760683	1.2	14.4634
4	6 (0°, 90°, 0°, 0°,90°, 0°)	12.80825	1.8	10.83498
5	8 (0°, 90°, 0°, 90°, 90°, 0°, 90°, 0°)	16.09736	2.4	8.648366
6	1 (+45°) Optimum value	**6.327142**	**0.3**	**26.64808**
7	2 (+45°, -45°)	6.787114	0.6	18.53027
8	4 (+45°, -45°, -45°, +45°)	9.404906	1.2	12.35524
9	6 (+45°, -45°, +45°, +45°, -45°, +45°)	12.54312	1.8	9.261559
10	8 (+45°, -45°, +45°, -45°, -45°, +45°, -45°, +45°)	15.84506	2.4	7.130748
11	4 (0°, 90°, +45°, -45°)	9.686484	1.2	14.02373
12	4 (+45°, -45°, 0°, 90°)	9.636799	1.2	13.72932
13	6 (0°, 90°, +45°, -45°, 0°, 90°)	12.94619	1.8	11.64500
14	6 (+45°, -45°, 0°, 90°, -45°, +45°)	12.96099	1.8	11.74003
15	8 (0°, 90°, +45°, -45°, -45°, +45°, 90°, 0°)	16.21539	2.4	9.352811
16	8 (+45°, -45°, 0°, 90°, 90°, 0°, -45°, +45°)	16.22071	2.4	9.383939

Type	**C. Hybrid composite face-sheets**	W_{min}	$t_{f,opt}$	$t_{c,opt}$
No.	Number of layers N_l and fiber orientations θ°	kg	mm	mm
1	2 (0°, 90°) *	8.278141	0.55	26.88342
2	4 (0°, 90°, 90°, 0°)	10.6859	1.1	18.98188
3	6 (0°, 90°, 0°, 0°,90°, 0°)	13.71244	1.65	14.74696
4	8 (0°, 90°, 0°, 90°, 90°, 0°, 90°, 0°)	17.05486	2.2	12.38379
5	2 (+45°, -45°) Optimum value	**8.572076**	**0.55**	**28.62513**
6	4 (+45°, -45°, -45°, +45°)	10.66419	1.1	18.85328
7	6 (+45°, -45°, +45°, +45°, -45°, +45°)	13.72522	1.65	14.82274
8	8 (+45°, -45°, +45°, -45°, -45°, +45°, -45°, +45°)	17.02776	2.2	12.22322
9	4 (0°, 90°, +45°, -45°)	10.66684	1.1	18.86895
10	4 (+45°, -45°, 0°, 90°)	10.84453	1.1	19.92187
11	6 (0°, 90°, +45°, -45°, 90°, 0°)	13.84348	1.65	15.52347
12	6 (+45°, -45°, 0°, 90°, -45°, +45°)	13.95869	1.65	16.20613
13	8 (0°, 90°, +45°, -45°, -45°, +45°, 90°, 0°)	17.15725	2.2	12.99051
14	8 (+45°, -45°, 0°, 90°, 90°, 0°, -45°, +45°)	17.22349	2.2	13.38301

Minimizing the Single-objective Function (Cost) for Honeycomb Sandwich Base Plate of Air Cargo Container Obtained by Applying the Matlab Program / Interior Point Algorithm

Table 4.10: 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 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**	C_{min}	$t_{f,opt}$	$t_{c,opt}$
No.	Number of layers N_l and fiber orientations θ°	€	mm	mm
1	1 (0°) *	137.1714	0.25	56.48681
2	2 (0°, 90°) *	118.652	0.5	44.05948
3	4 (0°, 90°, 90°, 0°)	107.200	1	30.53051
4	6 (0°, 90°, 0°, 0°,90°, 0°)	111.4206	1.5	23.93859
5	8 (0°, 90°, 0°, 90°, 90°, 0°, 90°, 0°)	122.393	2	20.33538
6	1 (+45°) *	158.8803	0.25	66.09594
7	2 (+45°, -45°) Optimum value	**121.0746**	**0.5**	**45.13181**
8	4 (+45°, -45°, -45°, +45°)	108.873	1	31.27108
9	6 (+45°, -45°, +45°, +45°, -45°, +45°)	113.588	1.5	24.89799
10	8 (+45°, -45°, +45°, -45°, -45°, +45°, -45°, +45°)	123.5793	2	20.86045
11	4 (0°, 90°, +45°, -45°)	108.6711	1	31.18161
12	4 (+45°, -45°, 0°, 90°)	108.3849	1	31.0549
13	6 (0°, 90°, +45°, -45°, 0°, 90°)	113.5705	1.5	24.89025
14	6 (+45°, -45°, 0°, 90°, -45°, +45°)	114.2991	1.5	25.21272
15	8 (0°, 90°, +45°, -45°, -45°, +45°, 90°, 0°)	123.9914	2	21.04289
16	8 (+45°, -45°, 0°, 90°, 90°, 0°, -45°, +45°)	124.005	2	21.04891

Type	**B. Epoxy woven carbon fiber face-sheets**	C_{min}	$t_{f,opt}$	$t_{c,opt}$
No.	Number of layers N_l and fiber orientations θ°	€	mm	mm
1	1 (0°) *	140.2582	0.3	29.68311
2	2 (0°, 90°)	194.9546	0.6	21.49366
3	4 (0°, 90°, 90°, 0°)	325.4702	1.2	14.46436
4	6 (0°, 90°, 0°, 0°,90°, 0°)	463.6546	1.8	10.8297
5	8 (0°, 90°, 0°, 90°, 90°, 0°, 90°, 0°)	605.0943	2.4	8.63563
6	1 (+45°) Optimum value	**133.3972**	**0.3**	**26.64621**
7	2 (+45°, -45°)	188.2577	0.6	18.52935
8	4 (+45°, -45°, -45°, +45°)	320.7102	1.2	12.35742
9	6 (+45°, -45°, +45°, +45°, -45°, +45°)	460.1121	1.8	9.266164
10	8 (+45°, -45°, +45°, -45°, -45°, +45°, -45°, +45°)	601.6967	2.4	7.13058
11	4 (0°, 90°, +45°, -45°)	324.4857	1.2	14.02858
12	4 (+45°, -45°, 0°, 90°)	323.8214	1.2	13.73456
13	6 (0°, 90°, +45°, -45°, 0°, 90°)	465.489	1.8	11.64138
14	6 (+45°, -45°, 0°, 90°, -45°, +45°)	465.6876	1.8	11.72943
15	8 (0°, 90°, +45°, -45°, -45°, +45°, 90°, 0°)	606.6783	2.4	9.33637
16	8 (+45°, -45°, 0°, 90°, 90°, 0°, -45°, +45°)	606.7495	2.4	9.368006

Type	**C. Hybrid composite face-sheets**	C_{min}	$t_{f,opt}$	$t_{c,opt}$
No.	Number of layers N_l and fiber orientations θ°	€	mm	mm
1	2 (0°, 90°) *	143.4716	0.55	26.87547
2	4 (0°, 90°, 90°, 0°)	208.3944	1.1	18.98257
3	6 (0°, 90°, 0°, 0°,90°, 0°)	281.5785	1.65	14.7464
4	8 (0°, 90°, 0°, 90°, 90°, 0°, 90°, 0°)	359.0121	2.2	12.39116
5	2 (+45°, -45°) Optimum value	**147.4526**	**0.55**	**28.63761**
6	4 (+45°, -45°, -45°, +45°)	208.0977	1.1	18.85125
7	6 (+45°, -45°, +45°, +45°, -45°, +45°)	281.7494	1.65	14.82204
8	8 (+45°, -45°, +45°, -45°, -45°, +45°, -45°, +45°)	358.6539	2.2	12.2326
9	4 (0°, 90°, +45°, -45°)	208.1317	1.1	18.86628
10	4 (+45°, -45°, 0°, 90°)	210.5132	1.1	19.92041
11	6 (0°, 90°, +45°, -45°, 90°, 0°)	283.3135	1.65	15.51434
12	6 (+45°, -45°, 0°, 90°, -45°, +45°)	284.8452	1.65	16.19232
13	8 (0°, 90°, +45°, -45°, -45°, +45°, 90°, 0°)	360.3662	2.2	12.99052
14	8 (+45°, -45°, 0°, 90°, 90°, 0°, -45°, +45°)	361.2634	2.2	13.38767

Minimizing Multi-objective Functions for Honeycomb Sandwich Base Plate of Air Cargo Container Obtained by Applying the Matlab program / Genetic Algorithm Solver

Table 4.14: Minimum weight and 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 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}	C_{min}	$t_{f,opt}$	$t_{c,opt}$
No.	Number of layers N_l and fiber orientations θ°	kg	€	mm	mm
1	1 (0°) *	12.01531	144.8178	0.25	59.87135
2	2 (0°, 90°) *	11.20569	117.9499	0.5	43.74869
3	4 (0°, 90°, 90°, 0°)	12.75303	106.6045	1	30.26684
4	6 (0°, 90°, 0°, 0°,90°, 0°)	15.46396	110.8359	1.5	23.67981
5	8 (0°, 90°, 0°, 90°, 90°, 0°, 90°, 0°)	18.68366	121.8783	2	20.10755
6	1 (+45°) *	13.07383	158.9881	0.25	66.14362
7	2 (+45°, -45°) Optimum value	**11.39432**	**120.4749**	**0.5**	**44.86638**
8	4 (+45°, -45°, -45°, +45°)	12.89323	108.4813	1	31.09758
9	6 (+45°, -45°, +45°, +45°, -45°, +45°)	15.63193	113.0846	1.5	24.67515
10	8 (+45°, -45°, +45°, -45°, -45°, +45°, -45°, +45°)	18.76753	123.001	2	20.60452
11	4 (0°, 90°, +45°, -45°)	12.86069	108.0457	1	30.90474
12	4 (+45°, -45°, 0°, 90°)	12.84807	107.8768	1	30.82999
13	6 (0°, 90°, +45°, -45°, 0°, 90°)	15.62833	113.0364	1.5	24.65382
14	6 (+45°, -45°, 0°, 90°, -45°, +45°)	15.67993	113.7272	1.5	24.95958
15	8 (0°, 90°, +45°, -45°, -45°, +45°, 90°, 0°)	18.80518	123.5051	2	20.82761
16	8 (+45°, -45°, 0°, 90°, 90°, 0°, -45°, +45°)	18.80284	123.4737	2	20.81372

Type	**B. Epoxy woven carbon fiber face-sheets**	W_{min}	C_{min}	$t_{f,opt}$	$t_{c,opt}$
No.	Number of layers N_l and fiber orientations θ°	kg	€	mm	mm
1	1 (0°) *	6.791502	139.6178	0.3	29.39965
2	2 (0°, 90°)	7.240928	194.3349	0.6	21.21934
3	4 (0°, 90°, 90°, 0°)	9.716592	324.8778	1.2	14.20213
4	6 (0°, 90°, 0°, 0°,90°, 0°)	12.76531	463.092	1.8	10.58052
5	8 (0°, 90°, 0°, 90°, 90°, 0°, 90°, 0°)	16.07114	604.7483	2.4	8.4825
6	1 (+45°) Optimum value	**6.2919**	**132.9296**	**0.3**	**26.43926**
7	2 (+45°, -45°)	6.751647	187.785	0.6	18.32011
8	4 (+45°, -45°, -45°, +45°)	9.367182	320.2003	1.2	12.13171
9	6 (+45°, -45°, +45°, +45°, -45°, +45°)	12.5018	459.5645	1.8	9.019118
10	8 (+45°, -45°, +45°, -45°, -45°, +45°, -45°, +45°)	15.80694	601.2114	2.4	6.916951
11	4 (0°, 90°, +45°, -45°)	9.645885	323.9312	1.2	13.78316
12	4 (+45°, -45°, 0°, 90°)	9.596906	323.2756	1.2	13.49293
13	6 (0°, 90°, +45°, -45°, 0°, 90°)	12.90446	464.9548	1.8	11.40508
14	6 (+45°, -45°, 0°, 90°, -45°, +45°)	12.91848	465.1425	1.8	11.48817
15	8 (0°, 90°, +45°, -45°, -45°, +45°, 90°, 0°)	16.18723	606.3024	2.4	9.170409
16	8 (+45°, -45°, 0°, 90°, 90°, 0°, -45°, +45°)	16.19311	606.3811	2.4	9.205251

Type	**C. Hybrid composite face-sheets**	W_{min}	C_{min}	$t_{f,opt}$	$t_{c,opt}$
No.	Number of layers N_l and fiber orientations θ°	kg	€	mm	mm
1	2 (0°, 90°) *	8.22948	142.8381	0.55	26.59508
2	4 (0°, 90°, 90°, 0°)	10.65319	207.955	1.1	18.78807
3	6 (0°, 90°, 0°, 0°,90°, 0°)	13.67477	281.0756	1.65	14.52376
4	8 (0°, 90°, 0°, 90°, 90°, 0°, 90°, 0°)	17.02175	358.5522	2.2	12.18759
5	2 (+45°, -45°) Optimum value	**8.573244**	**147.44**	**0.55**	**28.63205**
6	4 (+45°, -45°, -45°, +45°)	10.62152	207.5311	1.1	18.60044
7	6 (+45°, -45°, +45°, +45°, -45°, +45°)	13.68827	281.2563	1.65	14.60376
8	8 (+45°, -45°, +45°, -45°, -45°, +45°, -45°, +45°)	16.98819	358.103	2.2	11.98878
9	4 (0°, 90°, +45°, -45°)	10.62474	207.5742	1.1	18.61951
10	4 (+45°, -45°, 0°, 90°)	10.81531	210.1254	1.1	19.74876
11	6 (0°, 90°, +45°, -45°, 90°, 0°)	13.81375	282.9361	1.65	15.3473
12	6 (+45°, -45°, 0°, 90°, -45°, +45°)	13.91954	284.3523	1.65	15.97416
13	8 (0°, 90°, +45°, -45°, -45°, +45°, 90°, 0°)	17.11734	359.8318	2.2	12.75401
14	8 (+45°, -45°, 0°, 90°, 90°, 0°, -45°, +45°)	17.18276	360.7076	2.2	13.14165

* Intracell buckling constraint not satisfied.

Minimizing the Single-objective Function (Weight) for Honeycomb Sandwich Base Plate of Military Aircraft Pallets Obtained by Applying the Matlab program (Interior Point Algorithm)

Table 5.9: 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 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**	$W_{min,t}$	$t_{f,opt}$	$t_{c,opt}$
No.	Number of layers N_l and fiber orientations θ°	kg	mm	mm
1	1 (0°) ***	27.81370	0.25	35.89834
2	2 (0°, 90°) *	28.72835	0.5	26.12597
3	4 (0°, 90°, 90°, 0°) Optimum value	**40.74181**	**1**	**23.87249**
4	6 (0°, 90°, 0°, 0°,90°, 0°)	53.78803	1.5	23.37248
5	8 (0°, 90°, 0°, 90°, 90°, 0°, 90°, 0°)	66.83446	2	22.87282
6	1 (+45°) ****	21.17249	0.25	24.62252
7	2 (+45°, -45°) **	29.11382	0.5	26.78045
8	4 (+45°, -45°, -45°, +45°)	71.86022	1	76.70704
9	6 (+45°, -45°, +45°, +45°, -45°, +45°)	69.65052	1.5	50.30470
10	8 (+45°, -45°, +45°, -45°, -45°, +45°, -45°, +45°)	75.06879	2	36.85352
11	4 (0°, 90°, +45°, -45°)	72.58835	1	77.94331
12	4 (+45°, -45°, 0°, 90°)	70.93881	1	75.14262
13	6 (0°, 90°, +45°, -45°, 0°, 90°)	57.04666	1.5	28.90516
14	6 (+45°, -45°, 0°, 90°, -45°, +45°)	61.98758	1.5	37.29413
15	8 (0°, 90°, +45°, -45°, -45°, +45°, 90°, 0°)	67.15864	2	23.42323
16	8 (+45°, -45°, 0°, 90°, 90°, 0°, -45°, +45°)	67.15716	2	23.42073

Type	**B. Epoxy woven carbon fiber face-sheets**	$W_{min,t}$	$t_{f,opt}$	$t_{c,opt}$
No.	Number of layers N_l and fiber orientations θ°	kg	mm	mm
1	1 (0°) *	21.43149	0.3	25.54420
2	2 (0°, 90°) Optimum value	**27.06899**	**0.6**	**24.27249**
3	4 (0°, 90°, 90°, 0°)	39.48863	1.2	23.67249
4	6 (0°, 90°, 0°, 0°,90°, 0°)	51.90847	1.8	23.07282
5	8 (0°, 90°, 0°, 90°, 90°, 0°, 90°, 0°)	64.32791	2.4	22.47249
6	1 (+45°) **	20.85937	0.3	24.57282
7	2 (+45°, -45°)	46.45340	0.6	57.18439
8	4 (+45°, -45°, -45°, +45°)	41.85616	1.2	27.69220
9	6 (+45°, -45°, +45°, +45°, -45°, +45°)	51.90827	1.8	23.07249
10	8 (+45°, -45°, +45°, -45°, -45°, +45°, -45°, +45°)	64.32811	2.4	22.47282
11	4 (0°, 90°, +45°, -45°)	39.48879	1.2	23.67275
12	4 (+45°, -45°, 0°, 90°)	39.48873	1.2	23.67265
13	6 (0°, 90°, +45°, -45°, 0°, 90°)	51.90827	1.8	23.07249
14	6 (+45°, -45°, 0°, 90°, -45°, +45°)	51.90827	1.8	23.07249
15	8 (0°, 90°, +45°, -45°, -45°, +45°, 90°, 0°)	64.33206	2.4	22.47954
16	8 (+45°, -45°, 0°, 90°, 90°, 0°, -45°, +45°)	64.33335	2.4	22.48172

Type	**C. Hybrid composite face-sheets**	$W_{min,t}$	$t_{f,opt}$	$t_{c,opt}$
No.	Number of layers N_l and fiber orientations θ°	kg	mm	mm
1	2 (0°, 90°) *	27.39284	0.55	24.34041
2	4 (0°, 90°, 90°, 0°) Optimum value	**40.11522**	**1.1**	**23.77248**
3	6 (0°, 90°, 0°, 0°,90°, 0°)	52.84835	1.65	23.22282
4	8 (0°, 90°, 0°, 90°, 90°, 0°, 90°, 0°)	65.58108	2.2	22.67249
5	2 (+45°, -45°) **	27.38229	0.55	24.32249
6	4 (+45°, -45°, -45°, +45°)	67.11467	1.1	69.61364
7	6 (+45°, -45°, +45°, +45°, -45°, +45°)	66.27806	1.65	46.02453
8	8 (+45°, -45°, +45°, -45°, -45°, +45°, -45°, +45°)	72.10824	2.2	33.75465
9	4 (0°, 90°, +45°, -45°)	54.67556	1.1	48.49383
10	4 (+45°, -45°, 0°, 90°)	44.18670	1.1	30.68527
11	6 (0°, 90°, +45°, -45°, 90°, 0°)	52.84835	1.65	23.22282
12	6 (+45°, -45°, 0°, 90°, -45°, +45°)	52.84843	1.65	23.22296
13	8 (0°, 90°, +45°, -45°, -45°, +45°, 90°, 0°)	65.58108	2.2	22.67249
14	8 (+45°, -45°, 0°, 90°, 90°, 0°, -45°, +45°)	65.58108	2.2	22.67249

Minimizing the Single-objective Function (Cost) for Honeycomb Sandwich Base Plate of Military Aircraft Pallets Obtained by Applying the Matlab program (Interior Point Algorithm)

Table 5.10: 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**	$C_{min,t}$	$t_{f,opt}$	$t_{c,opt}$
No.	Number of layers N_l and fiber orientations θ°	€	mm	mm
1	1 (0°) ***	316.40706	0.25	35.89984
2	2 (0°, 90°) *	272.69147	0.5	26.12540
3	4 (0°, 90°, 90°, 0°) Optimum value	**321.65588**	**1**	**23.87555**
4	6 (0°, 90°, 0°, 0°,90°, 0°)	384.39321	1.5	23.37251
5	8 (0°, 90°, 0°, 90°, 90°, 0°, 90°, 0°)	447.15429	2	22.87248
6	1 (+45°) ****	227.48989	0.25	24.62250
7	2 (+45°, -45°) **	277.88381	0.5	26.78395
8	4 (+45°, -45°, -45°, +45°)	738.21030	1	76.70706
9	6 (+45°, -45°, +45°, +45°, -45°, +45°)	596.74222	1.5	50.30469
10	8 (+45°, -45°, +45°, -45°, -45°, +45°, -45°, +45°)	557.94438	2	36.92397
11	4 (0°, 90°, +45°, -45°)	747.95778	1	77.94333
12	4 (+45°, -45°, 0°, 90°)	725.87532	1	75.14262
13	6 (0°, 90°, +45°, -45°, 0°, 90°)	428.02677	1.5	28.90655
14	6 (+45°, -45°, 0°, 90°, -45°, +45°)	494.12974	1.5	37.29037
15	8 (0°, 90°, +45°, -45°, -45°, +45°, 90°, 0°)	451.48174	2	23.42133
16	8 (+45°, -45°, 0°, 90°, 90°, 0°, -45°, +45°)	451.48181	2	23.42134

Type	**B. Epoxy woven carbon fiber face-sheets**	$C_{min,t}$	$t_{f,opt}$	$t_{c,opt}$
No.	Number of layers N_l and fiber orientations θ°	€	mm	mm
1	1 (0°) *	456.9241	0.3	25.55159
2	2 (0°, 90°) Optimum value	**702.2996**	**0.6**	**24.27251**
3	4 (0°, 90°, 90°, 0°)	1208.4897	1.2	23.67249
4	6 (0°, 90°, 0°, 0°,90°, 0°)	1714.6800	1.8	23.07249
5	8 (0°, 90°, 0°, 90°, 90°, 0°, 90°, 0°)	2220.8702	2.4	22.47248
6	1 (+45°) **	449.2043	0.3	24.57248
7	2 (+45°, -45°)	961.7962	0.6	57.18441
8	4 (+45°, -45°, -45°, +45°)	1240.5414	1.2	27.73760
9	6 (+45°, -45°, +45°, +45°, -45°, +45°)	1714.6802	1.8	23.07252
10	8 (+45°, -45°, +45°, -45°, -45°, +45°, -45°, +45°)	2220.9440	2.4	22.48185
11	4 (0°, 90°, +45°, -45°)	1208.4946	1.2	23.67311
12	4 (+45°, -45°, 0°, 90°)	1208.4935	1.2	23.67297
13	6 (0°, 90°, +45°, -45°, 0°, 90°)	1714.6800	1.8	23.07249
14	6 (+45°, -45°, 0°, 90°, -45°, +45°)	1714.6800	1.8	23.07249
15	8 (0°, 90°, +45°, -45°, -45°, +45°, 90°, 0°)	2220.8702	2.4	22.47248
16	8 (+45°, -45°, 0°, 90°, 90°, 0°, -45°, +45°)	2220.8702	2.4	22.47248

Type	**C. Hybrid composite face-sheets**	$C_{min,t}$	$t_{f,opt}$	$t_{c,opt}$
No.	Number of layers N_l and fiber orientations θ°	€	mm	mm
1	2 (0°, 90°) *	480.5851	0.55	24.32251
2	4 (0°, 90°, 90°, 0°) Optimum value	765.0609	1.1	23.77251
3	6 (0°, 90°, 0°, 0°,90°, 0°)	1049.5367	1.65	23.22251
4	8 (0°, 90°, 0°, 90°, 90°, 0°, 90°, 0°)	1334.0122	2.2	22.67248
5	2 (+45°, -45°) **	480.5849	0.55	24.32248
6	4 (+45°, -45°, -45°, +45°)	1126.4990	1.1	69.61363
7	6 (+45°, -45°, +45°, +45°, -45°, +45°)	1229.2734	1.65	46.01849
8	8 (+45°, -45°, +45°, -45°, -45°, +45°, -45°, +45°)	1421.3693	2.2	33.75197
9	4 (0°, 90°, +45°, -45°)	959.9710	1.1	48.49291
10	4 (+45°, -45°, 0°, 90°)	819.7750	1.1	30.71188
11	6 (0°, 90°, +45°, -45°, 90°, 0°)	1049.5366	1.65	23.22251
12	6 (+45°, -45°, 0°, 90°, -45°, +45°)	1049.5460	1.65	23.22369
13	8 (0°, 90°, +45°, -45°, -45°, +45°, 90°, 0°)	1334.0151	2.2	22.67285
14	8 (+45°, -45°, 0°, 90°, 90°, 0°, -45°, +45°)	1334.0122	2.2	22.67248

Minimizing Multi-objective Functions for Honeycomb Sandwich Base Plate of Military Aircraft Pallets Obtained by Applying the Matlab program (Genetic Algorithm Solver)

Table 5.14: Minimum weight and cost multi-objective function with optimum face-sheet thickness and core thickness using the Matlab program (Genetic Algorithm Solver) for 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**	$W_{min,t}$	$C_{min,t}$	$t_{f,opt}$	$t_{c,opt}$
No.	Number of layers N_l and fiber orientations θ°	kg	€	mm	mm
1	1 (0°) ***	27.8190	316.4656	0.25	35.90726
2	2 (0°, 90°) *	28.7297	272.7141	0.5	26.12827
3	4 (0°, 90°, 90°, 0°) Optimum value	**40.7601**	**321.8760**	**1**	**23.90346**
4	6 (0°, 90°, 0°, 0°,90°, 0°)	53.7919	384.4445	1.5	23.37902
5	8 (0°, 90°, 0°, 90°, 90°, 0°, 90°, 0°)	66.8567	447.4552	2	22.91065
6	1 (+45°) ****	21.2190	228.1122	0.25	24.70143
7	2 (+45°, -45°) **	29.1134	277.8510	0.5	26.77979
8	4 (+45°, -45°, -45°, +45°)	71.9137	738.9264	1	76.79788
9	6 (+45°, -45°, +45°, +45°, -45°, +45°)	69.6671	596.9648	1.5	50.33292
10	8 (+45°, -45°, +45°, -45°, -45°, +45°, -45°, +45°)	75.1293	558.1994	2	36.95631
11	4 (0°, 90°, +45°, -45°)	72.6278	748.4853	1	78.01024
12	4 (+45°, -45°, 0°, 90°)	70.9506	726.0335	1	75.16268
13	6 (0°, 90°, +45°, -45°, 0°, 90°)	57.0678	428.2984	1.5	28.94099
14	6 (+45°, -45°, 0°, 90°, -45°, +45°)	62.0196	494.5878	1.5	37.34847
15	8 (0°, 90°, +45°, -45°, -45°, +45°, 90°, 0°)	67.1578	451.4852	2	23.42177
16	8 (+45°, -45°, 0°, 90°, 90°, 0°, -45°, +45°)	67.1757	451.7253	2	23.45223

Type	**B. Epoxy woven carbon fiber face-sheets**	$W_{min,t}$	$C_{min,t}$	$t_{f,opt}$	$t_{c,opt}$
No.	Number of layers N_l and fiber orientations θ°	kg	€	mm	mm
1	1 (0°) *	21.4376	456.9479	0.3	25.5546
2	2 (0°, 90°) Optimum value	**27.1269**	**703.0745**	**0.6**	**24.37079**
3	4 (0°, 90°, 90°, 0°)	39.5441	1209.2323	1.2	23.76667
4	6 (0°, 90°, 0°, 0°,90°, 0°)	51.9128	1714.7403	1.8	23.08015
5	8 (0°, 90°, 0°, 90°, 90°, 0°, 90°, 0°)	64.3376	2220.9996	2.4	22.4889
6	1 (+45°) **	20.9088	449.8683	0.3	24.6567
7	2 (+45°, -45°)	46.4650	961.9516	0.6	57.20412
8	4 (+45°, -45°, -45°, +45°)	41.8925	1240.6701	1.2	27.75392
9	6 (+45°, -45°, +45°, +45°, -45°, +45°)	51.9244	1714.8962	1.8	23.09992
10	8 (+45°, -45°, +45°, -45°, -45°, +45°, -45°, +45°)	64.3424	2221.0644	2.4	22.49712
11	4 (0°, 90°, +45°, -45°)	39.5021	1208.6698	1.2	23.69534
12	4 (+45°, -45°, 0°, 90°)	39.4892	1208.4967	1.2	23.67337
13	6 (0°, 90°, +45°, -45°, 0°, 90°)	51.9091	1714.6907	1.8	23.07386
14	6 (+45°, -45°, 0°, 90°, -45°, +45°)	51.9183	1714.8144	1.8	23.08954
15	8 (0°, 90°, +45°, -45°, -45°, +45°, 90°, 0°)	64.3296	2220.8926	2.4	22.47534
16	8 (+45°, -45°, 0°, 90°, 90°, 0°, -45°, +45°)	64.3293	2220.8886	2.4	22.47482

Type	**C. Hybrid composite face-sheets**	$W_{min,t}$	$C_{min,t}$	$t_{f,opt}$	$t_{c,opt}$
No.	Number of layers N_l and fiber orientations θ°	kg	€	mm	mm
1	2 (0°, 90°) *	27.39330	480.7324	0.55	24.34118
2	4 (0°, 90°, 90°, 0°) Optimum value	40.11958	765.1191	1.1	23.77989
3	6 (0°, 90°, 0°, 0°,90°, 0°)	52.84826	1049.5379	1.65	23.22266
4	8 (0°, 90°, 0°, 90°, 90°, 0°, 90°, 0°)	65.58908	1334.1192	2.2	22.68606
5	2 (+45°, -45°) **	27.40437	480.8805	0.55	24.35997
6	4 (+45°, -45°, -45°, +45°)	67.11657	1126.5245	1.1	69.61686
7	6 (+45°, -45°, +45°, +45°, -45°, +45°)	66.28129	1229.3643	1.65	46.03001
8	8 (+45°, -45°, +45°, -45°, -45°, +45°, -45°, +45°)	72.11027	1421.4176	2.2	33.75809
9	4 (0°, 90°, +45°, -45°)	54.73881	960.8250	1.1	48.60123
10	4 (+45°, -45°, 0°, 90°)	44.18745	819.5751	1.1	30.68654
11	6 (0°, 90°, +45°, -45°, 90°, 0°)	52.89797	1050.2033	1.65	23.30706
12	6 (+45°, -45°, 0°, 90°, -45°, +45°)	52.89229	1050.1273	1.65	23.29742
13	8 (0°, 90°, +45°, -45°, -45°, +45°, 90°, 0°)	65.60694	1334.3584	2.2	22.71639
14	8 (+45°, -45°, 0°, 90°, 90°, 0°, -45°, +45°)	65.59489	1334.1971	2.2	22.69593

* Intracell buckling constraint not satisfied.
** Skin stress constraint not satisfied.
*** Intracell buckling & skin stress constraints not satisfied.
**** Intracell buckling, overall buckling & skin stress constraints not satisfied.

Minimizing the Single-objective Function (Weight) for Honeycomb Sandwich Solar Panel of Satellite Application Obtained by Applying the Matlab Program / Interior Point Algorithm

Table 6.9: Minimum weight objective function with optimum face-sheet thickness and core thickness using the Matlab program (Interior Point Algorithm) for the solar sandwich panels of satellite application 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}	$t_{f,opt}$	$t_{c,opt}$
No.	Number of layers N_l and fiber orientations θ°	kg	mm	mm
1	1 (0°) ***	0.86286	0.25	25.80291
2	2 (0°, 90°) ***	0.960382	0.5	18.67393
3	4 (0°, 90°, 90°, 0°) Optimum value	**3.18261**	**1**	**91.64416**
4	6 (0°, 90°, 0°, 0°,90°, 0°)	3.399978	1.5	78.34674
5	8 (0°, 90°, 0°, 90°, 90°, 0°, 90°, 0°)	3.59451	2	64.06672
6	1 (+45°) ****	0.902493	0.25	27.50829
7	2 (+45°, -45°) **	2.298347	0.5	76.24557
8	4 (+45°, -45°, -45°, +45°)	3.232483	1	93.79014
9	6 (+45°, -45°, +45°, +45°, -45°, +45°)	3.351833	1.5	76.27507
10	8 (+45°, -45°, +45°, -45°, -45°, +45°, -45°, +45°)	3.629775	2	65.58412
11	4 (0°, 90°, +45°, -45°)	3.223137	1	93.38799
12	4 (+45°, -45°, 0°, 90°)	3.220225	1	93.26269
13	6 (0°, 90°, +45°, -45°, 0°, 90°)	3.352361	1.5	76.29782
14	6 (+45°, -45°, 0°, 90°, -45°, +45°)	3.372597	1.5	77.16856
15	8 (0°, 90°, +45°, -45°, -45°, +45°, 90°, 0°)	3.642261	2	66.12138
16	8 (+45°, -45°, 0°, 90°, 90°, 0°, -45°, +45°)	3.642307	2	66.12337

Type	**B. Epoxy woven carbon fiber face-sheets**	W_{min}	$t_{f,opt}$	$t_{c,opt}$
No.	Number of layers N_l and fiber orientations θ°	kg	mm	mm
1	1 (0°) *	2.293509	0.3	87.84464
2	2 (0°, 90°)	2.006371	0.6	64.6459
3	4 (0°, 90°, 90°, 0°)	2.066444	1.2	45.54407
4	6 (0°, 90°, 0°, 0°,90°, 0°)	2.353149	1.8	36.19402
5	8 (0°, 90°, 0°, 90°, 90°, 0°, 90°, 0°)	2.738999	2.4	31.11009
6	1 (+45°)	2.089141	0.3	79.05082
7	2 (+45°, -45°) Optimum value	**1.776369**	**0.6**	**54.74912**
8	4 (+45°, -45°, -45°, +45°)	1.923728	1.2	39.40308
9	6 (+45°, -45°, +45°, +45°, -45°, +45°)	2.248628	1.8	31.69654
10	8 (+45°, -45°, +45°, -45°, -45°, +45°, -45°, +45°)	2.638799	2.4	26.7986
11	4 (0°, 90°, +45°, -45°)	2.028745	1.2	43.9219
12	4 (+45°, -45°, 0°, 90°)	2.022044	1.2	43.63356
13	6 (0°, 90°, +45°, -45°, 0°, 90°)	2.408159	1.8	38.56107
14	6 (+45°, -45°, 0°, 90°, -45°, +45°)	2.412753	1.8	38.75874
15	8 (0°, 90°, +45°, -45°, -45°, +45°, 90°, 0°)	2.786593	2.4	33.15806
16	8 (+45°, -45°, 0°, 90°, 90°, 0°, -45°, +45°)	2.786828	2.4	33.16814

Type	**C. Hybrid composite face-sheets**	W_{min}	$t_{f,opt}$	$t_{c,opt}$
No.	Number of layers N_l and fiber orientations θ°	kg	mm	mm
1	2 (0°, 90°) *	2.372058	0.55	79.89921
2	4 (0°, 90°, 90°, 0°)	2.348988	1.1	56.73785
3	6 (0°, 90°, 0°, 0°,90°, 0°)	2.603265	1.65	45.51053
4	8 (0°, 90°, 0°, 90°, 90°, 0°, 90°, 0°)	2.99879	2.2	40.361
5	2 (+45°, -45°)	2.384513	0.55	80.43516
6	4 (+45°, -45°, -45°, +45°)	2.34358	1.1	56.50517
7	6 (+45°, -45°, +45°, +45°, -45°, +45°)	2.603169	1.65	45.50642
8	8 (+45°, -45°, +45°, -45°, -45°, +45°, -45°, +45°)	2.993121	2.2	40.11707
9	4 (0°, 90°, +45°, -45°) Optimum value	**2.338986**	**1.1**	**56.3075**
10	4 (+45°, -45°, 0°, 90°)	2.435475	1.1	60.45933
11	6 (0°, 90°, +45°, -45°, 90°, 0°)	2.665612	1.65	48.19329
12	6 (+45°, -45°, 0°, 90°, -45°, +45°)	2.68	1.65	48.8124
13	8 (0°, 90°, +45°, -45°, -45°, +45°, 90°, 0°)	3.036654	2.2	41.99028
14	8 (+45°, -45°, 0°, 90°, 90°, 0°, -45°, +45°)	3.119381	2.2	45.54997

Minimizing the Single-objective Function (Cost) for Honeycomb Sandwich Solar Panel of Satellite Application Obtained by Applying the Matlab Program / Interior Point Algorithm

Table 6.10: Minimum cost objective function with optimum face-sheet thickness and core thickness using the Matlab program (Interior Point Algorithm) for the solar sandwich panels of satellite application 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}	$t_{f,opt}$	$t_{c,opt}$
No.	Number of layers N_l and fiber orientations θ°	€	mm	mm
1	1 (0°) ***	9.360853	0.25	25.858458
2	2 (0°, 90°) ***	8.459965	0.5	18.732746
3	4 (0°, 90°, 90°, 0°) Optimum value	**33.23378**	**1**	**89.902862**
4	6 (0°, 90°, 0°, 0°,90°, 0°)	30.37841	1.5	72.264896
5	8 (0°, 90°, 0°, 90°, 90°, 0°, 90°, 0°)	30.06929	2	62.811292
6	1 (+45°) ****	9.886671	0.25	27.548589
7	2 (+45°, -45°) **	26.34964	0.5	76.235287
8	4 (+45°, -45°, -45°, +45°)	34.44314	1	93.790095
9	6 (+45°, -45°, +45°, +45°, -45°, +45°)	31.63237	1.5	76.29547
10	8 (+45°, -45°, +45°, -45°, -45°, +45°, -45°, +45°)	30.93193	2	65.584082
11	4 (0°, 90°, +45°, -45°)	34.31802	1	93.387933
12	4 (+45°, -45°, 0°, 90°)	33.69362	1	91.3809
13	6 (0°, 90°, +45°, -45°, 0°, 90°)	31.62664	1.5	76.277065
14	6 (+45°, -45°, 0°, 90°, -45°, +45°)	31.91038	1.5	77.189093
15	8 (0°, 90°, +45°, -45°, -45°, +45°, 90°, 0°)	31.09919	2	66.121701
16	8 (+45°, -45°, 0°, 90°, 90°, 0°, -45°, +45°)	31.09981	2	66.12369

Type	**B. Epoxy woven carbon fiber face-sheets**	C_{min}	$t_{f,opt}$	$t_{c,opt}$
No.	Number of layers N_l and fiber orientations θ°	€	mm	mm
1	1 (0°) *	36.8134	0.3	85.928807
2	2 (0°, 90°)	39.68375	0.6	62.75493
3	4 (0°, 90°, 90°, 0°)	54.46754	1.2	45.474236
4	6 (0°, 90°, 0°, 0°,90°, 0°)	71.74024	1.8	36.193637
5	8 (0°, 90°, 0°, 90°, 90°, 0°, 90°, 0°)	90.31787	2.4	31.107445
6	1 (+45°)	34.06695	0.3	77.100917
7	2 (+45°, -45°) Optimum value	**37.02625**	**0.6**	**54.21296**
8	4 (+45°, -45°, -45°, +45°)	52.57841	1.2	39.402047
9	6 (+45°, -45°, +45°, +45°, -45°, +45°)	70.33437	1.8	31.674764
10	8 (+45°, -45°, +45°, -45°, -45°, +45°, -45°, +45°)	88.9729	2.4	26.784316
11	4 (0°, 90°, +45°, -45°)	53.98261	1.2	43.915539
12	4 (+45°, -45°, 0°, 90°)	53.89516	1.2	43.63445
13	6 (0°, 90°, +45°, -45°, 0°, 90°)	72.4742	1.8	38.552792
14	6 (+45°, -45°, 0°, 90°, -45°, +45°)	72.53635	1.8	38.752554
15	8 (0°, 90°, +45°, -45°, -45°, +45°, 90°, 0°)	90.95566	2.4	33.157497
16	8 (+45°, -45°, 0°, 90°, 90°, 0°, -45°, +45°)	90.9588	2.4	33.167574

Type	**C. Hybrid composite face-sheets**	C_{min}	$t_{f,opt}$	$t_{c,opt}$
No.	Number of layers N_l and fiber orientations θ°	€	mm	mm
1	2 (0°, 90°) *	35.66015	0.55	77.99192
2	4 (0°, 90°, 90°, 0°)	40.32043	1.1	56.34138
3	6 (0°, 90°, 0°, 0°,90°, 0°)	48.36	1.65	45.55286
4	8 (0°, 90°, 0°, 90°, 90°, 0°, 90°, 0°)	58.136	2.2	40.345723
5	2 (+45°, -45°)	36.72917	0.55	81.428057
6	4 (+45°, -45°, -45°, +45°)	40.23868	1.1	56.078618
7	6 (+45°, -45°, +45°, +45°, -45°, +45°)	48.35914	1.65	45.550111
8	8 (+45°, -45°, +45°, -45°, -45°, +45°, -45°, +45°)	58.05927	2.2	40.099097
9	4 (0°, 90°, +45°, -45°) Optimum value	**40.18863**	**1.1**	**55.917748**
10	4 (+45°, -45°, 0°, 90°)	41.23023	1.1	59.265739
11	6 (0°, 90°, +45°, -45°, 90°, 0°)	48.65637	1.65	46.505495
12	6 (+45°, -45°, 0°, 90°, -45°, +45°)	49.36137	1.65	48.771542
13	8 (0°, 90°, +45°, -45°, -45°, +45°, 90°, 0°)	58.64883	2.2	41.994089
14	8 (+45°, -45°, 0°, 90°, 90°, 0°, -45°, +45°)	59.11387	2.2	43.488878

Minimizing Multi-objective Functions for Honeycomb Sandwich Solar Panel of Satellite Application Obtained by Applying the Matlab program / Genetic Algorithm Solver

Table 6.14: Minimum weight and minimum cost multi-objective function with optimum face-sheet thickness and core thickness using the Matlab program (Genetic Algorithm Solver) for the solar sandwich panels of satellite application 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}	C_{min}	$t_{f,opt}$	$t_{c,opt}$
No.	Number of layers N_l and fiber orientations θ°	kg	€	mm	mm
1	1 (0°) ***	0.864124	9.360493	0.25	25.8573
2	2 (0°, 90°) ***	0.960838	8.447771	0.5	18.69355
3	4 (0°, 90°, 90°, 0°) Optimum value	**3.13540**	**33.1435**	**1**	**89.61253**
4	6 (0°, 90°, 0°, 0°,90°, 0°)	3.241083	30.14342	1.5	71.50958
5	8 (0°, 90°, 0°, 90°, 90°, 0°, 90°, 0°)	3.548275	29.84092	2	62.07725
6	1 (+45°) ****	0.903409	9.886403	0.25	27.54773
7	2 (+45°, -45°) **	2.298146	26.35015	0.5	76.23691
8	4 (+45°, -45°, -45°, +45°)	3.185794	33.81814	1	91.78117
9	6 (+45°, -45°, +45°, +45°, -45°, +45°)	3.305465	31.0053	1.5	74.27989
10	8 (+45°, -45°, +45°, -45°, -45°, +45°, -45°, +45°)	3.583526	30.31282	2	63.59408
11	4 (0°, 90°, +45°, -45°)	3.176745	33.697	1	91.39178
12	4 (+45°, -45°, 0°, 90°)	3.173321	33.65116	1	91.24446
13	6 (0°, 90°, +45°, -45°, 0°, 90°)	3.30577	31.00945	1.5	74.29323
14	6 (+45°, -45°, 0°, 90°, -45°, +45°)	3.327076	31.2946	1.5	75.2098
15	8 (0°, 90°, +45°, -45°, -45°, +45°, 90°, 0°)	3.595982	30.47956	2	64.13003
16	8 (+45°, -45°, 0°, 90°, 90°, 0°, -45°, +45°)	3.597446	30.49916	2	64.19302

Type	**B. Epoxy woven carbon fiber face-sheets**	W_{min}	C_{min}	$t_{f,opt}$	$t_{c,opt}$
No.	Number of layers N_l and fiber orientations θ°	kg	€	mm	mm
1	1 (0°) *	2.248413	36.80574	0.3	85.90418
2	2 (0°, 90°)	1.95884	39.63577	0.6	62.6007
3	4 (0°, 90°, 90°, 0°)	2.020428	53.87326	1.2	43.56404
4	6 (0°, 90°, 0°, 0°,90°, 0°)	2.307252	71.12595	1.8	34.21912
5	8 (0°, 90°, 0°, 90°, 90°, 0°, 90°, 0°)	2.693784	89.71341	2.4	29.16455
6	1 (+45°)	2.042932	34.05499	0.3	77.06249
7	2 (+45°, -45°) Optimum value	**1.760318**	**36.97817**	**0.6**	**54.05842**
8	4 (+45°, -45°, -45°, +45°)	1.877143	51.95511	1.2	37.39857
9	6 (+45°, -45°, +45°, +45°, -45°, +45°)	2.202328	69.72134	1.8	29.70432
10	8 (+45°, -45°, +45°, -45°, -45°, +45°, -45°, +45°)	2.593729	88.37399	2.4	24.85926
11	4 (0°, 90°, +45°, -45°)	1.98204	53.35936	1.2	41.91224
12	4 (+45°, -45°, 0°, 90°)	1.975014	53.2653	1.2	41.60991
13	6 (0°, 90°, +45°, -45°, 0°, 90°)	2.363385	71.87739	1.8	36.63448
14	6 (+45°, -45°, 0°, 90°, -45°, +45°)	2.367	71.92579	1.8	36.79004
15	8 (0°, 90°, +45°, -45°, -45°, +45°, 90°, 0°)	2.741276	90.34918	2.4	31.20807
16	8 (+45°, -45°, 0°, 90°, 90°, 0°, -45°, +45°)	2.74231	90.36302	2.4	31.25257

Type	**C. Hybrid composite face-sheets**	W_{min}	C_{min}	$t_{f,opt}$	$t_{c,opt}$
No.	Number of layers N_l and fiber orientations θ°	kg	€	mm	mm
1	2 (0°, 90°) *	2.324571	35.61783	0.55	77.85591
2	4 (0°, 90°, 90°, 0°)	2.327185	40.15191	1.1	55.7997
3	6 (0°, 90°, 0°, 0°,90°, 0°)	2.578283	48.0124	1.65	44.43557
4	8 (0°, 90°, 0°, 90°, 90°, 0°, 90°, 0°)	2.953229	57.53084	2.2	38.40057
5	2 (+45°, -45°)	2.360294	36.09605	0.55	79.39303
6	4 (+45°, -45°, -45°, +45°)	2.321707	40.07858	1.1	55.564
7	6 (+45°, -45°, +45°, +45°, -45°, +45°)	2.585492	48.10891	1.65	44.7458
8	8 (+45°, -45°, +45°, -45°, -45°, +45°, -45°, +45°)	2.947055	57.44818	2.2	38.13488
9	4 (0°, 90°, +45°, -45°) Optimum value	**2.317042**	**40.01612**	**1.1**	**55.36324**
10	4 (+45°, -45°, 0°, 90°)	2.395176	41.0621	1.1	58.72532
11	6 (0°, 90°, +45°, -45°, 90°, 0°)	2.627158	48.66669	1.65	46.53864
12	6 (+45°, -45°, 0°, 90°, -45°, +45°)	2.681414	49.39301	1.65	48.87324
13	8 (0°, 90°, +45°, -45°, -45°, +45°, 90°, 0°)	2.991455	58.04256	2.2	40.04538
14	8 (+45°, -45°, 0°, 90°, 90°, 0°, -45°, +45°)	3.026998	58.51838	2.2	41.57480

* Intracell buckling constraint not satisfied.
** Bending stiffness and total deflection constraints not satisfied.
*** Bending stiffness, total deflection and intracell buckling constraints not satisfied.
**** Bending stiffness, total deflection, skin stress and intracell buckling constraints not satisfied.