UNIVERSITY OF MISKOLC
FACULTY OF MECHANICAL ENGINEERING AND INFORMATICS

MINIMUM WEIGHT AND COST DESIGN OPTIMIZATION OF HONEYCOMB SANDWICH STRUCTURES

PH.D. THESES

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CONTENTS

SUPERVISOR'S RECOMMENDATIONS

The Candidate completed his PhD doctoral research with a high degree of independence and precision. It should be emphasized that in addition to its excellent theoretical preparation, he also has a good practical sense, making static and dynamic measurements in the laboratory. These two excellent research qualities can be well traced in the theoretical explanations of the dissertation dealing with structural model and the dissertation's significant experimental work. The dissertation describes a well-thought-out, systematic research activity that incorporates a high level of theoretical knowledge and thorough practical experimental work into high-quality scientific work in terms of content and design.

Miskolc, 09.04.2021.

Prof. Dr. Károly Jármai & Dr. habil. 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	The density of epoxy woven glass fiber	kg/m^3
ρ_{cr}	The 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
$N_{l,opt}$	The 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 the global coordinate	N.m
$D_{f,x}$	Bending stiffness of the sandwich structure in a global coordinate	N.m^2
D_{min}	Minimum stiffness of a sandwich structure	N.m
$\tilde{S}_{11}$	Shear stiffness of a composite sandwich structure	N/m
S	Shear stiffness of a 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 the 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; its in-plane stiffnesses must be small compared with the in-plane stiffnesses of the face-sheets. The sandwich plates with face-sheets on both sides of the core. Each face-sheet may be anisotropic material like aluminum alloy or a fiber-reinforced composite laminate like epoxy woven glass fiber, epoxy woven carbon fiber, and hybrid composite layers (a combination of epoxy woven glass fiber layers and epoxy woven carbon fiber layers) but must be thin compared with the core.

The honeycomb sandwich structure provides low density and relative out-of-plane compression and shear properties. Honeycomb structures are natural or human-made structures with the honeycomb architecture to reduce the amount of materials used in industrial applications to achieve minimum weight and minimum cost. Honeycomb sandwich structures have made a remarkable development in engineering applications over the past 40 years. The application of honeycomb structures ranges from the aerospace and automobile industry to structural application. Expanded honeycomb structure production reached an astonishing degree of automation in the first decade of the 20th century. There is interest in investigating these honeycomb structures' performance and efficiency in multi-disciplinary applications due to their high specific strength.

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, maritime industry, 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 of honeycomb sandwich structures are high strength-to-weight ratios, increased flexibility, and ease of machining, weldability, and availability at low cost [1-3].

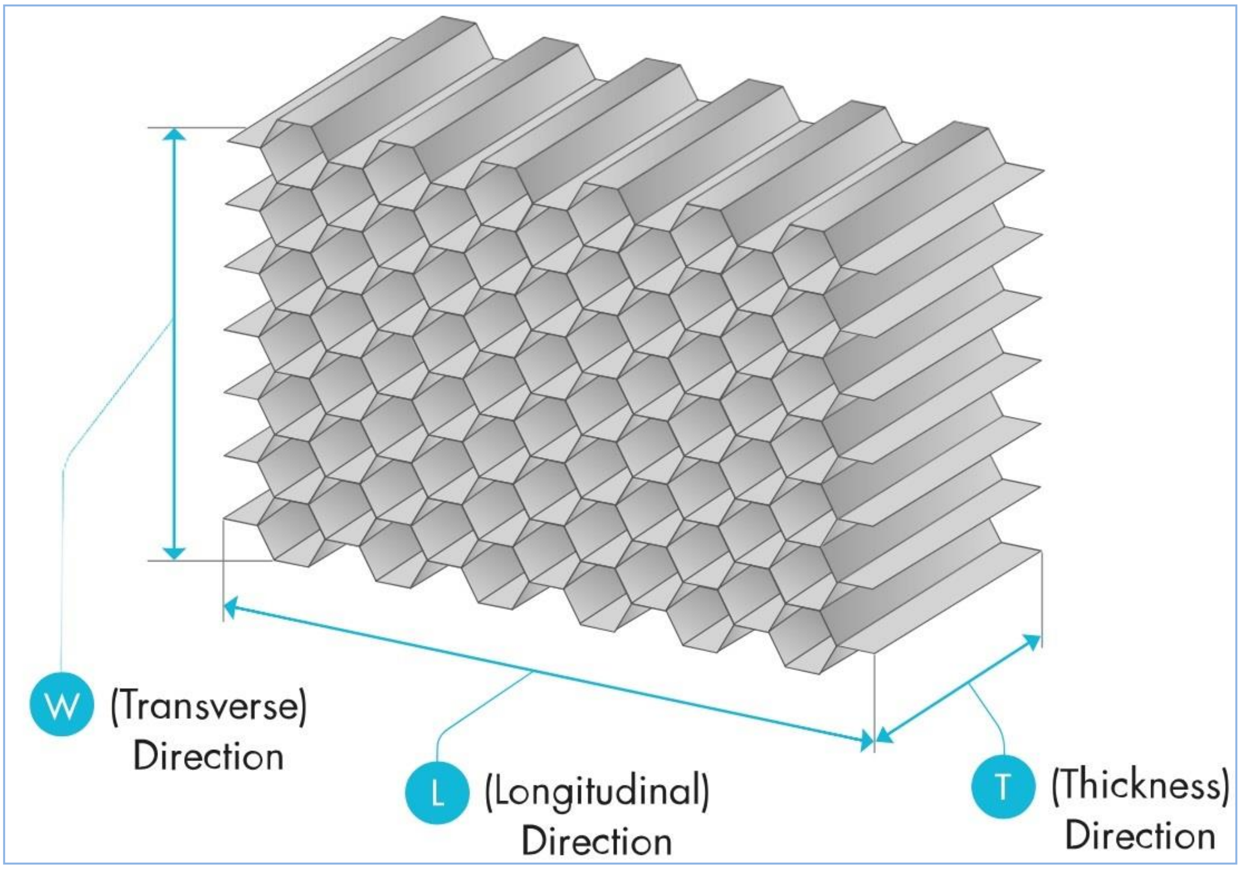


Figure 1.1: Illustration of the honeycomb core.

1.1. Background and Objectives of the Research

1.1.1. Fiber Reinforced Composites (FRC)

Technologically, the essential 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 designed 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. FRC 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 and 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 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 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 is utilized, but both carbon and glass fibers are inserted into a polymeric resin in the most common system. 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, 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 structural elements' geometrical design. Laminar composites and sandwich panels are two of the most common structural composites.

Laminar Composites: A laminar composite comprises 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°). The high strength direction for all laminae is the same for unidirectional layers (see Figure 1.2*a*); cross-ply laminates have alternating high strength layer orientations of 0° and 90° (see Figure 1.2*b*), and for angle-ply, successive layers alternate between $+\theta$ and $-\theta$ high strength orientations (e.g., ± 45°) (see Figure 1.2*c*). The multidirectional laminates have several high strength orientations (see Figure 1.2*d*). 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].

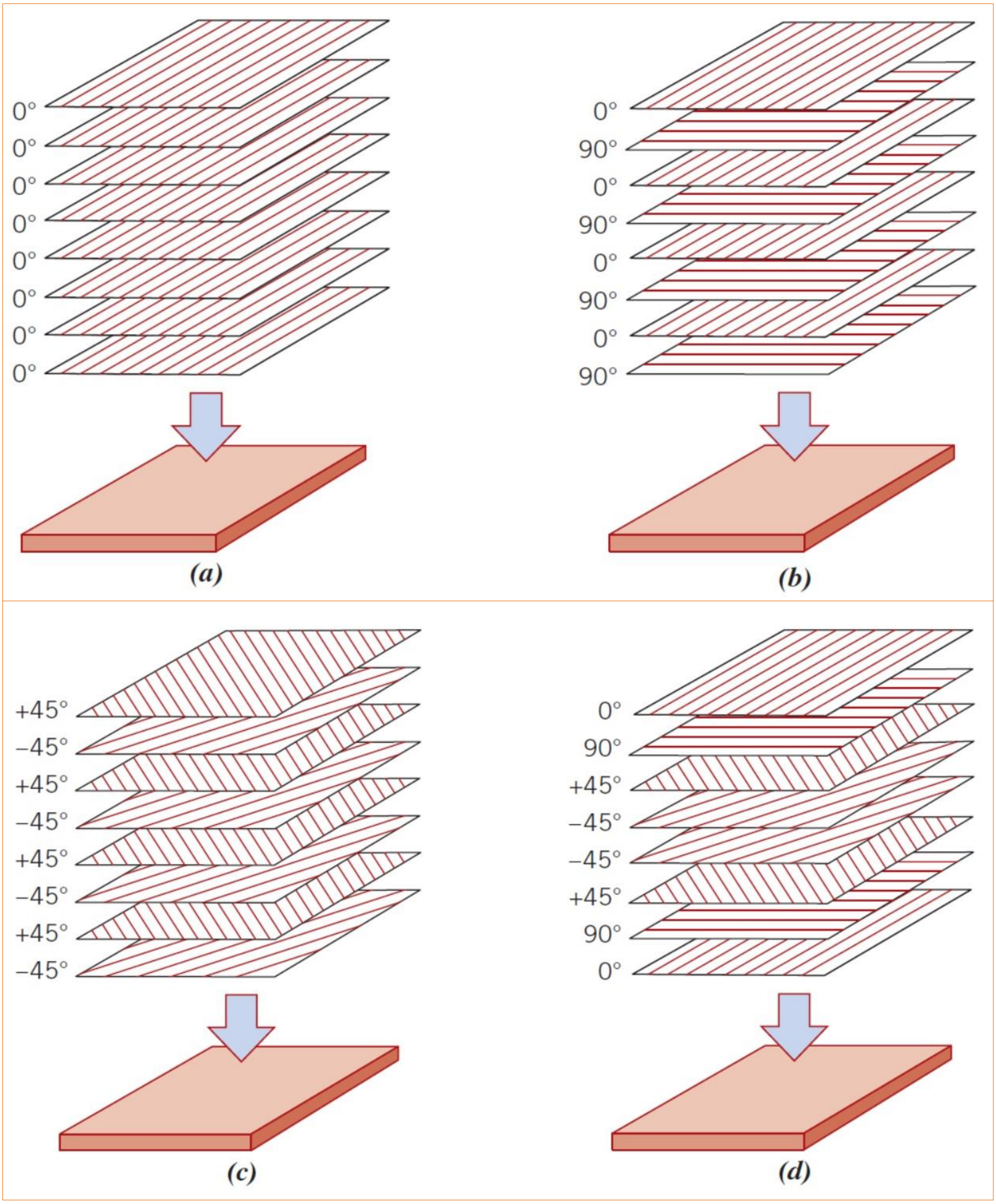


Figure 1.2: Lay-ups (schematics) for laminar composites. (*a*) Unidirectional; (*b*) cross-ply (0°, 90°); (*c*) angle-ply (±45°); and (*d*) multidirectional (cross-ply (0°, 90°) and angle-ply (±45°)) [4].

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 a relatively stiff and strong material, typically aluminum alloys, steel, and stainless steel, fiber-reinforced plastics, and plywood; they carry bending loads applied to the panel. When a sandwich panel is bent, one face experiences compressive stresses, the other tensile stresses. The core material is lightweight and typically has a low modulus of elasticity. Structurally, it serves several functions. First, it provides continuous support for the faces and holds them together. It must also have sufficient shear strength to withstand transverse shear stresses and be thick enough to provide high shear stiffness (to resist buckling of the panel). Tensile and compressive stresses on the core are much lower than on the faces. Panel stiffness depends primarily on the core material's properties and core thickness; bending stiffness increases significantly with increasing core thickness. Furthermore, faces must be bonded firmly to the core.

The sandwich panel is a cost-effective composite because core materials are less expensive than the faces' materials. Core materials typically fall within three categories: rigid polymeric foams, wood, and honeycombs. The widespread core consists of a honeycomb structure with thin foils formed into interlocking cells (having hexagonal and other configurations), with axes oriented perpendicular to the face planes; Figure 1.3 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, stainless steels, polymers, polypropylene, polyurethane, and kraft paper [4].

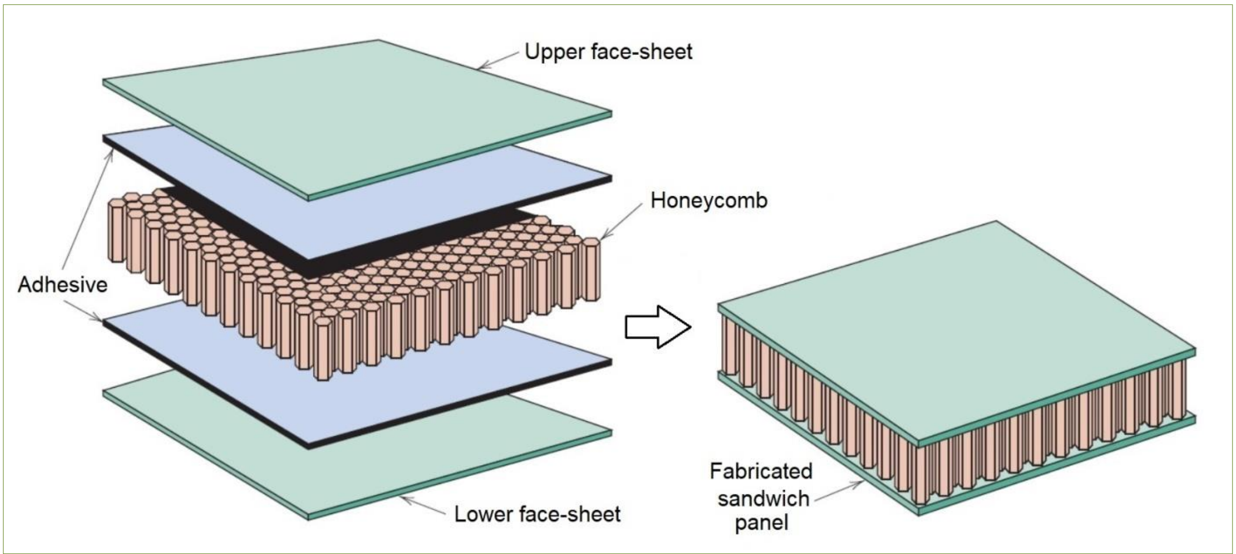


Figure 1.3: Schematic diagram showing the construction of a honeycomb core sandwich panel.

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 making the structure as rigid.

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, 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 keys is required to represent the optimal solutions of all conflicting objective functions.

Single and multi-objective optimization techniques were performed to obtain the optimum design values of the 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 known as polyepoxides containing at least two and more epoxide groups per monomer, 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 many 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 reduce 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

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

- Identify the honeycomb sandwich structure's mechanical behavior through a series of static and dynamic tests to manufacture the required applications.
- Investigation how to optimize the honeycomb sandwich structure in terms of weight and/or cost both separately and simultaneously.
- We are exploring the hybrid composite material using high cost, high stiffness composites (like carbon fiber) with low price, 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

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

In 1984, Gibson described a new method for maximizing stiffness per unit weight in sandwich beams with foam cores to obtain the optimum core thickness, face thickness, and core density [6]. 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 [7]. In 2007, Boudjemai et al. proposed a genetic algorithm for structural optimization of satellite structural designs [8]. In 2009, Inés et al. studied the structural behavior of composite sandwich panels for construction industry applications [9]. 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 [10]. 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 [11]. 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 [12]. 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 [13]. In 2011, Nguyen et al. clarified the possible advantages of ‘stepped’ facings with geometry modified to locally enhance the strength and stiffness at strategically important locations with minimum weight [14]. In 2012, Aly et al. evaluated the sandwich specimens' impact properties produced from many woven fabrics using polyester fibers as warp threads with different structure parameters such as weft yarn material and 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 [15]. In 2012, Xiang et al. develop a minimum weight optimization method for the sandwich structure under combined torsion and bending loads [16]. In 2012, Chen and Yan developed the models of finite elements for the resulting sandwich panels [17]. In 2012, Du et al. fabricated various sandwich panels with PRP composite skins and aramid honeycomb core in the laboratory. They evaluated the effects of honeycomb core height and cell size on the flexural properties of sandwich panels [18]. In 2012, Araújo et al. presented the optimization of active and passive damping of hybrid active-passive laminated sandwich plates by developed a finite element model for the analysis and optimization [19]. 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 [20]. In 2013, Ai et al. investigated the effects of random skin/core weld defects on out-of-plane tensile, compressive and in-plane shear behaviors for hexagonal cell aluminum honeycomb sandwich panels using ABAQUS/Explicit code [21]. In 2014, Rodrigues et al. optimized the material configuration of 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 [22].

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 [23]. 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 [24]. In 2014, Martínez-Martín and Thrall presented a multi-objective optimization procedure to design material properties of honeycomb core sandwich panels for a minimum weight and maximum thermal resistance within the context of origami-inspired shelters [25]. In 2014, Roy et al. predicted the honeycomb core's local buckling load and identified the material model of the Nomex™ honeycomb constituent. The specimens were subjected to bolt pull-out load tests [26]. 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 [27]. In 2015, Ebrahimi and Vahdatazad investigated honeycomb sandwich cylindrical columns' energy absorption characteristics such as square, triangle, kagome, and diamond core under axial crushing loads by nonlinear finite element analysis [28].

In 2015, Abbadi et al. presented experimental fatigue data for honeycomb sandwich panels with artificial defects and without defects [29]. In 2015, Ndiaye et al. investigated to characterize join bonds and defects in honeycomb sandwich composite structures. A suitable focal law gives the ultrasonic dispersive properties of the composite skin and glue layer behind [30]. In 2016, Bode investigated replacing the existing aluminum floor with a lighter composite in Nordisk containers, performed analytical and finite element calculations, and conducted small-scale and full-scale tests based on the calculation results and requirements [31]. In 2016, Zhao et al. examined the new long-span hollow core roof architecture's lateral compressive buckling performance with different length-to-thickness ratios by employed lateral compression tests and finite element analyses [32]. In 2016, Mariana developed innovative, lightweight design and joining concepts for air cargo containers made of carbon fiber woven composite to reduce weight [33]. 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 panels stiffness of a solar panel's hinge [34]. In 2016, Sun et al. presented periodical grids that were selected to reinforce sandwich structures' soft honeycomb cores [35].

In 2016, Liu et al. explored the characteristics of crashworthiness and mechanism of failure for square tubes of carbon fiber reinforced plastic (CFRP) filled with aluminum honeycomb subjected to quasi-static axial crushing [36]. In 2016, Kim et al. designed a fire-retardant sandwich structure to satisfy the limit of critical thermal radiation to humans using a phenolic foam-filled honeycomb and carbonized phenolic matrix aramid/glass hybrid composite faces [37]. In 2016, Wang et al. presented a methodology for axial compressed hexagonal honeycomb to aid in a honeycomb's design and selection. Series theoretical formulas for total energy absorption and specific energy absorption against geometrical configuration and loading situation were constructed based on folded elements [38]. In 2016, Karen et al. presented a hybrid evolutionary optimization technique based on the Multi-Island Genetic Algorithm [39].

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 [40].

In 2017, Adel & Steven presented a methodology for a combined weight and cost optimization for sandwich plates with composite face-sheets and foam core. The hybrid sandwich plates' weight and cost considered objective functions are subject to required equality constraints based on the bending and torsional stiffnesses [41]. 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 [42]. In 2017, Yan J. et al. conducted a large experiment on three typical blade sandwich structures to simulate the natural lightning-induced arc effects [43]. In 2017, Ingrole et al. presented novel design and performance improvement of new auxetic-strut and hybrid honeycomb structures for in-plane property enhancement [44]. In 2017, Wu et al. identified the crash responses and crashworthiness characteristics of bio-inspired sandwich structures formed of carbon fiber reinforced plastic (CFRP) panels and aluminum honeycomb core [45]. In 2017, Liu et al. investigated the lateral planar crushing and bending responses of carbon fiber reinforced plastic (CFRP) square tube filled with an aluminum honeycomb core [46]. In 2017, Zaharia et al. analyzed and determined the CFRP-Nomex sandwich structures specimens' mechanical properties to different types of tests, such as three-point bending, compression, and impact [47].

In 2017, Kececi and Asmatulu investigated the hydrophobic barrier films utilized to prevent moisture ingression into honeycomb sandwich structures [48]. In 2017, Hambric et al. redesigned a rotorcraft roof composite sandwich panel to optimize the loss of sound power transmission and minimize the sound of structure-borne. The gear meshing noise from the transmission has the most impact on speech intelligibility. The roof is framed by a grid of ribs constructed of honeycomb core and composite face-sheet [49]. In 2017, Wang et al. carried out comprehensive investigations of honeycomb structures embedded with the inclined cells to understand the mechanical behavior subjected to compression [50]. In 2017, Yalkin et al. improved the out-of-plane tensile and compressive performances of foam core composite sandwich structural regarding the simplicity of application and time consumption [51]. 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 [52]. In 2018, Iyer et al. investigated a comparative study between three points and four points bending sandwich composites made of rigid foam core and glass epoxy skin [53]. In 2018, Chawa and Mukkamala optimized a shipping container made of sandwich panels to reduce tare weight and stresses [54].

In 2019, Florence & Jaswin investigated vibrational analysis and flexural behavior of hybrid honeycomb core sandwich panels filled with three different energy-absorbing materials experimentally [55]. 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 [56]. In 2020, Zaharia et al. performed compression, three-point bending, and tensile tests to evaluate lightweight sandwich structures' performance with different core topologies [57]. 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 [58]. 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 [59].

2. MECHANICAL TESTS ON PREPREG SANDWICH CONSTRUCTIONS

2.1. Introduction

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

2.2. Materials and Methods

2.2.1. Four-Point Bending Test of Honeycomb Sandwich Panels

This test method is intended to determine the relationship between load and displacement as well as skin stress. The specimen lies on a span length, and the stress is uniformly distributed between the noses of loading. The sandwich panels' samples are made of an aluminum honeycomb core and orthotropic composite material face-sheets (see Figure 2.1). The composite face-sheets are made of phenolic woven glass fiber. The fiber orientation of the composite face-sheets was cross-ply. These specimens were made in the Kompozitor Ltd. Company (Budapest, Hungary). Numerical models are made for the same samples using the Digimat-HC modeling program to calculate the deflection, skin stress, and core shear stress to compare with the experimental results. The average skin stress and modulus can be determined by Equation below. These equations are applicable for a symmetrical sandwich panel with thin face skins [60]:

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

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

The four points of contact in the bending test, two points where loading is applied, and two support points. The 4-point bending test procedures are:

1. The loading equipment is arranged, as shown in Figure 2.1.
2. The load is applied to the samples using steel cylinders with loading pads.
3. The dimensions of the specimens and span length are measure in mm.
4. The load is applied at a constant rate that will cause the maximum load and then record the maximum load.
5. Measure the deflection of specimens at mid-span using a deflectometer and plot the load-deflection curves. This test is referring to MIL-STD-401B Sec.5.2.4 or ASTM C-393 [61].

The failure caused by this test could be shearing the core, shearing the bond between the skin facings and the core, direct compression or tension failure of the skins, localized wrinkling of thin facings at load points.

Figures 2.3 & 2.5 represent the experimental results (four-point bending test), including the deflection-load curve for the set of honeycomb sandwich specimens, and Figures 2.4 & 2.6 represent the numerical results (four-point bending test) including deflection, skin stress, and core shear stress for the honeycomb sandwich models set to the comparison. Because the results have the same behavior, so I showed some of them.

According to the experimental and numerical results shown in Tables 2.1 & 2.2, the most efficient way to reduce the deflection of sandwich panels is to increase the honeycomb core thickness, thus increase skin separation and lead to an increase in the stiffness-to-weight ratio. The most efficient way to reduce 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		Skin stress		Core shear stress	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	Skin stress	Core shear stress	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	5.32
2					1 (2-2)	1500	50.3	0.818	10.2	10.185	0.15
3					1 (2-2)	1600	53.6	0.872	11	10.864	1.24
4				19	2 (4-4)	1650	44.8	0.675	5.7	5.345	6.23
5					2 (4-4)	1950	53	0.798	7	6.317	9.76
6					2 (4-4)	2000	54.4	0.818	6.5	6.479	0.32
7					2.5 (5-5)	1800	52.4	0.687	4.5	4.854	7.29
8					2.5 (5-5)	1900	50.5	0.74	5	5.357	6.66

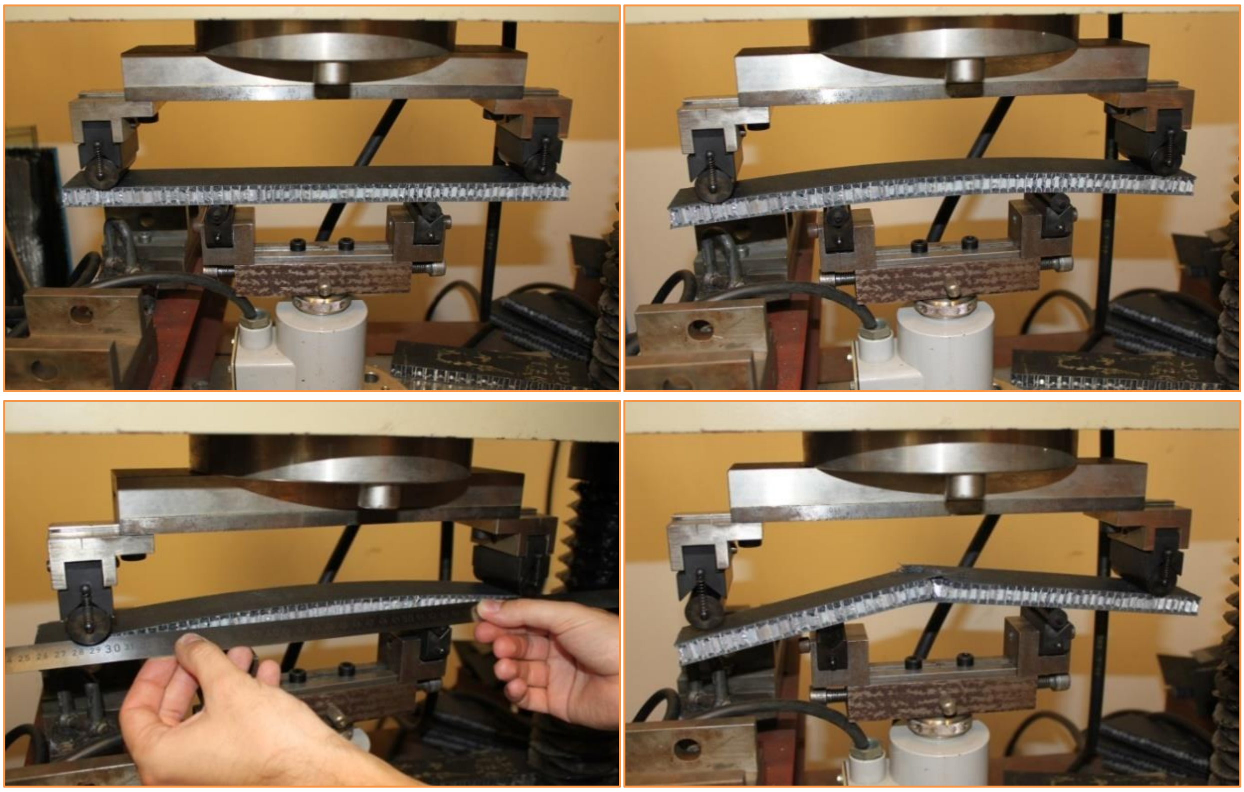


Figure 2.1: Experimental specimens (four-point bending test) for the sandwich panels consisting of aluminum honeycomb core and phenolic woven glass fiber face-sheet.

- *The Digimat-HC Program*

The Digimat-HC program (version 2017.0, MSC Software, Irvine, CA USA) is a multi-scale tool for modeling bending tests and in-plane shear sandwich panels. It is a complete, simple, accurate, and flexible software tool dedicated to sandwich and honeycomb structures. The program considers the effect of the microstructure for both the core and the sandwich's skins. For the honeycomb core, the homogenized properties are computed by the Digimat-HC program based on the honeycomb unit cell's geometry. For the skins, the same option is available. Skin is made of several layers piled up in a given order, with given orientations and thickness. Each layer can be defined at the macro or micro level.
The Digimat-HC program analysis procedures are the following:

1. *Core's tab*

The core model is the principal constituent of the sandwich structure, defined as the assembly of two face-sheets. The following parameters have to be defined: the name of the core, the type of core model, and the core thickness. A honeycomb core can be defined at the micro and/or macro level. When it is defined at the micro-level, homogenized properties will be calculated by the Digimat-HC program based on the microstructure and its base material properties. The microstructure tab is utilized to define information about the microstructure and the honeycomb core material: the cell's shape, the cell's dimensions, and the base material properties. The homogenize tab is used to define the homogenized macroscopic properties of the honeycomb core. These properties can be entered manually in the different fields or calculated from the microstructure information by a homogenization step.

2. Layer's tab

The second step of the analysis is defining layers. The foundation constituent of the skins is the plies. The homogenized properties of the layers can be defined utilizing the tab of homogenized properties. The shell element is the element type.

3. Sandwich's tab

The composition (pile-up sequence) of the skins can be defined using this tab (pile-up definition). The first parameter that has to be defined is the number of layers. The following parameters have to be defined for each layer used in the pile-up: the type of layer, the layer's orientation, and the ply's thickness.

4. Loading's tab

The 4-point bending is the type of loading. The following parameters have to be defined: the geometry of the panel, the force (F), the width of the loading pads, the orientation of the core definition, the mesh refinement level is Fine mesh, and the symmetric boundary conditions not be used with a sandwich presenting skins that are 'not equilibrated'. The finite element mesh will have around 9000 elements.

5. Results' tab

This tab is used to plot a 3D view of the sandwich. All tabs are shown in Figure 2.2.

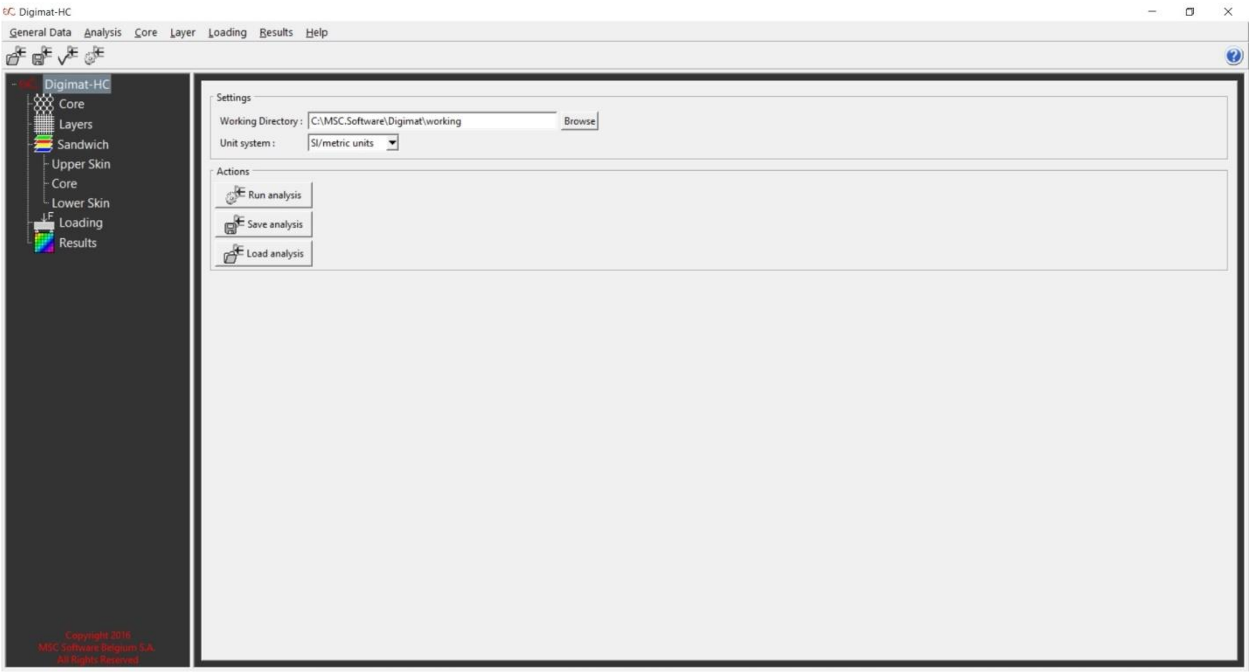


Figure 2.2: Experimental result (four-point bending test) for the specimen of the sandwich panel under applied load (P=1500 N) consisting of an aluminum honeycomb core (t_c=15 mm) and phenolic woven glass fiber face-sheets (t_f=1 mm).

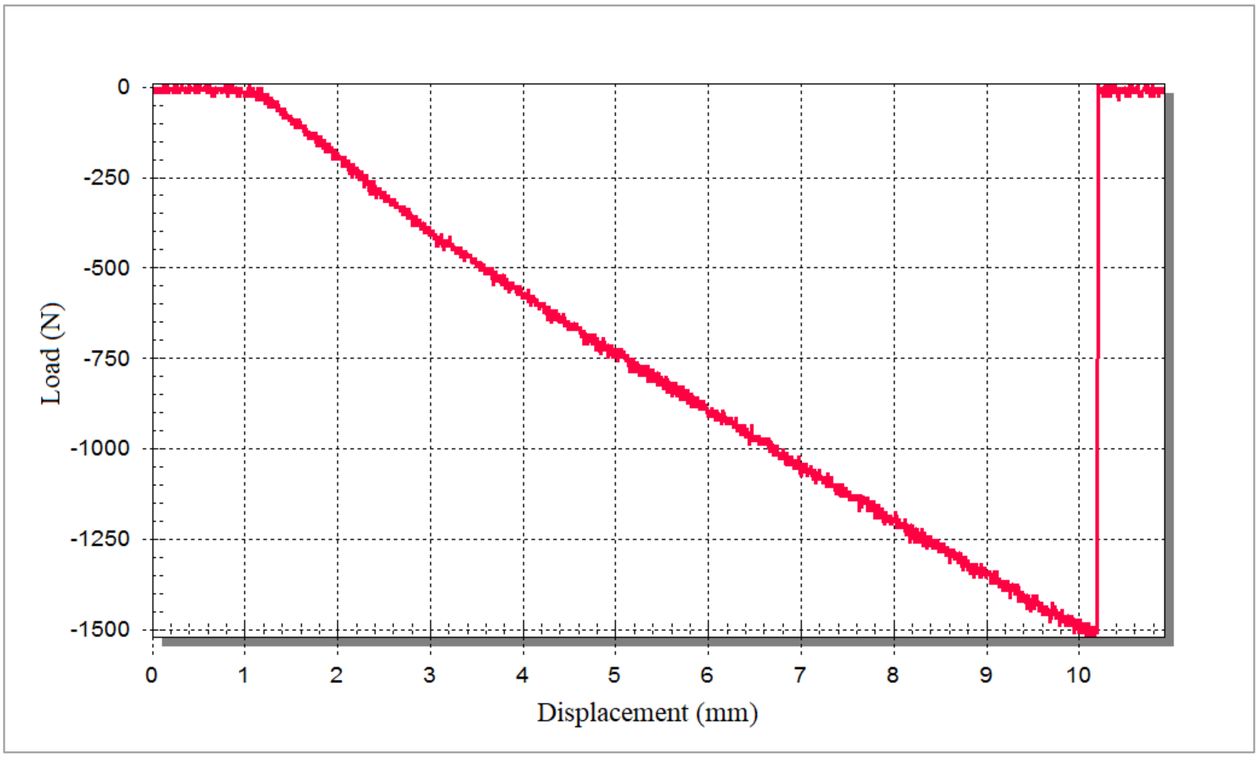


Figure 2.3: Experimental result (four-point bending test) for the specimen of the sandwich panel under applied load (P=1500 N) consisting of an aluminum honeycomb core (t_c=15 mm) and phenolic woven glass fiber face-sheets (t_f=1 mm).

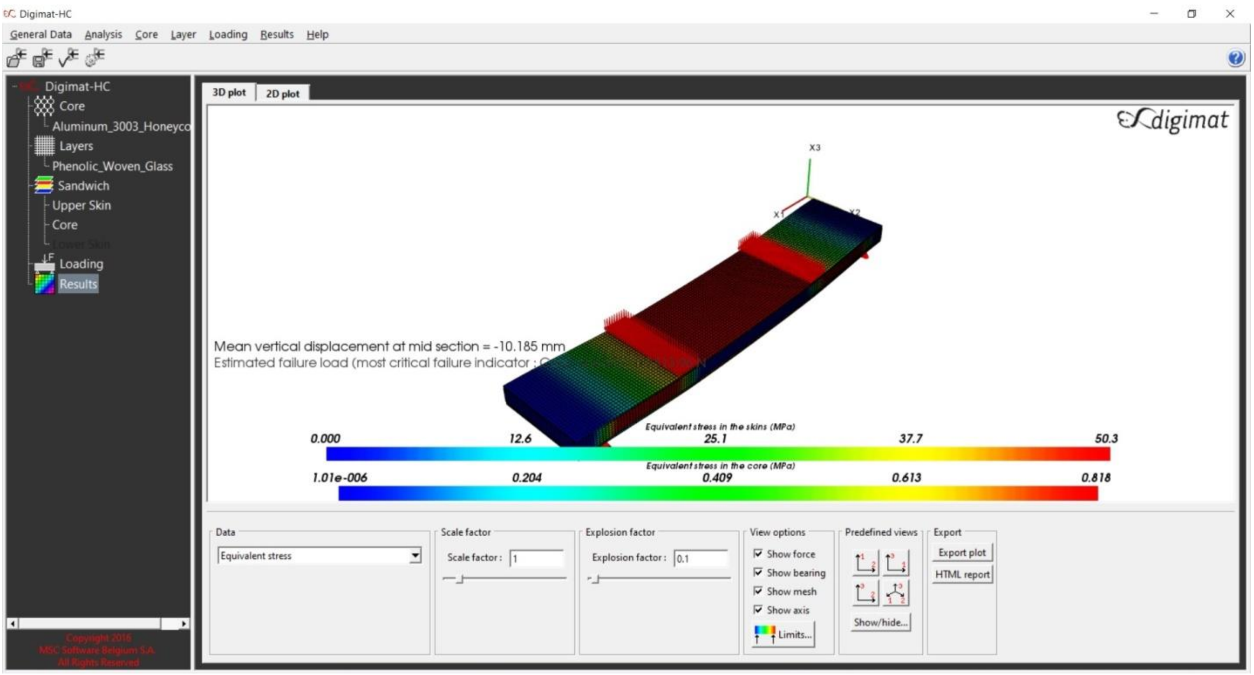


Figure 2.4: Numerical result (four-point bending test) for the specimen of the sandwich panel under applied load (P=1500 N) consisting of an aluminum honeycomb core (t_c=15 mm) and phenolic woven glass face-sheets (t_f=1 mm).

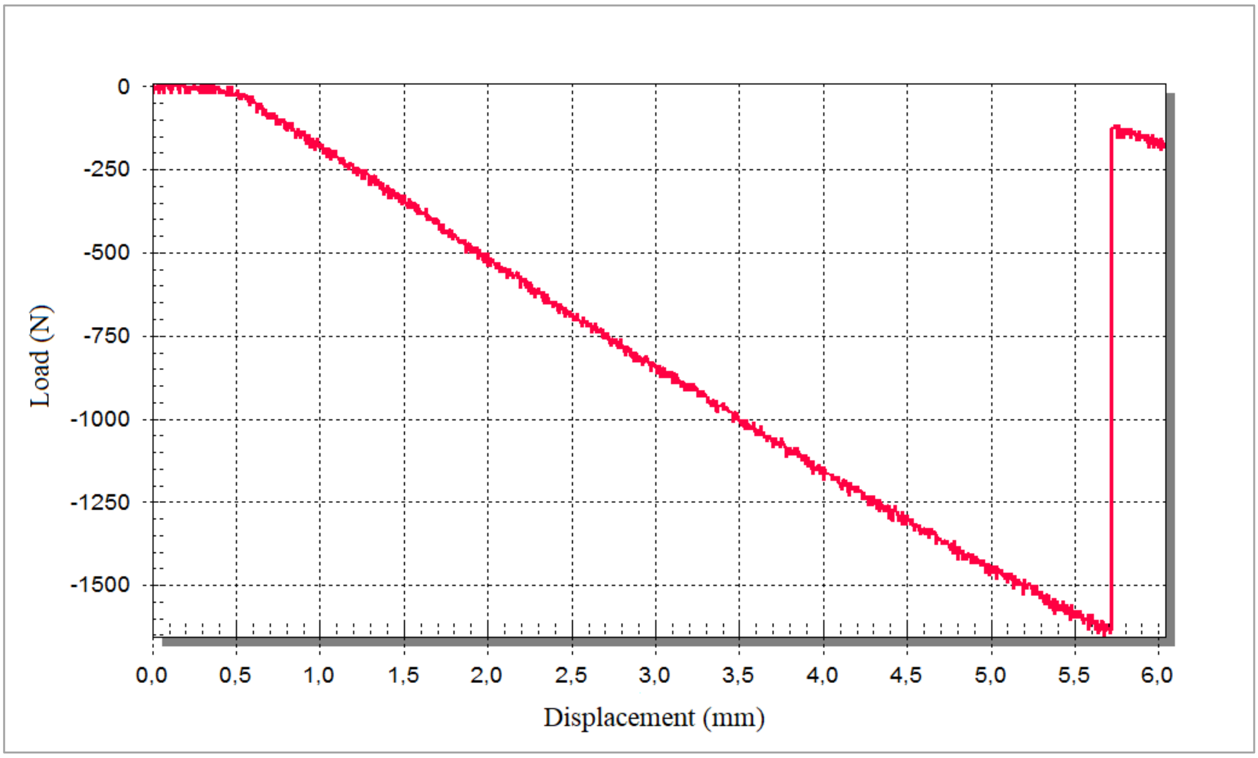


Figure 2.5: Experimental result (four-point bending test) for the specimen of the sandwich panel under applied load (P=1650 N) consisting of an aluminum honeycomb core (t_c=19 mm) and phenolic woven glass face-sheets (t_f=2 mm).

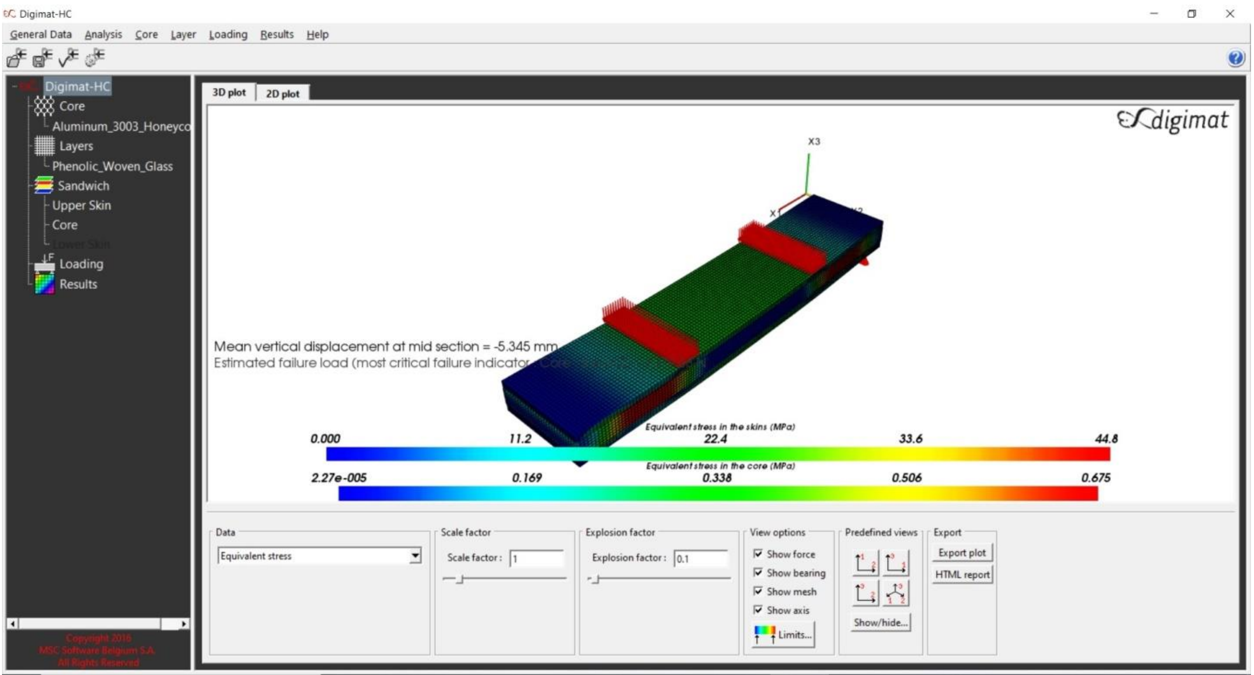


Figure 2.6: Numerical result (four-point bending test) for the specimen of the sandwich panel under applied load (P=1650 N) consisting of an aluminum honeycomb core (t_c=19 mm) and phenolic woven glass face-sheets (t_f=2 mm).

2.2.2. *Climbing Drum Peel Test*

This test method is intended to determine the adhesive bonds' peel resistance between the facing skins and the sandwich panel's core (see Figure 2.7). 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 [62]:

$$F_p(N) = F_r - F_i \tag{2.3}$$

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

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 Ltd. Company. The honeycomb core thickness does not affect the adhesive's peeling resistance between the face-sheets and the sandwich structure's core, but the thickness of the face-sheets affects. Because the thicker face-sheets, the harder it bends on the drum. These results of peeling resistance and force are shown in Table 2.3 and Figures 2.8 & 2.9. Because the results of the Peeling test have the same behavior, so I showed two of them.

- *Test device*

This method is most applicable when the facings being peeled are relatively thin. The peeling torque calculated from this test includes both the forces required to peel the adhesive bond and bend the skin. The peel test device consists of a flanged drum, flexible loading straps or cables, and suitable clamps for holding the test specimen (top clamp to loading the sample, and drum clamp to initially have the facings tangent to the face of the drum as shown in Figure 2.7).

- *Test procedure*

The test specimens must be clamped securely to the drum, as shown in Figure 2.7, and the other end of the sample clamped by the top clamp. The specimen and device peel then be pending from the top head of the testing machine by a pin through the drum clamp hole. The loading bar is then pinned to the fixed fittings in the lower head of the testing machine. An initial force is applied by loading the device in tension (equal to that obtained in the device's calibration for the load) to overcome the drum's resisting torque. The specimen is then ready for testing. The skin facing of the sandwich panel is peeled by the loading of the device in tension. The force versus distance peeled is recording. The average peeling force required to peel the facing is taken from the curve for the sandwich specimens' peeling, the maximum peeling force obtained during the test also [61].

Table 2.3: Experimental result (Peeling test) for a set of sandwich panel specimens consisting of an aluminum honeycomb core and phenolic woven glass fiber face-sheets (2-2) layers / 0.5 mm.

Index	Peak force	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

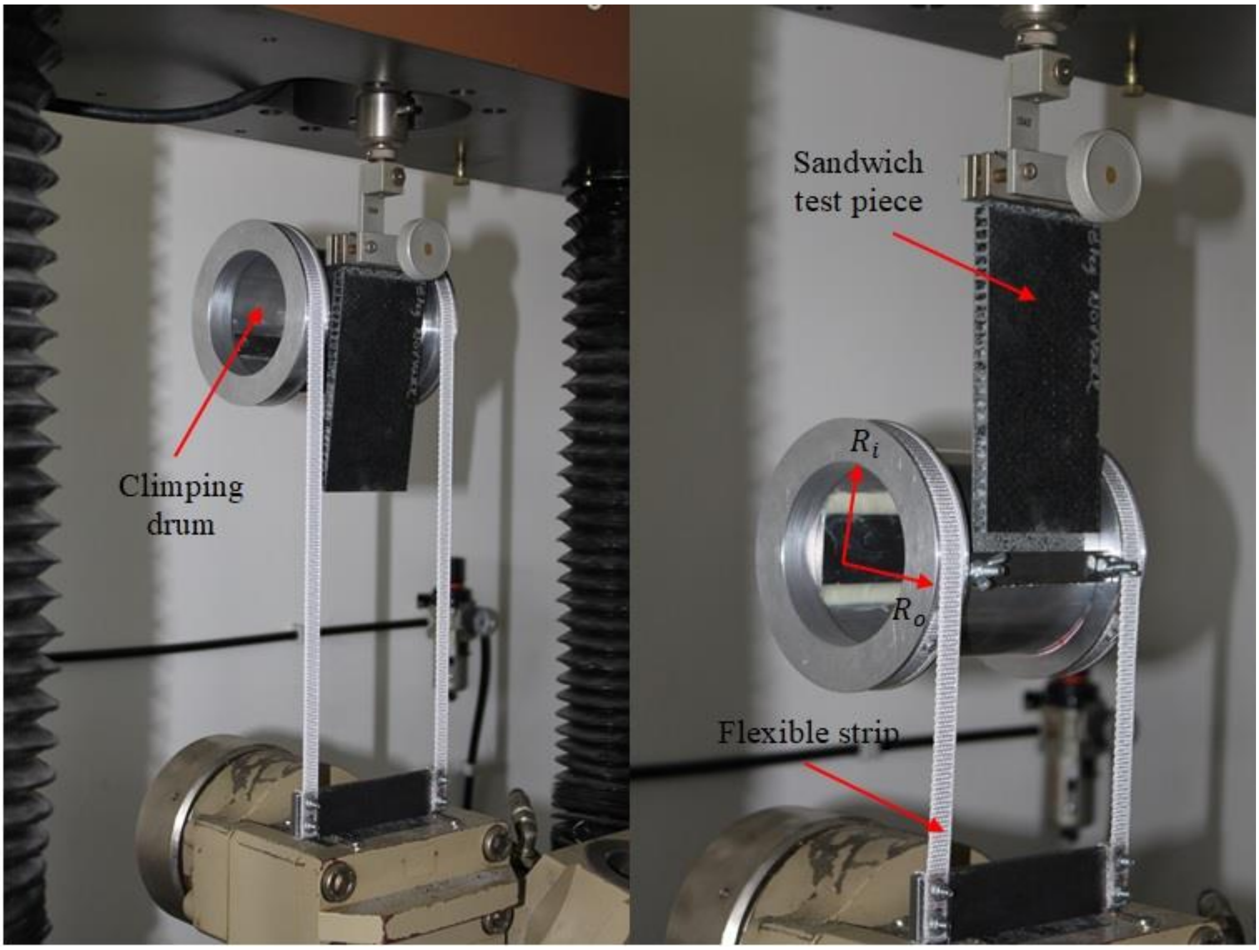


Figure 2.7: Climbing drum apparatus for the specimen of sandwich panels consisting of an aluminum honeycomb core and phenolic woven glass fiber face-sheets.

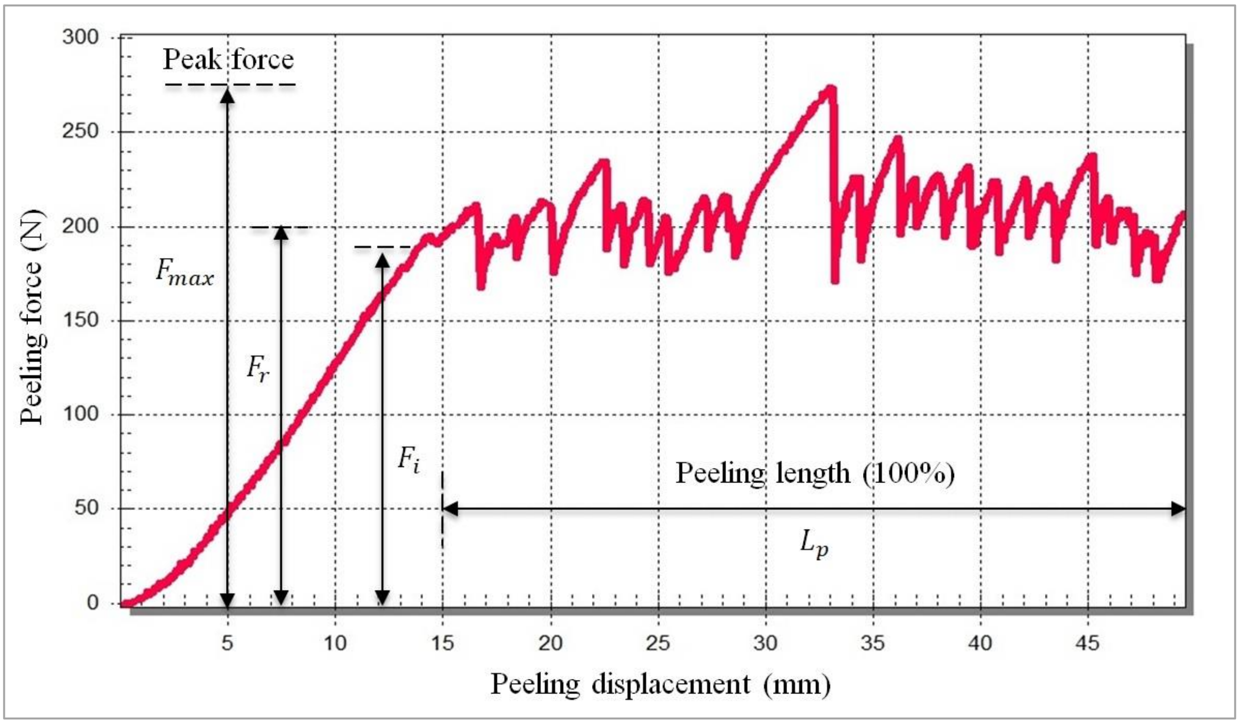


Figure 2.8: Experimental result (Peeling test) for specimen No.1 of sandwich panel consisting of an aluminum honeycomb core and phenolic woven glass fiber face-sheets (2-2) layers / 0.5 mm.

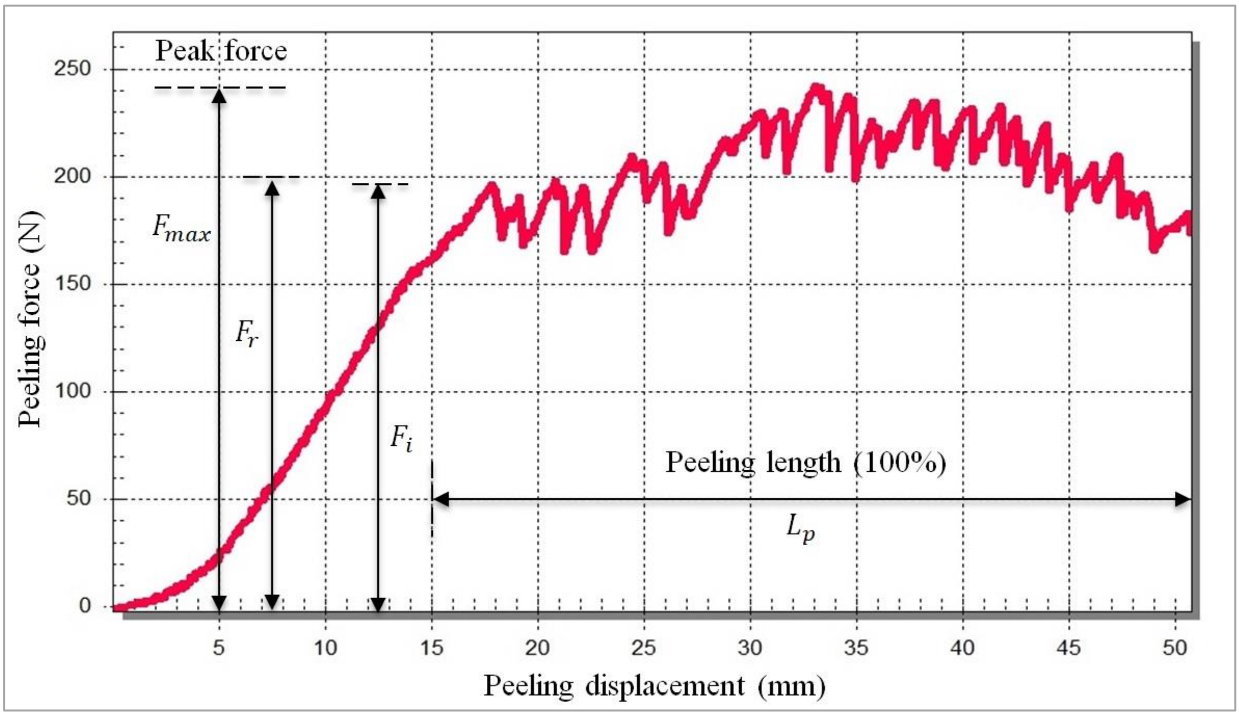


Figure 2.9: Experimental result (Peel test) for specimen No.2 of sandwich panel consisting of an aluminum honeycomb core and phenolic woven glass fiber face-sheets (2-2) layers / 0.5 mm.

2.2.3. Experimental Modal Analysis (Forced Vibration Test and Damping Test)

- *Introduction*

It might be hard to improve the system's mathematical model in some practical situations and predict its vibration characteristics within an analytical study. Experimental methods can be applied to measure the sandwich structure's vibration response to a known input in such cases. This helps in identifying the system in terms of its mass, stiffness, and damping. This section shows the different aspects of vibration measurement for honeycomb sandwich structure application. An electrodynamic shaker's working principle, utilized to excite honeycomb sandwich specimens to study its dynamic characteristics, is presented. The signal analysis, which determines the system's response under known excitation and shows it in a suitable form, is summarized along with descriptions of the spectrum analyzer, bandpass filter, and bandwidth analyzers. The experimental modal analysis deals with determining natural frequencies and damping ratio by vibration testing. The growing requests for economical design and effective utilization of materials through lightweight sandwich structures, these trends make resonant conditions more frequent during the structure's operation and decrease the system's safety. The periodic measurement of vibration characteristics for structures becomes necessary to assure sufficient safety boundaries. Any observed change in the natural frequencies or other vibration characteristics will indicate either a failure or a need to maintain. The measurement of the natural frequencies of a structure is useful to 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 procedure of the experimental modal analysis is described in the following section. Since any dynamic response of a structure can be obtained as a combination of its modes, a knowledge of the modal frequencies and modal damping ratios constitutes a complete dynamic description of the structure [63].

- *Equipment*

The measurement of vibration requires the following hardware:

1. A vibration source (electromagnetic shaker) to apply a known input force to the structure.
2. A transducer to convert the structure's physical motion into an electrical signal.
3. A signal conditioning amplifier makes the transducer characteristics compatible with the digital data acquisition system's input electronics.
4. An analyzer to perform the tasks of signal processing and modal analysis using suitable software.

- *Vibration Exciter*

The electromagnetic shaker can produce high input forces so that the response can be measured easily. The excitation signal is a swept sinusoidal type signal. The magnitude of a harmonic force F is applied at several discrete frequencies over a specific frequency range of interest in the swept sinusoidal input. At each discrete frequency, the structure is made to reach a steady-state before the response's magnitude and phase are measured. If the shaker is attached to the structure being tested, the shaker's mass will influence the measured response.

The shaker is attached to the structure through a short, thin rod, called a stringer, to isolate the shaker, reduce the added mass, and apply the force to the structure along the stringer's axial direction. The electrodynamic shaker can be used to determine the dynamic characteristics of machines and structures of materials.

When current passes through a coil placed in a magnetic field, a force F (in newtons) proportional to the current I (in amperes) and the magnetic flux intensity D (in teslas) is produced which accelerates the component placed on the shaker table:

$$F = DIl \tag{2.5}$$

Where l is the coil's length (in meters), the magnitude of the table's acceleration or component depends on the maximum current and the masses of the element and the shaker's moving element. The electrodynamic exciters generate forces up to 30,000 N, displacements up to 25 mm, and frequencies range of 5 Hz to 20 kHz [66].

- *Transducer*

A piezoelectric transducer (accelerometer) can be designed to provide signals proportional to either force or acceleration. In an accelerometer, the piezoelectric material works like a stiff spring that causes the transducer to have a resonant or natural frequency. An accelerometer is an instrument that measures the acceleration of a vibrating body. The maximum measurable frequency of an accelerometer is a fraction of its natural frequency.

- *Resistance Transducer (Strain Gauge)*

An electrical resistance strain gauge consists of a fine wire whose resistance changes when subjected to mechanical deformation. The strain gauges can also measure the vibration response. 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 wire is sandwiched between two sheets of thin paper. The strain gauge is bonded to the surface where the strain is to be measured. The manufacturer of the strain gauge offers 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 [63]:

$$\epsilon = \frac{\Delta L}{L} = \frac{\Delta R}{RK} \tag{2.6}$$

- *Analyzer*

The response signal, after conditioning, is sent to an analyzer for signal processing. A type that is commonly used is the fast Fourier transform (FFT) analyzer. Such an analyzer receives analog voltage signals (representing acceleration, strain, or force) from a signal-conditioning amplifier, filter, and digitizer for computations.

It computes the discrete frequency spectra of individual signals and cross-spectra between the input and the different output signals. The analyzed signals can find the natural frequencies, damping ratios in either numerical or graphical form.

- *Signal Conditioner*

Since the output impedance of transducers is not suitable for direct input into the signal analysis equipment, signal conditioners, in the form of charge or voltage amplifiers, are used to match and amplify the signals before signal analysis.

- *Signal Analysis*

In signal analysis, we determine a system's response under a known excitation and present it in a convenient form. The acceleration-time response of a honeycomb sandwich structure that is subjected to excessive vibration might appear. The acceleration-time response is transformed to the frequency domain, and the resulting frequency spectrum might appear [67-68].

- *Spectrum Analyzers*

Spectrum or frequency analyzers can be used for signal analysis. These devices analyze a signal in the frequency domain by separating the signal's energy into various frequency bands. Figure 2.10 shows a real-time octave and fractional octave digital frequency analyzer conditioning amplifier and exciter control devices [69].

Figure 2.10: Digital frequency analyzer, conditioning amplifier, and exciter control devices.

- *Time-Domain Analysis*

The time-domain analysis uses the time history of the signal (waveform). The signal is stored in an oscilloscope or a real-time analyzer, and any nonsteady or transient impulses are noted.

- *Frequency-Domain Analysis*

The frequency-domain signal or frequency spectrum is a plot of the amplitude of vibration response versus the frequency. It can be derived by using the digital fast Fourier analysis of the time waveform.

- *Results of Forced Vibration Test*

The experimental modal analysis, also known as modal analysis or modal testing, deals with natural frequencies, stress, acceleration, and damping ratios through vibration testing [64-65]. The experimental tests included a forced vibration test to find natural frequencies, stress, and acceleration responses. The sandwich panels' specimens are made of an aluminum honeycomb core and phenolic woven glass fiber face-sheets in the Kompozitor Ltd. Company (see Figure 2.11). The dimensions of these specimens are shown in Table 2.4. The fiber orientation of the composite face-sheets was cross-ply. We can notice through the experimental results shown in Table 2.5 and Figures 2.12 & 2.13, the increase in the honeycomb core thickness will lead to a rise in the honeycomb sandwich panels' natural frequencies, a decrease in the stress response, and a reduction in the acceleration response due to the increase in stiffness-to-weight ratio.

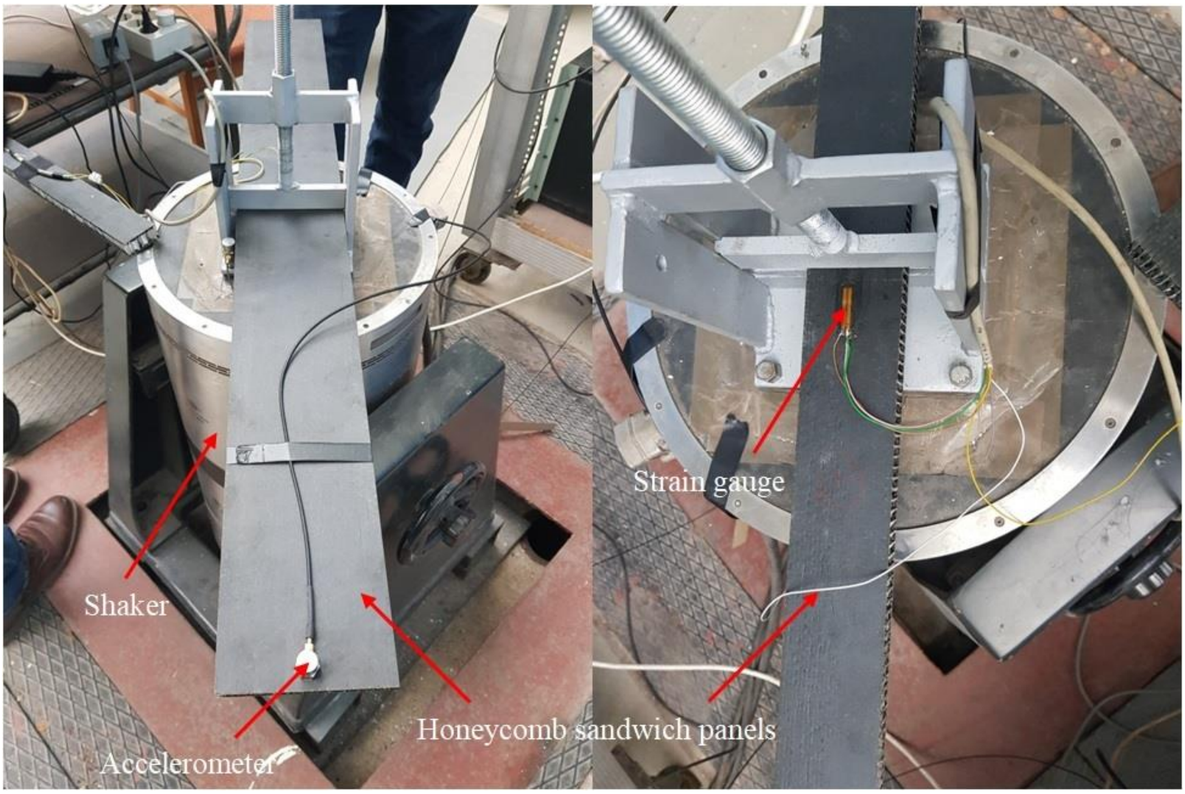


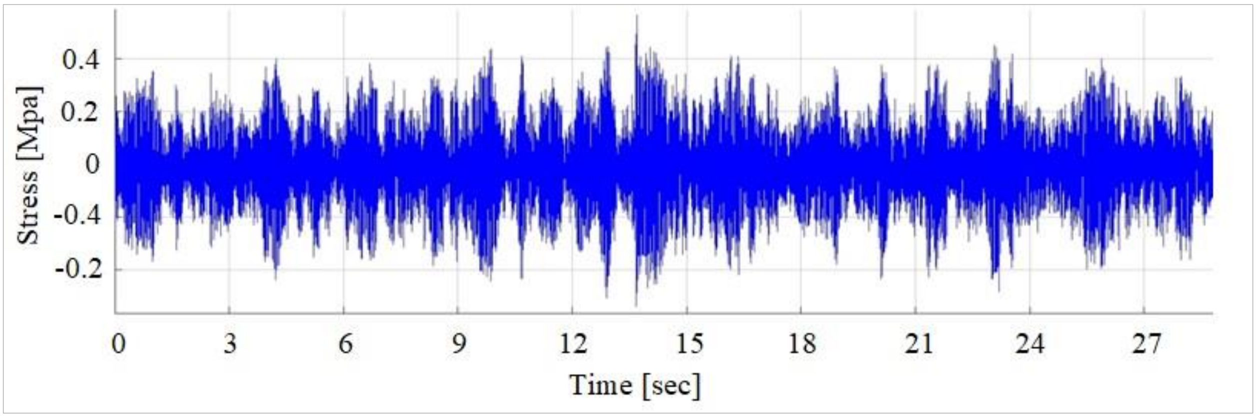
Figure 2.11: Experimental modal analysis (forced vibration test).

Table 2.4: Dimensions of experimental tests by applying forced vibration test for honeycomb sandwich specimens set.

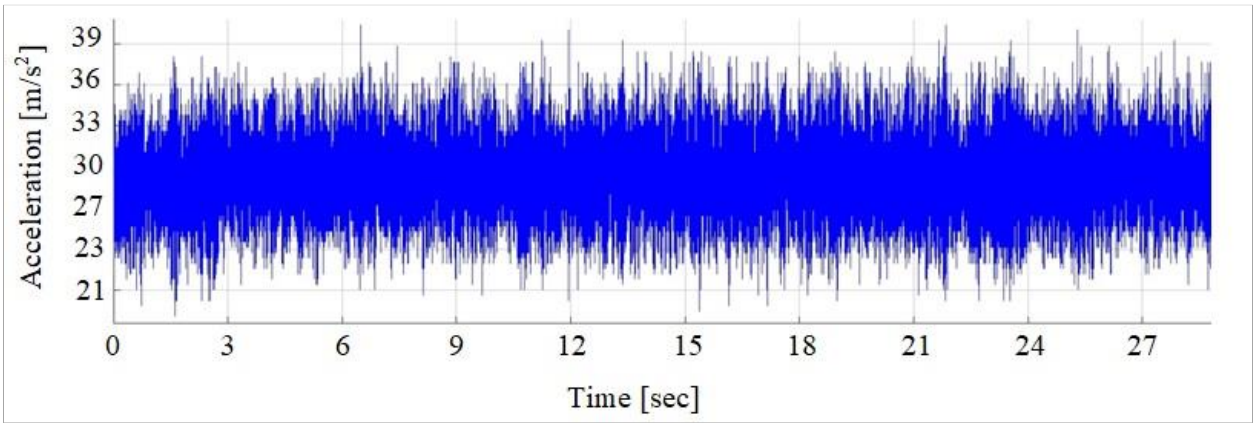
Specimens	Length	Width	Core thickness	Face-sheet thickness	Sandwich height
	l	b	t_c	$t_f(N_l)$	h
	mm	mm	mm	mm (Layers)	mm
S_1	1000	120	4	1 (2-2)	6
S_2	1000	120	20	1 (2-2)	22
S_3	1000	115	13	1 (2-2)	15
S_4	1130	54	18	1 (2-2)	20
S_5	710	43	16	1 (2-2)	18

Table 2.5: Experimental results (forced vibration test) for the sandwich panel specimens, consisting of an aluminum honeycomb core and phenolic woven glass fiber face-sheets.

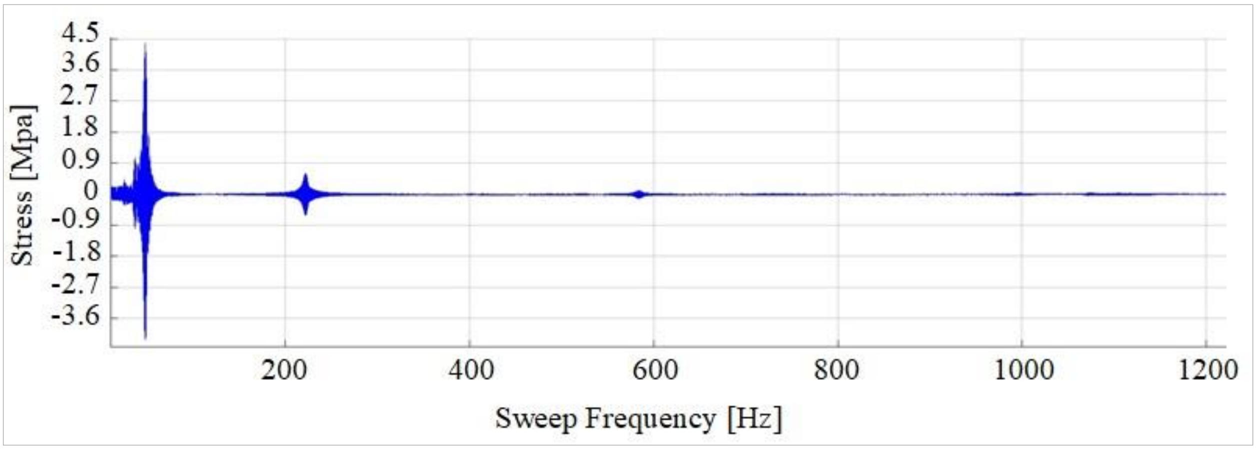
Range [Hz/sec]		(5-1200)	(10-1200)	(10-1200)	(10-1200)	(10-1200)
Gravity		2g	1g	1g	1g	1g
Specimens		S_1	S_2	S_3	S_4	S_5
Natural frequencies	f_1	14	56	38	34	50
	f_2	96	268	194	166	86
	f_3	254	350	244	210	408
	f_4	516	732	578	510	570
	f_5	812	826	666	572	1258
	f_6	1202	924	1086	980	1502
	f_7	1384	1434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



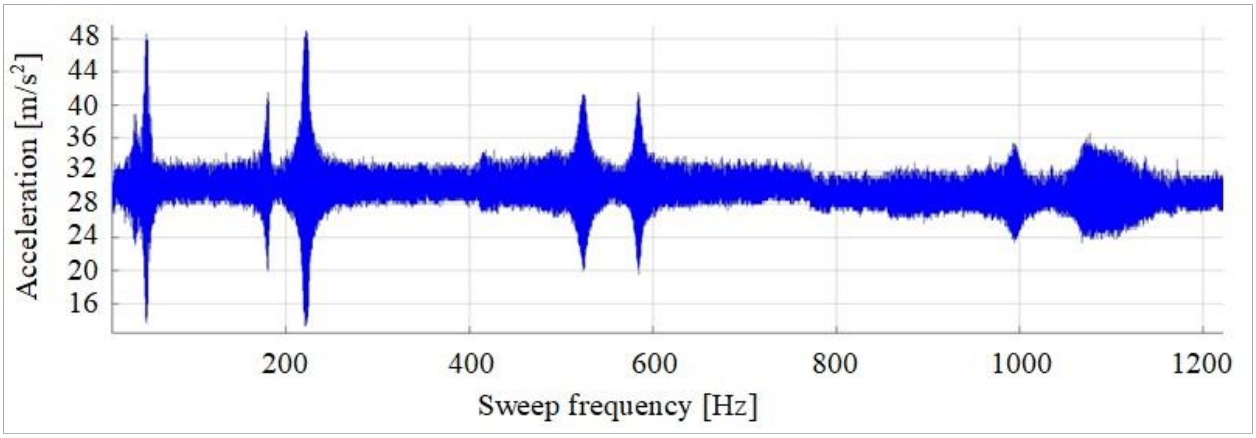
A. Stress response (white noise 10 – 1200 Hz).



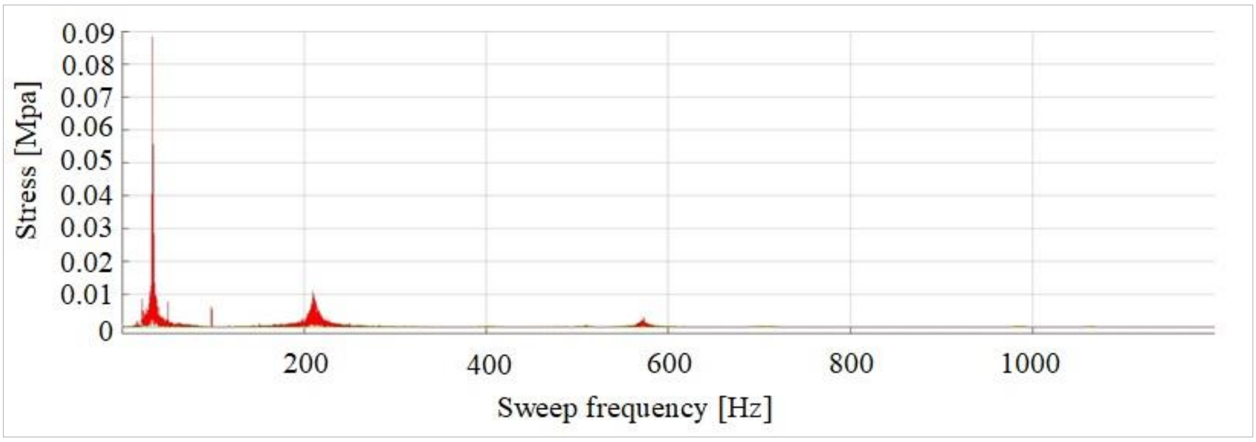
B. Acceleration response (white noise 10 – 1200 Hz).



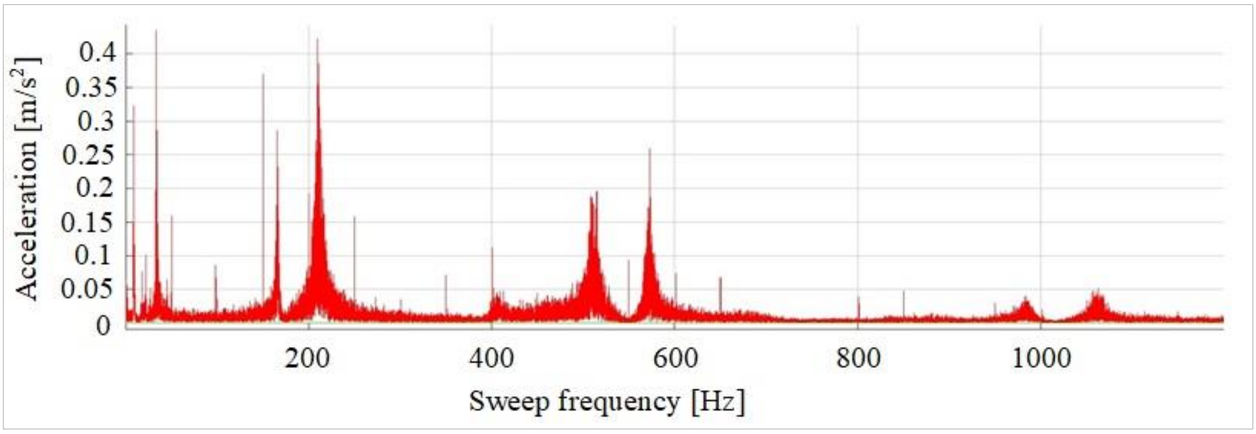
C. Stress vs. sweep frequency response (10 – 1200 Hz).



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

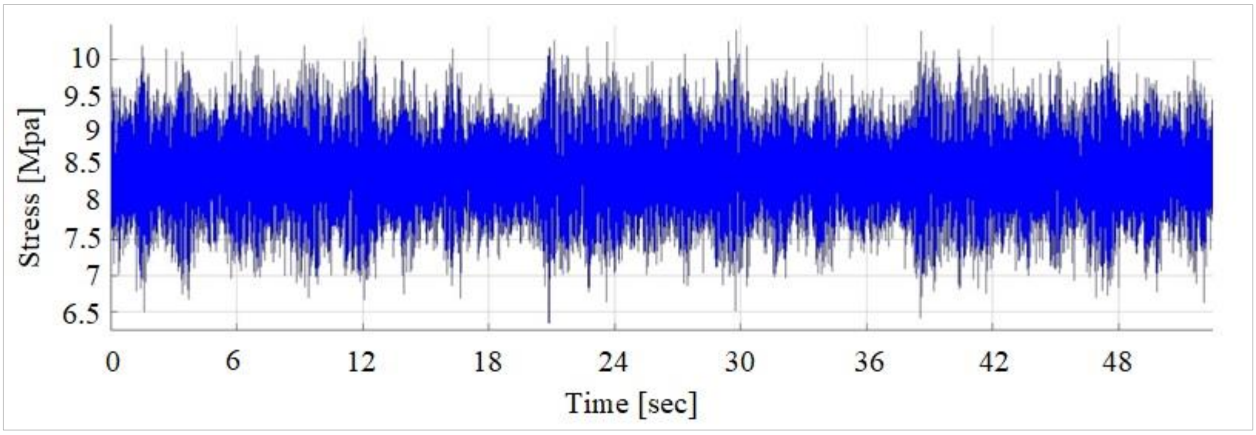


E. Stresses in frequency domain analysis by fast Fourier transform method (FFT).

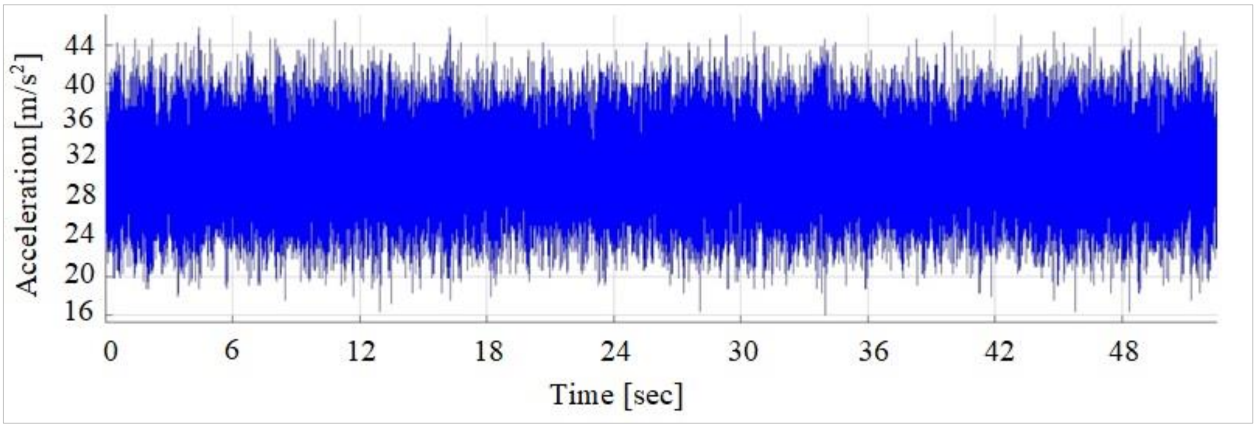


F. Acceleration in frequency domain analysis by fast Fourier transforms method (FFT).

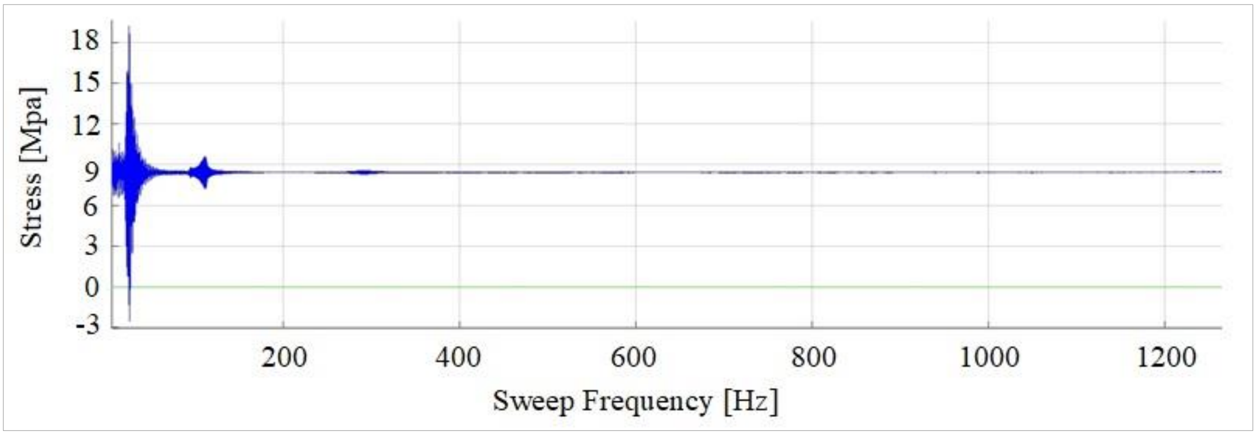
Figure 2.12 (A-F): Experimental result (forced vibration test) for the specimen of sandwich panel consisting of an aluminum honeycomb core (t_c=18 mm) and phenolic woven glass fiber face-sheets (t_f=1 mm).



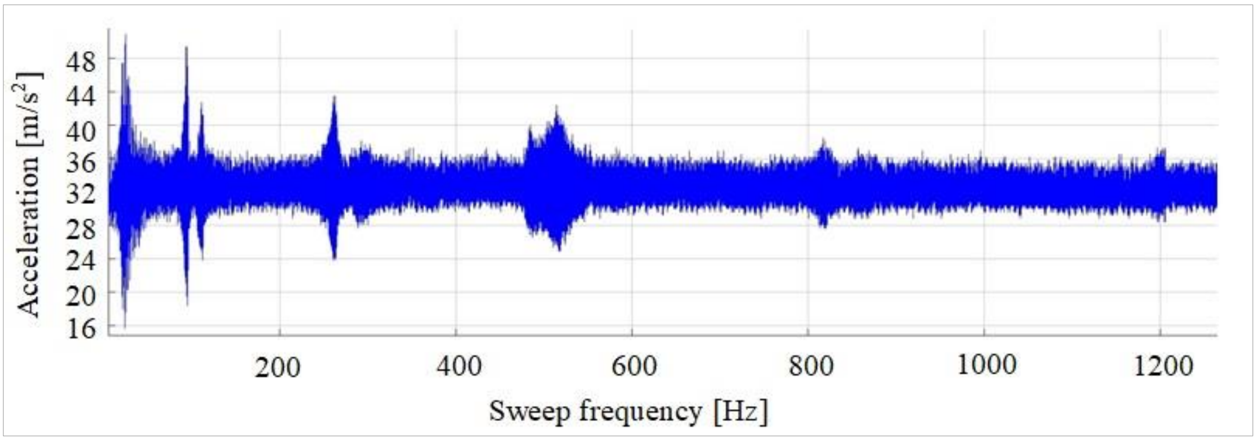
A. Stress response (white noise 10 – 1200 Hz).



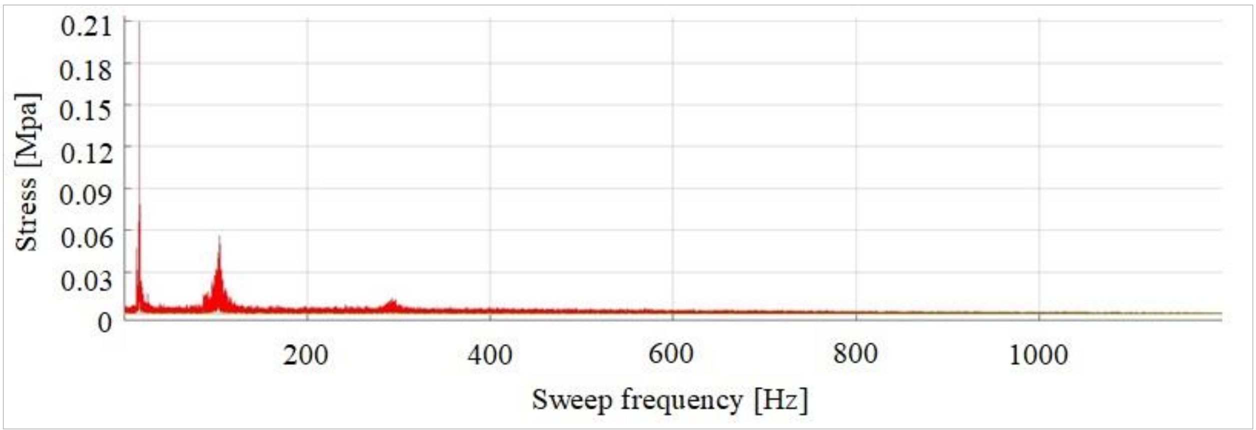
B. Acceleration response (white noise 10 – 1200 Hz).



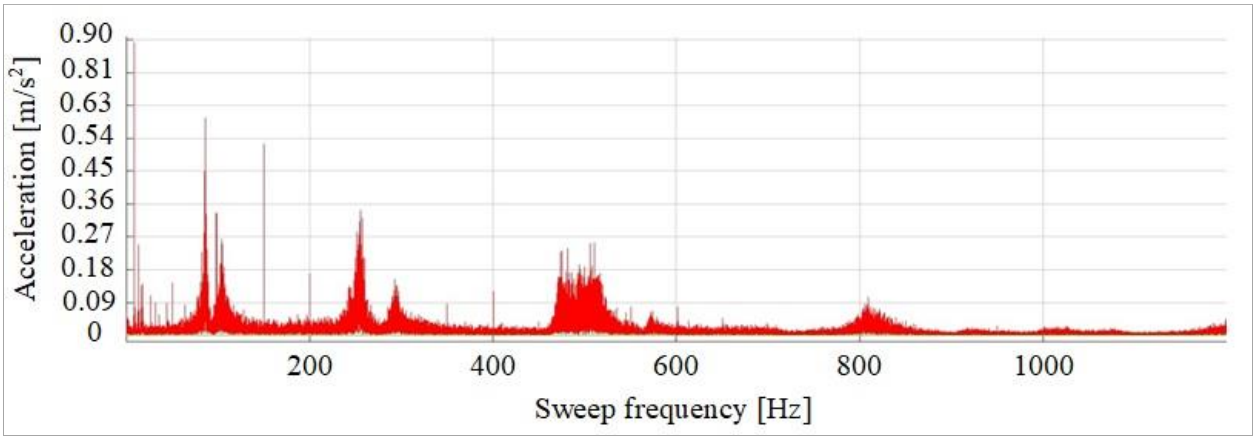
C. Stress vs. sweep frequency response (10 – 1200 Hz).



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 2.13 (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).

- *Results of Damping Test (Jones Measurement)*

This test method is intended to measure the damping; dynamic shear modulus, and acceleration of sandwich plate consisting of an aluminum honeycomb core and phenolic woven glass fiber face-sheets, thin rubber sandwich plate, and thick rubber sandwich plate with and without mass effect to compare between them are shown in Tables 2.6 & 2.7 and Figures 2.14. The acceleration frequency response, acceleration response in time domain analysis, and response function for three types of specimens (see Figures 2.15-2.20). Considering dynamic loading, the structure's behavior can be different from the static one [70-71].

The damping ratio and the dynamic shear modulus are directly proportional to the mass. Figures 2.15-2.20 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 show the honeycomb sandwich specimen.

The sandwich plate damping η_d can be defined:

$$\eta_d = \frac{1}{\sqrt{T_R^2 - 1}} \tag{2.7}$$

Where the transmissibility T_R is:

$$T_R = \left|\frac{\ddot{x}_2}{\ddot{x}_1}\right| \tag{2.8}$$

And, the dynamic shear modulus G_d can be defined:

$$G_d = \frac{m\omega^2}{2b} \tag{2.9}$$

The concepts of Newton's second law of motion, damping constant c, damping ratio η_d, the angular frequency ω, and natural frequency ω_n are:

$$F = ma, \qquad F = c\dot{x}, \qquad \eta_d = \frac{c}{c_{cr}}, \qquad \omega = 2\pi f, \qquad \omega_n = \sqrt{\frac{k}{m}} \tag{2.10}$$

Table 2.6: 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

Table 2.7: 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

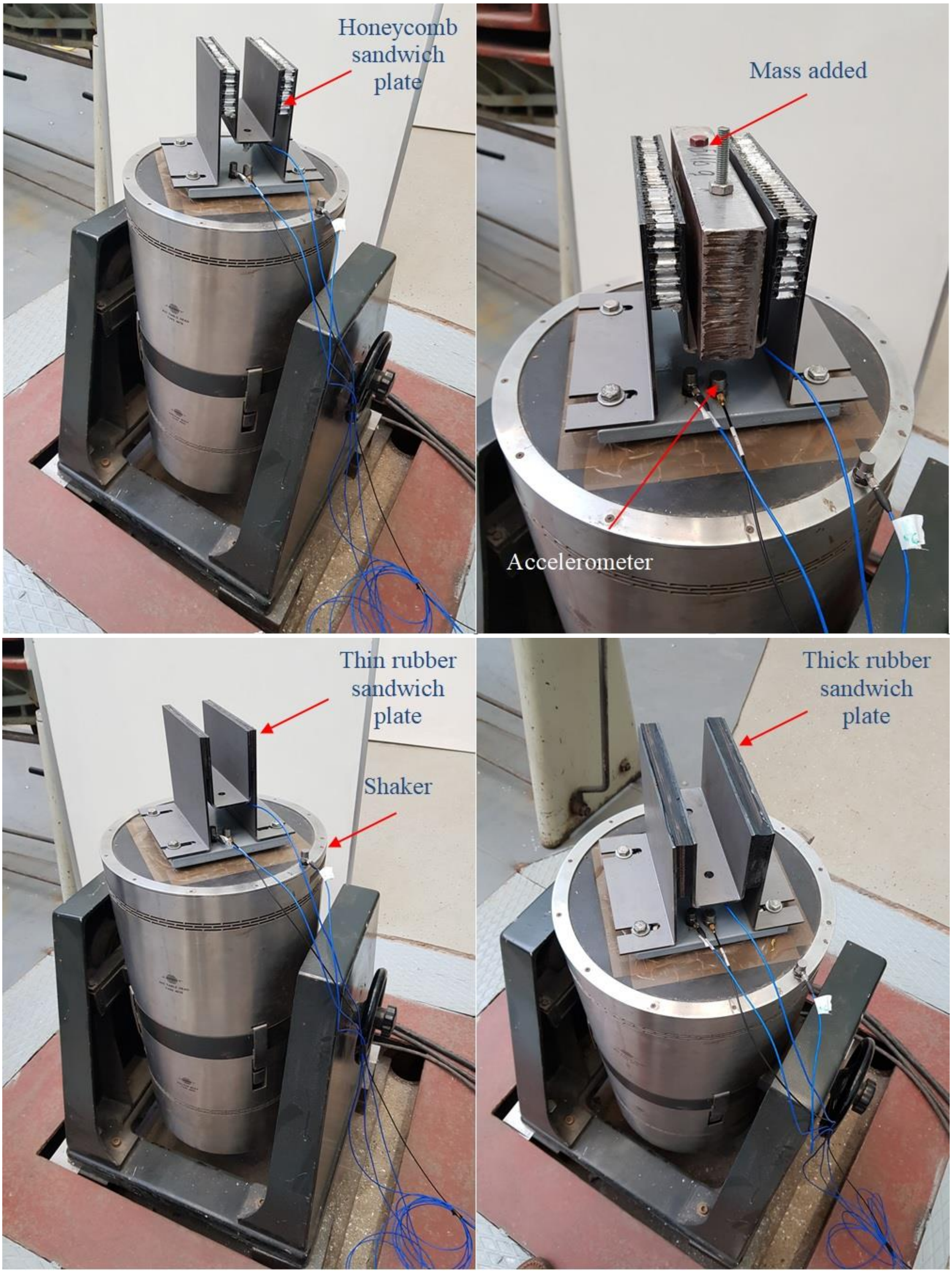


Figure 2.14: Jones measurement (damping test) for the sandwich plate specimen consisting of an aluminum honeycomb core and phenolic woven glass fiber face-sheets, thin rubber sandwich plate, and thick rubber sandwich plate with and without mass added effect.

Results of Jones measurement for honeycomb sandwich structure without weight

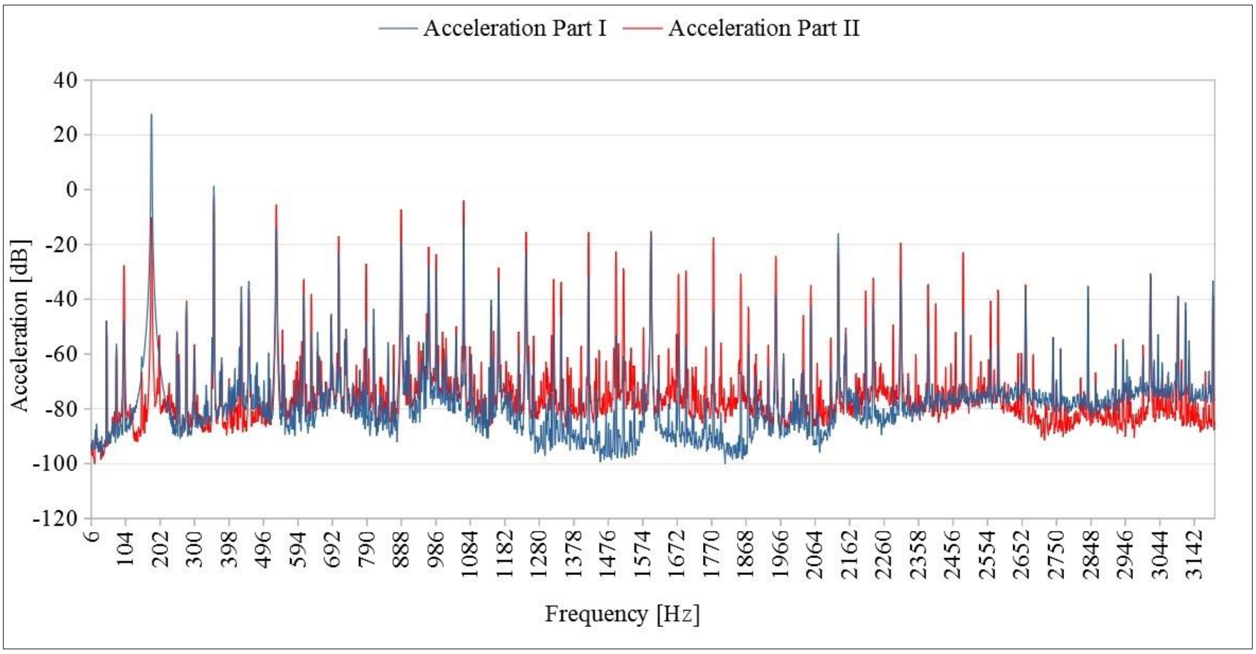


Figure 2.15: Jones measurement for honeycomb sandwich structure without weight, sine 177.5 Hz, 2g, shaker acceleration FFT.

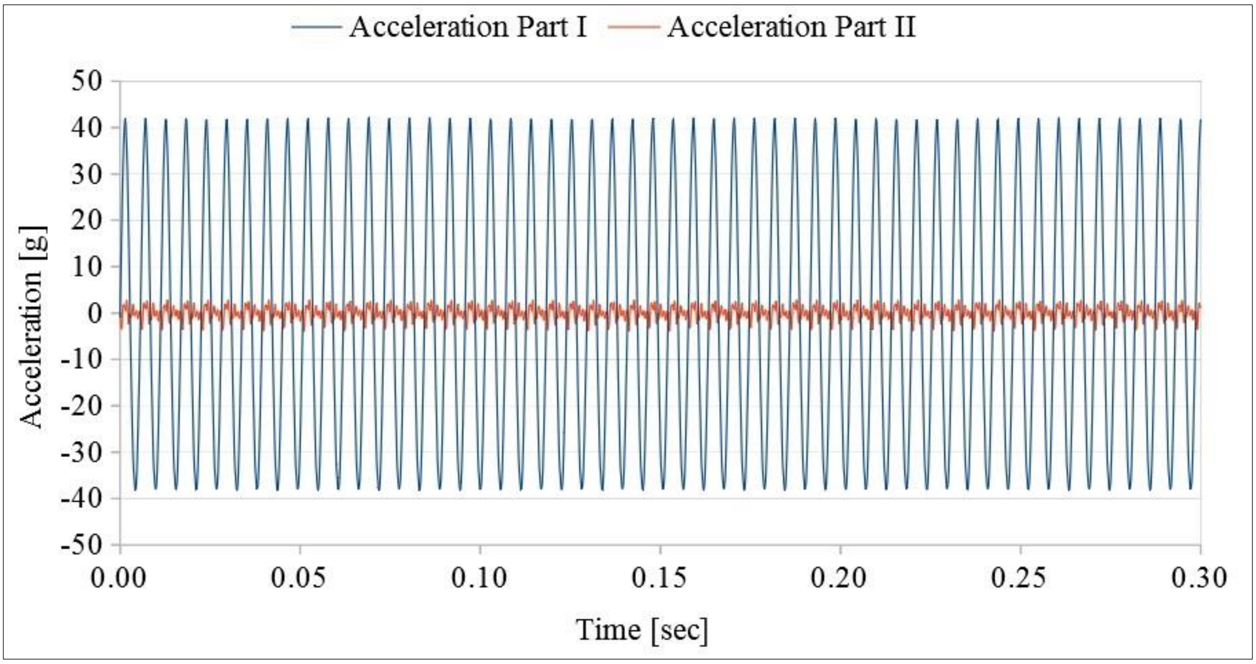


Figure 2.16: Jones measurement for honeycomb sandwich structure without weight, sine 177.5 Hz, 2g, shaker acceleration.

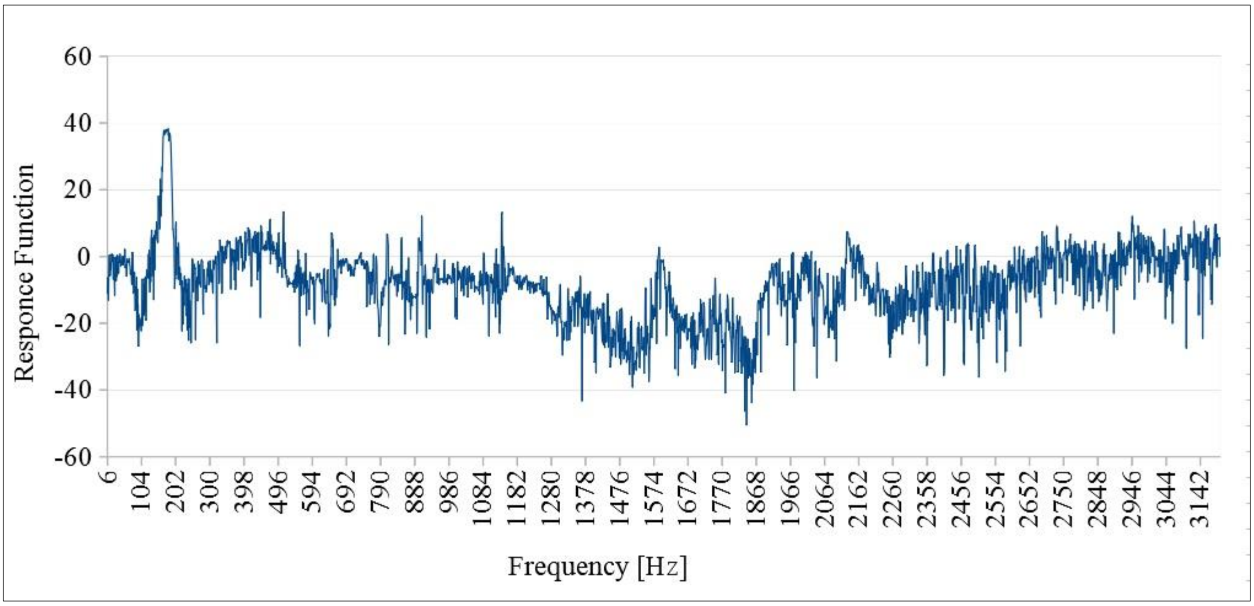


Figure 2.17: Jones measurement for honeycomb sandwich structure without weight, sine 177.5 Hz, 2g, shaker frequency response.

Results of Jones measurement for honeycomb sandwich structure with weight

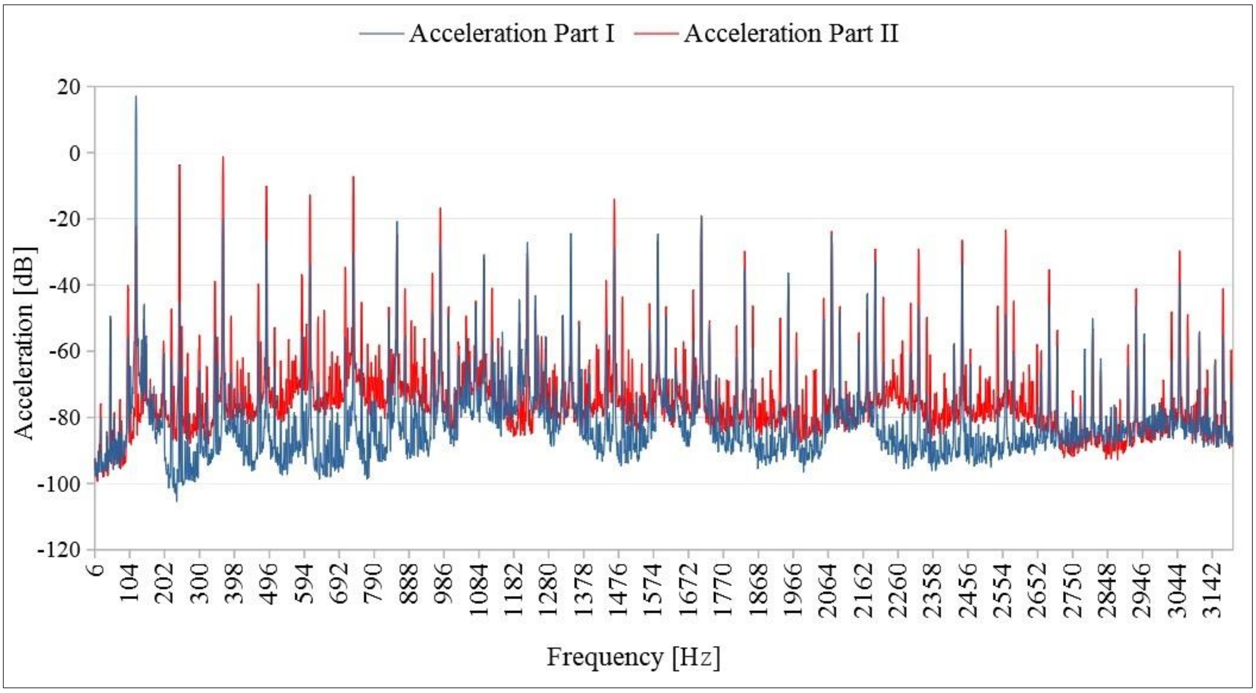


Figure 2.18: Jones measurement for honeycomb sandwich structure with added mass 5.116 kg, sine 122 Hz, 2g, shaker acceleration FFT.

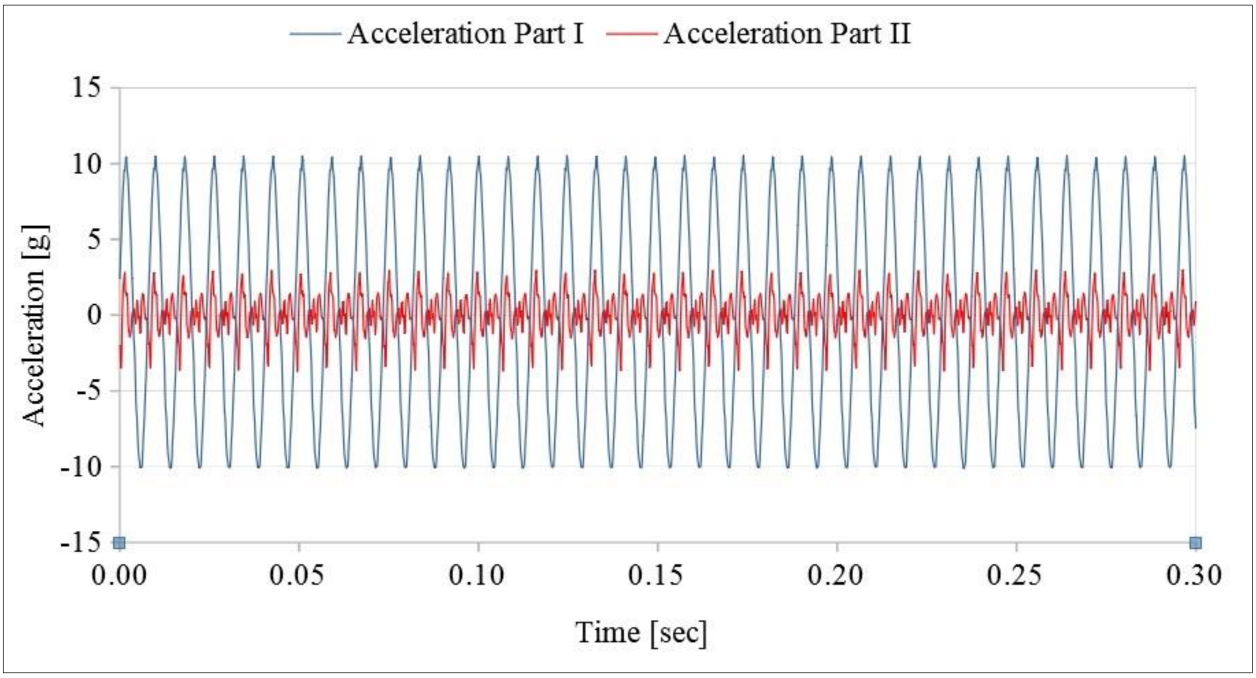


Figure 2.19: Jones measurement for honeycomb sandwich structure with added mass 5.116 kg, sine 122 Hz, 2g, shaker acceleration.

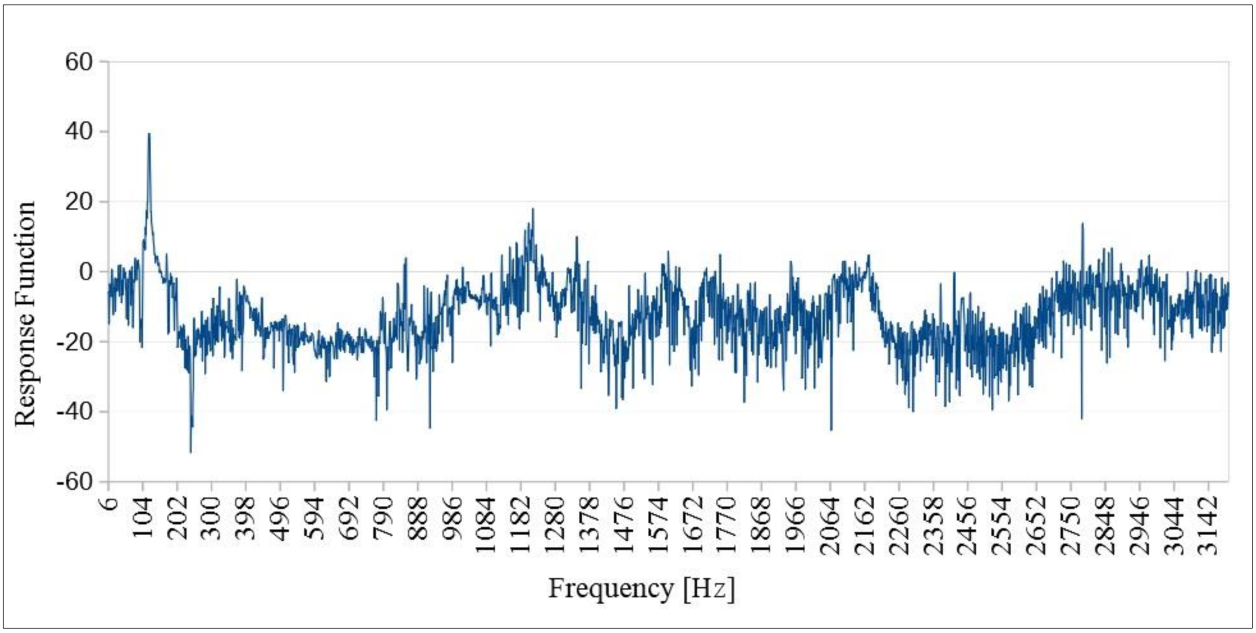


Figure 2.20: Jones measurement for honeycomb sandwich structure with added mass 5.116 kg, sine 122 Hz, 2g, shaker frequency response.

2.3. Summary

Four mechanical tests (static and dynamic measurements) were performed: four-point bending test, climbing drum peel test, forced vibration test, and damping test on a set of composite sandwich specimens. The specimens are made of an aluminum honeycomb core and phenolic woven glass fiber face-sheets with cross-ply fiber orientation.

Concerning the four-point bending test, the relationship between load and displacement and skin stress was calculated. Simultaneously, the numerical models are made using the Digimat-HC program to get the deflection and skin stress for comparison. The honeycomb core thickness increase leads to decreased sandwich panels' deflection due to the increased stiffness-to-weight ratio.

The peel test's adhesive bonds' peel resistance between face-sheets and honeycomb core of the sandwich specimens was determined. The honeycomb core thickness does not influence the adhesive's peeling resistance between the face-sheets and the sandwich structure's core. However, the thickness of the face sheets affects the difficulty of bending them on the drum.

The experimental tests included a forced vibration test to find natural frequencies, stress response, and acceleration response. When the honeycomb core thickness of the specimens increases, the natural frequency will increase and reduce stress response and acceleration response due to the rise in stiffness-to-weight ratio.

The acceleration frequency response, acceleration time response, and response function for the honeycomb sandwich plate, thin rubber plate, and thick rubber plate are presented for comparison. These responses decrease with an increase in the mass of the specimens.

According to the concepts of damping ratio, damping constant, Newton's second law of motion, and natural frequency (see Equation 2.7), when the mass added on the sandwich structure specimen increases, the sandwich structure’s acceleration will decrease. As the sandwich structure’s natural frequency is inversely proportional to the mass, it will reduce, and thus the angular frequency will decrease. The damping ratio and the dynamic shear modulus are directly proportional to the mass. The damping ratio will be increased by increasing the equivalent damping constant of the honeycomb sandwich structure. The dynamic shear modulus will increase with increasing mass because it is directly proportional to mass.

3. OPTIMIZATION METHOD

The mathematical modeling for the optimization processes of the constructed honeycomb sandwich structures was presented. The sandwich structure is consisting of an aluminum honeycomb core and different types of face-sheets. The face-sheets are consisting of an aluminum alloy or composite material. The composite face-sheets included phenolic woven glass fiber, epoxy woven glass fiber, epoxy woven carbon fiber, and hybrid composite layers, which combined layers of epoxy woven glass fiber and epoxy woven carbon fiber. The mechanical properties of face-sheet and honeycomb core materials, as shown in Tables 3.1 and 3.2. The composite sandwich plates are considered thin layers, symmetric concerning the midplane of the sandwich plates and/or symmetric concerning the face-sheets' midplane. Every face-sheet is composed of (1, 2, 4, 6, and 8) layers. The layup of the fibers of the face-sheets was restricted to sets of plies having orientation angles of cross-ply (0°, 90°), angle-ply (±45°), and multidirectional (0°, 90°) & (±45°). The optimal design variables were honeycomb core thickness t_c and face-sheet thickness t_f for aluminum face-sheets or the number of layers for composite face-sheets N_l to minimize the weight and/or the cost of the sandwich structures. During the optimization techniques, nine design constraints were taken into consideration. The constraints of the optimization problem are the total stiffness (bending stiffness and shear stiffness), the full deflection (bending deflection and shear deflection), facing skin stress (bending load), core shear stress, facing skin stress (end loading), overall buckling (bending critical buckling load and shear critical buckling load), shear crimping load, skin wrinkling (critical stresses and load) and intracell buckling.

These constraints were calculated to compare with yield stresses and applied loads of face-sheets and honeycomb core. The optimization procedure's flowchart is formulating the objective functions for the weight and/or the cost of the honeycomb sandwich structure. Formulate the constraints and defined the boundaries for the design variables; solve the single-objective optimization problem to minimize the total weight or the total material cost separately using the Matlab program (Interior Point Algorithm) version R2018a, MathWorks, Inc., Natick, MA, USA, and Excel Solver program (GRG Nonlinear Algorithm) Microsoft Excel 2010, Microsoft Corporation, Redmond, WA, USA, where GRG stands for "Generalized Reduced Gradient". This solver method looks at the gradient or slope of the objective function as the input values (or decision variables) change in their most basic form. It determines that it has reached an optimum solution when the partial derivatives equal to zero. Solve the multi-objective optimization problem to minimize the weight and the cost simultaneously by applying the Matlab program (Genetic Algorithm Solver with Pareto Front) and Excel Solver program (Weighted Normalized Method). The strategies of composite face-sheets have been solved using the Laminator, an engineering program that analysis laminated composite material according to classical lamination theory and the ply failure calculation based on Tsai-Hill failure criteria.

Table 3.1: Engineering properties of facing materials for sandwich structure construction [72].

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

Table 3.2: Engineering mechanical properties of aluminum honeycomb core materials [72].

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

- *The Laminator Program*

The Laminator program is used for the classical analysis of composite laminates. It’s an engineering program that analyses laminated composite plates according to classical laminated plate theory. The input consists of ply material properties, material strengths, ply fiber orientation and stacking sequence, mechanical loads, and/or strains. The output consists of apparent material properties of laminate, ply stiffness and compliance matrices, laminate "ABD" matrices, laminate loads and mid-plane strains, ply stresses and strains in global and material axes, and load factors for ply failure based on Tsai-Hill failure theory.

The Laminator program procedures are the following:

1. Set analysis and output options using the Settings tab.
2. Enter material data using the Materials tab.
3. Enter in material strength data using the Strength tab.
4. Enter the stacking sequence for the laminate using the Layup tab.
5. Enter laminate load data using the Loads tab.

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). Figure 3.1 illustrates the procedure followed in calculating optimal design variables to minimize the single objective function.

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:

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

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, 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 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:

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

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 price 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 case of 18 mm core height).

Step 1: Write a file (objecfun.m) for single objective function.

↓

Step 2: Write a file nonlconstr.m for the nonlinear constraints.

↓

Step 3: Set up and run the problem with the optimization application:

1. Open the optimization application.
2. Select Interior point Algorithm from the selection of solvers fmincon-Constrained nonlinear minimization.
3. Enter @objecfun in the objective function field to call the objecfun.m file to minimize.
4. Specify the initial point in the start point field where algorithm begins its search for a minimum, specified as vectors.
5. Define the nonlinear constraints as a separate file. Enter @nonlconstr.m in the nonlinear constraints field to call the nonlconstr.m file. The lower and upper bounds on the variables are defined, specified as vectors.
6. Specify options and select iterative to show algorithm information at the command window for each iteration.
7. Run solver and view results.

Figure 3.1: The flowchart of the single optimization procedure.

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). Figure 3.2 illustrates the procedure followed in calculating optimal design variables to minimize the multi-objective functions.

Step 1: Write a file (objfun.m) for multi-objective function.

↓

Step 2: Write a file nonlconstr.m for the nonlinear constraints.

↓

Step 3: Set up and run the problem with the optimization application:

1. Open the optimization application.
2. Select gamultiobj-Multiobjective Genetic Algorithm Solver from the selection of solvers.
3. Enter @objfun in the fitness function field to call the objfun.m file to minimize.
4. Added the number of independent variables for the fitness function in the number of variables field.
5. Define the nonlinear constraints as a separate file. Enter @nonlconstr.m in the nonlinear constraints field to call the nonlconstr.m file. The lower and upper bounds on the variables are defined, specified as vectors.
6. Specify options and select iterative to show algorithm information at the command window for each iteration.
7. Run solver and view results.

Figure 3.2: The flowchart of the multi-objective optimization procedure.

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 [73].

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 [74]:

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

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:

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

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:

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

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:

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

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:

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

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 $P_{wr,cr}$ skin wrinkling would occur 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: $E_f = \sqrt{E_{f,x}E_{f,y}}$

All these parameters are calculated using the Laminator program.

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

4.1. Introduction

Manufacturing a high-performance and lightweight structure with affordable cost without sacrificing strength has been challenging 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 reduce fuel consumption or increase aircraft turnover compared to conventional containers.

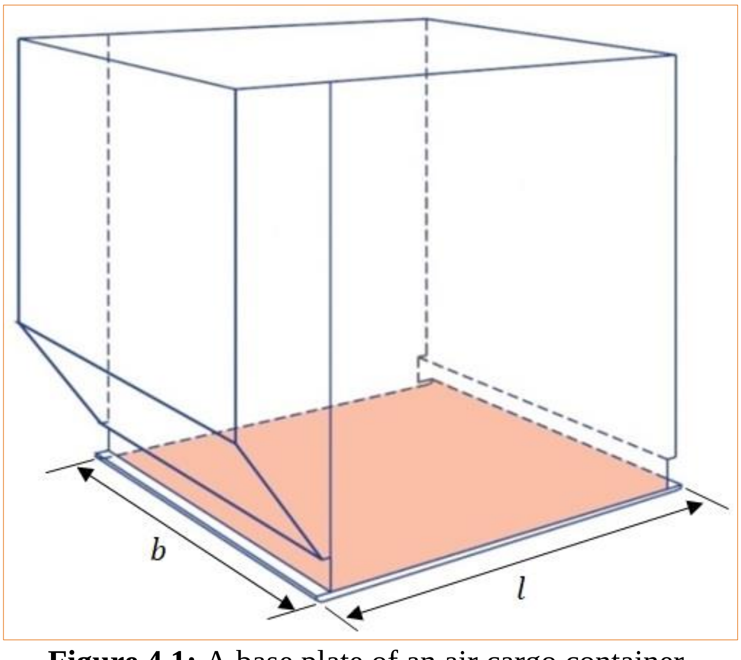


Figure 4.1: A base plate of an air cargo container.

4.2. Optimization Method

In this study, the replacement of an existing aluminum base plate in air cargo containers with a honeycomb sandwich base plate was investigated. The conventional bottom base plate of the air cargo container has dimensions (1440 mm by 1412 mm) and consisting of a solid (2.5 mm) thick aluminum plate which weighs (14.1 kg) and costs (65 €) approximately. The value of (1 kg) of reduced weight is approximately (199 $ per year). The total load on the air cargo container's base plate is (1588 kg) uniformly distributed. The maximum deformation may not exceed (9.5 mm). The mathematical modeling for the optimization processes is 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 sandwich plates' models consist 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 and 3.2, respectively [31].

Table 4.1: Technical data for the conventional base plate of air freight container [31].

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 [72].

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

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]
9.105	0.5	21.424

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]
73.709	0.501	21.409

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]
9.134	0.502	21.41

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]
73.756	0.512	21.175

– ***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) is 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		11.435	0.5	45.111

Type	**B. Epoxy woven carbon fiber face-sheets**	W_{min}	$t_{f,opt}$	$t_{c,opt}$
Number of layers N_l with fiber orientations θ°		kg	mm	mm
1 (+45°) Optimum value		6.326	0.3	26.646

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		8.572	0.55	28.624

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		121.027	0.5	45.111

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		133.397	0.3	26.646

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		147.422	0.55	28.624

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		11.435	0.5	45.111

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

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

Table 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		121.075	0.5	45.131

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

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

4.3.2. Optimization of Multi-objective Functions

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 symbols are the weighted 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 face-sheets.

Index	W_{min}	C_{min}	$t_{f,opt}$	$t_{c,opt}$
	kg	€	mm	mm
1	9.1027	73.3318	0.5036	21.1774
2	9.1097	73.3317	0.5045	21.1557
3	9.0979	73.3320	0.5029	21.1924
4	9.1102	73.3316	0.5046	21.1540
5	9.0959	73.3321	0.5026	21.1987
6	9.0982	73.3320	0.5029	21.1917
7	9.0959	73.3321	0.5026	21.1987
8	9.1100	73.3317	0.5046	21.1547
9	9.0982	73.3320	0.5029	21.1918
10	9.1097	73.3317	0.5045	21.1557
11	9.1102	73.3316	0.5046	21.1540
12	9.0948	73.3321	0.5024	21.2023
13	**9.0946**	**73.3321**	**0.5024**	**21.2029**
14	9.0956	73.3321	0.5026	21.1997
15	9.1027	73.3318	0.5036	21.1774
16	9.0979	73.3320	0.5029	21.1924
17	9.0979	73.3320	0.5029	21.1924
18	9.0946	73.3322	0.5024	21.2030

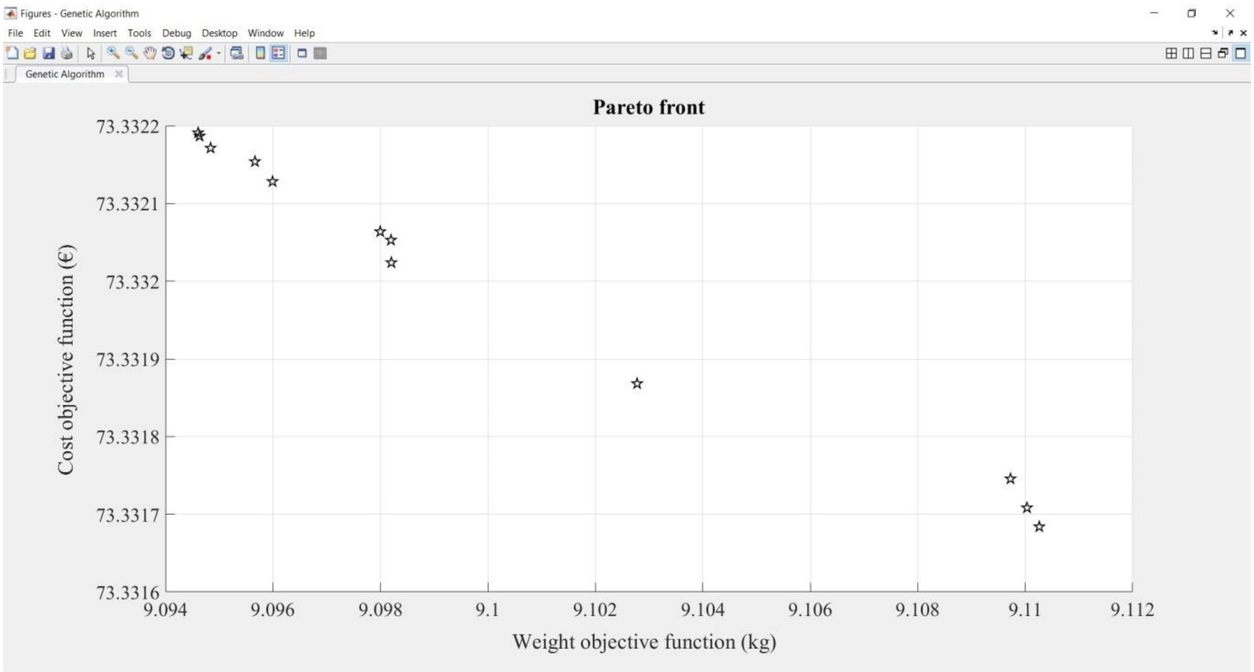


Figure 4.2: Pareto front curve for weight objective function and cost objective function simultaneously using the Matlab program (Multi-objective Genetic Algorithm Solver) for honeycomb sandwich base plate of an air cargo container.

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

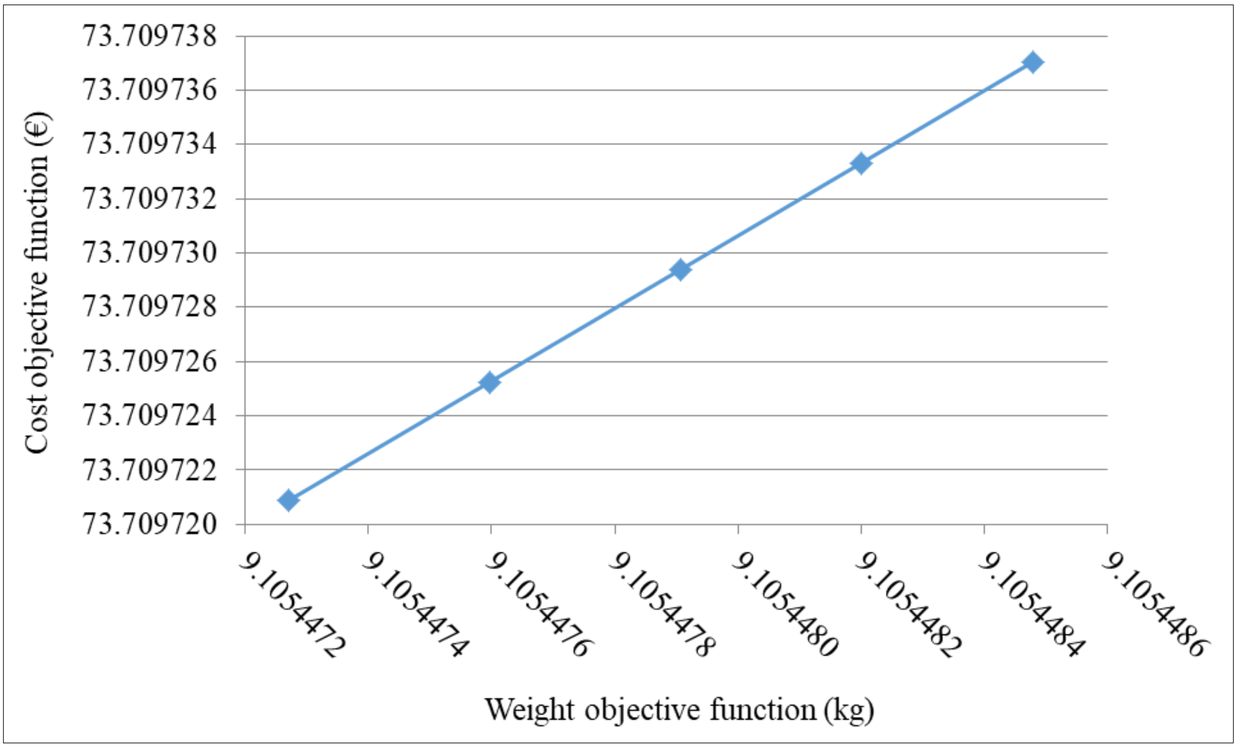


Figure 4.3: Compromise between multi-objective functions weight and cost using the Excel Solver program (Weighted Normalized Method) for honeycomb sandwich base plate of an air cargo container, face-sheets are of aluminum alloy.

– ***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		11.435	121.027	0.5	45.111

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		6.326	133.397	0.3	26.646

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		8.572	147.422	0.55	28.624

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		11.394	120.475	0.5	44.866

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

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

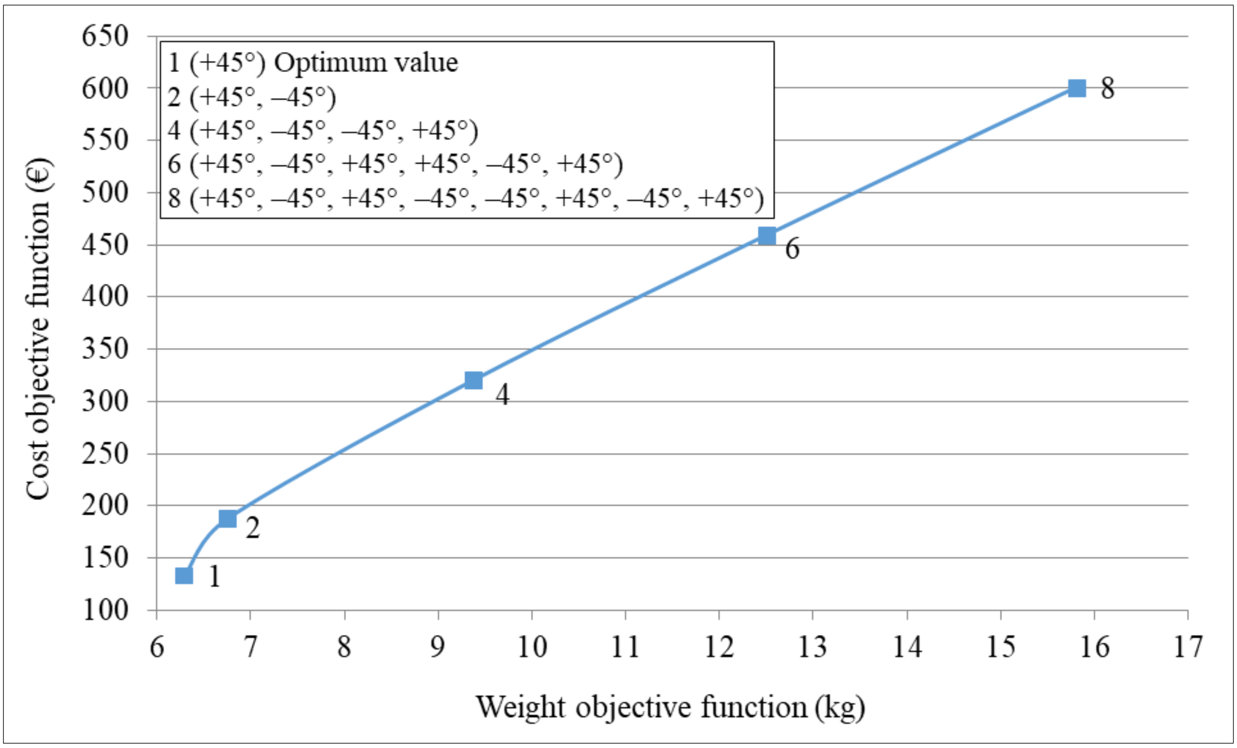


Figure 4.4(*a*): Minimum weight versus minimum cost objective function using the Matlab program (Genetic Algorithm Solver) for the sandwich base plate of air freight container consisting of an aluminum honeycomb core and epoxy woven carbon fiber composite face-sheets with a different number of layers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

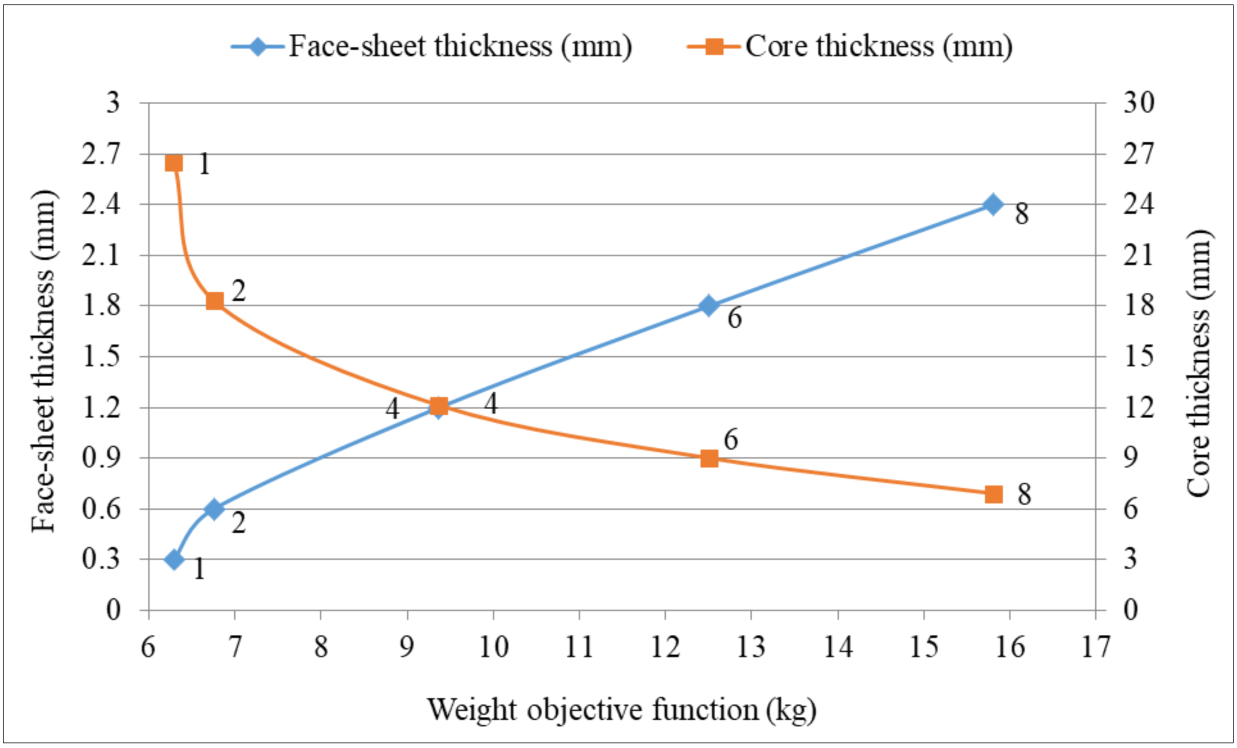


Figure 4.4(*b*): Minimum weight objective function versus optimum face-sheet and core thicknesses using the Matlab program (Genetic Algorithm Solver) for the sandwich base plate of air freight container consisting of an aluminum honeycomb core and epoxy woven carbon fiber face-sheets with a different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

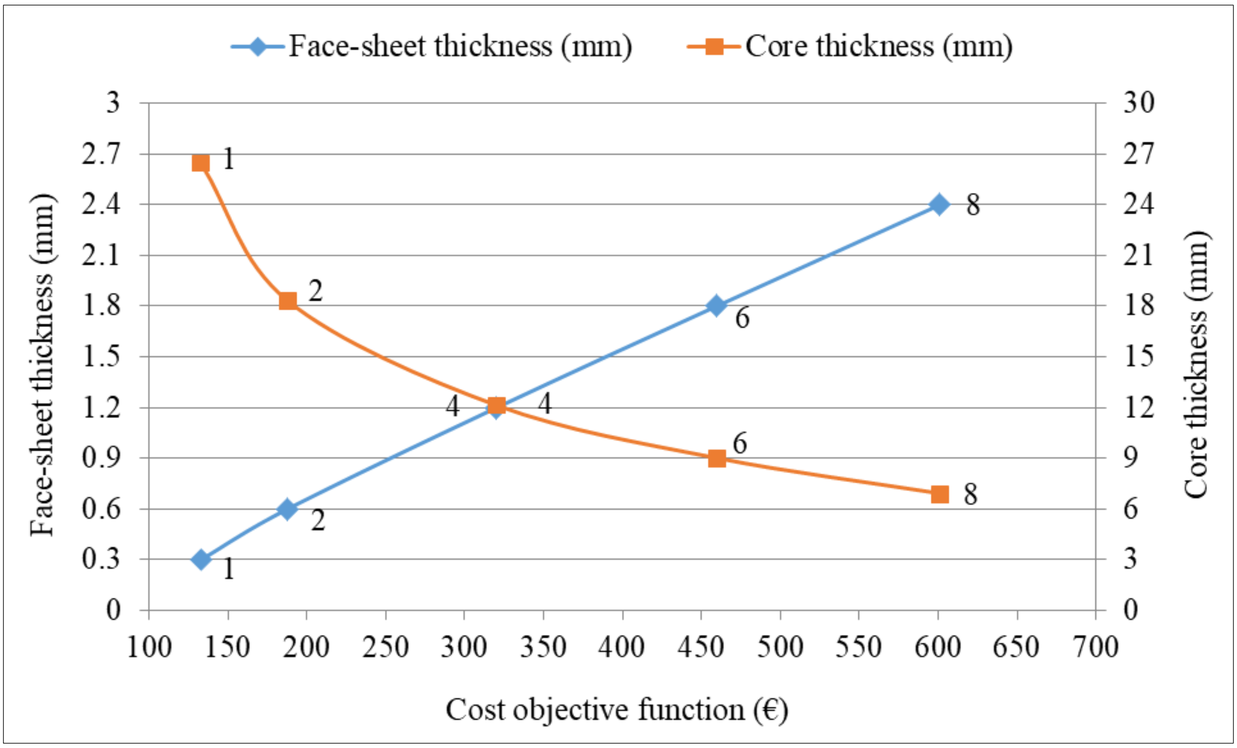


Figure 4.4(*c*): Minimum cost objective function versus optimum face-sheet and core thicknesses using the Matlab program (Genetic Algorithm Solver) for the sandwich base plate of air freight container consisting of an aluminum honeycomb core and epoxy woven carbon fiber face-sheets with a different number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

4.4. The Factor of Safety (FoS)

Design engineers must consider many factors, such as safety factors, to design an element or structure. Safety is one of the most important qualities to be considered when creating parts or products. The term "Factor of Safety" (FoS) or "Safety Factor (SF) is most commonly. A fundamental 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 safety factors for optimum design constraints for an air cargo container's base plate.

Table 4.15: Safety factors for optimum design constraints 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	1.1
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

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 and 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 [75].

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

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 face-sheets include aluminum alloy and composite material. The composite material face-sheets had 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 that 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, composite laminate face-sheets mechanical properties 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 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°). The best face-sheet according to minimum weight is epoxy woven carbon fiber, where the minimum weight, minimum cost, optimum face-sheet thickness, and optimum core thickness are (6.292 kg, 132.929 €, 0.3 mm, and 26.439 mm), respectively. This optimal sandwich plate provides (55.13 %) weight saving compared to the air cargo container's conventional aluminum base plate (14.1 kg). The epoxy woven carbon fiber having higher stiffness to weight ratio compared to epoxy woven glass fiber. The best face-sheet according to minimum cost is epoxy woven glass fiber, where the minimum weight, minimum cost, optimum face-sheet thickness, and optimum core thickness are (11.394 kg, 120.475 €, 0.5 mm, and 44.866 mm), respectively.

The hybrid composite face-sheet is considered as a compromise between epoxy woven carbon fiber face-sheet and epoxy woven glass fiber face-sheet, where the minimum weight, minimum cost, optimum face-sheet thickness, and optimum core thickness are (8.573 kg, 147.44 €, 0.55 mm, and 28.632 mm), respectively. The epoxy woven glass fiber has a higher strength to weight ratio and more flexible than epoxy woven carbon fiber. In the aluminum face-sheets of the honeycomb sandwich plates, the optimum face-sheet thickness and optimum core thickness ensure the minimum weight and/or minimum cost are (9.0946 kg, 73.3321 €, 0.5024 mm, and 21.2029 mm), respectively. The results give good agreement between the Excel Solver program and Matlab program and 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 decrease 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

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 face-sheets. The elaborated structural model could 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 centerpiece of the materials handling support system, designed in the late 1950s 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 [76].

5.2. Optimization Method

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. The pallet should sustain an extra acceleration of (1.5 g), so the total load times (2.5 g). The maximum deformation may not exceed (50 mm). The loading system is approximated by studying the panels inscribed between the supports (with dimensions of 665 mm by 2235 mm). The plate's boundary conditions are simply supported along the long edges and free along the shorter edges (see Table 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 is 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 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 [72].

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

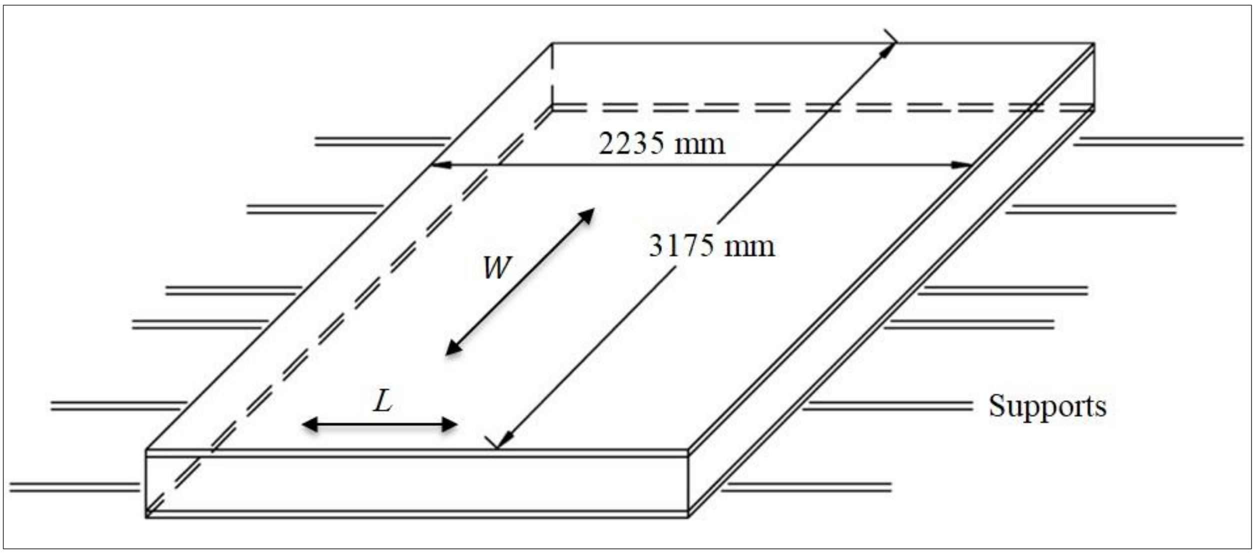


Figure 5.2: Dimensions of a base plate of military aircraft pallet with a supported beam [2].

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

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
60.626	0.804	50.59

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
469.138	1.39	28.357

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
63.152	1.008	41.59

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
469.14	1.389	28.361

– *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		40.741	1	23.872

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

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

Table 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		321.631	1	23.872

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

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

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		40.742	1	23.872

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

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

Table 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		321.655	1	23.875

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

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

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 symbols are the weighted sum of weight objective function and cost objective function in percentage (%), respectively, and the Matlab program (Multi-objective Genetic Algorithm Solver) is shown in Table 5.12 and Figure 5.6.

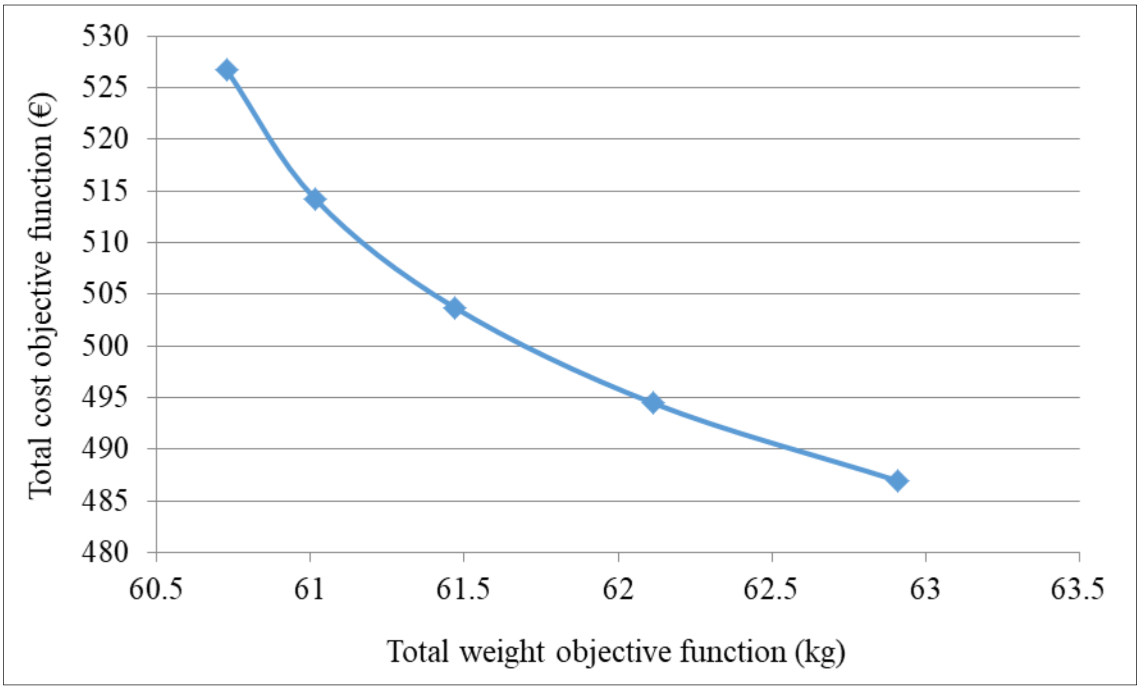


Figure 5.3: Compromise between multi-objective functions total weight and total material cost using the Excel Solver program (Weighted Normalized Method) for honeycomb sandwich base plate of military aircraft pallets, face-sheets are of aluminum alloy.

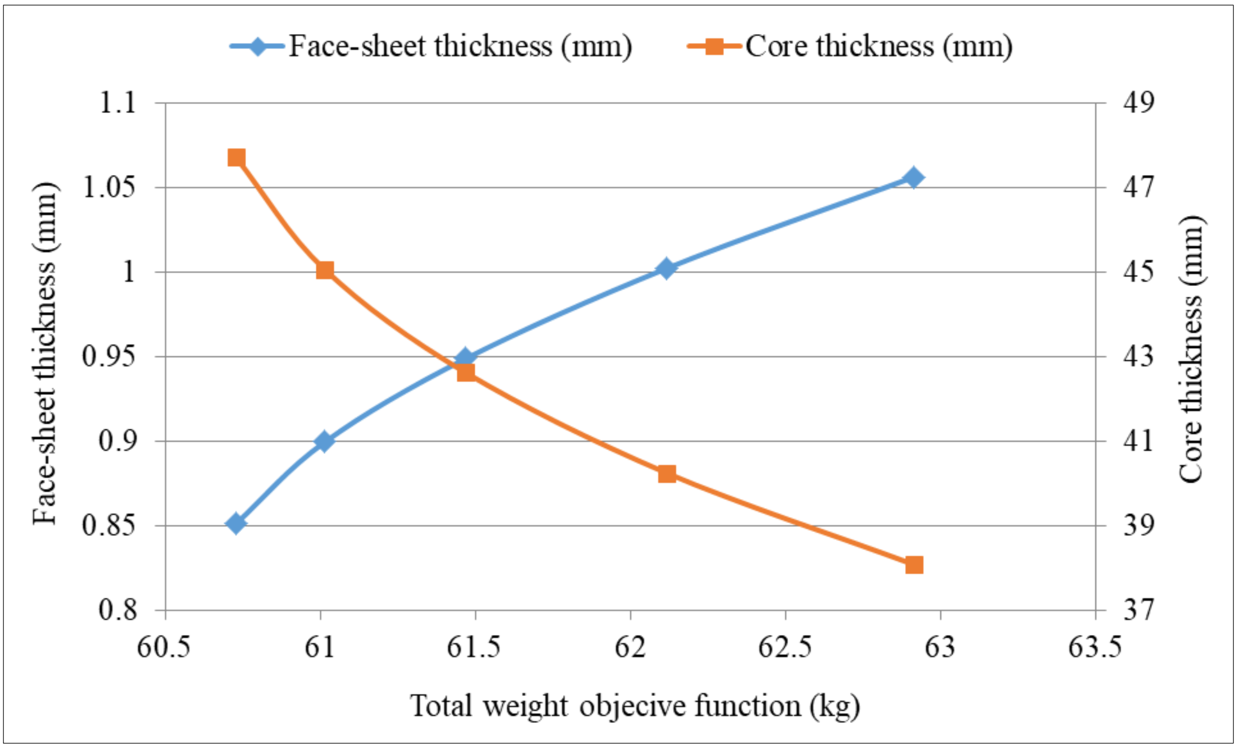


Figure 5.4: Minimum total weight objective function versus optimum face-sheet and core thicknesses using Excel Solver program (Weighted Normalized Method) for sandwich base plate of military aircraft pallets consist of an aluminum honeycomb core and aluminum face-sheets.

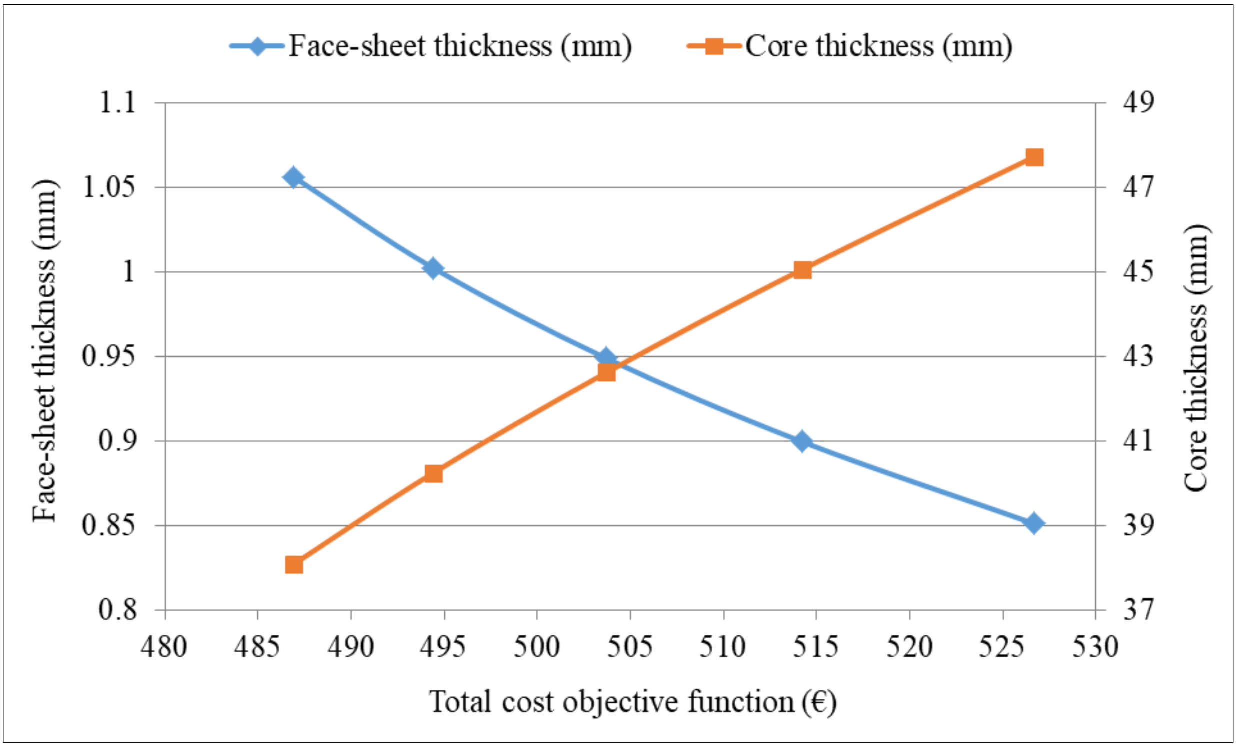


Figure 5.5: Minimum total material cost objective function versus optimum face-sheet and core thicknesses using Excel Solver program (Weighted Normalized Method) for sandwich base plate of military aircraft pallets consist of an aluminum honeycomb core and aluminum face-sheets.

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	62.911	486.914	1.056	38.088
2	60	40	62.115	494.433	1.002	40.252
3	70	30	61.468	503.727	0.949	42.627
4	80	20	61.015	514.222	0.899	45.062
5	90	10	60.727	526.691	0.851	47.73

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	61.46	504.892	0.945	42.86
2	62.364	491.817	1.019	39.525
3	61.931	496.851	0.987	40.885
4	61.309	507.09	0.933	43.419
5	60.694	532.34	0.833	48.852
6	61.586	502.366	0.957	42.258
7	**60.642**	**535.612**	**0.821**	**49.532**
8	61.777	499.745	0.973	41.582
9	61.074	514.595	0.901	45.081
10	60.941	517.284	0.887	45.719
11	60.711	528.177	0.846	48.032
12	62.178	493.748	1.007	40.064
13	62.008	496.002	0.993	40.652
14	62.364	491.817	1.019	39.525
15	60.817	522.838	0.866	46.905
16	60.711	528.177	0.846	48.032
17	60.908	520.513	0.877	46.374
18	61.219	509.724	0.921	44.009

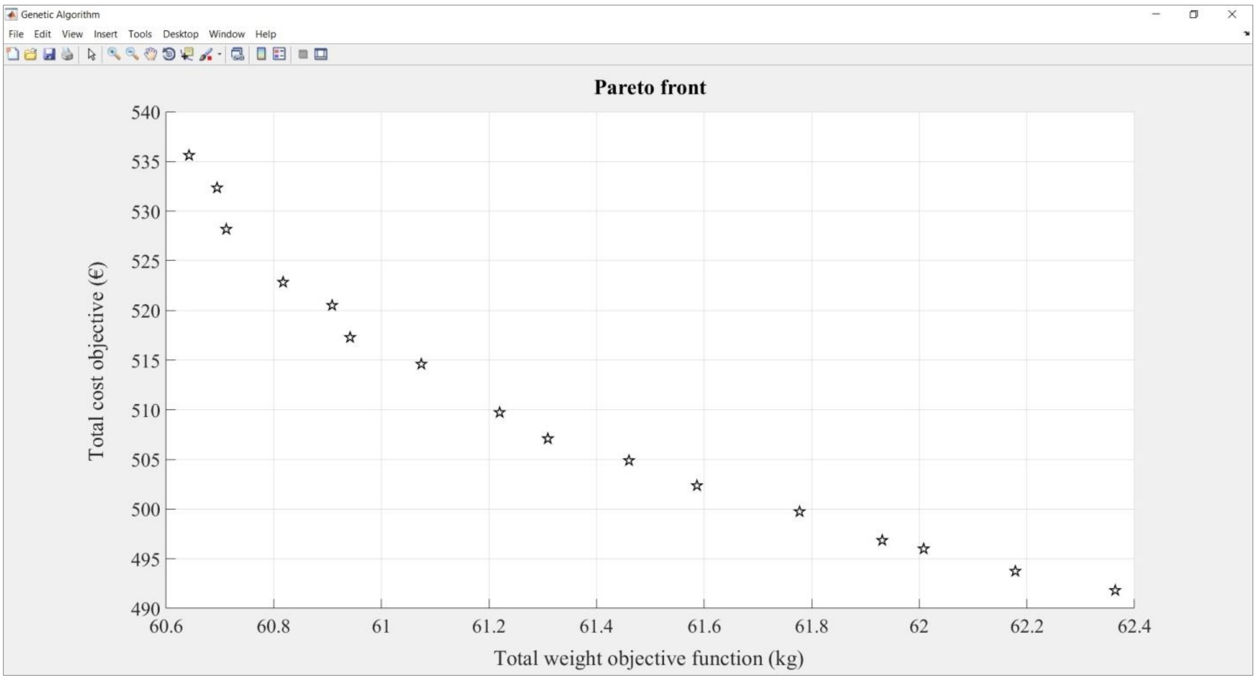


Figure 5.6: Pareto front set for multi-objective functions (total weight and total material cost) using the Matlab program (Genetic Algorithm Solver) for the sandwich base plate of military aircraft pallets consist of aluminum honeycomb core and aluminum face-sheets.

– ***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		40.742	321.631	1	23.872

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		27.069	702.299	0.6	24.272

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		40.115	765.06	1.1	23.772

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		40.76	321.876	1	23.903

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

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

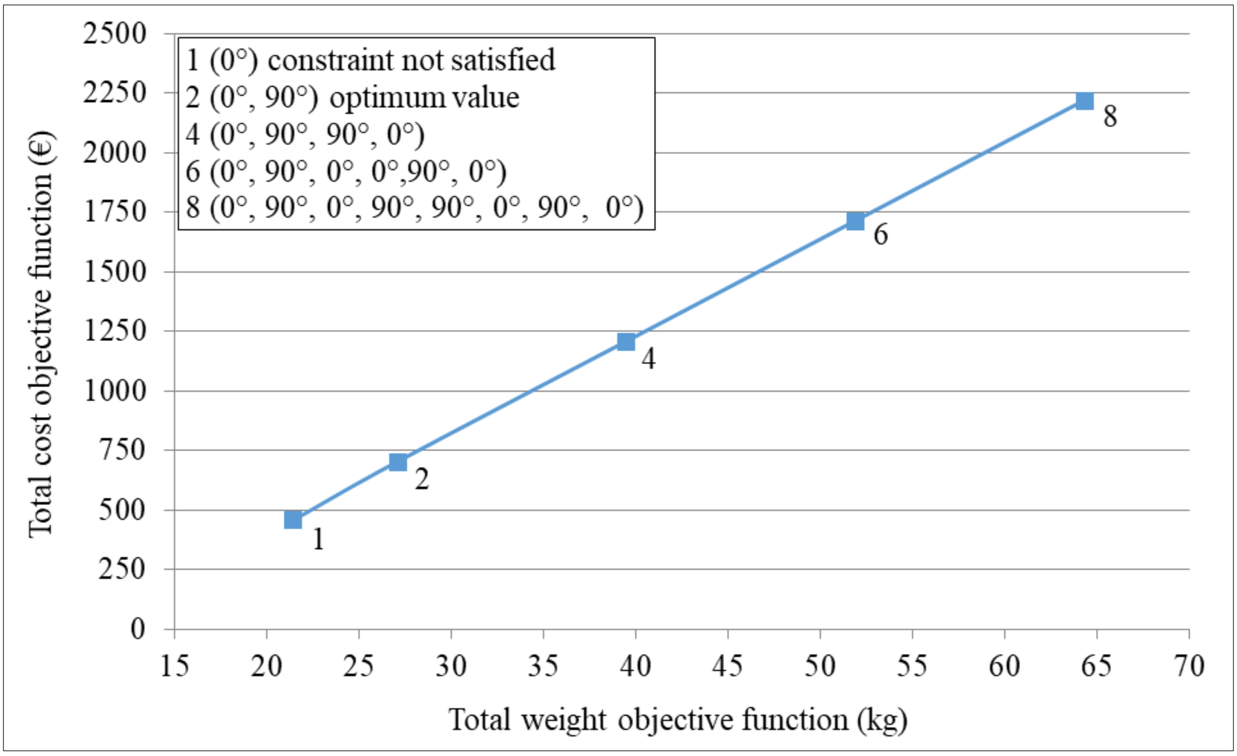


Figure 5.7(*a*): Minimum total weight versus minimum total material cost objective function using the Matlab program (Genetic Algorithm Solver) for honeycomb sandwich base plate of military aircraft pallets consisting of an aluminum honeycomb core and epoxy woven carbon fiber composite face-sheets with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

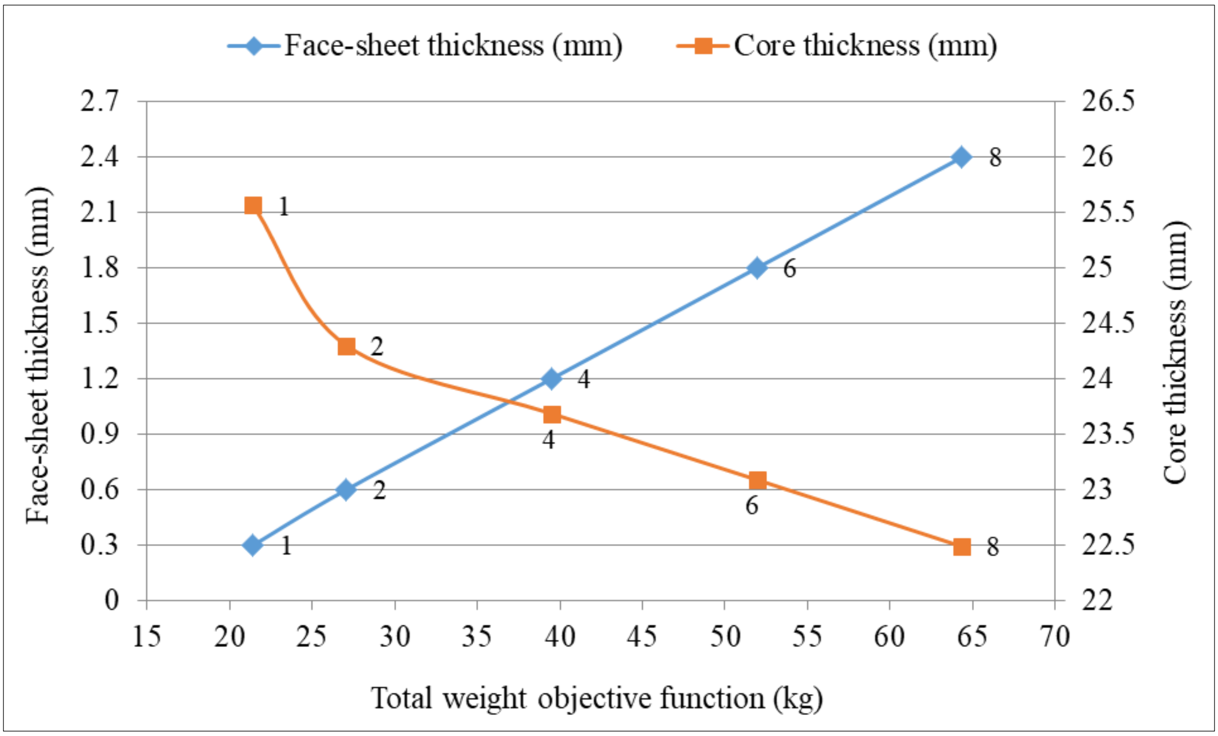


Figure 5.7(*b*): Minimum total weight objective function versus optimum face-sheet and core thicknesses using Matlab program (Genetic Algorithm Solver) for honeycomb sandwich base plate of military aircraft pallets consisting of an aluminum honeycomb core and epoxy woven carbon fiber face-sheets with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

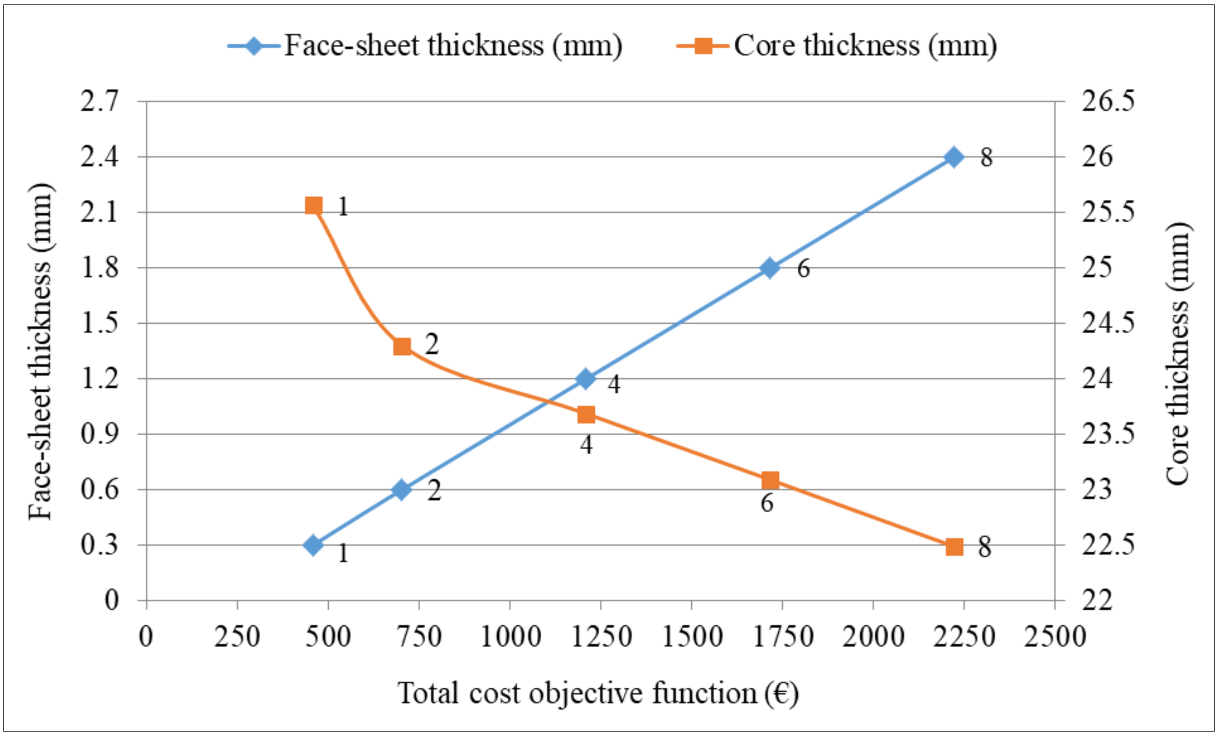


Figure 5.7(*c*): Minimum total material cost objective function versus optimum face-sheet and core thicknesses using Matlab program (Genetic Algorithm Solver) for honeycomb sandwich base plate of military aircraft pallets consisting of an aluminum honeycomb core and epoxy woven carbon fiber face-sheets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

5.4. *Saving Weight Calculator*

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 fuel cost savings and carbon cost savings, 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 [75].

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

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, composite laminate face-sheets' mechanical properties 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 (27.127 kg, 703.074 €, 0.6 mm, and 24.371 mm), respectively. This optimal sandwich plate provides a (66.25 %) weight saving compared to the conventional aluminum single base plate pallet (80 kg). For aluminum alloy face-sheets for honeycomb sandwich base plate of pallets, the optimum face-sheet thickness and optimum core thickness ensure the minimum weight and/or the minimum cost are (0.8212 mm, 49.532 mm, 60.642 kg, and 535.612 €), respectively. This optimal sandwich plate provides (24.2 %) weight saving compared to the conventional aluminum single base plate pallet (80 kg). 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

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 core/ face-sheet assembly's heterogeneous nature. 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

In this study, the optimum design of solar sandwich panels for microsatellite applications was verified. The mathematical modeling for the optimization processes is 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 [72].

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

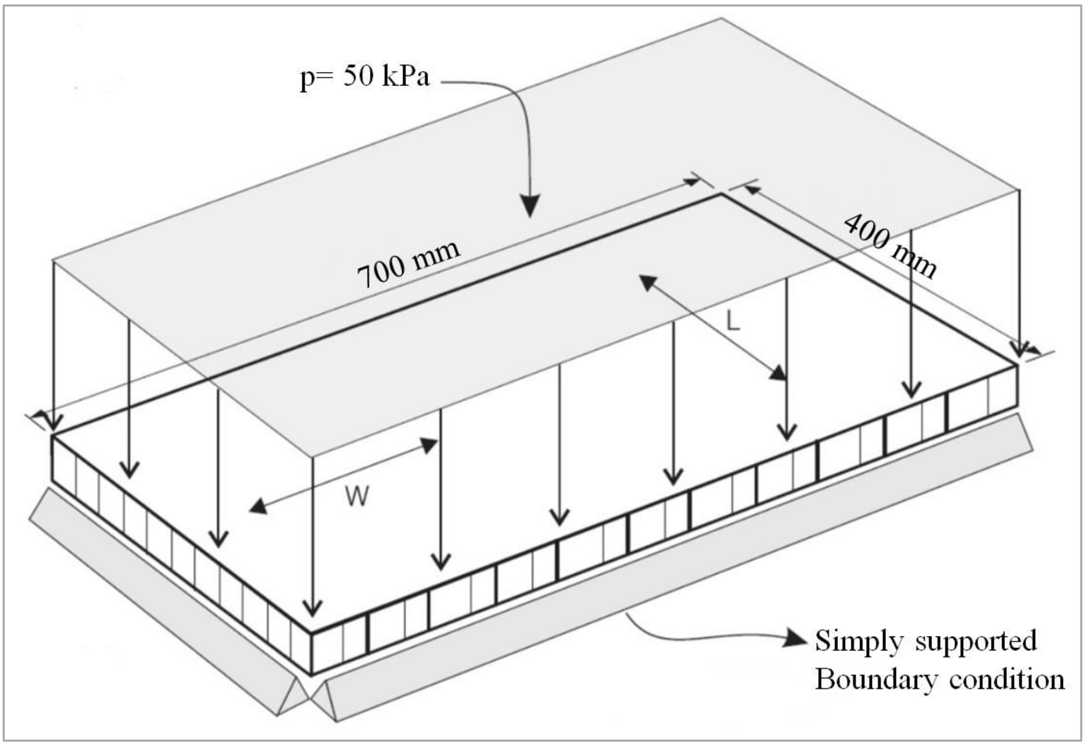


Figure 6.1: Honeycomb sandwich panel with simply supported boundary conditions on all four sides with a uniformly distributed pressure (p =50 kPa) applied on the upper face-sheet.

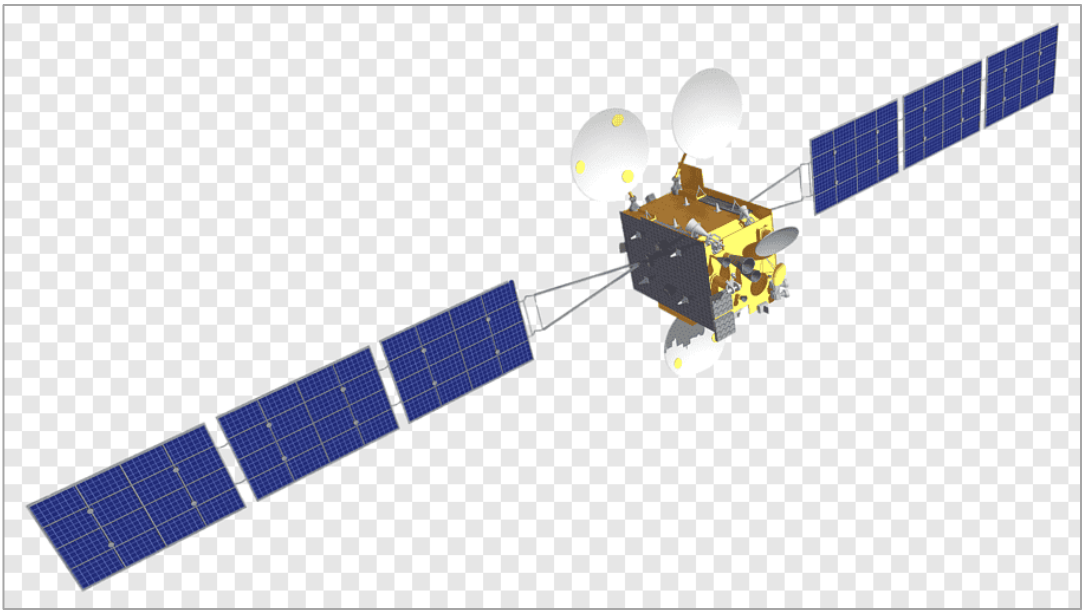


Figure 6.2: Satellite panels structure (ultra-high stiffness and strength per unit weight).

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

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 a satellite's honeycomb sandwich solar panels. The face-sheets are of aluminum alloy.

W_{min}	$t_{f,opt}$	$t_{c,opt}$
kg	mm	mm
2.293	0.487	66.972

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

C_{min}	$t_{f,opt}$	$t_{c,opt}$
€	mm	mm
21.657	1.025	46.645

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

W_{min}	$t_{f,opt}$	$t_{c,opt}$
kg	mm	mm
2.239	0.505	63.518

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 a satellite, in which the face-sheets are of aluminum alloy.

C_{min}	$t_{f,opt}$	$t_{c,opt}$
€	mm	mm
21.659	1.0256	46.637

– ***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		3.184	1	91.733

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		1.807	0.6	56.092

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		2.364	1.1	57.408

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°		€	mm	mm
4 (0°, 90°, 90°, 0°) Optimum value		33.803	1	91.733

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
2 (+45°, -45°) Optimum value		37.611	0.6	56.092

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
4 (0°, 90°, +45°, -45°) Optimum value		40.652	1.1	57.408

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		3.182	1	91.644

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		1.776	0.6	54.749

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		2.339	1.1	56.307

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°		€	mm	mm
4 (0°, 90°, 90°, 0°) Optimum value		33.233	1	89.903

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
2 (+45°, -45°) Optimum value		37.026	0.6	54.213

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
4 (0°, 90°, +45°, -45°) Optimum value		40.188	1.1	55.917

6.3.2. Optimization of Multi-objective Functions

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. The Matlab program (Multi-objective Genetic Algorithm Solver) is shown in Table 6.12 and Figure 6.6. W_1 and W_2 symbols are the weights of weight objective function and cost objective function in percentage (%).

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 a 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	2.357	22.428	0.688	56.675
2	60	40	2.333	22.701	0.643	58.558
3	70	30	2.313	23.055	0.596	60.742
4	80	20	2.303	23.351	0.563	62.43
5	90	10	2.295	23.741	0.526	64.508

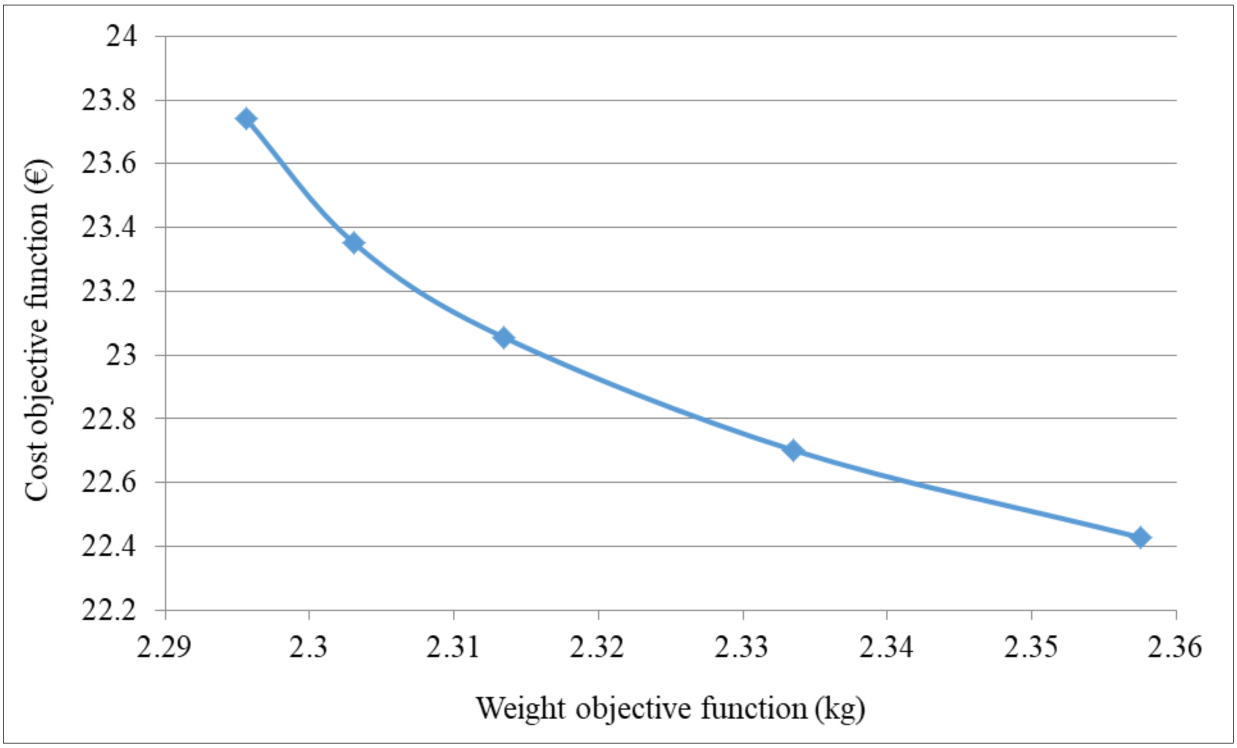


Figure 6.3: Compromise between multi-objective functions weight and cost using the Excel Solver program (Weighted Normalized Method) for honeycomb sandwich satellite panel, face-sheets are of aluminum alloy.

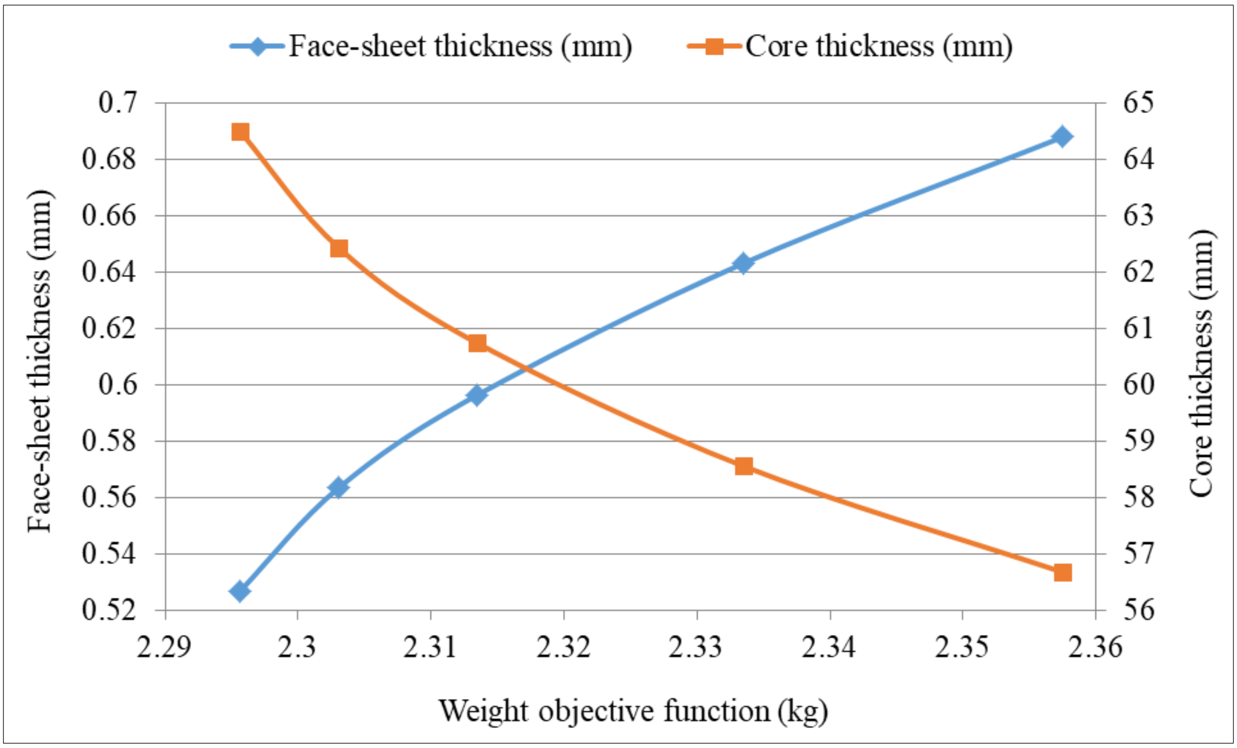


Figure 6.4: Minimum weight objective function versus optimum face-sheet and core thicknesses using the Excel Solver program (Weighted Normalized Method) for the sandwich panel of satellite consists of an aluminum honeycomb core and aluminum face-sheets.

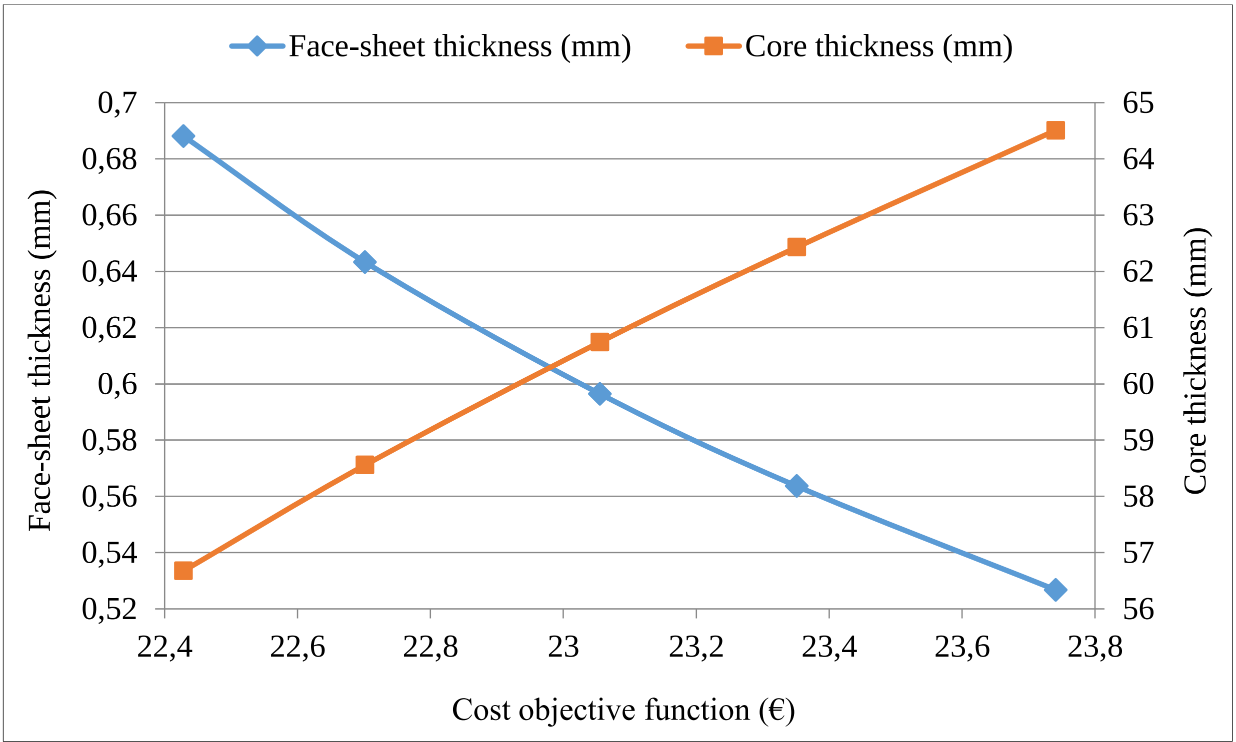


Figure 6.5: Minimum cost objective function versus optimum face-sheet and core thicknesses using the Excel Solver program (Weighted Normalized Method) for the sandwich panel of satellite consists of an aluminum honeycomb core and aluminum face-sheets.

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	**2.213**	**22.561**	**0.533**	**60.577**
2	2.217	22.519	0.54	60.283
3	2.225	22.099	0.58	58.038
4	2.375	20.754	0.832	48.064
5	2.244	21.943	0.61	56.864
6	2.365	20.839	0.816	48.697
7	2.281	21.368	0.691	53.199
8	2.218	22.301	0.557	59.182
9	2.308	21.099	0.738	51.268
10	2.263	21.434	0.668	53.929
11	2.316	21.026	0.751	50.739
12	2.375	20.754	0.832	48.064
13	2.251	21.685	0.636	55.44
14	2.213	22.561	0.533	60.577
15	2.344	20.869	0.792	49.335
16	2.257	21.509	0.656	54.432
17	2.291	21.178	0.715	52.052
18	2.337	20.928	0.781	49.77

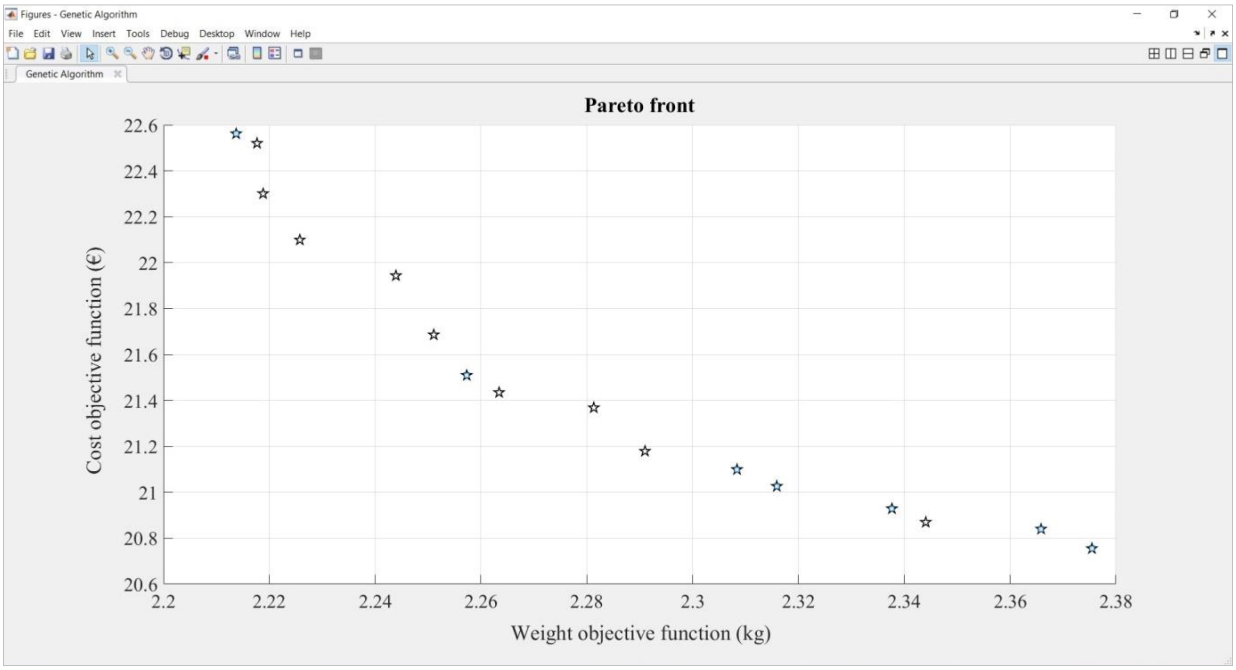


Figure 6.6: Pareto front set for multi-objective functions (weight and cost) using the Matlab program (Genetic Algorithm Solver) for solar sandwich panels of satellite consists of an aluminum honeycomb core and aluminum face-sheets.

– ***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 a satellite, obtained by applying the Excel Solver program are shown in Table 6.13, and the Matlab program (Multi-objective Genetic Algorithm Solver) is 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		3.184	33.803	1	91.733

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		1.807	37.611	0.6	56.092

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		2.364	40.652	1.1	57.408

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		3.135	33.143	1	89.612

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		1.76	36.978	0.6	54.058

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		2.317	40.016	1.1	55.363

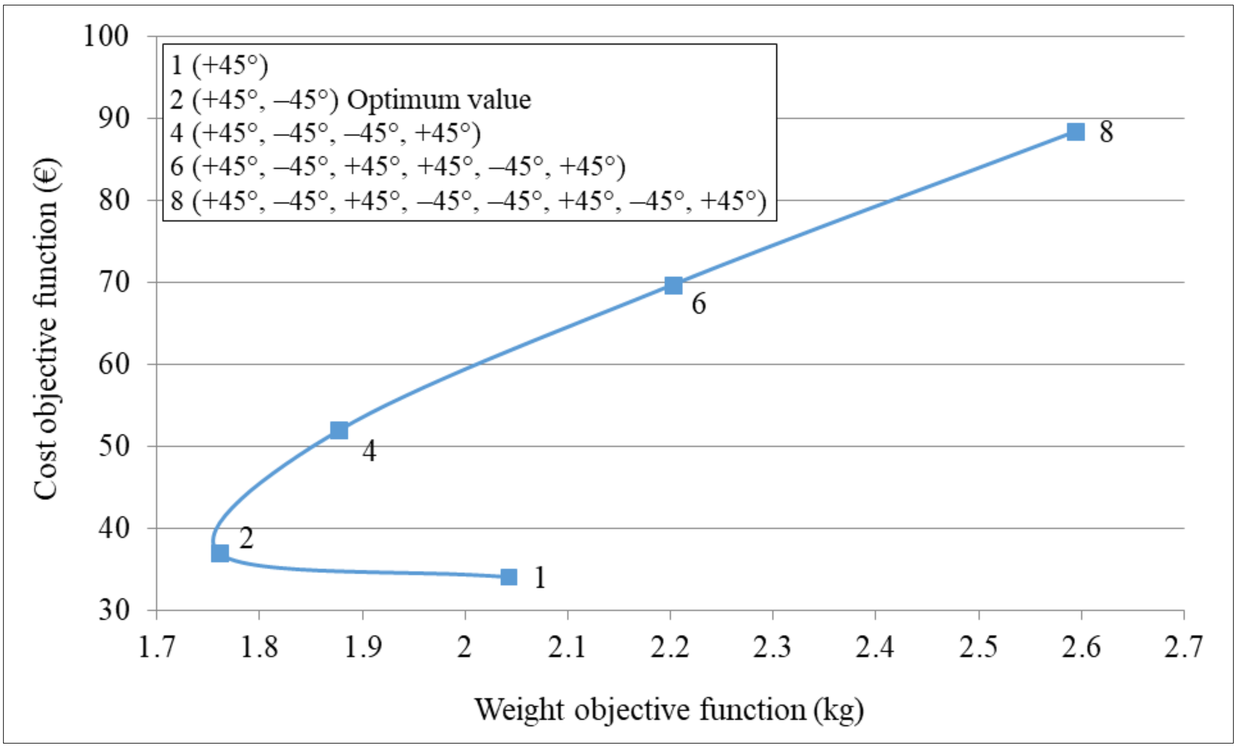


Figure 6.7(*a*): Minimum weight versus minimum cost objective function using the Matlab program (Genetic Algorithm Solver) for solar sandwich panels of satellite application consisting of an aluminum honeycomb core and epoxy woven carbon fiber composite face-sheets with a different number of layers N_l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

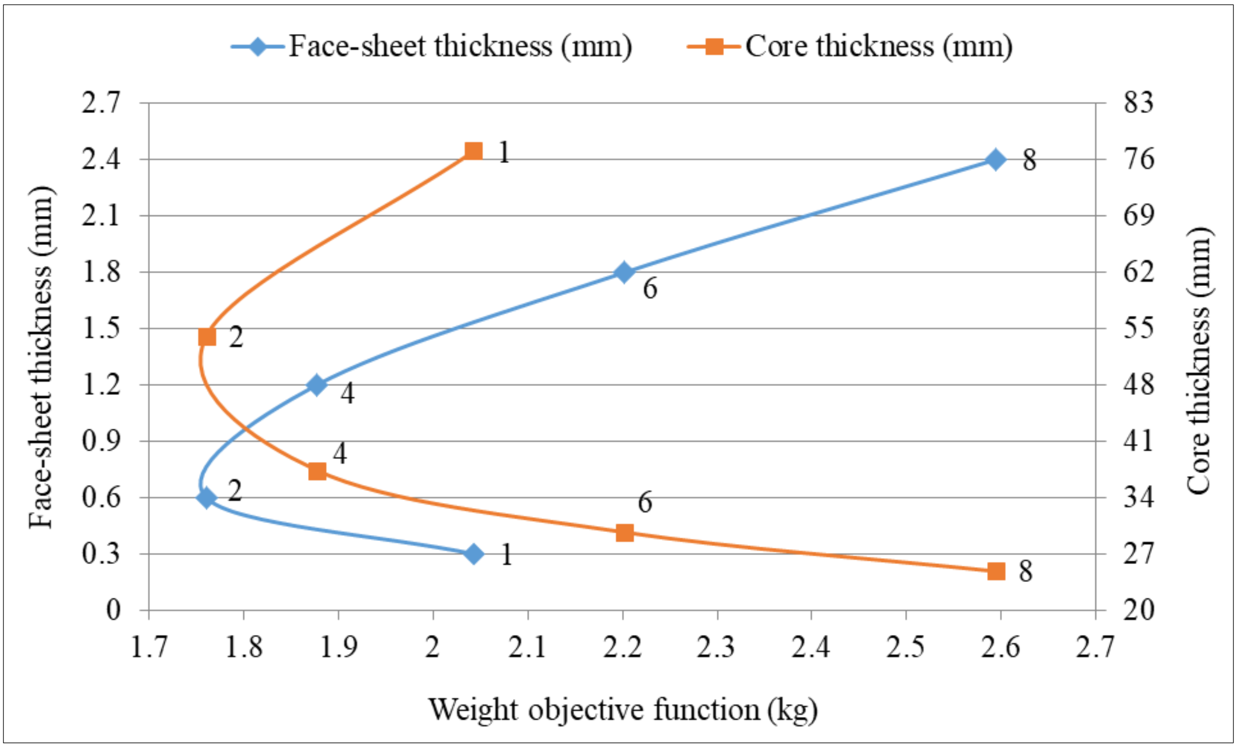


Figure 6.7(*b*): Minimum weight objective function versus optimum face-sheet and core thicknesses using the Matlab program (Genetic Algorithm Solver) for solar sandwich panels of satellite application consisting of an aluminum honeycomb core and epoxy woven carbon fiber face-sheets with a different number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

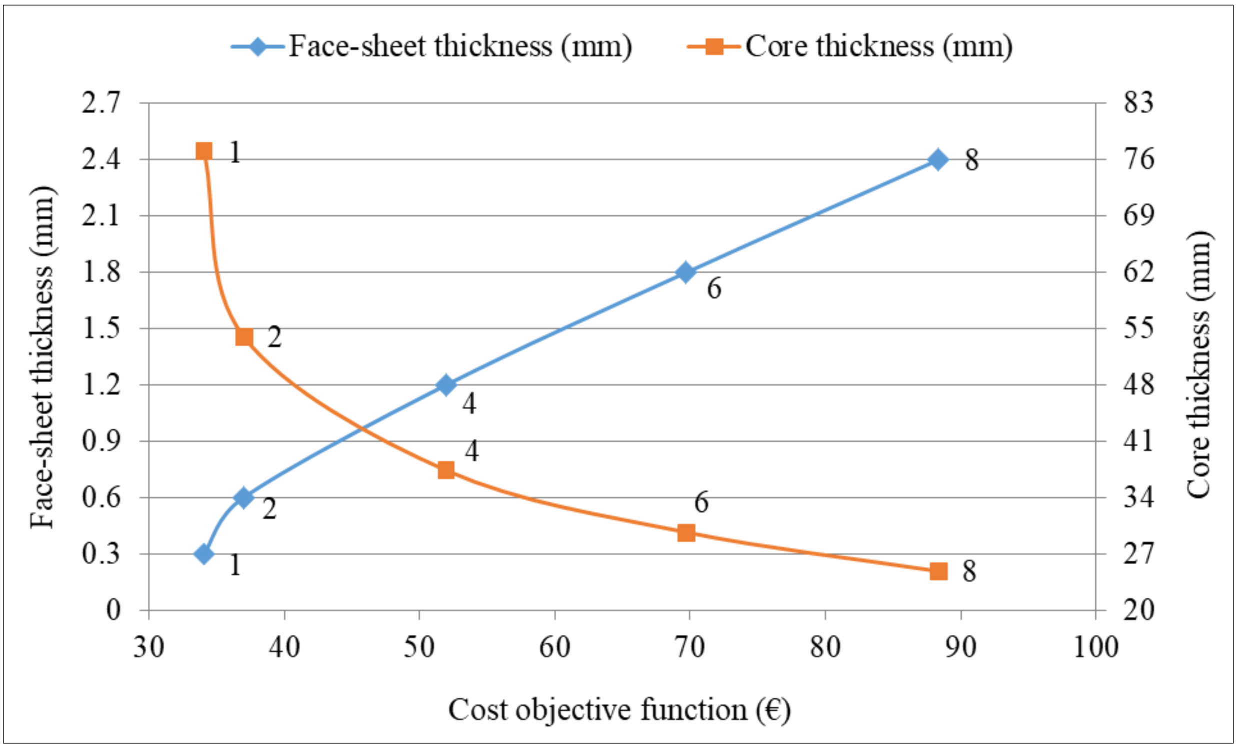


Figure 6.7(c): Minimum cost objective function versus optimum face-sheet and core thicknesses using the Matlab program (Genetic Algorithm Solver) for solar sandwich panels of satellite application consisting of an aluminum honeycomb core and epoxy woven carbon fiber face-sheets with a different number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

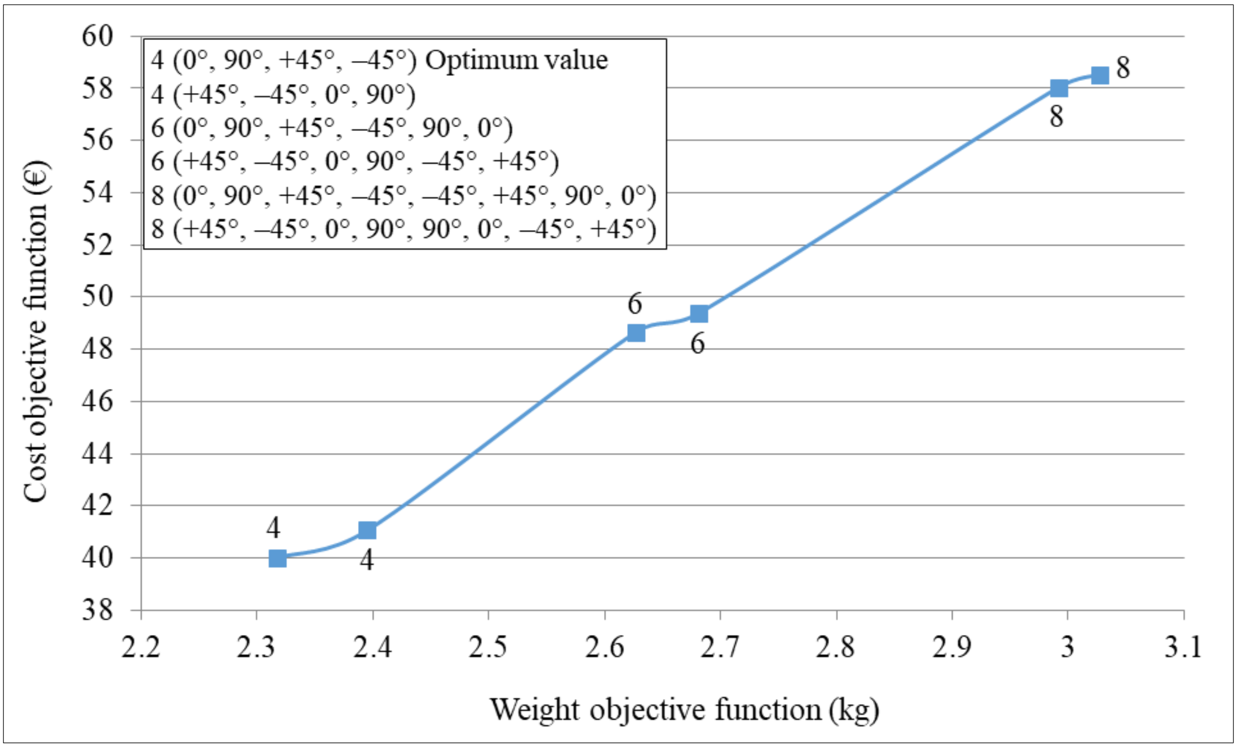


Figure 6.8(a): Minimum weight versus minimum cost objective function using Matlab program (Genetic Algorithm Solver) for solar sandwich panels of satellite application consisting of an aluminum honeycomb core and hybrid composite face-sheets with a different number of layers N_l and different fiber orientation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

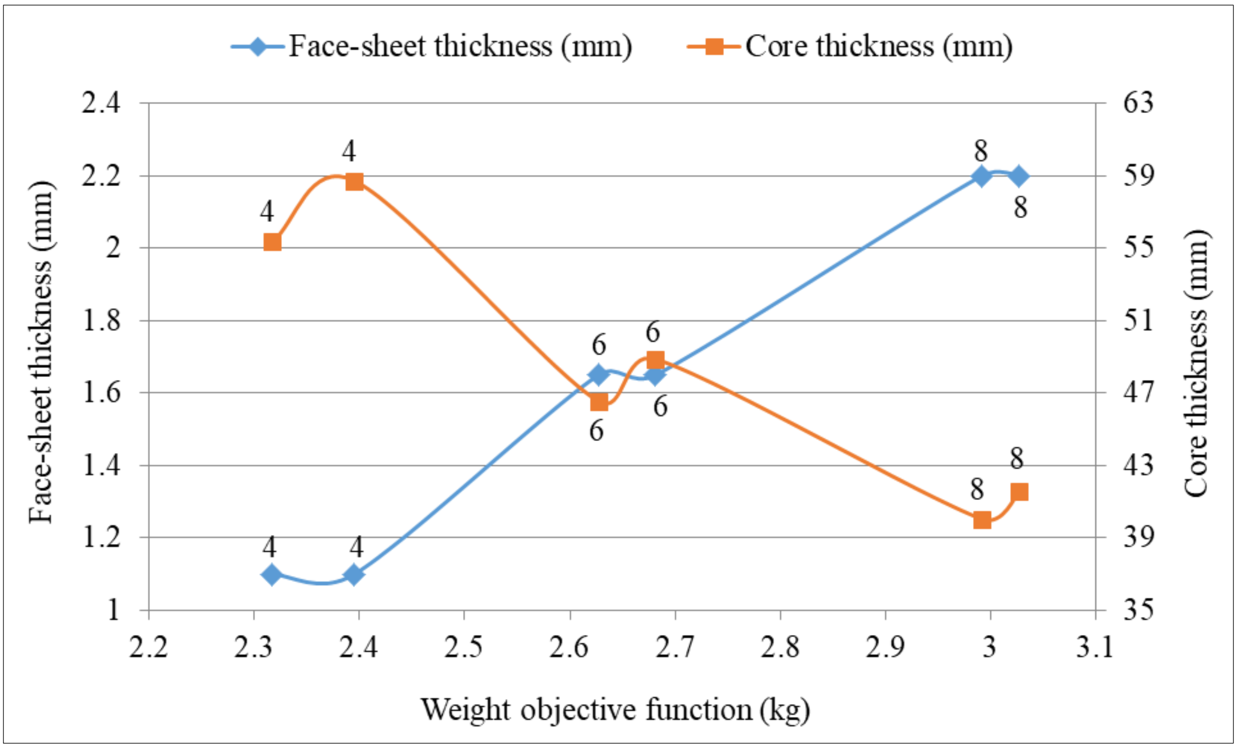


Figure 6.8(*b*): Minimum weight objective function versus optimum face-sheet and core thicknesses using the Matlab program (Genetic Algorithm Solver) for solar sandwich panels of satellite application consisting of an aluminum honeycomb core and hybrid composite face-sheets with a different number of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

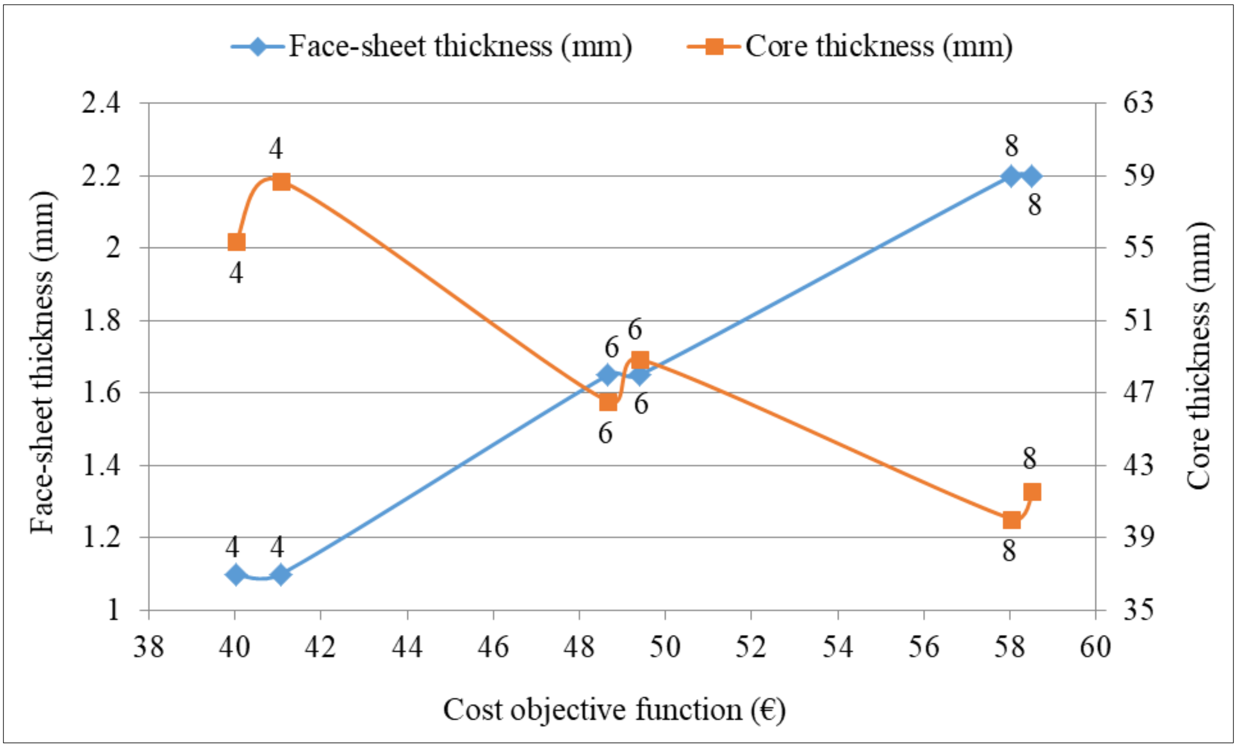


Figure 6.8(*c*): Minimum cost objective function versus optimum face-sheet and core thicknesses using the Matlab program (Genetic Algorithm Solver) for solar sandwich panels of satellite application consisting of an aluminum honeycomb core and hybrid composite face-sheets with a different number of layers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

6.4. Discussions

This study aimed to design a lightweight sandwich panel, which can be applied in a satellite application industry because the solar panels of a satellite require 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 had 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, composite laminate face-sheets' mechanical properties 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 (2.293 kg), with optimum aluminum face-sheet thickness and optimum core thickness are (0.487 mm, 66.972 mm), respectively, as well as the optimum solar sandwich panels of a satellite which ensuring the minimum cost is (21.657 €) with optimum aluminum face-sheet thickness, and optimum core thickness is (1.025 mm, 46.645 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 (2.239 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 a satellite which ensuring the minimum cost is (21.659 €) with an optimum thickness of aluminum face-sheet and optimum honeycomb core thickness are (1.0256 mm, 46.637 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 (2.357 kg, 22.428 €), 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 (2.213 kg) with the cost is (22.561 €), and the optimal thicknesses of aluminum face-sheet and honeycomb core are (0.533 mm, 60.577 mm), respectively. The minimum cost is (20.754 €) with weight is (2.375 kg), and the optimal thickness of the aluminum face-sheet and honeycomb core are (0.832 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 multidirectional 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 (1.807 kg), with optimum face-sheet thickness and honeycomb core thickness are (0.6 mm, 56.092 mm), respectively. The minimum cost is (37.611 €) with optimum face-sheet thickness, and honeycomb core thickness is (0.6 mm, 56.092 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 (1.776 kg) with optimal thickness of composite face-sheet (epoxy woven carbon fiber) and optimal thickness of honeycomb core are (0.6 mm, 54.749 mm), respectively. The minimum cost for epoxy woven carbon fiber face-sheet is (37.026 €) with an optimum face-sheet thickness and optimum honeycomb core thickness are (0.6 mm, 54.213 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 (1.807 kg, 37.611 €), respectively, with an optimum thickness of composite face-sheet and honeycomb core thickness are (0.6 mm, 56.092 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 and minimum cost are (1.76 kg, 36.978 €), respectively, with optimum face-sheet thickness and honeycomb core thickness are (0.6 mm, 54.058 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 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. The graph lines for these types of face-sheets are identical, named as (phenolic/epoxy woven glass fiber face-sheet).

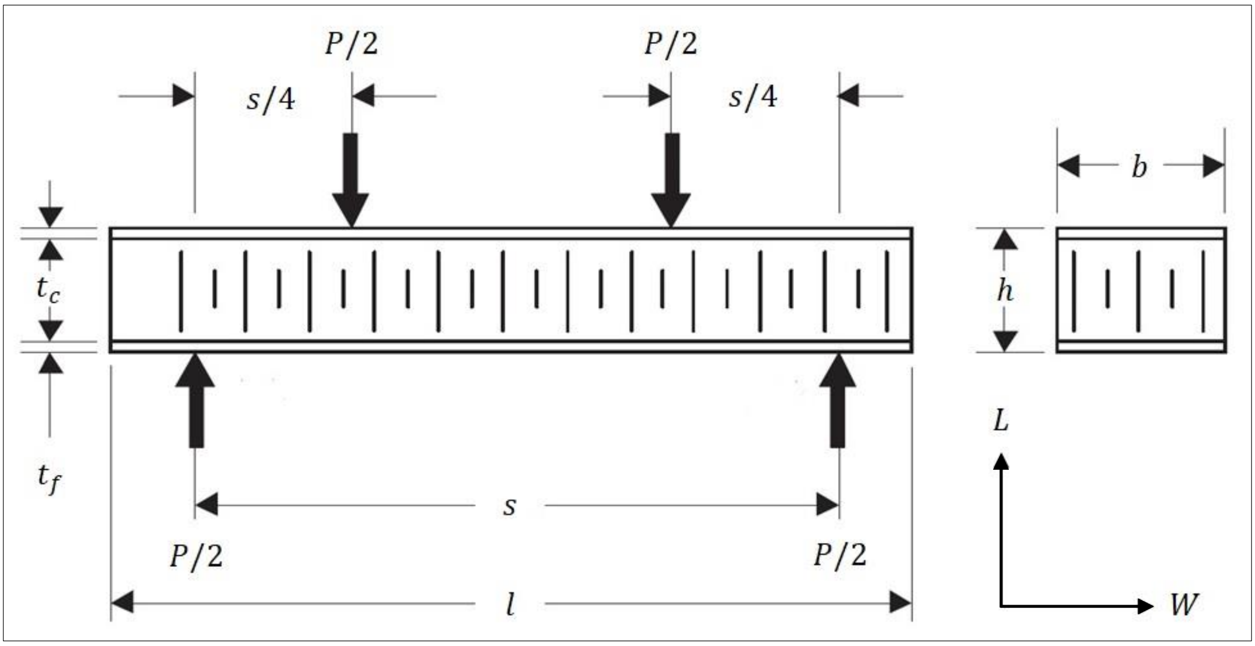


Figure 7.1: Set up and configure the honeycomb sandwich structure for a four-point bending test by applying the Digimat-HC program [72].

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

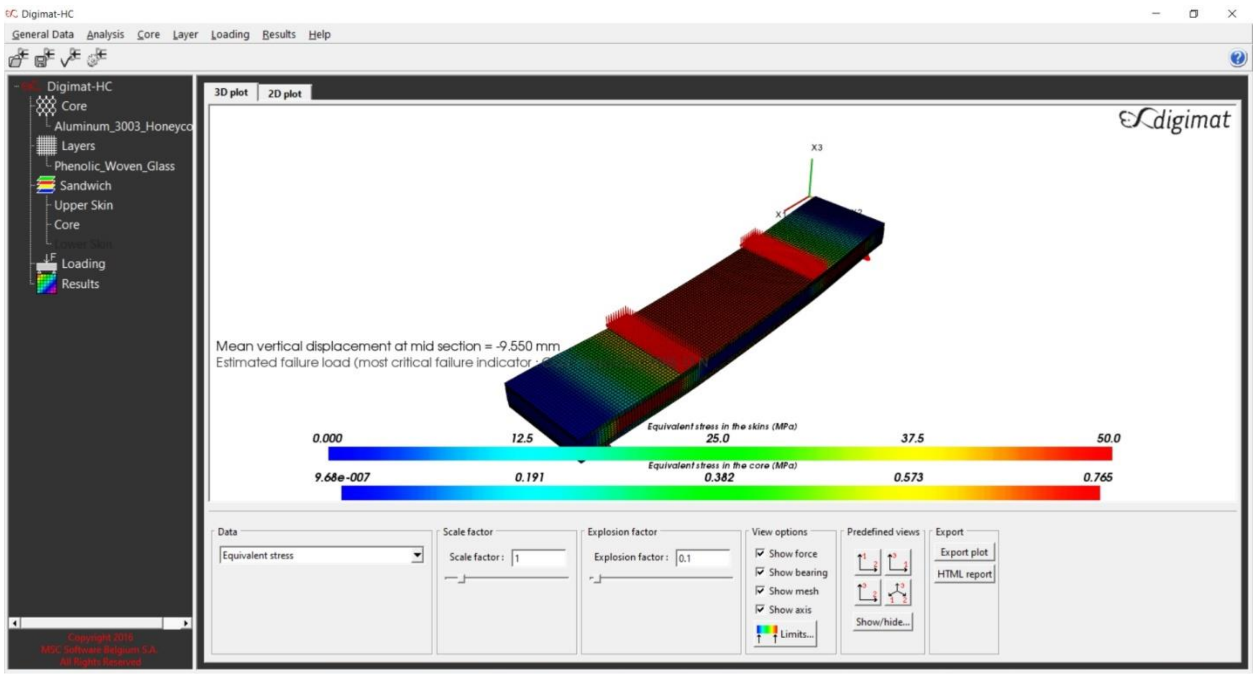


Figure 7.2: Numerical result (four-point bending test) for a model of the sandwich panel consists of an aluminum honeycomb core (t_c=15 mm) and phenolic woven glass face-sheets (t_f= 1 mm).

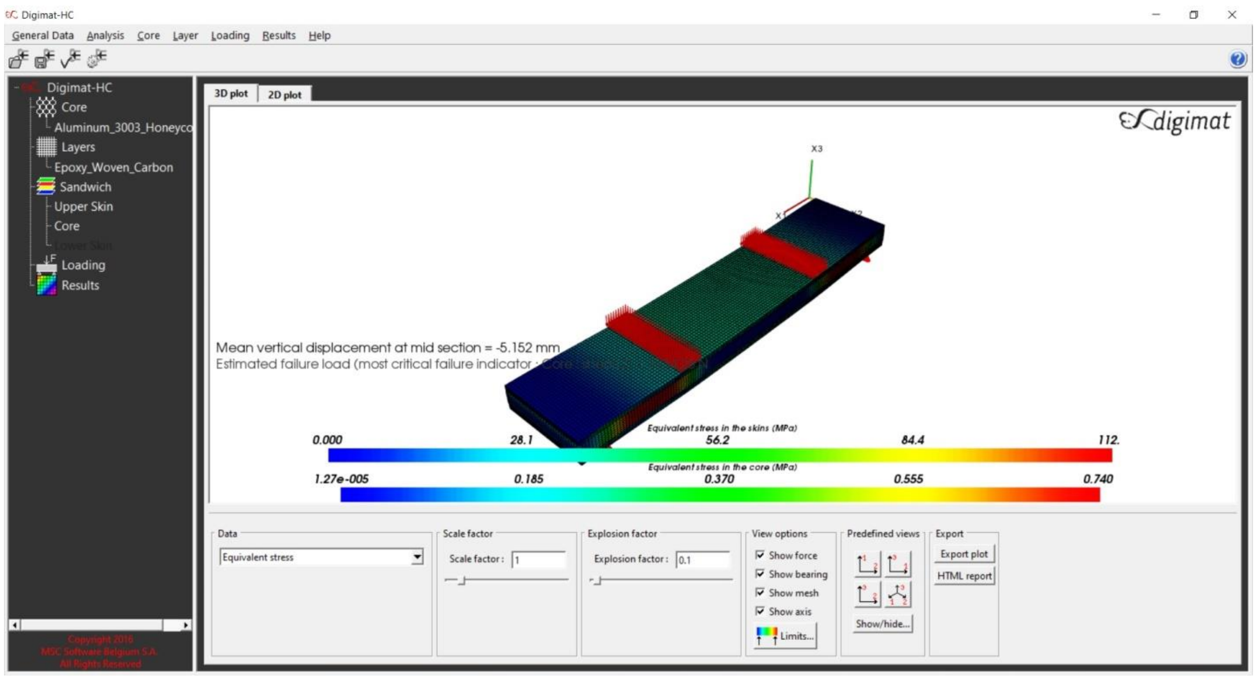


Figure 7.3: Numerical result (four-point bending test) for a model of the sandwich panel consists of an aluminum honeycomb core (t_c=15 mm) and epoxy woven carbon face-sheets (t_f= 1.2 mm).

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

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

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 face-sheet**	δ_{Num}	σ_{skin}	τ_{core}	t_f
No.	Number of layers N_l and fiber orientations θ°	mm	MPa	MPa	mm
1	1 (0°)	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

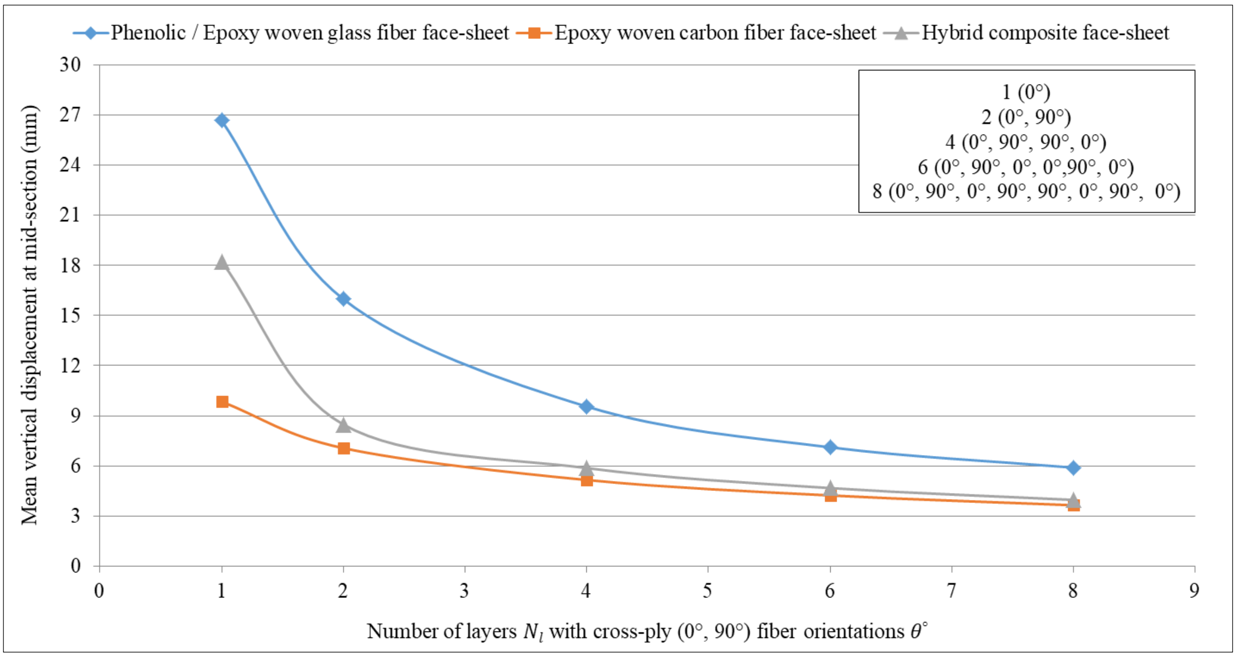


Figure 7.4(*a*): Comparison of deflection numerically using the Digimat-HC program (four-point bending test) for sandwich panels consisting of an aluminum honeycomb core (t_c=15 mm) and different composite material face-sheets of phenolic/epoxy woven glass fiber, epoxy woven carbon fiber, and hybrid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

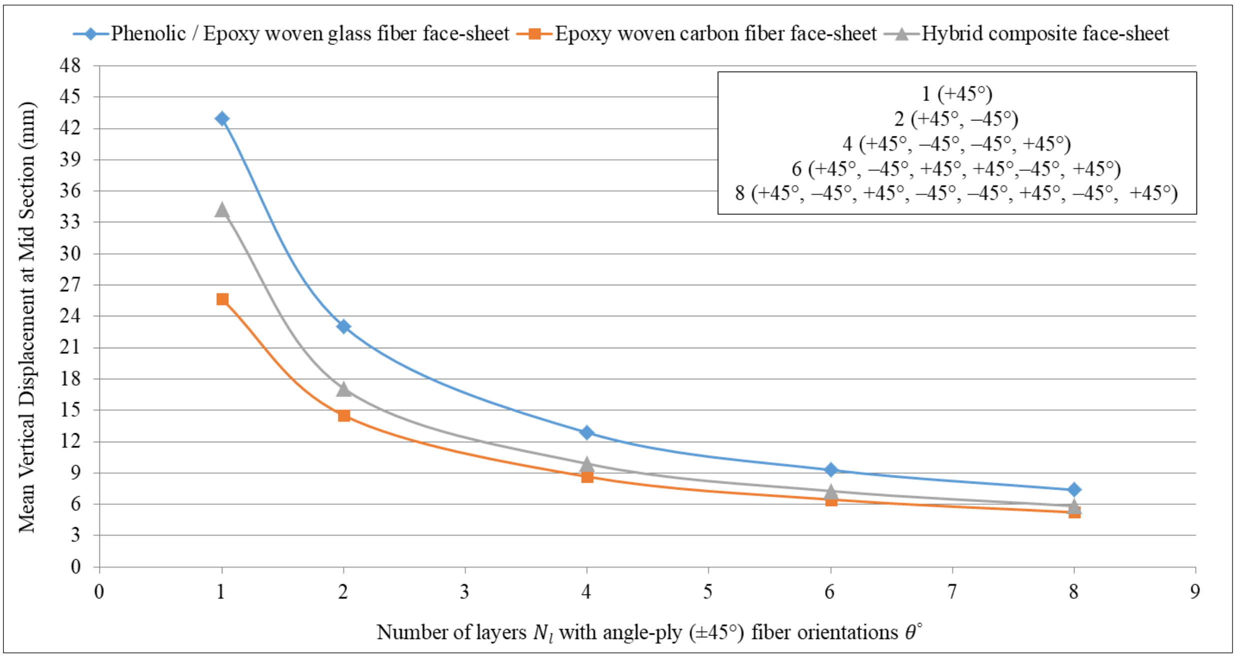


Figure 7.4(*b*): Comparison of deflection numerically using the Digimat-HC program (four-point bending test) for sandwich panels consisting of an aluminum honeycomb core (t_c=15 mm) and different composite material face-sheets of phenolic/epoxy woven glass fiber, epoxy woven carbon fiber, and hybrid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

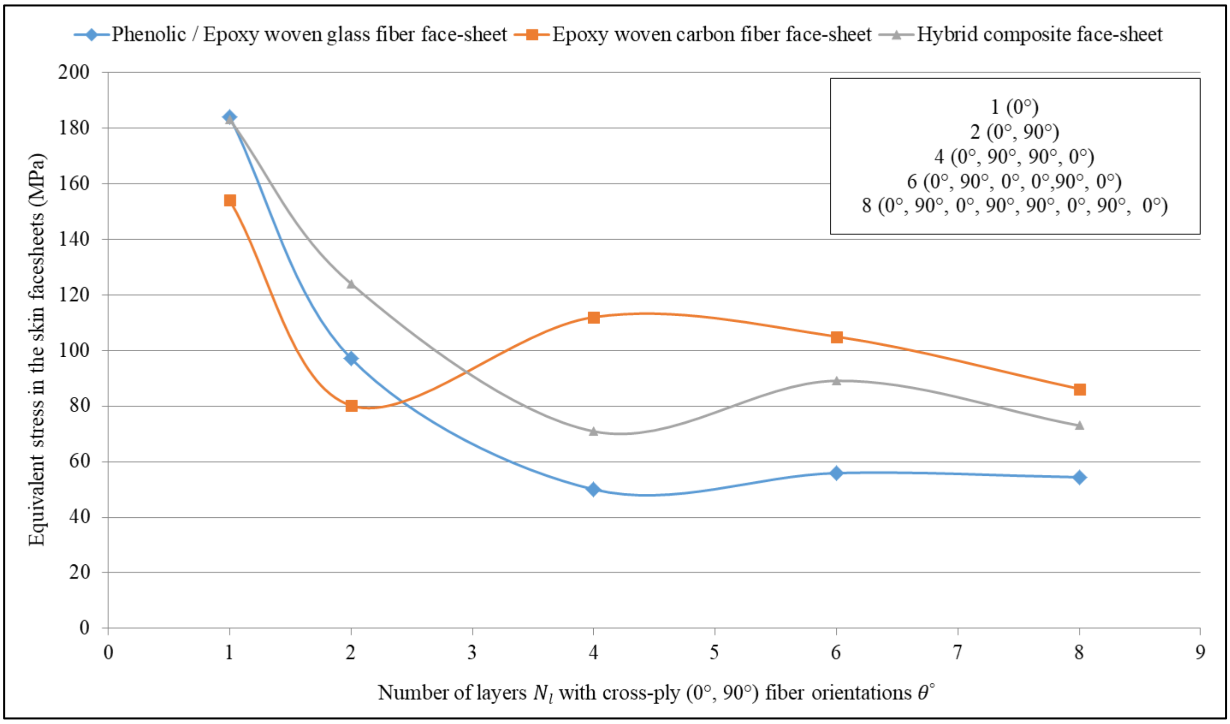


Figure 7.5(*a*): Comparison of face-sheet stress numerically using the Digimat-HC program (four-point bending test) for sandwich panels consisting of an aluminum honeycomb core (t_c=15 mm) and different composite material face-sheets of phenolic/epoxy woven glass fiber, epoxy woven carbon fiber, and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

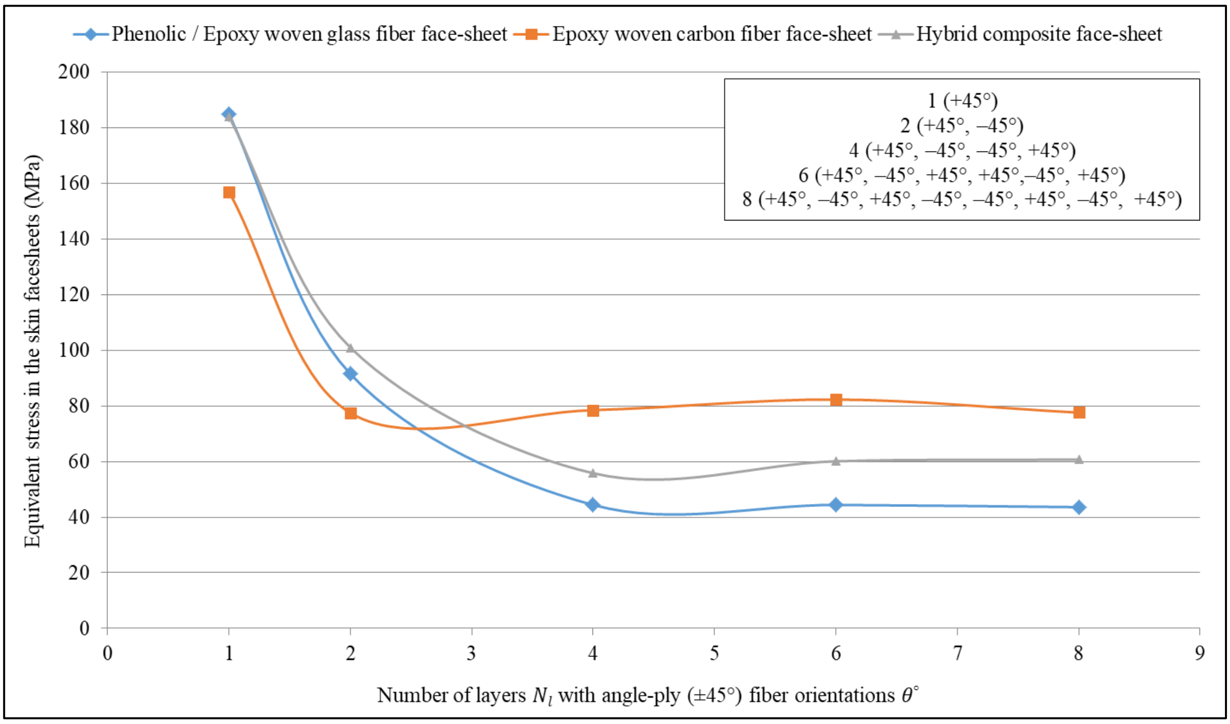


Figure 7.5(*b*): Comparison of face-sheet stress numerically using the Digimat-HC program (four-point bending test) for sandwich panels consisting of an aluminum honeycomb core (t_c=15 mm) and different composite material face-sheets of phenolic/epoxy woven glass fiber, epoxy woven carbon fiber, and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

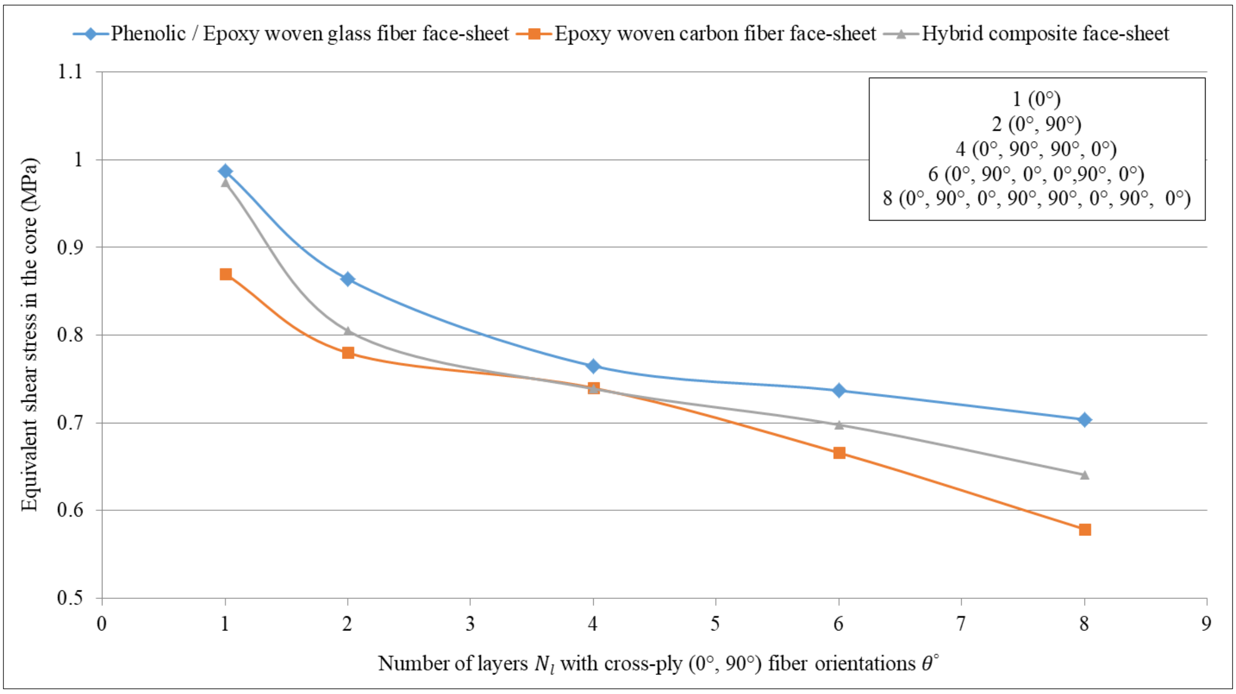


Figure 7.6(*a*): Comparison of core shear stress numerically using the Digimat-HC program (four-point bending test) for sandwich panels consisting of an aluminum honeycomb core (t_c=15 mm) and different composite material face-sheets of phenolic/epoxy woven glass fiber, epoxy woven carbon fiber, and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

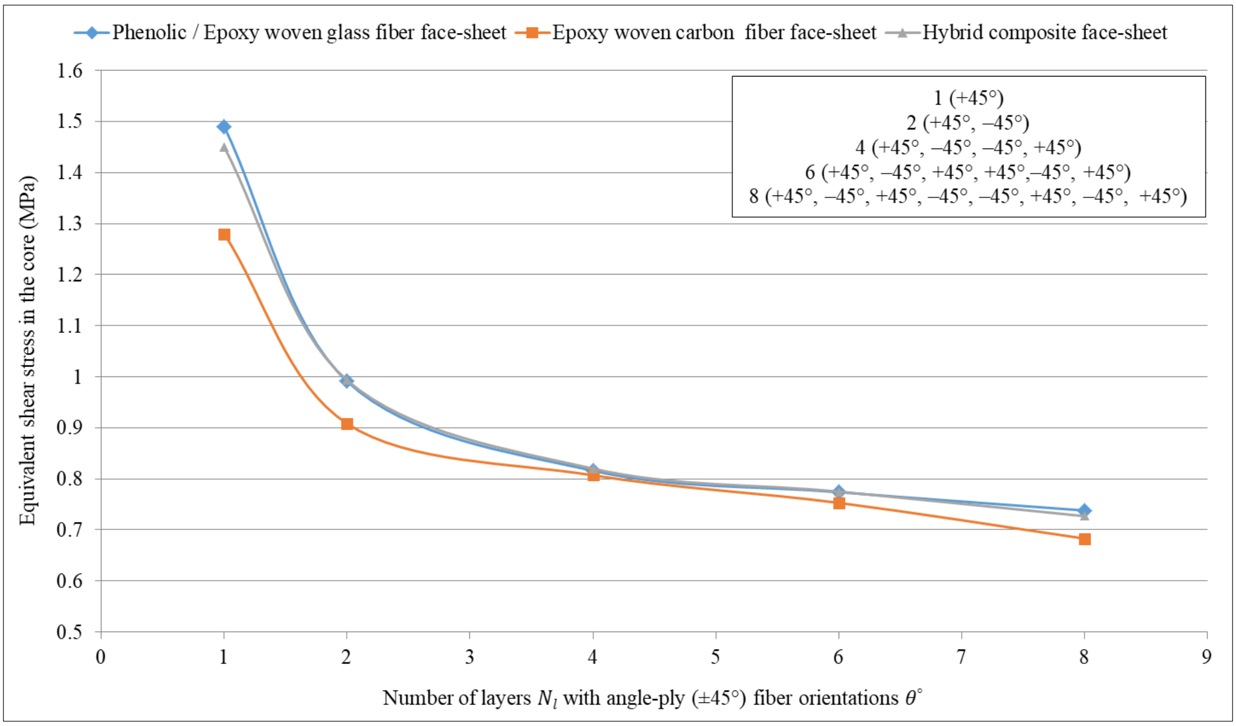


Figure 7.6(*b*): Comparison of core shear stress numerically using the Digimat-HC program (four-point bending test) for sandwich panels consisting of an aluminum honeycomb core (t_c=15 mm) and different composite material face-sheets of phenolic/epoxy woven glass fiber, epoxy woven carbon fiber, and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

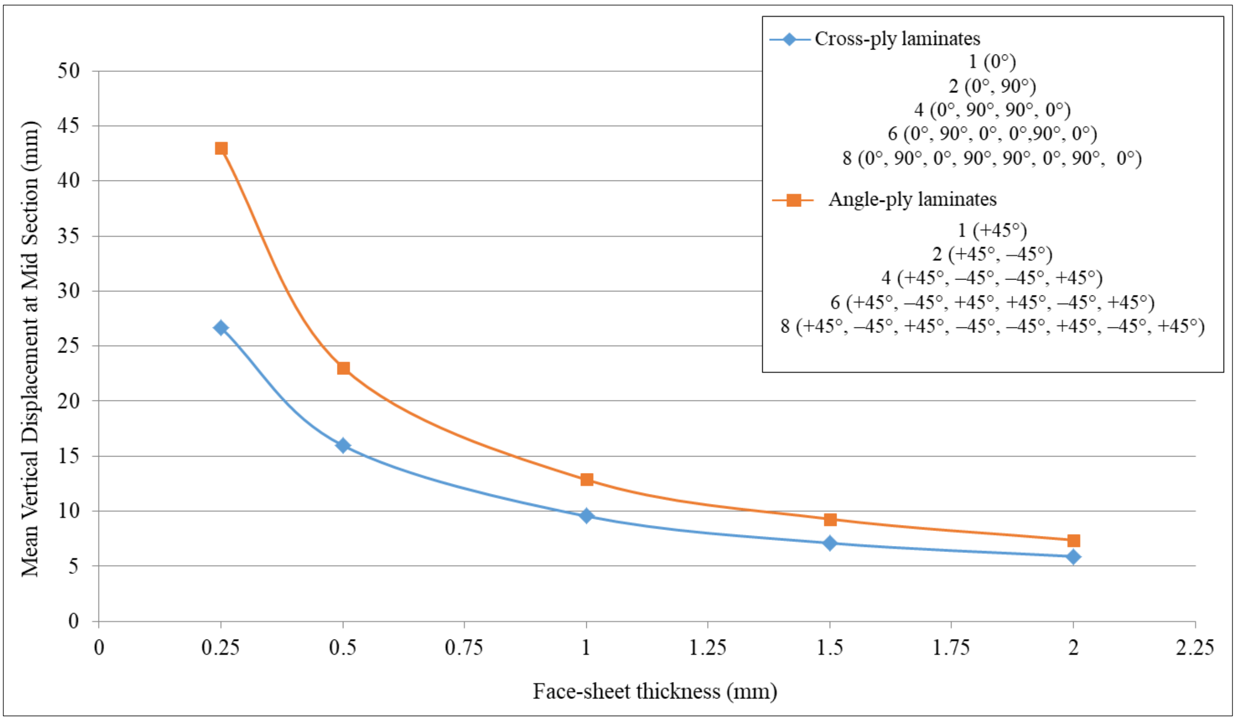


Figure 7.7: Comparison of deflection with face-sheet thickness and fiber orientation θ° numerically using the Digimat-HC program (four-point bending test) for sandwich panels consisting of an aluminum honeycomb core (t_c=15 mm) and composite material face-sheets of phenolic woven glass fiber.

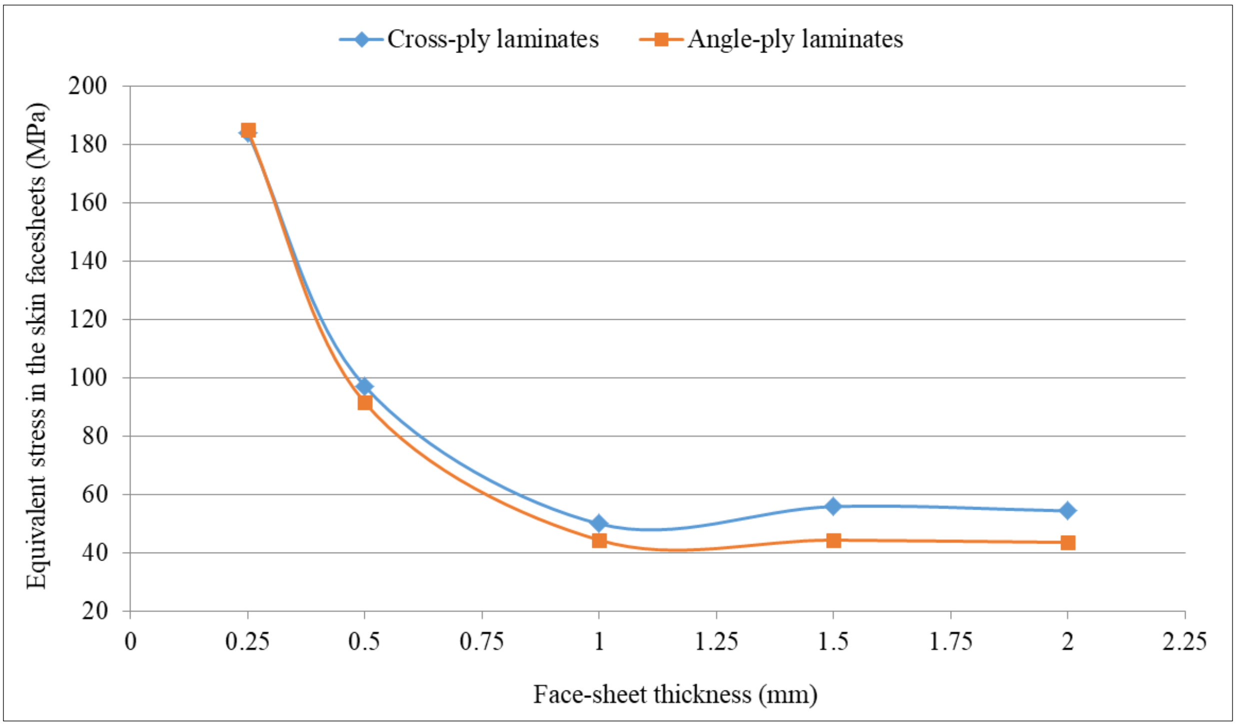


Figure 7.8: Comparison of face-sheet stress with face-sheet thickness and fiber orientation θ° numerically using the Digimat-HC program (four-point bending test) for sandwich panels consisting of an aluminum honeycomb core (t_c=15 mm) and composite material face-sheets of phenolic woven glass fiber.

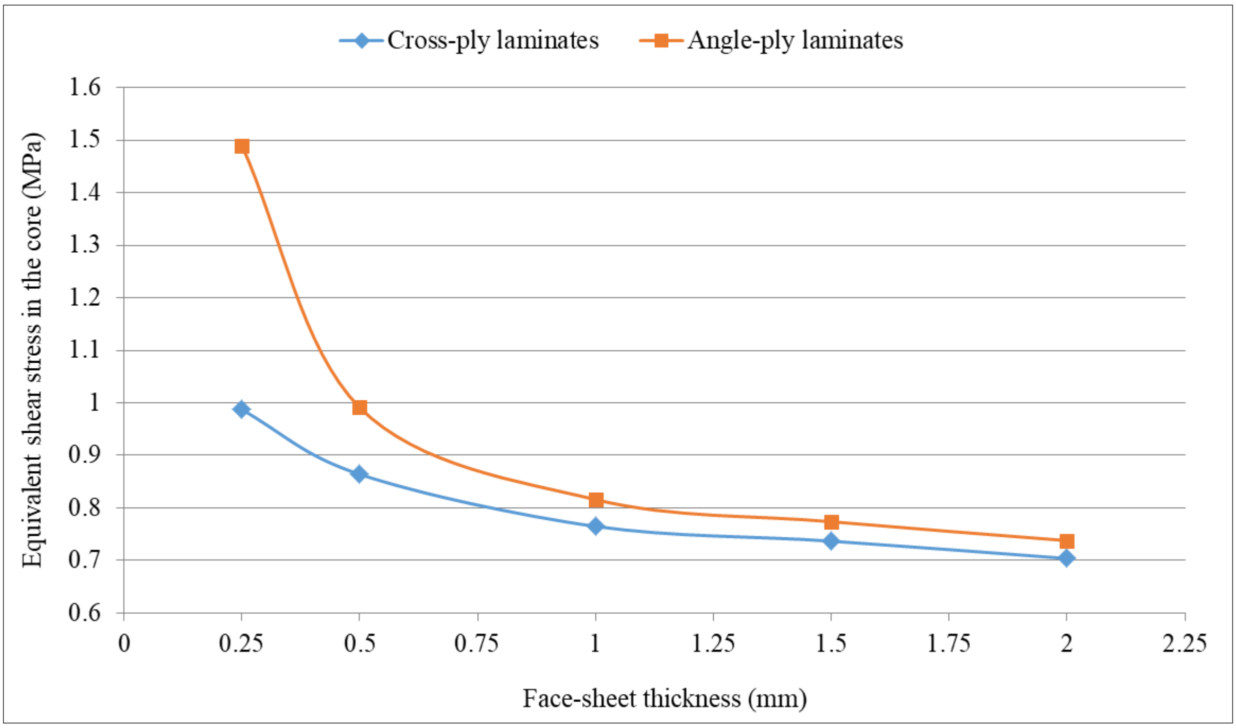


Figure 7.9: Comparison of core shear stress with face-sheet thickness and fiber orientation θ° numerically using the Digimat-HC program (four-point bending test) for sandwich panels consisting of an aluminum honeycomb core (t_c=15 mm) and composite material face-sheets of phenolic woven glass fiber.

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 the sandwich panels' face-sheets and every composite case study consisting of sixteen different fiber orientations. The numerical results, the mean vertical displacement at mid-section, equivalent stress in the face-sheets and equivalent shear stress in the honeycomb core in case of epoxy woven carbon fiber face-sheets of the honeycomb sandwich panels with fiber orientation cross-ply (0°, 90°) and angle-ply (±45°) are less than the aluminum alloy face-sheets, hybrid composite layers face-sheets, phenolic woven glass fiber, and epoxy woven glass fiber, respectively. While, the mean vertical displacement at mid-section and equivalent shear stress in the honeycomb core in case of cross-ply (0°, 90°) fiber orientation face-sheets are less than angle-ply (±45°) fiber orientation face-sheets of the honeycomb sandwich panels.

But, the equivalent stress in the face-sheets in case of angle-ply (±45°) fiber orientation are less than cross-ply (0°, 90°) fiber orientation face-sheets of the honeycomb sandwich panels. 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 new scientific results extracted from the experimental tests of the thesis are summarized as follows:

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

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

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

3. Optimum design of solar sandwich panels for satellite applications, the optimum face-sheet thickness and optimum core thickness ensure the minimum weight and minimum cost are two layers (+45°, -45°) of epoxy woven carbon fiber (1.76 kg, 36.978 €, and 0.6 mm 54.058 mm), respectively.

T3. The mean vertical displacement at mid-section, equivalent skin stress, and equivalent core shear stress for epoxy woven carbon fiber face-sheets of the honeycomb sandwich structures with fiber orientation cross-ply (0°, 90°) and angle-ply (±45°) are less than the aluminum alloy face-sheets, hybrid composite face-sheets, phenolic woven glass fiber face-sheets, and epoxy woven glass fiber face-sheets, respectively.

The mean vertical displacement at mid-section and equivalent core shear stress of cross-ply (0°, 90°) fiber orientation face-sheets are less than angle-ply (±45°) fiber orientation face-sheets of the honeycomb sandwich structures. While, the equivalent skin stress of angle-ply (±45°) fiber orientation is less than cross-ply (0°, 90°) fiber orientation face-sheets of the honeycomb sandwich structures. This statement was proved by Numerical analysis using the Digimat-HC program.

9. SUMMARY

Manufacturing a high-performance and lightweight structure with affordable cost without sacrificing strength has been challenging 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 measurement, numerical models, and theoretical solutions for honeycomb sandwich structures were presented.

The experimental tests included a four-point bending test in computing 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 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

The sandwich structure industry is evident in a wide range of honeycomb cores, composite panels, and assemblies engineered to meet design and manufacturing engineers' unique demands. The honeycomb sandwich structure offers 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 honeycomb's shear failure mode 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 rises exponentially compared to the single sheet material.

The use of the honeycomb core creates a dramatic increase in stiffness with minimal weight gain. The aluminum honeycomb core is 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. 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, 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.

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LIST OF PUBLICATIONS RELATED TO THE TOPIC OF THE RESEARCH FIELD

IN ENGLISH

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

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APPENDICES

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°) *	12.062	0.25	60.152
2	2 (0°, 90°) *	11.249	0.5	44.009
3	4 (0°, 90°, 90°, 0°)	12.798	1	30.534
4	6 (0°, 90°, 0°, 0°,90°, 0°)	15.507	1.5	23.938
5	8 (0°, 90°, 0°, 90°, 90°, 0°, 90°, 0°)	18.722	2	20.335
6	1 (+45°) *	13.065	0.25	66.096
7	2 (+45°, -45°) Optimum value	**11.435**	**0.5**	**45.111**
8	4 (+45°, -45°, -45°, +45°)	12.923	1	31.274
9	6 (+45°, -45°, +45°, +45°, -45°, +45°)	15.669	1.5	24.898
10	8 (+45°, -45°, +45°, -45°, -45°, +45°, -45°, +45°)	18.810	2	20.861
11	4 (0°, 90°, +45°, -45°)	12.907	1	31.181
12	4 (+45°, -45°, 0°, 90°)	12.886	1	31.058
13	6 (0°, 90°, +45°, -45°, 0°, 90°)	15.668	1.5	24.890
14	6 (+45°, -45°, 0°, 90°, -45°, +45°)	15.722	1.5	25.212
15	8 (0°, 90°, +45°, -45°, -45°, +45°, 90°, 0°)	18.841	2	21.043
16	8 (+45°, -45°, 0°, 90°, 90°, 0°, -45°, +45°)	18.842	2	21.049

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°) *	6.844	0.3	29.712
2	2 (0°, 90°)	7.287	0.6	21.493
3	4 (0°, 90°, 90°, 0°)	9.76	1.2	14.46
4	6 (0°, 90°, 0°, 0°,90°, 0°)	12.808	1.8	10.835
5	8 (0°, 90°, 0°, 90°, 90°, 0°, 90°, 0°)	16.097	2.4	8.648
6	1 (+45°) Optimum value	**6.327**	**0.3**	**26.648**
7	2 (+45°, -45°)	6.787	0.6	18.53
8	4 (+45°, -45°, -45°, +45°)	9.405	1.2	12.355
9	6 (+45°, -45°, +45°, +45°, -45°, +45°)	12.543	1.8	9.262
10	8 (+45°, -45°, +45°, -45°, -45°, +45°, -45°, +45°)	15.845	2.4	7.131
11	4 (0°, 90°, +45°, -45°)	9.686	1.2	14.024
12	4 (+45°, -45°, 0°, 90°)	9.636	1.2	13.729
13	6 (0°, 90°, +45°, -45°, 0°, 90°)	12.946	1.8	11.645
14	6 (+45°, -45°, 0°, 90°, -45°, +45°)	12.961	1.8	11.74
15	8 (0°, 90°, +45°, -45°, -45°, +45°, 90°, 0°)	16.215	2.4	9.353
16	8 (+45°, -45°, 0°, 90°, 90°, 0°, -45°, +45°)	16.22	2.4	9.384

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°) *	8.278	0.55	26.883
2	4 (0°, 90°, 90°, 0°)	10.686	1.1	18.982
3	6 (0°, 90°, 0°, 0°,90°, 0°)	13.712	1.65	14.747
4	8 (0°, 90°, 0°, 90°, 90°, 0°, 90°, 0°)	17.055	2.2	12.383
5	2 (+45°, -45°) Optimum value	**8.572**	**0.55**	**28.625**
6	4 (+45°, -45°, -45°, +45°)	10.664	1.1	18.853
7	6 (+45°, -45°, +45°, +45°, -45°, +45°)	13.725	1.65	14.822
8	8 (+45°, -45°, +45°, -45°, -45°, +45°, -45°, +45°)	17.028	2.2	12.223
9	4 (0°, 90°, +45°, -45°)	10.666	1.1	18.868
10	4 (+45°, -45°, 0°, 90°)	10.844	1.1	19.921
11	6 (0°, 90°, +45°, -45°, 90°, 0°)	13.843	1.65	15.523
12	6 (+45°, -45°, 0°, 90°, -45°, +45°)	13.958	1.65	16.206
13	8 (0°, 90°, +45°, -45°, -45°, +45°, 90°, 0°)	17.157	2.2	12.99
14	8 (+45°, -45°, 0°, 90°, 90°, 0°, -45°, +45°)	17.223	2.2	13.383

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°) *	137.171	0.25	56.486
2	2 (0°, 90°) *	118.652	0.5	44.059
3	4 (0°, 90°, 90°, 0°)	107.2	1	30.531
4	6 (0°, 90°, 0°, 0°,90°, 0°)	111.421	1.5	23.938
5	8 (0°, 90°, 0°, 90°, 90°, 0°, 90°, 0°)	122.393	2	20.335
6	1 (+45°) *	158.88	0.25	66.096
7	2 (+45°, -45°) Optimum value	**121.075**	**0.5**	**45.131**
8	4 (+45°, -45°, -45°, +45°)	108.873	1	31.271
9	6 (+45°, -45°, +45°, +45°, -45°, +45°)	113.588	1.5	24.898
10	8 (+45°, -45°, +45°, -45°, -45°, +45°, -45°, +45°)	123.579	2	20.86
11	4 (0°, 90°, +45°, -45°)	108.671	1	31.181
12	4 (+45°, -45°, 0°, 90°)	108.385	1	31.055
13	6 (0°, 90°, +45°, -45°, 0°, 90°)	113.571	1.5	24.89
14	6 (+45°, -45°, 0°, 90°, -45°, +45°)	114.299	1.5	25.212
15	8 (0°, 90°, +45°, -45°, -45°, +45°, 90°, 0°)	123.991	2	21.043
16	8 (+45°, -45°, 0°, 90°, 90°, 0°, -45°, +45°)	124.005	2	21.049

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°) *	140.258	0.3	29.683
2	2 (0°, 90°)	194.954	0.6	21.493
3	4 (0°, 90°, 90°, 0°)	325.47	1.2	14.464
4	6 (0°, 90°, 0°, 0°,90°, 0°)	463.654	1.8	10.829
5	8 (0°, 90°, 0°, 90°, 90°, 0°, 90°, 0°)	605.094	2.4	8.635
6	1 (+45°) Optimum value	**133.397**	**0.3**	**26.646**
7	2 (+45°, -45°)	188.257	0.6	18.529
8	4 (+45°, -45°, -45°, +45°)	320.71	1.2	12.357
9	6 (+45°, -45°, +45°, +45°, -45°, +45°)	460.112	1.8	9.266
10	8 (+45°, -45°, +45°, -45°, -45°, +45°, -45°, +45°)	601.696	2.4	7.131
11	4 (0°, 90°, +45°, -45°)	324.485	1.2	14.029
12	4 (+45°, -45°, 0°, 90°)	323.821	1.2	13.734
13	6 (0°, 90°, +45°, -45°, 0°, 90°)	465.489	1.8	11.641
14	6 (+45°, -45°, 0°, 90°, -45°, +45°)	465.687	1.8	11.729
15	8 (0°, 90°, +45°, -45°, -45°, +45°, 90°, 0°)	606.678	2.4	9.336
16	8 (+45°, -45°, 0°, 90°, 90°, 0°, -45°, +45°)	606.749	2.4	9.368

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°) *	143.471	0.55	26.875
2	4 (0°, 90°, 90°, 0°)	208.394	1.1	18.982
3	6 (0°, 90°, 0°, 0°,90°, 0°)	281.578	1.65	14.746
4	8 (0°, 90°, 0°, 90°, 90°, 0°, 90°, 0°)	359.012	2.2	12.391
5	2 (+45°, -45°) Optimum value	**147.452**	**0.55**	**28.637**
6	4 (+45°, -45°, -45°, +45°)	208.098	1.1	18.851
7	6 (+45°, -45°, +45°, +45°, -45°, +45°)	281.749	1.65	14.822
8	8 (+45°, -45°, +45°, -45°, -45°, +45°, -45°, +45°)	358.654	2.2	12.232
9	4 (0°, 90°, +45°, -45°)	208.131	1.1	18.866
10	4 (+45°, -45°, 0°, 90°)	210.513	1.1	19.92
11	6 (0°, 90°, +45°, -45°, 90°, 0°)	283.313	1.65	15.514
12	6 (+45°, -45°, 0°, 90°, -45°, +45°)	284.845	1.65	16.192
13	8 (0°, 90°, +45°, -45°, -45°, +45°, 90°, 0°)	360.366	2.2	12.991
14	8 (+45°, -45°, 0°, 90°, 90°, 0°, -45°, +45°)	361.263	2.2	13.387

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°) *	12.015	144.817	0.25	59.871
2	2 (0°, 90°) *	11.205	117.949	0.5	43.748
3	4 (0°, 90°, 90°, 0°)	12.753	106.604	1	30.266
4	6 (0°, 90°, 0°, 0°,90°, 0°)	15.464	110.836	1.5	23.679
5	8 (0°, 90°, 0°, 90°, 90°, 0°, 90°, 0°)	18.683	121.878	2	20.107
6	1 (+45°) *	13.074	158.988	0.25	66.143
7	2 (+45°, -45°) Optimum value	**11.394**	**120.475**	**0.5**	**44.866**
8	4 (+45°, -45°, -45°, +45°)	12.893	108.481	1	31.098
9	6 (+45°, -45°, +45°, +45°, -45°, +45°)	15.632	113.085	1.5	24.675
10	8 (+45°, -45°, +45°, -45°, -45°, +45°, -45°, +45°)	18.767	123.001	2	20.604
11	4 (0°, 90°, +45°, -45°)	12.861	108.046	1	30.904
12	4 (+45°, -45°, 0°, 90°)	12.848	107.876	1	30.829
13	6 (0°, 90°, +45°, -45°, 0°, 90°)	15.628	113.036	1.5	24.653
14	6 (+45°, -45°, 0°, 90°, -45°, +45°)	15.679	113.727	1.5	24.959
15	8 (0°, 90°, +45°, -45°, -45°, +45°, 90°, 0°)	18.805	123.505	2	20.827
16	8 (+45°, -45°, 0°, 90°, 90°, 0°, -45°, +45°)	18.803	123.473	2	20.813

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°) *	6.791	139.617	0.3	29.399
2	2 (0°, 90°)	7.241	194.335	0.6	21.219
3	4 (0°, 90°, 90°, 0°)	9.716	324.877	1.2	14.202
4	6 (0°, 90°, 0°, 0°,90°, 0°)	12.765	463.092	1.8	10.58
5	8 (0°, 90°, 0°, 90°, 90°, 0°, 90°, 0°)	16.071	604.748	2.4	8.483
6	1 (+45°) Optimum value	**6.292**	**132.929**	**0.3**	**26.439**
7	2 (+45°, -45°)	6.751	187.785	0.6	18.32
8	4 (+45°, -45°, -45°, +45°)	9.367	320.2	1.2	12.131
9	6 (+45°, -45°, +45°, +45°, -45°, +45°)	12.501	459.564	1.8	9.0191
10	8 (+45°, -45°, +45°, -45°, -45°, +45°, -45°, +45°)	15.806	601.211	2.4	6.917
11	4 (0°, 90°, +45°, -45°)	9.646	323.931	1.2	13.783
12	4 (+45°, -45°, 0°, 90°)	9.597	323.275	1.2	13.492
13	6 (0°, 90°, +45°, -45°, 0°, 90°)	12.904	464.954	1.8	11.405
14	6 (+45°, -45°, 0°, 90°, -45°, +45°)	12.918	465.142	1.8	11.488
15	8 (0°, 90°, +45°, -45°, -45°, +45°, 90°, 0°)	16.187	606.302	2.4	9.17
16	8 (+45°, -45°, 0°, 90°, 90°, 0°, -45°, +45°)	16.193	606.381	2.4	9.205

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°) *	8.229	142.838	0.55	26.595
2	4 (0°, 90°, 90°, 0°)	10.653	207.955	1.1	18.788
3	6 (0°, 90°, 0°, 0°,90°, 0°)	13.674	281.076	1.65	14.523
4	8 (0°, 90°, 0°, 90°, 90°, 0°, 90°, 0°)	17.022	358.552	2.2	12.187
5	2 (+45°, -45°) Optimum value	**8.573**	**147.44**	**0.55**	**28.632**
6	4 (+45°, -45°, -45°, +45°)	10.621	207.531	1.1	18.6
7	6 (+45°, -45°, +45°, +45°, -45°, +45°)	13.688	281.256	1.65	14.603
8	8 (+45°, -45°, +45°, -45°, -45°, +45°, -45°, +45°)	16.988	358.103	2.2	11.988
9	4 (0°, 90°, +45°, -45°)	10.624	207.574	1.1	18.619
10	4 (+45°, -45°, 0°, 90°)	10.815	210.125	1.1	19.748
11	6 (0°, 90°, +45°, -45°, 90°, 0°)	13.813	282.936	1.65	15.347
12	6 (+45°, -45°, 0°, 90°, -45°, +45°)	13.919	284.352	1.65	15.974
13	8 (0°, 90°, +45°, -45°, -45°, +45°, 90°, 0°)	17.117	359.831	2.2	12.754
14	8 (+45°, -45°, 0°, 90°, 90°, 0°, -45°, +45°)	17.182	360.707	2.2	13.141

* 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°) ***	27.813	0.25	35.898
2	2 (0°, 90°) *	28.728	0.5	26.126
3	4 (0°, 90°, 90°, 0°) Optimum value	**40.742**	**1**	**23.872**
4	6 (0°, 90°, 0°, 0°,90°, 0°)	53.788	1.5	23.372
5	8 (0°, 90°, 0°, 90°, 90°, 0°, 90°, 0°)	66.834	2	22.872
6	1 (+45°) ****	21.172	0.25	24.622
7	2 (+45°, -45°) **	29.113	0.5	26.78
8	4 (+45°, -45°, -45°, +45°)	71.86	1	76.707
9	6 (+45°, -45°, +45°, +45°, -45°, +45°)	69.651	1.5	50.304
10	8 (+45°, -45°, +45°, -45°, -45°, +45°, -45°, +45°)	75.069	2	36.853
11	4 (0°, 90°, +45°, -45°)	72.588	1	77.943
12	4 (+45°, -45°, 0°, 90°)	70.938	1	75.142
13	6 (0°, 90°, +45°, -45°, 0°, 90°)	57.047	1.5	28.905
14	6 (+45°, -45°, 0°, 90°, -45°, +45°)	61.987	1.5	37.294
15	8 (0°, 90°, +45°, -45°, -45°, +45°, 90°, 0°)	67.158	2	23.423
16	8 (+45°, -45°, 0°, 90°, 90°, 0°, -45°, +45°)	67.157	2	23.421

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°) *	21.431	0.3	25.544
2	2 (0°, 90°) Optimum value	**27.069**	**0.6**	**24.272**
3	4 (0°, 90°, 90°, 0°)	39.488	1.2	23.672
4	6 (0°, 90°, 0°, 0°,90°, 0°)	51.908	1.8	23.073
5	8 (0°, 90°, 0°, 90°, 90°, 0°, 90°, 0°)	64.328	2.4	22.472
6	1 (+45°) **	20.859	0.3	24.572
7	2 (+45°, -45°)	46.453	0.6	57.184
8	4 (+45°, -45°, -45°, +45°)	41.856	1.2	27.692
9	6 (+45°, -45°, +45°, +45°, -45°, +45°)	51.908	1.8	23.072
10	8 (+45°, -45°, +45°, -45°, -45°, +45°, -45°, +45°)	64.328	2.4	22.472
11	4 (0°, 90°, +45°, -45°)	39.488	1.2	23.672
12	4 (+45°, -45°, 0°, 90°)	39.488	1.2	23.672
13	6 (0°, 90°, +45°, -45°, 0°, 90°)	51.908	1.8	23.072
14	6 (+45°, -45°, 0°, 90°, -45°, +45°)	51.908	1.8	23.072
15	8 (0°, 90°, +45°, -45°, -45°, +45°, 90°, 0°)	64.332	2.4	22.479
16	8 (+45°, -45°, 0°, 90°, 90°, 0°, -45°, +45°)	64.333	2.4	22.482

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°) *	27.392	0.55	24.34
2	4 (0°, 90°, 90°, 0°) Optimum value	**40.115**	**1.1**	**23.772**
3	6 (0°, 90°, 0°, 0°,90°, 0°)	52.848	1.65	23.222
4	8 (0°, 90°, 0°, 90°, 90°, 0°, 90°, 0°)	65.581	2.2	22.672
5	2 (+45°, -45°) **	27.382	0.55	24.322
6	4 (+45°, -45°, -45°, +45°)	67.114	1.1	69.613
7	6 (+45°, -45°, +45°, +45°, -45°, +45°)	66.278	1.65	46.025
8	8 (+45°, -45°, +45°, -45°, -45°, +45°, -45°, +45°)	72.108	2.2	33.754
9	4 (0°, 90°, +45°, -45°)	54.675	1.1	48.493
10	4 (+45°, -45°, 0°, 90°)	44.186	1.1	30.685
11	6 (0°, 90°, +45°, -45°, 90°, 0°)	52.848	1.65	23.222
12	6 (+45°, -45°, 0°, 90°, -45°, +45°)	52.848	1.65	23.222
13	8 (0°, 90°, +45°, -45°, -45°, +45°, 90°, 0°)	65.581	2.2	22.672
14	8 (+45°, -45°, 0°, 90°, 90°, 0°, -45°, +45°)	65.581	2.2	22.672

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°) ***	316.407	0.25	35.899
2	2 (0°, 90°) *	272.691	0.5	26.125
3	4 (0°, 90°, 90°, 0°) Optimum value	**321.655**	**1**	**23.875**
4	6 (0°, 90°, 0°, 0°,90°, 0°)	384.393	1.5	23.372
5	8 (0°, 90°, 0°, 90°, 90°, 0°, 90°, 0°)	447.154	2	22.872
6	1 (+45°) ****	227.489	0.25	24.622
7	2 (+45°, -45°) **	277.883	0.5	26.784
8	4 (+45°, -45°, -45°, +45°)	738.21	1	76.707
9	6 (+45°, -45°, +45°, +45°, -45°, +45°)	596.742	1.5	50.304
10	8 (+45°, -45°, +45°, -45°, -45°, +45°, -45°, +45°)	557.944	2	36.923
11	4 (0°, 90°, +45°, -45°)	747.957	1	77.943
12	4 (+45°, -45°, 0°, 90°)	725.875	1	75.142
13	6 (0°, 90°, +45°, -45°, 0°, 90°)	428.026	1.5	28.906
14	6 (+45°, -45°, 0°, 90°, -45°, +45°)	494.129	1.5	37.290
15	8 (0°, 90°, +45°, -45°, -45°, +45°, 90°, 0°)	451.481	2	23.421
16	8 (+45°, -45°, 0°, 90°, 90°, 0°, -45°, +45°)	451.481	2	23.421

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°) *	456.924	0.3	25.551
2	2 (0°, 90°) Optimum value	**702.299**	**0.6**	**24.272**
3	4 (0°, 90°, 90°, 0°)	1208.489	1.2	23.672
4	6 (0°, 90°, 0°, 0°,90°, 0°)	1714.68	1.8	23.073
5	8 (0°, 90°, 0°, 90°, 90°, 0°, 90°, 0°)	2220.87	2.4	22.472
6	1 (+45°) **	449.204	0.3	24.572
7	2 (+45°, -45°)	961.796	0.6	57.184
8	4 (+45°, -45°, -45°, +45°)	1240.541	1.2	27.737
9	6 (+45°, -45°, +45°, +45°, -45°, +45°)	1714.68	1.8	23.073
10	8 (+45°, -45°, +45°, -45°, -45°, +45°, -45°, +45°)	2220.944	2.4	22.481
11	4 (0°, 90°, +45°, -45°)	1208.494	1.2	23.673
12	4 (+45°, -45°, 0°, 90°)	1208.493	1.2	23.673
13	6 (0°, 90°, +45°, -45°, 0°, 90°)	1714.68	1.8	23.073
14	6 (+45°, -45°, 0°, 90°, -45°, +45°)	1714.68	1.8	23.0725
15	8 (0°, 90°, +45°, -45°, -45°, +45°, 90°, 0°)	2220.87	2.4	22.472
16	8 (+45°, -45°, 0°, 90°, 90°, 0°, -45°, +45°)	2220.87	2.4	22.472

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°) *	480.585	0.55	24.322
2	4 (0°, 90°, 90°, 0°) Optimum value	**765.061**	**1.1**	**23.772**
3	6 (0°, 90°, 0°, 0°,90°, 0°)	1049.536	1.65	23.222
4	8 (0°, 90°, 0°, 90°, 90°, 0°, 90°, 0°)	1334.012	2.2	22.672
5	2 (+45°, -45°) **	480.585	0.55	24.322
6	4 (+45°, -45°, -45°, +45°)	1126.499	1.1	69.613
7	6 (+45°, -45°, +45°, +45°, -45°, +45°)	1229.273	1.65	46.019
8	8 (+45°, -45°, +45°, -45°, -45°, +45°, -45°, +45°)	1421.369	2.2	33.752
9	4 (0°, 90°, +45°, -45°)	959.971	1.1	48.493
10	4 (+45°, -45°, 0°, 90°)	819.775	1.1	30.712
11	6 (0°, 90°, +45°, -45°, 90°, 0°)	1049.536	1.65	23.222
12	6 (+45°, -45°, 0°, 90°, -45°, +45°)	1049.546	1.65	23.223
13	8 (0°, 90°, +45°, -45°, -45°, +45°, 90°, 0°)	1334.015	2.2	22.672
14	8 (+45°, -45°, 0°, 90°, 90°, 0°, -45°, +45°)	1334.012	2.2	22.672

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°) ***	27.819	316.465	0.25	35.907
2	2 (0°, 90°) *	28.729	272.714	0.5	26.128
3	4 (0°, 90°, 90°, 0°) Optimum value	**40.76**	**321.876**	**1**	**23.903**
4	6 (0°, 90°, 0°, 0°,90°, 0°)	53.792	384.444	1.5	23.379
5	8 (0°, 90°, 0°, 90°, 90°, 0°, 90°, 0°)	66.856	447.455	2	22.911
6	1 (+45°) ****	21.219	228.112	0.25	24.701
7	2 (+45°, -45°) **	29.113	277.851	0.5	26.779
8	4 (+45°, -45°, -45°, +45°)	71.913	738.926	1	76.797
9	6 (+45°, -45°, +45°, +45°, -45°, +45°)	69.667	596.964	1.5	50.332
10	8 (+45°, -45°, +45°, -45°, -45°, +45°, -45°, +45°)	75.129	558.199	2	36.956
11	4 (0°, 90°, +45°, -45°)	72.627	748.485	1	78.01
12	4 (+45°, -45°, 0°, 90°)	70.951	726.034	1	75.163
13	6 (0°, 90°, +45°, -45°, 0°, 90°)	57.068	428.298	1.5	28.941
14	6 (+45°, -45°, 0°, 90°, -45°, +45°)	62.019	494.587	1.5	37.348
15	8 (0°, 90°, +45°, -45°, -45°, +45°, 90°, 0°)	67.157	451.485	2	23.421
16	8 (+45°, -45°, 0°, 90°, 90°, 0°, -45°, +45°)	67.175	451.725	2	23.452

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°) *	21.437	456.947	0.3	25.554
2	2 (0°, 90°) Optimum value	**27.127**	**703.074**	**0.6**	**24.371**
3	4 (0°, 90°, 90°, 0°)	39.544	1209.232	1.2	23.766
4	6 (0°, 90°, 0°, 0°,90°, 0°)	51.912	1714.7403	1.8	23.08
5	8 (0°, 90°, 0°, 90°, 90°, 0°, 90°, 0°)	64.337	2220.999	2.4	22.489
6	1 (+45°) **	20.908	449.868	0.3	24.656
7	2 (+45°, -45°)	46.465	961.951	0.6	57.204
8	4 (+45°, -45°, -45°, +45°)	41.892	1240.6701	1.2	27.754
9	6 (+45°, -45°, +45°, +45°, -45°, +45°)	51.924	1714.896	1.8	23.099
10	8 (+45°, -45°, +45°, -45°, -45°, +45°, -45°, +45°)	64.342	2221.0644	2.4	22.497
11	4 (0°, 90°, +45°, -45°)	39.502	1208.669	1.2	23.695
12	4 (+45°, -45°, 0°, 90°)	39.489	1208.496	1.2	23.673
13	6 (0°, 90°, +45°, -45°, 0°, 90°)	51.909	1714.6907	1.8	23.074
14	6 (+45°, -45°, 0°, 90°, -45°, +45°)	51.918	1714.814	1.8	23.089
15	8 (0°, 90°, +45°, -45°, -45°, +45°, 90°, 0°)	64.329	2220.892	2.4	22.475
16	8 (+45°, -45°, 0°, 90°, 90°, 0°, -45°, +45°)	64.329	2220.888	2.4	22.475

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°) *	27.393	480.732	0.55	24.341
2	4 (0°, 90°, 90°, 0°) Optimum value	**40.119**	**765.119**	**1.1**	**23.779**
3	6 (0°, 90°, 0°, 0°,90°, 0°)	52.848	1049.538	1.65	23.222
4	8 (0°, 90°, 0°, 90°, 90°, 0°, 90°, 0°)	65.589	1334.119	2.2	22.686
5	2 (+45°, -45°) **	27.404	480.881	0.55	24.359
6	4 (+45°, -45°, -45°, +45°)	67.116	1126.524	1.1	69.616
7	6 (+45°, -45°, +45°, +45°, -45°, +45°)	66.281	1229.364	1.65	46.03
8	8 (+45°, -45°, +45°, -45°, -45°, +45°, -45°, +45°)	72.11	1421.417	2.2	33.758
9	4 (0°, 90°, +45°, -45°)	54.738	960.825	1.1	48.601
10	4 (+45°, -45°, 0°, 90°)	44.187	819.575	1.1	30.686
11	6 (0°, 90°, +45°, -45°, 90°, 0°)	52.898	1050.203	1.65	23.307
12	6 (+45°, -45°, 0°, 90°, -45°, +45°)	52.892	1050.127	1.65	23.297
13	8 (0°, 90°, +45°, -45°, -45°, +45°, 90°, 0°)	65.607	1334.358	2.2	22.716
14	8 (+45°, -45°, 0°, 90°, 90°, 0°, -45°, +45°)	65.594	1334.197	2.2	22.696

* 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°) ***	0.862	0.25	25.803
2	2 (0°, 90°) ***	0.9603	0.5	18.674
3	4 (0°, 90°, 90°, 0°) Optimum value	**3.182**	**1**	**91.644**
4	6 (0°, 90°, 0°, 0°,90°, 0°)	3.399	1.5	78.346
5	8 (0°, 90°, 0°, 90°, 90°, 0°, 90°, 0°)	3.594	2	64.0667
6	1 (+45°) ****	0.902	0.25	27.508
7	2 (+45°, -45°) **	2.298	0.5	76.245
8	4 (+45°, -45°, -45°, +45°)	3.232	1	93.7901
9	6 (+45°, -45°, +45°, +45°, -45°, +45°)	3.351	1.5	76.275
10	8 (+45°, -45°, +45°, -45°, -45°, +45°, -45°, +45°)	3.629	2	65.584
11	4 (0°, 90°, +45°, -45°)	3.223	1	93.388
12	4 (+45°, -45°, 0°, 90°)	3.22	1	93.262
13	6 (0°, 90°, +45°, -45°, 0°, 90°)	3.352	1.5	76.297
14	6 (+45°, -45°, 0°, 90°, -45°, +45°)	3.372	1.5	77.168
15	8 (0°, 90°, +45°, -45°, -45°, +45°, 90°, 0°)	3.642	2	66.121
16	8 (+45°, -45°, 0°, 90°, 90°, 0°, -45°, +45°)	3.642	2	66.123

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°) *	2.2935	0.3	87.844
2	2 (0°, 90°)	2.0063	0.6	64.646
3	4 (0°, 90°, 90°, 0°)	2.0664	1.2	45.544
4	6 (0°, 90°, 0°, 0°,90°, 0°)	2.353	1.8	36.194
5	8 (0°, 90°, 0°, 90°, 90°, 0°, 90°, 0°)	2.7389	2.4	31.11
6	1 (+45°)	2.0891	0.3	79.0508
7	2 (+45°, -45°) Optimum value	**1.776**	**0.6**	**54.749**
8	4 (+45°, -45°, -45°, +45°)	1.923	1.2	39.403
9	6 (+45°, -45°, +45°, +45°, -45°, +45°)	2.248	1.8	31.696
10	8 (+45°, -45°, +45°, -45°, -45°, +45°, -45°, +45°)	2.638	2.4	26.798
11	4 (0°, 90°, +45°, -45°)	2.0287	1.2	43.922
12	4 (+45°, -45°, 0°, 90°)	2.022	1.2	43.633
13	6 (0°, 90°, +45°, -45°, 0°, 90°)	2.408	1.8	38.561
14	6 (+45°, -45°, 0°, 90°, -45°, +45°)	2.412	1.8	38.758
15	8 (0°, 90°, +45°, -45°, -45°, +45°, 90°, 0°)	2.786	2.4	33.158
16	8 (+45°, -45°, 0°, 90°, 90°, 0°, -45°, +45°)	2.786	2.4	33.168

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°) *	2.372	0.55	79.899
2	4 (0°, 90°, 90°, 0°)	2.349	1.1	56.737
3	6 (0°, 90°, 0°, 0°,90°, 0°)	2.603	1.65	45.5105
4	8 (0°, 90°, 0°, 90°, 90°, 0°, 90°, 0°)	2.998	2.2	40.361
5	2 (+45°, -45°)	2.384	0.55	80.435
6	4 (+45°, -45°, -45°, +45°)	2.343	1.1	56.505
7	6 (+45°, -45°, +45°, +45°, -45°, +45°)	2.603	1.65	45.506
8	8 (+45°, -45°, +45°, -45°, -45°, +45°, -45°, +45°)	2.993	2.2	40.117
9	4 (0°, 90°, +45°, -45°) Optimum value	**2.339**	**1.1**	**56.307**
10	4 (+45°, -45°, 0°, 90°)	2.435	1.1	60.459
11	6 (0°, 90°, +45°, -45°, 90°, 0°)	2.665	1.65	48.193
12	6 (+45°, -45°, 0°, 90°, -45°, +45°)	2.68	1.65	48.812
13	8 (0°, 90°, +45°, -45°, -45°, +45°, 90°, 0°)	3.0366	2.2	41.9902
14	8 (+45°, -45°, 0°, 90°, 90°, 0°, -45°, +45°)	3.119	2.2	45.5499

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°) ***	9.3608	0.25	25.858
2	2 (0°, 90°) ***	8.459	0.5	18.732
3	4 (0°, 90°, 90°, 0°) Optimum value	**33.233**	**1**	**89.903**
4	6 (0°, 90°, 0°, 0°,90°, 0°)	30.378	1.5	72.264
5	8 (0°, 90°, 0°, 90°, 90°, 0°, 90°, 0°)	30.0692	2	62.811
6	1 (+45°) ****	9.886	0.25	27.548
7	2 (+45°, -45°) **	26.349	0.5	76.235
8	4 (+45°, -45°, -45°, +45°)	34.443	1	93.7901
9	6 (+45°, -45°, +45°, +45°, -45°, +45°)	31.632	1.5	76.295
10	8 (+45°, -45°, +45°, -45°, -45°, +45°, -45°, +45°)	30.932	2	65.584
11	4 (0°, 90°, +45°, -45°)	34.318	1	93.388
12	4 (+45°, -45°, 0°, 90°)	33.693	1	91.381
13	6 (0°, 90°, +45°, -45°, 0°, 90°)	31.626	1.5	76.277
14	6 (+45°, -45°, 0°, 90°, -45°, +45°)	31.9103	1.5	77.189
15	8 (0°, 90°, +45°, -45°, -45°, +45°, 90°, 0°)	31.0992	2	66.121
16	8 (+45°, -45°, 0°, 90°, 90°, 0°, -45°, +45°)	31.0998	2	66.123

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°) *	36.813	0.3	85.928
2	2 (0°, 90°)	39.683	0.6	62.755
3	4 (0°, 90°, 90°, 0°)	54.467	1.2	45.474
4	6 (0°, 90°, 0°, 0°,90°, 0°)	71.7402	1.8	36.193
5	8 (0°, 90°, 0°, 90°, 90°, 0°, 90°, 0°)	90.317	2.4	31.107
6	1 (+45°)	34.0669	0.3	77.101
7	2 (+45°, -45°) Optimum value	**37.026**	**0.6**	**54.213**
8	4 (+45°, -45°, -45°, +45°)	52.578	1.2	39.402
9	6 (+45°, -45°, +45°, +45°, -45°, +45°)	70.334	1.8	31.674
10	8 (+45°, -45°, +45°, -45°, -45°, +45°, -45°, +45°)	88.973	2.4	26.784
11	4 (0°, 90°, +45°, -45°)	53.982	1.2	43.915
12	4 (+45°, -45°, 0°, 90°)	53.895	1.2	43.634
13	6 (0°, 90°, +45°, -45°, 0°, 90°)	72.474	1.8	38.552
14	6 (+45°, -45°, 0°, 90°, -45°, +45°)	72.536	1.8	38.752
15	8 (0°, 90°, +45°, -45°, -45°, +45°, 90°, 0°)	90.955	2.4	33.157
16	8 (+45°, -45°, 0°, 90°, 90°, 0°, -45°, +45°)	90.958	2.4	33.167

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°) *	35.6601	0.55	77.992
2	4 (0°, 90°, 90°, 0°)	40.3204	1.1	56.341
3	6 (0°, 90°, 0°, 0°,90°, 0°)	48.36	1.65	45.552
4	8 (0°, 90°, 0°, 90°, 90°, 0°, 90°, 0°)	58.136	2.2	40.345
5	2 (+45°, -45°)	36.729	0.55	81.428
6	4 (+45°, -45°, -45°, +45°)	40.238	1.1	56.0786
7	6 (+45°, -45°, +45°, +45°, -45°, +45°)	48.359	1.65	45.5501
8	8 (+45°, -45°, +45°, -45°, -45°, +45°, -45°, +45°)	58.0592	2.2	40.0991
9	4 (0°, 90°, +45°, -45°) Optimum value	**40.188**	**1.1**	**55.917**
10	4 (+45°, -45°, 0°, 90°)	41.2302	1.1	59.265
11	6 (0°, 90°, +45°, -45°, 90°, 0°)	48.656	1.65	46.505
12	6 (+45°, -45°, 0°, 90°, -45°, +45°)	49.361	1.65	48.771
13	8 (0°, 90°, +45°, -45°, -45°, +45°, 90°, 0°)	58.648	2.2	41.994
14	8 (+45°, -45°, 0°, 90°, 90°, 0°, -45°, +45°)	59.113	2.2	43.488

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°) ***	0.864	9.3605	0.25	25.857
2	2 (0°, 90°) ***	0.9608	8.447	0.5	18.693
3	4 (0°, 90°, 90°, 0°) Optimum value	**3.135**	**33.143**	**1**	**89.612**
4	6 (0°, 90°, 0°, 0°,90°, 0°)	3.241	30.143	1.5	71.509
5	8 (0°, 90°, 0°, 90°, 90°, 0°, 90°, 0°)	3.548	29.841	2	62.0772
6	1 (+45°) ****	0.903	9.886	0.25	27.547
7	2 (+45°, -45°) **	2.298	26.35	0.5	76.237
8	4 (+45°, -45°, -45°, +45°)	3.185	33.818	1	91.781
9	6 (+45°, -45°, +45°, +45°, -45°, +45°)	3.305	31.005	1.5	74.279
10	8 (+45°, -45°, +45°, -45°, -45°, +45°, -45°, +45°)	3.583	30.312	2	63.594
11	4 (0°, 90°, +45°, -45°)	3.176	33.697	1	91.391
12	4 (+45°, -45°, 0°, 90°)	3.173	33.651	1	91.244
13	6 (0°, 90°, +45°, -45°, 0°, 90°)	3.305	31.0094	1.5	74.293
14	6 (+45°, -45°, 0°, 90°, -45°, +45°)	3.327	31.294	1.5	75.209
15	8 (0°, 90°, +45°, -45°, -45°, +45°, 90°, 0°)	3.595	30.479	2	64.13
16	8 (+45°, -45°, 0°, 90°, 90°, 0°, -45°, +45°)	3.597	30.499	2	64.193

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°) *	2.248	36.805	0.3	85.904
2	2 (0°, 90°)	1.958	39.635	0.6	62.6007
3	4 (0°, 90°, 90°, 0°)	2.0204	53.873	1.2	43.564
4	6 (0°, 90°, 0°, 0°,90°, 0°)	2.307	71.126	1.8	34.219
5	8 (0°, 90°, 0°, 90°, 90°, 0°, 90°, 0°)	2.693	89.713	2.4	29.164
6	1 (+45°)	2.0429	34.0549	0.3	77.0624
7	2 (+45°, -45°) Optimum value	**1.76**	**36.978**	**0.6**	**54.058**
8	4 (+45°, -45°, -45°, +45°)	1.877	51.955	1.2	37.398
9	6 (+45°, -45°, +45°, +45°, -45°, +45°)	2.202	69.721	1.8	29.704
10	8 (+45°, -45°, +45°, -45°, -45°, +45°, -45°, +45°)	2.593	88.374	2.4	24.859
11	4 (0°, 90°, +45°, -45°)	1.982	53.359	1.2	41.912
12	4 (+45°, -45°, 0°, 90°)	1.975	53.265	1.2	41.609
13	6 (0°, 90°, +45°, -45°, 0°, 90°)	2.363	71.877	1.8	36.634
14	6 (+45°, -45°, 0°, 90°, -45°, +45°)	2.367	71.925	1.8	36.79
15	8 (0°, 90°, +45°, -45°, -45°, +45°, 90°, 0°)	2.741	90.349	2.4	31.208
16	8 (+45°, -45°, 0°, 90°, 90°, 0°, -45°, +45°)	2.742	90.363	2.4	31.252

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°) *	2.324	35.617	0.55	77.855
2	4 (0°, 90°, 90°, 0°)	2.327	40.152	1.1	55.799
3	6 (0°, 90°, 0°, 0°,90°, 0°)	2.578	48.0124	1.65	44.435
4	8 (0°, 90°, 0°, 90°, 90°, 0°, 90°, 0°)	2.953	57.5308	2.2	38.4005
5	2 (+45°, -45°)	2.3602	36.096	0.55	79.393
6	4 (+45°, -45°, -45°, +45°)	2.321	40.0785	1.1	55.564
7	6 (+45°, -45°, +45°, +45°, -45°, +45°)	2.585	48.1089	1.65	44.745
8	8 (+45°, -45°, +45°, -45°, -45°, +45°, -45°, +45°)	2.947	57.448	2.2	38.134
9	4 (0°, 90°, +45°, -45°) Optimum value	**2.317**	**40.016**	**1.1**	**55.363**
10	4 (+45°, -45°, 0°, 90°)	2.395	41.0621	1.1	58.725
11	6 (0°, 90°, +45°, -45°, 90°, 0°)	2.627	48.666	1.65	46.538
12	6 (+45°, -45°, 0°, 90°, -45°, +45°)	2.681	49.393	1.65	48.873
13	8 (0°, 90°, +45°, -45°, -45°, +45°, 90°, 0°)	2.991	58.0425	2.2	40.0453
14	8 (+45°, -45°, 0°, 90°, 90°, 0°, -45°, +45°)	3.0269	58.518	2.2	41.5748

* 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.