Numerical Investigation of Polyphenylene Sulfide Basis Composite Materials for Airframe Structure

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ABSTRACT

This paper deals numerical simulations of composite material with Polyphenylene sulfide matrix and carbon and glass fibres; the main goal is determine ability of using proposed composite materials in airframe structure by numerical simulations, to predict the elastic properties of composite, CADEC software is used to show the effect of fiber type, number of layers and fiber orientation on the elastic properties. For this purpose the computational simulations by ANSYS 13 were carried out. The results show that the ability of using composite materials under study as skin of wing of aircraft under effects of pure inertial loads.

Key words: Polyphenylene sulfide, ANSYS, aircraft, numerical simulation, skin of wing.

INTRODUCTION:

Traditional materials for aircraft construction include aluminum, steel and titanium. The primary benefits that composite components can offer are reduced weight and assembly simplification. In the past twenty years, the use of composite materials in the aircraft industry, among others, has grown immensely. Composite systems offer an advantage over traditional aircraft materials (metals) because they tend to exhibit higher strength/weight and stiffness/weight ratios than metals, thus making the aircraft lighter and improving performance. [1]

In the early 1970s, composite materials were introduced to airframe structures to increase the performance and life of the airframe. In 1977, the National Aeronautics and Space Administration (NASA) Advanced Composite Structures Program introduced the use of composites in primary structures in commercial aircraft, i.e., the Boeing 737 horizontal stabilizer. In 1994, the Advanced General Aviation Transport Experiments consortium, led by NASA and supported by the Federal Aviation Administration (FAA), industry, and academia, revitalized composite material product development in general aviation by developing cost-effective composite airframe structures. Modern improved composite materials and matured processes have encouraged commercial aircraft companies to increase the use of composites in primary and secondary structures. Driven by the demand for fuel-efficient, light-weight, and high-stiffness structures that have fatigue durability and corrosion resistance, the Boeing 787 Dreamliner is designed with more than 50 percent composite structure, marking a striking milestone in composite usage in commercial aviation. Meanwhile, the Airbus A350 commercial airplane is being designed with a similar percentage of composite materials in its structure. [2, 3]

Thermoplastic composite materials have shown great promise as materials for current and future aircraft components. It is likely that thermoplastic composite components will enter airframe service in the near future in the form of replacement components which were previously manufactured from metals or thermosetting composites such as graphite/epoxy. Thermoplastic resins offer a number of advantages over conventional thermosetting resins such as epoxies. Thermoplastics exhibit chemical and impact resistance and may be used over a wide range of temperatures. They have a very low level of moisture uptake which means their mechanical properties are less degraded under hot/wet conditions. [4, 5]

A wide range of thermoplastics are available and in common use today. In the area of high performance thermoplastics, polyetheretherketone (PEEK) and Polyphenylene sulfide (PPS) are probably the most widely reported thermoplastic resins. [6]

Composite structures can be analyzed by using analytical and numerical methods. Generally, when a composite structure is modeled, some assumptions and simplifications have to be made. [7, 8] Rapid developments in computer hardware make the finite element method of complex determination responses increasingly applicable. The FEM is used worldwide to simulate the composite materials processes and has become a reliable numerical simulation technology. There are many FEM packages such as (MSC/NASTRAN, SUPERFORGE, ABAQUS, ALGOR, DIEKA, and ANSYS). [9, 10 and 11]

The overall objective of this research was to provide guidance into structural substantiation of composite airframe structures under repeated loads through an efficient approach that weighs both the economic aspects of certification and the timeframe required for testing, while ensuring safety.

In present paper the mechanical failure studies of composite materials with the basis of Polyphenylene sulfide (PPS) reinforced with glass and carbon fibers as the skin of wing of aircraft numerically by using a commercial finite element code ANSYS 13.

Modeling Process:

The computer program (ANSYS) is prepared for obtaining the optimum composite material it is possible used in the wing of aircraft structure through using fatigue failure criterion like (fatigue life, safety factor, …etc.) because is estimated that 90% of service failures of components that undergo movement of one form or another can be attributed to fatigue. Fatigue is one of the most common failure modes in all structural materials, including composite materials.

The element SHELL 93 (isoparametric 8-node structural shell) is used in idealization of wing structure in this model.

The model is restricted to take the effects of pure inertial loads on the structural behaviour of wing structure, so any effects associated with 3-D motion such as aero-dynamic pressure, induced shock wave, drag, and aero-heating loads (thermal loads) are neglected, and the inertia loads were interpreted as point loads. [12]

The displacement constraints (the boundary conditions for which the displacement of all DOF equal zero) were made at the region where the wing joined the fuselage structure. [12]

The variety of materials is restricted to base plate and upper skin to determine the composite material is valid for using for this purpose, on the other hand the stiffeners and honeycomb cross is assumed to be consisting single material are restricted to isotropic elastic material (special Ti alloy) used for manufacturing this type of wing as shown in the figure (1), the chemical composition and mechanical properties of basic materials used in these study shown in the table (1).

Material Properties:

The mechanical properties (Young's modulus, Shear modulus and Poisson's ratio) of the composite system used in this study are determined theoretically dependent on theoretical equations and by using the software called computer aided design environment for composite (CADEC 12) which is a specialized program specialist to composite materials and which depends on the use of theoretical equations for composite materials such as laminated theory, rule of mixture and other theories to calculate the engineering constants for composite Materials. Table (2) contains elastic constant of the composites materials of this work, on the other hand in the fatigue simulation, it will need for the data that represents the number of cycles until failure versus applied stress on the samples for each number of cycles and this data cannot be predicted mathematically such elastic properties so we will be using the experimental results of the fatigue test, which obtained from another research of our own. [13]

Finite Element Modeling:

The developments of suitable method, more accurately, for analysis various engineering structure are needed in order to investigate their behaviour under different loading condition. Whole dimensions of wing of Aircraft adopted for present work is shown in the figure (2). [14]

The model is consists of three parts lower skin, upper skin and longitudinal and transvers honeycomb stiffeners.

Skins Modeling:

The external skins are assumed to be consisting of lower plate and upper plate only as shown in figure (3).

The skins are created as governed surface with (162 keypoints) as shown in the figure (4).

The first step represents the keypoints creation, the second step represents the areas creation by keypoints that facilitates the element creation step where the elements are created as governed parts by the areas in the second step. The lower and upper plates each one is consisting of 60 rectangular plates and 8 triangular plates, the lace is consisting 20 rectangular plates.

Stiffeners Modeling:

The stiffeners or honeycomb sandwich cores in turn consists of two parts spars (longitudinal stiffeners), and ribs (transverse stiffeners), the wing is consists of 3 spars and 5 ribs as shown in figures (5).

Mesh Generation:

The wing of aircraft as previously stated is a complex layered composite structure, and the first step of the finite element analysis is to discretize the structure into finite elements connected at nodes. For a structure, as a wing, it is necessary to discretize it into a sufficient number of elements in order to obtain a reasonable accuracy. On the other hand, the more elements that are used, the more costly will be the analysis. The mesh generation of wing structure is as shown in figure (6).

Loading and Boundary Conditions:

The main goal of a finite element analysis is to examine how a model or a component responds to a certain loading condition. In this section load applied as vertex force on each keypoint mention above as shown in the figure (7), the combined forces for wing model represent the design load conditions for that model at which the optimum design can be obtained by performing the adopted method of structural optimization. [12]

The inertia forces applied to each keypoint in this model is obtained from another research and did not get into the details because it is a subject relating to aerodynamic engineering and the subject under study relating to behavior of composite materials the one hand of materials engineering.

The Solutions:

After completion of the application of the boundary conditions is a solution on the model and find results to evaluate the performance of composite materials for this purpose and based on the results of fatigue in the first place.

Results and Discussion:

This section shows briefly all results obtained from the numerical simulation of different types of composite materials (depending on type of fibers, number of layers and fibers orientation for carbon fibers) as the skin of wing of aircraft and the effect of this materials on wing behaviour under maximum inertia loads as mention above represented by the equivalent alternating stress, total deformation, fatigue life and safety factor.

Equivalent Von Mises Stress Results:

Equivalent von Mises stress is the stress used to query the fatigue S-N curve after accounting for fatigue loading type, R-ratio effects and any other factors in fatigue analysis [15]. Equivalent von Mises stress is the last calculated quantity before determining the fatigue life. Figures (8) and (9) shows contour plots for stress of the glass and carbon reinforced composites materials respectively, which display the overall distribution of the equivalent von Mises stress throughout the material, as well as to determine the approximate location and value of the maximum equivalent von Mises stress.

It can be seen from these figures that the highest values of equivalent von Mises stresses is concentrated in the region of connection of wing with fuselage, this is normal due to reaction force that are high in the contact area.

Also can be note the relative small changes in equivalent von Mises stress level as compared with the big difference in value of modulus of elasticity for each composite material this is probably because there is a convergence somewhat in other properties such as shear modulus and Poisson’s ratio, another reason that an overlap happen in the wing strength between the skins and the stiffeners since the material of stiffeners be one in all cases, so have a clear effect on the final stresses formed in the wing body.

The minimum value of equivalent von Mises stresses, means the maximum structural strength is obtained, and if we reviewed previous figures it, we find that the maximum equivalent stress consists in the material that consists of one layer of glass fiber which value (22.723 MPa), compared with the lowest value of stress that are present in the material that consists of a four layer of glass fiber and it value (19.85 MPa) where the increasing the number of layers and volume fraction increased the tensile strength, also can be note the increase the number of layers in composite material and thus increase elastic properties of composite material values, while in carbon fiber reinforced can be seen the clear effect of fibers orientation on final result of equivalent von Mises stress where the lowest value of stress that are present in the material that consists of (0°/90°/0°) of glass fiber and it value (18.247 MPa)

Generally it can be concluded that all types of proposed composite materials to be successful in resisting the equivalent von Mises stresses criterion because the highest value of stress consists in all models (22.723 MPa) is much less than the smaller-resistant of composite materials but the von Mises stresses is not the only criterion for the success or failure of these materials for use in the aircraft's wing, but also there are other criteria, as we will discuss later.

Total Deformation Results:

The figures (10) and (11) shows the total deformation in glass and carbon reinforced composites materials respectively.

The that figures display the overall distribution of the total deformation throughout the material, as well as to determine the location and value of the maximum deformation, where the highest values of total deformation is concentrated in the free end of the wing considering that way of connecting wing to aircraft makes cantilever beam and, according to the simple beam theory, the maximum deflection consists in the free end of the beam.

From previous figures can be also the relative small changes in total deformation as compared to the difference in value of mechanical properties between proposed composite materials and for the same reasons mention above.

The results of numerical simulation for total deformation in wing model shown that the greatest value of the total deformation in glass fiber reinforced composite materials in the material is composed of a single layer as well as the case of carbon fiber reinforced composite materials where we find that the more layers, the less amount of total deformation, as composite materials which owns greater modulus of elasticity and therefore be more stiffness showed deformation less where increasing the amount of total deformation with four layers of glass fiber toward material with a single layer of glass fiber, as well as the amount of total deformation in material with four layers carbon fibers increases to toward the material with a single layer of carbon fiber.

Finally, all types of proposed composite materials to be successful in total deformation criterion where the highest value of deformation does not exceed (0.27 mm), this is much less of affordability material under study.

Fatigue Life Results:

Fatigue life shows the available life for a given fatigue analysis. Figures (12) and (13) shows the counter plots of fatigue life in glass and carbon reinforced composites materials respectively, were used to display the overall distribution of life throughout the model of wing.

In stress life analysis, if the equivalent alternating stress is lower than the lowest alternating stress defined in the S-N curve, the life at that point will be used.

From the above figure note that all the proposed composite materials and according to fatigue life criterion, it can be successful but by return to the results of stresses of the equivalent alternating stresses formed in the wing note to be less than the fatigue endurance, was obtained from the experimental side [13] except single layer glass reinforced composite where the equivalent alternating stresses formed is more than fatigue endurance.

Fatigue Safety Factor Results:

The figures (14) and (15) shows counter plots with respect to fatigue failure at a given design life in glass and carbon reinforced composites materials respectively.

The maximum equivalent stress failure theory states that a particular combination of principal stresses causes failure if the maximum equivalent stress (σ_e) in a structure equals or exceeds a specific stress limit (σ_{limit}):

$$\sigma_e \geq \sigma_{limit}$$

Expressing the theory as a design goal: $\frac{\sigma_e}{\sigma_{limit}} < 1$

An alternate but less common definition states that fracturing occurs when the maximum equivalent stress reaches or exceeds the ultimate strength of the material [16]:

$$\frac{\sigma_e}{\sigma_{ut}}$$

In ANSYS, Maximum factor of safety displayed is 15, values less than one indicate failure before the design life has been reached. It can be noticed in previous figures the material which consist of three layers of carbon has the best value of safety factor, so the minimum value of safety factor for this material is (2.289), but It is obvious that all materials are safe because it's safety factor value is more than 1 which indicate that failure will not take place before the design life is reached except the material contain one layer of glass fiber where the minimum value of safety factor for this material is (0.706) and these is less than one which indicate that failure will take place before the design life is reached .

Conclusions:

From the numerical simulation results it can be concluded that it is possible to use the proposed composite materials (except No. 1) in the manufacture of skin in the wing of aircraft while keeping the same material stiffeners which consists of a titanium alloy, so if we compare the density of composite materials under study (1.43 g/cm^3 as average) with the density of titanium alloy (4.48 g/cm^3) it is possible to reduce the weight of skin by (68%) and this means increased efficiency and reduced fuel consumption due to weight reduction also not forget the low-cost resulting from the ease of manufacturing in addition a cheap cost of polymeric materials compared with titanium alloys.

But if we compare these composite materials with aluminum alloy such as (90Al+2.4Mg+0.23Cr+6.4Zn+0.97Zr) alloy, which are sometimes used in the manufacture of skin of the wing, which owns density (2.82 g/cm^3), it is also possible to replace these composite materials while reducing the weight of the skin by (50%) in addition to the benefits mentioned above.

Thus, the engineer of selection and design standing in front of several choices, the proposed composite materials could lead functionality, but to varying degrees, if the choice was based on light weight, the carbon fiber reinforced composite materials lighter than glass fiber reinforced, but from the other hand, glass fiber much cheaper than carbon fiber in addition to other considerations that have been studied in this study, such as fracture toughness and tensile strength ...etc.

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17.

Table (1), composition and mechanical properties of materials used in the study

Material	Density (kg/m^3)	Elastic modulus (GPa)	Ultimate strength (MPa)	Poisson's ratio	Shear modulus (GPa)
89Ti+7Al+4Mo	4480	113.8	1103	0.326	4.2
Polyphenylene sulfide	1.3	3.7	80	0.35	1.37
Glass fiber (two direction woven)	2.62	72	1995	0.3	27.69
Carbon fiber (unidirectional)	1.76	230	2475	0.3	88

Table (2) mechanical properties of composite materials used in the model.

Material type	E_x (GPa)	E_y (GPa)	E_z (GPa)	v_{xy}	v_{xz}	v_{yz}	G_{xy} (GPa)	G_{xz} (GPa)	G_{yz} (GPa)
1 G*	4.918	4.918	3.439	0.237	0.166	0.166	1.475	1.475	1.475
2 G	6.447	6.447	3.212	0.159	0.079	0.079	1.587	1.488	1.488
3 G	7.815	7.815	3.013	0.154	0.059	0.059	1.73	1.423	1.423
4 G	9.504	9.504	2.838	0.151	0.045	0.045	1.839	1.358	1.358
0°C	17.278	3.61	3.61	0.346	0.346	0.072	1.542	1.542	1.679
0°/90°C**	10.554	10.554	3.309	0.119	0.04	0.04	1.542	1.59	1.59
0°/90°/0°C	12.849	8.243	8.243	0.153	0.098	0.098	1.542	1.542	3.754
0°/45°/-45°/90°C	10.038	10.038	2.993	0.314	0.093	0.093	3.128	1.369	1.369

***glass fiber**
****carbon fiber**

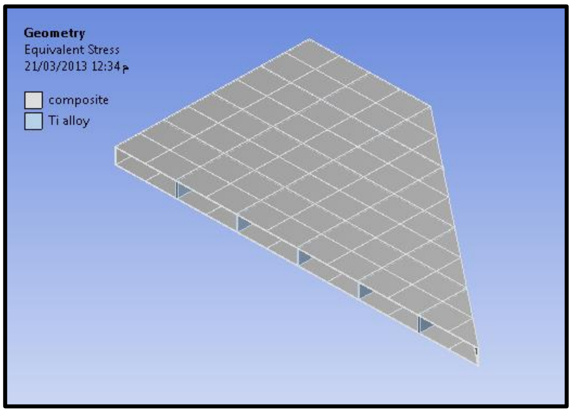

Figure (1), materials colors for modeling the wing.

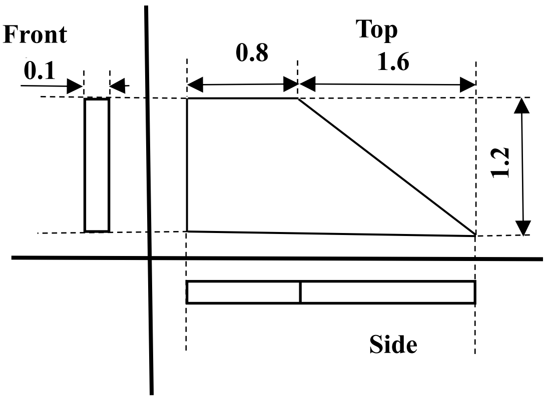

Figure (2), Aerodynamic shape of wing structure (all dimensions in meter).

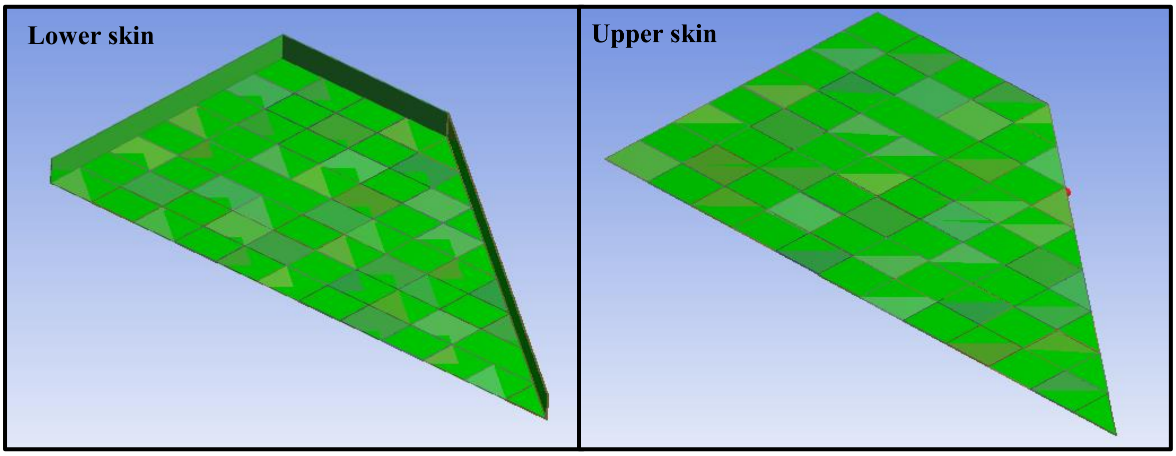

Figure (3), lower and upper plate for wing model.

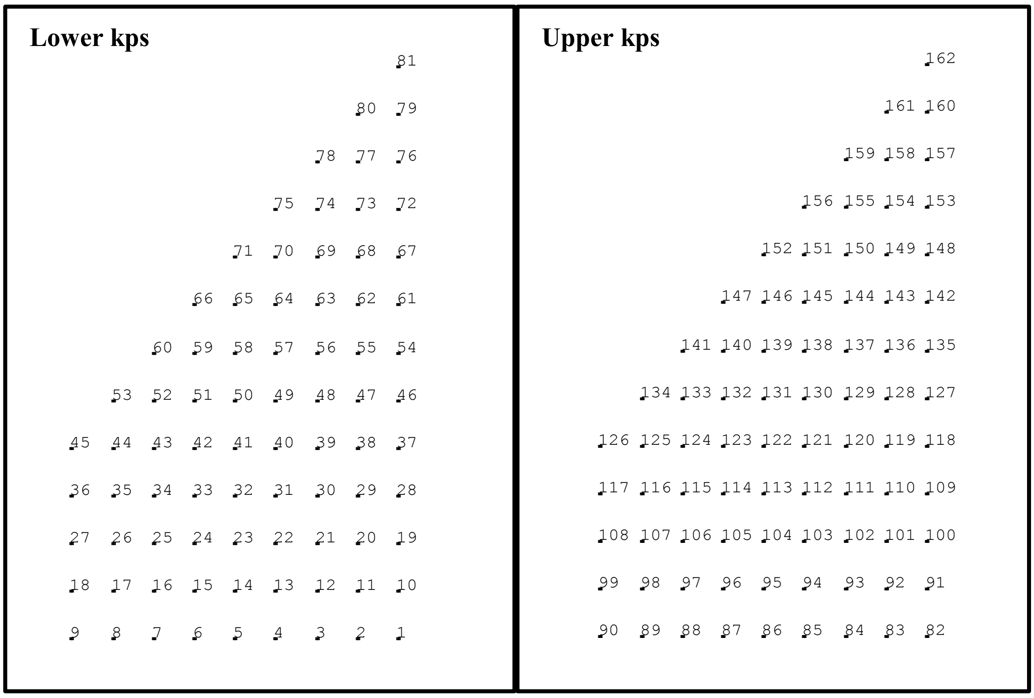

Figure (4), lower and upper created keypoints.

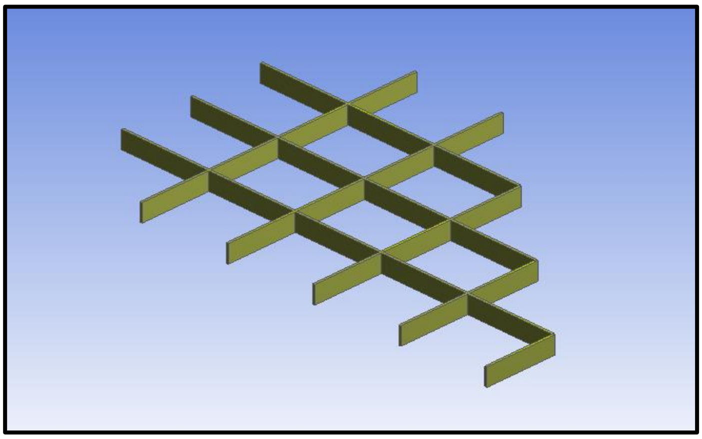

Figure (5), honeycomb sandwich cores.

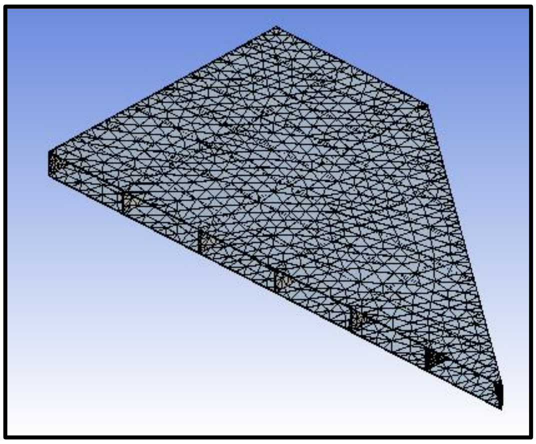

Figure (6): The meshed wing

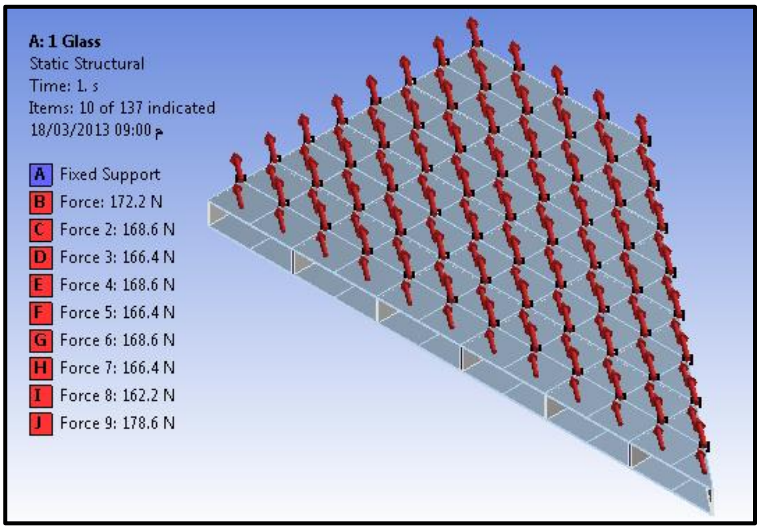

Figure (7): The applied boundary conditions on wing model.

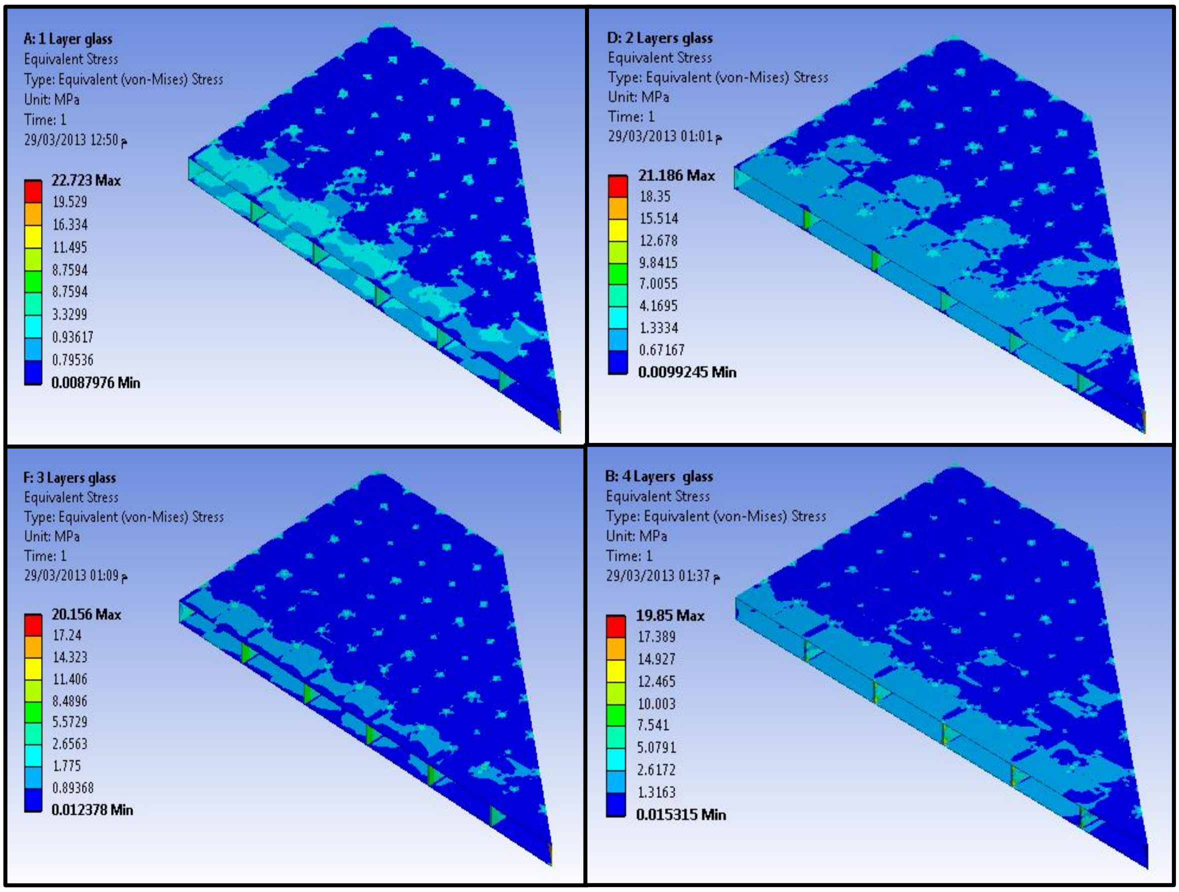

Figure (8), Contours of equivalent von Mises stress distribution of glass reinforced composite.

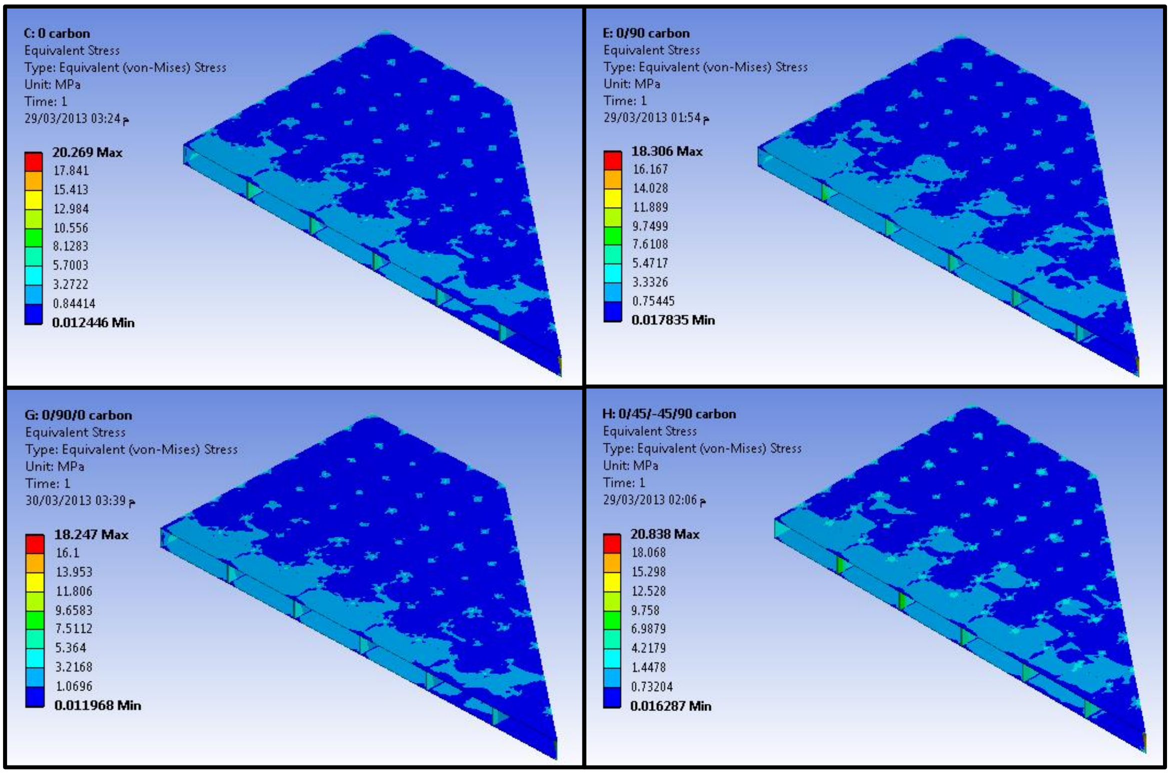

Figure (9), Contours of equivalent von Mises stress

distribution of carbon reinforced composite.

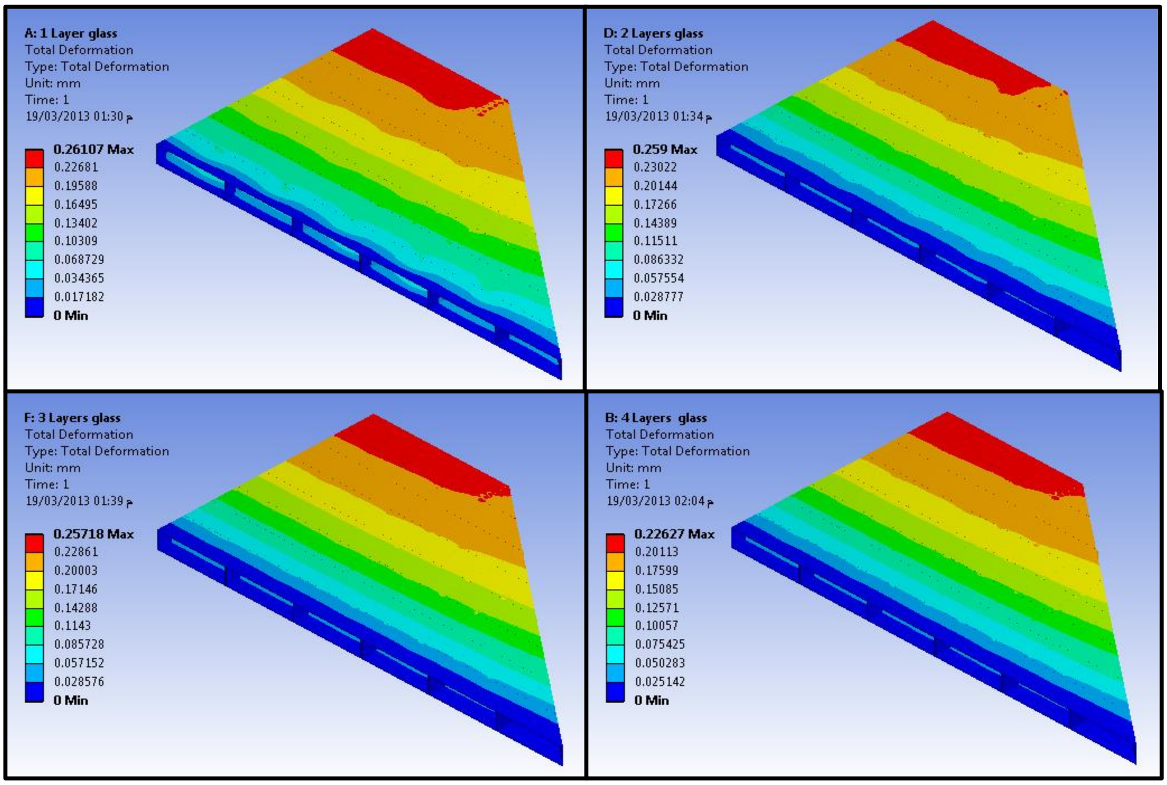

Figure (10), Contours of total deformation

distribution of glass reinforced composite.

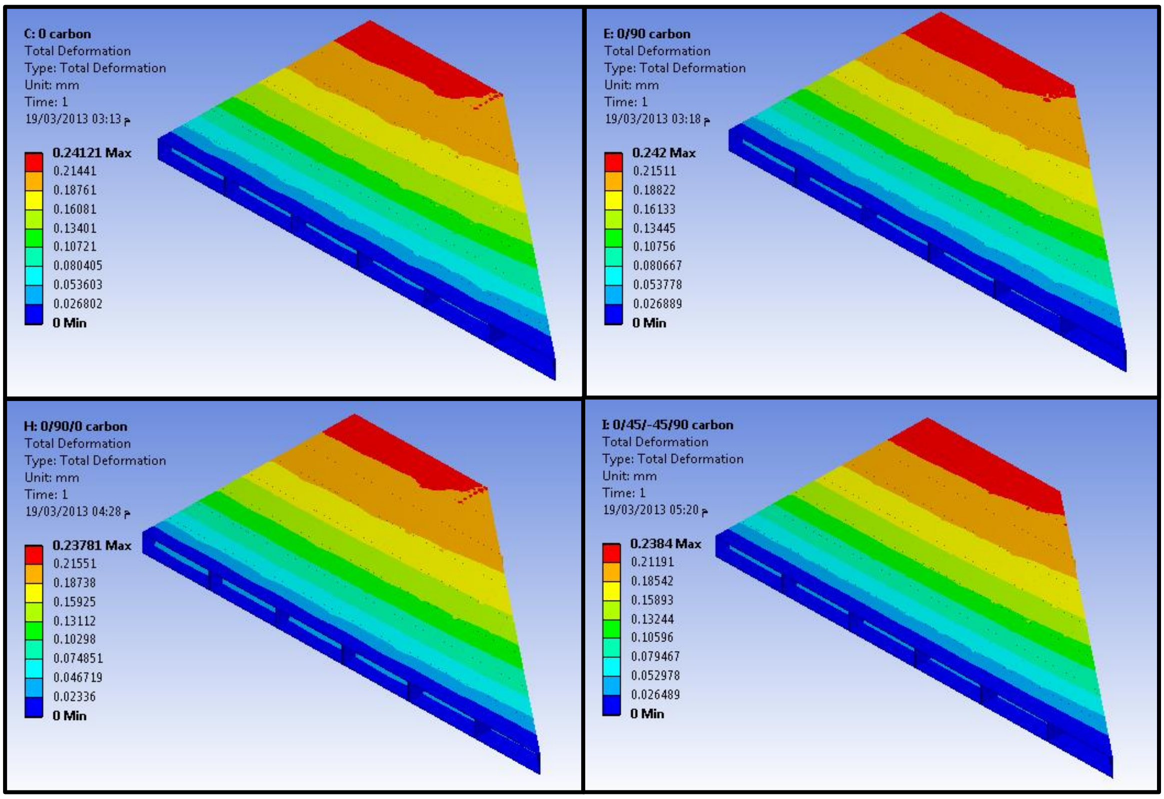

Figure (11), Contours of total deformation distribution of carbon reinforced composite.

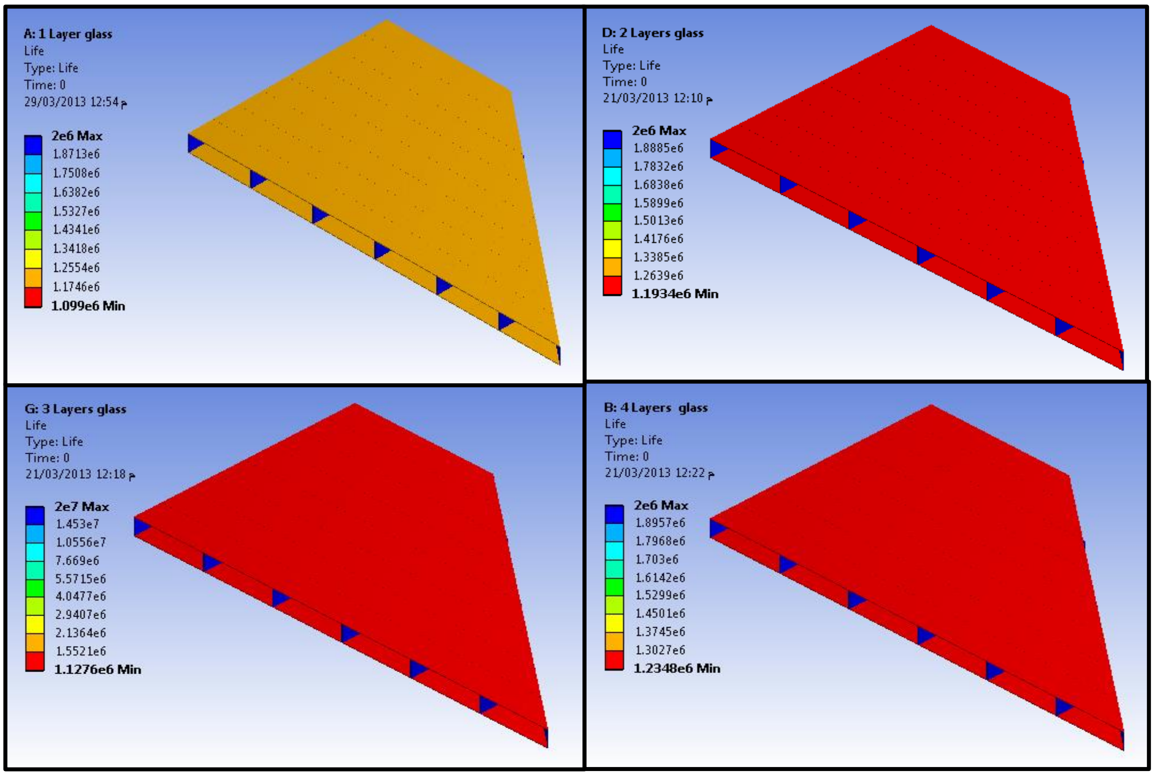

Figure (12), Contours of fatigue life distribution of glass reinforced composite.

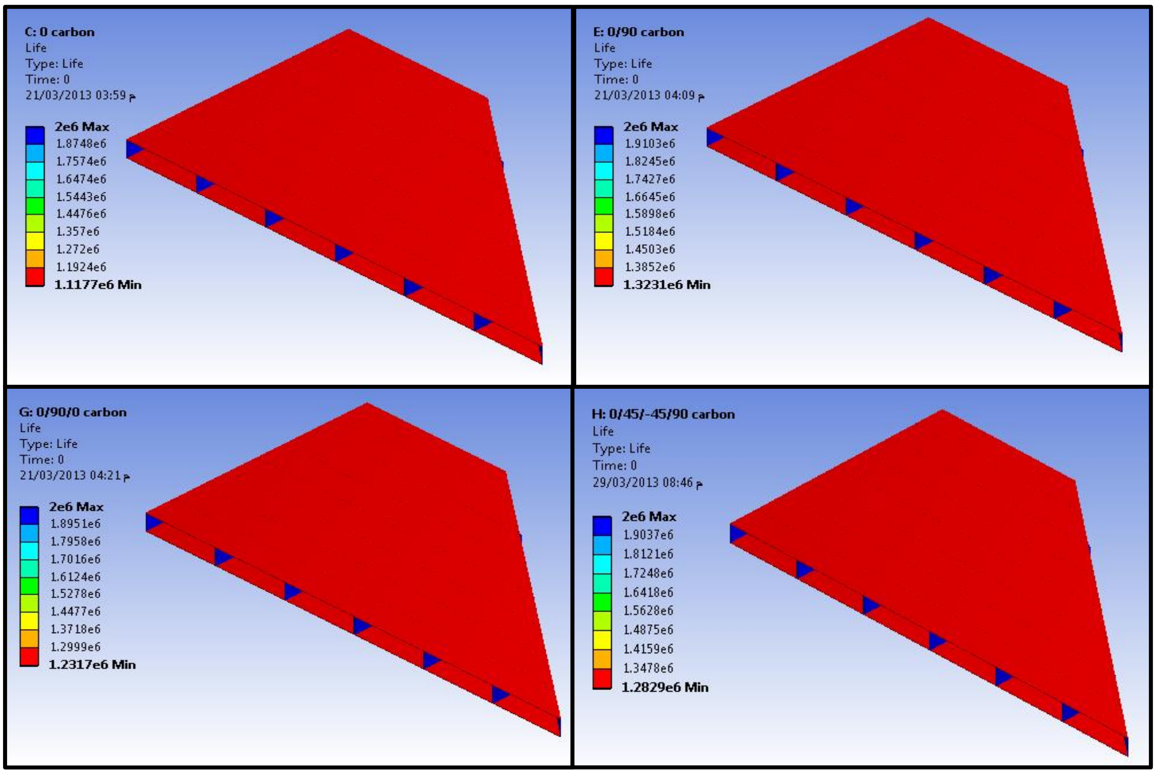

Figure (13), Contours of fatigue life distribution of carbon reinforced composite.

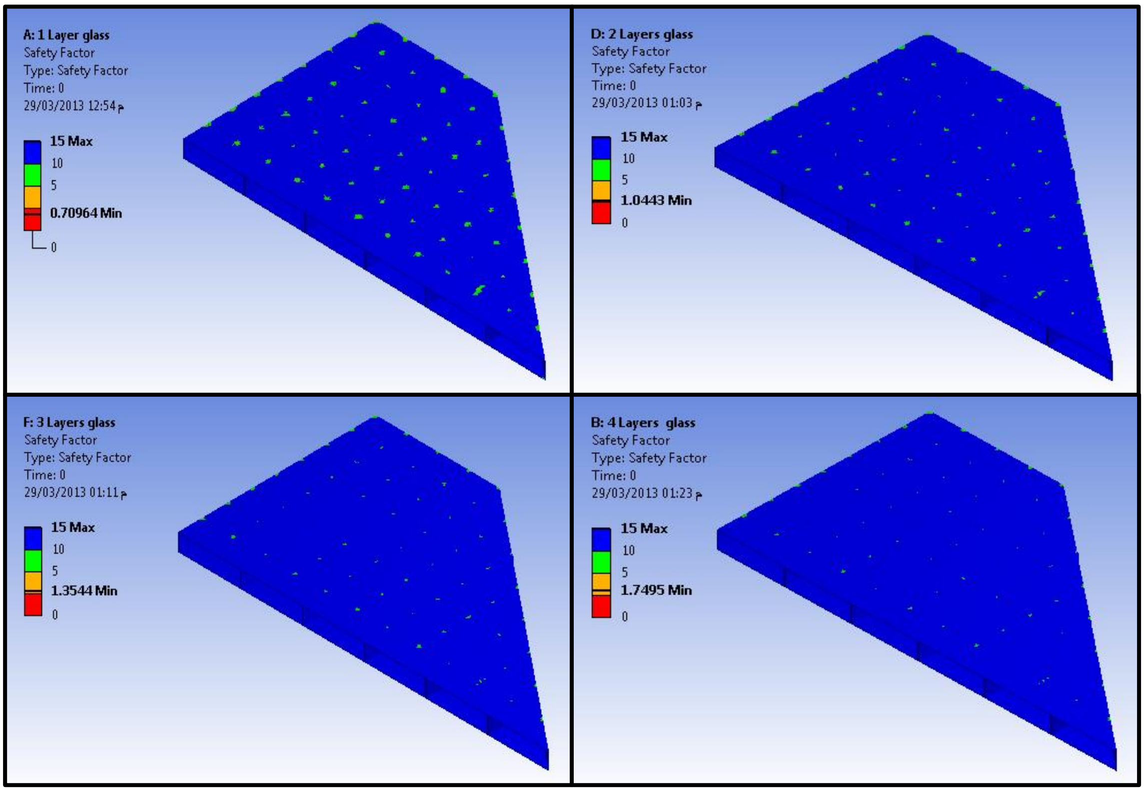

Figure (14), Contours plot of safety factor distribution of glass reinforced composite.

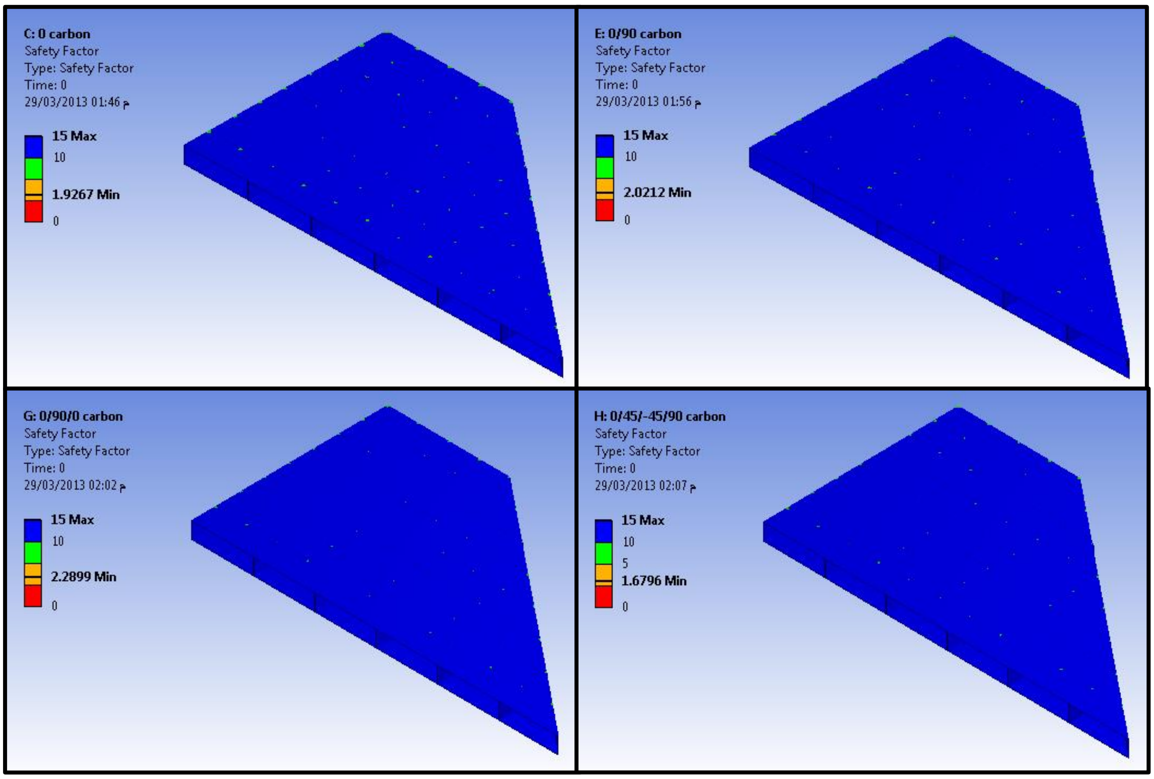

Figure (15), Contours plot of safety factor distribution of carbon reinforced composite.