Eng. & Tech. Journal, Vol. 29, No.9, 2011

Numerical and Experimental Investigation of Mechanical and Thermal Buckling Loads of Composite Laminated Plates

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Received on: 16/1/2011
Accepted on: 2/6/2011

Abstract

In this study, the effect of temperature, aspect ratio, number of layer and boundary conditions on critical buckling load of composite laminated plate is investigated experimentally and numerically. Simply-Simply-Free-Free and Clamp-Clamp-Free-Free boundary conditions, three temperatures (40°C, 60°C and 80°C) and four aspect ratio (1, 1.3, 1.5 and 2) will consider for the experimental work. The thickness of the plate was changed by increasing the number of layer.

It can be seen that when the temperature changes from 40°C to 80°C the maximum value of P_{cr} is about (225 N/mm) at (T = 40°C, a/b = 2 and NL = 4), the minimum value of P_{cr} is about (11.70 N/mm) at (T = 80°C, a/b = 1 and NL = 2). Also, it can be shown that in the case of symmetric cross ply laminate ($0^o/90^o/0^o$) when the thermal load increased by about 100 % the buckling load decrease by about 50 % at aspect ratio equal to 1. Finally, It is shown that the critical buckling load increases with increasing the aspect ratio at constant temperature, number of layers and boundary conditions.

Keywords: Composite plate; Thermal buckling; Finite element method

التقصي العددي والعملي لحمل الانبعاج الميكانيكي و الحراري في الصفائح المركبه

الخلاصة

هذه الدراسة ، تتناول تأثير درجة الحرارة و نسبة الطول إلى العرض و عدد الطبقات وحالات التثبيت على حمل الانبعاج في الصفائح المركبة عمليا وعدديا.المتغيرات التي درست في الجانب العملي تضمنت حالتين من طرق التثبيت (Free -Free–Simple -Simple) و(Free -Free–Clamp -Clamp) ، تسليط ثلاث احمال حرارية (40^oC ،60^oC ،80^oC) ونسب مختلفه من الطول الى العرض (1 ، 1.3 ، 1.5 ، 2) و تم تغيير سمك الصفيحة من خلال زيادة عدد الطبقات.

أظهرت النتائج أنه في حالة زيادة درجة الحرارة من (40°C) إلى (80°C)كانت القيمه العظمى للانبعاج (225 N/mm) وللحالة ($T=40^oC$ ، a/b=2 و NL=4) في حين كانت القيمة الصغرى هي (11.7 N/mm) وللحالة ($T=80^oC$ ، a/b=1 و NL=2). كما واظهرت النتائج انه في حالة الطبقة المتماثله ($0^o/90^o/0^o$) عند زيادة درجة الحرارة بنسبة (100 %) انخفضت قيمة الانبعاج بمقدار (50 %) عند نسبة الطول الى العرض تساوي 1. اخيرا، عند زيادة نسبة الطول الى العرض فان قيمة حمل الانبعاج سوف تزداد بثبوت درجة الحرارة، عدد الطبقات و طرق التثبيت.

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https://doi.org/10.30684/etj.29.9.17
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Introduction

Fiber reinforced laminated composite structures are finding increasing applications in engineering industries due to their lightweight and tailorable properties. Space structures in general are high performance structures of low mass and high reliability. Minimization of mass leads to thin-walled structures, which under compression or shear loading are endangered by buckling. The loading may be of mechanical or thermal type. The choice of rules for designing space structures is indispensable in order to find out the best compromise between the conflicting requirements of low mass and high reliability already in an early design stage [1].

William [2] studied the mechanical and thermal buckling strengths analysis of the perforated rectangular plates with central circular and square cutouts used finite element structural analysis method. Pandey et. al [3] presented buckling and post-buckling response of moderately thick laminated composite rectangular plates subjected to in-plane mechanical and uniform temperature loading.

There is a strong need for design rules with respect to buckling caused by combined mechanical and thermal loading. The aim of this research is to study the effect of thermal and mechanical loading on buckling of laminated composite plate under various boundary condition, aspect ratio and number of layer. Because the literature studied (e.g. [4] to [8]) does not yield them. The well known finite element system ANSYS is used for the purpose of comparison with experimental results.

Finite Element Model

Analyses performed in this design study utilized a finite element model of the plate. The model was developed in ANSYS 12.1, using the 100 elements. The global x coordinate is directed along the length of the plate, while the global y coordinate is directed along the width and the global z direction is taken to be the outward normal of the plate surface. There are 10 elements in the axial direction and 10 along the width. Reasons for choosing the particular mesh used in this study will be described later in the discussion of mesh convergence study. A linear buckling analysis was performed on the model to calculate the minimum buckling load of the structure.

The plates were analyzed under six different boundary conditions: simple – simple – free-free and clamped-clamped-free-free. Figs.(1 to 2) visually show the boundary conditions and the applied load as they were entered into ANSYS.

SHELL281 element is suitable for analyzing thin to moderately-thick shell structures. It is an 8-node element I, J, K, L, M, N, O and P with six degrees of freedom at each node; translations in the x, y, and z axes, and rotations about the x, y, and z-axes as shown in Fig. (3)[9]. SHELL281 may be used for layered applications for modeling laminated composite shells or sandwich construction. The accuracy in modeling composite shells is governed by the first order shear deformation theory.

In order to study the buckling of the plate, an eight node Lagrange finite element is employed in this study using ANSYS program. The stiffness matrix of the plate is obtained using the principle of minimum potential energy. The bending stiffness [K_b], and geometric stiffness [K_g] matrices can be expressed as

$$[k_b]=\int_A [B_b]^T [D_b][B_b]\,dA \qquad (1)$$

$$\left[k_g\right]=\int_A \left[B_g\right]^T [D_b]\left[B_g\right]dA \qquad (2)$$

Where

$$[D_b]=\begin{bmatrix} A_{ij} & B_{ij} \\ B_{ij} & D_{ij} \end{bmatrix}$$

$$\left[D_g\right]=\begin{bmatrix} \bar{N}_1 & \bar{N}_{12} \\ \bar{N}_{12} & \bar{N}_2 \end{bmatrix}$$

$$(A_{ij},B_{ij},D_{ij})=\int_{-h/2}^{h/2} \bar{Q}_{ij}\left(1,z,z^2\right)dz=$$

$$\sum_{k=1}^{N}\int \bar{Q}_{ij}^{(k)}\left(1,z,z^2\right)dz \quad (i,j=1,2,6)$$

$$(A_{44},A_{55})=\int_{-h/2}^{h/2}\left(\bar{Q}_{44},\bar{Q}_{55}\right)dz$$

or

$$A_{ij}=\sum_{k=1}^{N}\bar{Q}_{ij}^{(k)}\left(z_{k+1}-z_k\right)$$

$$B_{ij}=\frac{1}{2}\sum_{k=1}^{N}\bar{Q}_{ij}^{(k)}\left({z^2}_{k+1}-{z^2}_k\right)$$

$$D_{ij}=\frac{1}{3}\sum_{k=1}^{N}\bar{Q}_{ij}^{(k)}\left({z^3}_{k+1}-{z^3}_k\right)$$

Where [A] Extensional stiffness matrix.

[B] Bending – extension coupling matrix.

[D] Bending stiffness matrix.

k_1 and k_2 are the shear correction factors; for a rectangular cross section $k_1^2=k_2^2=5/6$ Whitney [10].

The application of the principle of total potential energy to the plate leads to the eigenvalue problem

$$\left[[K_o]-\lambda\left[K_{og}\right]\right]\begin{Bmatrix} u_i \\ v_i \\ w_i \end{Bmatrix}=0, \qquad (3)$$

$$[K_o]=[K_b],-\lambda_b\left[K_{og}\right]=\left[K_g\right] \qquad (4)$$

Experimental Work

The experimental work in this study is divided into two stages; the first is preparing the mould casting the specimens and preparing the buckling mould in Technical College – Baghdad workship. The second stage is executing the tensile, buckling and thermal buckling test at the Technical College – Baghdad laboratory.

Fig.(4) shows the main steps of experimental work of composite samples beginning from sample preparation process to sample testing.

Preparation of Mould

In this work, the Hand Lay - up procedure is used due to its low tool cost. Hand Lay–up is technique used to fabricate laminated composite plate and is the major process for the manufacture of fiber reinforcement plastic products.

The first step in the molding process is to use a piece of nylon paper (over head) over the wood plate and the glass sheet .Then, the fibers are laid in the mould in the desired orientation which is followed by the pouring liquid material (Epoxy + Hardener).

The liquid material is treated with a brush to distribute it uniformly and to saturate the fiber with the liquid material. The brush treatment is done with high accuracy and care to protect the fibers from getting torn and then other piece of nylon paper is used after the end of pouring and then the whole contents are pressed with a heavy weight for a period of (24) hours before the composite material sheet is obtained, as shown in Fig. (5)

Tensile Testing Specimens

The first type of the composite material specimens prepared in this work is the tensile test specimen. There are three different types of the tensile test specimens which are prepared in order to obtain the values of each mechanical property of the composite material according to the ASTM 3039 standard [11].

According to this dimension, the specimens have been cut by a cutter machine; Fig (6) shows the geometry of tensile test specimens.

The details of the data obtained from the tensile test are listed in table (1).

Buckling Testing Specimen

The second type of the composite material specimens prepared in this work is the buckling test specimen; there are two different types of the buckling test specimens (simply - simply - free - free) and (clamp - clamp - free - free) that were prepared according to supported method and dimension as shown in Fig. (7).

Method of Fixturing

The various boundary conditions considered in the mechanical buckling analyses (uniaxial compressive buckling) are described as follows; the two loaded edges of the rectangular plates are either simply supported or clamped. The lower edge of the plate is allowed to move freely in the loading direction (x-direction) by servo hydraulic cylinder and the upper edge kept stationary. The two unloaded edges are unconstrained from the transverse in-plane motions (called free case). The two cases of boundary conditions considered in the analysis are as follows:

1. Simply - Simply - Free – Free.
2. Clamped - Clamped - Free – Free.

Experimental Procedure

The specimen (composite laminated plate) was loaded in axial compression using a uniaxial tensile testing machine shown in Figs.(8) & (9). The specimen was mounted with the boundary condition selected in the tensile test machine along the top and bottom edges and kept free at the other two ends. For axial loading, the test specimen with boundary condition was placed between the two extremely stiff machine heads, of which the upper heads was fixed during the test, whereas the lower head was moved upwards by servo hydraulic cylinder.

The extensometer or dial gauge was mounted at the center of the specimen to detect the deflection in order to measure and draw the load - deflection curve from both dial gauge and force-length meter, the deflection is plotted on the x – axis and the load on the y – axis.

As expected, the load increases with increase in the deflection of composite laminated plate until it reaches the critical buckling load and then decreases. Again it increases with increase in the deflection and then the specimen fails and the load will be decrease.

Tables (2) and (3) show the comparisons between the results obtained from experimental work and the results from ANSYS computer program for different laminated schemes, various numbers of layers and various aspect ratios with two cases of boundary condition.

Thermal Testing Specimen

The third type of the composite material specimens prepared in this work is the thermal test specimens and they have same dimensions and geometry as the buckling specimen.

Thermal Buckling Test

For thermal buckling test, the plates are subjected to uniform temperature loading. This test is used to measure the effect of uniform temperature on the value of critical buckling load (p_{cr}) which is compared with the value of critical buckling load (p_{cr}) without heated. One type of plate boundary conditions is considered (simply - simply - free - free) and the test was carried out with different temperatures (40°C, 60°C and 80°C)

Thermal Test Instrumentation

1. Furnace with (0°C - 1100^{o}C).
2. Thermocouple sensor (K).
3. GUNT tensile machine.

Experimental Process:

The specimen (composite laminated plate) was held in the furnace and heated slightly above specified temperature [because it was found that the range of drop in temperature is 5°C during the period of moving the laminate plate from the furnace until mounting it in the GUNT tensile machine].

Table (4) presents a comparison between the different sets of experimental results and those obtained by the ANSYS program. The critical thermal buckling load results obtained experimentally and by ANSYS are shown in table (4) for cross -ply laminated plates with one type of boundary condition (SSFF).

Results and Discussion

Tables (2) and (3) represent a comparison between the results of the ANSYS program and the experimental work when there is no thermal loading.

It is clear from table (2) that in the case (SSFF) boundary condition a maximum value of P_{cr} is about (128.37 N/mm) and (108.6 N/mm) at (a/b = 1, NL = 3) for the finite element method and the experimental results respectively, while a minimum value of P_{cr} is about (4.81 N/mm) and (4.2 N/mm) at (a/b = 2, NL=1) for the finite element method and the experimental results respectively for orthotropic laminated plate. This behavior can be explained as follows: the critical buckling load decreases with increasing the aspect ratio and it also increases with increasing number of layers. But with cross ply laminated scheme the same behavior can be reported, where a maximum value of P_{cr} is about (270.81 N/mm) and (225.5 N/mm) at (a/b = 1, NL = 4) for the finite element method and the experimental results respectively, while a minimum value of P_{cr} is about (14.63 N/mm) and (12.6 N/mm) at (a/b = 2, NL = 2) for the finite element method and the experimental results respectively. The same behavior is presented in table (3) for (CCFF) boundary condition. It is clear from these tables that P_{cr} for (CCFF) boundary condition is greater than that of (SSFF). So, the percentage error between the FEM and experimental results is ranging from (9%) to (22%) for all the cases of laminate scheme.

The comparison between the results of the ANSYS computer program and experimental work when there is thermal loading with (SSFF) case of boundary condition is shown in table (4).

It can be seen that when the temperature changes from 40°C to 80°C the maximum value of P_{cr} is about (270.17 N/mm) and (225 N/mm) at (T = 40°C, a/b = 2 and NL = 4) for the finite element method and the experimental results respectively, the minimum value of P_{cr} is about (11.70 N/mm) and (11 N/mm) at (T = 80°C, a/b = 1 and NL = 2) for the finite element method and the experimental results respectively for cross - ply laminated plate. This behavior can be explained as follows, the critical buckling load drops, as the temperature changes from(40°C) to (80°C), while at constant the temperature, the critical buckling load increases with increasing aspect ratio and number of layers in (SSFF) case of boundary condition. It can be noted from the table that the percentage of error between the FEM and experimental results ranges from (6 %) to (20 %) for all the cases of laminate scheme.

It is found that the experimental results have less value than the ANSYS results and agreement between two methods is generally good.

Conclusions

Based on the results obtained from this study for laminated composite plate, it can be concluded that:-

1. It is seen that when the temperature loading increase by 100 % the buckling loading decrease about 15 % in the case of laminate scheme $0^o/90^o$.
2. When the temperature changes from 40°C to 80°C the maximum value of P_{cr} is about (270.17 N/mm) and (225 N/mm) at (T = 40°C, a/b = 2 and NL = 4) for the finite element method and the experimental results respectively, the minimum value of P_{cr} is about (11.70 N/mm) and (11 N/mm) at (T = 80°C, a/b = 1 and NL = 2) for the finite element method and the experimental results respectively for cross - ply laminated plate.
3. The boundary conditions have a very dominant effect on the buckling load in which the critical buckling load decrease by about (23 %) when the boundary condition change from CCFF to SSFF for the case of laminate scheme (0^o) and aspect ratio equal to 1..

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Table (1): Tensile Test Results of the Composite-Lamina

Test No.	Specimen No.	Modulus of Elasticity(Pa)	an Value
1 Uniaxial Tensile Test 1-Direction 0 Degree E1		2.70E+10	2.84E + 10
		2.73E+10	
		2.90E+10	
		2.79E+10	
		2.92E+10	
		2.98E+10	
		3.06E+10	
		2.87E+10	
		2.81E+10	
		2.61E+10	
2 Uniaxial Tensile Test 2-Direction 90 Degree E2		5.15E+09	5.26E +09
		5.66E+09	
		5.26E+09	
		5.11E+09	
		5.42E+09	
		5.58E+09	
		4.90E+09	
		5.38E+09	
		5.24E+09	
		4.91E+09	
3 Uniaxial Tensile Test at 45° to 1-Direction 45 Degree G12		2.30E+09	2.51E +09
		2.56E+09	
		2.51E+09	
		2.74E+09	
		2.62E+09	
		2.40E+09	
		2.52E+09	
		2.61E+09	
		2.46E+09	
		2.43E+09	

Table (2) A Comparison Between Results of ANSYS and Experimental work on Critical Buckling Load of Orthotropic and Cross - Ply Laminate Plate for Simple-Simple-Free-Free.

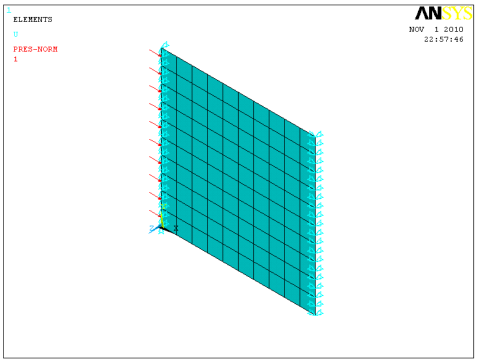
Laminat Scheme	Thicknes [mm]	/b	Experimental Critical Buckling Load [N/mm]	ANSYS Critical Buckling Load [N/mm]	Diff %
0°	1.27	1			
		1.3			-
		1.5			-
		2			-
0°/0°	2.54	1			-
		1.3			-
		1.5			-
		2			-
0°/0°/0°	3.81	1		1	-
		1.3		1	-
		1.5		1	-
		2		1	-
0°/90°	2.54	1			-
		1.3			-
		1.5			-
		2			-
0°/90°/0°	3.81	1		1	-
		1.3		1	-
		1.5		1	-
		2		1	-
0°/90°/0° /90°	5.08	1		1	-
		1.3		1	-
		1.5		1	-
		2		1	-
0°/90° /90°/0°	5.08	1		2	-
		1.3		2	-
		1.5		2	-
		2		2	-

Table (3) A Comparison Between results of ANSYS and Experimental work on Critical Buckling Load for Orthotropic and Cross-Ply Laminate Plate for Clamp-Clamp-Free-Free.

Laminate Scheme	Thickness [mm]	/b	Experimental Critical Buckling Load [N/mm]	ANSYS Critical Buckling Load [N/mm]	Diff %
0°	1.27	1		19.28	-
		1.3		19.27	-
		1.5		19.26	-
		2		19.24	-
0°/0°	2.54	1		150.70	-
		1.3		150.60	-
		1.5		150.52	-
		2		150.35	-
0°/0°/0°	3.81	1		489.72	-
		1.3		489.37	-
		1.5		489.12	-
		2		488.57	-
0°/90°	2.54	1		58.39	-
		1.3		58. 26	-
		1.5		58.31	-
		2		58.26	-
0°/90°/0°	3.81	1		476.32	-
		1.3		475.96	-
		1.5		475.75	-
		2		475.32	-
0°/90°/0° /90°	5.08	1		623.20	-
		1.3		622.83	-
		1.5		622.63	-
		2		622.22	-
0°/90°/ 90°/0°	5.08	1		1006.64	-
		1.3		1005.97	-
		1.5		1005.60	-
		2		1004.86	-

Table (4) A comparison Between results of ANSYS and Experimental work On Thermal Critical Buckling Load for Cross - Ply Laminated Plate for Simply-Simply-Free-Free.

Laminate Scheme	Temp [˚C]	a/b	Experimental Thermal Critical Buckling Load (N/mm)	ANSYS Thermal Critical Buckling Load (N/mm)	Diff%
0°/90°	40	1	13	14.34	- 10.38
		1.3	13.2	14.64	-10.92
		1.5	13.3	14.67	-10.30
		2	13.3	14.66	-10.23
	60	1	12	13.17	-9.76
		1.3	13	14.34	-10.33
		1.5	13.1	14.55	-11.13
		2	13.1	14.65	-11.89
	80	1	11	11.70	-6.38
		1.3	13	13.79	-6.12
		1.5	13.2	14.31	-8.43
		2	13.3	14.62	-9.97
0°/90°/0°	40	1	81	90.40	-11.61
		1.3	97.5	111.71	-14.57
		1.5	103	119.02	-15.55
		2	107	124.25	-16.12
	60	1	55	61.30	-11.46
		1.3	78	87.35	-11.98
		1.5	90	102.07	-13.41
		2	105	120.49	-14.75
	80	1	42	45.67	- 8.74
		1.3	63	68.90	- 9.36
		1.5	76	84.73	-11.49
		2	100	113.41	-13.41
0°/90°/90°/0°	40	1	169.4	198.233	-17.02
		1.3	208	245.53	-18.04
		1.5	220	260.39	-18.35
		2	225	270.17	-20.07
	60	1	115	133.56	-16.14
		1.3	163	192.71	-17.51
		1.5	190	225.22	-18.53
		2	220	263.11	-19.59
	80	1	87.4	98.83	-13.08
		1.3	131.5	150.76	-14.64
		1.5	159	185.81	-16.86
		2	210	248.57	-18.36



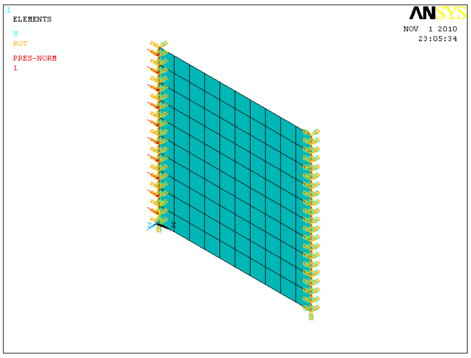


Figure (1) SSFF Boundary Condition **Figure (2) CCFF Boundary Condition**

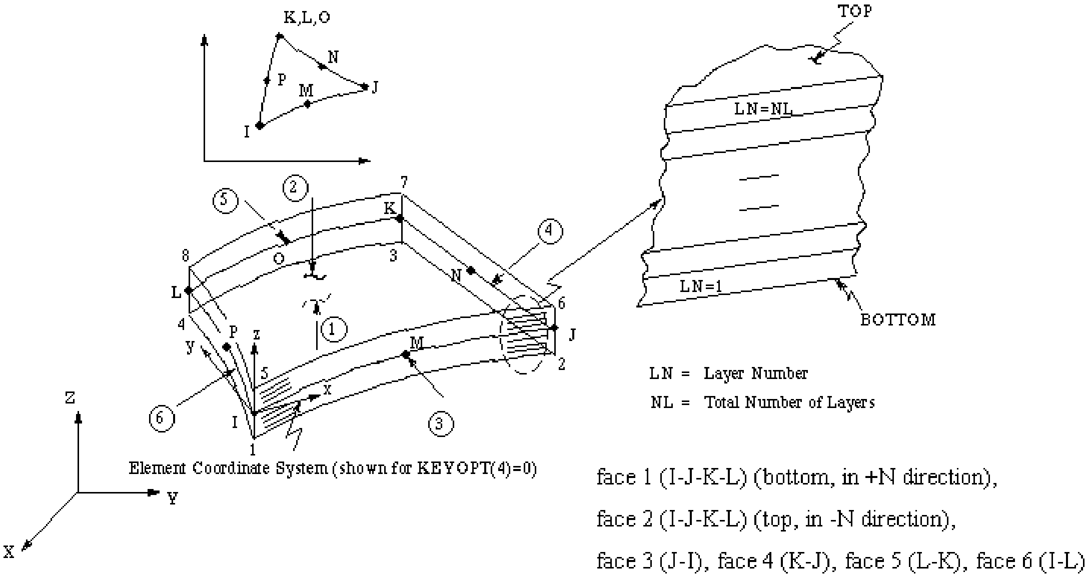


Figure (3) SHELL 281 Geometry [9].

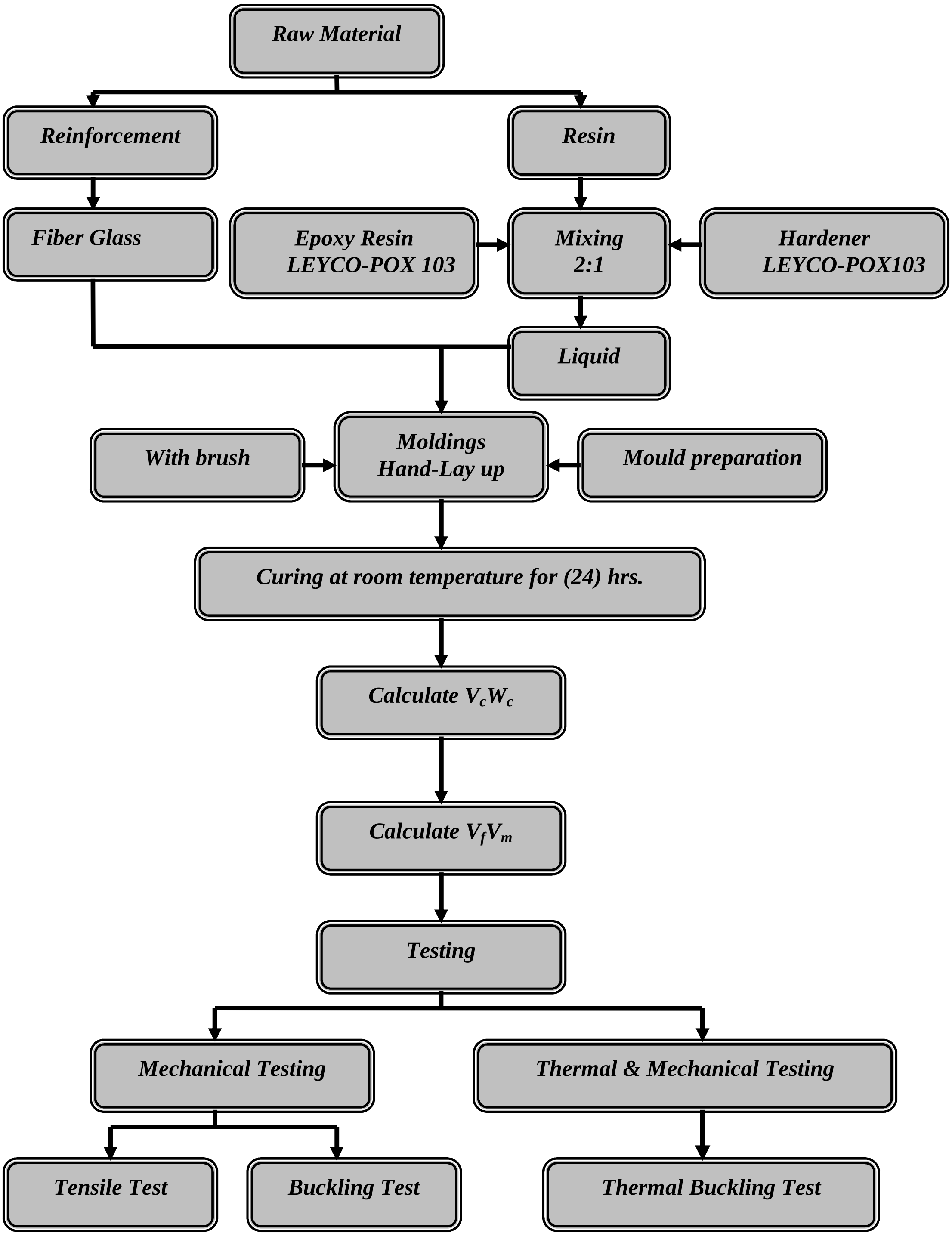


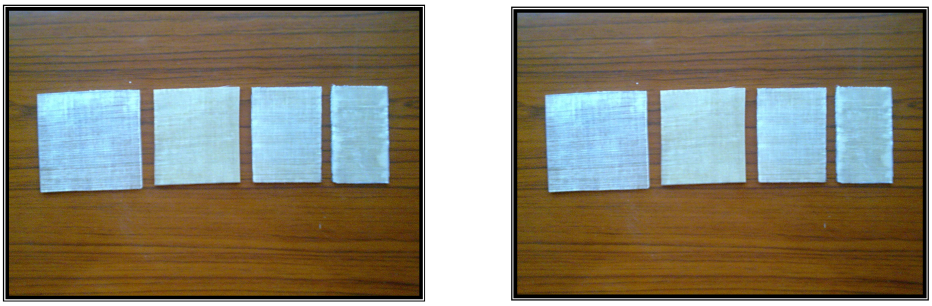
Figure (4) The Experimental Work from Composite Sample Preparation Process until Samples Testing Performed.

(a) (b)

Figure (5) Hand Lay – Up Method

0 Degree Angle 45 Degree Angle 90 Degree Angle

Figure (6) Tensile Specimen

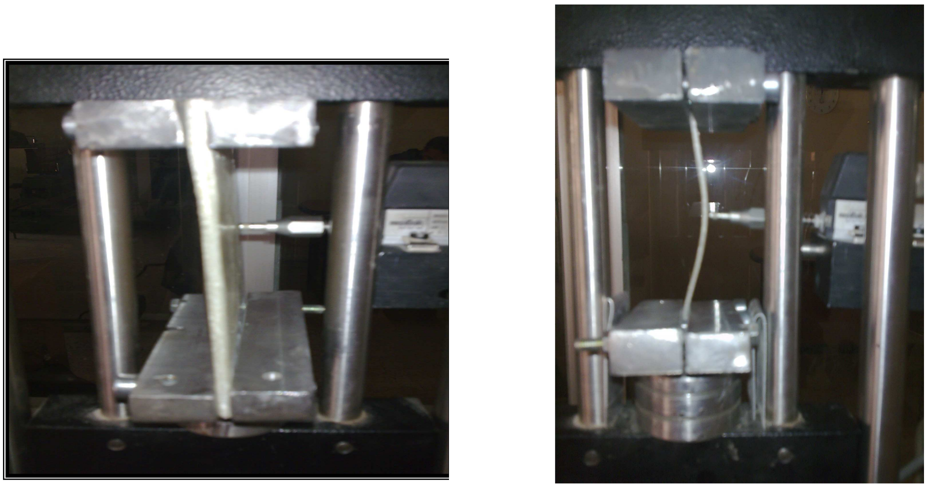


(SSFF) specimen (CCFF) specimen

Figure (7) Buckling Specimen

(a) Before Buckling **(b) After Buckling**

Figure (8) Specimen with SSFF Boundary Condition



(a) Before Buckling **(b) After Buckling**

Figure (9) Specimen with CCFF Boundary Condition