# Finite Element Analysis of Fire Extinguisher for Different Types of Composite Materials

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**Abstract**

The stress and strain concentrations of a fire extinguisher made of different types of composite materials are investigated. The prediction of the failure limit and its location in the proposed design is always the associated problem that is inescapable and difficult to be solved completely in the shape design of pressure vessel. A three dimensional analysis in finite element method was made for determining the concentration of stress and strain of the extinguisher. The extinguisher is made of polyester resin reinforced with different types of fiber glass. The aim of the present investigation is to study the effect of different levels of internal pressure and different types of composite material on the failure limit for limiting capability of applying that product in practical field.

The results are compared with those obtained from the corresponding model where xy-strain of composite material reinforced with random fiber glass increases with rate (98%) while in the composite material reinforced with fiber glass arranged with $45^o$ it increases with rate (99.8 %) due to increase in the internal pressure to (0.9-5) MPa. The comparison between theoretical and numerical results gives a good agreement.

**Keywords:** extinguisher, composite material, failure limit, pressure vessel, three dimensional analyses.

## التحليل باستخدام المحددة لمطفئة الحريق لانواع مختلفة من المادة المركبة

**الخلاصة**

تم بحث تركيز الإجهادات والانفعالات لمطفئة الحريق مصنعة من مواد مركبة مختلفة. ان التنبوء بحدود الفشل ومكانه في التصميم المقترح وهو في العادة متضمناً مشكلة لا مفر منها وصعوبة في إيجاد الحل المناسب لشكل الاسطوانة المصممة. التحليل الثلاثي باستخدام طريقة العناصر المحددة لأجل تحديد تركز الإجهاد والانفعال لمطفئة الحريق. مطفئة الحريق صنعت من البولستر المقوى بأنواع مختلفة من الألياف الزجاجية. الهدف من البحث الحالي دراسة تأثير مستويات مختلفة من الضغط الداخلي ولأنواع مختلفة من المادة الركبة على حد الفشل لتحديد إمكانية تطبيق ذلك المنتج في المجال العملي. النتائج قورنت مع ما تم الحصول عليها من الأنموذج حيث ان الانفعال بالاتجاه (xy) لمادة مركبة معززة بألياف زجاجية عشوائية يزداد بنسبة (98%) بينما في المادة المركبة المعززة بألياف زجاجية مرتبة ($45^o$) تزداد بنسبة (99.8%) نتيجة زيادة الضغط الداخلي من (0.9-5 MPa). المقارنة بين النتائج النظرية والعددية اعطت تطابقا جيداً.

**الكلمات المرشدة**: مطفئة ، مواد مركبة، حد الفشل، اسطوانة الضغط، التحليل الثلاثي الأبعاد.

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## Introduction

The pressure vessel is used in the petrochemical, gas storage and pharmaceutical industrial, etc. [1]. The associated stress concentration depends on the size, shape and location of Opening. As the design has the constraints, the stress concentration should be not exceeded the maximum of allowable stress in the structure. Those applications of pressure Vessel are demanded for more light weight, high-performance and low-Cost. The researches of shape design optimization attest that the shape changes can save the considerable mass and improve the performance of elements [2-5] Several method have been used for solving the problem of stress constriction and light weight on the shape of pressure vessel, which are including the analytic methods or the numerical approaches, such as computational simulation. As a result of high accuracy of Ansys. analysis of complex structure is regarded by many engineers and researches as a modern, robust, accurate, and visually sensible tool to provide solutions for many engineering and scientific problem[6].

R.H. Knapp et. al. [7] studied the filament-wound composite cylinders are used in the marine and transportation industries for storing breathing gases (SCUBA, firefighter tanks) and gaseous fuels (vehicles). These cylinders offer light weight, corrosion resistance, dimensional stability, and the ability to store more air than equivalent metal tanks. S. Golabi et. al. presented the results of the experiments and Finite Element Analysis (FEA) on torispherical heads with pressure on their concave side[8]. Sonmez is proposed the research objective, which is to obtain globally optimum shapes for two-dimensional structures subject to quasi-static load and restraints [9].

The reason of choosing this material for making the extinguisher because the polyester resin according to has properties the failure happen when temperature exceed the 60 C$^o$ which represented a very good characteristic where increasing temperature of the fire region and when the failure happen, the fire resistance material inside of the fire extinguisher distributed on fire region as show in table (1) [10].

The aim of this research is to study the effect of different levels of internal pressure and different types of composite material on the failure limit for limiting capability of applying that product in practical field.

**Experimental properties of composite material**

The study has made tensile tests on different types of composite material according to D412 ASTM [11] as shown in Fig.(1) where the tensile tests speed is equal to (3 mm/min).

The tensile test specimens were made from two types of composite material in which one layer of fiber glass was immersed in polyester resin with curing rate (0.7%). By depending on experimental tests the tensile modulus and tensile strength of each type of composite material as shown in Figs.(2,3) are limited. So that Poisson's Ratio is equal to (0.3). According of experimental data at temperature of (30 C$^o$) polyester resin reinforced with random fiber glass has (tensile modulus=12.1 GPa, tensile strength =55 MPa) and the polyester resin reinforced with fiber glass arrangement ($45^o$) angle has (tensile modulus=7.3GPa ,tensile strength =31 MPa ).

The experimental properties of composite material are used to build a new model of fire extinguisher in actual dimensions for three dimensional analysis by using finite element method. The properties of fiber glass are shown in Table (2) and the properties of thermosetting polyester resin are shown in Table (3) [12].

## Design and modeling

The vessel of fire extinguisher was built in 3D body according to standard dimensions by using Auto Cad software linked to Ansys. software and that model was analyzed under different levels of internal pressure which access the pressure applied to standard fire extinguisher vessel which is made of metal.

The design takes into account the stress concentration and strain in curve and sharp edge in fire extinguisher vessel.

The material of composite material used was thermosetting resin reinforced with fiber glass matrix of different arrangements (random and $45^o$) in thickness of (4 mm), approximate height of (320 mm) and diameter of (130 mm) as shown in Fig.(4).

The element type SOLID185 is used for 3-D modeling of solid structures. It is defined by eight nodes having three degrees of freedom. At each node translations were in the nodes x, y, and z directions. It also has mixed formulation capability for simulating deformations of nearly incompressible elastoplastic materials, and fully incompressible hyperelastic materials [13]. Solid185 structural solid geometry is shown in Fig. (5).

## The Numerical Method of Analysis

The finite element analysis uses direct solver where the system of simultaneous linear equations is generated by the finite element procedure is solved by using a direct elimination process. A direct elimination process is primarily a Gaussian elimination approach which involves solving for the unknown vector of variables {u} in Eq.(1) [13 ]:

[K] {u}={F} …………(1)

where:

[K] = global stiffness

{u} = global vector of nodal unknown

{F} = global applied load vector

Using direct solver gives a very good accuracy in three dimensional analysis and has performance in simulation of material deformation.

The analysis applies for two types of composite material and different levels of internal pressures at constant temperature (T=30 $C^o$).

## Theoretical design calculation

Depending on Tresca yield criteria, the yielding strain can be derived as follows[14]:

$$(s_x-s_y)^2+(s_x-s_z)+(s_y-s_z)+6(t^2_{xy}+t^2_{xz}+t^2_{yz})=2s_o \quad \ldots (2)$$

For plane stress,

$$s^2_x + s^2_y - s_x s_y + 3t^2_{xy} = s_o^2 \quad \ldots (3)$$

Pressure vessels are held together against the internal pressure due to tensile forces within walls of the container which is proportional to the pressure and radius of vessel and inversely proportional to the thickness of walls [15]. The stress of thin wall cylindrical vessel with hemispherical ends is sometimes called a "bullet" for its shape, and is determined as follows:

$$s_q = \frac{P.r}{t} \quad \text{.......... (4)}$$

$$s_{Long} = \frac{P.r}{2.t} \quad \text{.......... (5)}$$

where $\sigma_\theta$ is hoop stress, or stress in the circumferential direction, $\sigma_{Long}$ is stress in longitudinal direction, **P** is internal gauge pressure, **r** is the inner radius of cylinder, and **t** is wall thickness[15].

The determining wall thickness of **h**emispherical head is as follows [16]:

$$t_h = \frac{P*r}{2.*s_{all}*E-0.2*P} \quad \text{..... (6)}$$

And for **c**ylindrical vessel:

$$t_c = \frac{P*r}{2.*s_{all}*E-0.2*P} \quad \text{..... (7)}$$

where ***E*** is weld joint efficiency factor, determined by joint and degree of examination, and $\sigma_{all}$ allowable stress.

Table (4) shows the values of thickness of different types of composite material and safety factor.

The material type which is used in manufacturing the fire extinguisher is (ST-12 or steel grade no. 1.0330) and has properties shown in Table (5) and has density equal to (7850 kg/m$^3$) [17]. The value of volume is known, therefore the weight of extinguisher can be determined and it is equal to (2.4435 kg) while the density of composite material determined by taking rectangular specimen with dimensions of (20mm *12 mm *4 mm) and measuring its weight to determine the density which is equal to (1082 kg/m$^3$) therefore, the weight of composite extinguisher is (0.34 kg). The weight of extinguisher decreases with approximate ratio equal to (86%).

**Results and Discussion**

The study describes different levels of the internal pressures effects in which create variation strains distributed on the fire extinguisher vessel body. The study compares between theoretical results and numerical results as shown in Table (6).

The analysis gives a good prediction of stress and strain concentrations and determines the surfaces which requires more reinforce to prevent the failure which may happen in application field. Figs.(6) and (7) show the variation in maximum values of xy-shear stress with variation in internal pressure for different types of composite material.

The minimum and maximum values of xy-shear strain for different composite materials are shown in Appendices (A )

**a- The composite material reinforced With random fiber glass.**

This type of composite material is made from thermosetting polyester resin reinforced with random fiber glass.

The analysis results show that xy-shear strain is concentrated in the spherical head where the maximum xy-shear strain and yz-shear strain increase with approximate rate (98%) , so that xz-shear strain increases to (99.8%) as a results of increasing the stress from (0.9-5) N/mm$^2$ or (9-50) bar as shown in Figs.(8-11)

According to analysis results the failure of composite extinguisher happens when the pressure exceeds to (5 $N/mm^2$) while the metal fire extinguisher is designed for (2.5 $N/mm^2$).

Fig. (16) Shows the shear stress concentration on spherical head of composite fire extinguisher as a result of uniform distribution of internal pressure and increases with at the same approximate rate as that in shear strain rate.

**b- The composite material reinforced with fiber glass arranged with 45$^o$.**

Figs.(12-15) show the fire extinguisher which is made from thermosetting

polyester resin reinforced with fiber glass arranged with 45$^o$.

The xy-shear strain is increases with an approximate rate of (98.2%), yz-shear strain increases with approximate rate of (97.68%) and xz-shear strain increases with approximate rate of (98.2%) as a result of increasing the stress from (0.9-5) $N/mm^2$.

## Conclusions

The following conclusions can be drawn from this investigation:

- Modified proposal for applying the composite material in made the fire extinguisher in which the internal pressure is applied to exceed (5 $N/mm^2$) where the metal fire extinguisher is designed for (2.5 $N/mm^2$). That means the composite material can be used for making the fire extinguisher with safety factor of (1.85) of polyester resin reinforced with random fiber glass woven and applied successfully in this production.
- The weight of fire extinguisher made from composite material decreases with approximate rate (86%) of the weight of that made from metal because decreasing weight increases the efficiency of transfer the fire extinguisher in work field.
- The comparison between the results of two types of fiber glass which are used in composite material, shows that the first type of fiber glass (random fiber glass) is more suitable for manufacturing the fire extinguisher because the maximum strain at pressure of 5 $N/mm^2$ is equal to (0.646E-3) while the maximum strain in fiber glass arrangement with 45$^o$ is equal to (0.001071).
- xy and yz-shear strains in random fiber glass increase at rate of (98%) and xz-shear strain increases at rate of (99.8%) due to the increase in the internal pressure of (0.9-5 $N/mm^2$).
- xy and xz-shear strains in fiber glass with 45$^o$ increases at rate (98.2%), yz-shear strain increases at rate of (97.88%) due to the increasing in internal pressure (0.9-5 $N/mm^2$).

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**Table (1) Maximum Continuous-Use Temperatures for Various Thermosetting and Thermoplastics [10]**

| Materials | Materials Maximum Continuous-Use Temperature (°C) |
|---|---|
| **Thermosettings** | |
| Vinylester | 60–150 |
| Polyester | 60–150 |
| Phenolics | 70–150 |
| Epoxy | 80–215 |
| Cyanate esters | 150–250 |
| Bismaleimide | 230–320 |
| **Thermoplastics** | |
| Polyethylene | 50–80 |
| Polypropylene | 50–75 |
| Acetal | 70–95 |
| Nylon | 75–100 |
| Polyester | 70–120 |
| PPS | 120–220 |
| PEEK | 120–250 |
| Teflon | 200–260 |

**Table (2) Mechanical Properties of E-glass Fibers [12]**

| Glass type | Specific gravity | $S_{ult}$ (MPa) | Modulus of Elasticity (Gpa) | Liquids temperature °C |
|---|---|---|---|---|
| E-glass | 2.58 | 3450 | 72.5 | 1065 |

**Table (3) Mechanical Properties of Polyester resin [12]**

| Properties | Value |
|---|---|
| Specific density (at 20 Co) | 1.22 |
| Tensile stress at break | 65 N/mm2 |
| Elongation at break (50mm gauge length) | 3.0 % |
| Modulus of elasticity | 3600 N/mm2 |
| Density ( $r$ ) | 1268 kg/m3 |
| Rockwell Hardness | 70 |

**Table (4) Theoretical design calculation of required thickness of composite extinguisher vessel**

| *Type of composite material* | *Hemispherical head (mm)* $t_h$ | *Cylindrical thickness (mm)* $t_c$ | *Safety Factor S.F.* |
|---|---|---|---|
| *Polyester resin reinforced with one layer random fiber class* | 1.93 | 3.99 | 1.85 |
| *Polyester resin reinforced with one layer fiber class* $45^0$ | 1.9 | 4.0 | 1.04 |

**Table (5) Type of steel used in manufacturing of the extinguisher ST-12 properties [17]**

| *Spec. No.* | *Chemical composites (%)* | | | | | | *Yield stress* $(N/mm^2)$ | *Tensile strength* $(N/mm^2)$ | *Elongation rate (%)* | *Density* $Kg/m^3$ |
|---|---|---|---|---|---|---|---|---|---|---|
| | *C* | *Mn* | *P* | *S* | *Si* | *AL* | | | | |
| ST 12 | ≤0.10 | ≤0.50 | ≤0.035 | ≤0.035 | ≤0.50 | --- | 240 | 2/0-410 | ≥32 | 7850 |

**Table (6) Comparing the theoretical and numerical of the stress in the circumferential direction $\sigma_\theta$ and longitudinal direction $\sigma_{Long}$. at pressure 2 $(N/mm^2)$**

| *Stress type* | *Theoretical* | *Numerical* | *Disparity ratio(%)* |
|---|---|---|---|
| $\sigma_h$ *(MPa)* | 14.25 | 14.03 | 1.54 |
| $\sigma_L$ *(MPa)* | 28.5 | 29.4 | 3.06 |
| $g_{xy}$ | 0.01505 | 0.0139 | 7.64 |
| $t_{xy}$ *(MPa)* | 7.001 | 6.49 | 7.29 |

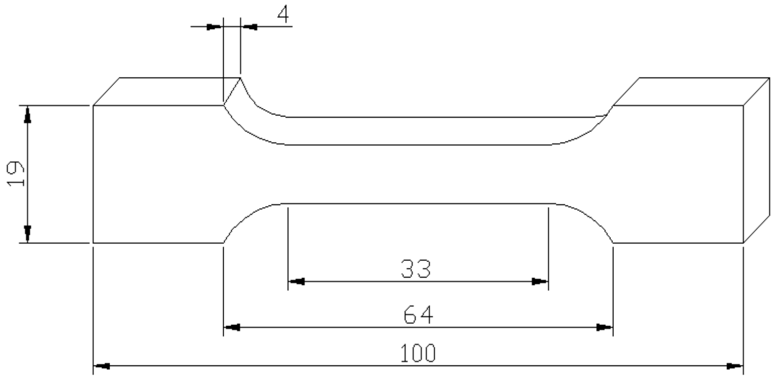



**Figure (1) Standard tensile test specimen (ASTM D412 )[11]**

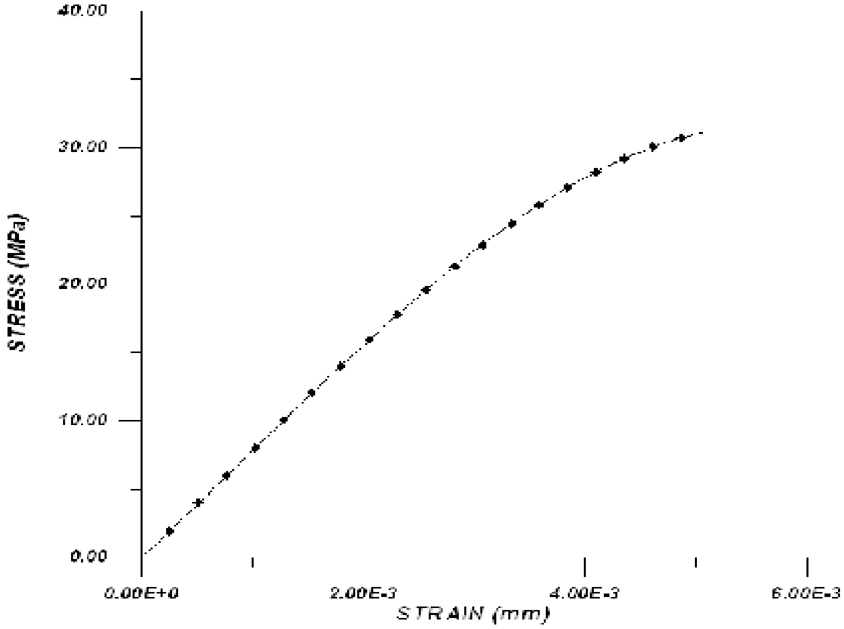



**Figure (3) Relationship between stress and strain for composite tensile specimen (45$^{o}$ fiber glass) (tensile speed=3 mm/min)**

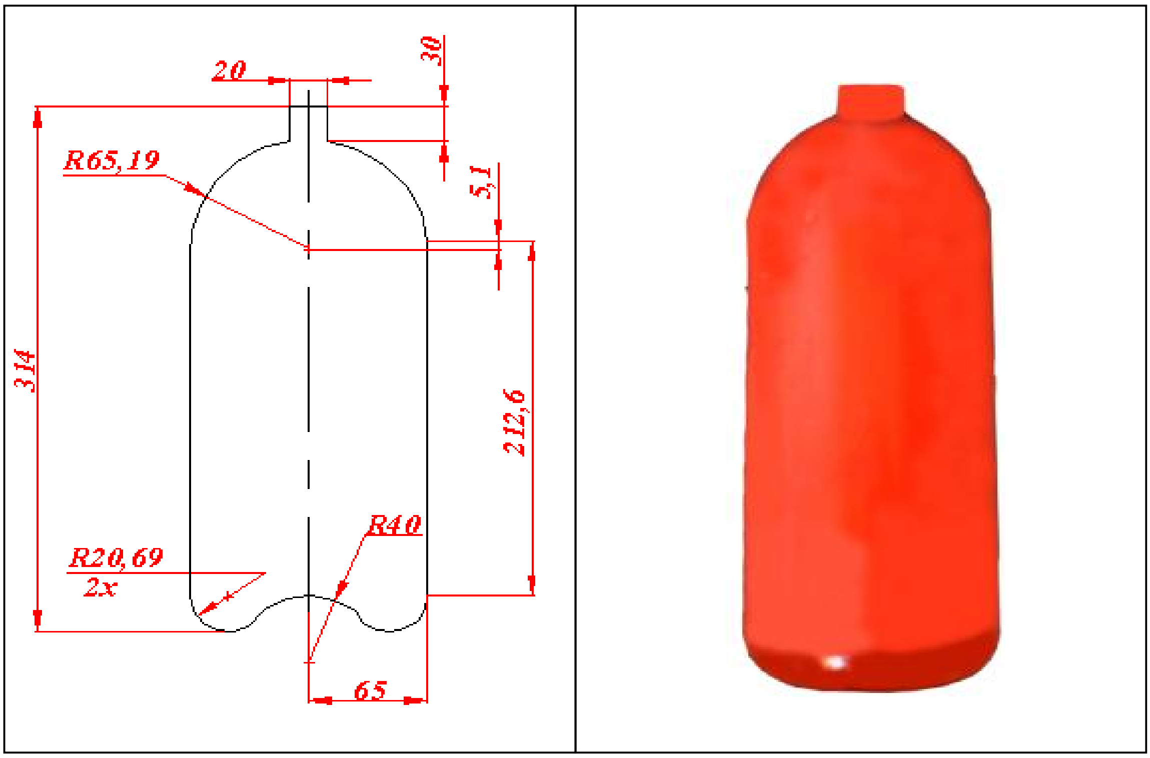



**Figure (4) Drawing and Photo of standard fire extinguisher made from metal**

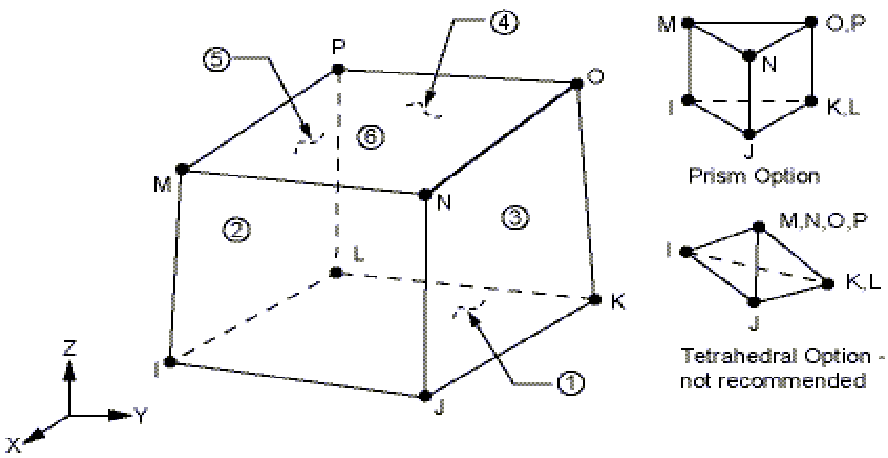



**Figure (5) Structural solid geometry of element Solid185[13].**

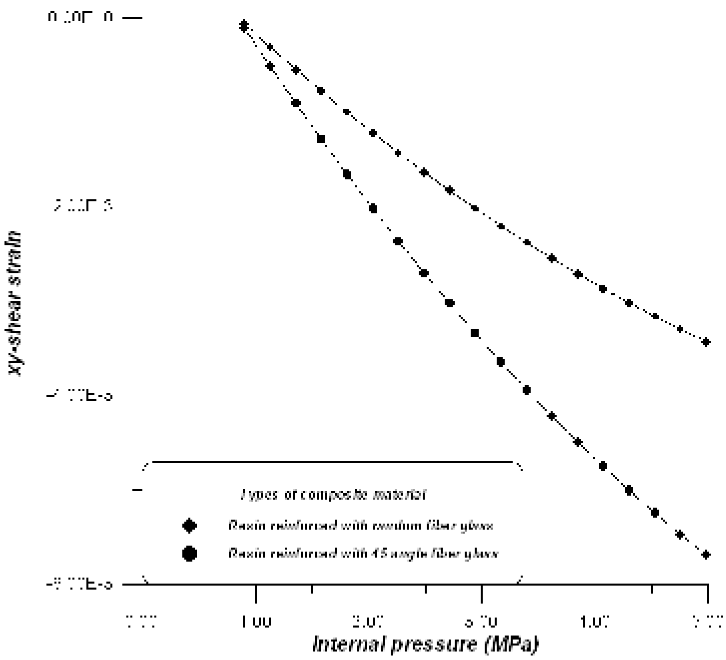



**Figure (6) Variation in minimum values of xy-shear strain of different Types of composite material at node number = 65**

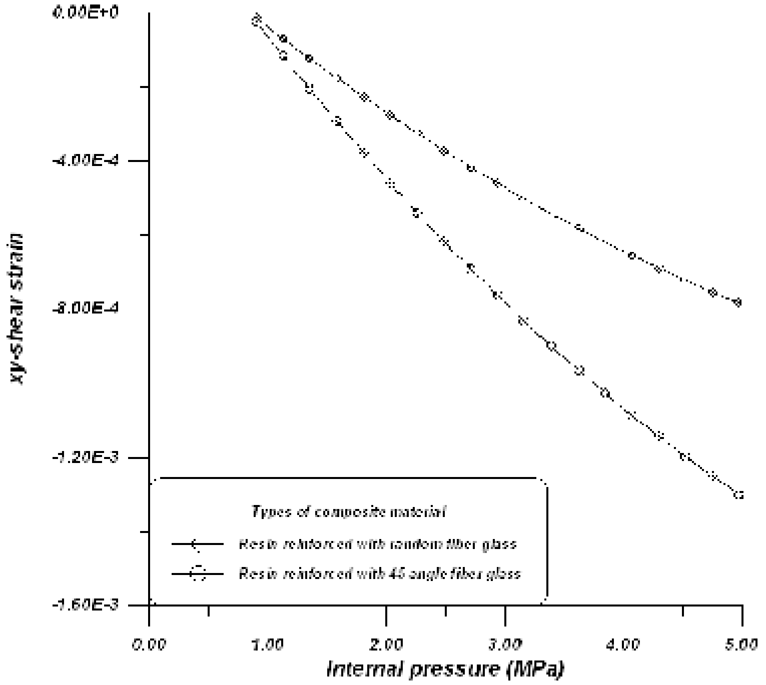



**Figure (7) Variation in maximum values of xy-shear strain of different types of composite material at node number = 2043**

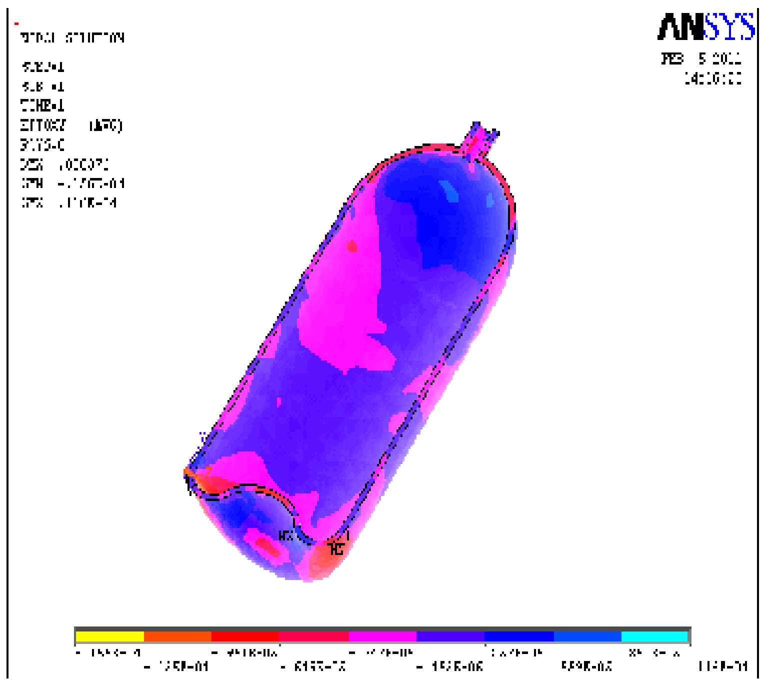



**Figure (8) xy- Shear strain analysis of random fiber glass at pressure 0.9**

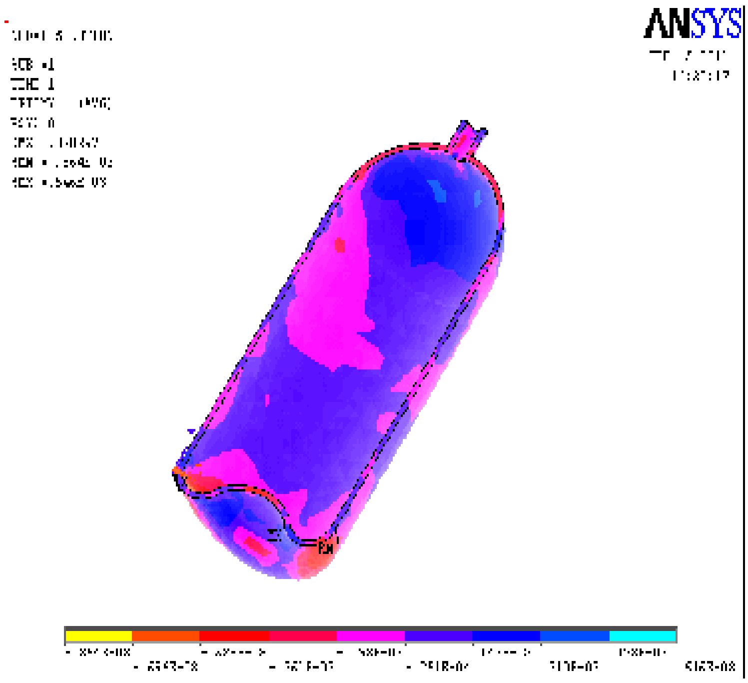



Figure (9) xy- Shear strain analysis of random fiber glass

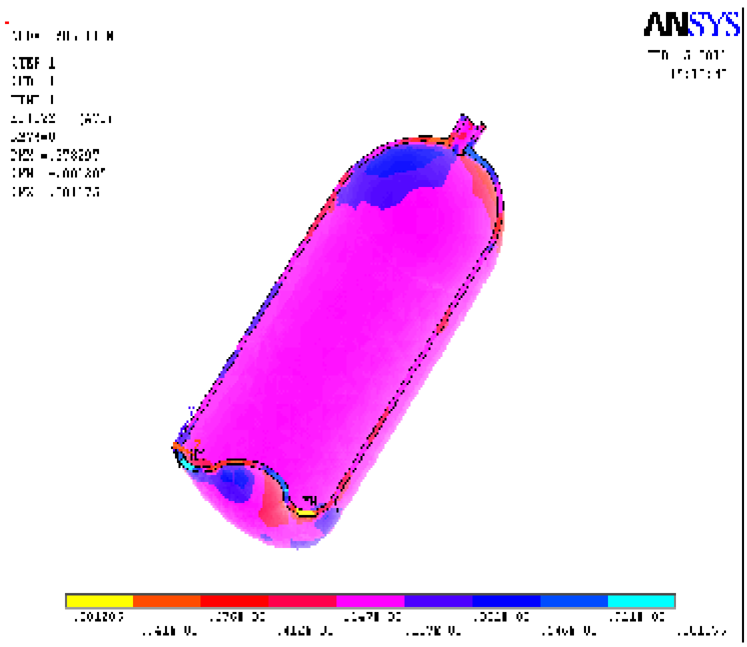



Figure (10) yz- Shear strain analysis of random fiber glass at pressure 5 $N/mm^2$

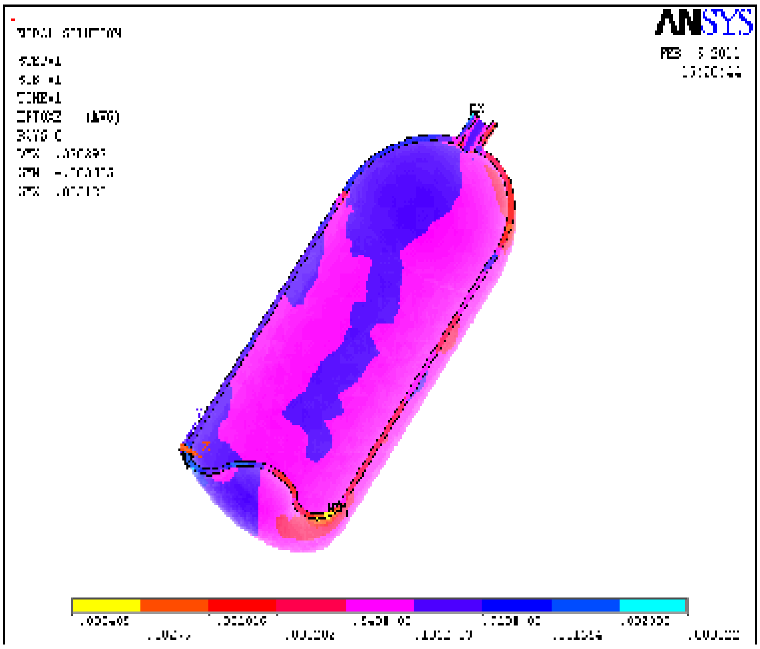


**Figure (11) xz- Shear strain analysis of random fiber glass at pressure 5 N/mm$^2$**

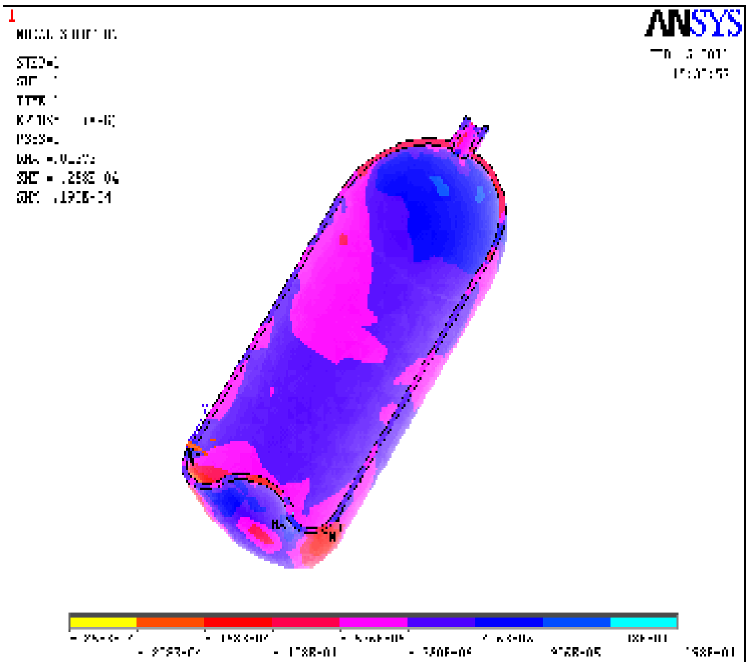


**Figure (12) xy- Shear strain analysis of fiber glass orientation with 45 degree at pressure 0.9 N/mm$^2$**

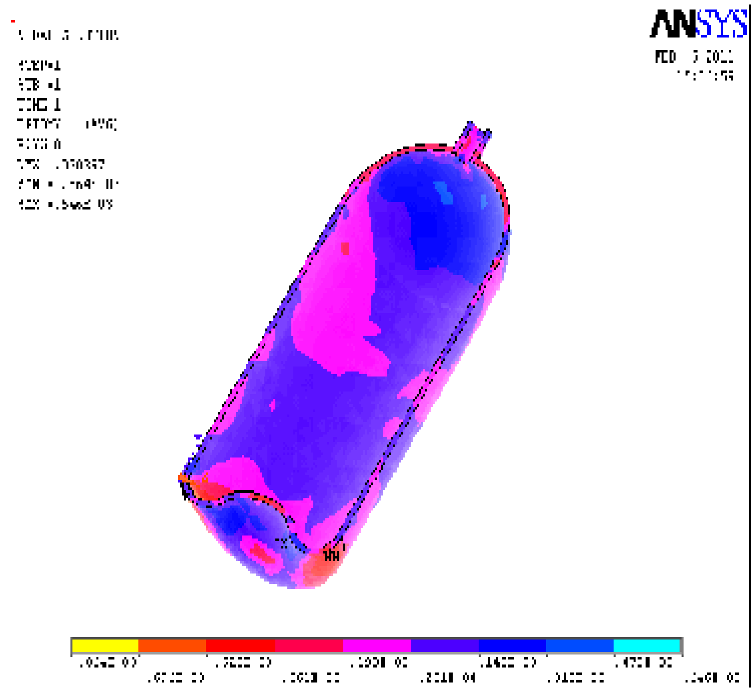


Figure (13) xy- Shear strain analysis of fiber glass orientation with 45 degree at pressure 5 N/mm$^2$

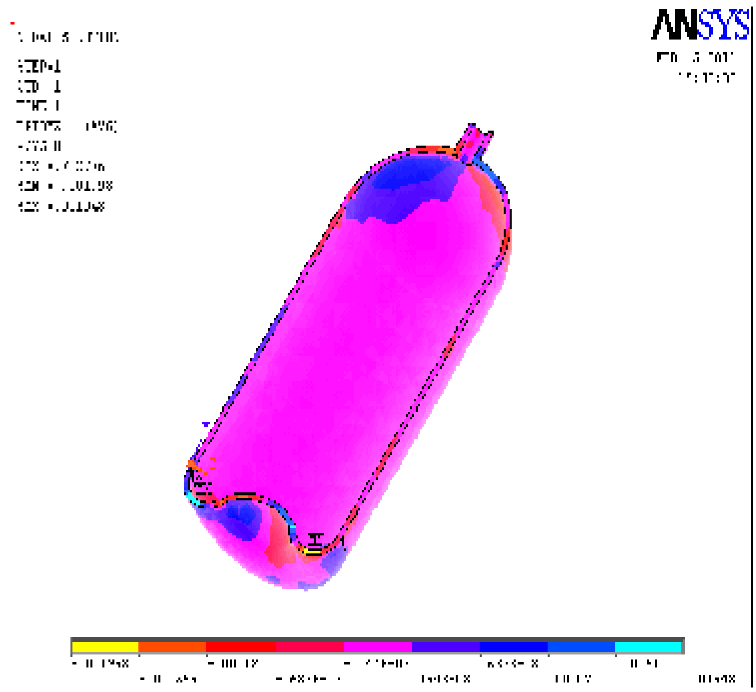


Figure (14) yz- Shear strain analysis of fiber glass orientation with 45 degree at pressure 5 N/mm$^2$

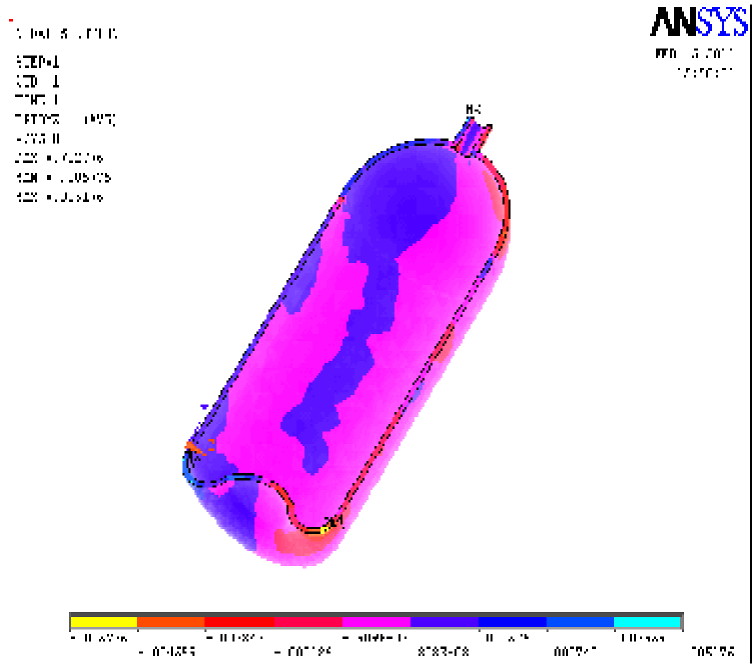



**Figure (15) xz- Shear strain analysis of fiber glass orientation with 45 degree at pressure 5 N/mm$^2$**

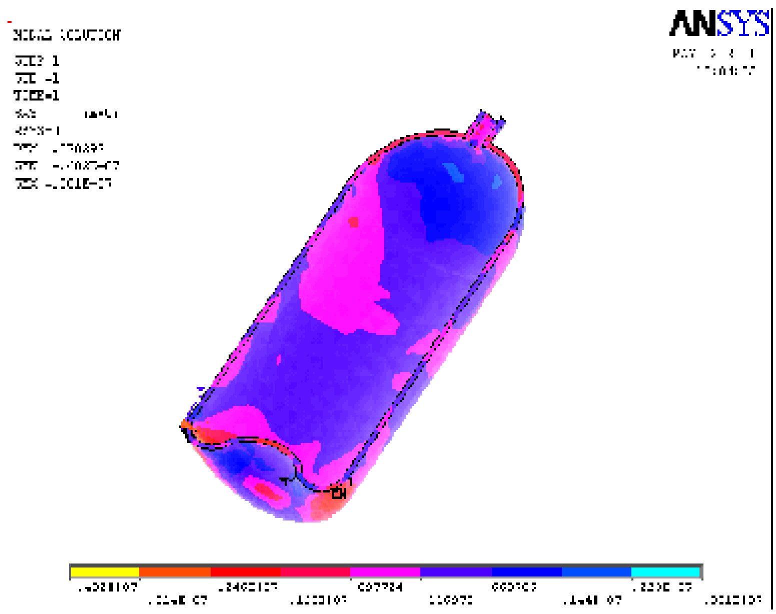



**Figure (16) xy- Shear stress analysis of random fiber glass at pressure 5 N/mm$^2$**

## Appendix (A)

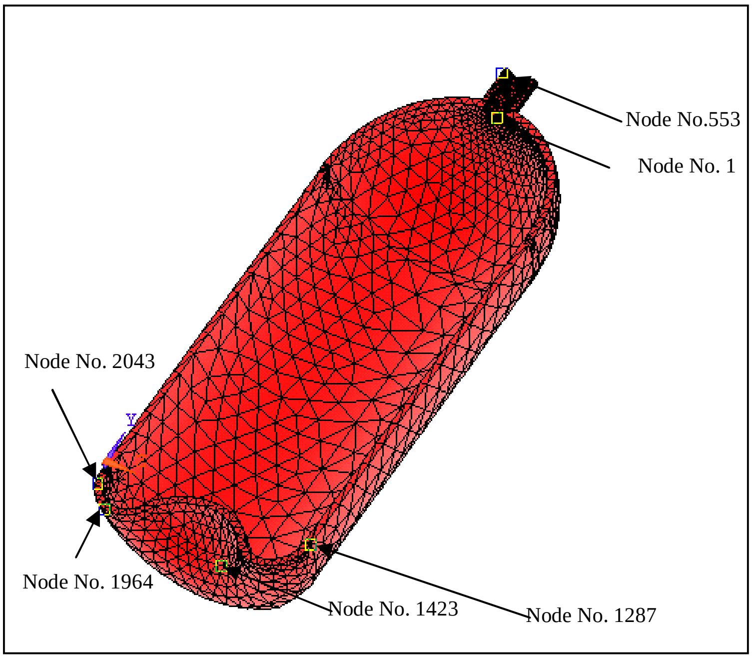
**The minimum and maximum values of xy-shear strain at pressure (0.9 MPa, 3MPa and 5 MPa) of composite material reinforced with random fiber glass are shown in the following tables.**

**Table (A-1) The minimum values of xy-shear strain at 0.9 MPa**

| NODE | 65 | 1290 | 207 | 1436 | 1979 | 1981 |
|---|---|---|---|---|---|---|
| VALUE | -0.61919E-04 | -0.44227E-04 | -0.37602E-04 | -0.15551E-04 | -0.20002E-04 | -0.62721E-04 |

**Table (A-2) The maximum values of xy-shear strain at 0.9 MPa**

| NODE | 2043 | 1987 | 1 | 1423 | 1964 | 553 |
|---|---|---|---|---|---|---|
| VALUE | -0.14153E-04 | -0.19752E-04 | 0.13228E-04 | 0.11627E-04 | 0.20176E-04 | 0.56161E-04 |



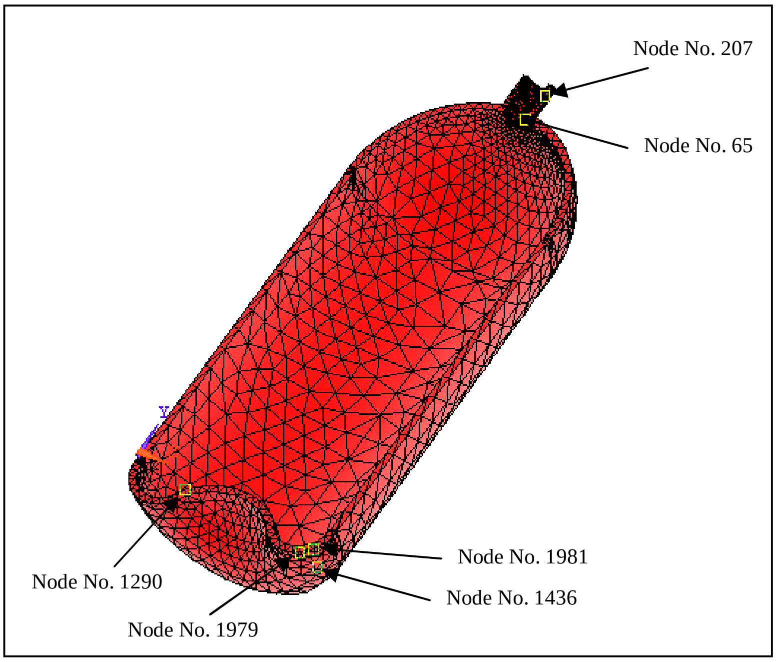

**Figure(A-1) The concentration of maximum values of xy-shear strain at shown nodes numbers of composite material reinforced with random fiber glass**

**Table (A-3) The minimum values of xy-shear strain at 3 MPa**

| NODE | 65 | 1290 | 207 | 1436 | 1979 | 1981 |
|---|---|---|---|---|---|---|
| VALUE | -0.20640E-02 | -0.14742E-02 | -0.12534E-02 | -0.51838E-03 | -0.66672E-03 | -0.20907E-02 |

**Table (A-4) The maximum values of xy-shear strain at 3 MPa**

| NODE | 2043 | 1987 | 1 | 1423 | 1964 | 553 |
|---|---|---|---|---|---|---|
| VALUE | -0.47175E-03 | -0.65840E-03 | 0.44095E-03 | 0.38756E-03 | 0.67254E-03 | 0.18720E-02 |




**Figure(A-2) The concentration of minimum values of xy-shear strain at shown nodes numbers of composite material reinforced with random fiber glass**

**Table (A-5) The minimum values of xy-shear strain at 5 MPa**

| NODE | 65 | 1290 | 207 | 1436 | 1979 | 1981 |
|---|---|---|---|---|---|---|
| VALUE | -0.34400E-02 | -0.24571E-02 | -0.20890E-02 | -0.86396E-03 | -0.11112E-02 | -0.34845E-02 |

Table (A-6) The maximum values of xy-shear strain at 5 MPa

| NODE | 2043 | 1987 | 1 | 1423 | 1964 | 553 |
|---|---|---|---|---|---|---|
| VALUE | -0.78626E-03 | -0.10973E-02 | 0.73492E-03 | 0.64593E-03 | 0.11209E-02 | 0.31201E-02 |

## ***Appendix (B)***

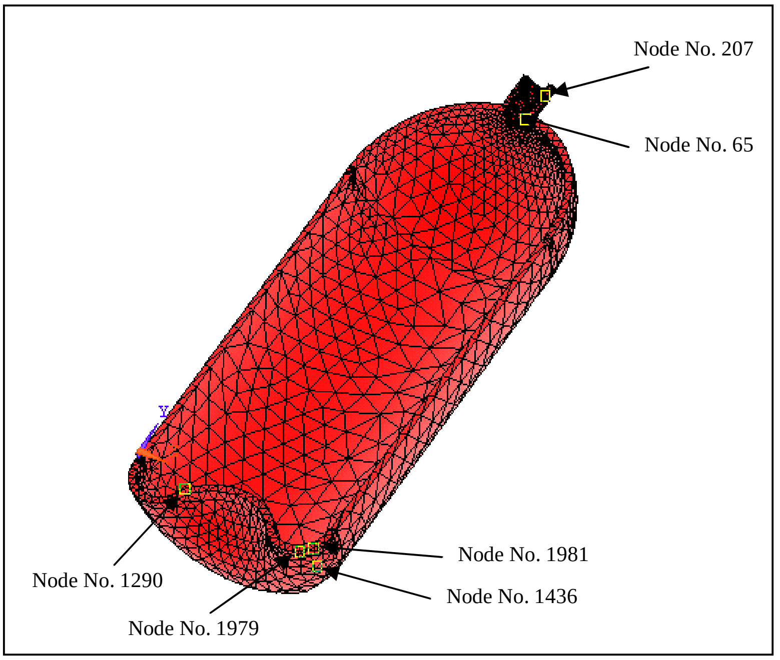
The minimum and maximum values of xy-shear strain at pressure (0.9 MPa, 3 MPa, and 5 MPa) of composite material reinforced with fiber glass with angle $45^o$ are shown in the following tables.

**Table (B-1) The minimum values of xy-shear strain at 0.9 MPa**

| NODE | 65 | 1290 | 207 | 1436 | 1979 | 1981 |
|---|---|---|---|---|---|---|
| VALUE | -0.10265E-03 | -0.73317E-04 | -0.62335E-04 | -0.25780E-04 | -0.33158E-04 | -0.10398E-03 |

Table (B-2) The maximum values of xy-shear strain at 0.9 MPa

| NODE | 2043 | 1987 | 1 | 1423 | 1964 | 553 |
|---|---|---|---|---|---|---|
| VALUE | -0.23461E-04 | -0.32744E-04 | 0.21929E-04 | 0.19274E-04 | 0.33447E-04 | 0.93101E-04 |



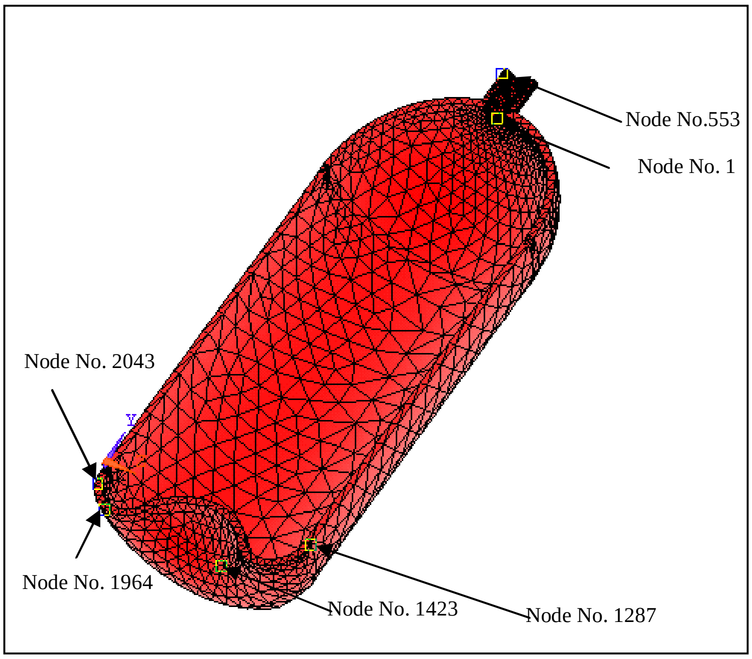

**Figure(B-1) The concentration of minimum values of xy-shear strain at shown nodes numbers of composite material reinforced with fiber glass 45°**

**Table (B-3) The minimum values of xy-shear strain at 3 MPa**

| NODE | 65 | 1290 | 207 | 1436 | 1979 | 1981 |
|---|---|---|---|---|---|---|
| VALUE | -0.34215E-02 | -0.24439E-02 | -0.20778E-02 | -0.85933E-03 | -0.11053E-02 | -0.34658E-02 |

**Table (B-4) The maximum values of xy-shear strain at 3 MPa**

| NODE | 2043 | 1987 | 1 | 1423 | 1964 | 553 |
|---|---|---|---|---|---|---|
| VALUE | -0.78205E-03 | -0.10915E-02 | 0.73098E-03 | 0.64247E-03 | 0.11149E-02 | 0.31034E-02 |




**Figure(B-2) The concentration of maximum values of xy-shear strain at shown nodes numbers of composite material reinforced with fiber glass 45°**

**Table (B-5) The minimum values of xy-shear strain at 5 MPa**

| NODE | 65 | 1290 | 207 | 1436 | 1979 | 1981 |
|---|---|---|---|---|---|---|
| VALUE | -0.57026E-02 | -0.40732E-02 | -0.34630E-02 | -0.14322E-02 | -0.18421E-02 | -0.57764E-02 |

**Table (B-6) The maximum values of xy-shear strain at 5 MPa**

| NODE | 2043 | 1987 | 1 | 1423 | 1964 | 553 |
|---|---|---|---|---|---|---|
| VALUE | -0.13034E-02 | -0.18191E-02 | 0.12183E-02 | 0.10708E-02 | 0.18582E-02 | 0.51723E-02 |