Experimental and Numerical Investigation of Creep Behavior In Isotropic Composites

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ABSTRACT

Creep testing is an important part of the characterization of composite materials. It is crucial to determine long-term deflection levels and time-to-failure for these advanced materials. The work is carried out to investigate creep behavior on isotropic composite columns. Isotropy property was obtained by making a new type of composite made from a paste of particles of carbon fibers mixed with epoxy resin and E-glass particles mixed with epoxy resin. This type of manufacturing process can be called the compression mold composite or the squeeze mold composite. Experimental work was carried out with changing the fiber concentration (30, 40 and 50% mass fraction), cross section shape, and type of composite. The creep results showed that the higher the fiber concentration, the more the creep resistance. Type of fiber plays a very critical role, where carbon/epoxy composite showed much higher creep resistance and also showed much higher modulus of elasticity than the E-glass/epoxy composite. Specimen shape factor noticed to play a very small role. However, square cross sectional area showed slightly higher resistance for creep than the rectangular cross sectional area. This difference is not critical and can be ignored. F.E.M simulation with ANSYS Inc. software was implied and results were compatible with the experimental work with a maximum discrepancy of (17.24%).

KEYWORDS: isotropic composite, creep, mass fraction, squeeze mold composite, ANSYS, fibers.

بحث عملي ونظري حول سلوك ظاهرة الزحف في المواد المركبة الايزوتروبية

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الخلاصة:

ان اختبار الزحف هو احد اهم الفحوصات في وصف المواد المركبة، انه ضروري وحاسم لايجاد الاستطالة على مدى الزمن والوقت المطلوب حتى تفشل فيه هذه المواد. في هذا البحث تم توجيه الطاقات للبحث والتحليل في ظاهرة الزحف على مواد مركبة ذات خواص ايزوتروبية ، ان الخاصية الايزوتروبية تم تحقيقها بصنع مركب جديد النوع مصنوع من عجينة من خليط دقائق الالياف الكاربونية ممزوجة مع الايبوكسي و دقائق الياف الزجاج ممزوجة مع الايبوكسي. هذا النوع من التصنيع يمكن ان يطلق عليه اسم " مركب قالب الضغط" او " مركب قالب الحشر". الجزء العملي من البحث قد تناول هذه الظاهرة مع الاخذ بنظر الاعتبار عدة امور، منها، تغيير نسب الدقائق الوزنية (30,40,50)%، شكل مقطع العينة، ونوع دقائق الالياف المستخدمة. ان نتائج البحث في اختبار الزحف قد بينت ان زيادة نسب تركيز الدقائق تؤدي الى زيادة واضحة في مقاومة المركب للزحف. ايظاً تم ملاحظة الاختلاف الواضح بين نوعية الالياف المستخدمة فمثلاً الياف الكاربون كانت ذات مقاومة اعلى بكثير من نظيرتها الياف الزجاج ، اما بالنسبة لشكل المقطع فقد تبين انه لا يلعب دوراً خطيراً وان العينات ذات المقطع المربع والمستطيل كانت نتائجها متطابقة تقريباً والاختلاف بينهما بسيط جداً ويمكن اهماله تم عمل

نمزذج لجميع العينات التي تم فحصها عملياً باستخدام التحليل العددي (F.E.M) وذلك باستخدام برنامج ال (ANSYS) وقد اظهرت النتائج تطابق كبير بين النتائج العملية وبين ما تم ايجاده نظرياً بهذا البرنامج بنسبة خطأ اعلاها (17.24%).

الكلمات المرشدة: مركب ايزتروبي، الزحف، النسب الوزنية، مركب قالب الحشر، الياف

1. INTRODUCTION

1.1 General

A composite is a structural material which consists of combining two or more constituents. The constituents are combined at a macroscopic level and are not soluble in each other. One constituent is called the reinforcing phase and the one in which is embedded is called the matrix. The reinforcing phase material may be in the form of fibers, particles or flakes. [1]

Creep is the time-dependent deformation which accompanies the application of stress to a material. At room temperatures, apart from the low-melting-point metals such as lead, most metallic materials show only very small creep rates which can be ignored. With increase in temperature, however, the creep rate also increases and above approximately 0.4 T, where T, is the melting point on the Kelvin scale, creep becomes significant. In high-temperature engineering situations related to gas turbine engines, furnaces and steam turbines, etc., deformation caused by creep can be significant and must be taken into account [2]. However, for polymers and composites, heat is not an important factor and creep can occur. [3]
The study case here is isotropic squeezed composite under creep for one hour to study effect of fiber concentration, type of specimen cross section area and type of fiber particles on the behavior of creep. Houshyar et al (2004) [4] studied the effect of continuous fiber concentration on the behavior of creep and for about the same test time in this research, their results came compatible to the ones obtained in this research regarding the fiber concentration part.

Many composite materials are being used today in all sorts of industries such as golf equipments, fishing equipments, car industry, electrical isolators, airplanes and aerospace industry

1.1 Research Objectives:

The aim of this work is to investigate the creep behavior of isotropic composite materials by studying the change in design parameters, loading, material properties, shape factor, mass fraction, and to achieve the above objective, the following steps are followed:

1. Experimental study will be achieved by constructing a creep test to the isotropic CFRP and GFRP composite by applying constant load for short period of time and for values of (2000, 2500 and 3000) N to study the creep behavior for different design parameters.
2. Finite element analysis is required using ANSYS software for the creep test simulation.

2. CREEP THEORY

2.1 The creep test:

The creep test is usually carried out at a constant temperature and under constant load conditions rather than at constant stress conditions. This is acceptable because it is more representative of service conditions. A creep device such as that shown in **fig. 1** is used for this purpose. Each end of the specimen is screwed into the specimen holder, the load is applied by adding weights to the arm and readings are taken at periodic intervals of extension against time, the equipment is often housed in a temperature-controlled room. [2]

2.2 Phenomenology of creep:

The results from the creep tests are plotted in graphical form to produce a typical curve as shown in **Fig.2**. After the initial extension OA which is produced as soon as the test load is applied, and which is not part of the creep process proper (but which nevertheless should not be ignored), the curve can be divided into three stages. In the first or primary stage AB, the movement of dislocations is very rapid. In the secondary stage BC, the work-hardening process of "dislocation pile-up" and "entanglement" are balanced by the recovery processes of "dislocation climb" and "cross-slip". The third or tertiary stage CD coincides with the formation of internal voids within the specimen and this leads to "necking", causing the stress to increase and rapid failure to result. [2]

2.3 Creep Theory

An empirical equation called the Arrhenius-type rate model is used to describe the creep in composite materials

$$\epsilon_{ss}^{0} = \epsilon_{min}^{0} = B\sigma^{n}\exp\left(\frac{-Q}{RT}\right) \qquad \textbf{Eq. (1)}$$

Where n is the stress exponent, Q is the activation energy for creep, R is the universal gas constant and T is the absolute temperature in Kelvin, to determine the various constants in **Eq. (1)** a series of isothermal tests are required. [2]. The isothermal creep test (which is the case of this research) implies that the temperature is to be constant at all times but the stress is not, meaning a three stresses at least must be applied on the test specimens at same constant temperature, this will lead to a change in the Arrhenius-type formula, where the creep law now becomes:

$$\epsilon_{ss}^{0} = \epsilon_{min}^{0} = B\sigma^{n} \qquad \textbf{Eq. (2)}$$

This equation can be linearized by taking logarithms of both sides such that:

$$\log \epsilon_{ss}^{0} = \log \epsilon_{min}^{0} = \log B + n \log \sigma \qquad \textbf{Eq. (3)}$$

Log-log plots of $\epsilon_{ss}^{0} = \epsilon_{min}^{0}$ versus σ often results in a bilinear relation in which the slope, n, at low stresses is equal to one indicating pure diffusion **Fig. 3** [9].

3. EXPERIMENTAL WORK

3.1 materials:

The materials used in this research are:

1. Carbon particles (from chopped carbon fibers) reinforced epoxy resin.
2. Fiberglass (E-glass) particles (from chopped E-glass fibers) reinforced epoxy resin

Typical properties of fibers and resin used are listed in **table 1**

3.2 Compression mold or Squeeze mold method:

Rather than laying up fiber in sheets and impregnating it with resin like the typical fiber manufacturing, compression molding Composite uses a paste of fibers mixed with resin that is squeezed out to make almost any shape. Since the fibers aren't oriented in any particular direction, the finished part is strong all around, having the isotropic property while remaining light. Lamborghini and Callaway (car manufacturers) teamed up together to develop this method on 2010. But since this is a new method that needs special tools and machines which does not exist in Iraq, a simpler and basic method was conducted to manufacture the test specimens; a method that was conducted after long time of trials and errors, the problem was to be able of finding a method to manufacture any shape with perfect smoothness, no gaps as possible and with the fastest time possible. The mold used to manufacture the specimen was made of wood with smooth surfaces inside. It is also known that creep at high stresses results in n greater than one which indicates a power law creep [5]

The following procedure explains how the mold must be made and used:

- The mold must be taped and oiled with car oils; the tape makes the surface of the specimen extremely smooth and also to be insulating layer between the mold and the specimen, while the car oil makes the operation of removing the specimen from the mold very easy.

- The cover of the mold must be closed after step (no. 1) from all direction leaving the narrow side opened, where the paste is to be compressed through this part as shown in **fig.5**
- After the calculations of fiber to matrix ratio are completed and the paste is ready, the paste is to be injected through the narrow part of the mold with a stick with continuous compression of the paste as shown in **fig. 6**, once the paste is all inside the mold, a small piece of wood with the same width and thickness of the opened side and with specified length is to be placed and then hammered to close the gap and compress the paste inside the mold.

3.3 Tensile test:

The tensile test specimens were manufactured according to ASTM D 3039 [6] (**fig.7** and **fig.8**). Young's modulus were obtained from the tensile test and listed in **table 2** , to be used as input data in ANSYS software.

3.4 Poisson's ratio:

Poisons ratio was measured for each tensile specimen and calculated, see **table 3,** these results are to be used as input data in ANSYS software.

3.5 Creep testing device

Since there was no creep device available in the nearby universities to be used for this specific study, where high load could be applied and the grips to be jaws and not hooks, a creep device was manufactured specially for this research. The device of test was designed then manufactured Similar to another model (MT 040). The model was designed for small specimens, therefore the device was to be taken in consideration the big sizes and strength of the tested specimens. Therefore a bigger size and a stronger device was manufactured not only to test creep but to be adjustable to work as a buckling device as well if needed, and to have the ability of applying loads of (up to 3000 N). All the parts of device were manufactured from carbon steel No. 45 to withstand the high loads. The schematic drawing for the device is shown in **fig. 1,** the weights of the device and digital dial gauge were calibrated in the ministry of planning / central system for calibration

3.6 Testing Procedure:

3.6.1 Creep specimens

Creep test specimen were manufactured according to ASTM D-638 [7] , but with different thickness, because one of the main objects of this research is to study the effect of cross sectional area shape on the creep test, In ASTM D 2990 [8] , (the standard for creep test) stated that "test specimens may be made by injection or compression molding with any particular shape if the object of test is to obtain design data" which is the case here, so the exact specimen details were used from the ASTM standard taking in consideration the same ratio between each length.

Test specimen was made with the following factors:

1. Two cross sectional area shape (square) and (rectangular) with maintaining the same effective area

2. Two Types of composites

- Carbon particles / epoxy resin
- E-glass particles / epoxy resin

3. Three different mass fraction (30 – 40 – 50) % wt/wt and for the two composites.

The Creep specimen dimensions are listed in **table 4** and shown in **fig. 9**

The specimens were compressed using a wooden mold as shown in **fig. 10**

Steps of manufacturing the creep specimens (letters represents steps in **fig. 10**

More details of manufacturing the creep specimen can be found in Ref. [10]

3.6.2 Conditioning

Test specimens were conditioned at 25 C^0 for (48) hours after manufacturing and then it was preconditioned in the test environment for (48) hours prior to testing as recommended in ASTM D-2990.

3.6.3 Final Specimens

The creep test specimens were all labeled and were ready to be tested. There were (36) specimens manufactured overall for the creep test, (18) specimens for each composite (**fig. 12** and **fig.13)**

3.6.4 Testing

- The conditioned specimen was mounted by the device grips and carefully aligned so that no eccentric misalignment would cause bending, each side of grips was screwed with the same amount so that the specimen is to be tightened at the entire surface to avoid slipping
- The digital dial gauge was adjusted and set to Zero.
- The full load was applied within a period not to exceed 5 seconds
- The timer was lunched at the start of the loading.
- Since the test is less than (1000) hours then the intervals were taken for each 5 minutes, to take readings of deformation for period of (60) minutes according to ASTM D-2990.
- A special document was created for each specimen to record exact data such as temperature, relative humidity, specimen dimensions, specimen weight; deflection with time, all these data was recorded prior to the testing process except for the deflection data, where all these data is required according to the ASTM D 2990.
- Once the period of test was completed, the load was removed rapidly and smoothly, the dial gauge and timer were shut off
- Calculations of other factors and graphing were employed for the final results.

3.7 Calculations of the creep constants and factors

Once the creep test process is completed for all specimens, the creep factors and constants was calculated and listed in **table 5**

4. RESULTS AND DISCUSSIONS

4.1 Experimental Results

When all Creep data were obtained, a graphical plot was drawn for each case of square shape compared to the rectangular shape, and each percentage compared to the other, and finally compared at three loads. The following graphs show the creep curves for this study, where it represent a creep curve at a secondary stage as planned from the beginning. Since the employed creep equation is only valid for secondary creep, and this was done by applying high stresses above the elastic limit, where this action leads to skipping the primary stage and jump straight to the secondary creep. There were two types of graphs plotted. One for a certain percentage at the three loads, and other one for one load with three percentages. Two of the graphs that represent a plot of a certain percentage at three loads are presented. Figures that represented a certain percentage at three loads (six graphs) (such as **fig 14** and **fig. 15**) showed graphical results of creep of both carbon particles reinforced epoxy and E-glass particles reinforced epoxy at three different loads in each figure, and with two cross sectional areas. The straight line represents the square shaped cross section specimen while the dotted line represents the rectangular shaped cross section specimen. It is shown when the mass fraction of composite increases, the composite tends to be more creep resistant in an obvious way. However the slope of the curves are not increasing in a steady behavior, meaning, each curve is increasing with different slope and the distance between curve and another are not constant in two cases only. For example the curves distance from each other (the amount of increase in creep resistance) are increasing almost identically in all six graphs except of one of them, this could be because of the method of curve fitting used to draw the graphs, other possible reason might be due to the environmental effect, where the specimens were tested at a little different temperature and relative humidity, but in general, the creep resistance was increased clearly with the increasing of the mass fraction. On the other hand, the behavior of the two different shapes was noticed to be negligible. The curves show that no critical difference was found between the two different shapes and are almost identical, as for the curves that are not identical, this is because of the curve fitting, where the amount of displacement that was gathered from both shapes was almost the same, but in different intervals. Meaning, for example, at 10 minutes a square shape specimen might have a displacement of 0.15 mm where the rectangular specimen has 0.18 mm of displacement, but when the final extension is reached at 60 minutes the square shaped specimen might have 0.3 mm displacement while the rectangular shaped specimen extension is 0.31 mm. It is obvious that the total extension is what matters. In this case it is not critical difference between both shapes. But, due to the different intervals, the curve fitting was different in some cases which gave a misleading idea that there is a critical different between both shapes, but in reality there aren't any different that can be taken in consideration. Also, graphs of the three percentages at a certain load was plotted as those shown in **fig.16** and **fig.17** which represented a certain load for the three mass fraction percentages (six graphs also) showed graphical results of creep for both carbon particles reinforced epoxy and E-glass particles reinforced epoxy at three different percentages in each figure. Each figure represents creep resistant at one load with three different mass fraction percentages. It is shown that with the increase of mass fraction the composite tends to be more creep resistance. The property of creep resistance from each percentage to another in the same composite is contrast. Fiberglass (E-glass) composites show constant increase in each percentage, that is almost increasing the same from one percentage of mass fraction to another. While in carbon composites, it is shown that the increasing in creep resistance from (40%) mass fraction to (50%) is twice of that from (30%) to (40%) mass fraction, this is because of the density of these fibers. E-glass fibers has a density of 2 gr/cm^3, and very low surface area as noticed with the manufacturing process. While carbon fibers have a density of 1.55 gr/cm^3 and very high surface area which was obvious when the specimens were manufactured. In other words, changing the mass fraction for e-glass composite makes a little difference in volume fraction while carbon fiber composites make a noticed difference in volume fraction. That is because of the density and surface area as mentioned above. This was noticed also when tensile test was made for the specimens, e-glass composites showed less improvement in modulus of elasticity than the carbon particles composite, where the modulus was improving strongly, which explain the reason of this behavior in the graphs above.

4.2 F.E.M (ANSYS) Results:

The specimen was meshed using SOLID186, a higher order 3-D 20-node solid element that exhibits quadratic displacement behavior [11]. Meshing was very fine, exactly (291904) nodes or (205235) elements.

Figures 18 and **19** are samples of the numerical solution that was obtained using ANSYS software. Where **fig.18** represents a square shaped specimen, while **fig.19** represents a rectangular shaped specimen.

It is noticed that the creep strain is expanding from low level at edges to high level at the middle of the specimen, which support the experimental work, where the highest creep strain in ANSYS is at the same part of the specimen that was assumed in the experimental work, which is the gauge length. All creep specimens in ANSYS showed the same creep strain distribution behavior in both square and rectangular specimens which supports the discussion earlier that is; both square and rectangular specimens had almost the same creep strain for the same composite at the same load. This means that the load distribution is the same in all specimens and hence no difference between the two specimens can be noticed at the same stress distribution, same volume and same materials that is made of. This will leave the only reason that was explained earlier in the experimental results which is the curve fitting issue; on the other hand ANSYS results also showed that there is no critical difference in creep strain between both square and rectangular specimens for the same composite at the same conditions. But, if results are to be compared for slight differences, then the square shaped specimen showed a slightly higher resistance to creep than the rectangular shaped specimen.

Discrepancy between Experimental and F.E.M solution (ANSYS) was between (0 – 17.24) % Maximum. This discrepancy can be due to many different factors, such as environment. Humidity for example plays a critical role in experimental work and continuously changing, while ANSYS software doesn't take it in consideration and even if it has been taken as a factor it would be constant and not changing. Other reason is may be due to the method of specimen fixing, in reality the specimen might have a slight misalignment or very small amount of slipping that can't be seen, while this type of problems doesn't exist in ANSYS.

5. – CONCLUSIONS

1. The creep results showed that when the mass fraction increases, the creep resistance increases. This means that mass fraction plays a critical role in the mechanical properties of the material. For example, a (30%) wt/wt mass fraction of carbon fiber particles reinforced epoxy at 2000 N showed a creep strain of (0.38%), then fiber concentration was increased to (40% wt/wt) and the creep strain reduced to (0.26%), while a (50%) wt/wt showed a creep strain of (0.21%)
2. Type of fiber plays a very critical role, where Carbon fibers showed much higher creep resistance and also showed much higher modulus of elasticity than the E-glass fibers. Therefore when it comes to strength and higher creep resistance, carbon fiber is most recommended, but E-glass is not that bad when the cost factor is to be taken in consideration, where the carbon fibers cost 4 times more than the E-glass fibers for the same amount.
3. Specimen shape factor is noticed to play a very small role, square cross- sectional area showed slightly higher resistance for creep than the rectangular cross-sectional area. This difference is not critical and can be ignored. For example, a (40%) wt/wt CFRP square shaped at 2500 N specimen showed a creep strain of (0.59%) while the rectangular shape of the same type of specimen showed a creep strain of (0.62%).
4. In general it was found that the creep resistance increased in CFRP from [30% to 40%] by (34.17%), and increased from [30% to 50%] by (49.74%). As for the GFRP, the creep resistance increased from [30% to 40%] by (13.01%), and increased from [30% to 50%] by (28.79%).

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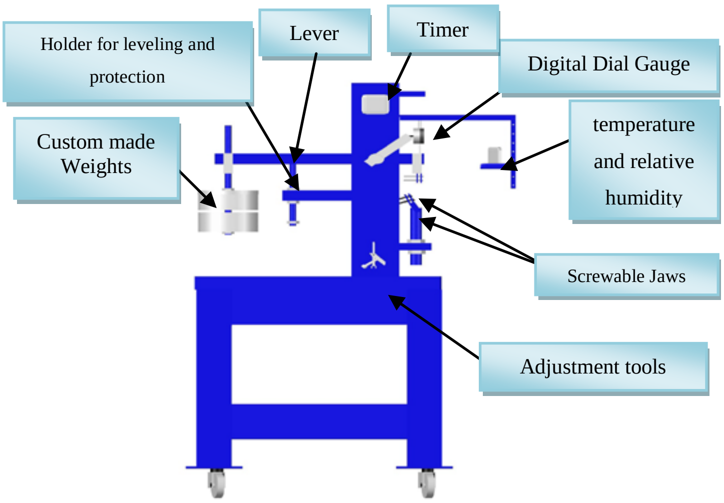

Fig.1 - Creep device.

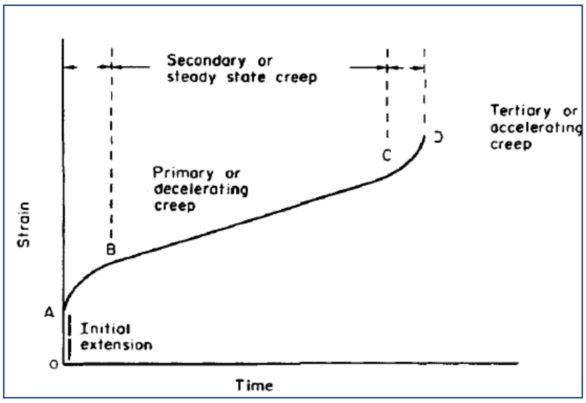

Fig.2 - Typical Creep Curve. **[2]**.

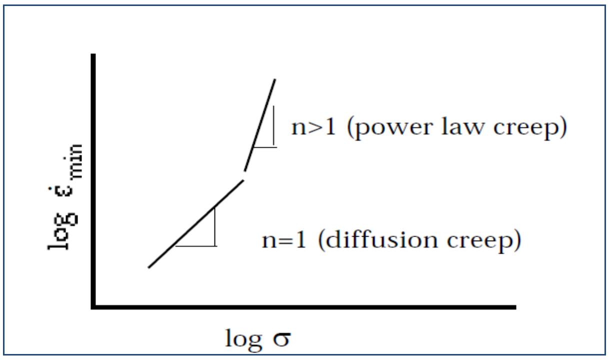

Fig.3 - Log-log plot of ϵ^{0}_{min} versus σ .

Table 1: Typical properties of fibers and resin used in this research.

Item	E	Density	σ_{ult}
CFRP	150 – 180 GPa	1.55gr./cm^3	4137 MPa
GFRP	72.40 GPa	2 g/cm3	3447 MPa
Epoxy	-	1.1 ± 0.05	≥ 25 MPa

CFRP: Carbon fiber (particles) Reinforced Epoxy

GFRP: Glass fiber (particles) Reinforced epoxy

Fig.4 – The mold.

Fig.5 - (The process of enclosing the mold).

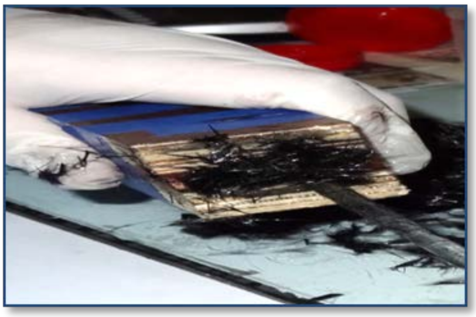

Fig.6 – The injection process.

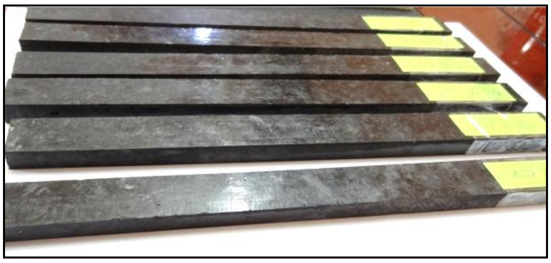

Fig.7 – CFRP tensile specimens

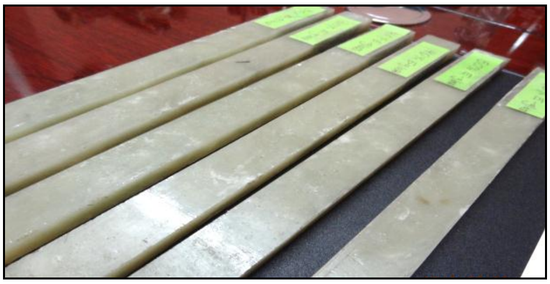

Fig.8 – GFRP tensile specimens

Table 2 – Young's modulus for Composites

Item	Young's modulus (Gpa)
30 % CFRP wt/wt	13.3
40 % CFRP wt/wt	18.3
50 % CFRP wt/wt	23.3
30 % GFRP wt/wt	4.6
40 % GFRP wt/wt	7.46
50 % GFRP wt/wt	10

Table 3 – Poisson's ratio for Composites

Item	Poisson's ratio
30 % CFRP wt/wt	**ν = 0.229**
40 % CFRP wt/wt	**ν = 0.211**
50 % CFRP wt/wt	**ν = 0.207**
30 % GFRP wt/wt	**ν = 0.262**
40 % GFRP wt/wt	**ν= 0.256**
50 % GFRP wt/wt	**ν = 0.2**

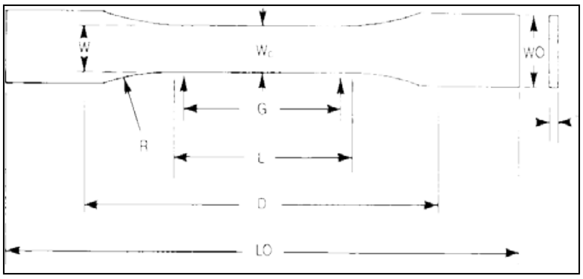

Fig.9 – Dimensions of creep specimen

Table 4 – Creep specimen dimensions

Symbol	Value
W—Width of narrow section	10 mm for square shape 14.28 mm for rectangular shape
L—Length of narrow section	38 mm
WO—Width overall,	15 mm for square shape 20 mm for rectangular shape
LO—Length overall	100 mm
G—Gage length	34 mm
D—Distance between grips	69 mm
T	10 mm for square shape 7 mm for rectangular shape

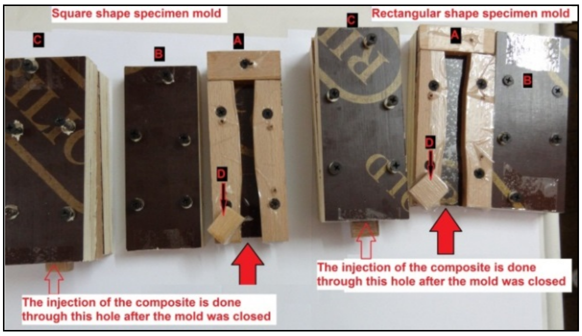

Fig.10 – Creep specimens mold shape and Procedure

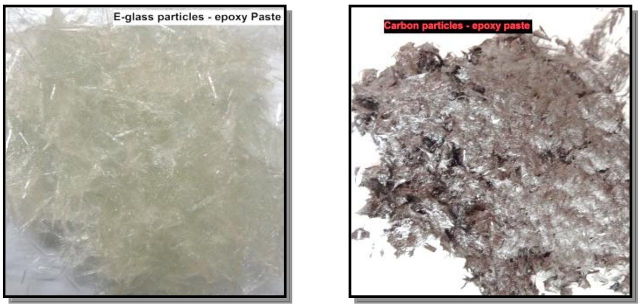

Fig.11 – Carbon/epoxy paste AND E-glass/ Epoxy paste.

Fig.12 – Carbon/epoxy Creep specimens

Fig.13 - E-glass/epoxy Creep specimens.

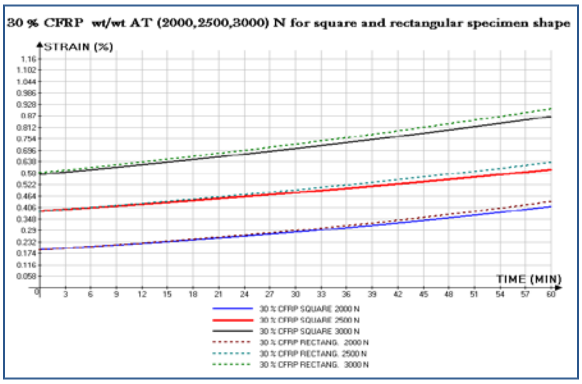

Fig.14 - Plot of 30% CFRP at three loads**.**

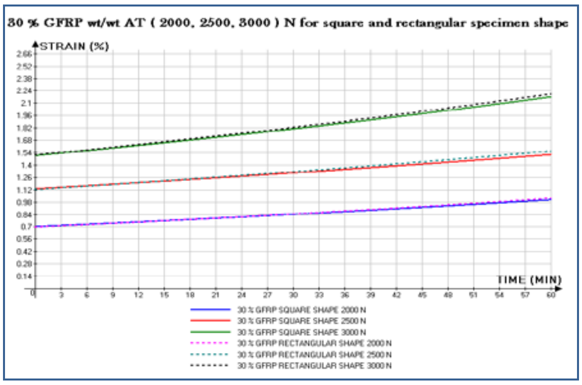

Fig.15 - Plot of 30% GFRP at three loads**.**

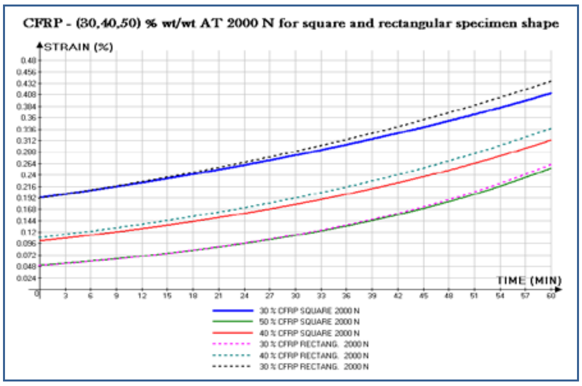

Fig.16 - Plot of 2000 N load for all three CFRP percentages.

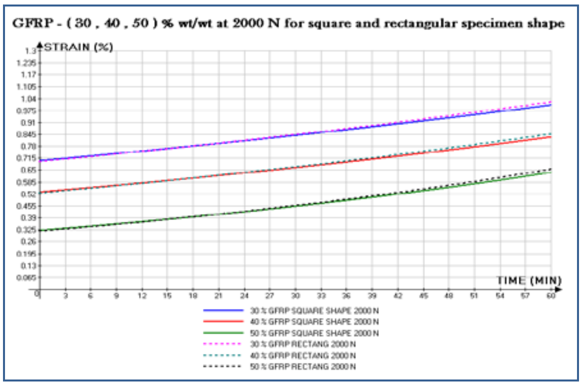

Fig.17 - Plot of 2000 N load for all three GFRP percentages.

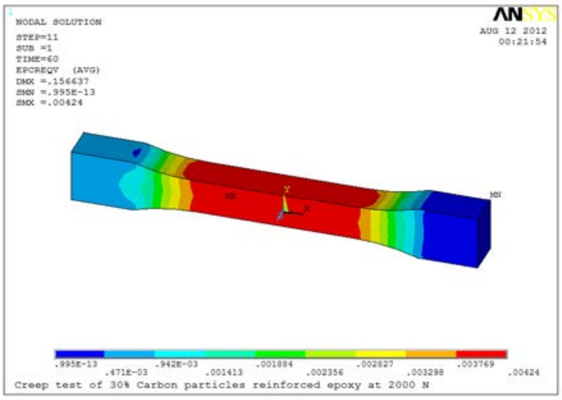

Fig.18 - Creep test of 30% Square Carbon/epoxy at 2000 N

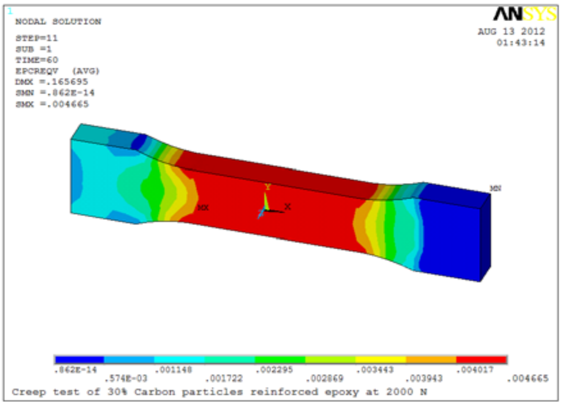

Fig.19 - Creep test of 30% rectangular Carbon/epoxy at 2000 N

Table 5 – Creep constants

Item	n	B
30 % CFRP SQU.	1.98	$1.67*10^{-07}$
30 % CFRP REC.	1.86	$2.39*10^{-07}$
40 % CFRP SQU.	1.73	$3.53*10^{-07}$
40 % CFRP REC.	1.57	$5.71*10^{-07}$
50 % CFRP SQU.	1.41	$9.22*10^{-07}$
50 % CFRP REC.	1.27	$1.40*10^{-07}$
30 % GFRP SQU.	1.94	$1.88*10^{-07}$
30 % GFRP REC.	1.89	$2.18*10^{-07}$
40 % GFRP SQU.	2.3	$6.41*10^{-08}$
40 % GFRP REC.	2.22	$6.41*10^{-08}$
50 % GFRP SQU.	2.62	$6.41*10^{-08}$
50 % GFRP REC.	2.5	$6.41*10^{-08}$