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Dynamic Behavior of the Hybrid Composite Materials Subjected to Tensile Stresses at High Strain Rate

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Abstract:

This study aims to the design and manufacture of a split Hopkinson tension bar apparatus. The dynamic tensile behavior of hybrid composite materials at high strain rates is investigated. The most important characteristic of split Hopkinson apparatus is a (gun system) responsible of dynamic tension process depending on a spring system in its operation. Two groups of materials were tested at different strain rates; first group is woven fiber glass/ epoxy composite, woven carbon fiber/ epoxy composite and hybrid woven glass/ woven carbon epoxy laminates. The experimental results for the first group showed that the values of maximum stress, specific absorbed energy and kinetic energy increased approximately 12.4 %, 11% and 10% respectively for woven fiber glass/ epoxy composite when it's hybridized with woven carbon fiber/ epoxy composite. In the second group using woven jute fiber as a natural material which have low cost and is environmental friendly, when these materials are hybridized with glass fibers and carbon fibers resulted in improves of the tensile properties. When woven jute fiber hybridized with glass fibers the value of maximum stress, absorbed energy and kinetic energy increase by approximately 38.33%, 38% and 55 % respectively. On the other hand hybridization of woven jute fibers with woven carbon fibers lead to increase in the values of maximum stress, absorbed energy and kinetic energy approximately 43%, 44% and 68% respectively. Based on experimental results the modulus of elasticity is increased with increasing the strain rates. The first group yielded higher properties than the second group. Also the effect of stacking sequence on tensile test has been investigated experimentally. Static tensile test carried out for comparison of dynamic test results and assessment of these results analytically by using Johnson-Cook constitutive model.

***Key Words:** Dynamic behavior, Hybrid composite materials, High strain rate, Split Hopkinson tension bar.*

السلوك الديناميكي للمواد المركبة الهجينة المعرضة لاجهادات شد بمعدلات انفعال عالية

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الخلاصة:

هذه الدراسة تهدف الى تصميم وتصنيع جهاز عمود هوبكنسون المجزء لقياس الشد الديناميكي و التحقق من سلوك الشد الديناميكي للمواد المركبة الهجينة ولمعدلات انفعال عالية. اهم ما يميز جهاز عمود هوبكنسون المجزء هو (منظومة الاطلاق) المسؤولة عن عملية احداث الشد الديناميكي لانها تعتمد في عملها على منظومة النابض. تم اختبار مجموعتين من المواد وبمعدلات انفعال مختلفة، تضمنت المجموعة الاولى الياف زجاجية محاكة، الياف كاربونية محاكة و مادة مركبة هجينة من الالياف الزجاجية المحاكة والالياف الكاربونية المحاكة. اظهرت نتائج اختبارات المجموعة الاولى ان قيم كل من الاجهاد الاعظم، طاقة الامتصاص النوعية والطاقة الحركية تزداد تقريبا بنسب٤ , ١٢ %، ١١ % و ١٠ % على التوالي للالياف الزجاجية عندما تهجن مع الالياف الكاربونية. في المجموعة الثانية تم استخدام الياف الجوت المحاكة كمادة طبيعية ذات كلفة واطئة وصديقة للبيئة، عندما تهجن هذه المادة مع الالياف الزجاجية المحاكة والياف الكاربون المحاكة يؤدي الى تحسن بخواص الشد. تزداد قيم كل من الاجهاد الاعظم، طاقة الامتصاص النوعية والطاقة الحركية تقريبا بنسب ٣٨,٣٣ %،٣٨ % و ٥٥ % على التوالي عندما يتم تهجين الياف الجوت المحاكة مع الالياف الزجاجية، من ناحية اخرى تهجين الياف الجوت المحاكة مع الياف الكاربون المحاكة يقود الى زيادة في قيم الاجهاد الاعظم، طاقة الامتصاص النوعية، الطاقة الحركية تقريبا بنسب ٤٣ %، ٤٤ % و ٦٨ % على التوالي. استنادا الى نتائج الاختبارات لوحظ بان معامل المرونة يزداد بازدياد معدلات الانفعال، المجموعة الاولى لها مواصفات اعلى من المجموعة الثانية، كذلك تم التحقق عمليا من دراسة تأثير تسلسل الطبقات على الشد. تم اجراء اختبار الشد الستاتيكي لغرض مقارنته مع نتائج اختبار الداينمك و تقييم النتائج تحليليا باستخدام نموذج جونسون كوك.

1. Introduction:

The split Hopkinson bar (SHB) system have been widely used in investigating the behavior of materials under high strain rate loading above about 200 s^{-1} [1].The Hopkinson bar apparatus was first suggested by Bertram Hopkinson in 1914 [2], as a way to measure stress pulse propagation in a metal bar. In 1949 H.Kolsky [3], refined Hopkinson's technique by using two Hopkinson bars in series, to determine the dynamic behavior of several materials (polythene, rubber, PMMA, copper and lead). A version of the kolsky bar system that is effective in tension was developed in the 1960 s [4]. The basic principle of this system is identical to the compression system, except that a method for generating a tensile wave must be used, and special tension grips are required for the specimen. There are two basic approaches to generate a tensile wave in input bar. The first approach, known as an impact-tension approach, consists of firing a tubular projectile at flange at the end of a bar, thereby generating a tensile wave within the bar. The second, and less common, approach consists of storing a large tensile strain within a section of a bar and then suddenly releasing it is so as to generate a tensile wave (this is known as the direct-tension approach). Most of the previous researches indicate the use of split Hopkinson tension bar to test a variety of materials, among those materials are the hybrid composite materials. Hybrid composites are more advanced composites as compared to conventional FRP composites [5]. Composite containing a combination of different fiber types can be referred to as hybrid composites. The advantages of hybrid composite material are offer better flexibility in the selection of fiber and matrix materials which helps in better tailoring of the mechanical properties, better wear resistance and low thermal expansion coefficient. An example of a generic lay-up hybrid can be seen in **Figure (1).** [6].

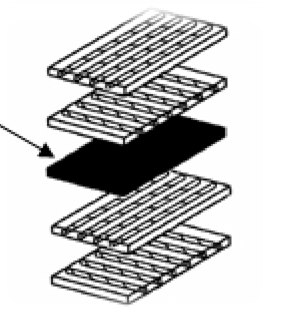


Fig .(1) Generic Hybrid Composite [6]

W.J.Kang, S. S. Cho and H. Huh [7] used a new split Hopkinson bar apparatus specially designed for the dynamic tensile test of sheet metals. The experiments provides stress-strain curves for strain rates ranged from 2500 to 5000/sec. H. Huh et.al. [8]performed a high strain rate tensile tests using SHTB for auto-body sheet metals in order to construct their appropriate constitutive models for use in crash-worthiness evaluation. Mohd Shahiddin Suhadi et.al. [9] investigated the effect of high strain rate loading on the tensile strength for mild steel by using Hopkinson bar technique. In this test mild steel specimen has been impacted at series of 2.5 m and 2.9 m height using tensile split Hopkinson pressure bar apparatus. Woven-carbon, woven-glass and hybrid woven-carbon/woven-glass epoxy laminates have been prepared and tested in tension at quasi-static and an impact rate of strain by J.Harding et.al [10]. K.Mohamed Kaleemulla and B.Siddeswarappa [11]investigated the fabric-reinforced hybrid composite laminates with different volume fraction of the constituent materials; epoxy resin, plain-woven glass fabric and textile satin fabric. Impact behavior and fracture toughness of the laminates were investigated. A preliminary study on hybrid and non-hybrid composite were presented by R.T.Durai Prabhakaran et.al. [12]. Materials used in this study include commercially available epoxy resin. The reinforcement materials used are commercially available carbon / glass hybrid fabric, carbon fiber and glass fiber roving. Yuanxin Zhou et.al. [13] investigated the dynamic and quasi-static tensile behavior of carbon fiber and unidirectional carbon fiber reinforced aluminum composite. The complete stress-strain curves of fiber bundles and the composite at different strain rates were obtained. An experimental and analytical investigation for the behavior of E-glass fiber reinforced composite hybridized with a layer of Kevlar 29 fiber, under high velocity impact were presented by R.J.Muhi et.al. [14]. The experimental work includes the placement of the Kevlar layer at four different locations to verify the effects of the stacking sequence on the impact behavior. A banana fiber and silica powder reinforced composite materials is developed by Singh V.K et.al [15] scanning electron microscopy shows that banana fibers are well dispersed in the resin matrix. Soma Dalbehera and S.K.Acharya [16] investigated a new hybrid composite with epoxy as a resin and reinforcing both bio waste (jute) and traditional filler (glass) as a continuous layered mat composites were used by keeping the position of glass and jute fabric as (0˚-90˚) and (45˚-45˚) for all stacking sequences.

2. Experimental Work:

2.1 Experimental Set-up:

In this study the split Hopkinson tension bar is designed for the examination of the dynamic behavior of various materials at high strain rates. It consists of a gun system, incident, transmitted and striker bars, grips, the supports, fixing and data acquisition system that consist of: four strain gages (foil type, 120 Ω, gage factor = 2) bounded on the incident and transmitted bars, Wheatstone bridge, digital oscilloscope and personal computer. The operating of the gun system depends on the spring force instead of pressure force that generated from gas in the gas gun systems used in most devices. This allowing flexibility for testing, easy operating mechanism and choosing the required velocity for the test. The SHTB apparatus is schematically shows in **Figure (2).** The tension bars are 20 mm in diameter and 1500 mm long. The striker bar has diameter and length, 20 mm, 640 mm respectively. The incident, transmitted and striker bars are all made of 410 stainless-steel. The idea for the design of gun system was inspired by Ruaa Asttaifo [17] which offered a unique design for the gun system dependent on the spring in its operation for dynamic compression testing.

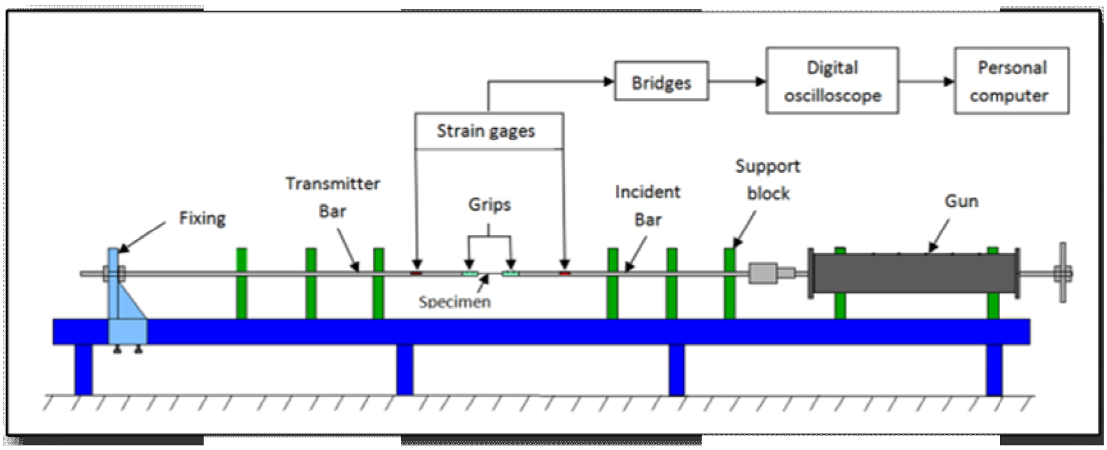


Fig .(2) Schematic of split Hopkinson tension bar

2.2 Materials and Specimen Geometry:

Two groups of materials were tested, the first group included woven-carbon, woven-glass and hybrid woven-carbon/ woven-glass epoxy laminates. These laminates were manufacturing by varying stacking sequence of woven-carbon and woven-glass fabrics for different number of layers. The second group included woven-jute, hybrid woven-jute/woven-carbon and hybrid woven-jute/ woven-glass epoxy laminates. These laminates were tested in the same way the first group. The binder material used in this experiments was Sikadur-330 (is a two part, solvent free, thixotropic epoxy based impregnating resin/ adhesive). A dog-bone specimen was designed with the shape and dimensions shown in **Figure (3),** performed for high strain rate tests on woven composite materials. Also, the specimens used in all tests should have the same geometry so as to avoid any uncertainties related to size effect. The specimen width is designed to minimize stress concentration at its ends by selecting a smooth radius of curvature in the transition region [18].

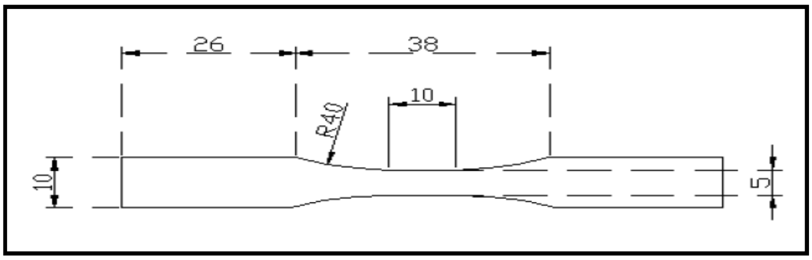


Fig .(3) Specimen's dimensions in millimeters [18]

3. Theoretical Analysis

From the one – dimensional wave propagation theory the dynamic stress-strain response of the specimen may be derived from strain histories in a section of the bars [19]. The stress (σ), strain (ε) and strain rate ($\dot{\varepsilon}$) on the specimen can be obtained:

$$\sigma_s = E \frac{A}{A_s} \varepsilon_T \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

E: is the elastic modulus of the bar, *A:* is their cross-sectional area, A_s : is cross sectional area of specimen and ε_T: is the strain in the transmitted bar.

$$\varepsilon_s = \frac{-2C}{L_s} \int_0^t \varepsilon_R \, dt \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

$$C = \sqrt{\frac{E}{\rho}} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

ε_s: Specimen strain, C: is the velocity of the elastic wave in the bar, L_s: the length of the specimen , ε_R : strain reflected to the incident bar and ρ: density of the bars.

$$\dot{\varepsilon}_s = \frac{-2C}{L_s}\varepsilon_R \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4)$$

$\dot{\varepsilon}_s$: Specimen strain rate.

Thus, the stress-strain behavior of specimen is determined simply by measurement made on the elastic wave in tensile split Hopkinson bar. The above equations relate strain gauges measurement to stress-strain behavior in the deforming specimen and require that the wave within the pressure bar must be one dimensional and the specimen must deform uniformly.

The total energy, absorbed energy of the specimen can be calculated by the following equations:

$$E_{Total} = \frac{1}{2} * mV^2 \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5)$$

m: The mass of the striker bar.
V: The striker bar velocity.

$$E_o = \int F_{av.} * V\, dt \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (6)$$

Where:
$F_{av.}$: The average force on the specimen.
V: The striker bar velocity.

The kinetic energy of the incident bar after the incident wave passes can be expressed as [20]:

$$K_I = \frac{1}{2}\rho_B A_B C_B^3\, T\, {\varepsilon_I}^2 \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (7)$$

Where:
ρ_B and C_B : The density and elastic bar wave speed of the bar material, respectively.
A_B : The cross section area of the bar.
ε_I: Strain in the incident bar.
T: The duration time of the incident pulse as expressed by equation:

$$T = \frac{2L}{C_{st}} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (8)$$

Where:
L: The length of a striker bar.
C_{st} : The elastic wave speed of the striker bar material.

The kinetic energies associated with the reflected and transmitted pulses are:

$$K_R = \frac{1}{2}\rho_B A_B C_B^3\, T\, \varepsilon_R{}^2 \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(9)$$

$$K_T = \frac{1}{2}\rho_B A_B C_B^3\, T\, \varepsilon_T{}^2 \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(10)$$

The contribution of kinetic energy to the specimen deformation is:

$$\delta_k = K_I - K_R - K_T \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(11)$$

4. Dynamic Test:

The laminate stacking sequence for each group of tested specimens shown in **Table (1):**

Table .(1) Laminate Stacking Sequence

	Material	Stacking Sequence			Range of Strain Rates 1/s
First Group	Woven fiber glass/ epoxy composite	F	FF	FFF	402 – 883.1
	Woven carbon fiber/ epoxy composite	C	CC	CCC	424.6 – 886.39
	Hybrid woven glass/ woven carbon epoxy laminates	FC	FCF	CFC	686.2 – 883.7
Second Group	Woven Jute fiber/ epoxy composite	J	JJ	JJJ	306.11 – 490.69
	Hybrid woven jute/ woven glass epoxy laminates	JF	JFJ	FJF	406.8 – 795.6
	Hybrid woven jute/ woven carbon epoxy laminates	JC	JCJ	CJC	416.5 – 875.15

5. Quasi-Static Test:

Quasi static test was performed by tensile test machine (WDW-200E/ 50 KN). In this test the specimens of each group were tested at strain rate of ~1 /s. The results of this test were compared with that of dynamic test.

6. Results and Discussion:

6.1 Dynamic Test

The experimental results shown in **Figure (4) To Figure (6)** indicate that the maximum stress, strain and elastic modulus are increased with increasing the strain rate. Hybrid woven glass/ woven carbon epoxy laminates yielded higher properties than woven fiberglass/ epoxy composite and lower than woven carbon fiber/ epoxy composite. Turns out by the results the value of maximum stress increased about 12.4 % for woven fiber glass/ epoxy composite when it's hybridized with woven carbon fiber/ epoxy composite, This indicates that there is a clear improvement in the properties of glass fibers when hybridized with carbon fibers.

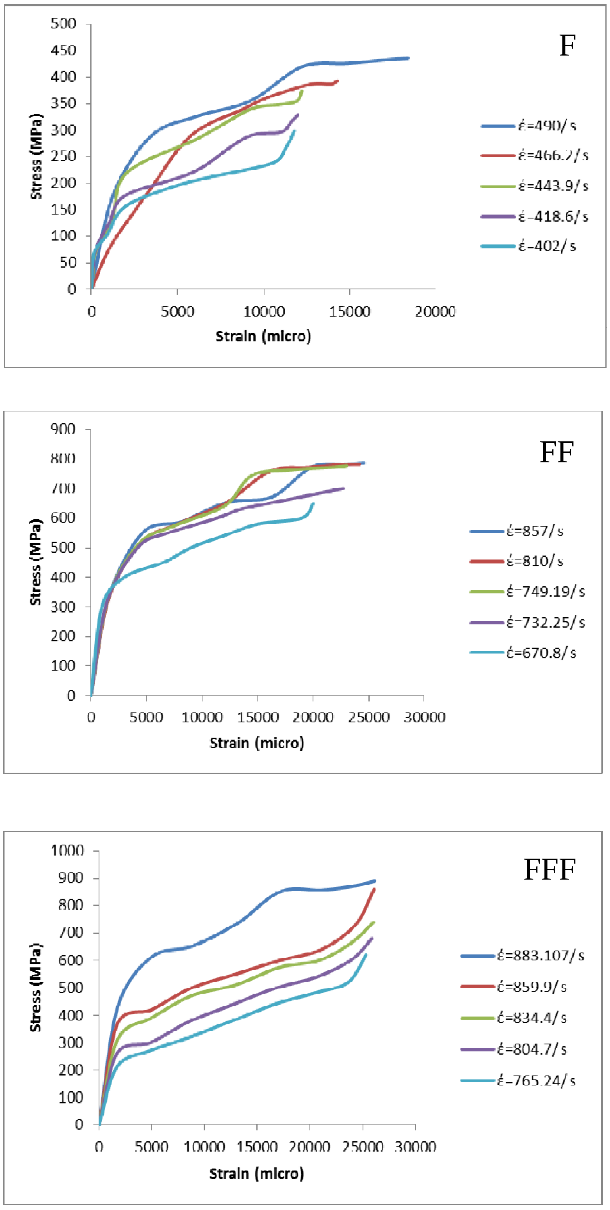


Fig .(4) Stress-strain curves for woven fiber glass/ epoxy composite.

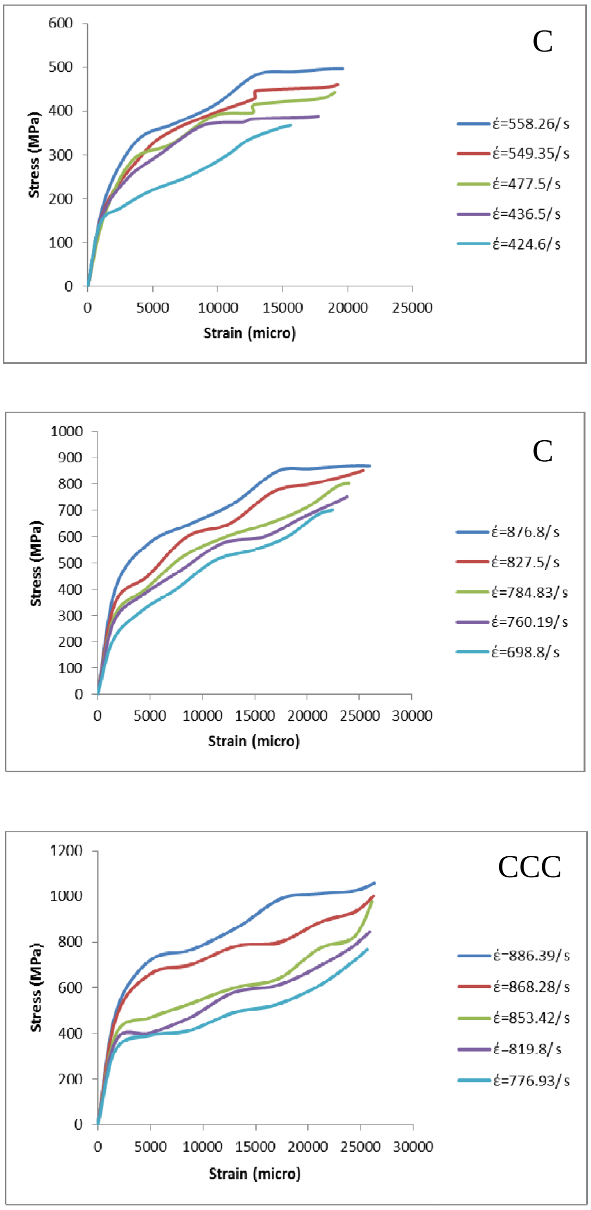
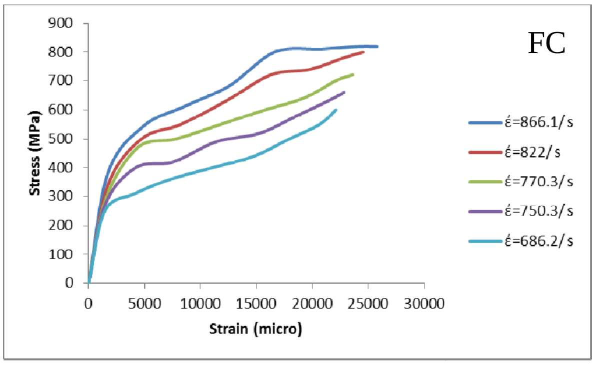
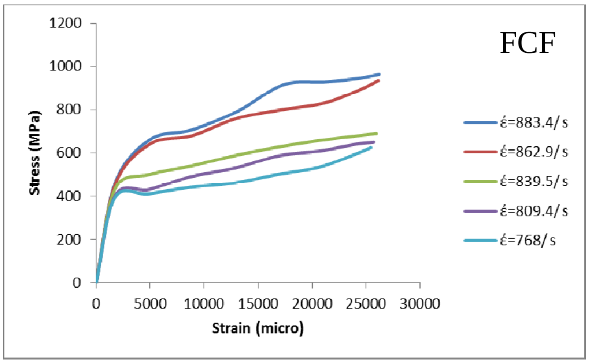


Fig .(5) Stress-strain curves for woven carbon fiber/ epoxy composite.





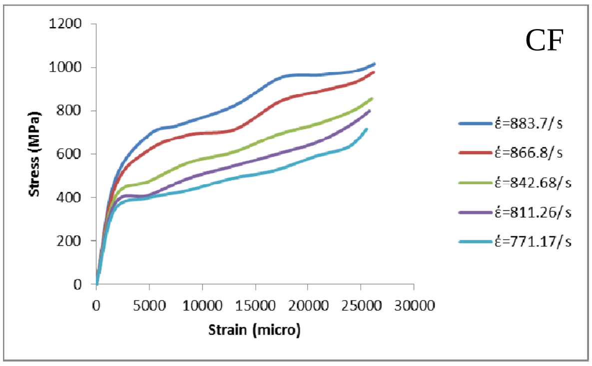
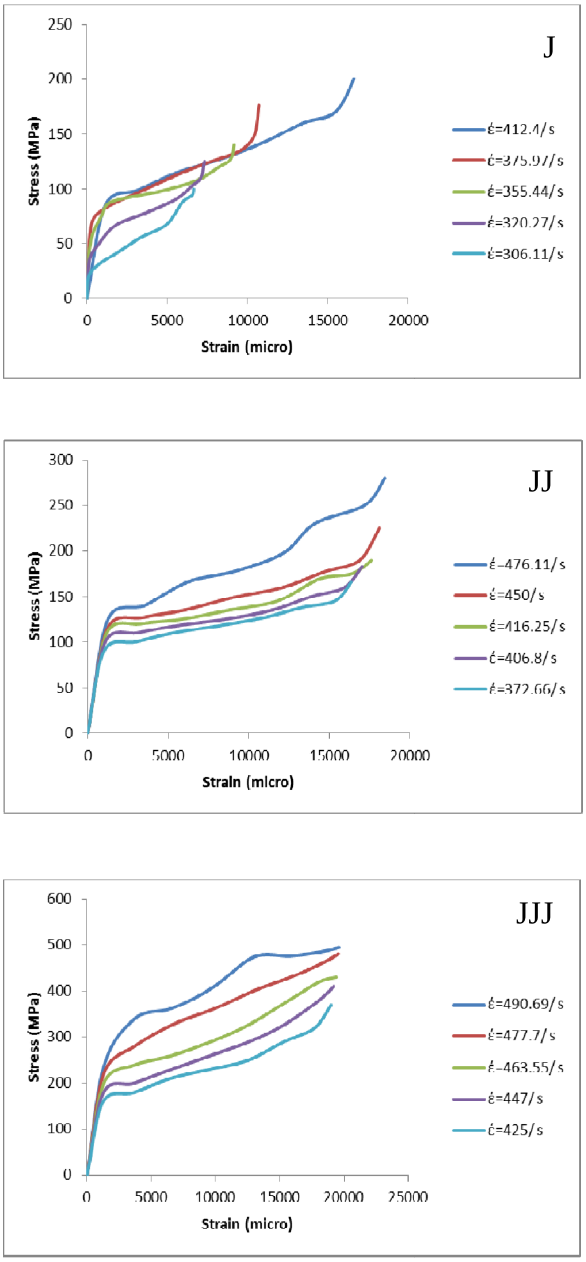


Fig .(6) Stress-strain curves for hybrid woven glass/ woven carbon epoxy laminates

It can be seen that the **Figures (7, 8, and 9)** present the stress-strain curve and strain rate for woven-jute, hybrid woven-jute/woven-carbon and hybrid woven-jute/ woven-glass epoxy laminates. Woven-jute, hybrid woven-jute/woven-carbon and hybrid woven-jute/ woven-glass epoxy laminates have the same dynamic behavior, but the values of stress, strain and modulus of elasticity are less. When the woven jute fibers hybridized with woven glass fibers the value of maximum stress increase by approximately 38.33 %. On the other hand, hybridization of woven jute fibers with woven carbon fibers leads to increase in the value of maximum stress about 43 %. This is evident by looking at the **Figure (9)** that the maximum tensile stress was observed in CJC, and these considered the best stacking sequence gives the best improvement in the properties of jute



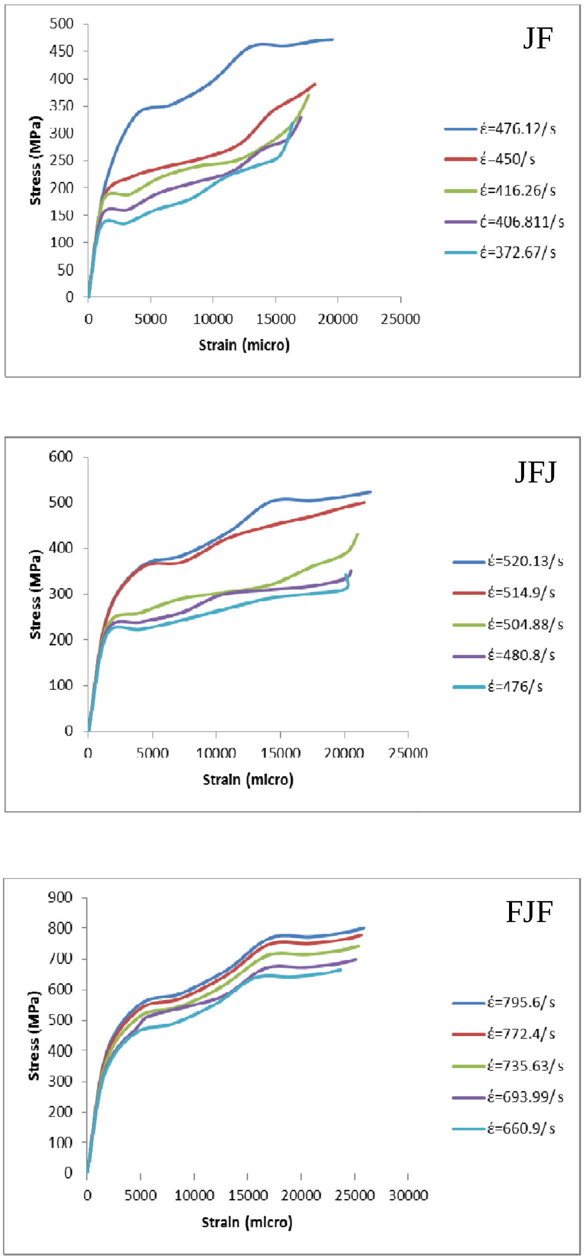
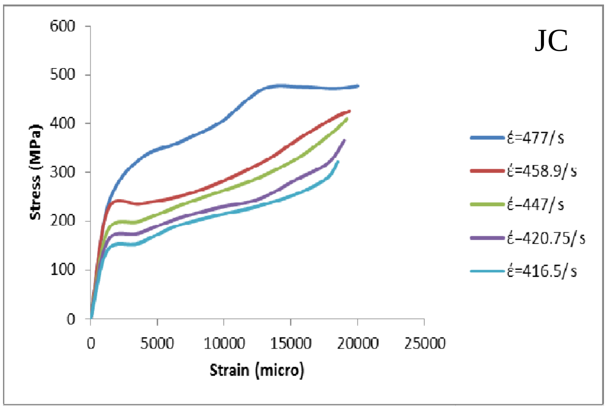
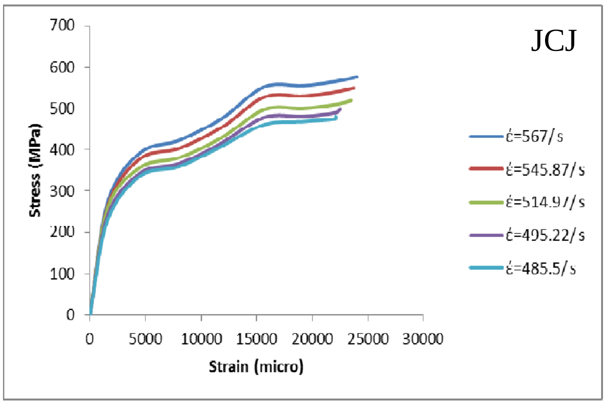


Fig .(7) Stress-strain curves for woven jute fiber/ epoxy composite.

Fig .(8) Stress-strain curves for hybrid woven jute /woven glass epoxy laminates.





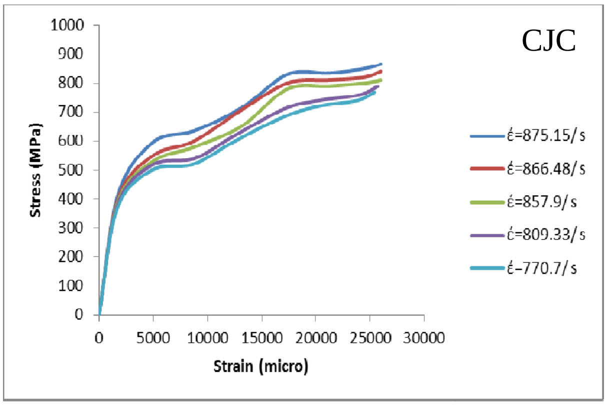


Fig (9) Stress-strain curves for hybrid woven jute /woven carbon epoxy laminates.

The following table shows the range of the modulus of elasticity for the both groups.

Table .(2) Values of modulus of elasticity

	Material	Range of modulus of elasticity (GPa)
First Group	Woven fiber glass/ epoxy composite	85.73 - 136
	Woven carbon fiber/ epoxy composite	90.4 – 137.67
	Hybrid woven glass/ woven carbon epoxy laminates	120.06 – 136.28
Second Group	Woven jute fiber/ epoxy composite	76.98 – 129.85
	Hybrid woven jute/ woven glass epoxy laminates	96.4 – 132.8
	Hybrid woven jute/ woven carbon epoxy laminates	99.07 – 133.33

It is worth mentioning that the increase in modulus of elasticity is marginal of all the materials tested. From the stress-strain curves it can be seen that all the materials show an initial linear elastic region followed by nonlinear deformation. The start of nonlinearity in the curves is an indication of the initial matrix cracking followed by progressive failure of the fibers.

Based on experimental results the specific absorbed energy for the specimen and the contribution of kinetic energy to the specimen deformation are increased with increasing strain rate, as shown in **Figure (10) and Figure (11).** In all materials the specific absorbed energy and contribution of kinetic energy to the specimen deformation depends on strain, due to the microscope mechanisms linked to dissipated energy. In addition as the deformation progresses (so the strain increases) this requires more energy. The increase in the values of absorbed energy and kinetic energy for glass fibers after hybridized with carbon fibers approximately 11% and 10% respectively. For the jute fibers, it is clear that the best improvement in properties when hybridized with carbon fibers, where the increase in the values of the absorbed energy and kinetic energy approximately 44 % and 68% respectively. On the other hand, hybridization of jute fibers with glass fibers lead to increase in the value of absorbed energy and kinetic energy 38 % and 55% respectively.

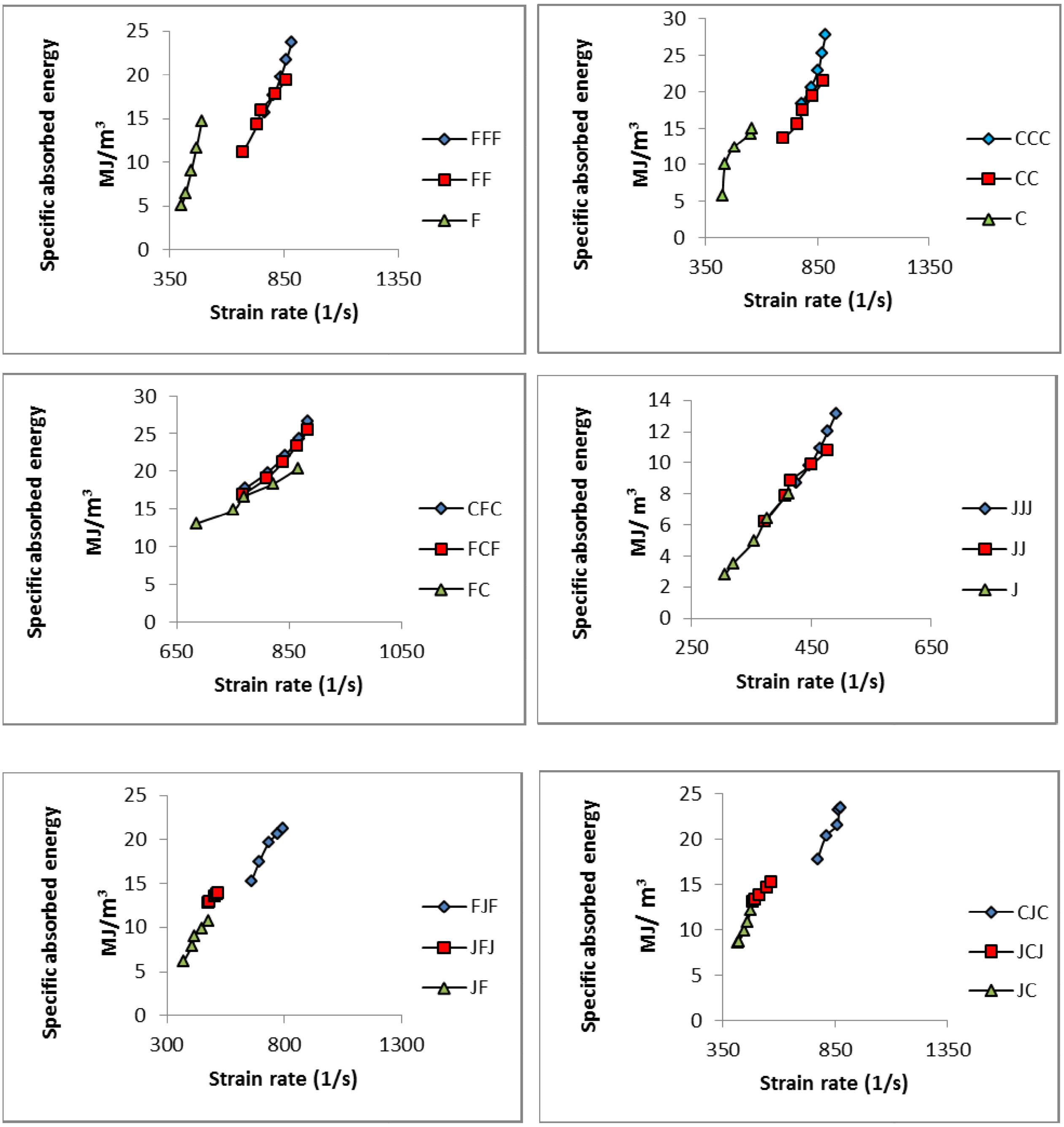


Fig . (10) Strain rate Vs. Specific Absorbed Energy

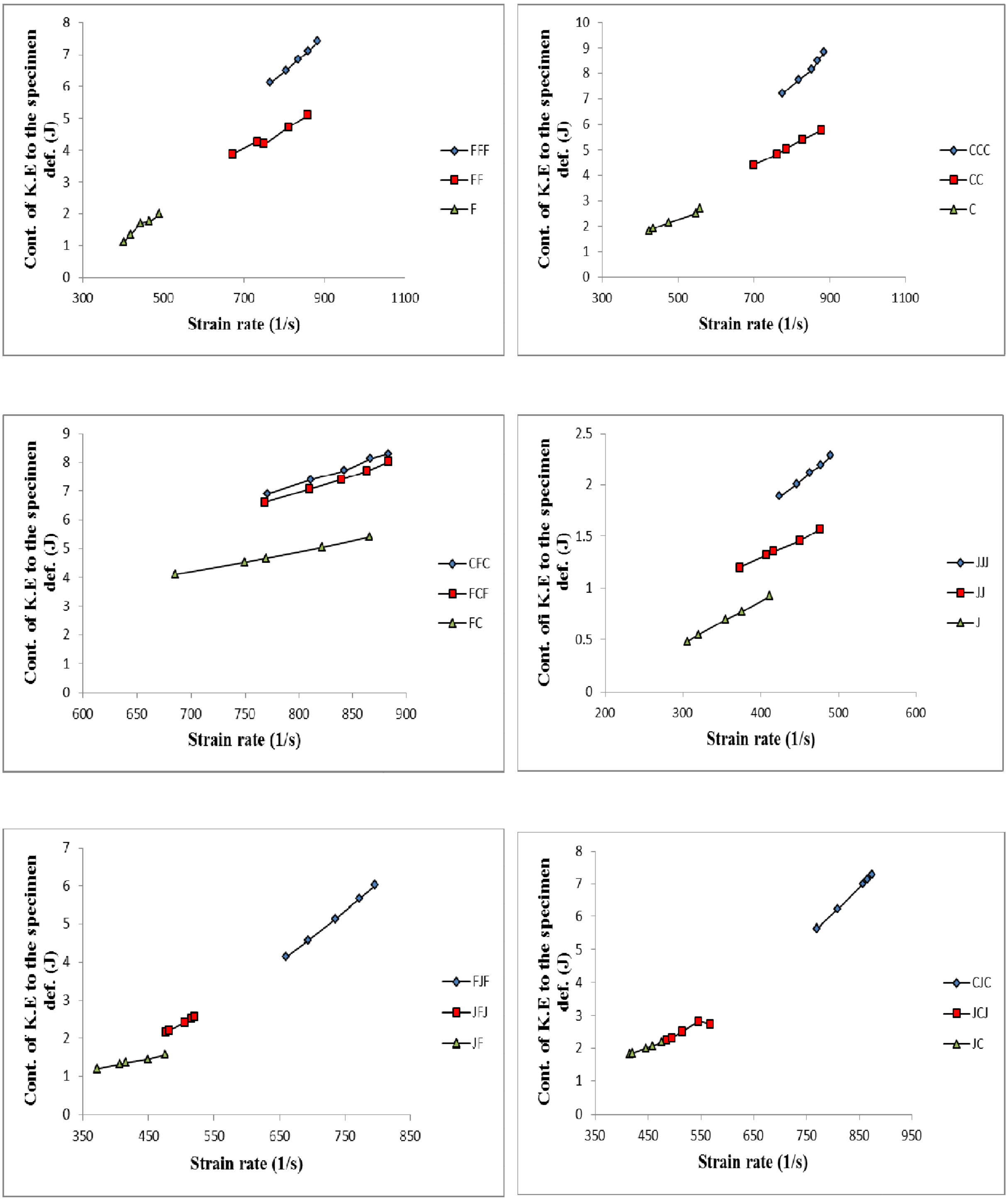


Fig .(11): Strain rate Vs. Contribution of Kinetic Energy to the Specimen Deformation

6.2 Quasi-Static Test:

The experimental results of the quasi-static showed that the values of stress less than the stress obtained from dynamic test for two the groups tested as shown in **Figure (12),** because the material is able to withstand higher load and failure strain at high strain rates comparing with at low strain rates. The modulus of elasticity values less than the values extracted in dynamic test, these values for the first group ranged from 28 to 44 GPa for woven fiber glass/ epoxy composite, 29 to 45.7 GPa for woven carbon fiber/ epoxy composite and 39.5 to 44.93 GPa for hybrid woven glass/ woven carbon epoxy laminates. While the second group ranged from 20.7 to 37.8 GPa for woven jute fiber/ epoxy composite, 29.1 to 40 GPa for hybrid woven jute/ woven glass epoxy laminates and 30 to 40.3 GPa for hybrid woven jute/ woven carbon epoxy laminates.

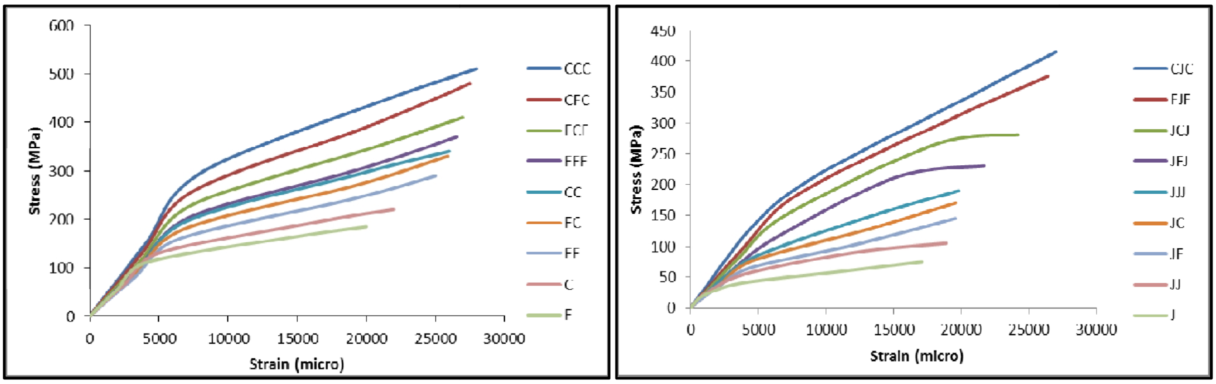


Fig .(12): Static Stress-Strain Curves

7. Analytical Assessment of Results:

Johnson-Cook constitutive model was introduced by Johnson and Cook [21] in 1983. This is an empirical model that accounts for the effects of strain, strain rate and temperature on the Flow stress. The Johnson-Cook constitutive relation is represented by equation (12):

$$\sigma = [A + B\,\varepsilon^n]\,[1 + C\,Ln\,\dot{\varepsilon}]\,[1 - T^{*m}] \qquad \text{...........................} \quad (12)$$

Where T^* is homologous temperature (neglected in this study).

The Johnson-Cook equation consist of five material constant such as *A*, *B*, *n*, *C* and m to be determined. The first brackets in the above equation is a strain hardening term, the second brackets is the strain rate hardening term and the third bracket is a thermal softening term (neglected in this study). Where ε is the equivalent plastic strain, constant *A* is the yield stress corresponding to 0.2 % offset strain; constant *B* and exponent n represent the strain hardening effects of the material. The expression in the second set of brackets represents the strain rate effect through constant *C*. [22]

In this study, an offset of 0.2 % strain is plotted on the stress-strain at a strain rate of ~1/ s to determine constant *A*. Constant *B* is 10^y of the Log (Plastic stress) Vs Log (Plastic strain) plot for the plastic region of the quasi-static data (~1/ s), n is the slope of Log (Plastic stress) Vs Log (Plastic strain) as shown in figure (13). Strain rate sensitivity constant *C* is determined as the slope of the linear fit of Ln (Strain rate) Vs (Dynamic stress/ Static stress) as shown in figure (14).By using equation (12), stress-strain behavior of hybrid woven glass/ woven carbon epoxy laminates is obtain at strain rate 686.2/ s, theoretical and experimental results are presented in figure (15).

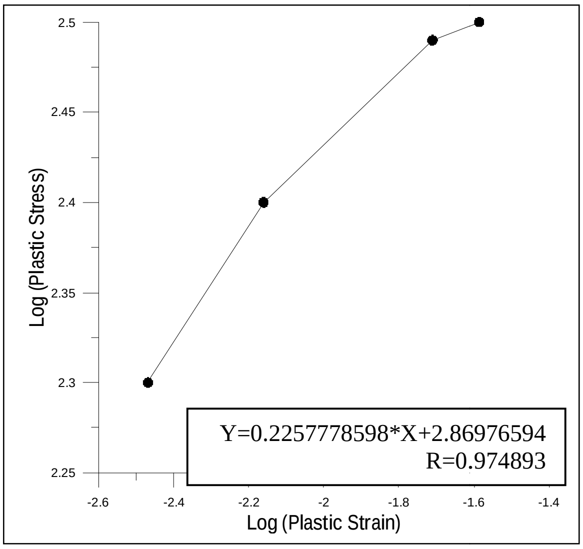


Fig .(13) Constant *B* and *n*.

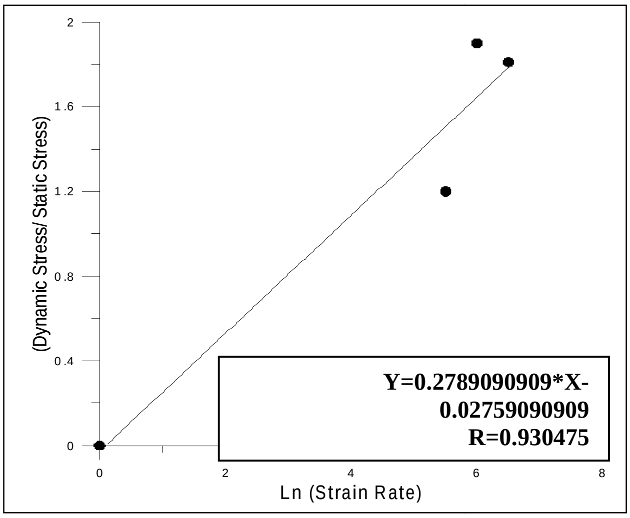


Fig .(14): Rate sensitivity constant *C*.

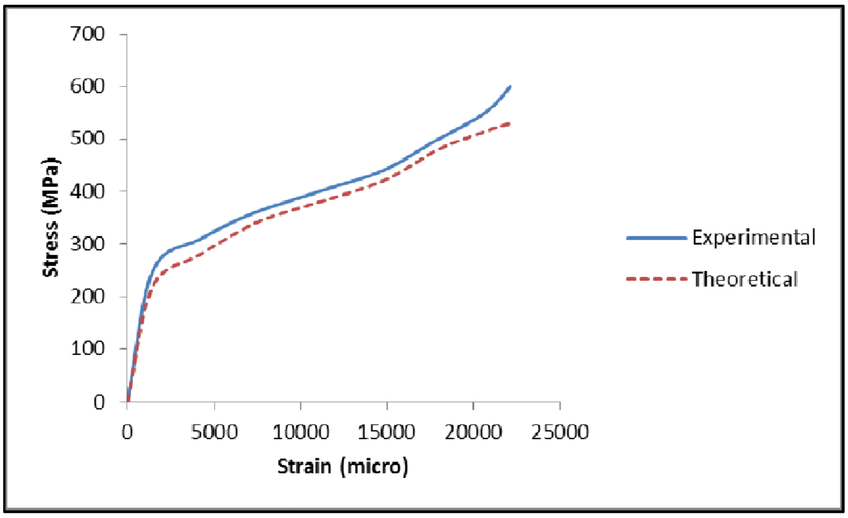


Fig . (15): Stress-Strain Curve for hybrid woven glass/ woven carbon epoxy laminates.

As in the previous case there is a reasonable match between the theoretical and the experimental results in the range of tested strain rates. The same procedure is used for hybrid woven jute/ woven carbon (JC), woven carbon fiber/ epoxy composite (C) at a strain rate of 416.5 /s, 424.6 /s respectively. The materials constant are provided in the **Table (3).**

Table .(3) The constants in the Johnson-Cook constitutive model

	A (MPa)	B (MPa)	n	C
C	103	80	0.241	0.327
FC	150	200	0.225	0.27
JC	73	78	0.354	0.369

Figure (16) showed the theoretical and experimental results for woven carbon fiber/ epoxy composite and hybrid woven jute/ woven carbon epoxy laminates:

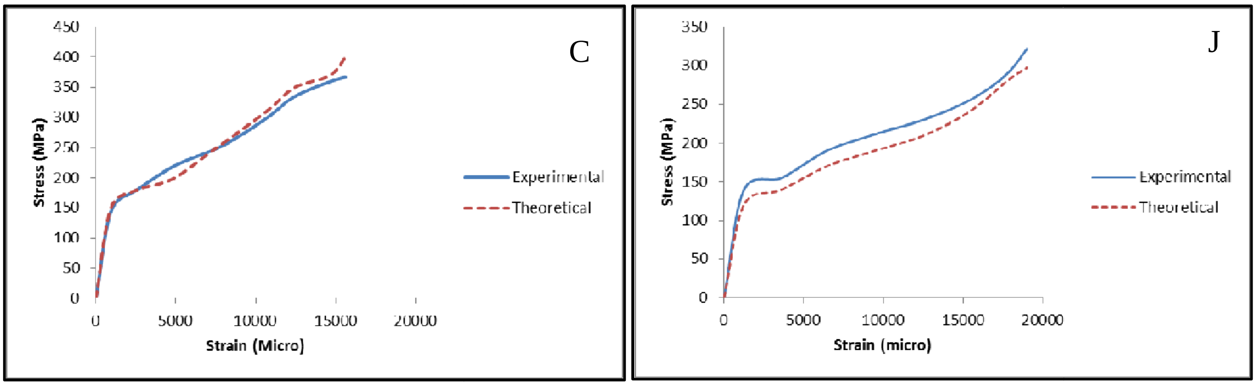


Fig .(16) Stress-Strain Curve

It is clear that there is a reasonable match between the theoretical and experimental value of stresses.

8. Conclusion:

1- Experiments have been carried out with a split Hopkinson bar apparatus specially designed for the dynamic tensile tests. This design allowed conducting tests in an easy and simplified manner because of the mechanism of the spring system.

2- For both groups tested, the results of the dynamic tests showed the maximum stress, strain, modulus of elasticity, specific absorbed energy and kinetic energy are all increased with increasing the strain rate. The first group showed a clear improvement in the mechanical properties of glass fiber when hybridized with carbon fiber.

3- The results of the second group of materials which included natural materials and environmentally friendly representative (jute), showed significant improvement in the properties of this material when hybridized with carbon fiber and glass fiber. The significant improvement in the properties of jute was clear when hybridized with carbon fibers. This is evident when the achieved values of stress, strain, modulus of elasticity, absorbed energy and kinetic energy.

4- Based on the study of the mechanical properties of different layered stacking sequences of hybridized, the maximum stress, strain, modulus of elasticity, absorbed energy and kinetic energy values are observed in (CFC) in the first group and (CJC) in the second group.

5- Quasi-static test results showed that the values of the maximum stress and modulus of elasticity are less than that found in dynamic experiments.

6- Depending in the results that have been obtained from the analytic method, there is a reasonable match between the theoretical and the experimental results in the range of tested strain rates.

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