Computerized Testing Machines to Study the Effect of Strain Rate on Mechanical Properties of CFRP

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***Abstract*- (In this paper, a universal testing machine and an impact testing apparatus have been upgraded by using a high-accuracy data acquisition and control system interfaced to a personal computer with proper sensors and actuators. The purpose of upgrade is to increase the accuracy of the measurements and to perform advanced material testing procedures that are not possible with the old configuration. The modernization process not only permits the accurate data acquisition and convenient operation but also the ability to study the effect of strain rate on the tensile properties of materials. Also, an experimental study of the response of CFRP (Carbon Fiber Reinforced Plastic) material to low and intermediate strain rates has been carried out)**

***Index Terms*—Machine Interfacing, Computerized Testing Machines, Strain Rate Effect, CFRP Properties.**

I. Introduction

Computerized material testing machines have replaced conventional machines in many applications due to many reasons. Computerized systems provide better measurement accuracy, high speed data acquisition, test path control and convenient operation. Furthermore, data can be presented and viewed more clearly and in different options at the same time [1, 2]. Additionally, computerized machines provide the ability to perform more tests and under different conditions such as constant strain, accelerated test, constant load, cyclic load and other conditions [1, 2]. Due to their high data acquisition rate, computerized systems can be used to measure the instantaneous strain rate and load during various instants of the test. Some computerized machines have the provision to control the movement of the crosshead by the software and, hence, offer better control of the strain rate and load.

Computerized testing machines address themselves in the study of material properties at dynamic loads where the strain rate may reach large quantities. The tests performed at relatively high strain rate are very important to characterize the properties of materials used in different industrial applications where the material is subjected to rapid stresses. An accurate simulation needs accurate information of material data at a strain rate up to 50 sec^{-1} since the strain rate of localized deformation may reach 100 sec^{-1} during equipment crash or rapture [3]. Experimental techniques used to characterize the relation between the stress and the strain are varying according to the strain rate. At low strain rate of about 1 sec^{-1}, general mechanical or hydraulic tensile testing machines can be used to acquire the stress-strain curves because the process of deformation is quasi-static and isothermal. When the strain rate become larger than 10 sec^{-1}, the inertia effect and stress wave propagation reach levels of critical importance because the tensile properties are changed remarkably with respect to the amount of strain rate. The split Hopkinson pressure bar apparatus, which is also called Kolsky's bar [4], is a popular experimental technique for identification of dynamic material characteristics at a high strain rate ranging from 1000 to 10000 sec^{-1}. However, at an intermediate and low strain rates of less than 500 sec^{-1}, Kolsky's theory for one-dimensional stress wave propagation is not valid and the split Hopkinson bas is no longer applicable since the quasi-static and dynamic aspects of deformation take place simultaneously at these strain rates. Hence, a special testing equipment need to be developed in order to obtain the stress-strain curves.

Mechanical, pneumatic and servo-hydraulic loading methods have been used to measure the material properties at the intermediate strain rates. Dudder [5] attempted to obtain the material properties using a drop weight method. Winkel and Adams [6] extended the drop weight method to test the composite materials. Adams and Adams [7] developed an impact tensile testing apparatus to test composite materials based on pendulum impact tester. They added a piezoelectric load cell to measure the high-frequency force generated by the impact head. They utilized photoelectric sensor to measure the velocity of the pendulum head and digital storage oscilloscope to capture the signals from load cell and photoelectric sensor. Later, Fermie and Warrior [8] used modified Rosand instrumented falling weight apparatus to study the effect of high strain rate on the properties of composite materials under tensile and compressive loads.

Many researchers studied the effect of strain rate on the behavior of composite materials. The effect of strain rate on the properties of Scotchply type 1002 was investigated by Staab and Gilat [9]. Huo and Ruiz [10] studied the properties of CFRP T300/914 lamination at different strain rates. They performed three types of tests, tension, compression and in-plane shear to measure the in-plane mechanical properties of the woven CFRP. Pardo et al [11] conducted a study to determine the tensile behavior of a unidirectional E-glass/polyester composite in relation to the strain rate. Several orientations of fibers in the composite were tested with a high-speed hydraulic tensile machine, which covers a range of loading rate from quasi-static up to approximately 20 m/s. Vaynman et al [12] studied the effect of strain rate and temperature on mechanical properties of precipitation hardened ferritic steel. They utilized Kolsky's bar for strain rates above 290 sec^{-1} and computerized testing machines supplied by MTS Corporation for low strain rates ranging from 0.001 and 0.1 sec^{-1}.

In this work, two conventional machines have been upgraded using high accuracy data acquisition and control hardware in addition to a visual software built using Microsoft VS 2005. The first machine is a hydraulic tensile testing machine and it is used to study the properties under quasi-static and low strain rates. The other machine is the impact pendulum which has been upgraded to test the materials under intermediate strain rates of up to 100 sec^{-1}. A high resolution and high speed ADC converter is utilized in the interfacing hardware in order to improve the accuracy of the current testing machines and make it suitable to measure strain rates.

II. THE TESTING MACHINES AND UPGRADE KIT

A. Tensile Testing Machine

This conventional machine was purchased in 1970 by College of Engineering-University of Basra. It is manufactured by WPM in West Germany. It has model number ZD100 with maximum capacity of 100 ton and stroke speed of 5mm/sec. It incorporates dial indicator to measure the load and a ruler to visually measure the displacement. It is shown in Fig. 1 below.

A pressure sensor IMP-A7003 (supplied by Impress Sensors and Systems) is utilized to sense the pressure of hydraulic in the loading piston. By multiplying the pressure by the area of the piston, the force is obtained. A calibration procedure is executed to ensure accurate load measurement using an ISO traceable proof ring. The displacement of the crosshead is measured by converting it into angular motion using rack and pinion mechanism, then a high resolution rotary encoder type LS S66 having resolution of 6000 pulse/rev is used to sense the angular motion. An electrically controlled solenoid valves are employed to control the operation of the crosshead by the PC software. The positions sensor is calibrated properly using a vernier scale to ensure precise displacement measurement.

Fig. 1 Universal Testing Machine ZD100.

B. The Impact Testing Apparatus

This apparatus is manufactured by WPM. It is used to perform conventional impact test such as Izod and Charpy tests. It is shown in Fig. 2 below. It has an impact hammer of weight 25 kg and swinging lever of effective length of 1 m. The hammer initial position can be adjusted to obtain various impact speeds and energy. The maximum energy the device can provide is 400 J and the maximum hammer speed is 6 m/s. Following the method used by Adams and Adams [7] and ISO 8256 and ASTM D1822 standards for tensile impact test [13], the apparatus has been upgraded in order to be able to do impact tensile test in which the strain rate is high. A rotary encoder having resolution of 6000 pulse/rev has been coupled to the hinge in order to sense the angle of the swinging arm as shown in Fig. 2. A gripping mechanism for tensile specimen has been designed, manufactured and attached to the device. The impact force is transmitted from the hammer to one end of the specimen by dual pronged tub striking a grip attached to the specimen. The other end of the specimen is attached to a grip which is fixed to a load cell. The load cell is fixed to the machine base as shown in Fig. 3. A dynamic load cell type Instron 2527-101 is employed to measure the dynamic force inherent during impact test. The grips incorporate a preloading screw to hold the specimen and to reduce the possibility of slipping during the test.

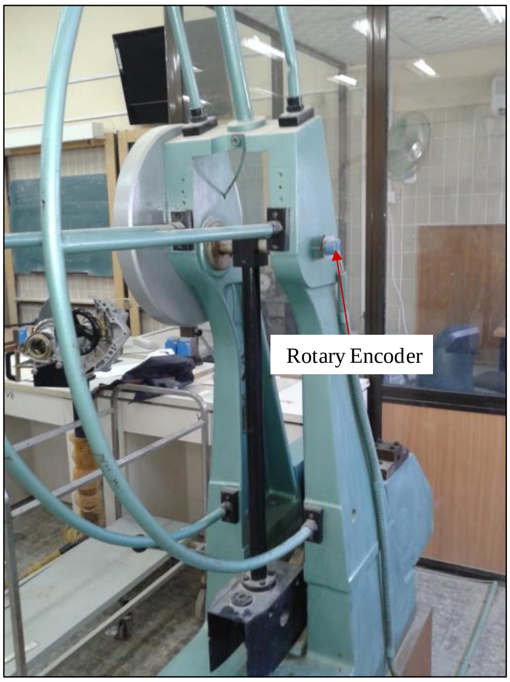

Fig. 2 Impact Testing Apparatus

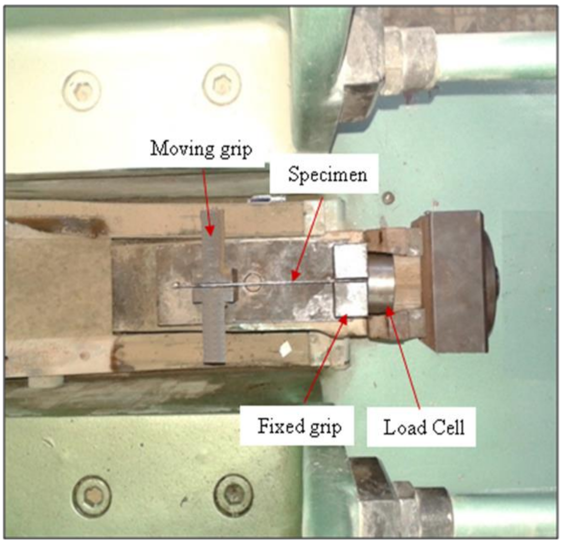

Fig. 3 Impact Tensile Gripping Mechanism

C. The Interfacing Device UDAC-2

The developed interfacing device is shown in Fig. 4 below. It is fully designed and constructed in this work. The front panel contains a power indicator LED while the rear panel contains the connectors which can be used to connect the device to the tensile machine and to the PC. There are three DB9 male connectors used to connect the device to the tensile machine to read the signals of the pressure gauge and the displacement sensors and also to connect to the motion control servo motor. The later controls the speed of the crosshead and, hence, the strain rate.

The interfacing device incorporates three main modules, the USB module, ADC module and motion control module as shown in Fig. 5.

Fig. 4 The Interfacing Device UDAC-2.

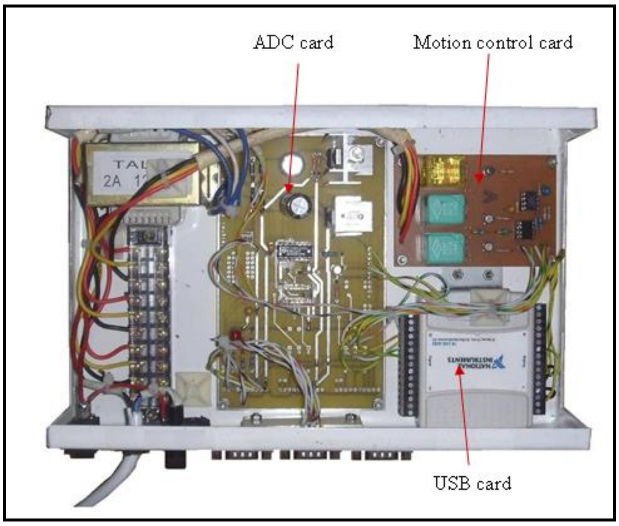

Fig. 5 Details of UDAC-2.

1. USB Module

This module is used to connect the device to the PC using USB port. The NI USB-6008 device is used to implement it. The main function of this module is to communicate with the ADC and motion control modules, configure them and read/write data to them. The acquired data is transmitted to the PC through USB port while the control data received from the PC is forwarded to other modules through the digital I/O lines. Moreover, this module incorporates 4-channel 12-bit ADC to measure signals at sampling rate of up to 10000 sample/second. This ADC is used to capture the signals of piezoelectric load cell and strain gauges used in the impact tensile test.

2. ADC Module

This module contains the main analog to digital converter (ADC), the analog filter, position decoder and the power supply. A high accuracy sigma-delta ADC type AD7780 is utilized in this configuration to measure signals at 24-bit resolution and up to 1000 sample/sec. It features 24-bit sigma-delta, 1 to 100 V/V differential amplifier and 10 input channels which can be configured as 5 differential input channels to eliminate common mode noise. These channels can be used to measure the signals from pressure and load sensors and also strain gauges directly without pre-conditioning amplifier due to their high input impedance and internal amplifier. This module is configured and read by the USB module through a number of digital lines. The data sampling rate can be set between 0.1 and 1000 sample/sec. The analog filter is implemented before the ADC to reduce any high-frequency noise in the input signals. The sigma-delta digital filter of the ADC will further eliminate undesired noise from the acquired signals. The digital position decoder accepts the digital signals from rotary encoder (signal A and B) as input. The output is the direction of motion as logic signal and the speed as square wave signal. These signals are forwarded to the USB module which can interpret them and produce the position as a numeric value.

3. Motion control module

This module contains the parts required to control the solenoid valves which in turn controls the motion of the tensile machine crosshead. The parts include the relays and their driver circuit.

F. The PC Software

PC software for universal testing and impact testing machines has been developed using Microsoft Visual Studio 2005. The specimen dimensions and other test information can be defined in addition to the type of test required and relevant standard. The collected data can be processed by applying smoothing filters such as moving averaging, digital filters and wavelet transform to eliminate any noise and unwanted vibration from the signals. The results can be stored in the database of the software along with the defined test entity. Moreover, data can be presented in many forms of graphs and tables and can be exported to other software. The software is installed to an industrial touch panel PC for more reliability and convenience.

III. Experimental Procedure

A. Test Specimen

The ASTM D3039/3039M standard, which describes the test methods for tensile properties of polymer matrix composite materials, has been adopted to select the appropriate test specimen dimensions. A rectangular-shaped test specimen of thickness 1 mm is used. In order to comply with the loading capacity of the impact testing machine, the width of the specimen is chosen as 10 mm with gage length of 40 mm. The specimen is shown in Fig. 6. A CNC machine is used to cut the specimens from a Newport CFRP sheet having 1 mm thickness and 0º fibers orientations.

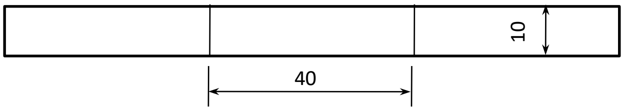

Fig. 6 Test Specimen.

B. Results

Tensile tests are performed to obtain the Newport CFRP material properties at low and intermediate strain rates. Four strain rates are chosen to characterize the tensile properties of the composite material, 0.01, 0.1, 10, and 50 sec^{-1}. The first two strain rates are obtained by using the tensile testing machines while the other two rates are obtained by using the impact tensile machine. The strain rate of 0.01 sec^{-1} is regarded as quasi-static. Each test is repeated three times with the same conditions for each strain rate and the average values are considered. The load is measured using the pressure sensors for the tensile machine and piezoelectric load cell for the impact testing machine. Strain gages type Vishay CE-06-250UN-120 are used to measure the strain in the specimens. These gages are bonded to the specimens using Vishay Bond-200 general purpose adhesive.

Table I list the obtained failure stresses and strains at different strain rates for 0º lay-up unidirectional CFRP. The strain rates indicated in the table are the averaged values over the test period. For impact tensile tests, the strain rate is a function of time due to uncontrolled motion of the impact hammer. Hence, the average strain rate is calculated by dividing the total strain by the test period starting from the beginning of loading till the fracture.

TABLE I
FAILURE STRESS AND STRAIN DATA FOR NEWPORT CFRP

Stroke speed (m/s)	Avg. strain rate (sec^{-1})	Failure stress (MPa)	Failure strain (m/m)	Testing machine
0.000513	0.0112	743	0.0136	Tensile
0.00524	0.0916	774	0.0128	Tensile
0.521	10.31	892	0.0121	Impact
2.63	48.74	968	0.0120	Impact

From Table I it can be concluded that failure stress increases when the strain rate is increased, while the failure strain is almost not affected by the strain rate. To characterize the Stress-Strain curves at different strain rates, polynomial curve fitting is applied to fit the obtained stress-strain data at the measured strain rates. Then another curve fitting is performed across the strain rate to characterize the data at selected strain rates of 0.01, 1, 10 and 50 sec^{-1}. Fig. 7 shows the interpolated stress-strain curves for the selected strain rates. It is clear from the figure that the strength of the CFRP material increases as the strain rate becomes higher.

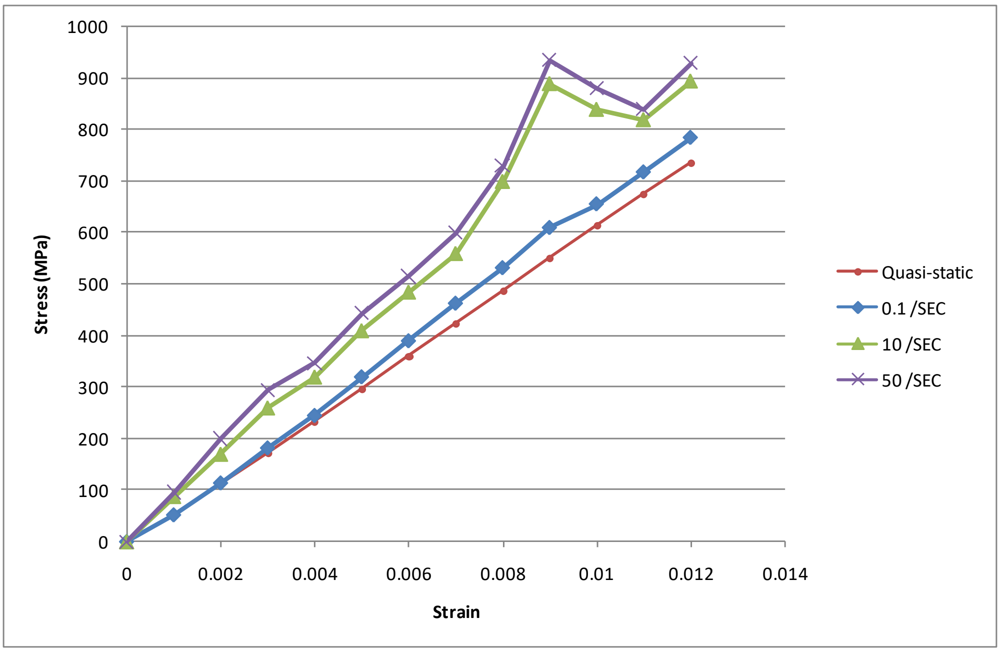

Fig. Stress-Strain Curves at Different Strain Rates. 7

IV. CONCLUSIONS

Two conventional testing machines have been upgraded, the universal testing machine and pendulum impact apparatus. The old measurement system of the universal testing machine has been removed and replaced by a computerized system. The developed hardware added important features including the high accuracy and ability to measure the relatively high strain rate and dynamic load in impact tensile testing. The computerized system presents the test data more conveniently and all the data can be stored for future analysis and review. The upgraded systems have been employed to study the effect of strain rate on the tensile mechanical properties of Newport CFRP material at low and intermediate strain rates. Testing results have shown that the strength of the CFRP material generally increases when the strain rate is increased.

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VI. BIOGRAPHIES

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