Design and Manufacture of Miniature Testing Machine for Composite Materials

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Abstract. Today, there are many commercial test machines in industry and laboratory with many different sizes. However, their prices are high. Some laboratories made their own equipment at lower price based on their situation, demand and purpose of test. In this paper, the design of the frame structure and the operating systems, as well as the calibration of a small tensile and bending test machine for low- to medium-stiffness composite materials are presented. The construction is made of aluminum. The loading is created by an actuator which is controlled by an Arduino micro-controller. A Hocdelam USB-9090 (the same as that of NI USB-6009 but with less accuracy) data acquisition card is connected to a personal computer through an interface with load cell and strain gauge by the amplifier to record the force and the displacement during a test. The rate of loading is identified by the rate of actuator which is maintained stable thanks to the adjustment of PWM (Pulse Width Module) with Arduino. The machine is able to conduct tensile and bending tests with a loading up to 3000 N with a sensitivity of 1 N. It is possible to conduct tests on composite specimens at speeds of 1.7 ~ 300 mm/min. This machine is able to obtain results for mechanical properties which are in good agreement with the data obtained from a commercial machine, the differences are less than 5%.

Keywords: miniature testing machine, frame structure, specific speed, data acquisition, composite material.

1. Introduction
Nowadays, the material industry is increasing rapidly so that demands of measurement of the mechanical properties of materials are significantly growing up. Hence, various universal test machines are developed for industrial or study purposes in the world. Some laboratories made their test machines based on their purposes of study and their economic conditions. Many researchers are interested in designing miniature testing machines to obtain the mechanical properties of materials [1-4]. Pantherpan and his colleagues [1] proposed a simple miniature disc-type tensile specimen and fixtures to hold specimens with the help of a rigid pin to predict the mechanical properties of materials.

In our study, a small tensile and bending test machine for low- to medium-stiffness (Young’s modulus is less than 10 GPa) composite materials are presented. The construction of the miniature testing machine is designed as a universal test machine. However, it is on a small scale with a shaped
aluminum structure for strong load-bearing ability. The system composing a linear actuator and connectors allows to create a load up to 3000N and to maintain the loading rate stable during the test. The frame also ensures the co-axial movement of the tensile specimen and grips and the linear motion of the actuator.

In terms of data acquisition, a GUI LabVIEW program is written to help users assess the mechanical properties of material generally. Force is recorded by a load cell, strain is measured by a strain gauge and displacement of grips is identified by a linear potentiometer. Because the voltage outputs of the load cell and the strain gauge are very small (few mV), they need to be amplified before they are transferred to a data reading card. As a result, the accuracy of acquired data depends on the resolution of the data collecting card. In our case, a USB-9090 Hocdelam data acquisition card is used. The resolution of this 10-bit Analog to Digital Converter (10-bit ADC) is high enough to obtain accurately the signals of sensors.

2. Design and manufacture

2.1. Operating principle
For a miniature testing machine conducting both tensile and bending tests, the basic components must be the frame, the force generation system, grips for the tensile test and fixtures for the bending test. There are also necessary components such as force, displacement and strain measurement devices. The machine must meet some technical requirements such as loading rate, the coaxial movement and the load-bearing capacity. The operating principle of the miniature testing machine is shown in Fig. 1.

![Fig. 1: Operating principle of testing machine in the tensile test (a) and bending test (b) with: 1. Frame; 2. Force generation system; 3. Grips; 4. Fixtures](image)

2.2. Construction
After creating the final design idea of the miniature testing machine, the components are chosen by considering their advantages and disadvantages.

2.2.1. The frame
In terms of construction, the design requires the machinability, the maintainability and the load-bearing capacity. For the frame, the shaped aluminum profiles are selected (Fig. 2). These treated aluminum bars have appropriate mechanical properties and are suitable for assembly structure.
Fig. 2: Shaped aluminum and design idea for the frame

Besides the frame, the design of intermediate parts for installing the force generation component and for ensuring the co-axiality is shown in Fig. 3.

Fig. 3: The intermediate parts for installing force generation component

2.2.2. The force generation system
With outstanding advantages, the linear actuator is chosen as the solution for the force generation component of the testing machine (Fig. 4). This device uses an axial drive mechanism and ensures the standardization for the purpose of easy maintenance, repair and replacement.

Besides, for installing the force measurement device, the designed intermediate connection parts have grooves to ensure that the device does not rotate during a test (Fig. 5). In addition, the grips for tensile test and the fixtures for bending test are attached below the force measuring device as shown in Fig. 6.

All intermediate parts, grips and fixtures are made of C45 steel due to its strength and machinability.

2.2.3. The measurement devices
Firstly, due to the advantages of high accuracy and high standardization, the loadcell (Fig. 7 (a)) is selected as a force measurement solution in the testing machine. Loadcell is a device used to convert force or weight into electrical signals and used to measure large, static or slow-changing forces. Loadcell operates on the principle of Wheatstone bridge circuit. To satisfy technical requirements and limited funding, the selected loadcell can measure a maximum load of 1000 N for both tensile and compression forces.

Next, the strain gauge (Fig. 7(b)) is selected as a strain measurement device in this testing machine. The strain gauge is actually a resistor, whose resistance changes when the length of the resistor changes and thus gives the strain value. Similar to loadcell, strain gauge uses the Wheatstone bridge circuit to ensure high accuracy.
Finally, a linear potentiometer (Fig. 7(c)) is used as a device to measure the displacement of grips in tensile test or the deflection of specimens in bending test. It is similar to a digital absolute indicator but it has outstanding advantages such as higher accuracy and ability to connect with readers to capture data continuously in real time.

![Linear actuator (a) and its internal structure (b)](image)

**Fig. 4:** Linear actuator (a) and its internal structure (b)

![The intermediate part for installing the force measurement device](image)

**Fig. 5:** The intermediate part for installing the force measurement device

![The fixtures (a) and the grips (b)](image)

**Fig. 6:** The fixtures (a) and the grips (b)
Fig. 7: The measurement devices: Loadcell (a), strain gauge (b) and linear potentiometer (c)

The final design is presented in Fig. 8.

Fig. 8: Final design of the miniature testing machine for tensile test (a) and bending test (b)

2.3. Structural analysis
The sizing of components and the structural analysis are realized by finite element method using ABAQUS software.

Mechanical properties of materials are given in Table 1.

| Table 1. Material properties |
|-----------------------------|
| Materials       | Young's Modulus (MPa) | Poisson ratio | Ultimate tensile strength (MPa) | Yield strength (MPa) |
| Shaped aluminum | 69000                 | 0.33          | 110                            | 95                  |
| C45 steel       | 190000                | 0.29          | 630                            | 310                 |

2.3.1. Load and boundary conditions
The load and boundary conditions are presented correspondingly in Fig. 9 and Fig. 10.
Fig. 9: Load and boundary conditions for shaped aluminum components

In fact, the real applied forces on the parts are very complex due to the influence of many factors such as the gap in the assembly and the interaction between components. However, the loading magnitude and rate are small in our test condition. So, these influencing factors will be ignored to simplify the setting of load and boundary conditions but still ensure the properties and operation principles of the components.

The frame structure can be considered as a truss. Using the theory of truss, the internal forces in the members of the truss can be calculated in case of only one external load which is the force created by the actuator during the test.

For the boundary conditions, all shaped aluminum components and intermediate parts are fixed at the position of connection.

Fig. 10: Load and boundary conditions for other intermediate parts

2.3.2. Meshing

For the shaped aluminum parts, because of the complicated surface shape, the swept meshing technique is applied with element type of C3D8R (Fig. 11). In addition, the mesh will be fine in stress concentration regions and coarse in the remaining regions.

For other parts, because their shape is simpler, structured meshing technique is applied with the same element type of shaped aluminium parts (Fig. 12). The structured meshing technique generates structured meshes using simple predefined mesh topologies. Abaqus/CAE transforms the mesh of a regularly shaped region, such as a square or a cube, onto the geometry of the region needing to mesh.
Fig. 11: Meshing models of the aluminum profile parts using bias technique with minimum size of 2 and maximum size of 10

Fig. 12: Meshing models of other parts with element size of 1

2.3.3. Simulation results
To avoid plastic deformation in the frame during loading, the maximum stresses in components do not allow to overcome the yield stress of material. To compensate for the errors from modeling simplification and mechanical properties of materials in a structural calculation, a safety factor of 3 is taken into account. Results of stress and displacement field of some parts are presented in Fig. 13 and Fig. 14. After analyzing the structure, the results show that the frame ensures durable conditions during operation: the maximum stress of all components showing in Table 2 is less more three times than the yield stress of the material. Besides, the displacement of all components is negligible (less than 0.05 mm). It means that the frame is considered solid and ensures the co-axial during a test.

Table 2: Comparison of stress to material ultimate tensile stress

| Parts               | $\sigma_{\text{max}}$ (MPa) | $\sigma_{\text{YS}}/3$ (MPa) |
|---------------------|------------------------------|------------------------------|
| Shaped aluminum     | 0.728                        | 32                           |
| Others (C45 steel)  | 25.08                        | 103                          |
Fig. 13: Results of Von Mises stress (a, c) and resultant displacement (b, d) of some shaped aluminum parts

Fig. 14: Results of Von Mises stress (a, c) and resultant displacement (b, d) of some other parts

2.4. Control system

The main force of the machine is generated by a linear actuator. According to the specification of producer, maximum operating voltage of the linear actuator is 24 V corresponding to the speed of 5 mm per second. There is a limitation that the linear actuator is not able to de-assembly to set up a control system. Hence, it must be connected to a H-Bridge which transfers the signal to Arduino to control PWM. Therefore, it is possible to obtain the specific speeds satisfying the ASTM standard or the others.

In addition, a potentiometer linear 50 mm is connected to the linear actuator by mechanical connectors to transfer signals of displacement to Hocdelam USB-9090 card for the feedbacks of controlling. The connection should be ensured the co-axial during testing. It is also supposed to record the displacement in bending test.
2.5. Data acquisition

The data acquisition system composes a load cell, a strain gauge, two amplifiers (VAmp) for load cell and strain gauge and a Hocdelam USB-9090 card (10 bits Analog to Digital Converter) as shown in Fig. 16. The DAQ system receives the signals of output voltage from the load cell and the strain gauge, then amplifies and transforms these signals to ADC values. After calibration the sensors, these ADC values are transformed to force and strain values which are shown on computer with LabVIEW software.

First of all, the data acquisition requires the signal to be stable. Due to the effect of voltage amplifier, the noise of electric signal is slightly high. To tackle these problems, it is possible to use a Kalman filter (which is not presented in this paper) in home-made LabVIEW program to reduce the noise. In addition, it is also combined with the block of sample variances to process signals smoother. Therefore, the calibration procedure in the next step is simple.

The calibration of the loadcell is realized by measuring different calibrated test weights and its corresponding output voltages as presented in Fig. 17. The output voltage is amplified and transformed to ADC value. In our system, 1 ADC is equivalent to 0.1 kg. For all different weights, the gain value is adjusted until the value of ADC corresponding to test weight with smallest errors by changing potentiometer of amplifier as shown in Fig. 18.
The results of calibration of loadcell is shown in Fig. 19. It can be seen that the ADC value increases linearly with the test weight for the chosen gain value of amplifier.

![Load Cell Calibration Graph](image)

**Fig. 19:** Result of calibration of loadcell

In terms of strain gauge calibration, in our study, the approach method is using the cantilever beam theory with a standard steel beam having known cross-section dimension and Young’s Modulus. This system composes a long beam which is fixed in one end and free in another end (Fig. 20). A dial indicator measures values of the displacement at free end when there is an applied load. The cantilever beam theory allows to define the stress state in beam. From the Young’s modulus, it is possible to estimate strain at where a strain gauge is attached to the surface.

![System for Calibrating Strain Gauge](image)

**Fig. 20:** System for calibrating strain gauge (at the red dot): 1) Weights; 2) Dial Indicator; 3) Steel beam; 4) Clamp

Fig. 21 presents the strain gauge calibration using cantilever beam theory. The beam is fixed at point B and is applied a load P at point A. The vertical displacement at point C is given by the dial indicator. A strain gauge is attached to the upper surface of the beam at point D. The position of these
points is defined via the distance to the fixed end B such in Fig 21. The Young’s modulus of material is defined by following equation:

\[
E = \frac{p}{y \times I_x} \left( \frac{z^3}{6} - \frac{L^2}{2} z + \frac{L^3}{3} \right)
\]

where \(y\) is the displacement at a point far from fixed end a distance of \(z\), \(I_x\) is area moment of inertia related to the \(x\) axis \((I_x = b \cdot h^3 / 12)\) and \(b\) is width of beam.

![Fig. 21: The cantilever beam for strain gauge calibration](image)

At point C, the displacement is measured by a dial indicator and the results are shown in Table 3.

| \(M\) (kg) | \(P\) (N) | \(y\) (mm) |
|------------|-----------|------------|
| 0          | 0         | 0          |
| 0.1        | 0.98066   | 2.428      |
| 0.2        | 1.96132   | 5.022      |
| 0.3        | 2.94198   | 7.73       |
| 0.4        | 3.92264   | 10.418     |
| 0.5        | 4.9033    | 13.018     |

Based on the results obtained from Table 3, evaluated Young’s Modulus is 196306 MPa (1.8% difference in compared to theory value \(E_{\text{theory}} = 200000\) MPa). Hence, the result is valuable.

The local stress at point D is defined in the form below:

\[
\sigma = \frac{P \times l}{I_x} \times \frac{h}{2}
\]

where \(l\) is the distance from the fixed end to attached strain gauge, \(h\) is the thickness of the beam.

With calculated Young’s Modulus of 196306 MPa and the 30x3 mm cross-section of the beam, the strain at point D is estimated by \(\varepsilon = \sigma / 196306\) and shown in Table 4.

On the other hand, the output voltage of strain gauge is amplified and transformed to ADC value. To obtain the highest accuracy of strain gauge, the corresponding ADC value must be highest. It means that 1 ADC corresponds to smallest measurable strain. In the range of gain value of used amplifier, the maximum ADC value corresponding to 0.1 kg is 7. The next steps of calibration are similar to ones in loadcell calibration. The final gain value for strain gauge amplifier is obtained from measured results in Table 3 and the obtained accuracy of strain gauge is nearly 8.
Table 4: The obtained strain and ADC value corresponding

| M (kg) | \( \sigma \) (MPa) | \( \epsilon \) (\( \mu \)m/m) | ADC value |
|--------|--------------------|-------------------------------|-----------|
| 0.1    | 10.3514            | 52.7                          | 7         |
| 0.2    | 20.7028            | 105.5                         | 13        |
| 0.3    | 31.0542            | 158.2                         | 19        |
| 0.4    | 41.4056            | 210.9                         | 26        |
| 0.5    | 51.7571            | 263.6                         | 33        |

The results of calibration of strain gauge is shown in Fig. 22. It can be seen that the ADC value increases linearly with the test weight for the chosen gain value of amplifier.

3. Results and validation

Fig. 24 shows the complete test machine under tensile test. It composes the construction, the control system for linear actuator and signal processing and acquisition system.

Fig. 22: Results of calibration of strain gauge

Fig. 23: A GUI LabVIEW for tensile test
In terms of assessing the accuracy of our test machine, the strain acquisition is verified first, then some experimental results are analyzed. The strain measured directly by strain gauge is compared with one defined by the Digital Image Correlation (DIC) method (which is not presented in this paper). The results of stress-strain curve of natural fiber composites are shown in Fig. 25 and Fig. 26. It is clear that the strains measured by two different methods are equivalent. Hence, it can be concluded that the calibration of strain gauge is accurate (maximum difference is about 15%).

Fig. 24: Miniature testing machine in tensile test: 1. Control system; 2. Data acquisition system; 3. Computer

Fig. 25: Comparison of two strains on 15% coir/epoxy composite measured by DIC (dot) and strain gauge (line)

Fig. 26: Comparison of two strains on 43% paper/epoxy composite measured by DIC (dot) and strain gauge (line)
Because the composite materials in this study are made of coir fibers in form of sheet and having random orientation, they are not only an orthotropic composite as usually but also considered to be in-plane isotropic elastic material. Therefore, their shear modulus can be calculated in two different ways corresponding for two material behaviours. Table 8 shows the shear modulus of 15% fiber composite calculated from two different ways. The difference between two values of shear modulus is small (less than 5%), it can be concluded that the experimental results of 15% fiber composite group are reliable.

Table 5: Comparison of shear modulus of 15% fiber composite

| Specimens | 15% fiber composite |
|-----------|---------------------|
| \( G_x(MPa) = \frac{E}{2(1+\nu_{xy})} \) | 1257 |
| \( G_y(MPa) = \left( \frac{f}{G_f} + \frac{1-f}{G_m} \right)^{-1} \) | 1218 |
| Error (%) | 3.1 |

From these results, it can conclude that the test machine allows to realize tests and acquire the data which is acceptable and valuable. Furthermore, the stability of machine is good with smooth curve of mechanical properties.

4. Conclusion

In this study, the design, calibration and compliance measurement of a miniature test machine for tensile test were discussed. The design has the load bearing capacity up to 3000 N. The machine permits the minimum loading rate of 1.7 mm per minute and the strain precision of 8. On the other hand, the recorded data is smooth enough to be probable to get the mechanical properties of material pretty accurate. In addition, the machine performance and compliance measurement are appreciated during tensile test. The machine has also an additional advantage that is lower cost and smaller size compared to the commercial ones. Moreover, it is ideal for the mechanical properties of the medium-strength materials. In the future, it will be supported with more accuracy card, more powerful load generator and well-being structure.

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