

Development of a Portable Universal Testing Machine for Investigating the Mechanical Properties of Medium-Strength Materials

Muhammad Rizal^{1,*}, Udink Aulia¹, Radinal Yudiansyah¹,

¹Department of Mechanical Engineering, Faculty of Engineering, Syiah Kuala University (USK), Darussalam, Banda Aceh 23111, Indonesia

*Corresponding author: muh.rizal@usk.ac.id

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Abstract – The tensile test is reliable for revealing the fundamental stress-strain relationship. However, researchers have challenges when applying sufficient equipment to comprehend and assess the tensile characteristics of low-to-medium-strength materials. This study describes the design and construction of a portable universal testing machine (UTM) for investigating the mechanical characteristics of medium-strength materials. The components of this machine include two stepper motors, a load cell, a load cell amplifier, a linear potentiometer, and a data acquisition system. The capability of this machine component is designed for a load of 10 kN with a maximum stroke of 150 mm with vertical motion. Samples of jute and glass fiber composites were tested at room temperature on this machine. The generated results were compared with those obtained from a commercial UTM to validate the developed machine. The values of the mechanical characteristics that a commercial UTM measured are quite similar to those acquired from the measurements that were taken by this machine. The conclusion is that this testing machine is simple, portable, reliable, and might be constructed cheaply.

Keywords: Tensile test; universal testing machine; portable UTM; medium-strength materials test.

Introduction

The features and qualities of a material are evaluated under a variety of situations, loads, and settings before it is chosen to be used in the production of a product. This evaluation is based on the material's overall performance under these factors. A standard testing procedure is implemented to provide a person not very experienced with the material with a means to quantify the material's properties. A universal testing machine is utilized to accomplish this task. The standard UTM machines produced by industries are neither precisely user-friendly nor cost-effective. As well as this, there are occasions when high-capacity machines do not detect low measurement results (Gunter *et al.* 2021).

Many researchers are interested in developing miniature tensile testing methods to determine the mechanical characteristics of low-strength materials accurately. Lim and Kim (2013) developed a miniature tensile tester with a low capacity and intended to pull 6061 aluminum material. They construct horizontal models with a maximum load capacity of 2 kN and a maximum stroke of 20 mm. This system can carry out tensile tests on small tensile specimens at rates ranging from 0.001 to 1.0 mm/s. Baharuddin and Yani (2018) proposed a vertical type of tensile machine with a maximum load of 5 kN for testing copper and aluminum. The servo motor that drives this tensile testing apparatus has a 100-watt output, and the power is transferred to the device through a V-belt. Cruz *et al.* (2020) also designed and constructed a tensile-compression loading apparatus with a maximum load capacity of 2.5 kN. Even advancements in materials and requirements for the design of micro products call for testing machines with low loads and excellent precision. For example, testing thin workpieces and superelastic kinds of bio-materials need testing equipment with these characteristics (Gunter *et al.*, 2021; Singh, 2022).

However, there has been a tremendous increase in the development of materials of medium-strength, such as composites with a variety of natural or synthetic fiber reinforcement combinations (Rizal *et al.*, 2019) (Karimah

et al., 2021; Saidi *et al.*, 2022). The composite material hybrid jute/kenaf/e-glass has also been subjected to tensile testing, which shows that the tensile load used in the test is not more than 0.5 kN. The majority of tests performed on composites made with natural fibers fall somewhere in the range of 5 to 8 kN (Srinivasan *et al.*, 2014). Consequently, developing an appropriate testing instrument with a simple and accurate system to accommodate the characterization of the mechanical properties of these materials is a challenge that must be overcome.

Therefore, in this article, a portable universal testing machine is designed and built with a vertical type using a mechanical drive using two stepper motors and equipped with force and displacement measuring devices with maximum values of 10 kN and 150 mm, respectively. Tensile and flexural testing may also be performed on the developed instrument using the required fixtures and specimens in these directions. After this UTM has been developed, two samples of jute and glass fiber composites are used in the testing. Sample reports are compared to the outcomes of testing performed using a commercial UTM to validate the effectiveness of the designed UTM.

Materials and Methods

The design concept of the developed UTM

The newly developed UTM is intended to be used for testing materials of medium strength in the load range that has been specified. These materials include those made of soft metals, composites, polymers, and other materials, in terms of the loading capacity of the proposed UTM, the specimen dimension, and the preparation procedures as standard for a commercial machine. The general structure of the universal testing machine is shown in Figure 1, and all of the machine's developed apparatus specifications are shown in Table 1.

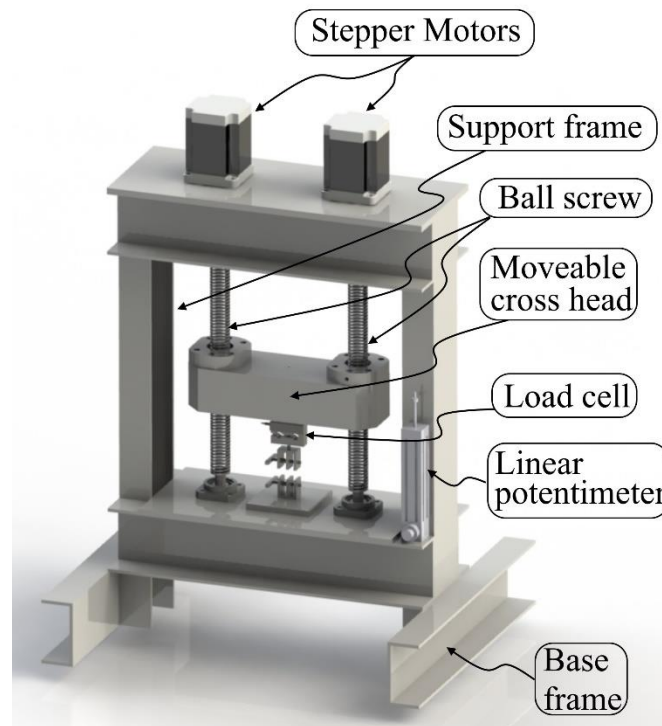


Figure 1. The overall structure of the designed UTM

Table 1. Requirement of the developed UTM

Type mounting	Vertical with two supports
Load Capacity	10 kN
Maximum stroke	150 mm
Drive mechanism	Twin lead screw and two stepper motors @9.2 Nm.
Sensor	Load cell (10kN) and Linear potentiometer (150 mm)

The developed machine has a number of general features, including the ability to carry out tensile, compression, and bending tests; an easy-to-use and control system (only on, off, and select speed); the absence of hydraulic or pneumatic air supplies; portability; an easy-to-carry or move instrument; a compact instrument; and easy operation.

Analysis of strength-driven component

The maximum torque, tension, and buckling forces that occur when the UTM is subjected to the maximum load as designed must be considered in order to ensure the strength of the driving components. Based on the maximum axial load designed for single ball screw F_a , 5 kN, and lead P , 5 mm, with an efficiency η of 96%, the maximum torque imposed on the ball screw can be calculated by the following equation:

$$T = \frac{F_a P}{2\pi\eta} = \frac{(5000)(0.005)}{2(3.14)(0.96)} = 4.14 \text{ Nm} \quad (1)$$

Compared to the driving torque of the selected motor, which is 9.2 Nm, the torque value is significantly lower, indicating that the selection was suitable. The maximum stress that occurs in a ball screw with a diameter (d) of 20 mm due to axial and torsional loads can be determined by the following equation:

$$\sigma_{eq} = \frac{4F_a}{\pi d^2} \sqrt{1 + \frac{12P^2}{\pi d^2 \eta^2}} = 16.5 \text{ MPa} \quad (2)$$

The equivalent stress that occurs in the ball screw is less than the allowable stress of 147 MPa, so the selection of diameter is safe and suitable for this design. The maximum axial force that can be accepted by a ball screw so that it does not buckle can be determined with the condition that the shaft end is fixed and free as follows:

$$F_c = f_b \frac{d_1^4}{l^2} \cdot 10^4 = 0.25 \frac{16^4}{400^2} (10^4) = 10.24 \text{ kN} \quad (3)$$

Where f_b is the mounting factor (0.25), d_1 is the base diameter of the ball screw (16 mm), and l is the length of the ball screw rod (400 mm). The calculation results show that the maximum axial load that can be accepted is 10.24 kN, while the designed UTM machine is only 5 kN, so the rigidity of this machine structure is adequate.

Mechanical system and construction

The primary support structure of the designed UTM is a U-channel made of construction steel that conforms to ASTM A36. This ensures that the UTM is both strong and durable. On the other hand, frictional elements such as the bearing and ball screw, both of which are composed of alloy steel (SAE 52100). The moveable cross head is propelled by a pair of ball screws, each of which is powered by a stepper motor (NEMA 34). A stepper motor driver (B1206) is utilized to synchronize the movements of the two ball screws. A stepper motor controller (YF-18) is utilized to control the rotational speed and direction of the stepper motor. The construction of the developed UTM fabrication results and the appearance of the supporting components is shown in Figure 2.

The developed tensile machine has a load cell of the S-type with a capacity of 10 kN. This load cell is positioned between the moveable crosshead and the upper mechanical grip to measure the axial force while pulling or pressing the specimen. In contrast, the lower specimen grip is permanently attached to the base frame. This force sensor is coupled to a load cell amplifier (JY-S60) to amplify and condition the analog signal. The displacement of the machine crossheads was measured using a precision linear potentiometer (KTC 150) with a linearity of 0.05% and a maximum displacement of 150 mm. This was done so that the material strain rate could be determined.

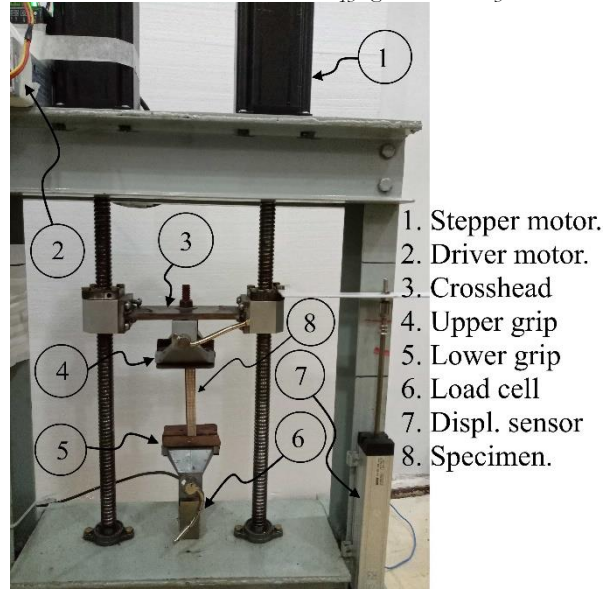


Figure 2. Photograph of developed UTM

Results

The performance of the newly constructed UTM needed to be evaluated before it could be used for data collection for either experimental or commercial purposes. Supporting sensors include commercial load cells such as the Zemic H3-C3-1000 kg-3B, which has a full-scale scale output of 2.0023 mV/V and a non-repeatability of less than 0.01% FS. The displacement sensor receives an input voltage of up to 5 V and has a 3.33 mV/mm sensitivity across its full-scale scale range. With a sampling rate of 2 kHz, the NI-Daq NI-9221 performs as the data-collecting device for both sensors.

Every data point acquired and presented by the data acquisition device is a raw signal that must be filtered before the signal's essential data can be provided accurately. The results of a test to acquire force and displacement signals using a UTM machine are depicted in Figure 3. It can be observed that the filtered data results reveal linear, and the filtered data will be required for plotting and calculating the property values of the material being tested by utilizing this tensile machine.

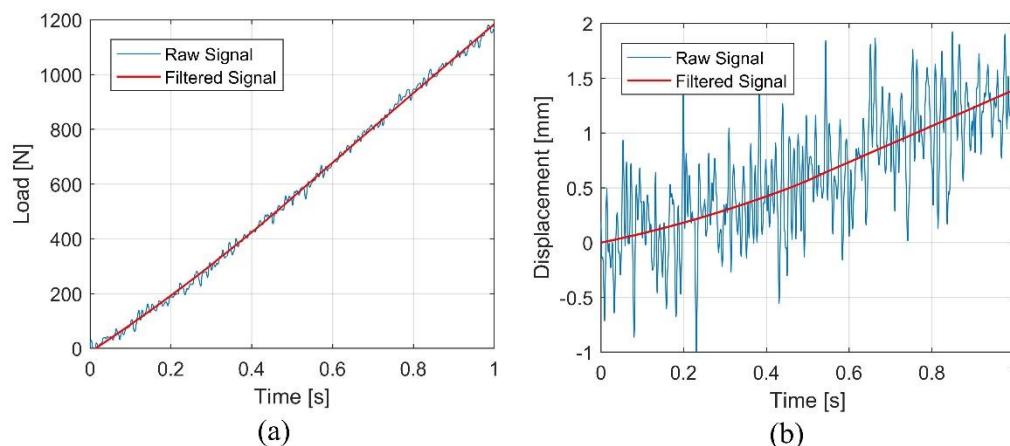


Figure 3. Raw and filtered signals from sensors: (a) force signal; (b) displacement signal.

Discussion

In order to verify the performance of the newly developed UTM, two different types of composite, jute and glass fibers reinforced polymer, were used as test specimens. A mixture of polyester resin and hardener with a

ratio of 10:1 was used to produce the matrix component for this experiment. Using the hand lay-up technique, the specimen laminates were fabricated with dimensions of 350 mm × 350 mm, equating to an average thickness of around 5 mm. The compression molding apparatus was used to apply pressure to the specimen laminates while they were at room temperature. After the step of compression, the laminates of jute fiber-reinforced polyester composite (JFRP) and glass fiber-reinforced polyester composite (GFRP) were cut into the required ASTM D638-10 (ASTM D638, 2010) standard size for the next experimental test, as shown in Figure 4. All the tensile tests have been carried out using similar specimens and a crosshead velocity of about 5 mm/min. This has been done so that the findings from the developed UTM may be compared with the stated test results generated from a commercial UTM to evaluate the performance. The real photographs of actual tensile tests carried out on the commercial UTM (Capacity 50kN) and the developed UTM are displayed in Figure 5.

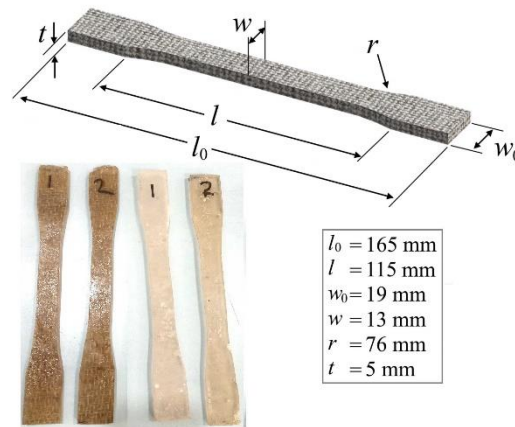


Figure 4. Schematic of tensile specimen dimensions and actual specimen.

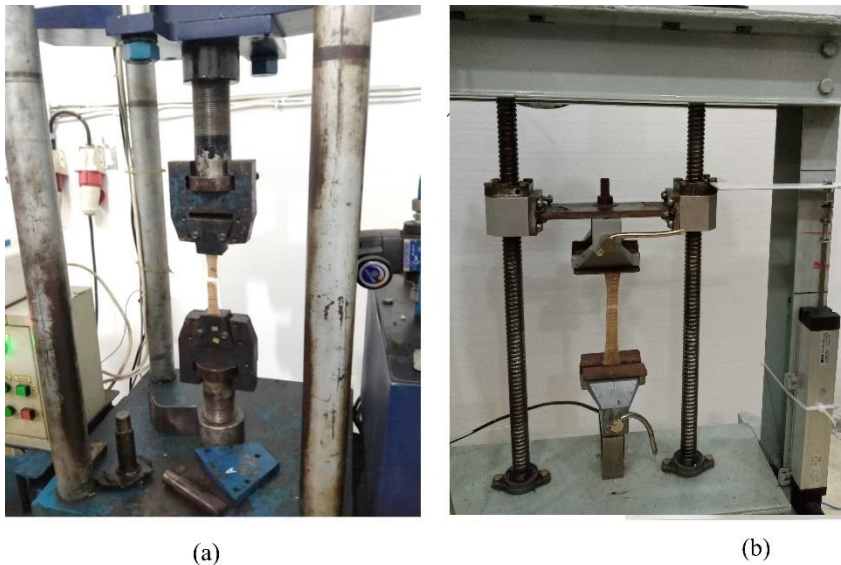


Figure 5. The photographs of actual tensile tests: (a) commercial UTM; (b) developed UTM.

Figure 6 depicted the tensile curve results of the stress versus the strain rate for jute and glass fiber composites using commercial and developed UTM. For jute composite, it can be observed that the graph reveals that the tensile curve of the two types of fiber composites is almost the same. When comparing the findings of commercial and designed UTM machines for yield stress, ultimate tensile strength, strain rate, and Young's modulus, the absolute errors for the jute tensile test are 2.49 percent, 3.92 percent, 6.67 percent, and 9.55 percent,

respectively. The error range for glass fiber composite, another material used in the tests, is 1.12%–10.64%. This indicates that the developed UTM performance test results are reliable and validated. However, the differences in these data have many influencing factors, including the sample's homogeneity and the cut's accuracy (Saadati *et al.*, 2020; Kowshik *et al.*, 2022). However, what is significant is that the grip on the developed UTM still slips for stresses above 40 MPa, which is visible in the tensile curve for glass fiber composite materials. Tables 2 and 3 provide a detailed overview of the comparison's findings, including the relevant characteristics and data.

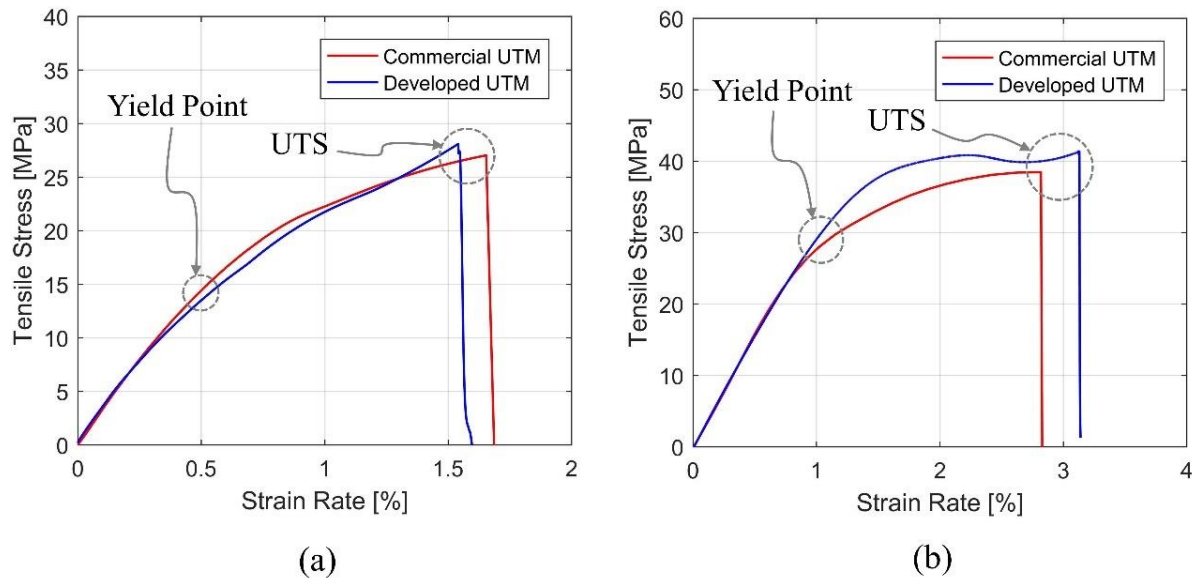


Figure 5. Tensile stress-strain curve: (a) jute fiber composite; (b) glass fiber composite.

Table 2. Comparison of mechanical properties of jute fiber composite.

Mechanical Properties	Yield Strength (MPa)	UTS (MPa)	Strain Rate (%)	Modulus Elasticity (MPa)
Developed UTM	13.33	28.087	1.54	3427
Commercial UTM	13.67	27.027	1.65	3117
Absolut Error (%)	2.49	3.92	6.67	9.95

Table 3. Comparison of mechanical properties of glass fiber composite.

Mechanical Properties	Yield Strength (MPa)	UTS (MPa)	Strain Rate (%)	Modulus Elasticity (MPa)
Developed UTM	25.49	40.76	3.12	3015
Commercial UTM	24.36	38.39	2.82	3049
Absolut Error (%)	4.64	6.17	10.64	1.12

All test curves for both composites show a linear range at low strain, followed by a transition into a plastic zone up to the breaking point at a strain of 1.5–3.0%. Compared to glass fiber composites, which can reach up to 38–40 MPa in tensile strength, jute fiber composites have a maximum tensile strength of 27–28 MPa. Previous studies reported that the tensile strength of jute fiber composites was in the range of 23–40 MPa and that the tensile strength of glass fiber composites was in the range of 28–78 MPa (Dobah *et al.*, 2016; El-wazery *et al.*, 2017; Sajin *et al.*, 2022). Hence, this material's elongation and tensile properties align with those reports.

Conclusion

In this work, a portable universal testing machine (UTM) for investigating the mechanical properties of medium-strength materials was designed, constructed, and tested. The developed UTM is designed using the

concept of a double drive motor and lead screw to tension test sample material up to 10 kN with a maximum stroke of 150 mm in the vertical direction. Force and displacement measurement devices use a strain gauge-based load cell and a linear potentiometer, whose data were acquired with one NI-9221 device. Two types of composites, jute, and glass fiber polymers, were used for validation tests to evaluate the performance of the developed UTM. The obtained curves have the same shape as in the case of a standard or commercial UTM. The results show that the absolute error of the comparison test is in the range of 1.5% to 10%. This indicates that the developed UTM can be used for tensile testing with quite accurate and reliable results. However, it's important to ensure that the sample's grip is sufficient for a relatively high tension so that it does not slip.

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