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Research Article

# Design and Construction of Tensile Testing Machine for Shape Memory Alloy Material Labouratory Test

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## I N F O

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## A B S T R A C T

Abstract. In this paper, the research focused on the design and construction of a tensile testing machine specifically for Shape Memory Alloy (SMA) rod and spring material tensile testing. We designed the machine to evaluate the mechanical properties of SMAs, primarily focusing on their unique ability to return to a predefined shape after deformation. Components were carefully selected and assembled to ensure precise force application, strain measurement, and control during testing. The structure of the machine is similar to that of an industrial one; however, it is budget-friendly. The machine consists of a frame, one step motor that controls a cross-head movement on a sliding bed, three grippers, a digital force gauge, a water heater hold, a controller and Arduino that controls the step motor, and a 24v adaptor. The final machine was tested and calibrated, demonstrating its capability to conduct tensile tests accurately. The completed system has been successfully implemented in the laboratory, contributing to enhanced understanding and analysis of shape memory alloys.

**Keywords:** Tensile Properties, Shape Memory Alloys, Digital Force Gauge, Controller, Thermo-Mechanical Coupling

## Introduction

Tensile test equipment, often referred to as a tension tester, tensile tester, or pull tester, is a universal testing machine designed to measure the tensile strength of materials. Historically, Leonardo da Vinci is credited with being the first to conceive the concept of tensile testing. He conducted experiments by measuring the tensile strength of string using a static load, where a bucket filled with sand served as the weight (L. and P., 1999). The tensile test is conducted for various reasons, primarily to verify material specifications and ensure the quality of materials for engineering applications (Rivki et al., no date); it is carried out to assess how a material behaves when subjected to uniaxial tensile loading (SARAY, BHULLAR, and GÜNEY, 2015). Tensile testing provides insight into how a material responds to static loading. However, under dynamic conditions, the material can withstand significantly lower loads. Additionally, the tensile properties of a material are influenced by temperature, with higher temperatures generally leading to a decrease in tensile strength (Fábián and Gergely, 2020).

During the test, the applied tensile load and the resulting extension are recorded to determine the material's stress and strain. The uniaxial tensile test is a fundamental and widely used engineering method to evaluate material properties such as ultimate strength, yield strength, Young's modulus, percentage reduction in area, and percentage elongation (Khayal, 2019).

There are two main types of tensile testing machines: hydraulic and electromechanical (ADMET, 2005). In hydraulic machines, a single or dual-acting piston is used to move the crosshead up and down. In contrast, electromechanical machines utilize an electric motor, a gear reduction system, and one or more screws to control the movement of the crosshead (ADMET, 2005). Numerous tensile testing machines are designed and built for laboratory use. A small-scale benchtop tensile testing machine has been developed specifically for testing metal specimens with a maximum load capacity of 20 kN (Testing, 2023). A compact and user-friendly tensile testing machine was designed to enable students to perform miniature tensile tests in the classroom. This machine operates at speeds between 0.001 and 1.0 mm/s (Lim and Kim, 2013). A portable benchtop tensile machine was created for single cyclic loading of super-elastic biomaterials, including tissues. The machine operates at speeds ranging from 0.01 to 10 mm/s (Gunter et al., 2021).

Most of the tensile testing machines available on the market are very expensive. For this reason, we chose to design and construct our tensile testing machine, which is budget-friendly and suitable for SMA material testing. The tensile testing machine will be designed specifically for evaluating the mechanical properties of Shape Memory Alloys (SMAs). This machine will allow researchers and students to perform accurate tests to determine the tensile strength, elasticity, and deformation characteristics of SMA materials under controlled conditions. The research has the following objective:

- To design a tensile testing machine that can handle the unique properties of shape memory alloys.
- To ensure precision and repeatability in tensile tests.
- To give an easy operation and data collection.

## Conceptual Design

The machine is designed to have a single-column stand with a sliding bed attached to the upper part. A step motor is attached to the upper end of the sliding bed, controlling the movement of a crosshead along a screw-threaded shaft. There is a digital controller attached to an adjustable stand and a digital force gauge attached to the crosshead. There are three grippers, with one attached to the loading cell, the second gripper attached at the middle of the column, and the third one attached to the base of the machine. A water heater holder is attached to the lower part of the column stand, and a cap covers the column and step motor from the top. The design of the machine is actualized as follows:

### Components required to be designed and constructed

The machine consists of the following main parts:

- Frame
- Moving head
- Sliding bed actuator (model no. 1605). This consists of a step motor, screw rod, moving nut, and bearing
- SMA wire gripper
- (ST-PMC1) single-axis motion controller
- Digital force gauge (model no.: HP-500N)
- Heating Chamber

The components to be designed and fabricated are the moving cross-head, frame and heating chamber. The remaining components which include the loading cell, controller, Arduino, step-motor and sliding bed are purchased from the store and assembled.

### Design for the frame

The frame of tension testing equipment consists of 3 major parts, which are given below and described separately. A few factors have been considered in designing the frame to increase operator safety, accuracy of results, and cost reduction. It is single-column vertical testing equipment. A force sensor is installed on the moving crosshead to measure precisely, while a control unit is installed on the side to make it safe for the operator and easily connect with power and a computer. The main structure is made of steel to make it stable and support heavy objects, and it has a hot water chamber for SMA spring testing.

The main components are given below:

- Frame
- Moving crosshead
- Water heater chamber holder
- Elongation scale

### Frame

The frame is single-column support. The main part of the frame is a table base on which the column stands. The base has a gripper where the specimen for the application of the tensile test is attached. We have used rectangular pipe with an outer size of 80x60 mm and a thickness of 3 mm for the frame body. The stress on the frame is calculated as:

$$\sigma = \frac{F}{A} \quad (1)$$

The effective area of the rectangular pipe is calculated as:

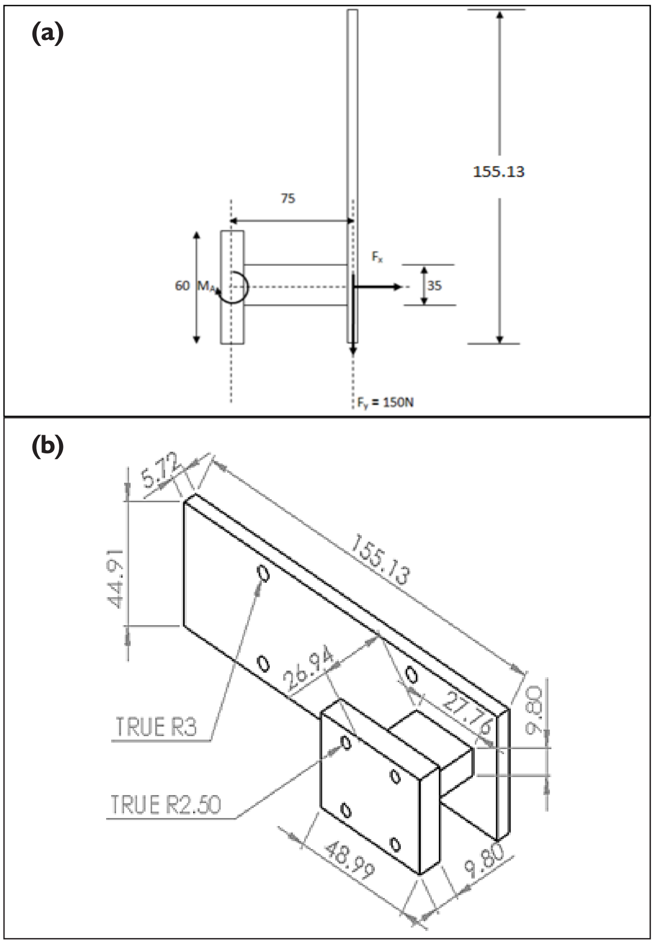
$$[(80 \times 60) - (74 \times 54)] \times 10^{-3} = 0.804\ m^2$$

$$\sigma = \frac{150}{0.804} = 186.6 \approx 200\ Nm^{-2}$$

Using the factor of safety of 2.5, the stress is going to be 500 N/m$^2$ on the frame

## The Moving Crosshead

Figure 1 shows the crosshead; it is the component that carries the force sensor and is attached to the moving nut of the sliding bed. The upper crosshead is used to test the specimen. The lower crosshead is the part that is movable, and its screws may be loosened for adjusting the height of the crosshead. Both of the crossheads are marked with a tapered slot at the center. These slots have racked jaw pairs, which are mainly used for holding and gripping the specimen during the tensile test. The moving crosshead was constructed using mild steel, and it is shown below:




**(a) Moving cross Head 1 (b) Moving crosshead 2**
**Figure 1.Crosshead**

$$\sum f_{x=0};\quad \sum f_{y=0};\quad \sum M_{A=0} \tag{2}$$

Hence, from Figure 1,

$F_y = 150$

$F_x = 0$

$MA = 75\,x\,150x\,10^{-3} = 11.25\,Nm$

## Elongation scale

The elongation scale is the part which is generally used for measuring length move by the cross-head. It is placed on the frame and has total length of 1000mm.

## Digital Force Gauge

Figure 2 shows the digital force gauge. The device offers multiple testing modes and allows for convenient data storage, enabling easy transfer to a computer for statistical analysis. It includes testers with various functions, along with test beds and clamps. A stepper motor is mounted on top to rotate the spindle, while the force sensor, connected to the spindle and driven by the motor, can measure forces up to 150N. This force sensor will be linked to a computer for data collection during experiments (Gmbh and Fh-s, 2017).

## Feature

- Five testing modes and three display methods are available to enhance testing efficiency to the maximum extent.
- Three measuring units: N (Newton), kg (kilogram), and lb. (pound) for selection and conversion.
- Maintain the display result of peak value until manually cleared.
- Max and min comparison values can be set for statistical analysis. The buzzer will alarm if it exceeds the comparison value.
- Up to 896 testing results can be stored for later use.
- The data can be transferred through a cable to a computer for analysis.

The following modes are associated with the loading cell:

### PEAK

When "PEAK" is displayed, it indicates Peak Mode (Peak Holding Mode), where the peak value is retained until manually reset. If "AUTO PEAK" is shown, it signifies Automatic Release Mode, where the peak value is held for 2 seconds before being automatically cleared. When "PEAK" is not visible, the device is in Track Mode (Real-time Load Value Mode), and the screen updates in real-time based on the applied load.

### LO BAT

When the voltage drops below 7.0V, "LO BAT" is displayed, indicating low battery. Testing can still be performed while charging.

### MEM

"MEM" is displayed when data is saved in the storage. When the "DATA" button is pressed to view stored data, "MEM" will flash.

### Display

In this mode, default thrust (tension) is represented as a negative value ("-"), while pull values are shown as positive (the "+" is not displayed).

### CMP (Comparative Function)

When adjusting the comparative value via CPDT, the "CMP" function is activated and displayed. By default, the comparative function covers the full measurement range, but it can be adjusted as needed.

### SET (Button Functional Setting)

To enter the settings, press the SET button when the device is powered on. The first option to appear will be "TEST," and a digit setting window will open after 2 seconds. Use the SEND and SET buttons to configure the test mode. Press SET again to cycle through options like “AODT,” “LODT,” “HIDT,” and “CPDT.” A digit setting window will appear for each option after 2 seconds. Set the parameters using the SEND and MEMO buttons. When “Set end” is displayed, the settings are complete, and the device enters testing mode.

The “TEST” mode is displayed in four digits with the following options:

- -0000: Real-time load value mode
- 0001: Standard testing mode
- 0002: Push-pull peak value mode
- 0003: Pull peak value mode
- 0004: Push peak value mode
- 0005: External contact break-make mode
- 0006: External contact make-break mode
- 0000: Real-time load value (random tracking) mode

During testing, the device tracks changes in the data value until it returns to zero, at which point the PEAK function is no longer active. In the default 0001 standard testing mode, the device supports three statuses: real-time load value, peak value holding, and automatic peak value. If “PEAK” is not displayed, the device is in real-time load value mode, and the testing value will vary with the load. Pressing the Peak button will display “PEAK,” indicating peak value holding, where the maximum testing value (for pull force or pressure) is shown. Pressing the Peak button again displays “AUTO PEAK,” meaning the device is in automatic peak mode, where the maximum testing value will be displayed for 2 seconds before disappearing.

In 0002 push-pull peak value mode, the maximum load in both directions (pressure and pull force) is measured. For connector testing, this mode measures the maximum load value (Fc, Ft) in both push and pull directions.

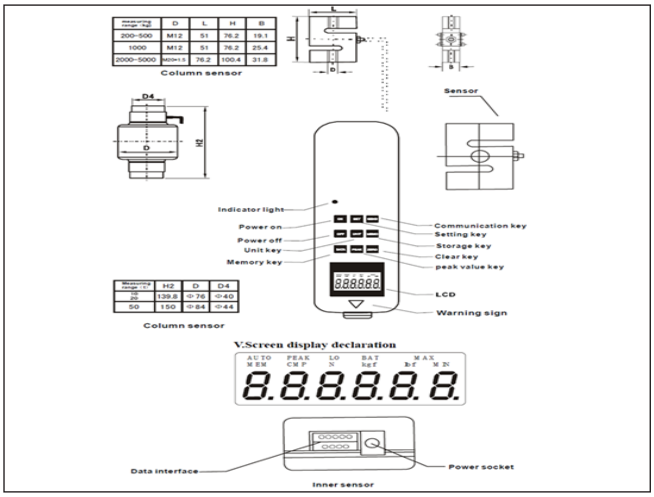



**Figure 2.Fore sensor structural diagram (Gmbh and Fh-s, 2017)**

0003 Pull Peak Value Mode: During push-pull testing, this mode controls only the maximum load (Ft) for pull force.

0004 Push Peak Value Mode: In this mode, during push-pull testing, it measures only the maximum load (Fc) for push force.

0005 and 0006 Switch Contact Make-Break Testing Mode: This mode measures the precise load value during the moment when a contact either makes or breaks. When the applied load exceeds the set value of Fa and the contact shifts from breaking to making or vice versa, the load value on the screen freezes, displaying the measured value. Connect PIN 4 and PIN 5 of the data interface (using the data plug from the accessories) as the contact signal. Testing cannot proceed unless Fa (sensing range) is set.

AODT (Sensing Value Setting): This sets the sensing value Fa for both push and pull force testing simultaneously. For example, in push force testing, when the value exceeds the sensing threshold, “Push” appears to begin testing. Once the value drops below the sensing threshold, the push-force test concludes. Similarly, for pull force testing in the opposite direction, if the value exceeds the sensing threshold, “Pull” initiates the test, and once the value falls below the threshold, the pull force test concludes.

LODT (Minimum Value Setting): Sets the minimum testing value. If the test value falls below the minimum threshold, it will be out of range, and “MIN” will be displayed.

HIDT (Maximum Value Setting): Sets the maximum testing value. If the test value exceeds the maximum threshold, it will be out of range, and “MAX” will be displayed.

CPDT (Comparison Value Setting): When the test value exceeds the set comparison value, an alarm sounds. LODT, HIDT, and CPDT work together to help the device evaluate the test data.

If you’re unsure about the settings, it’s best to reset the device. After turning it off and back on, hold the setting button for more than 4 seconds until you hear a “DI” sound, which will reset the device to its default settings. The default values are as follows:

- TEST: 0001 (Standard testing mode)
- AODT, LODT: 1% of the full measurement range
- HIDT, CPDT: Full measurement range

Data Interface (9-PIN): The force sensor has 9 pins on the back, each with a different function, as shown in Figure 3.

## Control Unit

Load exertion or the test specimen arrangement is held mostly in the loading unit. Corresponding test variations and the load application are usually obtained from the unit known as the control unit (Electric and Siemens, no date). It further categories into two main parts are:

- Load Measuring Unit
- Control Devices

## Load Measuring Unit

The grips deflect the specimen, which is based on the load that is applied to the specimen. The applied deflections are converted into the load pointer, which is then displayed as the load and can be seen on the control unit display [101].

Application load range can be adjusted within the unit of load measuring range, usually marked with the units (0-00 KN, 0-250 KN, 0-500 KN, 0-1000 KN, and so on). The overall accuracy of the machine is determined by the accuracy of the measuring unit.

We have used the electrical control unit as shown in Figure 4, which consists of switches and buttons. The reason to use an electric control system is due to its precision [101]. It is easy to operate; buttons will be used to relocate or input the data. It also has a digital meter that shows the input command and the results. It is attached to the side of the tension tester and connects with the step motor to control its speed and position.

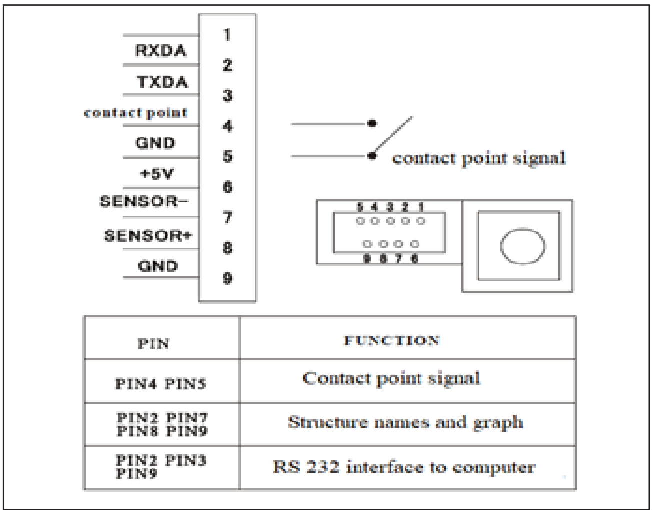



**Figure 3.Outline and mounting dimension chart (Gmbh and Fh-s, 2017)**

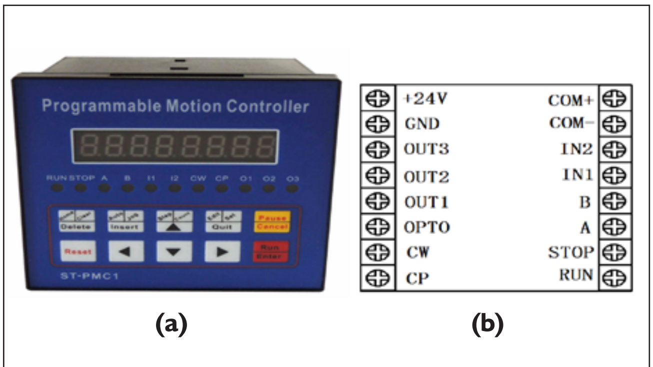



**Figure 4.(a) Single-axis step-motor operation panel controller (b) Back panel diagram**

### Features

- Single-axis operation capable of performing a variety of complex tasks, including both positioning and non-positioning control.
- Maximum output frequency: 40 kHz.
- Output frequency resolution: 1 Hz.
- Programmable with up to 99 rows.
- Continuous displacement range: -7,999,999 to 7,999,999.
- Operating modes: Auto-run mode, manual operation, program editing mode, and parameter setting status.
- Auto-run feature: Start and stop operations can be controlled via the panel buttons, with additional control possible by adding switches connected to the terminal on the back.
- Manual operation functions: Allows for position adjustment, with adjustable jog speed and number of jog steps.
- Parameter setting function: Allows adjustment of settings like starting frequency, acceleration/deceleration curves, reverse clearance, manual run length, manual speed, return-to-zero speed, and interrupt jump line.
- Program editing functions: Enables insertion, deletion, and modification of programs. The controller can also detect and report erroneous instructions.
- Return-to-zero function: The device can return to zero from both positive and negative directions.
- External operation functions: Allows interrupt operations through parameter settings and external switches connected to terminals A and B. \
- Power supply: DC 24V.
- 8-segment digital LED displays.
- 6 input status indicators.
- Output status indicator.
- CP pulse signal indicator.
- CW direction signal indicator.

### Back Panel Diagram and Signal Descriptions

- CP, CW, OPTO: Stepper motor drive signals.
- CP: Pulse signal.
- CW: Direction signal.
- OPTO: Common ground for CP and CW signals.
- RUN: Initiates program execution, same as the “Run” button on the operation panel.
- STOP: Pauses the program, similar to the “Pause” button on the operation panel. When restarted, the program resumes from where it left off.
- A: A operation; B: B operation.
- “A operation” and “B operation” are key features of the controller. For stepper motors, typically used in precise positioning control, the displacement and speed are simply set in the program to control the motor’s movement.

- IN1 and IN2: Switching signal input terminals.
- OUT1, OUT2, and OUT3: Switching signal output terminals.
- COM+ and COM-: Power supply for external input and output devices (DC 24V). COM+ is positive terminal, and COM- is the negative.
- +24V: Positive power supply; GND: Negative power supply.

### Input and Output Signals

Figure 5 shows the input circuit switch. It has the following functions:

- RUN, STOP, A, B, IN1, and IN2 are input signals, all sharing the same input interface circuit.
- OUT1, OUT2, and OUT3 are output signals with a shared output interface circuit.
- Both input and output signals are optically isolated to prevent interference between internal and external controllers.
- The status of input and output signals is indicated on the panel. When the input signal is low, the switch is closed, and the corresponding indicator light turns on. For output signals, when output 0 is low, the indicator light remains off.

When the switch is activated and the input level is low, the front panel indicator lights will turn ON, and the program interprets this as a value of 0. Figure 6 shows the output circuit switch

When there is low output or load conduction, the front panel indicator lights will turn ON, and the program recognizes this as a value of 1.

### Controller Connection Diagram

The controller connection diagram is illustrated in Figure 7.

## Operation Flow Chart

The cost analysis is presented in Table 1 as follows:

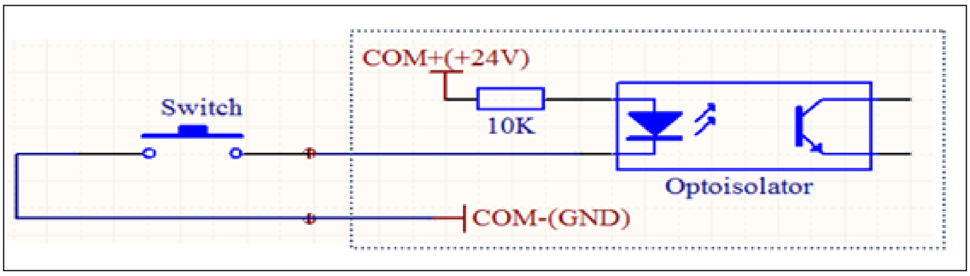



**Figure 5.Input Circuit Switch (Electric and Siemens, no Date)**

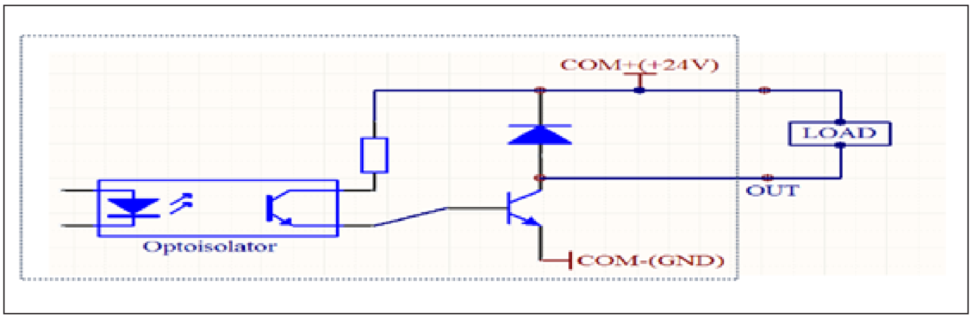



**Figure 6.Output Circuit Switch (Electric and Siemens, no Date)**

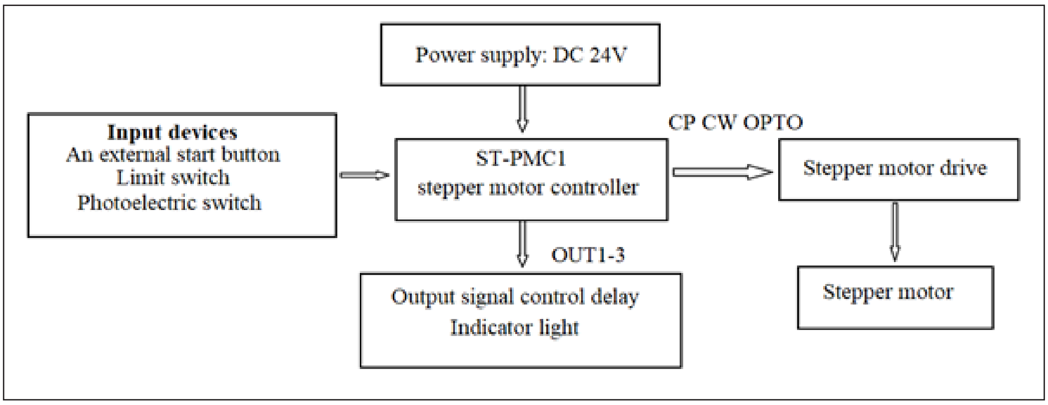



**Figure 7.Controller Connection Diagram (Electric and Siemens, no Date)**

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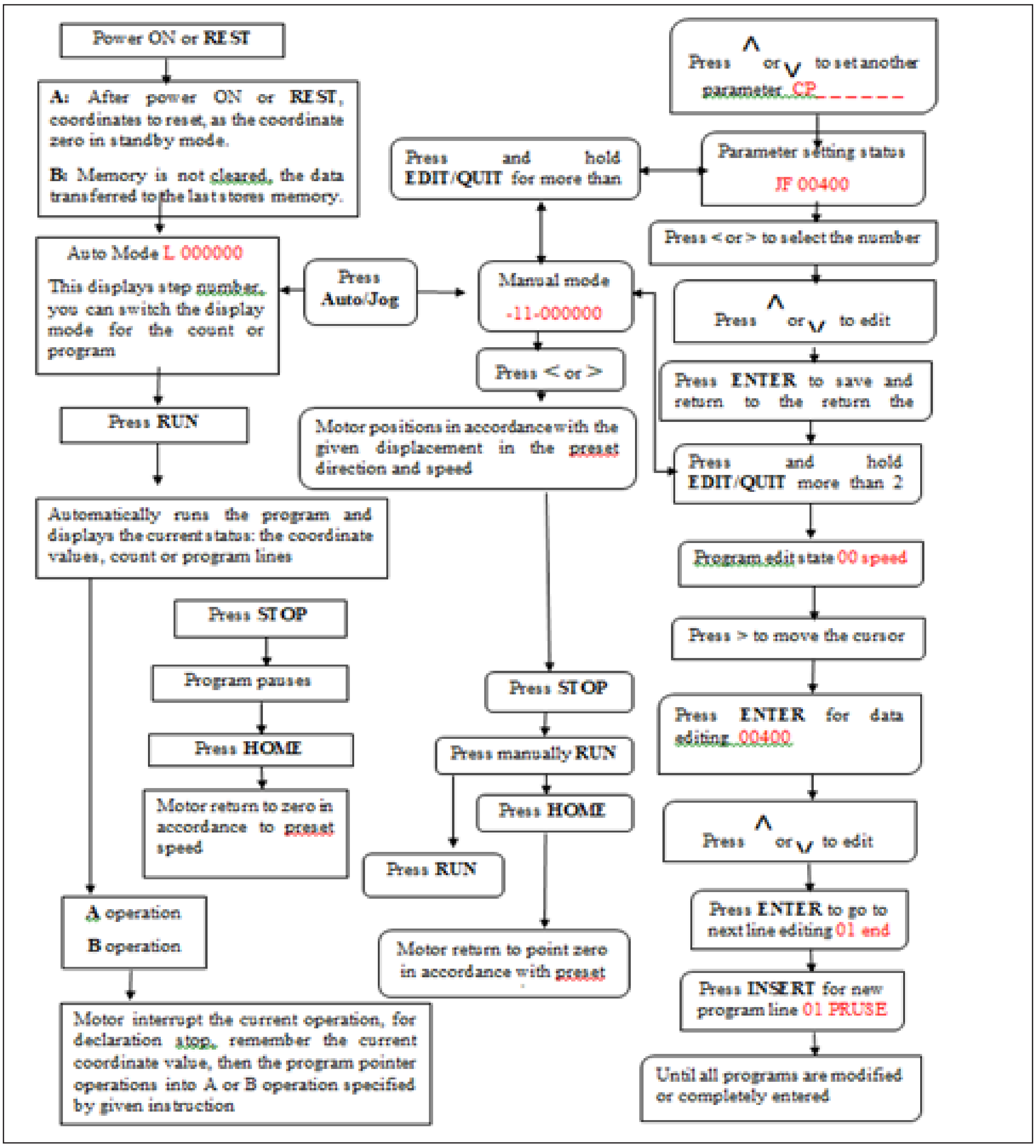



**Figure 8.Flow chart of controller (Electric and Siemens, no date)**

## Design Drawing

Figure 9 shows the autographic view of the SMA tensile testing machine. The model has been designed in Solidworks, and the Autographic view is presented here. The figure clearly presents the force tester and the loading plane, which will load the SMA spring, and the force stretch will be noted, which will act as the experimental data.

## Assembly of components

A detailed view and assembled view of the SMA tension testing equipment is presented along with its exploded view in Figure 10. The red box on top is used to cover the stepper motor and placed on the top of the load cell in Figure 10. The stepper motor is located right under the top case, which is connected with a spindle and helps it to rotate. The force sensor is also mounted on the moving head, which is attached to the spindle, and it moves by spindle movement. There is a gripper attached under the forced sensor, which is used to hold the testing object. Gripper in the middle is attached to use the device at room temperature without a heating chamber. There is a semi-circled holder for the heating chamber, and the gripper is also placed just below the heating chamber to hold the object during the temperature-controlled experiment. An electrical control unit is also displayed on the right side of the device, which is mainly used for controlling the stepper motor.

## Estimated Cost analysis

### Construction

The construction process involves only the two components. The remaining components are selected from the store and assembled. In the first place, the frame is constructed from a rectangular hollow pipe made of steel, followed by the construction of the crosshead. The construction involves cutting the parts to the designed size, followed by welding using electric arc welding. Figure 11 shows the frame and crosshead.

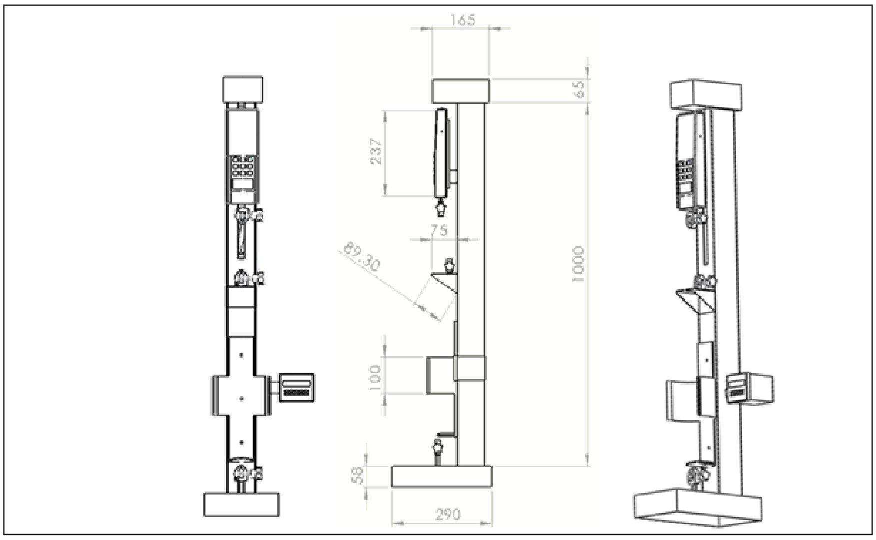



**Figure 9.Autographic View of The SMA Machine**

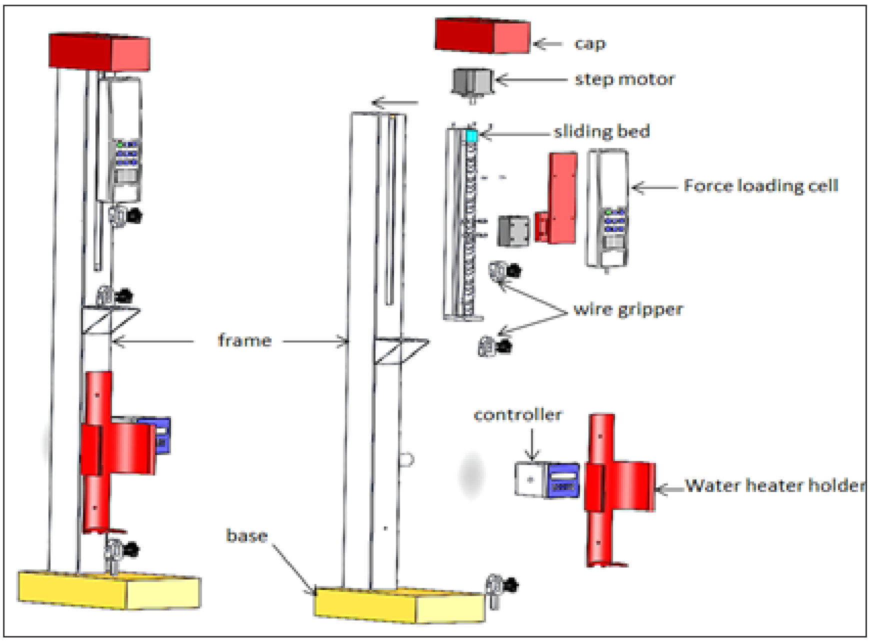
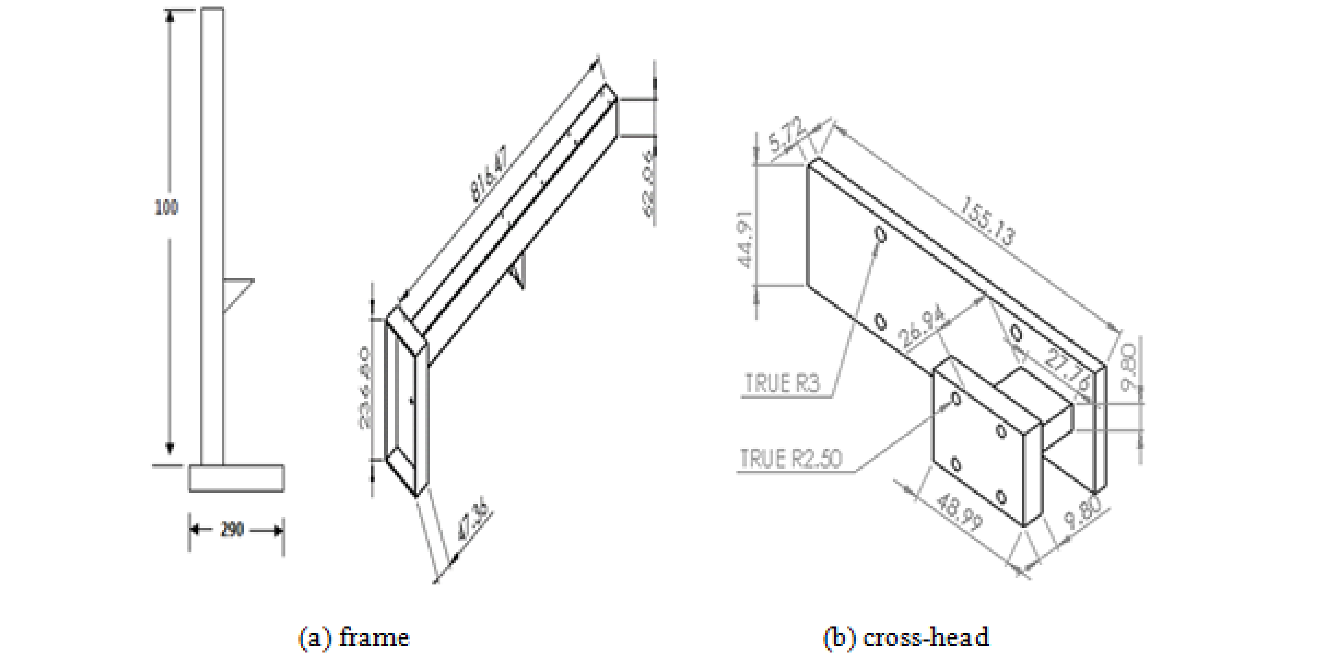



**Figure 9.Autographic View of The SMA Machine**

**Table 1.Cost analysis**

| S.No | Component | Material | Quantity | property | Price/Yuan |
|---|---|---|---|---|---|
| 1 | Frame | Steel rectangular pipe (80x60) | 1 | 500 N/m$^2$ | 100 |
| 2 | Sliding bed actuator | | 1 | 1605 | 332 |
| 3 | Wire gripper | Steel | 1 | | 62 |
| 5 | Force sensor | | 1 | 50kg | 500 |
| 7 | Connecting wire | Copper | 1m | 0.3mm | 25 |
| 8 | Labour | - | - | - | 150 |
| Total | | 905 | | | |




**(a) Frame (b) Cross-Head Figure 11.Frame and Cross-Head Fabrication**

## Experiment test

Experimental arrangement is shown in Figure 12. For the testing procedures, different rules must be applied for the application of tensile tests. E.g., strain ranges and load ranges must be selected in order for fitting the range. The values required for the recording must be very close to the top scale selected as convenient, short of running past full-scale skills. Past experience must be used for the selection of the range for some particular specifications or tests. Many of the testing systems based on the computer must have an automatic selection of range, and it will capture the data even if a small range is selected initially. Every specimen identity must be verified, and appropriate identification of the data must be recorded accurately for reporting and the recording of the test. The required dimension for the calculations of the area of cross-sections of reduced sections should be recorded and measured. The measurement taken must be recorded and measured repeatedly for each of the specimens and not considered the perfect consistency of the preparation of the sample. The plot load axis zero and the load indicator zero must be set for the placement of the specimens in grips. After the specimen is set in the place, reset zero must not be applied.

After the placement of the specimen in grips, the closing of grips is used for securing the specimen. For the removal of the preload before starting the test, the load should be unloaded physically by the movement of the loading mechanism. For this purpose, we never have to employ the zero adjustments. In some of the cases, preload is needed, and it might be introduced deliberately. If the initial curve portion is linear, we can correct the zero strain by extending a straight portion in the initial curve region of the stress train to the zero strain and load. The valve of the strain at the intercept of zero loads is generally known as the “foot correction,” and it is deducted from observed readings, which must be taken from the strain scale.

While installing the extensometer, a correction of mechanical zero must be set by the technician. The zero readout strain must be set once the extensometer is put with the specimen. The performed test must be incomplete confirmation with specifications of the test and must be constantly repeated for each of the tests. It is critical that the specifications of the test be followed for the testing of speed. Some of the materials are very sensitive to speed tests, due to which different results may be given at different speeds. Many of the measuring instruments do not have the capability of responding to the accurate test results recorded if the high speed of the test is used. The whole process must be monitored by the technician to observe any problems arising during the procedure. The curving of the stress versus strain graph rather than straight in the initial portion is the most common sign of a problem. This problem might indicate the non-straight specimen, the improper extensometer installment, or the off-center specimen loading.

## Result for SMA spring

Here are the graphical results of SMA spring and are presented in Figure 13. We will use the results of the experiment and the simulation results for comparison. The simulation is used to simulate hysteresis behaviors of shape memory alloy. Different loads are applied to the spring, and the corresponding stretch is measured. Figure 13a-f presents the comparison of the simulation and the experimental result for the force and the stretch ratio. The figure depicts that the simulation and experimental results are very close to each other.

In this experiment, we used 4 springs of length 50mm, 60mm, 70mm, 80mm, 90mm, and 100mm to compare with simulated results of the same length. We have kept the temperature and loading rate constant at 50 °C and 0.5 mm, respectively.

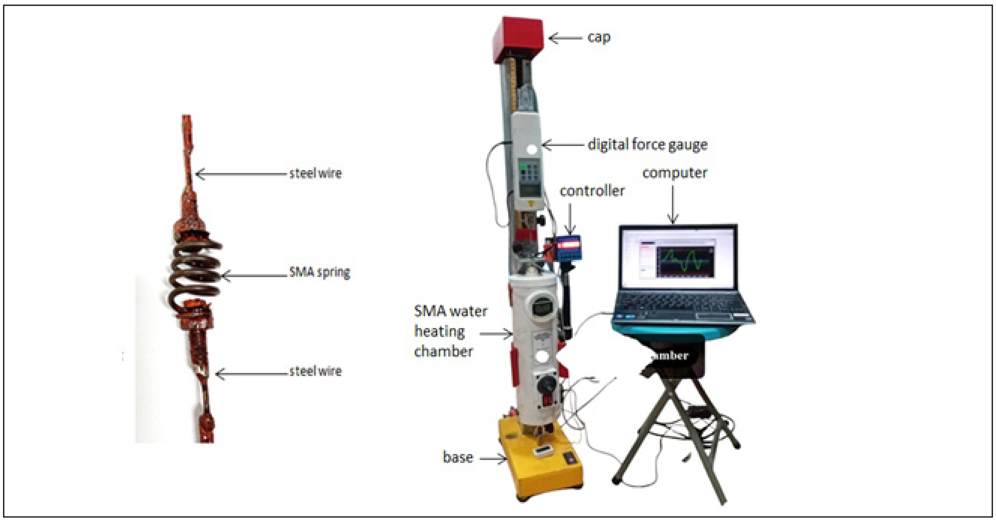
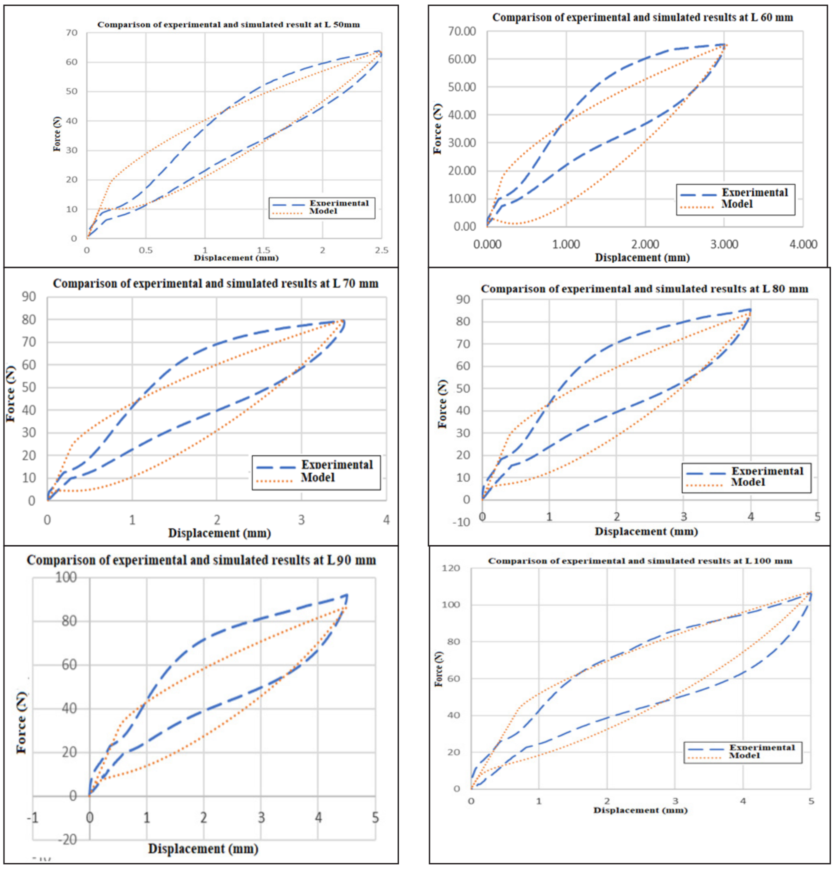



**Figure 12.Experimental Setups**




**(a) L 50mm at T 50 oC and loading rate 0.5mm, (b) L 50mm at T 60 oC and loading rate 0.5mm, (c) L 70mm, T 50 oC and loading rate 0.5mm/s, (d) L 80mm T 50 oC and loading rate 0.5mm/s, (e) L 90mm, T 50 oC and loading rate 0.5mm/s, (f) L 100mm T 50 oC and loading rate 0.5mm/s Figure 13.Comparison between simulated and experimental results of SMA Spring**

## Discussion

Figure 12 shows the fabricated tensile testing machine under experimental testing; Figure 13 shows the comparison of simulated and experimental data obtained from the developed tensile testing machine. We kept the temperature constant and increased the length, and both of them show similar behavior with the change in length. Figure 15 a, b, c, d, e, and f show the comparison of simulated and experimental data, with lengths of 70, 60, 70, 80, 90, and 100 mm, respectively. We can see both of them show similar behavior with the change in length. It can be seen that a wider hysteresis loop is obtained accounting for the same temperature of 50 $^{o}$C. The same test was repeated by changing length and keeping the temperature constant at 50 oC A comparison of simulated and experimental hysteresis is shown above.

## Conclusion

A tensile testing machine is successfully designed and constructed and has a friendly budget. The machine is specifically fabricated for Shape Memory Alloy material tensile testing. Several experimental tensile tests are conducted on SMA springs, and the experimental data are simulated using a known popular thermomechanical algorithm. The simulated and experimental data produced a closed fitting, indicating that the fabricated machine served the purpose it was intended.

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