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Automation in the Test Rig to determine the Load-Deflection characteristics of Helical Spring Washers

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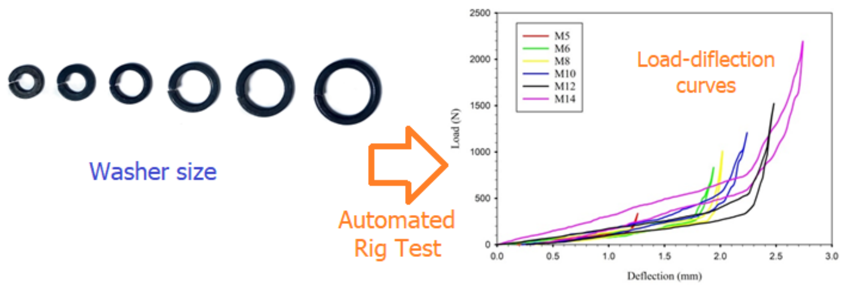
ABSTRACT

In the mechanical system the induced vibrations and dynamic conditions are responsible for loosening the components in nut-bolted assembly. The washer plays a vital character in nut-bolted linkages and prevents the loosening of components. The selection of size and type of washer mainly depends on the size of nut and bolt, frequency and amplitude of vibrations induced in the structure, which ultimately determines the required load-deflection properties of spring washers. In the present work, the design and development of an automated test-rig that can determine the load-deflection characteristics of spring washers have been investigated. The stepwise and manual operation of the old test-rig is converted into continuous and gradual movement. The main controller used is Arduino Mega 2560 board which controls the stepper motor and display of load for corresponding deflection on monitor of Arduino IDE software. The load-deflection properties obtained from manual test-rig and newly developed automated test-rig are similar in nature. The use of stepper motor and Arduino programing provides the freedom to obtain a very small step size for deflection which helps to obtain smooth curves in load-deflection diagram without any manual error. The time required to obtain the load and deflection values on the serial monitor of an Arduino IDE software is not affected by the decreasing the step size.



Keywords: Automation; Test-rig; Helical spring lock washer; Stepper motor; Arduino

INTRODUCTION

According to the usage, nuts and bolts have supplementary importance in the bolted joint assemblies as compared to the washers. Hence, less concentration is given to the reuse and durability of washers. Various types of washers are used for different nut-bolt joints. Spring washers like helical spring lock washers (HSLW), Belleville washers, wave washers, and curve washers are mostly used where the joints are loosened due to dynamic loading. HSLW, sometimes referred to as split washers, are frequently employed to stop nut-bolt assemblies from loosening in dynamic conditions. These washers absorb the initial driving torque till it becomes flat. As a consequence of increased frictional force, the contact area among nut and bolt threads is exposed to the supplementary normal force. This additional force created by these types of washers prevents the joint from loosening. Hence, to restrict the joints from loosening, the use of split washers is preferred.[1] If the tightening torque exceeds its standard value, the washer material starts to deform permanently. Due to this permanent deformation, HSLW behaves like plain washers and is of no use during vibrating conditions as they are unable to provide reaction spring back force.[1] The National and International standards do not reveal specific information on the reusability of spring washers or how to assess the efficiency of the reused washers. So, it's important to understand the load-deflection properties for their effective use in various operating conditions.

Many investigations on the above facts have tried to define the load-deflection properties of various helical springs and split washers. These properties are studied using experimental, FEA, and analytical techniques. Many researchers have used UTM for experimental analysis to study the load-deflection properties of various spring washers.[2–4] It might not be acceptable to analyze the

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load-deflection characteristics of tiny-size washers using the UTM. A test-rig was developed to evaluate the effectiveness of the sensor, which was used to scrutinize the load-deflection properties of helical springs. In addition, researchers have also analyzed the effect of compressive and shear force of helical spring on its wire.[5] The small test-rig was conceptualized and created to study the load-deflection properties of spring washers. The experimental results obtained were compared with analytical & FEA values and the experimental results were close to FEA results as compared to analytical results.[6] UTM was used to investigate the load-deflection characteristics of rubber-metal and pure-metal disc springs and found that the hysteresis of the first is lower than the second.[2] INSTRON 1255 universal static-dynamic testing machine was used for experimental and numerical analysis of load-deflections characteristics of Belleville washers by filling the elastomers, and the observed results were boosted. It was observed that most of the stress is absorbed by the elastomer instead of the washer material. According to numerical analysis, the most critical portion of the Belleville washer observed a decline in stresses.[3] The load-deflection characteristics of superelastic SMA (Shape Memory Alloy) Belleville washers were explored using INSTRON 5585H universal test machine (UTM), which has an application in seismic resisting devices. This investigation was performed with numerous stack combinations for different loads and temperatures. Effective agreements were found between the test and the simulation findings.[7,8]

Other than experimental methods, researchers have also stressed on the FEA method and metallurgical analysis to investigate the performance of various helical springs, spring washers, and bolted joints.[9–13]

The FEA model is also used to investigate the loosening performance of fasteners due to the vibrations caused by dynamic shear loads.[12] Similarly, the tightening and loosening processes of threaded fasteners due to shear loads were examined using the FEA method, and the results were in good agreement.[9] Likewise, for transverse load criteria, loosening characteristics of M10 conical spring washers were explored using the FEA technique. The loading condition was tested for two different loads, which concluded that more emphasis is required to clarify the loosening resistance of the conical spring washers.[13] The investigations on helical spring lock washers, for various operating criteria, were performed using experimental and FEA approach. This critical literature survey has anticipated the need for design optimization of helical spring lock washers in order to improve the performance in terms of load-deflection properties, load-bearing capacity, and best locking force. The test-rig developed was used to investigate load-deflection properties of the helical spring washers and the results were in good agreement with the FEA values. This developed test-rig is suitable to investigate the small sample sizes of various spring washers for lower axial loading conditions.[14,15] The drawbacks of the test-rig developed and used by Wagh et.al.[14,15] were fluctuations in axial load reading, more time required for experimentation, and manual error. These drawbacks caused difficulty in obtaining the exact reading of axial force for a particular deflection. Further developments in the test were done to record the load cell reading using an Arduino controller and Arduino IDE software. These modifications reduced the time to record the reading of reaction forces which were directly displayed on the serial monitor of Arduino IDE software.[16] Mechanical devices which possess motion transmission using human interference have greater chances of error in recording the readings which leads to a loss in efficiency and reliability of the existing system. Hence, these above drawbacks can be eliminated using the data acquisition system with few design modifications in the existing test-rig.

The stepper motors, Arduino controllers, and Arduino IDE software are used to control and build more efficient & reliable systems.[17–20] The pulse width modulation (PWM) method is used to control the stepper motor speed using Arduino.[20] For example, a low-cost programmed PCB drilling machine was developed in which the holes from the PCB layout were automatically spotted with the help of G code software.[19] An exemplar of a rebar bending machine was developed using the stepper motor, Arduino IDE software, and an Arduino controller.[20] Shah et al[20] have developed a program in Arduino IDE software and Arduino controller to control the motion of a stepper motor to bend a 3mm diameter aluminum wire. Renuka et al.[18] developed a low-cost and uncomplicated system for exact weighing the packaging material in which values are cross verified using the Arduino. Latha and Murthy[17] have developed a model using HX711 analog-to-digital converter to measure the weight. The wireless weight-bearing system is developed in which the load cell signals are reported on smartphone.[21]

The above literature survey reveals that the electronic control mechanism helps to build a more efficient and reliable system. So, the existing test-rig is converted into an automated test-rig using a stepper motor, Arduino controller, and Arduino IDE software. The results obtained are discussed further.

2. Design and Development of test-rig

The present investigation is focused to design and develop an automated test-rig for measuring the load-deflection properties of spring washers. The present test-rig evolved from the concept and design used by Wagh and Desale in 2018.[15] The rotary movement of the spindle and vertical movement of the pressure plate are motorized in a modified test-rig. Instead of stepwise rotation in a manual test-rig, the spindle is rotated gradually using a stepper motor for continuous linear movement of the pressure plate. The Arduino controller and Arduino IDE software and used to record the load cell readings for desired step size to minimize the error.

2.1 Mechanical System

The basic mechanical operating principle of the test-rig developed in this paper is similar to the manual test-rig developed by Wagh and Desale in 2018.[15] The detailed assembly of all the mechanical components of the test-rig is displayed in Figure 1. In the test-rig, two rigid plates made up of mild steel are kept apart by mounting four mild steel columns at corners. The rigid plate No.1 (base plate) is used to mount the load cell, fix the guideway rods, and provide support to the test-rig. The load cell (model No.: RSL 410) is mounted in between two spacer plates for measuring the load whereas the spring washer is placed on the sample mounting plate. The function of rigid plate No. 2 (middle plate) is used to provide support to the threaded spindle, stepper motor and rigid plate No. 3 (upper plate). The stepper motor is bolted to rigid plate

No. 2 and connected to the threaded spindle pulley through the belt drive. The direction of rotation of the stepper motor controls the rotary movement of the spindle and thus the linear movement of the pressure plate. The threaded spindle, guide-ways, and linear bearings allow the pressure plate to move only in vertical upward and downward directions. The upward and downward movement of the pressure plate helps to record the loading and unloading forces exerted on the washer samples.

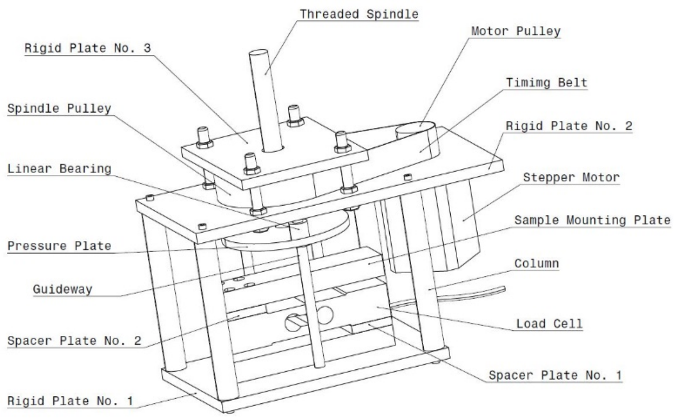


Figure 1: Isometric view of test-rig

2.2 Data acquisition system

In order to make the test-rig automatic, the data acquisition system (Figure 2) consists of a load cell, Arduino Mega board, Arduino IDE software, joystick, input/output device, etc. to control the linear movement of the pressure plate. In this system, the Arduino Mega board is the main controller which has 54 digital I/O pins and 16 analog I/O Pins. Digital pins are used to access the signals from digital devices such as proximity sensors, whereas analog pins are used to access analog signals from analog devices such as temperature sensors. The joystick is one of the input devices used to rotate the stepper motor in the required direction. The power supply unit (S-120-24) works as an AC-DC converter and supplies the required power to the load cell and stepper motor. The PC/laptop which is loaded with Arduino IDE software is used for programming (input device) as well as an output device to display the load values from the strain gauge (Load Cell) for the specified vertical deflection of the washer sample. USB cable connects the Arduino Mega board to the input device through which it receives power and input signals to control the stepper motor. The software program calculates the number of rotations for the stepper motor from the specified input value which enables it to rotate in the desired direction.

The Arduino board is the main controller, which acts as the brain of the system to communicate the signals between input and output devices, and further mechanical actions are controlled by it. Arduino works on a 5V power supply which is been supplied through an external adapter or PC/Laptop through USB. Power distribution is done in a power supply that gives the required power to the devices like a 12V supply to the load cell and a 24V supply to the motor driver. The load cell is connected to the analog pin of Arduino, whereas the joystick is connected to the digital pin. The stepper motor is connected to the controller through the motor driver.

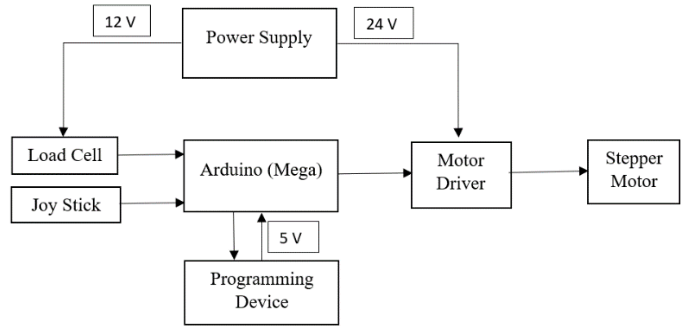


Figure 2: Block Diagram of Test-rig

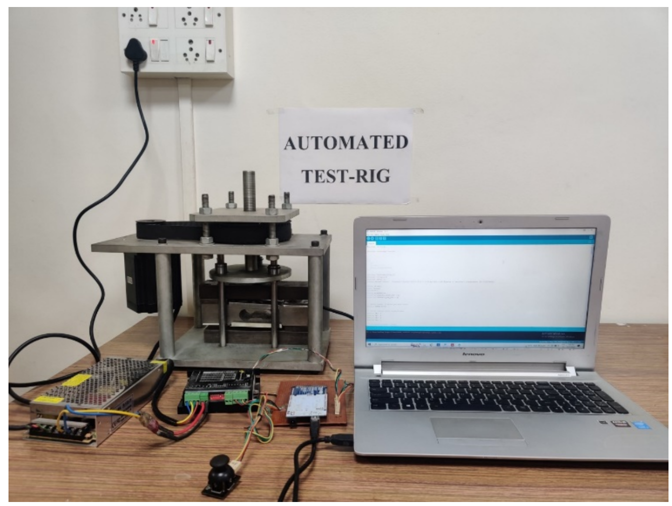


Figure 3: Photographic view of Setup

2.3 Experimental Procedure

The construction of the test-rig and electrical connections are discussed in the above sections. Initially, different helical spring lock washer samples are cleaned using acetone and dried completely under hot air. The dimensions of the washer sample are measured precisely using a Vernier caliper (least count 0.01 mm) and recorded as given in Table 1. The HSL washer sample is placed at the center of the sample mounting plate. The joystick is manually operated to rotate the Stepper motor in a downward direction until the pressure plate slightly touches the sample. Arduino Program is open to ensure it is ready for further processing. Further, the maximum deflection of the HSL washer sample corresponds to the vertical distance traveled by the pressure plate (in mm) is entered as input in the program. Once the program is run using Arduino IDE, the pressure plate slowly travels vertically downward till the maximum deflection of the washer is achieved. During this movement (loading) of the pressure plate, for every 0.02 mm distance traveled corresponding load cell values are recorded and stored in the computer. Once the specified distance is reached, the pressure plate stops for one sec and the motor starts to rotate in the opposite direction. This vertical upward movement of the pressure plate releases the load from the washer which gives the load values for the unloading condition. These both loading and unloading recorded values are used to plot the load-deflection properties of spring washers.

2.4 Range of sample parameters

The HSL washer samples used in the present work are made of spring steel material (En42J). These samples are selected from the same manufacturing batch from the industry (Kulkarni Engineers, Kothrud industrial estate, Pune, India).

M5 M6 M8 M10 M12 M14

Figure 4: Image of washer samples

Table 1: Specifications of HSL washers for preliminary test (All Dimensions are in mm)

	Samples of HSL washer					
	M5	**M6**	**M8**	**M10**	**M12**	**M14**
Inner-Diameter (ID)	5.35	6.58	8.51	10.65	12.28	15.03
Outer-Diameter (OD)	8.83	10.21	12.64	15.46	17.65	20.56
Width (w)	1.74	1.81	2.07	2.41	2.69	2.77
Thickness (t)	1.34	1.82	2.12	2.46	2.72	2.81
Cross-sectional Area (A)	2.33	3.29	4.39	5.93	7.32	7.78
Height (H)	2.60	3.77	4.15	4.69	5.20	5.55
Maximum Deflection (H-t)	1.26	1.95	2.03	2.23	2.48	2.74
Height after Loading-Unloading Cycle	2.42	3.51	3.82	4.47	4.94	5.22
Loss of Height (%)	6.93	6.90	7.95	4.70	5.00	5.95

Table 2: Specifications of M10 HSL washers for repeatability test (All Dimensions are in mm)

	Sample					CV
	1	**2**	**3**	**4**	**5**	**%**
Internal Diameter (ID)	10.81	10.65	10.64	10.53	10.68	0.84
Outer Diameter (OD)	15.56	15.46	15.49	15.54	15.49	0.24
Width (w)	2.37	2.41	2.43	2.51	2.41	1.82
Thickness (t)	2.46	2.46	2.47	2.46	2.45	0.26
Height (H)	4.65	4.69	4.73	4.61	4.77	1.21
Maximum Deflection (H-t)	2.19	2.23	2.26	2.15	2.32	2.61
Height after loading-Unloading cycle	4.45	4.47	4.30	4.27	4.52	---
Loss of Height (%)	4.3	4.9	9.09	7.3	5.2	

The samples were manufactured according to the DIN 127B standard. The photographic view of M5, M6, M8, M10, M12, and M14 washers is shown in Figure 4. Additionally, five more M10 HSL washer samples (Sample No. '1', '2', '3', '4' and '5') are selected for repeatability test. The dimensions of sample washers are measured with the help of Vernier Caliper (Mitutoyo) and given in Tables 1 and 2.

RESULTS AND DISCUSSION

The types of washer and tightening torque have a major impact on the performance of the bolted-joint assembly. The internal reaction force generated by the spring washers prevents the bolted joint from loosening. To understand the performance of bolted joints under various operating conditions, the role of the washer and its load-deflection properties needs an exhaustive investigation. In order to evaluate the performance of different spring washers efforts have been made to design and developed an automated test rig and the experimental results obtained are discussed in detail.

3.1 Preliminary Experiments

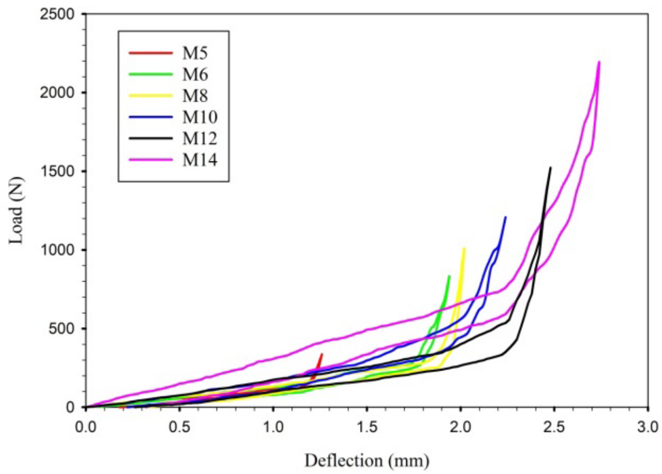
The above-outlined experimental approach is used to ascertain the load-deflection properties of the different-sized washers. The dimensions and specifications of samples used to determine the load-deflection properties are documented in Table 1. The cross-sectional area and maximum deflection (H-t) are calculated for each washer sample and their values are also documented in Table 1. It has been noted that the width and thickness of washers increase with the increase in size, which results in increased cross-sectional area.

3.1.1 Load-deflection Properties

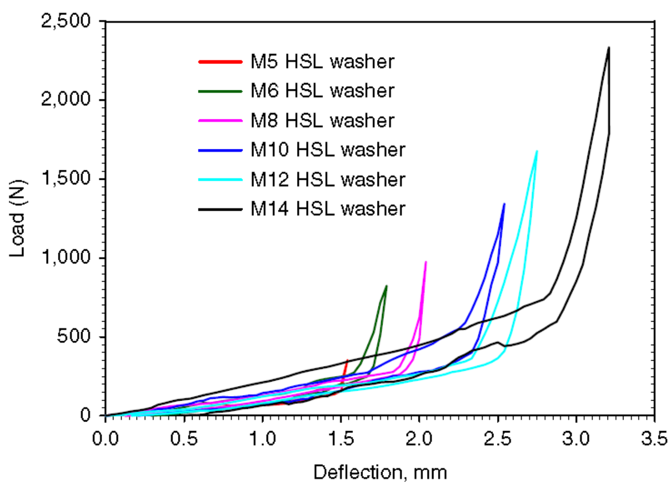
The detailed design, dimensions, electronic components, and operating procedure of the test rig are discussed in the above sections. The range of parameters used in the present investigation is also discussed. The steps of the experimental procedure are systematically followed to obtain the load-deflection properties of HSL washers and the results obtained are presented in Figure 5. From Figure 5 (a) it is observed that till the elastic point the load-deflection curves for loading and unloading conditions are parallel to each other and further it shows an exponential rise. The nature of the characteristic curves of HSL washers obtained from this automated test-rig is similar to the curve obtained by Wagh (2018)[15] as shown in Figure 5(b). The difference in load values in Figure 5 (a) and 5 (b) are due to different the make and shape (difference in dimensions) of the samples used in the present experiments and by Wagh (2018).[15] Ideally, the loading and unloading curves should overlap each other however due to loss in strain energy the unloading path followed by the samples is different from the loading conditions as shown in Figure 5.

3.1.2 Load and Strain Energy at Elastic Point:

The values of reaction forces at an elastic point for each sample washer are determined from the load-deflection curves shown in Figure 5 (a). The reaction forces at elastic points for different washers (M5 to M14) are observed 171.09 N, 269.45 N, 291.17 N, 447.16 N, 556.84 N, and 745.27 N for loading condition and observed 122.62 N, 255.96 N, 277.06 N, 337.31 N, 399.43 N, and 592.48 N for unloading condition, respectively. These reaction forces at elastic points during loading and unloading conditions



a) Using existing automatic test rig



b) Results obtained by using the test rig developed by Wagh 2018[15]

Figure 5: Load-Deflection Curves obtained for different size of Helical Spring Washer

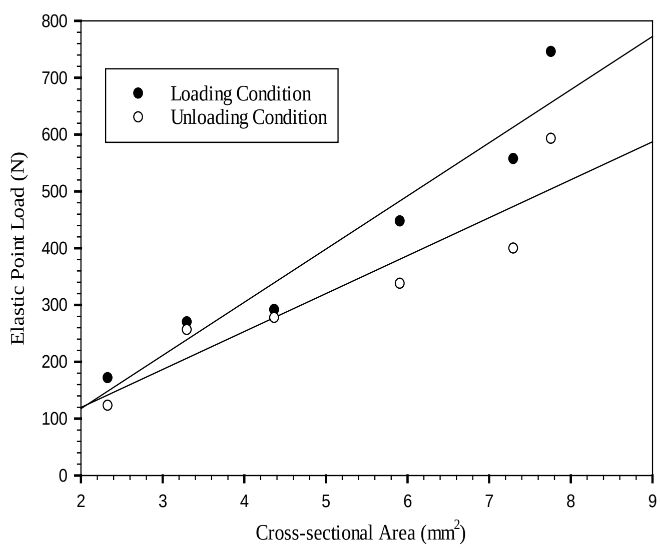


Figure 6: Change in Elastic point load for washers with different cross-sectional areas

along with the respective washers' cross-section area are graphically presented in Figure 6. It has been noted that for the given material the reaction forces at elastic limit increase with the increasing cross-sectional (size) area of washers.

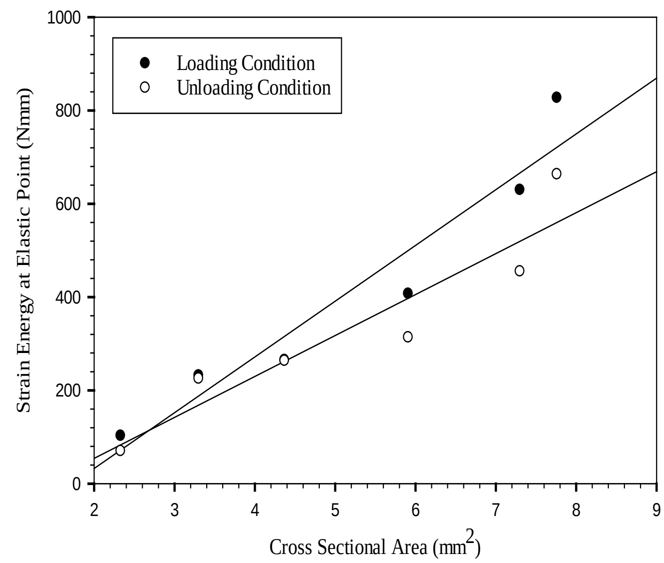


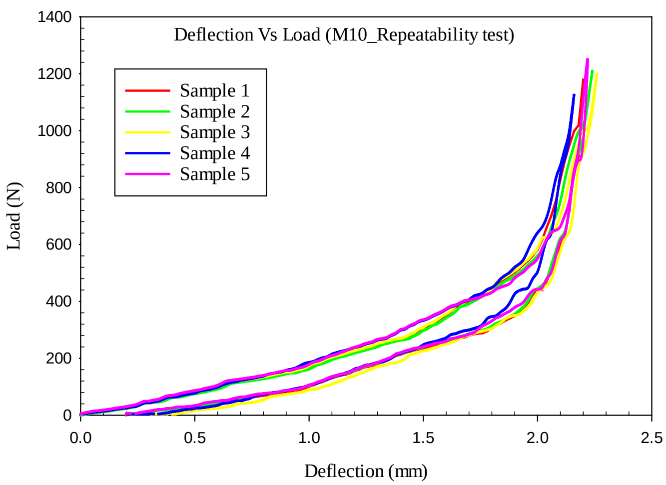
Figure 7: Change in Strain Energy for washers with different cross-sectional areas

Similarly, the strain energy of each washer is determined by calculating the area under the curves within the elastic limit. The stain energy of HSL washers, namely, M5, M6, M8, M10, M12 to M14 during loading condition is 102.66 N-mm, 231.73 N-mm, 264.97 N-mm, 406.92 N-mm, 629.23 N-mm, 827.25 N-mm, respectively. Similarly, for unloading condition the strain energy of different HSL washers are observed 69.9 N-mm, 225.27 N-mm, 263.31 N-mm, 313.7 N-mm, 455.36 N-mm, and 663.58 N-mm, respectively. These strain energies of different washers with the respective cross-sectional area are graphically presented in Figure 7. It has been noted that the rate of increase in strain energy increases with increasing the size (cross-sectional area) of washers. From Figure 5 (a), the load-deflection curve reveals that the position of the unloading curve is lower than the loading curve which leads to the loss of free height of helical spring lock washers. Thus, the loss of strain energy is observed due to the shifting of the elastic point in a vertically downward direction.

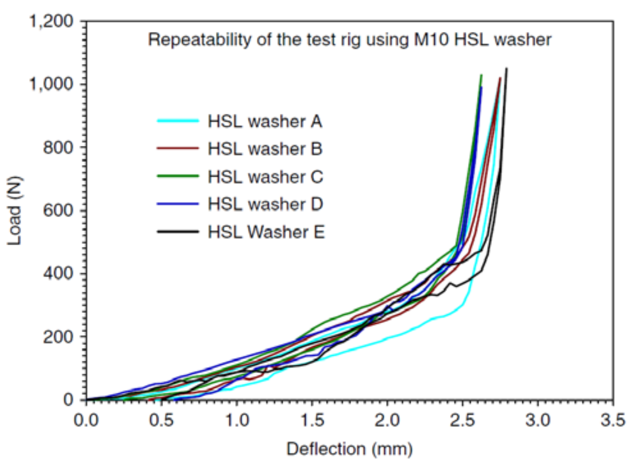
3.2 Repeatability Results

The load-deflection properties for five M10-size helical spring lock washers were determined by the same person to validate the consistency of the test-rig. The samples selected for the repeatability test were from the same batch of production. The specifications of five M10 size HSL washer samples namely, '1', '2', '3', '4', and '5' are given in Table 2. The coefficient of variation is determined to verify that the variation of dimensions is within acceptable limits.

According to the maximum deflection of the washers, the experiments were performed to obtain the loading and unloading curves and presented in Figure 8(a). It is observed from Figure 8 (a) that the loading and unloading curves closely overlapped each other, and the minor variation may be due to variations in dimensions of the washers. The coefficient of variation for Inner Diameter (ID), Outer Diameter (OD), Width (w), Thickness (t), Height (H), 0.94%, 0.26%, 1.98%, 0.18%, 0.96 %, respectively. Additionally, the repeatability test results of M10 HSL washers using a manual test rig developed by Wagh (2018) are presented in Figure 8 (b). It is observed that the repeatability test results obtained by automated test-setup are more consistent compared to the results determined by using a manual test-rig developed by Wagh (2018).[15] This confirms that the automated test rig gives better results compared to the manual test rig and is also easy to operate.



Results obtained by automated test rig



Results determined using manual test rig [Wagh 2018][15]

Figure 8: Repeatability Test Results using Automated and manual test rigs

Conclusions

In the current research, an attempt has been made to design and develop an automated test rig to obtain the load-deflection characteristics of HSL washers. Compared to the old test rig the manual interference during experimentation has been entirely eliminated. Thus, subsequent inferences can be drawn;

a. The experimental procedure of manual test-rig was monotonous, cumbersome, and time-consuming. The old test rig required two persons for conducting the experiment one for rotating the spindle with the desired degree of rotation and another for recording the data manually. While the present automated test-rig consists stepper motor controlled by an Arduino board and Arduino IDE software for recording the reaction load for desired selected step size (deflection) for both loading and unloading conditions. This facilitates the generation, recording, and storing of the experimental data which is free from manual error.
b. The load-deflection characteristic curves obtained by the present automated test-rig are similar in nature to the load-deflection curves generated by the manual test-rig.
c. In the present test rig, the desired step size can be easily changed in the program for obtaining the experimental data. While the reduction in step size for deflection in manual test rig increases the number of readings makes the experiment more tedious.
d. The repeatability test results of the present test rig are more reliable and consistent compared to the old manual test-rig.

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Conflict of Interest

Authors do not have any conflict of intetrest for this work.

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