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Comparative Analysis of Bolted Joint Assemblies Subjected to Cyclical Transverse Mechanical Stress

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BY

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Comparative Analysis of Bolted Joint Assemblies Subjected to Cyclical Transverse Mechanical Stress

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Undergraduate Departmental Honors Thesis

Under the Guidance of:

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Abstract

This research was conducted to determine the effectiveness of commonly-used washers in engineering structures by observing the difference in applied torque specifications and torque required to loosen bolted joint assemblies after being subjected to cyclical transverse mechanical stress. Two types of washers were tested: flat washers and split-ring helical lock washers. The physical concepts tested throughout this paper are theorized to scale to any size of bolted joint assembly. Based on the variables tested, the results are inconclusive. While the observed results did display the assemblies paired with split-ring helical lock washers required- on average- a greater force to loosen them, more extensive tests with improved means are needed in order to come to a more definitive conclusion.

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Introduction

Within the design process of almost every complex structural engineering project, there lies a need to bring two surfaces together. Whether it be a wind turbine or a railroad bridge, when components of these structures are assembled, the general intent is for them to stay that way. In many of these projects, the bolted joint assembly accomplishes just that. When the bolt, the nut, or both are tightened down, they pull the two joining surfaces together creating a strong clamping force. The washer can accomplish different tasks based on its design. Flat washers are generally used in applications that require the clamping force of the assembly to be distributed over a greater surface area to prevent structural damage. The flat washer's material width is roughly the same as the span of its inner diameter. This ratio provides the optimum distribution for most loads the assembly will be subjected to. Split-ring helical lock washers are used for a variety of reasons, but this research focuses on their ability to provide increased tension on the bolt assembly per unit of applied torque when compared to other washers [1]. This study is to determine if the lock washer's increased clamping capabilities are significantly different when compared to the flat washer under transverse loads. The components of the assemblies used throughout testing are as follows:

- Bolts- ASTM A307 Grade A Galvanized/Waxed 3/8-16 Hex-Head Bolt Course Thread
- Nuts- ASTM A563 Grade A 3/8 Hex Nut
- Washers-
    - Flat Washer- SAE Washer for 3/8 Bolt
    - Split-Ring Helical Lock Washer- Heavy SRHLW for 3/8 Bolt

Research Questions

The implementation of bolted joint assemblies is commonplace in industries such as tower and bridge construction. Inherent natural conditions constantly test the integrity of these structures through the application of transverse shear loads, specifically on their joints. The following questions were at the heart of this research:

- Is there a statistically significant difference in the ability of flat washers and split-ring helical lock washers to maintain the necessary clamping force to hold bolted joint assemblies together?
- What are the benefits, if any, of using one type of bolted joint assembly over another in certain engineering structures?

Rationale

Once in-use and exposed to the elements, structures begin to wear. Structures on which we rely heavily such as transmission and cell towers, as well as railroad and public transportation bridges undergo numerous inspections throughout their lifespan because of the constant stress they endure and the potential for disaster upon failure. Some of the stresses induced on these structures include common, climate-based instances like wind and ice and in more severe cases, natural disasters such as tornados, hurricanes, and earthquakes. All these examples can cause transverse shear stress on the structures and eventually strain them to the point of critical failure. This study will simulate and analyze the stresses on the joints of these structures.

Purpose

The overarching goal of this research is to provide the tower and bridge industries with practical information on the best washer type to use in the bolted joint assemblies holding their structures together. This could allow engineers to design more fatigue-resistant structures in the future as well as spur the respective industries to improve upon existing structures. This could result in a reduction to worker fatalities and cost due to constant inspections and maintenance.

Hypothesis

To answer the research questions, Flat Washers (FW) and Split-Ring Helical Lock Washers (LW) are tested and the following hypotheses are formed. This study compares the average change in torque (tightening minus loosening torque) of bolted joint assemblies when subjected to transverse stress.

$$H_0: \mu_{FW} = \mu_{LW}$$

$$H_A: \mu_{FW} \neq \mu_{LW}$$

Literature Review

At the heart of this research lies a concept first analyzed in the late 1960's. A German engineer by the name of Gerhard Junker proposed a theory regarding threaded fasteners and how they significantly loosen when under constant transverse loading. Junker developed a machine to simulate the aforementioned conditions.

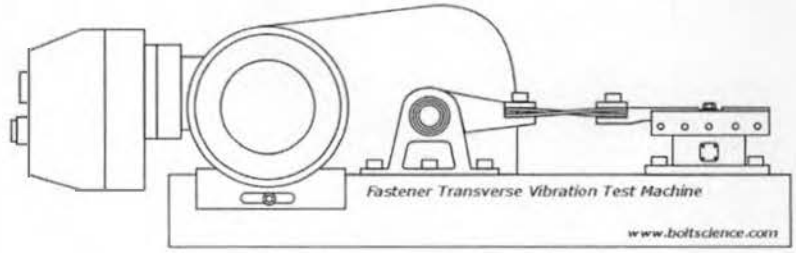

Figure 1: The Junker Machine

A similar machine was developed for this research in comparing types of washers when subjected to similar loads. In some of the transverse displacements tested by Junker, he observed that the bolt's head and threads have a small window in which they are not acted on by friction and therefore, tend to loosen [2]. It is in this moment that split-ring helical lock washers are theorized to provide a significant benefit over the flat washer. The split-ring washers used in this research, contrary to popular belief, are not to be used as a locking mechanism. They provide next to zero locking capability at all and are more similar to flat washers when in-use [3]. Due to the lock washer being normally flat when installed correctly, this instead, provides added tension between the assembly and the bearing surface. This added tension is intended to keep the assembly from loosening during its moment of low friction.

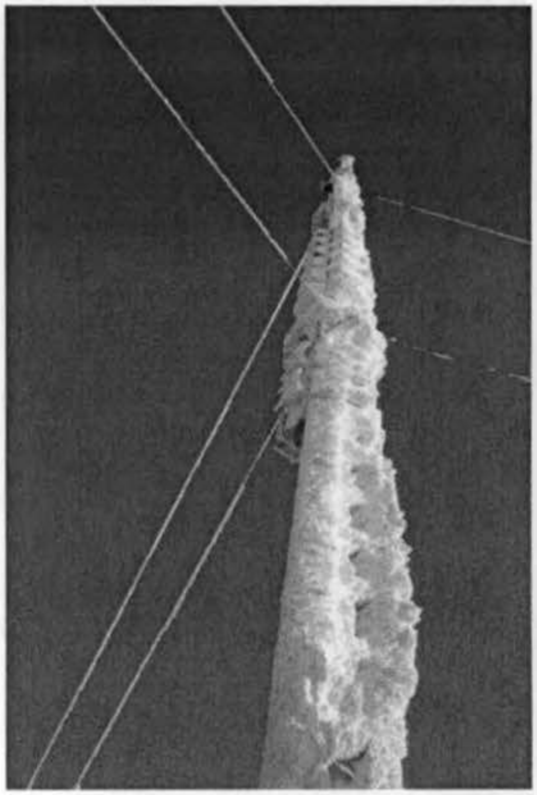

Figure 2: Ice-Covered Tower

According to a 2011 report by Consolidated Engineering, Inc., a company specializing in structural analysis of structures within numerous tower industries, ice and special winds cause forty-eight percent of the top-five tower failures, almost one third of all tower failures [4]. These natural factors create abnormal stress on the structures, particularly on the joints and their assemblies. As the wind acts on the tower, immense transverse loads are applied to these critical areas and can compromise the bolted joint assembly in a few ways with loosening being one of them. Similar stresses can affect a bridge of a long enough span in a similar way.

Methods

In order to put the hypothesis to the test, a machine was developed that would apply consistent shear loads on the joints in rapid succession. The motion for the machine starts at one end with a 1.0 HP motor. The motor would operate at 5600 RPM at its nominal voltage of 24 Volts DC. A hub was fabricated to fit over the motor's shaft. The rotational motion of the hub was translated to linear motion in an aluminum block running on a track via a connecting rod with ball joints at either end. This block was then connected to the actual testing apparatus, which consisted of two mild steel plates that would be fastened together. These plates were table-ground on their interfacing surfaces to create a smooth, low-friction environment. Four, inline, evenly-displaced through holes were drilled and reamed to accommodate 3/8" bolt shanks. The two plates made contact with a compression spring through the latter half of the push stroke and the first half of the pull stroke. The top plate was directly connected to the aluminum block while the bottom plate was directly in contact with the spring. This created two separate systems that would solely rely on the bolted joint assemblies to prevent loss of interface between the two surfaces. The entire machine was elevated on four spring legs. This feature was implemented to reduce the shock applied to the motor from the violent return

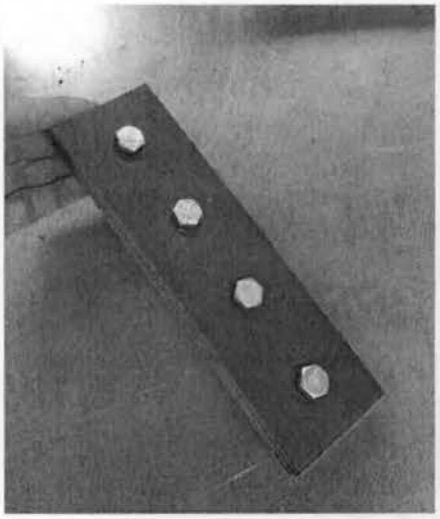

Figure 3: Jointed Steel Plates

stroke induced from the compression spring and the motor itself. The machine was also fitted with a proximity sensor/counter combo to accurately depict the number of cycles the machine had made when testing.

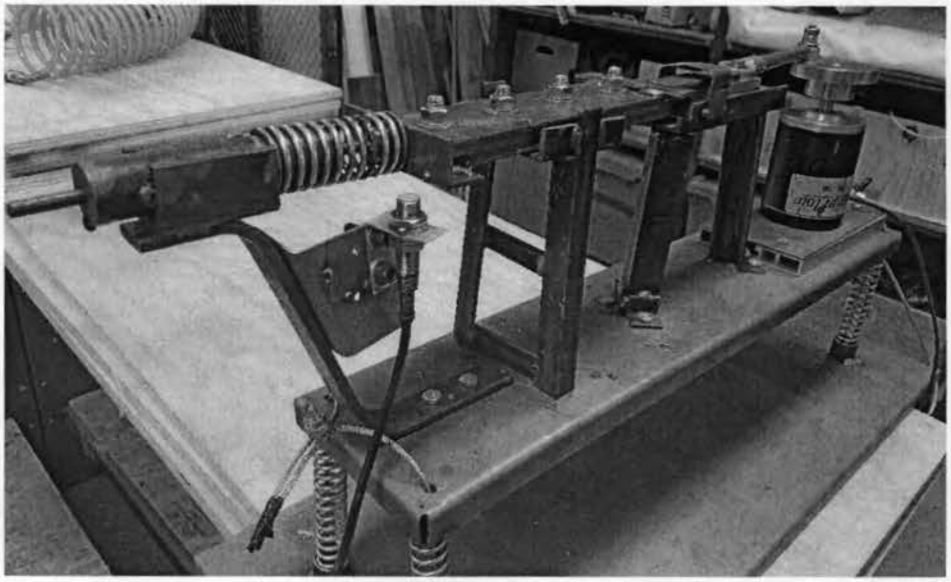

Figure 4: Machine for Transverse Motion

The materials listed in the abstract of this paper, the bolts, nuts, and washers, were used as the assemblies that held the steel surfaces together. The only difference between the assemblies tested was in the type of washer- flat washers and split-ring helical lock washers. Each assembly was installed the same using two wrenches: a 3/8" drive socket wrench with a 9/16" socket and a 9/16" combination wrench. Between the drive and the socket on the socket wrench, a "socket extension torque sensor" was installed that relayed the output to a high performance strain gauge. The strain gauge provided maximum (+) and

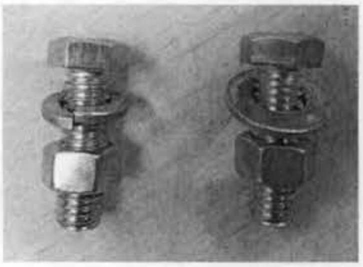

Figure 5: Bolted Joint Assemblies

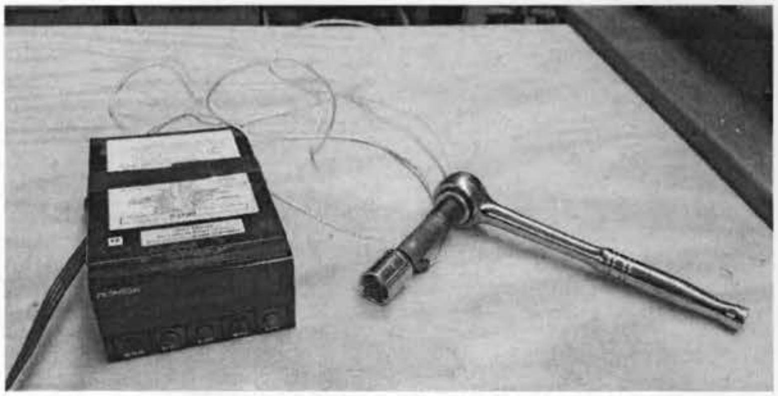

Figure 6: Strain Gauge and Torque Sensor

minimum (-) reading detection that gave us the ability to track the applied torque when tightening (+) and loosening (-). Both products were purchased from Omega Engineering. The strain gauge readout was set to foot-pounds for the duration of testing.

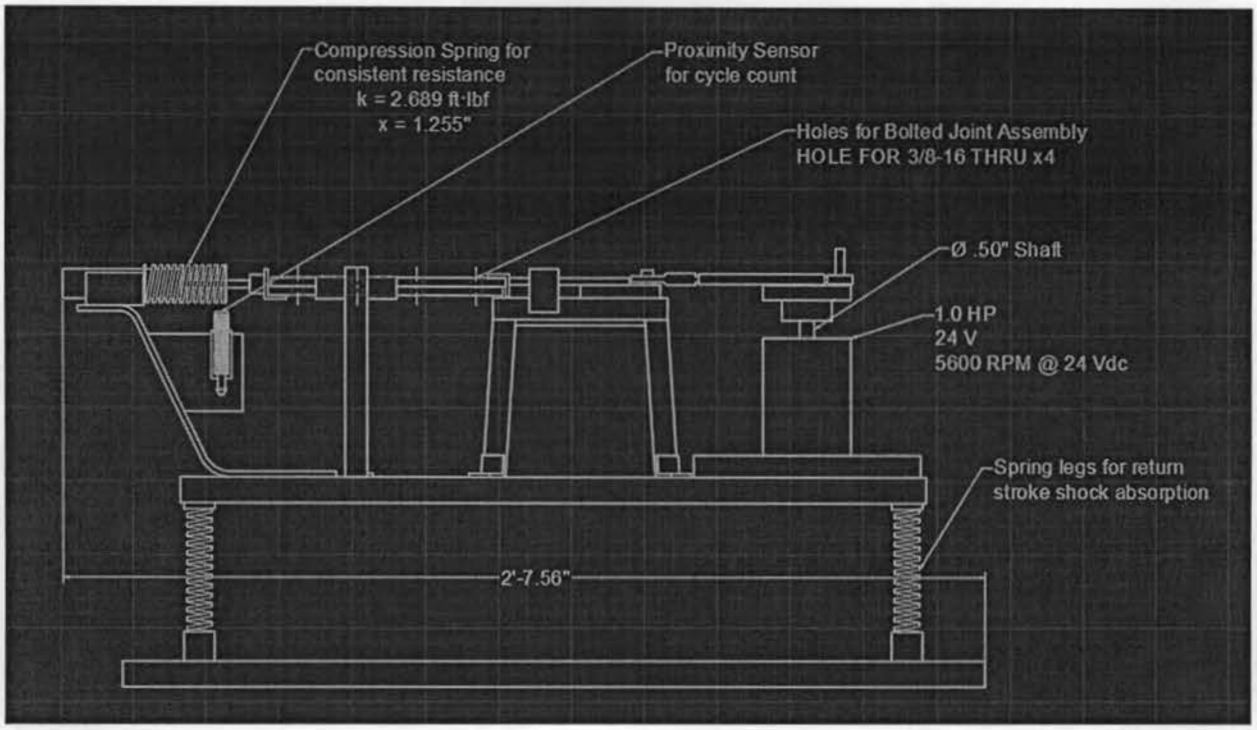

Figure 7: Technical Drawing

Each of the four through holes in the steel plates were assigned a number- one, two, three, and four- increasing from spring end to motor end. The assemblies were installed in these holes top to bottom- nut, washer, bolt- a common practice in the related industries. Whether installing or removing the assemblies, the order taken was hole four, hole three, hole two, then hole one. This order was maintained throughout the entirety of testing to prevent varying clamping forces acting on the plates. From this, one must not compare assemblies from different holes, but instead only compare assemblies from their matching holes (one, two, three, or four). The socket wrench equipped with the torque sensor/strain gauge arrangement would act on the nut while the combination wrench was applied to the bolt head and pinned against the solid angle iron structures to prevent the assembly from freely spinning during tightening. Each assembly was carefully torqued to the ASTM A307 standard 15 ft·lbs for galvanized/waxed bolts with some recorded variance. The maximum value feature on the strain gauge was utilized to record the applied torque on each assembly. A total of eight tests were conducted: one static test and three dynamic tests per washer type. Each test was intended to last 500 cycles. Providing another form of consistency verification aside from cycle count, each dynamic test was timed with a stopwatch. Concluding each test, the assemblies were removed with identical wrench orientation and assembly order to installation. Due to the strain gauge displaying negative values when loosening, the minimum value feature was utilized to identify the magnitude of required torque.

Results

After testing commenced, gathered data was put through an analysis of variance. The method used was a Two-Factor ANOVA with Replication within Microsoft Excel. Firstly, the analysis showed there was a statistically significant difference between the control groups (no cycles) and the test groups (500 cycles). The P-value was less than 0.0001. The interaction of all variables showed little significance (P-value = 0.79).

To further investigate any significant differences, two more types of tests were run: F-Tests and t-Tests. The F-Test Two-Sample for Variances for the control group of assemblies showed the variances between flat washers and split-ring helical lock washers can be assumed to be unequal. Similarly, the F-test Two-Sample for Variances for the assemblies subjected to 500 cycles showed the variances between the two types of washers can be assumed to be unequal. Based on the t-Test Two Sample Assuming Unequal Variances for the control group the null hypothesis failed to be rejected (P-value = 0.43). However, the t-Test Two Sample Assuming Unequal Variances for the assemblies subjected to 500 cycles displayed a P-value of 0.04 and resulting in an inability to draw a definite conclusion.

Discussion

The ANOVA tests were run first in an attempt to identify if the machine actually significantly loosened the assemblies. After determining beyond a reasonable doubt that the assemblies were significantly loosened by the machine, the interaction between all variables was analyzed. With the interaction test resulting in a P-value of 0.79, it was assumed that there was minimal difference amongst the variables. With the ANOVA tests completed, the pairwise F-tests and t-tests were ran to identify any other possible differences. The F-Tests Two-Sample for Variances were ran to determine what type of t-Test would be used. Both F-tests for the control groups and the 500 cycle groups displayed unequal variances. This prompted the use of the t-Test Two-Sample Assuming Unequal Variances. This test showed within the group that underwent zero cycles, there is little difference between the two types of washers in their ability to hold the assembly together. This result supports the earlier statement that when the lock washer is normally flat, there is minimal locking capabilities. Based on the results, it is reasonable to believe that the flat washer and the lock washer have nearly identical locking capabilities. When the t-Test Two-Sample Assuming Unequal Variances for the 500 cycle groups was run, a P-value less than 0.04 was returned. This result leads to the following speculation: If the lock washer has near-identical locking capabilities with the flat washer, then why do the assemblies paired with a lock washer require a greater force to take them apart? One explanation could be an observation Gerhard Junker made back in 1969. While the lock washers have little locking capabilities, the additional axial forces acting on the assembly hold it together better in that moment of minimal friction. This would explain why the flat washers require less force to loosen as they do not have that added axial force and tend to loosen in that same moment. However, with an assumed level of significance set at 0.05, the result of 0.04 is riding the fence. As a result, the data is inconclusive. The following recommendations are made to further enhance this study and come to a more ascertainable conclusion.

- Increase test sample size for all contributing variables

- Compare assemblies of different sizes
- Arrange assemblies in different orientations
- Test lubricated as well as dry assemblies
- Examine instances of additional cycle counts (250, 750, 1000, ...)
- Build a machine(s) that induces stress comparable to that on specific infrastructure

Conclusion

While it is currently unknown if split-ring helical lock washers would better serve specific engineering structures, with more time and funding, it is believed this can be determined. Through implementing different variables like different sizes of bolted joint assemblies, orientations of assembly locations, and number of cycles per test, a more accurate and reliable set of data can be produced.

References

[1] West Coast Lockwasher, "wclo.com," [Online]. Available: http://www.wclco.com/pdf/lockwash/lw.pdf. [Accessed 8 February 2019].

[2] G. H. Junker, "New Criteria for Self-Loosening of Fasteners Under Vibration," SAE International, 1969.

[3] R. T. Barrett, "Fastener Design Manual," NASA, Cleveland, Ohio, 1990.

[4] D. K. Davies, "North American Tower Failures:Causes and Cures," Consolidated Engineering Inc., Evansville, Indiana, 2011.

Appendices

Appendix A: Test Data

Flat Washer Test Data

Flat Washer Null Test		Assembly Position				Cycles	Time (s)
		1	2	3	4		
Torque ft·lbf	Pre Test	15	14.9	15.9	15.5	0	0
	Post Test	11.8	11.4	11.1	1.4		
	Pre-Post	3.2	3.5	4.8	14.1		

Flat Washer Test 1		Assembly Position				Cycles	Time (s)
		1	2	3	4		
Torque ft·lbf	Pre Test	14.7	14.9	14.8	15.5	499	57.63
	Post Test	5.2	0.5	0.2	1		
	Pre-Post	9.5	14.4	14.6	14.5		

Flat Washer Test 2		Assembly Position				Cycles	Time (s)
		1	2	3	4		
Torque ft·lbf	Pre Test	14.8	15.4	15	14.8	500	55.31
	Post Test	6.2	7.7	3.7	0.6		
	Pre-Post	8.6	7.7	11.3	14.2		

Flat Washer Test 3		Assembly Position				Cycles	Time (s)
		1	2	3	4		
Torque ft·lbf	Pre Test	15.2	15.1	15	15.2	499	56.74
	Post Test	3.9	0.5	10.6	2.8		
	Pre-Post	11.3	14.6	4.4	12.4		

Split-Ring Helical Lock Washer Test Data

Split-Ring Helical Lock Washer Null Test		Assembly Position				Cycles	Time (s)
		1	2	3	4		
Torque ft·lbf	Pre Test	14.7	15.3	14.7	15.1	0	0
	Post Test	2.9	12.6	9.4	11.6		
	Pre-Post	11.8	2.7	5.3	3.5		

Split-Ring Helical Lock Washer Test 1		Assembly Position				Cycles	Time (s)
		1	2	3	4		
Torque ft·lbf	Pre Test	15	15	15.4	14.7	502	55.31
	Post Test	2.7	3.7	4.9	4.4		
	Pre-Post	12.3	11.3	10.5	10.3		

Split-Ring Helical Lock Washer Test 2		Assembly Position				Cycles	Time (s)
		1	2	3	4		
Torque ft·lbf	Pre Test	15	15.9	14.9	15.1	500	56.28
	Post Test	2	11.9	11	10.8		
	Pre-Post	13	4	3.9	4.3		

Split-Ring Helical Lock Washer Test 3		Assembly Position				Cycles	Time (s)
		1	2	3	4		
Torque ft·lbf	Pre Test	15	15.4	15.1	14.8	500	58.44
	Post Test	0.8	9.7	4.1	11.5		
	Pre-Post	14.2	5.7	11	3.3		

Appendix B: Test Results

ANOVA

Two-Factor with Replication

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Sample	8.926875	1	8.926875	0.637405	0.42894	4.061706
Columns	273.1302	1	273.1302	19.50231	6.45E-05	4.061706
Interaction	0.991875	1	0.991875	0.070823	0.791386	4.061706
Within	616.2208	44	14.00502			
Total	899.2698	47				

Null Data F-Test

Two-Sample for Variances

	Flat	*SRHLW*
Mean	6.4	5.825
Variance	26.83333	17.04917
Observations	4	4
df	3	3
F	1.573879	
P(F<=f) one-tail	0.359242	
F Critical one-tail	9.276628	

Null Data t-Test

Two-Sample Assuming Unequal Variances

	Flat	*SRHLW*
Mean	6.4	5.825
Variance	26.83333	17.04917
Observations	4	4
Hypothesized Mean Difference	0	
df	6	
t Stat	0.173601	
P(T<=t) one-tail	0.433944	
t Critical one-tail	1.94318	
P(T<=t) two-tail	0.867888	
t Critical two-tail	2.446912	

Cyclic Data F-Test

Two-Sample for Variances

	Variable 1	*Variable 2*
Mean	8.65	11.45833
Variance	16.560909	11.09538
Observations	12	12
df	11	11
F	1.4925952	
P(F<=f) one-tail	0.2587587	
F Critical one-tail	2.8179305	

Cyclic Data t-Test

Two-Sample Assuming Unequal Variances

	Variable 1	*Variable 2*
Mean	8.65	11.45833
Variance	16.56091	11.09538
Observations	12	12
Hypothesized Mean Difference	0	
df	21	
t Stat	-1.84987	
P(T<=t) one-tail	0.039228	
t Critical one-tail	1.720743	
P(T<=t) two-tail	0.078455	
t Critical two-tail	2.079614	