NASA/TP—2018-219787

# Preload Loss in a Spacecraft Fastener via Vibration-Induced Unwinding

*Christopher DellaCorte and S. Adam Howard*
*Glenn Research Center, Cleveland, Ohio*

*Daniel P. Hess*
*University of South Florida, Tampa, Florida*

April 2018

## NASA STI Program . . . in Profile

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA Scientific and Technical Information (STI) Program plays a key part in helping NASA maintain this important role.

The NASA STI Program operates under the auspices of the Agency Chief Information Officer. It collects, organizes, provides for archiving, and disseminates NASA's STI. The NASA STI Program provides access to the NASA Technical Report Server—Registered (NTRS Reg) and NASA Technical Report Server—Public (NTRS) thus providing one of the largest collections of aeronautical and space science STI in the world. Results are published in both non-NASA channels and by NASA in the NASA STI Report Series, which includes the following report types:

- TECHNICAL PUBLICATION. Reports of completed research or a major significant phase of research that present the results of NASA programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA counter-part of peer-reviewed formal professional papers, but has less stringent limitations on manuscript length and extent of graphic presentations.

- TECHNICAL MEMORANDUM. Scientific and technical findings that are preliminary or of specialized interest, e.g., "quick-release" reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.

- CONTRACTOR REPORT. Scientific and technical findings by NASA-sponsored contractors and grantees.

- CONFERENCE PUBLICATION. Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or co-sponsored by NASA.

- SPECIAL PUBLICATION. Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.

- TECHNICAL TRANSLATION. English-language translations of foreign scientific and technical material pertinent to NASA's mission.

For more information about the NASA STI program, see the following:

- Access the NASA STI program home page at http://www.sti.nasa.gov

- E-mail your question to help@sti.nasa.gov

- Fax your question to the NASA STI Information Desk at 757-864-6500

- Telephone the NASA STI Information Desk at 757-864-9658

- Write to:
  NASA STI Program
  Mail Stop 148
  NASA Langley Research Center
  Hampton, VA 23681-2199

NASA/TP—2018-219787

# Preload Loss in a Spacecraft Fastener via Vibration-Induced Unwinding

*Christopher DellaCorte and S. Adam Howard*
*Glenn Research Center, Cleveland, Ohio*

*Daniel P. Hess*
*University of South Florida, Tampa, Florida*

National Aeronautics and
Space Administration

Glenn Research Center
Cleveland, Ohio 44135

---

April 2018

# Acknowledgments

The authors wish to acknowledge the contributions of the many colleagues and team members who assisted in the broad array of experimental and analytical tasks undertaken to identify and understand the preload loss phenomenon. In alphabetical order, they are: James Akers, Robert Bruckner, Dale Dragony, Robert Jankovsky, Trevor Jones, Kevin Konno, Richard Manco, Kim Otten, Jesus Partida, Duane Revilock, Chuck Ruggeri, Jim Szelagowski, and Jim Winkel. Their tireless work greatly helped elucidate the subtle effects observed during test and, importantly, helped guide recommendations for preventing critical fastener preload loss and unwinding.

*Level of Review*: This material has been technically reviewed by a committee of peers.

Available from

NASA STI Program
Mail Stop 148
NASA Langley Research Center
Hampton, VA 23681-2199

National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161
703-605-6000

# Contents

# Preload Loss in a Spacecraft Fastener via Vibration-Induced Unwinding

Christopher DellaCorte and S. Adam Howard
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio 44135

Daniel P. Hess
University of South Florida
Tampa, Florida 33620

## Summary

Sound engineering practice requires that fasteners and bolted joints maintain preload in service. NASA recently concluded a series of vibration tests of a multicomponent structure intended to simulate an upper stage section of a launch vehicle. The stacked components were joined through six circumferentially placed bolted cup-cone-style pyrotechnic joint mechanisms designed to share spacecraft structural loads and then enable separation during ascent. Over the course of the vibration test campaign, all six bolted cup-cone mechanisms experienced some degree of preload loss with two mechanisms losing half of their original bolt preload. A subsequent forensic anomaly investigation concluded that vibration-induced unwinding of the preload nut-and-bolt assemblies occurred despite the use of safety wire and high levels of thread friction. A series of experiments were done to better understand how large, heavily preloaded fasteners could unwind. Additionally, thread friction torque was measured and the fastener locking capability of safety wire was evaluated. The friction coefficient between the clamped cup-cone components was characterized and finally a highly instrumented mechanism-level vibration test was done to reproduce the unwinding phenomenon to better understand the mechanism's behavior. The conclusion drawn was that vibration and structural forces led to relative motion (sliding) of the clamped components, resulting in self-loosening and unwinding effects on the nut-and-bolt assembly. To counter this phenomenon, more effective fastener locking methodologies were recommended and a follow-on effort was initiated to quantify the relationship between preload, component motion, and resulting unwinding forces. It is hoped that elucidation of these effects can be used to design more effective fastener locking features.

## Nomenclature

| | |
|---|---|
| EFT–1 | Exploration Flight Test 1 |
| ESA | European Space Agency |
| MJT | multi-jackbolt tensioner |
| MVF | multipurpose vibration facility |
| PSM | Pyramidal Separation Mechanism |
| rpm | revolutions per minute |
| SDL | Structural Dynamics Laboratory |
| SLS | Space Launch System |
| STA | structural test article |

# 1.0 Introduction

## 1.1 Background

The Orion spacecraft and the Space Launch System (SLS), NASA's new human-rated deep space capsule and launch system currently under development, includes many innovations aimed at significant vehicle capability improvements. One strategy to minimize vehicle mass (for a given payload) is to enable the separable aerodynamic fairings to carry a portion of the vehicle's structural loads (Ref. 1). Under this approach, during the early portions of the ascent when loading is highest, the service module aerodynamic fairing (secondary load path) carries a portion of the overall structural load, thus reducing the load carried by the substructure (primary load path). This enables the substructure to be designed for lower loads, resulting in a minimal mass structure. Later in the ascent, when load levels drop and the aerodynamic shield is jettisoned, the remaining primary load-carrying structure is adequately sized, not oversized, and carries minimum mass into orbit. By utilizing jettisoned elements in the load path, payload capacity to orbit can be maximized.

A key design attribute for this approach is that the separation mechanism for the aerodynamic shield must be able to withstand structural and aerodynamic loads and allow for clean and effective separation at the required point in the vehicle's ascent. In a paper presented at the Aerospace Mechanisms Symposium in 2014, the load-sharing aerodynamic shield and separation system design were introduced and described in detail (Ref. 1). Figure 1 and Figure 2 illustrate the primary hardware components.

Among these components are the six, circumferentially located Pyramidal Separation Mechanism (PSM) cup-cone

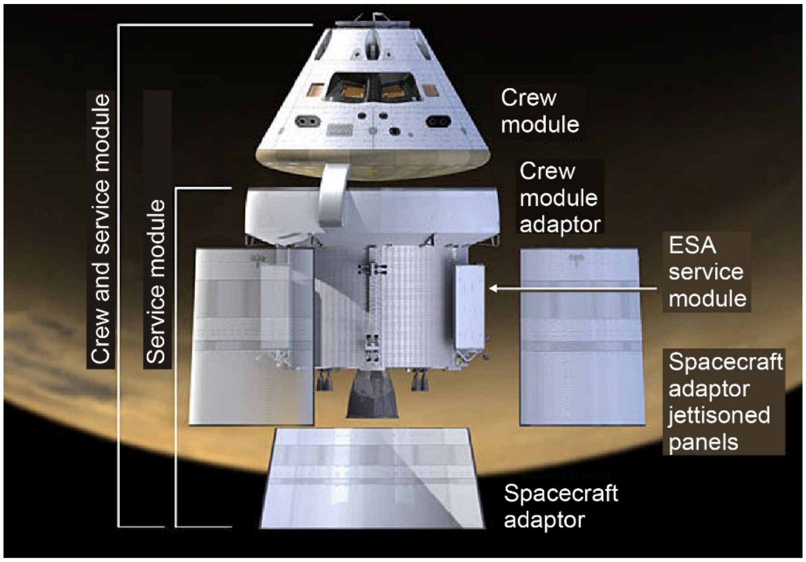

Figure 1.—Orion configuration showing aerodynamic shield panels (spacecraft adaptor panels) after being jettisoned (Ref. 1). ESA, European Space Agency.

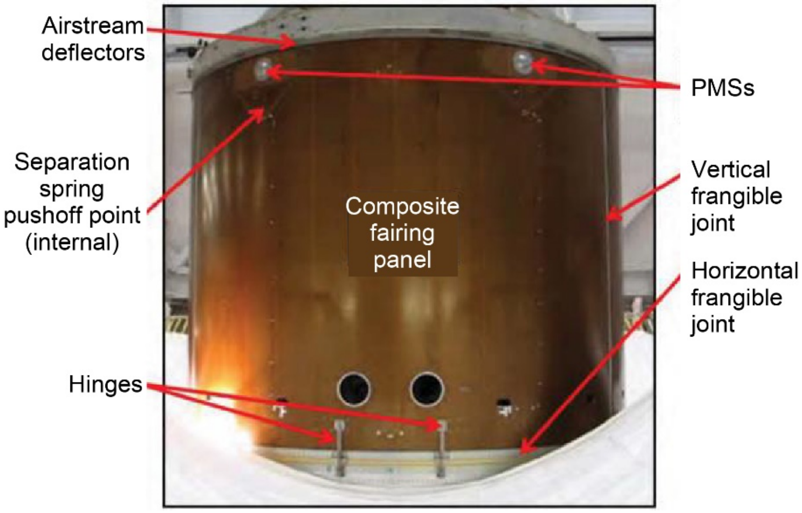

Figure 2.—Orion fairing components (one of three aerodynamic shield panels shown) location of two Pyramidal Separation Mechanisms (PSMs) (Ref. 1).

interfaces. Two PSMs connect the upper end of each of the three fairing panel segments to the spacecraft. Figure 3 shows a cross section of a typical PSM cup-cone device.

The PSMs are a variant of the cup-cone separation mechanism. As the name implies, a four-sided truncated pyramid shape is employed in lieu of circular shapes in order to impart lateral and torsional stiffness to the mechanism. The cup-cone plates are heavily clamped with a pyrotechnic separation bolt. When actuation of the mechanism is triggered, a pyrotechnic charge locate inside the separation bolt is fired. The charge causes a complete fracture across the separation bolt immediately adjacent to the supernut, allowing the male PSM plate to disengage from the female PSM plate.

In order to facilitate tightening of the separation bolt to the proper preload, a Superbolt® multi-jackbolt tensioner (MJT) (Nord-Lock, Inc.), also known as a Superbolt® supernut, is used. The supernut is a threaded ring, which contains a circumferentially placed set of jackbolts that when tightened pull the threaded ring away from the bolt against the clamped parts, thus stretching the bolt while minimizing torque at the separation plane. Figure 4 shows a typical supernut-bolt style fastener.

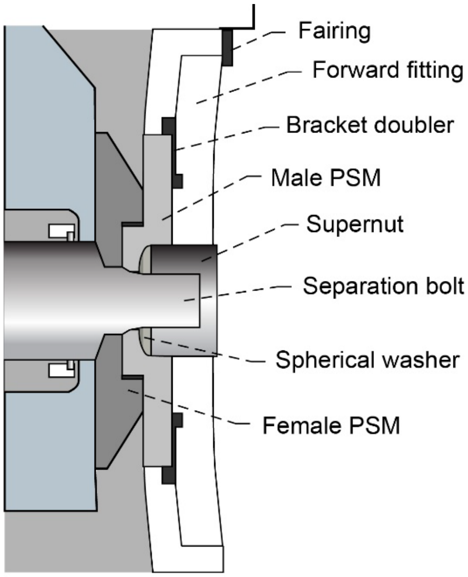

Figure 3.—Pyramidal Separation Mechanism (PSM) cross section (Ref. 1).

This design is favored for large bolts because, compared to torquing the large primary bolt directly, much lower torques are required for each jackbolt. In addition, by careful use of a tightening sequence, bending of the bolt can be avoided. In the PSM, the separation bolt mates with a supernut. Jackbolts on the nut are turned to stretch the Superbolt®, which is fractured internally through the employment of a pyrotechnic charge built into the bolt head.

Typical of cup-cone designs, a small clearance exists between the cup and cone surfaces to avoid pinching and jamming and to ensure free and definite separation (Ref. 2). To minimize wear and further prevent sticking, the titanium alloy PSM plates are coated with a multilayer commercially available coating that combines a hard-anodizing layer that is overcoated with a $MoS_2$-pigmented solid lubricant layer. The Canadize® coating (General Magnaplate Corporation) is similar to other such multilayer surface treatments optimized for titanium to prevent galling and wear (Refs. 1, 3, and 4).

A major consequence of lubricating the cup-cone surfaces is their propensity to slip when heavily loaded. Indeed, during oscillatory load-stiffness tests of the PSM (Ref. 1), slip was noted as depicted in Figure 5. The magnitude of the slip is small and limited to the small clearance between the cup-cone surfaces.

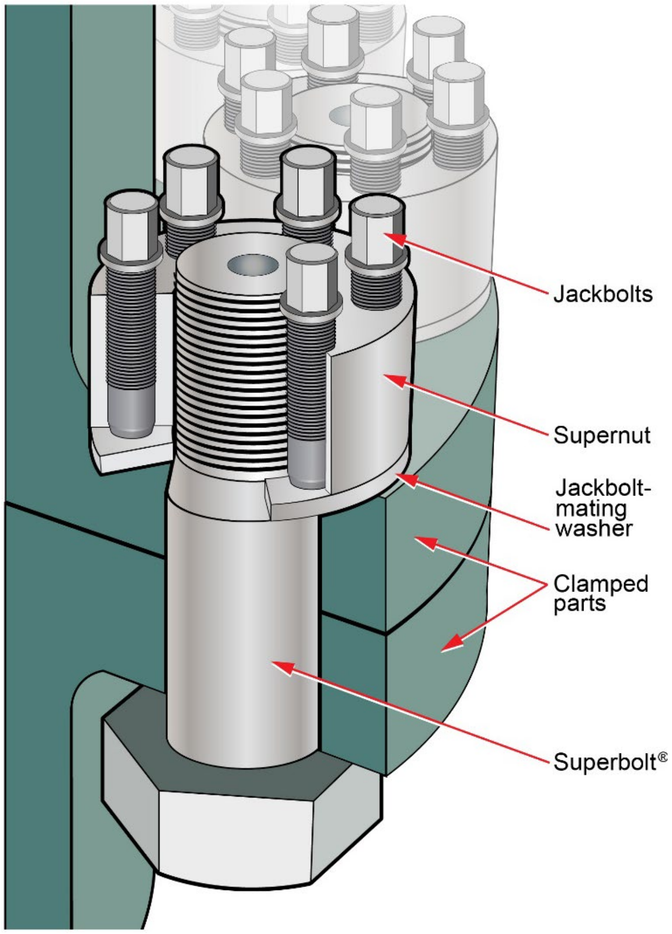

Figure 4.—Typical Superbolt® assembly showing operating principles. Images from manufacturer catalog (www.fairfieldindustrialsales.com).

The overall design soundness of the load-sharing aerodynamic fairing concept with the PSMs was recently put to the test. Figure 6 shows build photographs of the Exploration Flight Test 1 (EFT–1) flight hardware in which the PSM locations and their relation to the vehicle and shield can be readily seen.

In December of 2014, NASA conducted EFT–1. During the ascent and 6 min and 15 s into the approximately 4-hr flight test, the command was given to fire the pyrotechnic charges, detach the no longer needed aerodynamic shield, and separate the upper stage from the lower main propulsion stage. All flight instrumentation and imaging indicate that the fairings properly separated and that the concept and the function of the PSM were successful.

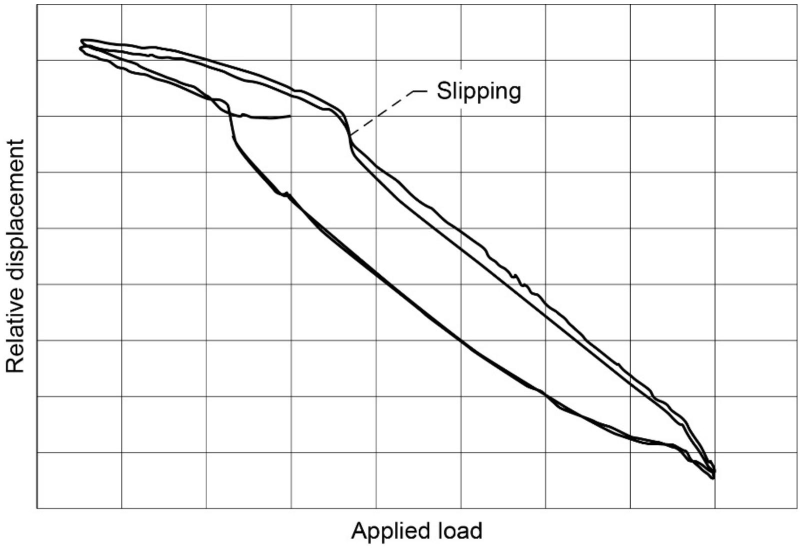

Figure 5.—Pyramidal Separation Mechanism load versus displacement. Note slip occurs due to lubrication and the presence of a small clearance between plate surfaces (Ref. 1).

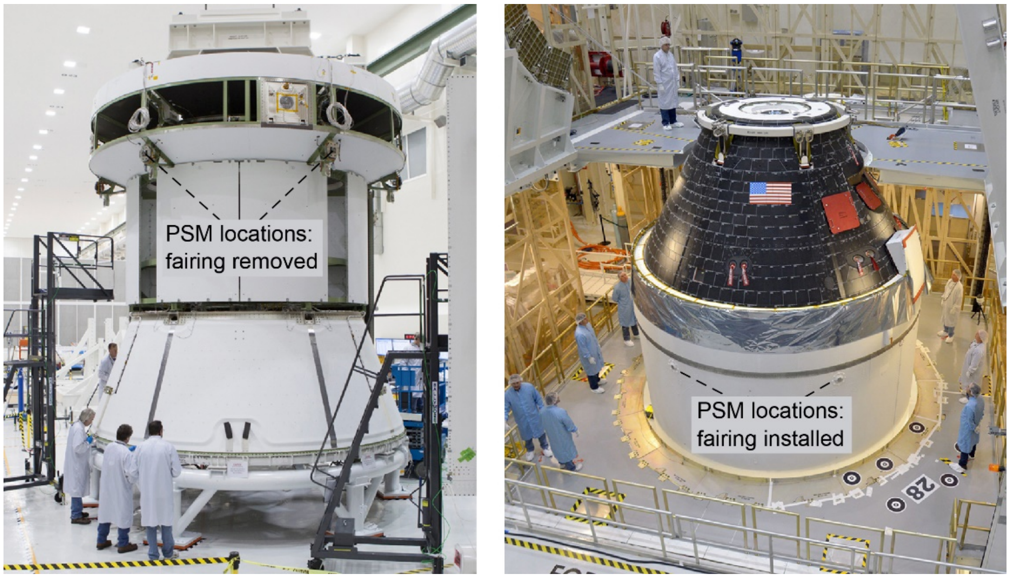

Figure 6.—Pyramidal Separation Mechanism (PSM) locations on Exploration Flight Test 1 flight vehicle.

## 1.2 Recent Developments

Since the successful EFT–1, additional high-level tests have been conducted on the SLS system. In particular, a structural test article (STA) consisting of a test mass (simulating the capsule and crew module) situated above a structural mockup of the service module, with the PSMs and aerodynamic fairing installed, was placed on NASA's new multipurpose vibration facility (MVF) and exposed to a series of high-energy, high-frequency, random and sinusoidal vibration tests (Ref. 5). These tests were conducted to evaluate the effectiveness of the load-sharing concept and check out many other spacecraft systems and their response to vibration. As such, the test article experienced far more vibration (duration, magnitude, and frequency) energy than expected from a launch.

Over a 4-month test period, the STA was placed under vibratory loads for over 4 total test hours. It is important to note that in flight, these components are typically subjected to lower vibration levels that last for only several minutes. In any case, sometime during the later stages of the testing period,

TABLE I.—PYRAMIDAL SEPARATION MECHANISM (PSM) SEPARATION BOLT—POST-TEST DATA

| PSM location, deg | 0 | 60 | 120 | 180 | 240 | 300 |
|---|---|---|---|---|---|---|
| Preload loss, percent | 51 | 11 | 32 | 46 | 26 | 20 |

loud banging noises were noted that seemed to emanate from the PSMs. Prior to installation, four surface-mounted strain gauges were mounted on the shank of the separation bolts to monitor the bolt strain while the Supernut jacking bolts were torqued. The strain (and bolt preload) levels were not tracked during test, making it impossible to track the preload levels during the test campaign. After the test campaign was completed, the strain gauge wires were reconnected and the preload levels in the six PSM separation bolts were measured. Table I shows the change in PSM separation bolt preload loss that occurred during the test campaign.

The loss of preload was unexpected. The separation bolts are carefully designed and installed to maintain a heavy clamping force on the cup-cone interface to assure proper joint stiffness, to carry the launch loads, and to prevent plate gapping. A forensic investigation was subsequently undertaken to uncover the root cause for the preload loss and to develop guidance for recovery.

## 1.3 Forensic Investigation Plan

There are three avenues for loss of preload in the separation bolts: permanent stretch (plastic deformation) of the separation bolts due to overload, unthreading of the supernut and/or jackbolts, and finally, a reduction in the thickness of the stack of parts clamped between the supernut and separation bolt. Thickness reduction of the stack can be the result of plastic deformation, wear of contacting surfaces, or a combination of the two. A comprehensive forensic investigation was undertaken to explore each of these three failure paths.

## 1.4 Forensic Investigation Results

First, prior to disassembly of the PSMs, a visual inspection including the taking of record photographs was conducted. Then the PSM components (cups, cones, washers, etc.) were removed with careful attention paid to the presence and location of any wear debris, damage, and the plate locations and orientation with respect to the test setup. Last, the six separation bolts were inspected for damage and overall length so that their post-test condition could be compared to the as-installed pretest state.

Measurements and other dimensional inspection of the separation bolts indicated that no permanent stretch of the bolts occurred. This suggests that the loads experienced by the bolts during installation and test did not exceed the material's yield strength.

Dimensional measurements were made of the PSM components clamped between the separation bolt and the supernut. These components (depicted in Figure 3) include the male and female cone and cup and the spherical load washer against which the jackbolts contact. Localized wear marks in the Canadize® coating were noted in many places but most notably on the cup-cone faces near the centrally located separation bolt and on the angled cup-cone surfaces. However, profilometry measurements indicate that very little material removal appears to have occurred. Indeed, the PSM cups and cones were still well within dimensional tolerances. Further confounding the forensic efforts, the PSM cups and cones had been tested previously as part of a series of subcomponent level life tests (Ref. 1). It could not be determined whether the wear marks on the Canadize® coatings were the result of earlier tests or the present vibration test campaign that resulted in the PSM preload loss. In any case, the magnitude of observed wear was not consistent with the levels of preload loss observed.

The final preload loss avenue to be considered was unwinding of the jackbolts or the supernut ring with respect to the separation bolt. Visual reviews of the pretest closeout photos (after assembly but prior to the STA vibration test campaign) and those taken after test but prior to PSM disassembly were revealing. Safety wires were used to prevent individual rotation of the jackbolts and the supernut. Prior to test, torque stripes (paint marks) were applied to the jackbolt heads and the supernuts and Superbolts®.

Though the pretest photos were of low quality and not available for all of the PSMs, those that were clear suggested that the jackbolts had not experienced any rotation during test. However, the jackbolt/supernut assemblies had all undergone some unwinding with respect to the separation bolt during the test. The amount (degrees) of unwinding correlated with the preload loss percentages noted in Table I. The unwind magnitudes ranged from a few degrees to over 10° of rotation. In addition, it was determined that the safety wire used to secure the supernut from rotating on the separation bolt had been incorrectly installed. These observations are an indication that the loss of preload was primarily due to unwinding of the supernuts in response to the test environment.

## 1.5 Supernut Unwind Assessment

The observation that this primary fastener had lost preload due to unwinding of the nut was initially surprising. The PSM cup and cone plates are clamped with a large, highly preloaded fastener, the separation bolt. The high preload was expected to provide a large thread friction-induced torque value that should prevent loosening. Therefore, the observed loss of preload via nut unwinding was not expected. However, based upon the literature, the observed preload loss is, in fact, not surprising or novel. The general phenomenon of self-loosening of fasteners, was studied in earnest by G. Junker, a pioneering fastener engineer credited with developing a widely used lab test to study the phenomena affiliated with the “vibration loosening of fasteners (Ref. 6).”

In a conventionally designed bolted joint, the fastener and preload level is selected to ensure that the clamped components transmit design loads and are held rigidly together. In essence, the bolt, nut, washers, and other structural elements behave as one solid, rigid component. Joints are analyzed to ensure that under peak loads, no gapping or motion of the clamped components occurs. Indeed, much of this “good bolted joint” design philosophy has its origins in bolted piping systems used for high-pressure steam systems. In such systems, gapping of the clamped components (e.g., steam pipe flanges) would result in leakage and joint failure. In the PSM bolted joint, motion between clamped components is part of the design intent.

The cup and cone surfaces of the PSM joint are coated with an effective solid lubricant applied to reduce friction and wear. The design, common for cup-cone interfaces, includes a small dimensional clearance to preclude jamming and foster proper separation when the separation bolt is actuated. During development testing of the PSM, as reported previously and shown graphically in Figure 5, slipping of the cup-cone interface was confirmed. Thus, it appears that the PSM is a special case for bolted joint design; the case in which sliding of the components does occur despite high preload and high prevailing torque of the fastener.

This special case has been studied in the literature (Refs. 7 and 8). It is also mentioned peripherally in the NASA–STD–5020, Requirements for Threaded Fastening Systems in Spaceflight Hardware, and the NASA Fastener Design Manual (Refs. 9 and 10). In the standards and in several papers, it is noted that when relative motion between the fastener and the clamped components is encountered, thread friction cannot be relied upon for preload retention. Rather, a positive locking feature, such as a cotter pin or other locking device, should be employed. In the present case of the PSM, safety wire was employed as the secondary locking feature and the thread friction-induced torque offered by the bolt preload was considered the primary locking feature. To determine the efficacy of these features, a series of experiments were undertaken. Namely, the thread friction torque of the supernut-separation bolt was assessed under different loads and lubrication conditions and the torque capability of safety wire was measured. In addition, the friction behavior of the PSM lubricant at varying stages of wear was assessed.

## 1.6 Experimental Measurements

In an effort to bring credible friction data to the forensic investigation, the friction coefficient between the cup and cone surfaces was assessed. Prior PSM component tests (Ref. 1) done in a slow-speed reciprocating loading test verified (Figure 5) that slippage of the cup-cone interface does occur when the applied shear loads are sufficiently high. That testing, however, did not produce friction coefficient data that could be used for modeling and first-principles engineering analyses. For the present investigation, titanium pins and disks were coated with the Canadize® surface treatment and evaluated in a pin-on-disk tribometer (Ref. 11). With this test rig, the friction for the sliding materials was recorded in a series of tests in which the load, sliding velocity, and counter-face materials were varied. Figure 7 shows a representative friction coefficient trace for a Canadize®-coated disk and pin. During the early portion of the test, the friction is low with little dynamic variation. As the coating wears through, exposing the underlying titanium, friction becomes erratic eventually rising to a high level equivalent to the baseline case. The data are summarized in Table II.

Since inspection of the worn surfaces of the cups and cones revealed predominantly intact Canadize® coatings with no deep gouges or underlying substrate metal (Ti64) transfer or galling, it is inferred that the PSM cup and cone plates were free to slide during the vibration testing. The next experiment involved assessing the lubrication condition of the supernut-separation bolt thread interface. This was done in a load frame with rotary torque capability as described in the following section.

In a typical bolted joint, the thread friction torque is relied upon to prevent unwinding and loss of joint preload. The majority of this friction arises from the sliding interface between nut and bolt threads. To better understand the PSM preload loss, a series of tests were undertaken to quantify the thread friction of the separation bolt-supernut threads. The supernut-separation bolt thread assembly is loaded in compression using a load frame in Figure 8.

TABLE II.—PYRAMIDAL SEPARATION MECHANISM PIN-ON-DISK FRICTION COEFFICIENT SUMMARY (~5 N LOAD, 1.6 m/s SLIDING VELOCITY, AIR)

| Pin/disk condition | Initial | Steady state | End of test |
|---|---|---|---|
| Coated pin/coated disk | ~0.3 | 0.05 to 0.010 (smooth) | 0.6 (erratic) |
| Uncoated pin/coated disk | ~0.2 | 0.03 to 0.15 (smooth) | 0.5 (erratic) |
| Baseline Ti64 versus Ti64 | ~0.3 to 0.6 (erratic) | | |

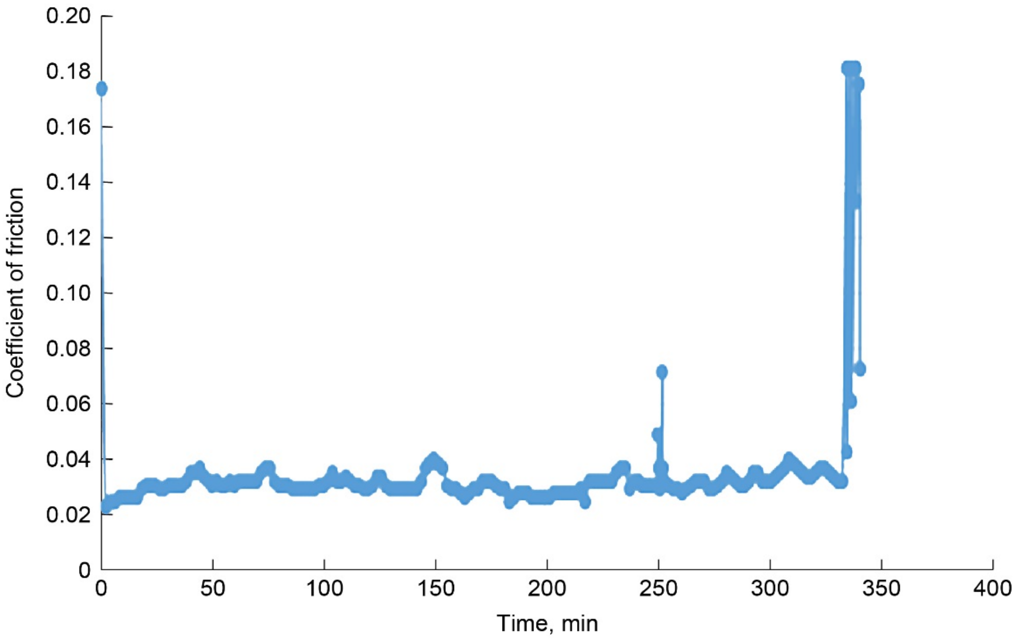

Figure 7.—Coefficient of friction coefficient versus time for uncoated Ti pin sliding against a Canadize®-coated Ti disk under a 9.81 N load at 600 rpm. Friction is low and steady until coating is worn through exposing underlying Ti surface.

Figure 8.—Supernut-separation bolt loaded in load frame to measure prevailing (thread friction) torque.

With this setup, axial loads between 2,267.96 to 20,411.66 kg (5,000 to 45,000 lb) are applied to the threaded joint while a rotary actuator is used to turn the bolts and record breakaway and running torque. Rotation was at constant speed and data were acquired until a steady-state torque at each of the three tested load levels (2,267.96; 11,339.81; and 20,411.66 kg (5,000; 25,000; and 45,000 lb)) was achieved. Three different lubrication conditions were tested. First, the nut-and-bolt assembly was tested in the "as-received from vibration test" condition. In this state, remnants of the assembly lubricant (grease) remained. Next, the nut-and-bolt threads were thoroughly cleaned with solvent and detergents to represent a "dry-unlubricated" case. Last, a fluorocarbon-based grease containing solid lubricant additives was applied liberally to the threads. The data are summarized in Table III.

TABLE III.—PYRAMIDAL SEPARATION MECHANISM SEPARATION BOLT PREVAILING TORQUE SUMMARY

| Thread lubrication | 2,267.96 kg (5,000 lb) load | 11,339.81 kg (25,000 lb) load | 20,411.66 kg (45,000 lb) load |
|---|---|---|---|
| As-received (used grease) | 20.34 N•m (15 ft•lb) | 162.70 N•m (120 ft•lb) | 237.27 N•m (175 ft•lb) |
| Dry-unlubricated (no grease) | Not tested | 237.27 N•m (175 ft•lb) | 291.50 N•m (215 ft•lb) |
| New grease | Not tested | 151.85 N•m (112 ft•lb) | 196.59 N•m (145 ft•lb) |

The results were in line with expectations. The highest friction torque was observed in the unlubricated case, followed by the case where the small amount of remaining assembly grease was present on the separation bolt threads and last, the lowest friction was found for a case where fresh grease was applied liberally to the threads prior to installation. In quantitative terms, the friction torque under the highest load

(20,411.66 kg (45,000 lb)) ranged from 196.59 N•m (145 ft•lb) for the test with fresh grease to 291.50 N•m (215 ft•lb) for a well-cleaned (alcohol and soap and water) bolt. Corresponding nut factors ranged from 0.03 to 0.06.

The second test that has been conducted is to ascertain the torque resistance of the safety locking wire. In this series of tests, surrogate separation bolts were manufactured to replicate the separation bolt end features and threads, but were long enough to allow installation in a torsion load frame. With this setup, various lock wire configurations could be readily installed and tested without any bolt preload that could mask the torque results. Figure 9 shows the safety lock wire test setup that mimics the STA vibration test condition.

In this case, the single lock wire runs at a slight axial angle because the center post on the separation bolt face is positioned below the wire connection point on the jackbolt. A second test was run where the wire was fully horizontal to the jackbolt location as shown in Figure 10.

Also tested was a single wire using a separation bolt with a large-diameter raised-wire connection intended to increase the rotational diameter of the wire to enhance restraining torque (Figure 11).

Lastly, multiple wires were tested in all configurations. Figure 12 shows a double lock wire arrangement with a coincident axial wire attachment.

Figure 9.—Supernut-separation bolt safety wire configuration used during structural test article vibration test. Note the relatively small diameter center post and incorrect (backward) winding direction around the center post.

Figure 10.—Supernut-separation bolt safety wire configuration using proper horizontal alignment and correct winding direction around center post.

Figure 11.—Supernut-separation bolt safety wire configuration using improper angled alignment with correct winding direction around a large diameter center post.

Figure 12.—Supernut-separation bolt safety multiple-wire configuration using proper horizontal alignment with correct winding direction around a large-diameter center post.

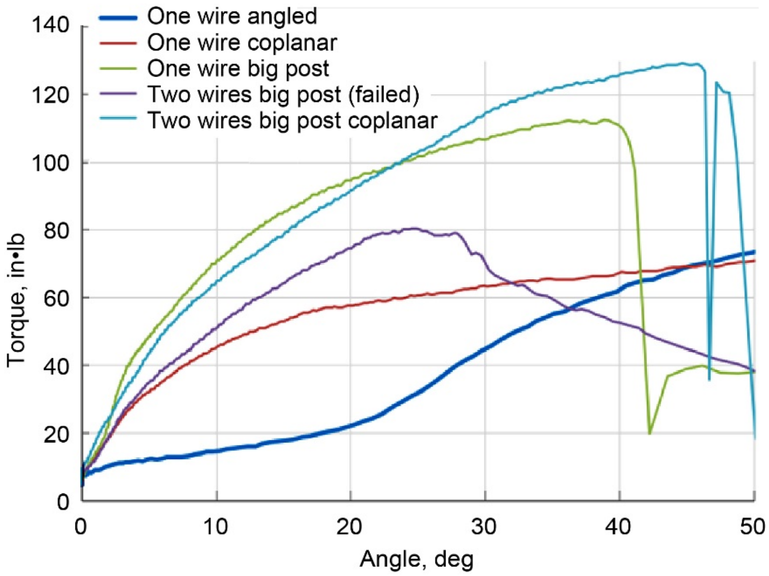

Figure 13.—Torque required to rotate the supernut-separation bolt against different safety wire configurations over a large angle.

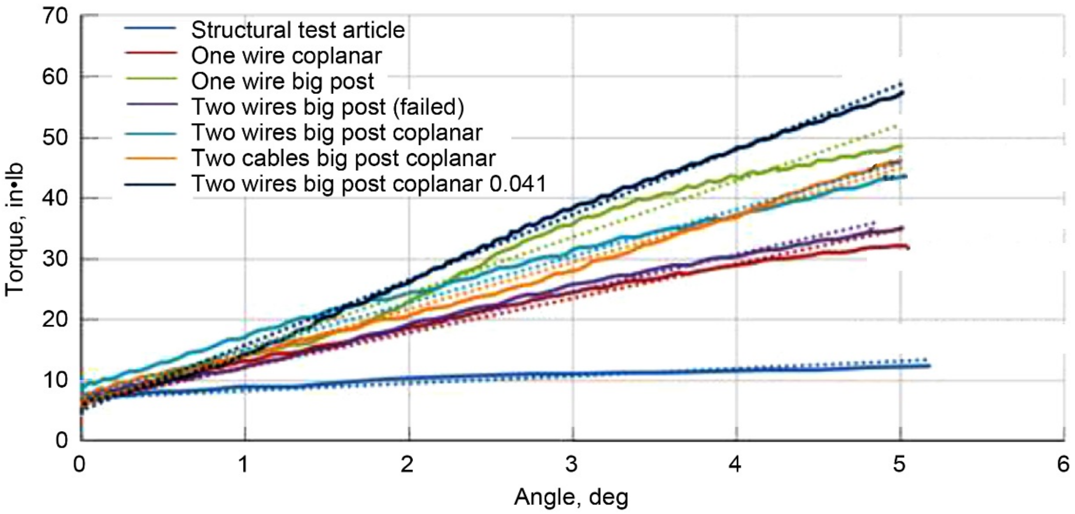

Figure 14.—Torque required to rotate the supernut-separation bolt against different safety wire configurations over the very first 5° (with stiffness curve fits).

The data for the lock wire experiments are summarized in Figure 13.

Though these results indicate that the use of multiple wires and large wire attachment posts improve the torque restraining capabilities, none of the lock wires provide significant preload retention. It is estimated that the preload is reduced by 50 percent through a bolt rotation of only 15°. Therefore, any restraining device needs to prevent unwinding by less than 5°. For all of the wiring arrangements tested (and depicted in the graph), the maximum restraint offered is well below 13.56 N•m (120 in•lb or (10 ft•lb)) at 5° of rotation. From the data, it appears that safety wire is ineffective at preventing some loss of preload.

This observation is noted in the fastener standard (Ref. 9). Figure 14 replots the available data for only the first critical 5° of rotation. Here you can see that the STA configuration, where the central wire was wrapped in the backward direction, offers essentially no torque restraint. However, even the best wire configuration using two large diameter wires (1.041 mm (0.041 in.)) wrapped correctly around a large center post only offers ~6.78 N•m (~60 in•lb) of restraint.

These experiments provide data that support a root cause theory in which the loads encountered during the STA vibration tests resulted in cup-cone relative motion (sliding), a condition known to lead to unwinding. Further, the inability of safety wire to prevent small amounts of unwinding was observed. The next step is to validate the root cause theory. To this end, a series of component-level vibration tests were conducted using a heavily instrumented PSM to determine if a preloaded separation bolt can be unwound against prevailing torque through vibration-induced plate motion.

## 1.7 Experimental Verification

NASA Glenn's Structural Dynamics Laboratory (SDL) facility was configured for a single PSM component-level vibration test as depicted in Figure 15.

Using this configuration, prescribed planar motions drive the mounting plate (blue) and impart forces and motions through the cup-cone interface and into the mass plate, which results in shear and other forces at the cup-cone interface. Several types of instrumentation were used to monitor the tests.

The vibration table facility controls and monitors acceleration inputs to the test fixture. Accelerometers mounted on the mass plate and mounting plate provide resulting g-levels. Four piezoelectric load cells are used between the mounting plate (blue) and the longeron support plate (green) to monitor input forces to the PSM. Finally, high-speed photogrammetry and video cameras are used to image the side and top of the fixture. With these instruments, the relative motion of the plates, the forces on the plates, and the angular placement between the supernut and the separation bolt can be ascertained. The experimental setup installed in the SDL facility with its instrumentation is shown in Figure 16.

A top view showing the supernut and the torque stripe (witness marks) on each fastener appears in Figure 17.

A series of tests were done beginning at low vibration levels to induce relative cup-cone plate motion (sliding along the interface between the cup and cone). Unfortunately, the design of the vibration test fixture limited the force levels that could be achieved. The piezoelectric load cells and the relatively small bolts used to anchor the load cells began to slip at vibration energy levels insufficient to achieve cup-cone plate sliding. Instead, the vibration energy input appears to have mostly imparted a tipping motion to the mass plate, resulting in a dynamic axial load being applied to the separation bolt. A shear load on the bolt was desired. For this reason, the initial vibration test campaign did not result in supernut-separation bolt test campaign did not result in supernut-separation bolt unwinding. Some preload loss (~5 to 10 percent) was observed but was not attributable to unwinding.

In an effort to demonstrate the unwinding phenomenon, the preload level was reduced to about half the normal value. The following vibration campaign then resulted in the supernut unwinding and significant loss of preload between the cup and cone plates. A post-test inspection revealed (and this was corroborated by photogrammetry) that the motion induced in the cup-cone interface was axial opening and closing of one side of the plates, similar to the slight opening and closing of a hinge. This motion was sufficient to achieve unwinding at lower preload levels.

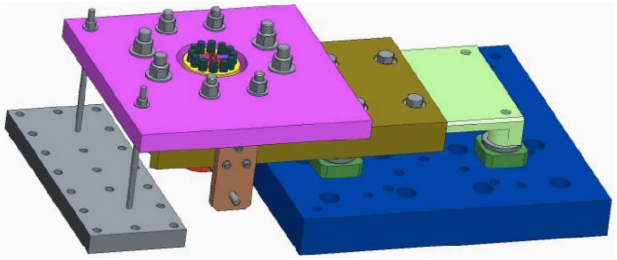

Figure 15.—Pyramidal Separation Mechanism vibration test configuration. Cup-and-cone plates are fastened between longeron simulator (brown) and mass plate (fuchsia) and preloaded with supernut-separation bolt. Supernut and bolt end face are visible pointing up in the model.

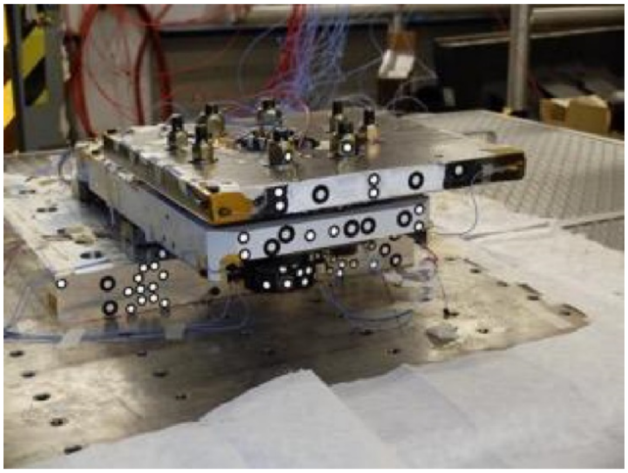

Figure 16.—Pyramidal Separation Mechanism vibration test configuration installed in Structural Dynamics Laboratory facility.

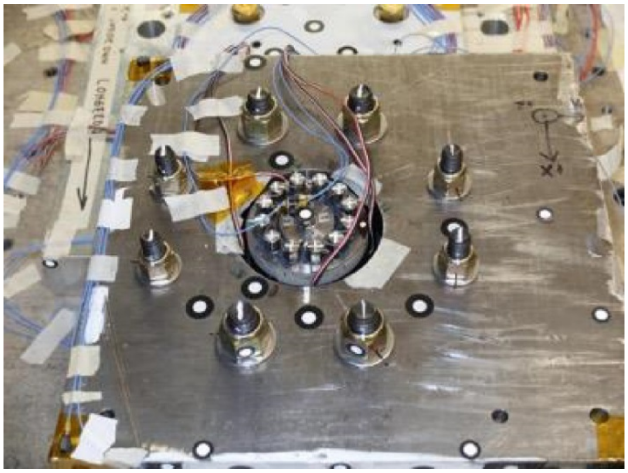

Figure 17.—Pyramidal Separation Mechanism vibration test configuration top view.

## 1.8 Discussion of Experimental Results

The experimental results highlight that the PSM is a special case for bolted joint design. The preload is high as is the prevailing torque (thread friction-induced drag torque). To ensure proper cup-cone separation, the clamped surfaces are coated with an effective solid lubricant. Last, the PSM joint carries significant static and dynamic loads. Taken together, the PSM joint seems to follow the behavior of bolted joints subjected to vibration loads as studied by Junker in the 1960s and more recently Pai and Hess and also by Light (Refs. 6, 7, and 11).

Historically, aircraft fasteners were frequently observed to loosen in use despite being properly tightened. Junker devised a lab test in which two sheets of metal clamped together by a simple bolt and nut are subjected to oscillatory shear in a plane perpendicular to the fastener axis. Junker observed that whenever the plates experienced relative sliding, the nuts backed off (unwound). He further noted that the rate of preload loss was proportional to the preload level. In other words, the tighter the joint, the faster it loosened. When the preload was lost, the unwinding phenomena stopped.

Junker developed several theories of why a slipping joint resulted in fastener unwinding and these have been further researched, modeled, and experimentally corroborated. One pathway leading to unwinding is the sliding action and forces between moving contact surfaces such as the underside of the bolt head and its mating part. Another pathway is jostling and nutation or rocking of the nut and its mating thread. In this case, the small clearances between the thread tips and adjacent thread roots provide room for the nut to translate. Under heavy preload, there is a tendency for the threads to loosen in small steps, but the preload discourages tightening when the motions are reversed. Light and Pai elaborate on these phenomena (Refs. 7 and 11). An excellent video, prepared by Bolt Science Limited. (Ref. 12), shows this effect as well as the operation of a lab vibration test named after Junker (Ref. 6). The takeaway from this discussion is that loss of preload in a joint where slipping occurs in the presence of vibration is a known phenomenon. It is rarely encountered for heavily preloaded fasteners because the clamped parts of such highly loaded joints do not often slip. For the PSM application, relative motion occurs and is intended by design. Thus, the conclusion that unwinding as observed in the Junker's test is likely analogous to the unwinding experienced during the Orion vibe test campaign.

An interesting corroborating detail regarding the preload loss for the full-scale STA test can be found by examining the unwind levels for the test campaign shown in Table I. Only two of the six PSMs lost a significant portion of their preload. Four PSMs only experienced modest levels of preload loss and commensurate unwinding. Initially, the reason for this variation was unknown. However, upon deeper examination, the reason is clearer. The test mass used in the STA campaign provided a heavy static (gravity) load to only four of the PSM locations. These four PSM bolts experienced the least unwinding. The other two PSMs, the 0 and 180° locations, were not subjected directly to the heavy static load from the test mass. Thus, during vibration testing, the two lightly loaded PSMs likely experienced more cyclic sliding motion (up and down) while the four heavily loaded PSMs likely only underwent sliding motion when the vibration load levels exceeded the test mass loads. Since Junker's type unwinding is a function of sliding magnitude and cycles, the four heavily loaded locations would be expected to undergo less unwinding. Such an observation again gives credibility to the root cause theory that joint sliding is a key factor. Whenever the loading profile exceeds the load needed to induce slip, loosening is a potential outcome.

In the PSM, the use of an effective and necessary solid lubricant coating causes slippage. Indeed, slippage is a design feature. Therefore, the unwinding of the supernut is a consequence of the design. To prevent preload loss, the fastener locking mechanism must be highly effective and it has been shown that safety wire is inadequate. Unfortunately, quantifying the unwinding torques due to vibration remains unresolved. In the absence of clarity on this topic, more positive and robust locking features must be considered.

An example of a more robust locking device, the cotter pin, is shown in Figure 18.

The approach is a much more effective restraint than the safety wires as shown in Figure 19, which plots the unwind force for the bladed cotter pin alongside the data shown previously for the safety wire.

Though it remains to be determined what the unwinding forces due to vibration are and whether the cotter pin approach

Figure 18.—Bladed cotter pin used for positive locking of supernut-separation bolt.

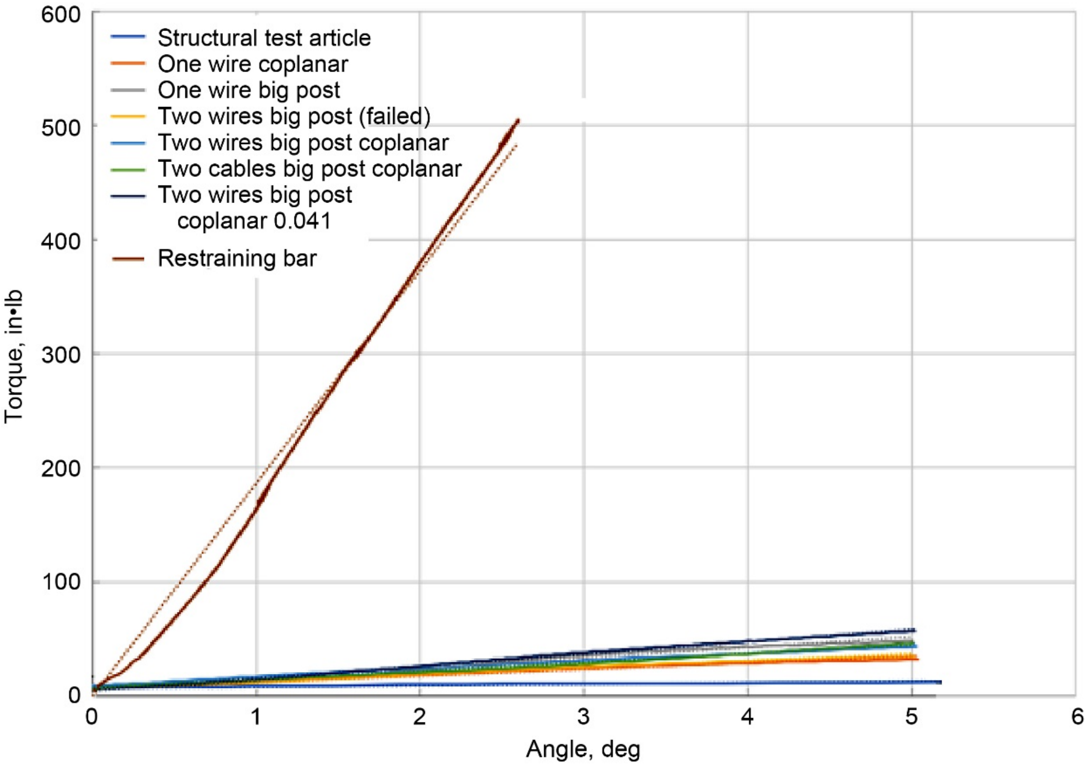

Figure 19.—Unwind torque versus angle of rotation for the bladed cotter pin used for positive locking of supernut-separation bolt.

is sufficient to prevent supernut unwinding and preload loss, it is clear that simple designs can be effective.

## 2.0 Root Cause Failure Theory and Recovery Plan

The forensic examination has brought to light the information needed to develop a plausible root cause theory for the loss of preload in the PSM. The PSM's lost preload due to fastener unwinding, which was caused by inadequate positive fastener locking features. The unwinding was the result of sliding motion experienced by clamped components enabled by effective lubrication and heavy vibration loads. The unwinding observed is consistent with the findings reported by Junker and others.

A sensible recovery plan is to provide positive locking features, such as cotter pins, that are capable of restraining levels of unwind torque that represent a significant percentage of the prevailing torque. Going forward, it is recommended to continue experimental and analytical investigations to quantify unwind forces with respect to environmental (loads, vibrations, etc.) and other factors. The results of such investigations could lead to valuable design guidance for the proper engineering of bolted joints.

## 3.0 Concluding Remarks

The Orion Pyramidal Separation Mechanism (PSM) is a special case of the bolted joint. The joint is heavily preloaded in order to ensure high stiffness and the effective transmission of multidirectional loads, yet is expected to experience minute slip motions and, when triggered, separate without binding. These requirements lead to the use of an effective solid lubricant. Combined with the high-energy, vibratory nature of the operating environment resulted in unwinding of the primary preload nut-and-bolt assembly.

Interestingly, low-speed, single-joint component tests of the PSM did not reveal any unwinding. Only when the system was tested on a vibration table was unwinding and loss of preload observed. These results, again, highlight the value of well-instrumented system-level tests. The forensic investigation also highlights the need to enhance the awareness of the vibration loosening phenomenon and a potential reexamination of the fastener standard in regard to positive locking features and proper bolted joint design.

Glenn Research Center
National Aeronautics and Space Administration
Cleveland, Ohio, April 18, 2018

# References

1. Martinez, Henry, et al.: Testing Orion's Fairing Separation System. 42nd Aerospace Mechanism Symposium, NASA/CP—2014-217519, 2014, pp. 273–285. http://ntrs.nasa.gov
2. Gallon, John C.; Umland, Jeff; and Cholakian, Tanya: Testing and Analysis of Separation Joints for Mars Science Laboratory. Proceedings of the IEEE 2008 Aerospace Conference, IEEEAC paper 1208, version 1, 2007, pp. 1–8.
3. Burns, Joanne R.: Lubrication of Titanium "State of the Art." Naval Ship Research and Development Center R&D Report 138/67, 1967.
4. "Synergistic" Coatings for Titanium and Titanium Alloys Prevent Hydrogen Absorption. CANADIZE 3–603–1M General Magnaplate Product Sheet. General Magnaplate Corporation, Linden, NJ, 2003.
5. Sorge, Richard N.: Space Power Facility—Capabilities for Space Environmental Testing Within a Single Facility. NASA/TM—2013-217816, 2013. http://ntrs.nasa.gov
6. Junker, G.: New Criteria for Self-Loosening of Fasteners Under Vibration. SAE Technical Paper 690055, 1969.
7. Pai, N.G.; and Hess, D.P.: Experimental Study of Loosening of Threaded Fasteners Due to Dynamic Shear Loads. J. Sound Vib., vol. 253, no. 3, 2002, pp. 585–602.
8. Jiang, Yanyao, et al.: An Experimental Study of the Self-Loosening of Bolted Joints. J. Mech. Design, vol. 126, no. 5, 2004, pp. 925–931.
9. Requirements for Threaded Fastening Systems in Spaceflight Hardware. NASA–STD–5020, 2012.
10. Barrett, Richard T.: Fastener Design Manual. NASA Reference Publication 1228, 1990. http://ntrs.nasa.gov
11. Light, D.J.: Vibration Loosening of Threaded Fastenings. CME Chart Mech. Eng., vol. 30, no. 5, 1983, pp. 56–60.
12. Bolt Science Limited: Details of the Junker Transverse Vibration Fastener Test Machine. 2016. http://www.boltscience.com/pages/junkertestvideo.htm Accessed March 26, 2018.