Lessons Learned Developing Separation Systems For Small Satellites

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ABSTRACT: Several lessons learned developing separation systems for small satellites are presented. The relationship between vibration environment and quasi-static loading is shown. The relationship of separation system wiring harness schematic to the real harness is shown. The impact of dissimilar structures to load peaking is illustrated. The relationship between velocity, separation springs and tip-off is discussed. The relationship between flatness of adjoining structures and stress in the structures is discussed.

INTRODUCTION

Engineers at PSC have learned some valuable lessons developing separation systems for small satellites.

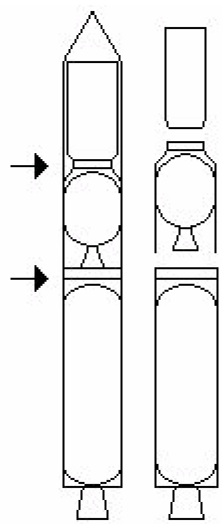


Figure 1. Separation systems separate satellites from rockets and the stages of rockets

Figure 2. A separation system: The Lightband

Engineers at PSC have designed, manufactured, tested and installed separations systems for use on launch vehicles such Shuttle, Atlas V, Delta II, Delta IV, Pegasus, Taurus, Minotaur, Athena, Peacekeeper, and Falcon I. This includes work on secondary systems such as ESPA, CASPAR, RSA and MITEX. PSC's primary product is the Lightband. 57 Lightbands have been built to date.

This presentation is about the boring, second and third order design considerations that as a sum, when missed, may create an exciting first order problem.

VIBRATION ENIRONMENTS AND QUASI-STATIC LOADING

As with all structures, separation systems are susceptible to failure induced by vibration from ground test and flight. Separation systems combine extreme and conflicting requirements: they react loading like a stiff structure during flight (not separated), and then act as if the structure no longer exists (separation). To behave this way, separation systems have sinuous load paths, parts with high internal strain (preload) and a need to maintain and control low friction in some parts. The sinuous load paths reduce stiffness, the low friction can allow motion at high loading at high frequencies. Lubricated surface finishes can be worn away, leading to high friction. Preload can decrease as loads generated by high frequency vibration loosen parts in the mechanism.

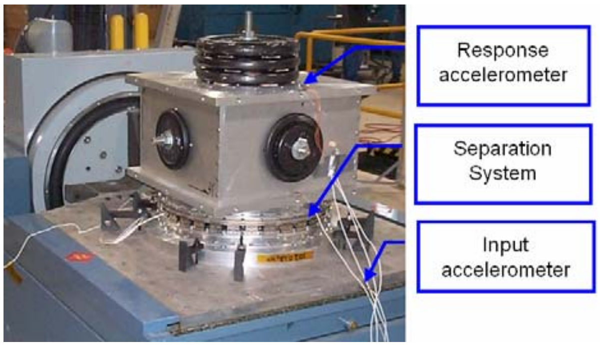


Figure 3. An electrodynamic exciter produces vibration in a test

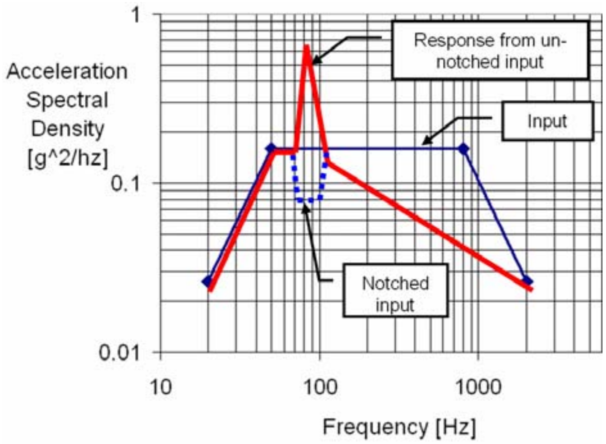


Figure 4. Random vibration level, a notional response and notching

As an example of how random vibration can create high quasi-static loading, consider the following: a 200 lb satellite is mistakenly given un-notched vibration levels appropriate to a 50 lb satellite (whose vibration levels are generally much higher). Using the Miles Relation, the equivalent quasi-static limit load factor is 42.5 g. This correlates to the response of the test item to the un-notched input. This load factor easily exceeds the static limit of this design. Further, this load factor may be applied hundreds or thousands of times depending on the duration of the vibration test. As such, it may be a substantial fatiguing environment (many cycles of high loading) to the primary structure which includes the separation system. Cracks can form and grow in parts and preloaded joints can degrade.

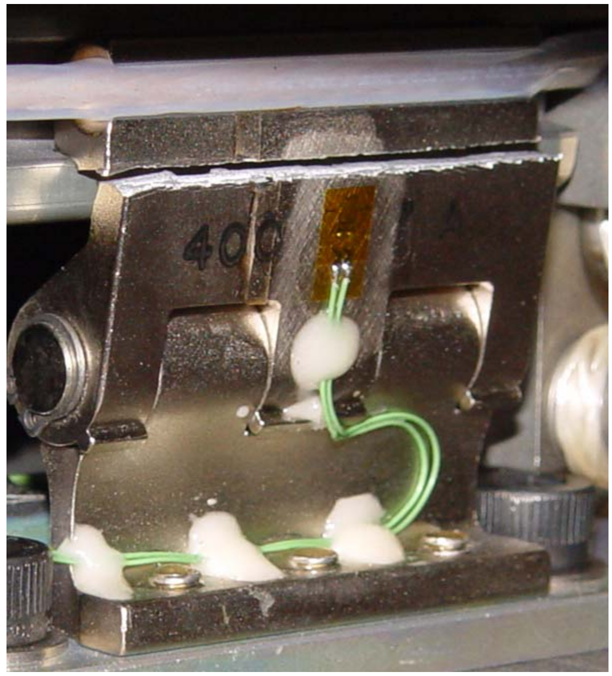


Figure 5. A leaf from a lightband cracked in half during a random vibration test

To preclude failure, test engineers often notch the input or limit the input via feedback from the response accelerometers. Additionally, engineers limit the input levels and duration. The methods employed to determine and limit input are not trivial and are well beyond the scope of this presentation.

Lesson Learned

Random vibration testing can produce many cycles of very high quasi-static loading on the primary structure. Several methods are available to pre-empt structural failure.

WIRING HARNESS

The wiring harness that passes through the separation system allows engineers to control satellites when attached to the launch vehicle. It also allows the adjoining vehicles to detect the separation event via separation switches which change state after separation. The harness conveys the separation signal to the initiator of the separation event.

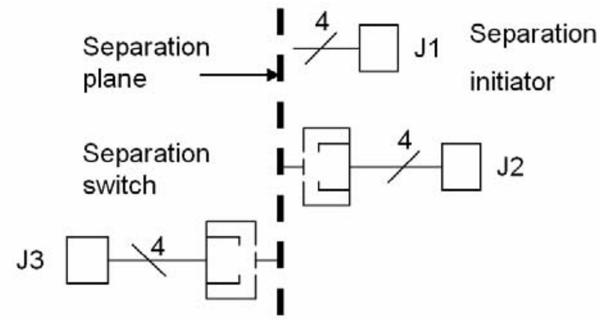


Figure 6. A minimal wiring harness schematic

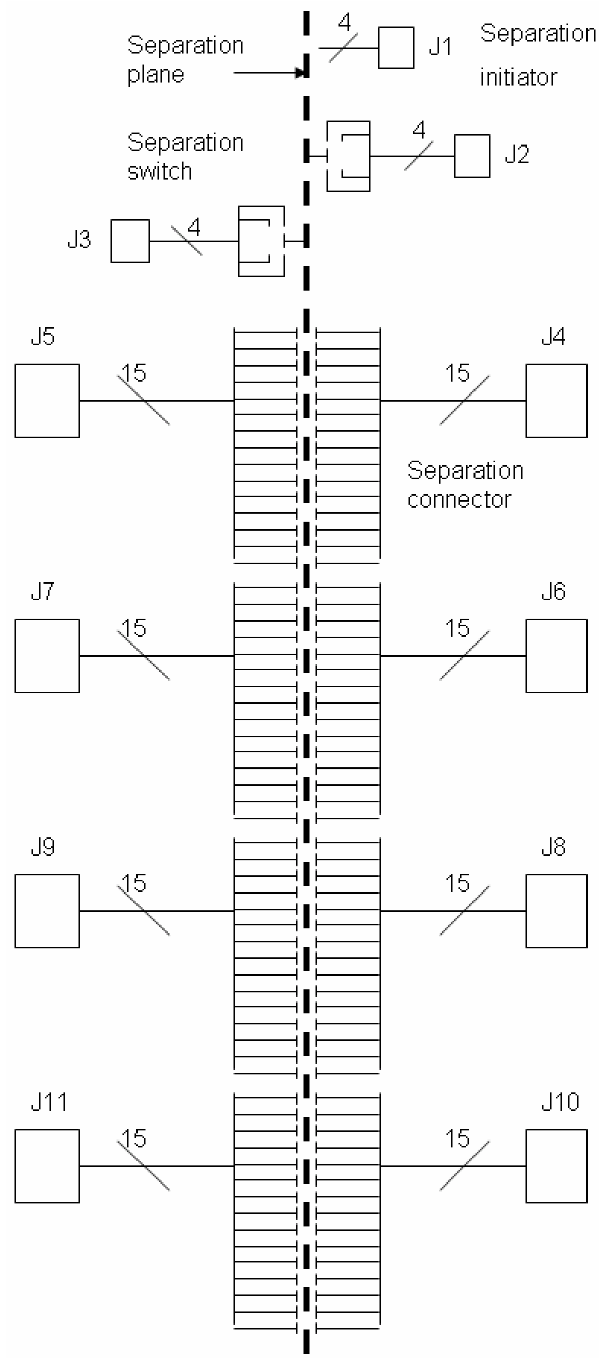


Figure 7 A fully featured wiring harness schematic

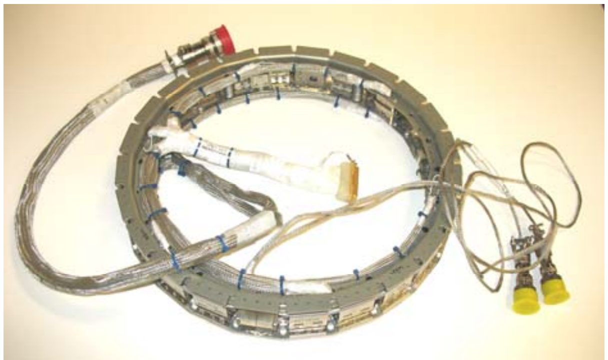


Figure 8. A fully featured 3.0 lb harness on a 5.2 lb separation system (Lightband)

A fully featured harness can weigh half as much as the separation system and cost about one third as much. Additionally volume and stiffness of the harness can grow by orders of magnitude. The connectors on the harness are often taller than the separation systems. Often an assembled harness cannot be formed after assembly because it is so stiff. It must be formed to the net shape prior to assembly. PSC engineers have seen several examples where the harness was made, modified and remade as engineers attempted to create a complete design.

Lesson Learned

Wiring harnesses are a major element of separation system design. If the net shape of the harness is not predetermined, a substantial risk of the harness not fitting may result.

LOAD PEAKING AND DISSIMILAR STRUCTURES (SQUARE PEG, ROUND HOLE)

Separation systems are often round while small satellites are often square or hexagonal. Structurally, this creates load peaking. Load peaking is the concentration of load in areas of high stiffness such as corners, edges and areas of reinforcement. Unfortunately, separation systems are limited by line loading (units of force per unit of length of circumference). Like many satellite structures, circular separation systems are inefficient at reacting high line load.

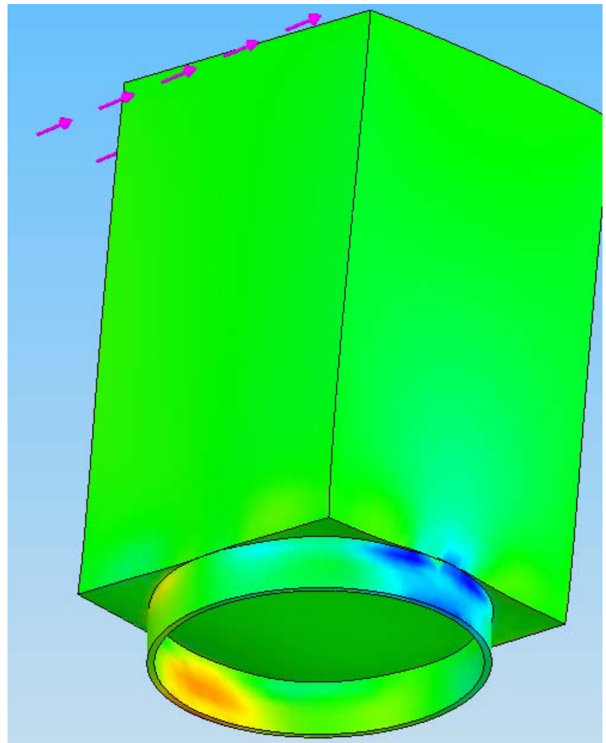


Figure 9 A round separation system and a square satellite can create high line loading

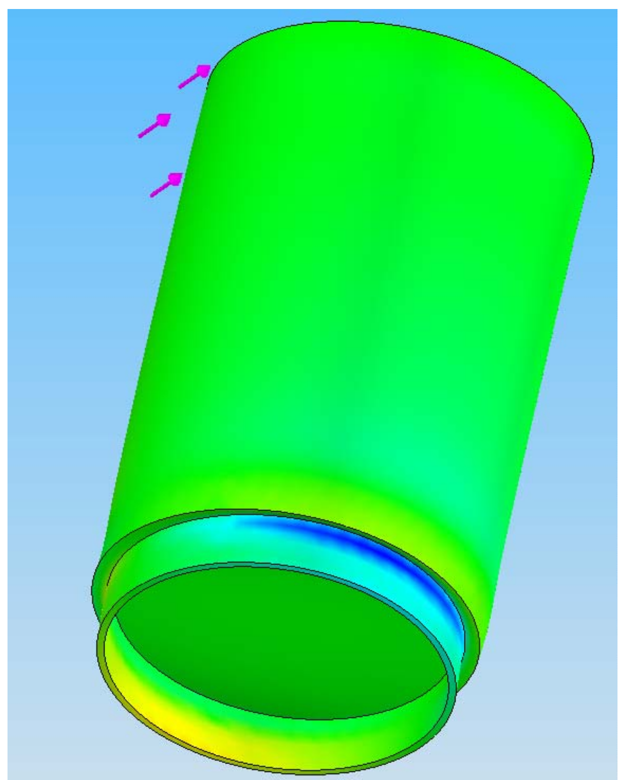


Figure 10 A round separation system and a round structure can minimize line loading

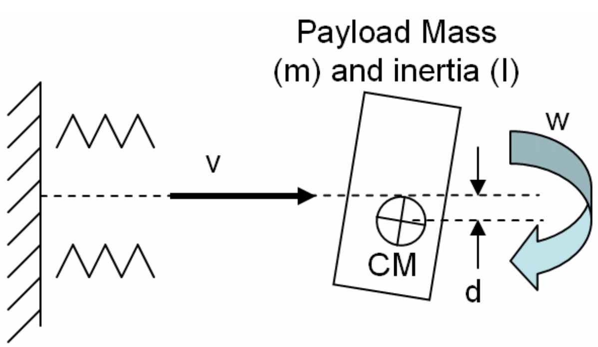
Lesson Learned

Engineers should design to the maximum allowable line load of the adjoining structures and ideally, have a design that minimizes the extremes of line loading. Such a design is also structurally efficient.

TIP-OFF, VELOCITY AND SEPARATION SPRINGS

Tip-off is the rate of rotation about any axis of a satellite as a result of the separation event. In about one in three cases, a tip-off is desired to affect dynamic stability, to induce even solar heating or to counter pre-separation rates. When tip-off is to be minimized the specification is often less than, or equal to, 1.0 degree/second/axis.

When the sum of the separation springs is not through the center of mass of the adjoining structure, tip-off will result.



$$w = mvd/I \quad (1)$$

Where w is the tip-off rate [angle per unit time]; m is the mass of the separating vehicle; v is the relative velocity; d is the distance between the center of mass (CM) and the resultant location of the separation springs; I is the mass moment of inertia about the center of mass of the separating vehicle. This relation is for most purposes an over simplification because it assumes the other vehicle is many times more massive (>10x) and has many times more inertia (>10x) than the separating vehicle. It also assumes the pre-separation rates are all zero.

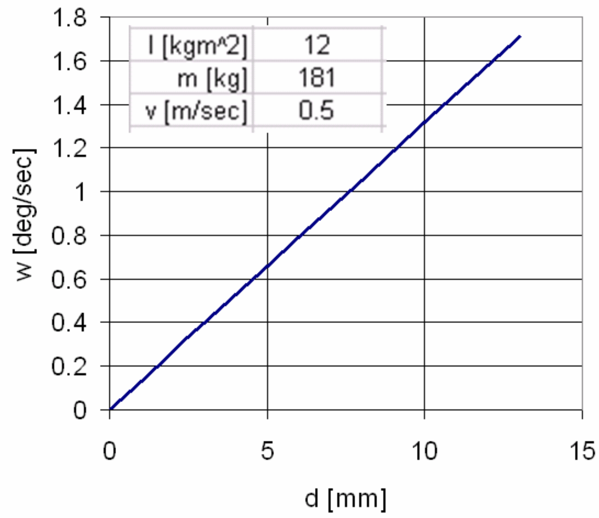


Figure 11. An illustration of equation 1

The separation springs may be moved on a separation system so they push through the CM. However it may be easier to move the CM. The lower the delta-V required, the lower the tip-off.

Sometimes tip-off is desired as this may beneficially produce even solar heating or dynamically stabilize the vehicle. In such cases, migrating the separation springs to one side of the CM or allowing the CM offset (d) to be significant affects the desired tip-off.

v is the relative velocity of the two separated vehicles. Separation springs create v. However, as the v demand increases, the number and mass of separation springs increases with the square of v.

$$S = ((mM)/(m + M))\ (v\text{^}2/2*E) \quad (2)$$

Where S is the number of separation springs required; m is payload mass; M is final stage mass; v is the relative velocity between m and M and E is the stored energy of a separation spring that is converted to v.

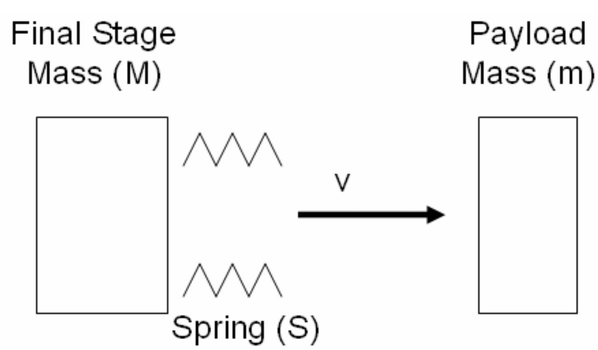


Figure 12. The relative velocity, v, is created by the separation springs (S)

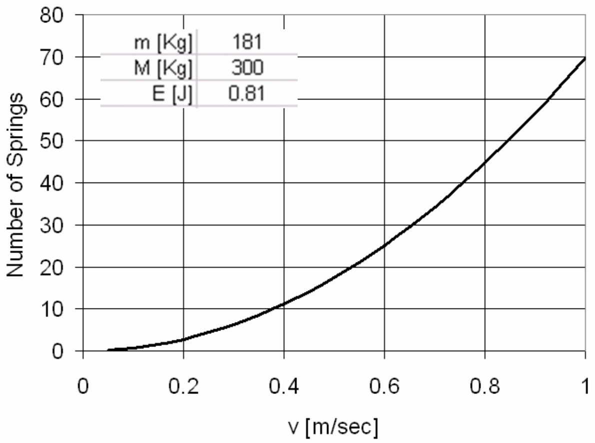


Figure 13. From equation 2, the number of springs required increases with the square of v

Lesson Learned

Tip-off is induced by the distance between the CM and the center of the spring force. Because springs store energy inefficiently, relative to rocket engines, they produce velocity poorly. The launch cost of spring weight must be traded for velocity.

FLATNESS OF ADJOINING VEHICLES AND SEPARATION SYSTEMS

A separation system joins two other vehicles. If the mating surface of the two other vehicles are not flat, stress may detrimentally build in the separation system.

Figure 14. A separation system (Lightband) attached to a thrust cone (Falcon I)

In the extreme, when the adjoining vehicles are too warped, an attempt to join to the separation system to BOTH adjoining structures may simply break it. Joining a separation to an (only one) adjoining structure is generally not going to increase stress because separation systems are generally much more flexible than adjoining structures.

It may be tempting to design flexible features to attenuate stress as the warped structures are joined. However, this can lead to unacceptably low stiffness (first mode frequency) of the entire system. So, to achieve both a low stress and high stiffness system, flatness of the adjoining structures needs to be controlled.

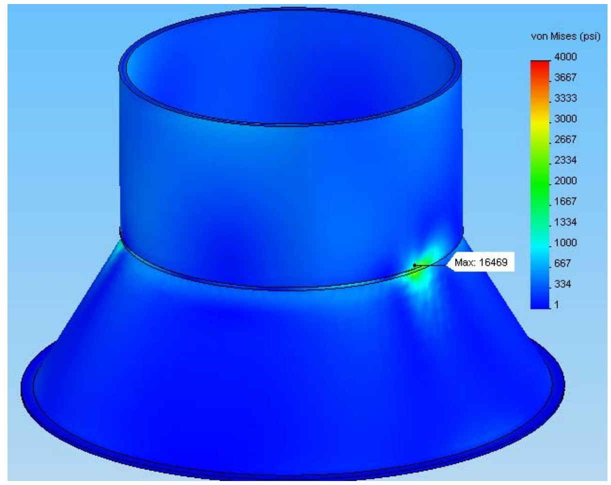


Figure 15 Joining a warped (0.010 inches) thrust cone to a flat cylinder can create high stresses

Finite element models (FEMs) nominally assume perfect flatness of adjoining structures. As such, FEMs can obscure this potentially significant reduction in structural margin.

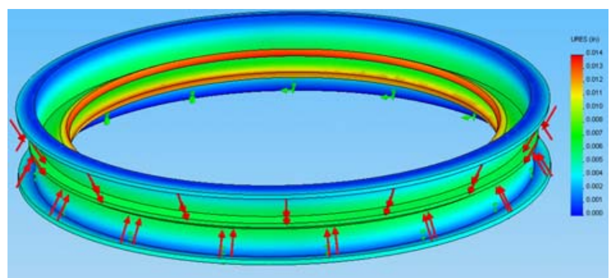


Figure 16. A v-band is preloaded radially inward by the band tension. Warping can result.

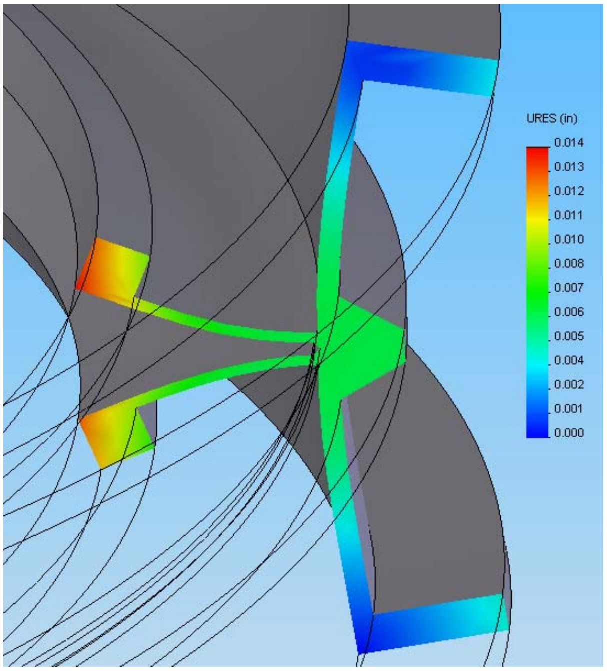


Figure 17 In the cross section of a V-band a warp of 0.004 inches at the interface to adjoining structures is created by preload

V-bands embody the perverse nature of mechanical assembly: not only do they warp in proportion to preload, but a warp applied to them can affect their preload. Critically as many mechanisms engineers have observed in test, the structural performance (strength and stiffness) is highly correlated to preload.

PSC engineers often observe substantial changes in internal strain as structures are joined. A 20% change in preload as the separation system is fastened to an adjoining structure has been observed.

Just as changing the boundary conditions in the FEM will change the stress, so too bounding a separation system will change the stress in a separation system.

PSC engineers have found a flatness maximum rate of 0.00015 inches per inch to be a sufficient flatness specification. In a 38 inch diameter separation system, this equates to and overall flatness of 0.005 inches. This is a nominal specification. When adjoining structures are more flexible, flatness may be changed.

Structures adjoining separation systems that are easy to make, may be expensive to make flat. Alternatively, structures that are expensive can be easy to make flat. For example, a thrust cone from the final stage engine to the launch vehicle interface can be made by riveting machined rings to conical sheets. The riveting process can stress the thrust cone. This may manifest its self as warping (i.e. lack of flatness) when the riveted structure is removed from its tooling. To attain flatness requirements, the riveted structure must be machined at additional set-up and cost.

Alternatively, the thrust cone could be directly machined from a coarse conical forging.

Engineers should consider the conjecture that all manufacturing and joining processes (riveting for assembly, fastening to adjoining structures, curing of composites) increase strain energy and thus can warp structures.

Lesson Learned

The flatness of the adjoining surfaces directly affects the strength margin of the separation system. Preloading reduces flatness of structures.

References

1. NASA TM-86538, Design And Verification Guidelines For Vibro-acoustic And Transient Environments, March 1986, George C Marshall Space Flight Center, NASA.