Innovative Technologies for Improved Launch Probability—Delta IV Day-of-Launch Monitoring

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On Wednesday, 27 April 2005, an audience witnessed the unveiling of the Delta IV Space Launch Complex 6 (SLC-6) as it was dedicated at the Vandenberg Air Force Base (VAFB) in California. Reconstructed to support the United States Air Force Evolved Expendable Launch Vehicle program, SLC-6 serves as the West Coast launch site for the Boeing Delta IV launch vehicle. When tanking and launching a vehicle at a launch site such as SLC-6, many considerations must be made; for example, fly-out clearances between the vehicle and the launch pad structures, loads induced by ground winds, and controllability.

Subscale wind-tunnel testing was performed and a set of limitations on the ground winds for tanking and day of launch was established, called wind placarding. Due to the limited amount of testing performed, as well as the applied uncertainty and scale factors, the resulting ground wind placards established for SLC-6 were relatively low, restricting launch availability.

To increase the velocity of ground winds allowed during launch and increase the launch probability at SLC-6, a two-pronged approach was established. Additional wind-tunnel testing was planned to mitigate potential conservatism in the placards attributed to extrapolation required by the limited existing test data. Second, a vehicle base-mounted strain gage system was proposed for use on launch day to monitor full-scale vehicle base bending moments as a function of wind speed and direction. It was believed that the placards (and thus launch availability) could be significantly improved by using the full-scale measured data to anchor the wind-tunnel-derived wind placards. In addition, launch-day operations could be modified to include real-time assessment of the bending moment data to augment wind speed and direction considerations.

This paper focuses on the innovative strain gage system; it will be updated at a later date to include the results and implications of the additional wind-tunnel testing. The paper also describes the base bending strain gauge technique, including calibration and full-scale testing. Finally, the paper presents the advantages, results, and future actions of this technique.

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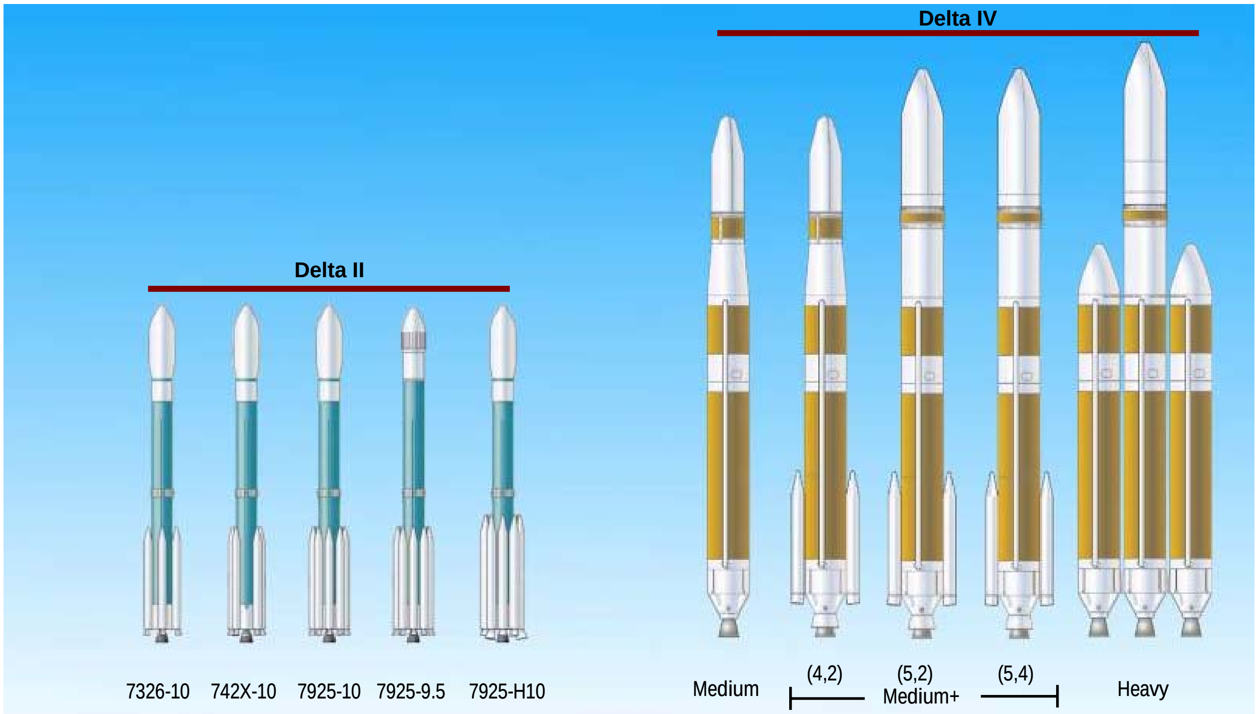
I. Space Launch Complex 6

SLC-6 is the West Coast launch site for the Boeing Delta IV family of launch vehicles (Fig 1). The site provides the Air Force with the strategic capability to launch national security satellites to polar, sun-synchronous, and high-inclination orbits. The launch site will be able to support all five configurations of the Delta IV family.



	7326-10	742X-10	7925-10	7925-9.5	7925-H10	Medium	(4,2) Medium+	(5,2) Medium+	(5,4) Medium+	Heavy
GTO (kg)	890	1,030	1,760	1,830	2,130	4,230	5,940	4,870	6,820	12,760
LEO (kg)	2,470	2,880	4,600	4,780	5,650	9,110	12,300	10,620	13,870	21,890
GEO (kg)						1,140	2,040	1,690	2,790	6,280

GTO = 185 x 35,786 km at 28.7 deg Delta II and 27.0 deg Delta IV. LEO = 407 km circular at 28.7 deg. 6P197001
GEO = 35,786 km circular at 0 deg

Figure 1. The Delta IV family of launch vehicles.

The 132-acre SLC-6 (Fig. 2) features structures similar to the Boeing Delta IV SLC-37 launch site at Cape Canaveral Air Force Station, Florida, with a Fixed Umbilical Tower, Mobile Service Tower, Fixed Pad Erector, Launch Control Center and Operations Building, and a Horizontal Integration Facility. SLC-6 also features a Mobile Assembly Shelter that protects the launch vehicle from adverse weather.

SLC-6 was first designed for the Manned Orbiting Laboratory (MOL) space station project in the 1960s; however, that program was cancelled before the first launch. SLC-6 was later selected to be the West Coast launch pad for an Air Force Space Shuttle. The *Challenger* tragedy in 1986 shifted launch vehicles for satellites from the shuttle to unmanned rockets. Subsequently, SLC-6 was mothballed until 1998, when SLC-6 was selected as the VAFB Delta IV launch pad.

SLC-6 underwent major reconstruction to support the United States Air Force Evolved Expendable Launch Vehicle program. After years of hard work and dedication, on Wednesday, 27 April 2005, the Delta team unveiled the completed Space Launch Complex to an audience at the Vandenberg Air Force Base in California.

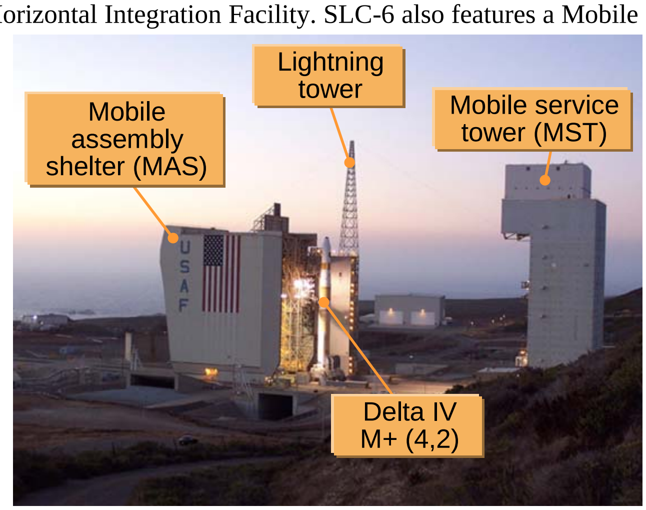


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Figure 2. Space Launch Complex 6.

The topography surrounding the launch pad is unique and the pad experiences relatively high ground winds and unique weather patterns. The pad borders the coastline and lies within small hills and knolls, which can amplify the already high ground winds and cause challenges when tanking and launching the vehicle. The loads induced by these amplified ground winds cause structural concerns and make it difficult for the vehicle to be controlled and clear the launch pad structures at liftoff.

The launch pad, the vehicle, and the unique topography were modeled at a 100:1 scale. Wind-tunnel testing (Fig. 3) was performed on the model and a set of limitations on the ground winds for tanking and day of launch was established, called wind placarding.

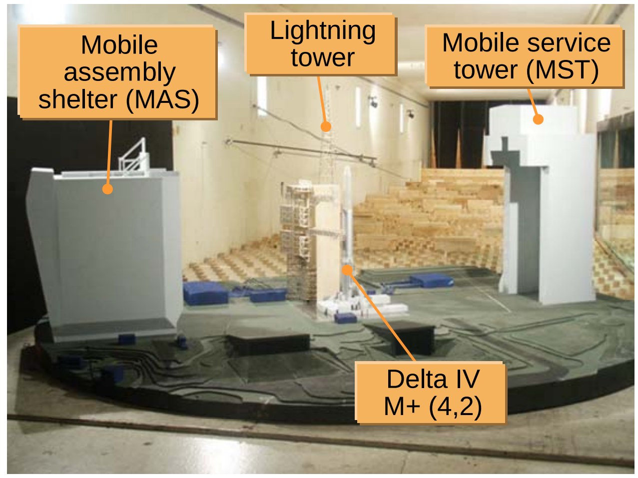

Figure 3. 100:1 Delta IV Medium+ (4,2) wind testing.

The following section provides more details on ground winds effects on launch vehicles. Section III describes in detail the innovative base moment monitoring system and how it relates to wind placarding. This system consists of assessing real-time ground wind effects on the vehicle by monitoring strain gages at its base. Section IV discusses future goals.

II. Background—Ground Winds Effects on Launch Vehicles

Although ground winds affect launch vehicles in various ways, the two primary effects discussed in this paper relate to structural capability and liftoff clearances. Generally, launch vehicles are protected from wind and environments prior to the launch attempt by buildings that surround the vehicle.

For Delta IV, the buildings are rolled a safe distance away from the vehicle on launch day to allow for vehicle propellant loading and checkout before launch. Wind predictions are made for the day and during the day to determine if conditions are and will remain acceptable for all operations up to and including launch. Vehicle structural capability and liftoff clearances are two of the primary factors in establishing the wind constraints for launch day.

Limiting wind conditions are established for the pre-launch time period based on unfueled and fueled vehicle structural capability. Wind blowing on the vehicle with any given speed and direction will induce both a steady and a fluctuating wind shear load. With the vehicle being cantilevered from the four-point tie-down bolts at the base, this shear load results in vehicle excitations, primarily at the first fundamental bending (cantilever) mode of the vehicle. When propellant is loaded on the vehicle, the frequency of this fundamental bending mode is reduced because of the additional propellant mass. When the wind blows over a cylindrical body, vortex shedding (circular flow separating from the vehicle body) occurs, creating an oscillatory shear force on the vehicle. This oscillatory shear force occurs at a specific frequency (called the vortex shedding frequency), which is a function of wind velocity. The net force from vortex shedding is generally orthogonal to the wind direction. If the vortex shedding frequency approaches the vehicle fundamental bending frequency for either the fueled or unfueled condition, low-frequency vehicle oscillations are greatly amplified. This low-frequency vehicle vibration results in significant base bending moments on the vehicle and launch table structure (Fig. 4).

It can be difficult to predict (and thus derive placarding data for) the vehicle response (base bending moment) based on wind speed and direction measurements for several reasons. The primary reasons include:

1) Wind velocity and direction are typically measured at a location significantly removed from the vehicle.

2) Variability in wind shear profile makes predictions difficult. Measured velocity and direction at a specific elevation does not provide a corresponding velocity and direction up the vehicle or down the vehicle from the measured height, and the wind shear profile is not necessarily consistent from day to day and direction to direction.

3) Obstructions such as buildings and structures can shield the vehicle and guide or turn the wind direction such that the velocity and direction measured at the wind tower may be different than the wind impinging on the vehicle.

4) Local terrain effects influence wind velocity, direction, and profile, making vehicle response inconsistent from one wind direction to another wind direction.

5) Vehicle lift and drag coefficients and center of pressure vary with wind speed and direction due to the launch vehicle not being a single cylindrical body, but rather having protuberances (such as feed lines) and multiple bodies (such as solid rocket motors) that create variability in vehicle response.

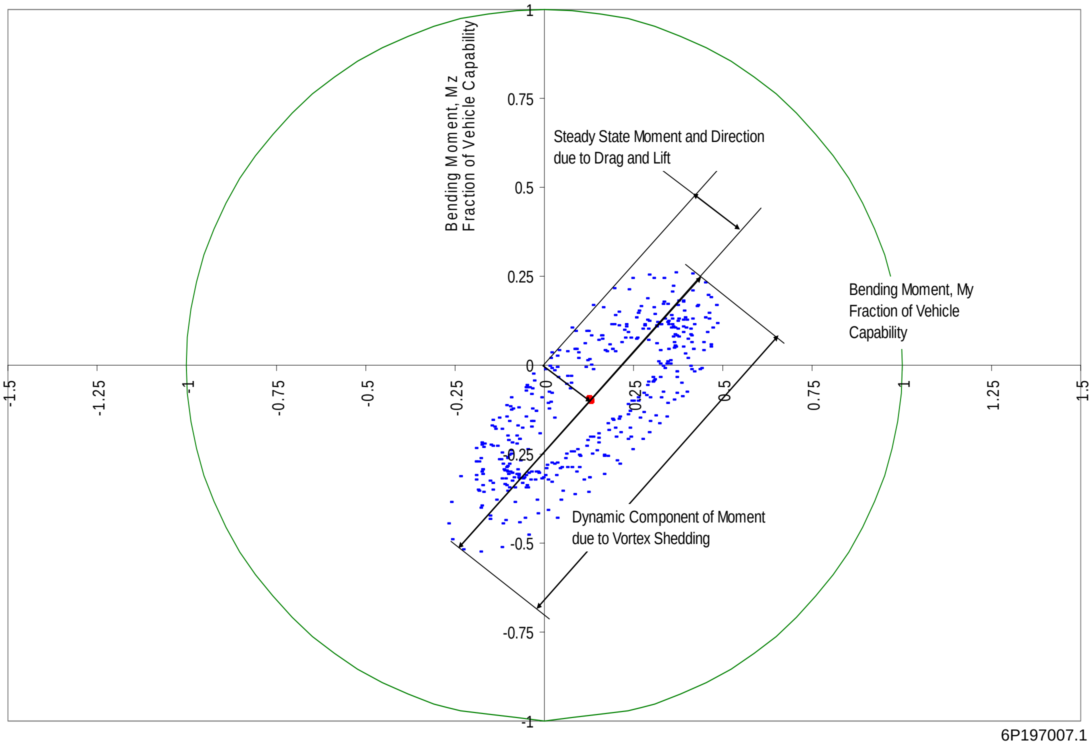

Figure 4. Measured full-scale moment due to drag, lift, and vortex shedding.

The traditional launch vehicle approach to predicting ground-wind-induced loads involves subscale wind-tunnel testing to establish moment coefficients for the vehicle as a function of wind-tower-measured wind speed and direction. Scaling considerations are required in the wind-tunnel testing to achieve dynamic similitude (mass, lengths, diameter, frequencies) to the full-scale structure and wind speed. The location of the wind speed anemometer relative to the vehicle geographic terrain and obstructions also must be properly represented.

For both Delta Launch sites, wind speed measurement occurs approximately 1800 ft or more from the vehicle. This adds a level of complexity requiring two different scale models for the test. A small (1:3000) scale model is used to capture the terrain effects and differences in tower-measured wind speed versus launch-pad-measured wind speed. A larger (1:100) scale model is used to obtain aerodynamic and aero elastic bending moment response as a function of local launch pad wind speed and direction. The larger scale model captures the effects of buildings and structures local to the launch pad. Wind speed placards established from the large-scale model testing are adjusted using the smaller scale model test data to account for wind-tower-to-pad wind speed variations as a function of direction.

Even with a subscale test, vehicle ground wind responses may still be inaccurate and difficult to predict. This is because modeling of the aerodynamic loading on a structure requires special consideration of flow conditions to obtain similitude between the scale model and the full-scale prototype. In general, the requirements are that the model and prototype be geometrically similar, that the approach mean wind speed vertical profile at the model site have a shape similar to the prototype flow, and that the Reynolds numbers be equal. The degree of match or mismatch between model and prototype in these various areas of similitude introduces inaccuracies in the wind-tunnel testing representation of the full-scale prototype.

Additional inaccuracies can be introduced due to the different location at which full-scale winds are measured relative to the vehicle reference wind speed location used in the wind-tunnel testing. In the testing, the reference wind speed location is 200 ft above the pad (for a clean pad configuration). For the West Coast Delta IV launch site, the wind speed measurement location is approximately 1800 ft away from the vehicle. These different locations require that vehicle moments calculated for the reference wind speed at its location be converted to the corresponding wind speed at the full-scale prototypes wind measurement location. These conversion factors were determined in our testing using a 1:3000 scale model test, but once again, this sort of testing introduces inaccuracies, some of which are unique to this type of scale model test. In any case, even after a subscale wind-tunnel testing, inaccuracies (usually involving moment over-prediction to varying degrees) will still exist, thus some additional load validation is needed. Full-scale moment measurements using the strain gage system can provide the required validation data.

Liftoff clearances are related to structural wind limits and represent a second set of placards that can limit launch probability. Wind speed, wind direction, vehicle acceleration at liftoff, lift and drag, steady-state and dynamic load, and/or vehicle initial rate and velocity conditions influence the motion of the vehicle post-liftoff. Once the vehicle is released from the tie-down bolts, wind drag and lift on the vehicle cause the vehicle to drift sideways.

Initial conditions and rate affect the control system response that steers the engine thrust to stabilize the vehicle. Engine thrust vector provides lateral load causing additional vehicle drift. Positive clearance must be maintained between the vehicle structures and ground support equipment to avoid vehicle damage and failure.

The effects of lift and drag coefficients, wind velocity and direction, and vehicle initial rates and velocities determine the vehicle drift direction and velocity as the vehicle ascends from the launch pad. Each direction has different obstructions that must be cleared, along with different drag and lift coefficients that affect the vehicle drift path. Therefore, a liftoff wind placard is established for the fueled vehicle at liftoff as a function of wind direction or azimuth. The initial conditions are established prior to launch day based on the structural moment predictions from wind-tunnel testing. Additionally, the lift and drag coefficients that affect vehicle drift are derived from the wind tunnel-testing and are used as a part of the drift calculation.

A. Benefits of a Real-Time Load-Monitoring System

The conservative traditional approach of predicting ground-wind-induced loads through wind-tunnel testing can result in restrictive wind limitations that reduce launch probability. Additionally, the restrictive limits and conservatively calculated loads can result in expensive launch scrubs and vehicle inspections when structural wind limitations are unintentionally exceeded due to a wind placard violation. Providing a real-time monitoring system that directly measures vehicle base bending moment response is beneficial for several reasons.

First, actual vehicle loads are being directly measured and can be compared to structural capability limits in the event of an anomalous wind condition. This enables immediate evaluation of vehicle structural health and disposition of the anomalous wind event, possibly avoiding a launch scrub.

Second, full-scale vehicle response data are gathered using actual winds, wind speed, direction, profile, and terrain and obstruction data. These data can be compared with the wind tunnel results to improve future predictions and placards for the measured wind directions and velocities.

Third, in the event of a valid structural capability violation, analysis and health status of the vehicle structure can be based on actual measured loads, not conservative predictions. Fewer critical locations would require detailed analysis and inspection. The evaluation would be based on real load exceedances, and not on a predicted load exceedance. Load uncertainty is reduced, and a better, more reliable, and quicker evaluation and disposition for repair or rationale for flight can be made for the launch vehicle structure.

Because of the benefits mentioned above, a system was developed, using a set of strain gauges at the base of the vehicle, to monitor in real time ground-wind-induced loads. The following section provides details of the strain gauge technique for monitoring loads.

III. Base Moment Monitoring System—Strain Gauge Technique

As stated above, a system was created to measure and monitor the loads on the vehicle induced by the ground winds. Strain gages were mounted on the base of the vehicle to measure the bending moments and axial loads. The wind speed and direction data were gathered from a wind tower (Tower 301) located just southwest of the launch pad. The tower measured wind speed and direction from the 102-ft and 301-ft levels.

Four pairs of gages were placed on the vehicle, each pair above the four vehicle tie-down clevises (Fig. 5). The gage pairs provided a degree of redundancy. The gages were connected to a data acquisition system located in the pad terminal room at SLC-6 to acquire and record the data. Special software was developed to convert the strain gage data to vehicle base bending moments, and a user-friendly graphical interface was developed to facilitate reading the bending moments in real time. The system was set up so that engineers in Huntington Beach, California, could monitor the data and remotely control the data acquisition software on the computer located at SLC-6 in Vandenberg.

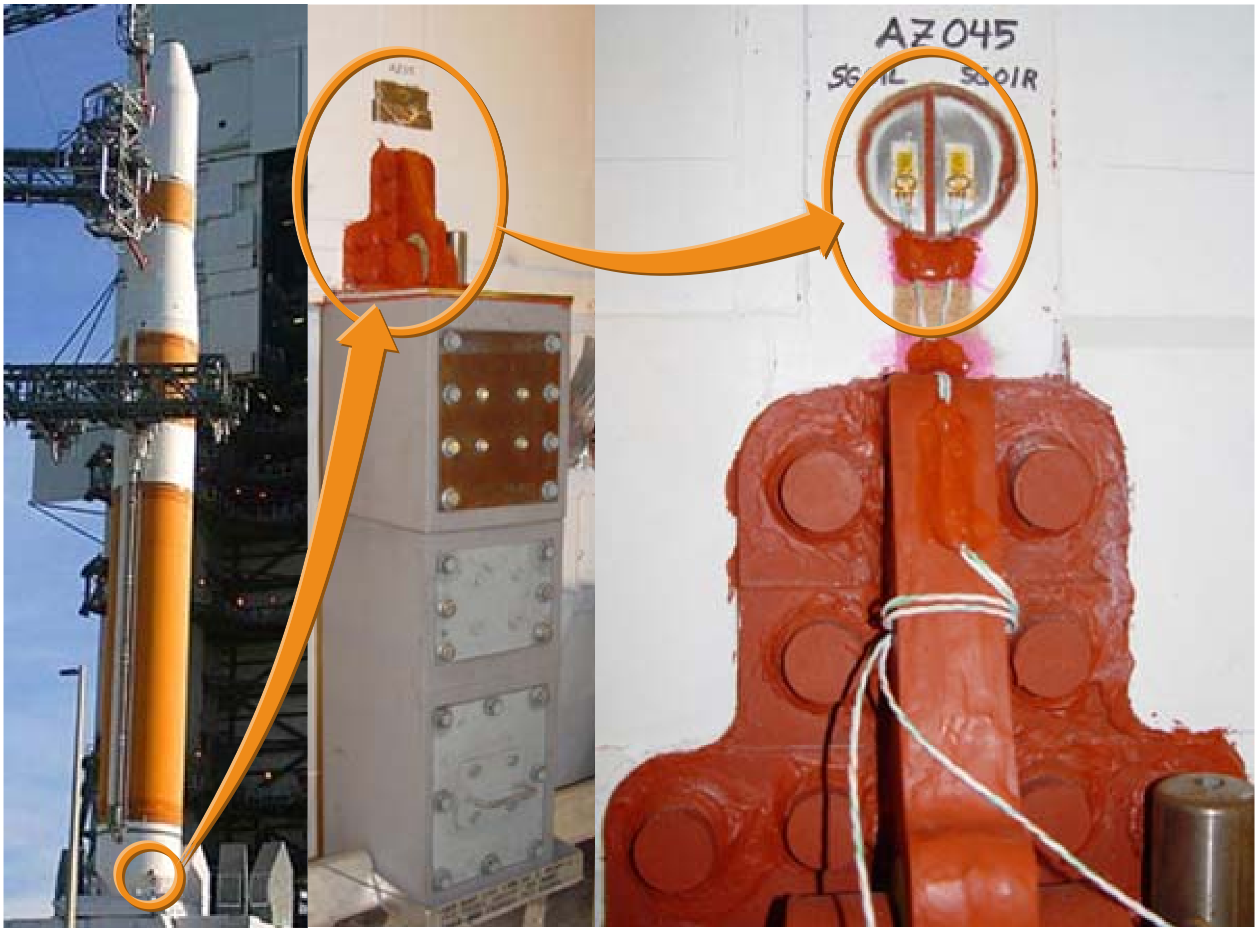

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Figure 5. Strain gages located at the four tie-down bolts at the base of the vehicle.

The Delta team installed the strain gages on the first vehicle to launch from SLC-6 and designed a test to calibrate the strain gages and test the system. The calibration test was performed by inducing known bending moments at the base of the vehicle while measuring and recording the change in strain due to this induced load. The moments were induced by applying known lateral radial shear loads of sufficient magnitude near the top of the vehicle, specifically, the second-stage encapsulation ring (Fig. 6). The loads applied to the vehicle for the test were derived to be well within the structural capability of the launch vehicle. Lateral radial loads aligned through the vehicle centerline, thus minimizing torque-loading. Four separate lateral load cases were performed.

In addition to the calibration testing performed, the system was monitored and the gages calibrated during nominal launch-preparation activities. These activities included the solid rocket motor mounting, propellant tanking test, and the encapsulated payload mate to the vehicle (Fig. 7).

During the propellant tanking test, the protective structures (Main Service Tower and Mobile Assembly Tower) were rolled back, thus exposing the launch vehicle to ground winds. As seen in Fig 7, the tanking test was accomplished without the encapsulated payload mated to the vehicle. The test represented a launch countdown rehearsal. Data were gathered for the vehicle exposed to winds for the empty condition, full condition, and during the dynamic propellant loading and unloading conditions. Time histories of the wind speed and direction data, noted from Tower 301, and the base bending moment time histories were correlated. These correlated data were then compared to the wind placards established from the sub--scale testing. The measured vehicle wind loads data during the propellant test indeed suggested that these wind placards were too restrictive and conservative.

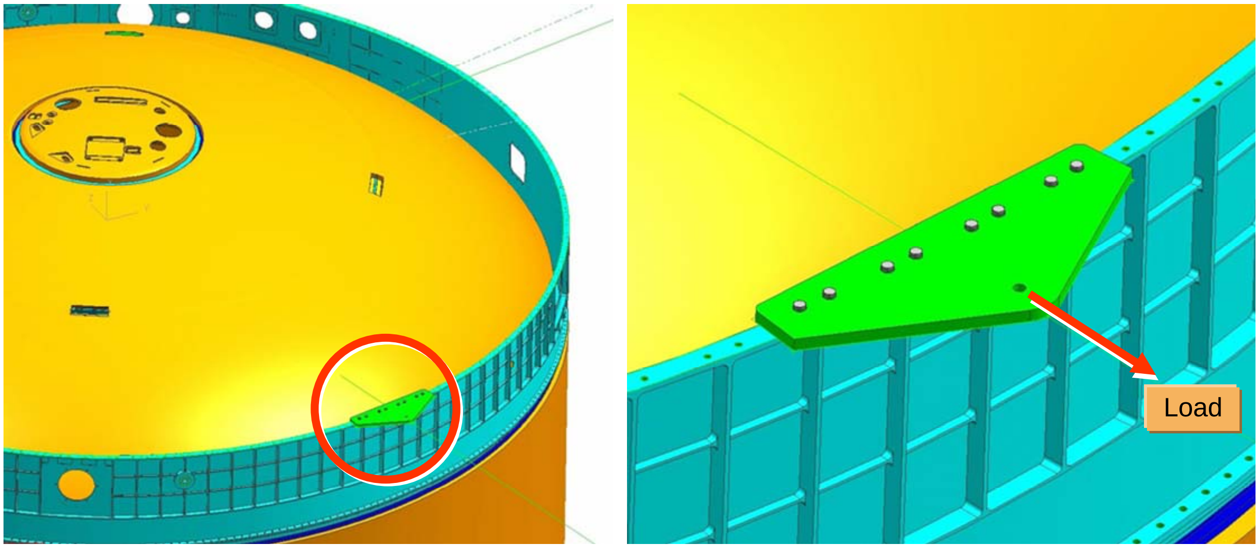

Figure 6. Calibration test—applied load on the second-stage fuel forward skirt encapsulation.

A. Day-of-Launch (DOL) Operations

The calibration test and launch preparation activities enabled the Delta Team to derive an accurate set of load calibration coefficients and to prove out the base moment monitoring system. The team developed a process with the customer to utilize this system for live monitoring during the actual DOL operations.

A decision tree was developed to outline the process and help clarify the options available to the launch conductor. As a baseline, the launch conductor would use the established wind placards to decide whether to proceed into tanking, for instance. However, if the ground winds forecast were not favorable, or if the wind placards were exceeded during any of these operations, the launch conductor would then utilize the real-time measured data using the decision tree to assess how the measured moments compared to the structural capability of the launch vehicle and predicted moments for the given wind conditions. If the loads were well within the capability of the vehicle and within predicted trends, then, with customer concurrence, the launch conductor could decide to continue processing toward launch.

B. SLC-6 First Flight

The data from this base moment monitoring system resulted in increasing the ground wind placards. This increase improved the launch probability for the first flight out of SLC-6. In addition, the system proved invaluable during the DOL operations and helped to avert a potential launch scrub and vehicle inspection.

Actual tower measurements and the forecast for the ground winds for the day of launch were favorable. However, once the protective structures were rolled back and the vehicle was exposed to the ground winds, an unpredictable squall suddenly hit the pad with high wind speeds that exceeded the vehicle wind placards. The base moment monitoring system was active and the actual loads on the vehicle were shown to be well within its structural capability. The use of the strain gages allowed continued launch processing and flight. Without this system, a scrub would have been called, operations would have been halted, and many days would have been lost performing vehicle inspections and analyses.

IV. Future Goals

A. Automated Liftoff Placard

A future goal is to investigate developing a way to automate the liftoff placard evaluation based on real-time measured base bending moments. Because the dynamic bending moment and rate and velocity are directly related, and because the steady-state moment and wind velocity and direction are related, it may be possible to convert the measured base bending moment into velocity, direction, and vehicle rate in real time, which could be used to assess acceptability of ground winds at liftoff. This would result in eliminating the current need for a human decision on wind limit violation.

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Figure 7. Solid rocket motor mounting, propellant tanking test, and encapsulated payload mate to vehicle.

B. Liftoff Clearance Placards

Another goal is to use the data gathered from this system to improve the liftoff clearance ground wind placards. Results from the Delta IV base bending moment monitoring show that the predicted vehicle ground-wind-induced rates and velocities correlate very well to the ground-wind-induced base bending moment. So when initial conditions based on the wind tunnel test results are used as input to the liftoff placard, the resulting allowable wind speed at liftoff becomes conservative in a similar manner to that of the structural placard. Results from the Delta IV measured base bending moment will be used in the future to improve initial-condition predictions. Improved predictions of initial conditions will possibly translate into a higher allowable wind speed for liftoff conditions.

V. Conclusions

Space Launch Complex 6, renovated to serve as the West Coast launch pad for the Boeing Delta IV family of launch vehicles, represents a vital asset to the United States. It provides the Air Force with the strategic capability to launch national security satellites to polar, sun-synchronous, and high-inclination orbits. However, its unique topography lends to sustained ground winds throughout the year. These ground winds can challenge successful launch vehicle tanking and launching operations.

As discussed above, this new, innovative technique used to measure actual bending moment loads on the Delta IV launch vehicle enabled the Delta team to revise the wind placards established from sub--scale testing and permitted the vehicle to be processed and launched in higher ground wind conditions.

In addition, as shown in the example above from the first flight from Space Launch Complex 6, this innovative strain gage technique cleared the vehicle structurally when it experienced unpredicted high winds while exposed on the pad. For the first flight, this technique served as the primary vehicle structural load indicator and allowed the vehicle to be loaded with propellants and to prepare for launch. This ultimately led to a successful Delta IV launch on the first day it was attempted on the West Coast.

Because of these highly favorable results, the Delta team recommends that all future Delta IV vehicles be instrumented with base bending moment strain gauges and be monitored during launch attempts. This system will provide benefits for future Delta vehicles in structural health monitoring, improved structural and liftoff wind placards, reduced risk of launch scrubs, and improved launch probability.