21st AIAA Aerodynamic Decelerator Systems Technology Conference and Seminar
23 - 26 May 2011, Dublin, Ireland

AIAA 2011-2562

Orion Steel Riser Development and Design for the Capsule Parachute Assembly System

Robert J. Sinclair[1] and Anothony T. Taylor.[2]
Airborne Systems North America, Santa Ana, CA, 92704

Mathew D. Janda[3]
Airborne Systems North America, Santa Ana, CA, 92704

The Orion Steel Riser design was initiated from an NASA IDAT recommendation to provide robustness to the Orion Parachute Risers in order to counteract abrasion and bending of the Orion structure during off attitude deployments. This utilized new wire rope technology encompassing a compacted, four strand wire rope construction (termed 'XLT-4'). The Steel Riser design comprised of six, parallel, 3/8 in diameter XLT-4 wire ropes terminated by ball and shank swages. A Pin and Clevis design attached the Steel Riser to the textile riser, and a fitting (termed 'Puck') housed the opposing ball ends to the Orion structure. Testing showed little to no degradation against static bends and the design provided adequate tensile strengths for parachute design load conditions. Simulated abrasion testing was detrimental on the riser design and further investigation is being conducted to the adequacy of the test conditions and solutions to the riser design. Mortar and deployment testing is further ongoing to understand and control the deployment energy of the Steel Riser and end attachments. Development of a modified swage end and soft link attachment to provide even load sharing due to bends is currently in work.

I. Introduction

In 2007 the National Aeronautics and Space Administration (NASA) set out to provide a Crew Module (C.M.) termed 'Orion' that would replace the retiring Shuttle program and provide necessary means of transporting astronauts to the International Space Station (ISS), the Moon and Mars. Lockheed Martin was contracted to design the Orion framework and structure. The Orion spacecraft would incorporate a parachute recovery system, known as the 'Crew Exploration Vehicle Parachute Assembly System' (CPAS) and later revised to the 'Capsule Parachute Assembly System' for Nominal, Pad Abort and Low Orbit re-entry conditions. This incorporated two Variable Porosity Conical Ribbon Drogue Parachutes, three Ring-Sail Main Parachutes, three Conical Ribbon Pilot Parachutes and additional Forward Bay Cover Parachutes. Airborne Systems was contracted to design, manufacture and deliver these parachute systems and subsystems.

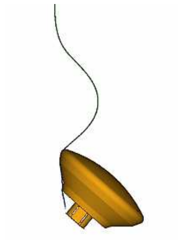

Figure 1. *Simulation of Inverted Riser interaction with CM*

In late 2010 the Integrated Design Analysis Team (IDAT) mandated the design and development of a wire rope riser (Steel Riser) construction to replace a portion of the existing Main and Drogue Parachute textile risers. This riser system would terminate into the Orion forward bay structure (Orion upper bay) and provide robustness against potential contact with the Orion structure during off vehicle attitudes. The primary design drivers were to resist abrasion, crushing, and bending over edges without failure of the riser under the parachute load conditions. Other design drivers were high strength per weight of the wire ropes (i.e. minimized system weight), material volume constraints, wire rope flexibility to integrate the system and handling, resistance to bird-caging and shock environments as well as providing a torque neutral and/or resistant Steel Riser.

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[1] Design Manager, Airborne Systems, 3000 W. Segerstrom Ave, Santa Ana, CA 92704, AIAA Senior Member.
[2] Technical Director, Space Systems Business and Technical Development, Airborne Systems, 3000 W. Segerstrom Ave, Santa Ana, CA 92704, AIAA Associate Fellow.
[3] Design Engineer, Space Systems, Airborne Systems, 3000 W. Segerstrom Ave, Santa Ana, CA 92704.

II. History

Gemini and Apollo parachute systems incorporated wire rope risers comprising of several, parallel, 7x19 construction wire ropes with specialized swaged terminations. The links were designed as a pin and clevis connection to the fabric portion of the Riser. Later in the Apollo program the riser may have used a high strength corrosion resistance steel wire material called 'Carbon Rocket Wire' with higher tensile strengths than standard wires for that time. Riser deployments were critical and instigated new methods to properly control the mass and wire rope characteristics. Damage and/or riser kinking caused during mortar deployments was mitigated by coiling the Riser with a predetermined back-twist and embedding the Riser in a Polyurethane foam mold. Intensive testing also determined abrasion and bending degradation factors.

Since the time of Apollo a wire rope riser have not been considered a desirable option due to the additional mass gain. Modern riser protection largely encompass several varying layers of abrasion resistant materials over high strength textile webbing or cord in the higher risk areas of the riser. However, due to the extreme orientations of Orion's reentry and the programs continued effort to minimize risk; again, a heightened awareness to protect the riser with a more robust riser configuration was instigated. This drove to the development of the Orion Steel Riser.

III. Research and Development

There have been numerous technological advances in the material strengths and wire rope design since the Apollo era. Initial consideration was to develop the system around existing standard wire rope constructions due to heritage and ease of manufacturability. However, consideration was given to new wire rope technology, namely compacted and hybrid designs. Wire rope manufacturers have developed lighter, more durable constructions by compacting the strands to develop stronger, more abrasion resistance wire rope; therefore, translating into a reduction in system weight. Several manufacturers have built upon this technology developing wire rope constructions to fit customer applications and needs. Other designs have incorporated utilizing high strength textiles cores surrounded by an "armor" of compacted wire ropes; however, as this design promised substantial weight savings it was also viewed as an emerging technology and lacked desirable heritage.

WireCo WorldGroup headquartered in Kansas City, Missouri developed a four strand, compacted wire rope construction for dynamic and shock resistance applications; known as XLT-4. The design is inherently torque neutral and was seen as a more robust wire rope construction due to the larger outer wires and smooth outer finish from the compaction processes. This compacted process improved the strength to weight ratio of the wire rope to that of standard constructions of the same material and diameter. The construction was also resistant to bird caging and was torque resistant, but also appropriate for swivel applications. This design was seen as a complete replacement to previous aircraft wire ropes and hoisting applications. The XLT-4 was seen as a superior wire rope design and was determined as the bases to build upon the Steel Riser design.

Riser Material	Strength (kip)	Strength per Weight (lb/lb per ft.)
Kevlar (PIA-T-87130A, Ty X, Cl 13)	20.0	383,900
3/8", XLT-4 Wire Rope	16.0	57,100
3/8", 7x19 Wire Rope	12.0	49,400
3/8", 19x7 Wire Rope	10.8	44,500

Table 1. *Comparison of material strengths per weight ratios*

IV. Steel Riser Design

A. Design Requirements

The Steel Riser design load criteria was based upon the requirements for the Main and Drogue Parachute Design Load Limits (DLL). The Drogue and Main Parachutes grew during the design from 34,083 lb and 35,983 lb to the Robust Initial Condition loads of 42,235 lb and 46,446 lb. Steel Riser safety factors were initially set at 2.0 for flight hardware, but later reduced to 1.6, given the understanding that each assembly would be proof loaded to 60% of the Minimum Breaking Force (MBF) of the wire rope assembly. Further testing would provide abrasion, bending, load sharing and material degradation factors. From the parachute riser load case scenarios the sizing of the wire ropes was then determined.

The design was focused on minimizing the wire rope diameter in order to obtain greater flexibility, conserve space and lower weight (lower diameter wire ropes tend to have greater strength per weight ratios than that of larger wire ropes). In order to withstand the environments and load conditions as well as suitable for integration, multiple, parallel wire ropes had to be used. Therefore, the constraint was determined as utilizing the largest number of wire ropes to withstand the load conditions, but also appropriate for geometric termination concerns. Various studies were completed using between four to seven parallel wire ropes as seven or more assemblies created geometric concerns and four or less usually would contribute to stowage and integration concerns. Six wire rope assemblies were determined as a space conscience and a more torque neutral geometry. The six riser construction would allow the wire ropes to be bundled in a 2 by 3 layer for integration and stowage, but provide a balanced geometric arrangement upon deployment and line stretch. An expandable Teflon sleeve was also introduced to the design in order to help organized the riser for handling and integration. This also provided a level of protection against minor damage and wear to the wire ropes. Additional ties and Polyolefin heat shrink helped keep the bundle together before deployment.

The wire rope assembly length was derived from the IDAT discussions to provide risk mitigation against C.M. surfaces. The Main Parachute was originally developed at a 34.6 ft length and the Drogue was once 18.2 ft due to the attitude and orientations upon parachute deployments. The 34.6 ft originated from a 270 degree C.M. reentry attitude; wrapping the Steel Riser across the heat shield. The larger lengths created substantial additional mass to the parachute assemblies and created deployment concerns. Future studies showed a lesser concern at larger attitudes and the lengths were reduced to a more deployment friendly and weight conscience 17.5 ft and 5.0 ft, respectively.

B. Wire Rope Construction

The XLT-4 was chosen as the superior wire rope design due to its suitability for dynamic conditions and robustness against harsh environments and bending stresses. The historical 7x19 aircraft wire rope construction (as used during Apollo) was determined as a surrogate design for the less developed XLT-4. 304 stainless steel was chosen as the wire material due to its non-corrosive properties, this provided additional challenges in that stainless steel is not readily used in the wire rope industry and created longer lead times. Out-gassing of the lubricates in the space environment was also a concern and a cleaner, soapy like lubricate 'Oakite' was chosen to perform as the manufacturing lubricate. No other lubricates were added during the fabrication of the wire ropes as the desire for a clean product outweighed potential fatigue resistance (risers were determined a one time use and fatigue cycling was out of the realm of industry standard use). After the wire rope went through the manufacturing stages an additional thermal process was used to stress relieve the wires and provided an additional cleaning process to burn off manufacturing contaminates. The combination of the thermal stress relieving and compaction processes (added compressive residual stresses) provided greater wire rope strength per weight ratio and a tougher wire rope construction.

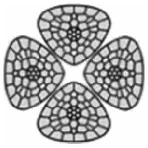

Figure 2. *XLT-4 Cross-Section*

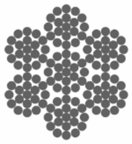

Figure 3. *7x19 Cross-Section*

C. Termination

Military specification ball and shanks ends were determined as lighter and more appropriate terminations for the wire ropes. The swage end materials were that of 300 series stainless steel. The ball ends provided some movement in the housing structure and were considered a higher efficiency termination. Swaging was held tighter than industry standard tolerances in order to allow for equal load sharing between the wire rope assemblies.

A threaded fitting captured the ball ends and a clevis would encapsulate the fitting and attach to the textile riser end. As the parachute design loads increased so did the termination design. A continuous suspension line parachute riser pushed the need to increase the amount of pin attachments. The link changed from a single pin to four smaller diameter pins for the Main Parachute and two smaller diameter pins for the Drogue Parachute. The C.M. attachment design developed in line with the fitting design. This design encapsulated the ball ends in the same manner, but directed the wire ropes out at a slight angle in order to bundle them together at a predetermined distance to be cut away at the appropriate operating conditions. The ends termed 'Pucks' were unthreaded and plates were mated and bolted over the ends to secure them to the forward bay structure.

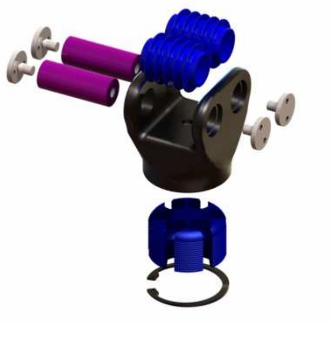

Figure 4. *Exploded view of Drogue Link*

V. Testing

A. Deployment Testing

One of the major concerns for the Steel Riser was the Drogue mortar deployment. Apollo developed extensive testing and techniques to keep the wire ropes from kinking and twisting during deployments. Initial testing of the larger Drogue lengths at 18.2 ft resulted in back-twisting the riser in a mold and encapsulated the coil with a two part Polyurethane foam to dissipate energy and uncoil the wire ropes in a predetermined arrangement. These quick looks at the dynamic effects of the wire ropes helped understand dynamic factors of the Steel Riser design and additional design maturity. However, a reduction in riser length meant that orders of a foot rather than tens of feet would have to be stowed in the mortar. This mitigated concern over riser deployment damage and elevated the necessity of using a mold to help riser deployments. A pneumatic mortar system was than developed to better understand the deployment arrangement of the Steel Riser and link attachments. Current testing is ongoing.

Figure 5. *Test Polyurethane mold of 18.2 ft. Drogue Steel Riser*

Figure 6. *Pneumatic Mortar Testing*

The Main Parachute Steel Risers were routed from the Puck attach points and out of the Fairlead (Orion Steel Riser opening) to their respective Main Parachutes Bays. The Steel Riser was then routed down the side of the Main Parachute and coiled around the bottom of the Main Parachute Deployment Bag. This segregated the Steel Riser and attachment link from the textile riser. Due to the lower Main Parachute deployment velocities, deployment damage was not seen as a high risk.

B. Tensile Testing

Destructive testing was completed on every lot of the XLT-4 wire rope. This assured that the wire rope assemblies met the MBF and ping test requirements. All assemblies went through non destructive testing of 60% of the MBF to assure adequate swaging processing. The additional thermal stress relieving process helped improve the tensile strength of the wire rope by approximately 10%. The ball and shank swaging reduced the actual breaking strength of the wire rope by 5-10%, but the assemblies were still well above the MBF requirement. Tolerances of the wire rope assemblies reached a maximum deviation of ¼ in between assemblies, and destructive tensile tests of the completed six wire rope bundles provided little to no reduction in strength. Length tolerances between wire rope assemblies during straight tensile tests did not seem to drastically affect the overall riser strengths as elongation of the wire ropes were far greater than the maximum tolerances. Elongations at break were between 1.25 in to 1.35 in.

C. Bend and Abrasion Testing

Additional testing to verify degradation factors for the Steel Riser was conducted. The initial testing entailed damaging the Steel Riser over Orion bend obstacles, abrading the Steel Riser, and also crushing the risers to simulate Fairlead interaction. Destructive testing was completed after damaging the wire ropes to the Main Parachute DLL. Static bends over obstacle edges imparted little to no effect on the tensile strengths of the wires ropes. Crushing of two risers over each other provided additional degradation of between 10-15% reduction of the actual wire rope assembly breaking strength. Abrasion testing incorporated bending the riser over the tunnel obstacle (0.875 in radius) at the Main Parachute DLL and cycling this obstacle back and forth at a low rate; this is assumed very conservative. The outcome had a detrimental effect on the riser after 6-8 inches of sweep length and further work is being completed to understand the reasoning behind the failure and whether this is a representative risk for the parachute riser system.

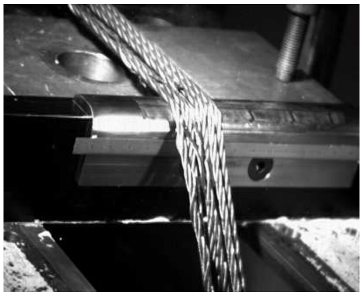

Figure 7. *XLT-4 Abrasion Testing*

Additional destructive tensile tests were completed on the Main Steel Risers from previous testing, which twisted the risers to several revolutions in a simulated Fairlead and C.M. weight and releasing them. All risers had little degradation due to crushing and fairlead interaction.

VI. Summary and Continued Work

A Steel Riser design for CPAS was reinitiated from the Apollo program in order to mitigate riser damage during contact with C.M. structure. Continued testing is being conducted on the proper Drogue Steel Riser orientation for deployment conditions and a better understanding of the wire rope abrasion characteristics are being investigated. Additional work is continuing to establish proper degradation factors.

Concern over load sharing at the shorter Drogue lengths have opted to develop a swage design that would terminate each six wire ropes separately to six or seven continuous suspension lines. This design should provide better load sharing capabilities between wire ropes, reduction in system weight, and better flexibility for integration and stowage. This also should aid in deployment of the riser due to reducing the amount of hardware in the deployment train and would be designed for both the Main and Drogue Parachute systems.