10-14 July 2016, Vienna, Austria

Z-2 Threaded Insert Design and Testing

Amy Ross[1] and Richard Rhodes[2]
NASA Johnson Space Center, Houston, TX 77058

and

Robert J. Jones[3], David Graziosi[4], Jinny Ferl[5], Mitch Sweeney[6], and Stephen Scarborough[7]
ILC Dover, Frederica, Delaware 19946

NASA's Z-2 prototype space suit contains several components fabricated from an advanced hybrid composite laminate consisting of IM10 carbon fiber and fiber glass. One requirement was to have removable, replaceable helicoil inserts to which other suit components would be fastened. An approach utilizing bonded in inserts with helicoils inside of them was implemented. During initial assembly, cracking sounds were heard followed by the lifting of one of the blind inserts out of its hole when the screws were torqued. A failure investigation was initiated to understand the mechanism of the failure. Ultimately, it was determined that the pre-tension caused by torqueing the fasteners is a much larger force than induced from the pressure loads of the suit which was not considered in the insert design. Bolt tension is determined by dividing the torque on the screw by a k value multiplied by the thread diameter of the bolt. The k value is a factor that accounts for friction in the system. A common value used for k for a non-lubricated screw is 0.2. The k value can go down by as much as 0.1 if the screw is lubricated which means for the same torque, a much larger tension could be placed on the bolt and insert. This paper summarizes the failure investigation that was performed to identify the root cause of the suit failure and details how the insert design was modified to resist a higher pull out tension.

Nomenclature

AES	= *Advanced Exploration Systems*
ARGOS	= *Active Response Gravity Offload System*
ASTM	= *American Society of Testing and Materials*
CDR	= *Critical Design Review*
COTS	= *Commercial Off the Shelf*
EMU	= *Extra-vehicular Mobility Unit*
EVA	= *Extra-Vehicular Activity*
EVVA	= *Extra-Vehicular Visor Assembly*
FoS	= *Factor of Safety*
FSA	= *Feed water Supply Assembly*
HUT	= *Hard Upper Torso*
In-lb.	= *Inch Pound*
LSS	= *Life Support System*

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[1] Advanced Pressure Garment Technology Development team lead, Crew Survival and Space Suit Systems Branch, MS EC5 2101 NASA Parkway

[2] Space Suit Engineer, Crew Survival and Space Suit Systems Branch, M/S EC5 2101 NASA Parkway.

[3] Sr. Design Engineer, SSA Product Group, One Moonwalker Rd. Frederica, DE, 19946, AIAA Member

[4] Chief Engineer, Advanced Suit Product Group, 2200 Space Park Dr. Ste 300, Houston, TX 77058, AIAA Member

[5] Design Engineering Manager, Space Suit Assembly, One Moonwalker Road, Frederica, DE, AIAA Senior Member

[6] Engineering Technician, Advanced Suit Product Group, 2200 Space Park Dr. Ste 300, Houston, TX 77058

[7] R&T Manager, Product Development Group, One Moonwalker Rd. Frederica, DE, 19946

MSPV = *Multi-Position Suit Purge Valve*
NBL = *Neutral Buoyancy Laboratory*
OOA = *Out of Autoclave*
PLSS = *Portable Life Support System*
PPRV = *Positive Pressure Relief Valve*
psi = *pounds per square inch*

I. Background

NASA's Advanced Exploration Systems (AES) Advanced Extra-Vehicular Activity (EVA) project contracted with ILC Dover to design and build an advanced prototype pressure suit designated as the Z-2 Space Suit. The purpose of the suit is to bring together multiple mobility joint designs in a single suit platform meant for planetary exploration. The suit was fabricated with materials that are oxygen and vacuum compatible with the proper pedigree to be manned rated to use in hazardous test environments. The Z-2 suit incorporates design features that allow it to interface with some EMU hardware. Interfaces such as integrated ventilation lines, integrated audio, purge and relief valves, and volumes reserved for the Primary Life Support System (PLSS) feed water supplies are examples of interfaces that are included. The Z-2 Space Suit is designed to operate nominally at 8.3 psid with a maximum operating pressure of 10.6 psid. The suit is pressure tested to 13.2 psid for structural integrity verification and proof tested to 17.6 psid as part of the pre-delivery certification testing. The Z-2 Suit is designed to withstand an ultimate pressure of 21.2 psid.

Notable features of the Z-2 Suit include an elliptical helmet bubble with a removable protective bubble that functions as an Extra-Vehicular Visor Assembly (EVVA), rear-entry composite upper torso, rolling convoluted shoulders, waist bearing with integrated sizing feature, composite brief, hybrid composite and aluminum rear hatch with Life Support System (LSS) passthroughs, and conformal walking boots. The suit also comes equipped with a self-donning shoulder and waist harness, as well as bolt on brackets that can interfaces with NASA's Active Response Gravity Offload System (ARGOS). ILC Dover subcontracted with several companies in order to aid in the design, analysis and fabrication of the composites and bearings on the suit. The suit as delivered was designed to fit a smaller population of test subjects than other advanced suits previous have. This presented several unique challenges in fitting all of the design elements into the architecture and still meeting range of motion and other functional requirements.

II. Introduction

Three requirements drove the design of the Z-2 suit to have composite upper torso, hatch and brief: (1) the structures interfaces, such as bearings and body seal closures, need to be precisely controlled, (2) incorporation of several life support interfaces, such as the portable life support system, relief valve, and purge valve, and the internal line routing of these components, and (3) the need for a lightweight and robust structure (Figure 1). Composite elements are also advantageous because they are resistant to damage from dust and debris and they can be designed to offer protection to the crew member in the event of a fall onto a hard object. A trade selection was performed to determine the proper fiber and resin system to construct the composite. Several goals were derived in order to down select to a final system. The goals included a desire to have high strength and stiffness to weight ratios, high impact resistance, advance the technology, -250ºF to 250ºF temperature compatibility, good hot/wet properties since the suit would be used in the Neutral Buoyancy Lab (NBL), and be at a reasonable cost and lead time. Also desired was picking a system that potentially already had MATCO data available (already be space qualified), A&B design allowable values available and able to be processed out of autoclave (OOA). The team investigated over 30 resins and several fiber combinations. Ultimately, a hybrid layup of S-2 fiberglass and IM10 carbon fiber with epoxy resin in prepreg form was selected.

Along with the fiber/resin system selection and impact analysis, the size, shape and interface surfaces of the composites were also concurrently designed. Suit design experience as well as composite design were combined to derive what the mating surface of each composite to metallic hardware would be.

Figure 1. Z-2 Composite Components As Fabricated. *The HUT, Brief and Hatch.*

The design of the interface flanges of the composites allowed some of the inserts to be a “T” style insert that was installed through the entire thickness of the laminate. The flange portion of the insert provides a mechanical lock as a redundancy to the adhesive aiding in the pullout load that the insert can withstand. In some locations it was not possible to utilize at “T” style insert and a blind insert was used instead (Figure 2). These inserts rely completely on the bond strength of the adhesive to resist pullout. After fabrication, a failure of the adhesive bond of the inserts to the composites occurred prompting an investigation. It was determined that the inserts did not need to withstand loads induced from pressure cycling, as originally designed for, but instead tension induced from torqueing the screws to bolt on hardware which creates a much higher stress on them. This paper discusses the failure investigation and design and testing work that determined how to properly incorporate threaded inserts into the composite flanges.

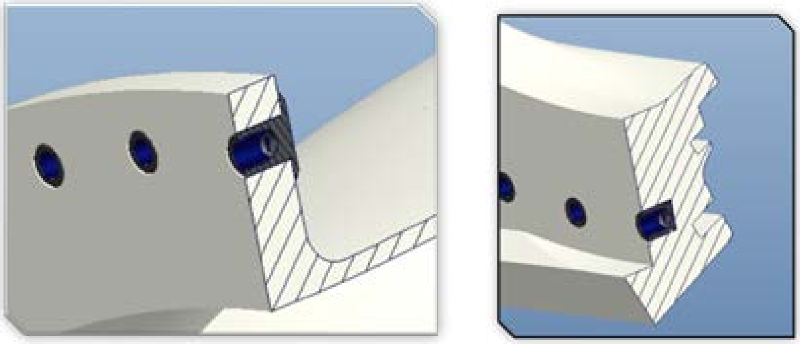


Figure 2. Z-2 Composite Flanges. *Some of the flanges allowed t-inserts to be installed while other required blind inserts.*

III. Problem Description

During the assembly of the Z-2 Suit, popping and cracking noises were heard coming from the composite elements when various screws were being torqued at approximately 4-5 in-lbs. A discussion with the composite subcontractor and calculations confirmed that there should be no material damage at these low loads. The torque was increased to values used on the EMU for the same size fasteners deemed necessary to obtain a sufficient clamping force for proof testing:

– 9 in-lbs. for #4 screws
– 14 in-lbs. for #6 screws
– 14 in-lbs. for #8 screws
– 24 in-lbs. for #¼-28 screws

The suit was pressurized from 4.3 psig to 8.3 psig while evaluating an issue with the hatch. The pressure was reduced and increased several times. While at 8.3 psig, it was noticed via an audible noise that the neck ring was leaking near the latch. The screws on the neck ring were re-torqued to verify they met the prescribed torque value. Also at 8.3 psig, it was noticed that the PPRV and MSPV blanking plates were leaking. These blanking plates cover passthroughs in the composite when the purge valve and relief valve are not installed. The screws were found to turn 1 ¼ turns while re-torqueing. The suit was then pressurized to 10.6 psig when it was noted that the MSPV blanking plate was leaking excessively and the test was discontinued.

After disassembly of the suspect interfaces, it was found that the Witten style inserts bonded into the composites were backing out. This was found at the neck ring, PPRV, MSPV, brief top, and HUT waist.

After the failure was noted, all further suit assembly activities were put on hold. Initial data was gathered and reviewed and brainstorming took place to determine how to proceed in studying the failure. Photographs were taken of all locations with inserts that were lifted out of plane of the composite flanges. Measurements were taken to document how much each insert had lifted. No patterns were noted and the lifted inserts occurred at random intervals. One insert that had lifted on the MSPV flange was able to be fully removed with little effort. It was found that the insert extracted cleanly and that all of the Hysol remained in the hole and the impressions from the vents on the insert could be seen inside the hole in the epoxy (Figure 3). An attempt was made to remove a lifted insert on the Brief but it was not able to be removed by hand.

Design information for all inserts and their corresponding holes was gathered. Also, the insert bonding process that was used was reviewed as that had not been previously provided to ILC.

The inserts were custom designed by the composites subcontractor styled after a Witten Insert, a company that fabricates inserts for composites. The bond line thickness is .005" which was recommended by Witten and the spacing was controlled by glass micro-spheres added to the epoxy. A ratio of 10% spheres in the epoxy was chosen for bonding. The inserts have vertical vents machined into the barrels that allow excess epoxy to flow out of the hole during the installation process. Per the drawings provided, the inserts had a 63 micro inch finish.

A Hysol epoxy was selected as the adhesive for bonding in the inserts. This is a common adhesive to use in the aerospace industry especially in composites due to its exceptionally high shear strength property of 4200 psi at room temperature. Calculations were performed to show that the adhesive would be adequate to hold the inserts against loads induced from pressurizing the suit. It would later be determined that the pre-load tension that torqueing the fasteners places on the inserts is significantly higher than the tension from the pressure load of the suit and was not included in the insert safety factor calculations.

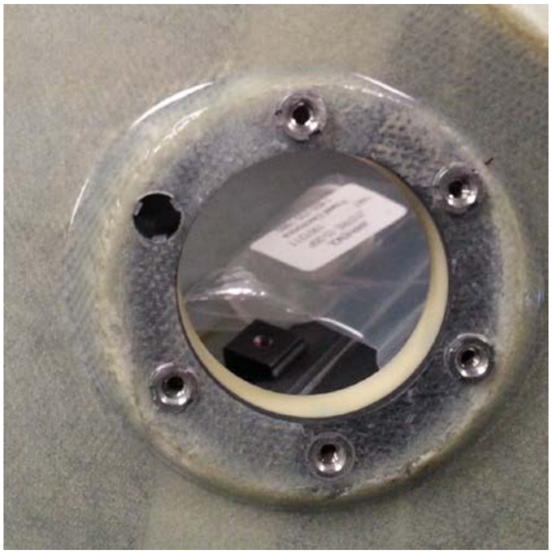
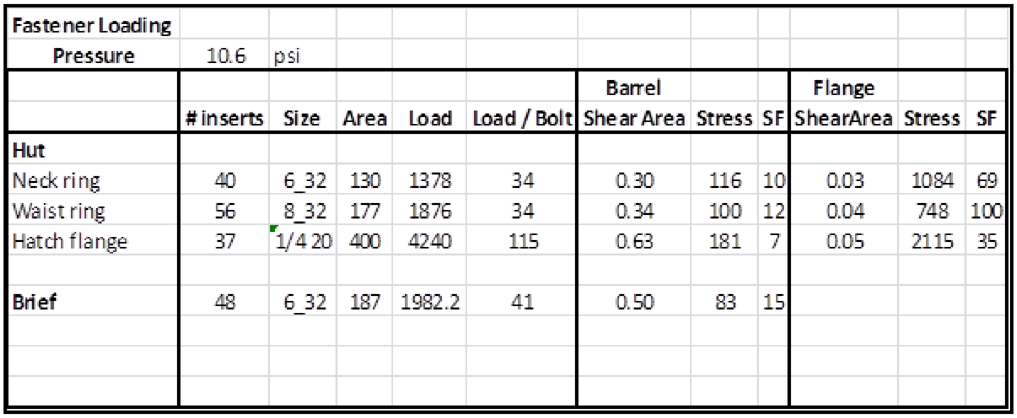


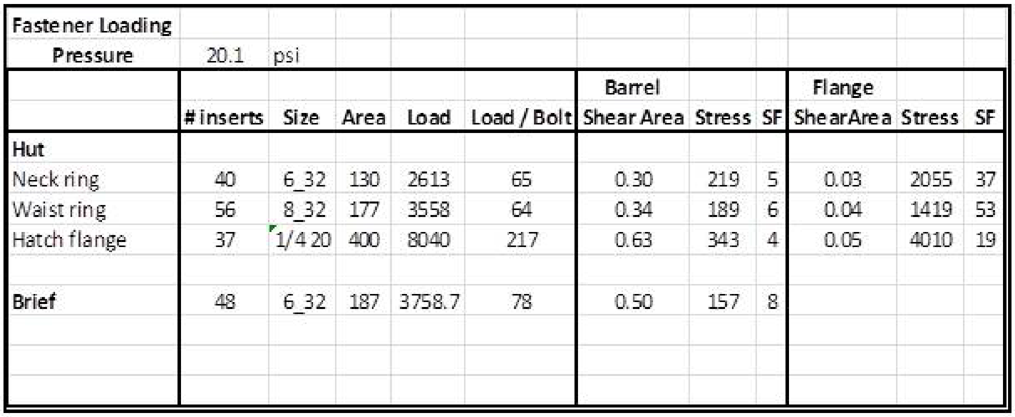
Figure 3. MSPV Flange. *Location where an insert was able to be fully removed and leave the adhesive intact.*

Insert fastener calculations from the Z-2 Critical Design Review (CDR) were examined. These tables compare a flanged (t-style) insert versus a blind insert at both 10.6 and 20.1 psi. The adhesive property assumes a lap shear strength of 1200 psi at 350F which was supplied by the epoxy vendor (Table 1 and 2).



Fastener Loading											
Pressure	10.6	psi									
						Barrel			Flange		
	# inserts	Size	Area	Load	Load / Bolt	Shear Area	Stress	SF	ShearArea	Stress	SF
Hut											
Neck ring	40	6_32	130	1378	34	0.30	116	10	0.03	1084	69
Waist ring	56	8_32	177	1876	34	0.34	100	12	0.04	748	100
Hatch flange	37	1/4 20	400	4240	115	0.63	181	7	0.05	2115	35
Brief	48	6_32	187	1982.2	41	0.50	83	15			

Table 1. FoS Calculations. *Initial Factor of Safety Calculations From Subcontractor for Blind and Flange Inserts at 10.6 psig*



Fastener Loading											
Pressure	20.1	psi									
						Barrel			Flange		
	# inserts	Size	Area	Load	Load / Bolt	Shear Area	Stress	SF	ShearArea	Stress	SF
Hut											
Neck ring	40	6_32	130	2613	65	0.30	219	5	0.03	2055	37
Waist ring	56	8_32	177	3558	64	0.34	189	6	0.04	1419	53
Hatch flange	37	1/4 20	400	8040	217	0.63	343	4	0.05	4010	19
Brief	48	6_32	187	3758.7	78	0.50	157	8			

Table 2. FoS Calculations. *Initial Factor of Safety Calculations From Subcontractor for Blind and Flange Inserts at 20.1 psig*

Based on these calculations the minimum safety factor is 4 for the blind fastener at 10.6 psi. The minimum safety factor is 35 at 10.6 psi for the flanged insert. Pullout testing of the inserts was not performed at the time the decision was made to use this style of insert.

During a meeting to review the failure investigation it was realized that the pre-load, or bolt, tension transferred into the inserts from torqueing the screws was not considered in the stress calculation. Bolt tension is determined by dividing the torque by a k value multiplied by the thread diameter of the bolt. The k value is a factor that accounts for friction in the system. A common value used for k for a non-lubricated screw is 0.2. The k value can go down by as much as 0.1 if the screw is lubricated which means for the same torque, a much larger tension could be placed on the bolt and insert. Shear stress on the insert is determined by dividing the bolt tension by the shear area. The shear area of the insert is found by multiplying the insert length by the insert circumference. It was found that the plug load induced on each fastener is subtractive and not additive to the total load the fasteners sees from torqueing so this value was not included in the calculation. Calculations determined that assuming a k value of 0.2 and at room temperature, the safety factor drops to below 2 for the waist and neck inserts. If the k value is lowered to .1, a majority of the inserts drop below a factory of safety (FoS) of 2 and the neck and waist drop below 1. Safety factors will also drop as the temperature is elevated. It was unknown the exact k value of the components.

From the initial investigation, several conclusions were reached. There was an adhesive failure between the insert and the Hysol. The reason for this was that there was no adhesive left on the inserts when extracted and the Hysol in the hole remained intact. The failure occurred during the torqueing of the fasteners as this is when the cracking noises were heard. It was then realized that the pressure load on the fasteners/inserts is an order of magnitude lower that the preload induced due to torque. Also noted was the fins created in the Hysol by the vents on the inserts were not cracked off indicating that the inserts did not spin but were rather lifted straight out of the holes. Only the blind inserts were suspect at this point since the t-inserts have a flange that mechanical resists the preload for torqueing. Finally, it was realized that the FoS on the inserts was lower that what was understood when presented at CDR.

IV. Failure Investigation

A failure investigation was conducted per the prescribed method ILC follows on failures on the EMU. A brainstorming sessions generates a list of any potential cause of the failure and categorizes them under design, process, material, environment, and personnel. Failure sheets were utilized to capture the cause category, actions to carry out to understand the cause, a cause likelihood rating, and a summary of the investigation in that cause. Several causes were generated and the findings are detailed below.

A. Bond Line Thickness

The objective of this activity was to determine if the bond line thickness selected of 0.005” is adequate to achieve full strength on the adhesive. After a review of the insert, composite, and hatch drawings it was determined that two locations, the MSPV/PPRV and Hatch locations did not have the proper gap to achieve this thickness. After the investigation into the insert design (detailed below), it was found that 0.005” is an acceptable thickness per the epoxy manufacturer, Henkle. Therefore, it was decided to test all samples with a 0.005” bond line thickness.

The composite and Hatch had to be re-machined to remove the old epoxy after the inserts were extracted. It was at this time that the blind holes were opened to the proper diameter to allow proper bond line thickness. This was determined to not be the root cause of the failure.

B. Material Out of Shelf Life

The objective of this activity was to determine if the Hysol did not achieve its published shear strength of 4200 psi because it was out of shelf life. Certs provided by the composites manufacturer and later confirmed by conversation with them showed that only one lot of Hysol was used to bond the inserts in all three components. The lot of Hysol was manufactured on December 18, 2013. It was received on November 20, 2014. The lot was tested on January 28, 2014 and shown to meet the specification. The Brief inserts were bonded 3/25/15-4/10/15, HUT and Hatch Inserts 7/4/15-7/8/15. ILC's ST for Hysol states that the shelf life is 1 year from the date of receipt. Since the bonding was done within a few months of the date of receipt, then the Hysol was not out of shelf life when used. This was determined to not be the root cause of the failure.

C. Insert Degreasing

The objective of this activity was to determine if the proper degreasing step was performed on the inserts prior to bonding. The Hysol adhesive is sensitive to surface preparation and grease or particulate left on the insert could weaken the bond strength. Per the bonding procedure utilized, the inserts were degreased with Acetone. Per the adhesive manufacturer, Henkle, the Hysol bonding procedure states that either Acetone or IPA can be used to prepare the surface. During later testing utilizing G10 cylinders and inserts, it was determined that IPA adequately degreased the surface to achieve sufficient bond strength. This was determined to not be the root cause of the failure.

D. Insert Surface Preparation

The objective of this activity was to determine if the proper surface preparation was performed on the inserts prior to bonding. Commercial Off the Shelf (COTS) inserts would not have worked in the Z-2 design because either their depth or diameter exceeded what the composite flanges could contain. Therefore custom inserts were designed in a similar style to Witten inserts which are COTS inserts. The Z-2 custom inserts were designed with a smooth barrel with 2 - 4 vent slots for adhesive to carry up and out the bore. The machined finish on the inserts was 63 micro inches. The finish of the inserts was designed to be the same as other machined components in the suit. The insert that was removed by hand had adhesive remaining in the shape of the vent slots, indicating that the adhesive properly covered the surface features.

Investigation into industry standards revealed that Witten inserts have either a diamond knurl or an annular ring or flange to resist pull-out. Some also have flats on the bottom flange to resist torque-out. The heavy duty Witten fastener inserts have a spiral rib for pull-out (Figure 4).

To assess the strength of the inserts bonded into the composites and the aluminum hatch frame, a commercial fastener pull tester was utilized to remove all of the suspect blind inserts. The pull tester was calibrated on an Instron machine and then was centered over each blind insert over a plate with a through hole to allow the distribution of the pull forces over a large area (Figure 5). The parts were inspected after the inserts were removed to ensure there was no damage.

Figure 4. Whiten Inserts. *Benchmarking shows COTS inserts have features on the outside of the cylinder to provide more locking interfaces.*

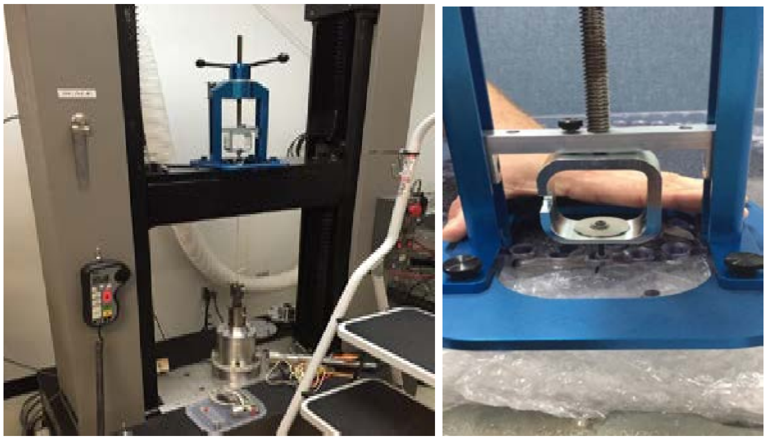


Figure 5. Insert Extraction. *A pull tester was used to extract the failing inserts to determine how much force was required to remove them.*

In general, the inserts required very little force to remove. This indicated that either some of the inserts had already been broken free by the initial torqueing when the suit was assembled or that the inserts were not bonded in adequately. It was found that most inserts in the composites pulled out cleanly leaving all of the Hysol in the hole with the vents left intact. The exceptions were the inserts at the top of the hatch. They required a significantly higher force to remove and some of the inserts had Hysol remaining around the barrel. The decision was made by ILC and NASA not to remove the hinge inserts in the hatch because of their length which produced a very high factor of safety and was not considered to be a concern as these inserts are not in the suit's load path when pressurized.

Post inspection of the hatch revealed a potential reason why the hatch inserts took more force to remove. During the machining of the hatch frame, the aluminum was anodized including the blind holes drilled for the inserts. There was concern that bonding to the anodize would cause an issue with strength and therefore attempted to remove the anodize. This process was not precise and fearing it would open the diameter of the hole, only the anodize on the lower portion of the hole was removed. It is believed that in addition to creating a cone shaped hole for the adhesive to bond to, it also roughed up the surface of the hole creating better adhesion. The cone shape of the hole would put the epoxy into compression as the insert was removed which could have resulted in a higher pull out load and also caused some of the epoxy to remain on the outside of the insert.

In preparation for testing the inserts, a test needed to be performed to select a material that the inserts could be bonded into. As IM10 carbon fiber, the fiber used in the Z-2 composites, was in short supply and would take time to fabricate samples, a replacement, easily bought, fiber glass composite known as G-10 Garolite was selected for testing. Lap shear strip samples of both IM10 and G10 were fabricated. Several other variables including preparation of the strips (no sanding vs sanding) and the amount of spacer beads added to the adhesive was included in this test. The strips were bonded using Hysol and either not sanded or sanded using 400 grit paper in a cross hatch pattern and cleaned using acetone. The samples were bonded with Hysol mixed with no spacer beads, 2% and 10% beads by weight. The adhesive was allowed to reach full cure before testing. 5 samples were tested for each condition. The lap shear testing was performed per ASTM D5868 "Lap Shear Adhesion Test For Fiber Reinforced Plastics".

Both IM10 and G10 samples had comparable results (see Table 3). Sanding combined with no spacer beads produced the highest shear strength. Some of the samples failed due to a tensile failure of the composite and others failed due to an inner laminar shear failure of the composite. The samples did not reach the advertised shear strength of the Hysol which is 4200 psi. This was due to the fact that the composites were failing before the adhesive. It was decided that G10 would be acceptable to use for testing since no shear strength difference was

	IM10		G10	
	Peak Load (lbf)	Std. Dev.	Peak Load (lbf)	Std. Dev.
No sanding/2% beads	892.9	51.8	1524	202.6
Sanding/No beads	2283.2	103.5	2302.3	66.1
Sanding/2% beads	1634.3	258.5	1109.6	151
Sanding/10% beads	1936.3	187.1	1991.8	85.3

Table 3. Test Data Comparing IM10 to G10 Samples. *A tensile test was performed to determine if G10 was an acceptable substitute for IM10 for testing.*

revealed between the two.

Other ideas on how to increase pull out strength were discussed. Recommendations included grit blasting or sanding of the outside of the inserts with 200-400 grit alumina or silica carbide, grit blast or sand the composite holes and clean with DI water and allow to dry, add knurling or ribs to the inserts, use 1-2% by weight of the microspheres and ensure that conditions of where test samples are made is the same as where final parts will be bonded. Some discuss was had over what an acceptable k value would be for analysis. A recommendation was made to plan for a low k value of .1 or to look for test data on helicoils to see if there is an accepted value.

Witten and Henkle, the manufacturer of Hysol, were contacted to discuss this failure and determine what recommendations they had to improve the results of the bond strength. Witten recommended media blasting the inserts with 300-500 grit alumina oxide powder and adding either a knurling or groove features to the outside of the inserts. Henkle recommended only adding 0.5% microspheres to the epoxy and commented that anything higher would reduce the adhesive strength. Henkle also recommended preparing the bonded surfaces with an IPA wipe to both degrease and clean and that a bond line thickness of 0.005” to 0.040” would be acceptable to achieve the full strength of the adhesive.

A second round of lap shear samples were tested this time using aluminum as the substrate for the specimens to determine if the maximum strength of the Hysol could be achieved and if a variation in the amount of microspheres, this time 0.5 and 2 % would cause a difference in strength. The specimens were cleaned with acetone and cured for 24 hours to handle and then a final cure at 150F for 2 hours. These samples also pulled lower than the advertised strength by half. It was recommended by Henkle to try sanding instead of media blasting the strips. ILC and NASA decided to move to testing inserts in G10 and aluminum cylinders to test for strength. G10 would be used for the composite interfaces and aluminum cylinders to represent the Hatch frame.

A test matrix was constructed to determine how to modify the design and preparation of the inserts and blind holes to improve adhesion. Variables in the setup included the type of adhesive to use, size of the bond line, the proper amount of microspheres to use in the epoxy, what type of media blast to use on the inserts (sanding wasn’t an option due to the shape and quantity of the inserts), how to degrease and clean the inserts and the blind holes and if grooves or flanges needed to be added to the inserts and holes to give the adhesive more purchase area to react against. To facilitate getting to an answer quickly, it was decided to eliminate testing individual variables to combine them together in a way to achieve the best result possible using engineering judgement and consensus from the community.

The decision was made to stay with Hysol because it has the highest listed shear strength and is commonly used in the aerospace industry to bond inserts into composites. Also, it was already used on the t-inserts that are remaining in the composites. As it was recommended by the epoxy manufacturer, it was decided to test all samples with a 0.005” bond line thickness and to mix 0.5% microspheres by weight. All insert samples were media blasted and some were prepared with a groove or grooves and some were not to capture whether grooves improved the strength. Similarly, all bored holes in the cylinders were scraped with a machining tap to score the walls of the holes circumferentially and some were prepared with a groove or grooves and some were not. The holes and inserts were cleaned with IPA. Also some samples were created to test how much the pull out strength would be affected by the dimensional accuracy of the grooves to determine if critical inspection would be necessary on the final parts.

The inserts were pulled per ASTM D1002, borrowing the cross head speed from this specification. The final K value was determined by using a load washer on the Z-1 suit placed in between a clamp ring and adjoining hardware and measuring the load induced from torqueing a screw to 11, 17 and 22 in-lbs. Six tests were conducted utilizing different screws with and without fabric under the clamp ring. The final k value used for analysis was .15.

It was determined that a final round of testing would verify that the fix was adequate in all locations and under the correct loading conditions. The final set of cylinder samples to test was determined by the following rationale:

- The HUT MSPV/PPRV locations because they would be cycled the most and because the FoS is low
- The HUT Neck location because it has a low FoS
- The Brief because it has the highest total load
- The HUT Waist because it has a high load and a low FoS
- The Hatch locations

The HUT specimens were tested both with and without undercuts to determine if they were necessary there. If proven not necessary, it would mean that time and money would not need to be spent adding the undercuts to the HUT. The Brief specimens were prepared with undercuts due to the fact that the Brief already had the undercuts added to it.

Because the k value was lowered to .15, several of the locations would not have a 2.0 FoS if the full strength of the Hysol were achieved and were torqued to the values used on the EMU, traditionally accepted as the proper values for torqueing. For the EMU torque values are as follows in Table 4:

SCREW SIZE	50%	75%	100%
NAS110XE02-XX (2-56)	1	2	3
NAS110XE04-XX (4-40)	3-4	5-7	7-9
NAS110XE06-XX (6-32)	6-8	9-11	12-15
NAS110XE08-XX (8-32)	10-12	15-18	20-24
NAS110XE3-XX (10-32)	10-12	15-18	20-24

Table 4. EMU Torque Specification. *These values were used originally on Z-2 and later modified via test data.*

Therefore it was necessary to adjust some of the torque values to achieve a 2.0 FoS. Testing was performed on the Mark III suit to verify if torqueing screws to these lower values would cause a leak and they were found not to. 4-40 fasteners were lowered from 9 to 8 in-lbs., 6-32 fasteners on the neck were lowered from 15 to 10 in-lbs., and the 8-32 fasteners on the waist were lowered from 24 to 15 in-lbs. Based on the shear strength of the adhesive and the FoS on each insert, a Total load value was calculated. There was a concern that the adhesive would lose its strength after repeated cycling. Therefore, the samples were cycled 50 times on the Instron machine to a 1.0X load of the total load calculated and then pulled to failure. If the sample was able to hold through a 2.0X of the total load then it was considered a pass.

E. Blind Insert vs T-Insert

The objective of this activity was to determine if blind inserts are adequate at all locations to resist operational loads, or whether T-inserts are needed in some locations. The pre-load tension created in the inserts was not considered in the initial calculations for the factors of safety for the inserts. Had the bond strength calculation been

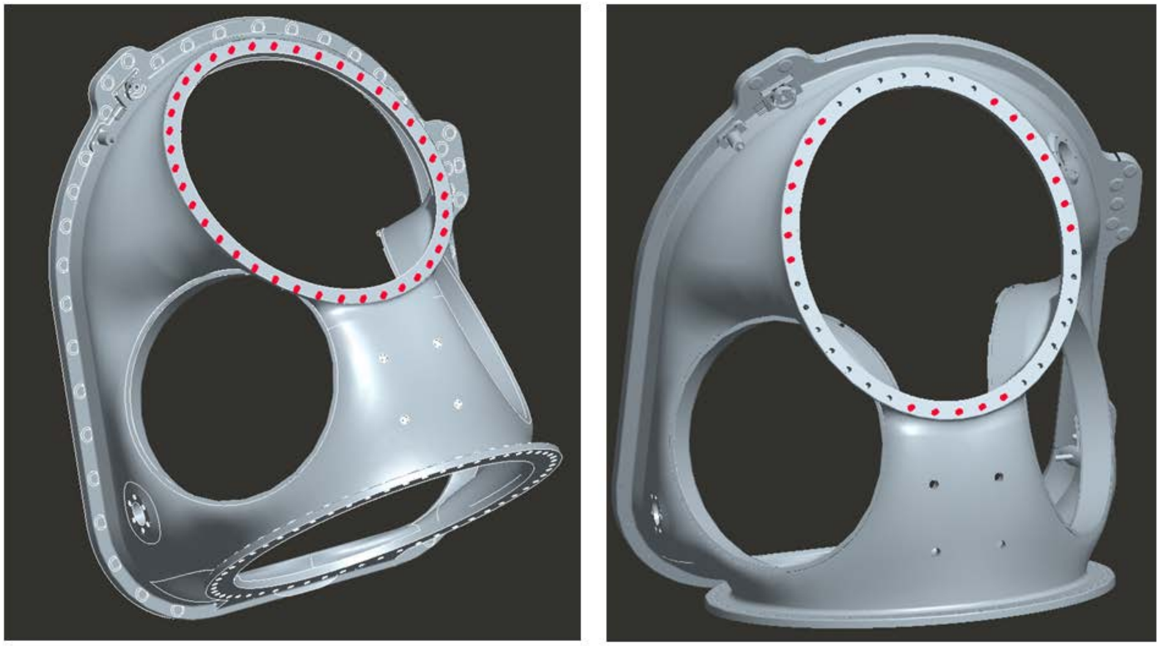


Figure 6. Neck ring Blind Inserts. *Several blind inserts were converted to T-inserts.*

done correctly, the composite flanges could have been altered to eliminate all blind inserts. By the time the error in calculation was detected, the composites were already fabricated. As such, it was determined that the neck flange was the only location that has a flange geometry that would allow some of the blind inserts to be replaced with t-inserts adding the mechanical advantage of a flange to the pull out strength. Figure 6 details which blind holes were converted to through holes to accept a t-insert. The other inserts that were unable to be converted are addressed by altering the surface finish of the inserts to improve adhesive strength. This was determined to not be the root cause of the failure.

F. Improper Microsphere Mix Ratio

The objective of this activity was to determine if the correct amount of microspheres was used in the adhesive. A standard industry practice is to use microspheres mixed into the adhesive to ensure a proper bond line thickness. The spheres act as a shim and are of the same diameter as the desired bond line thickness. In the case of the Z2 inserts, this was designed to be 0.005". The bonding procedure called out using 10% by weight of the spheres mixed into the epoxy. ILC conducted several lap shear tests with the spheres being mixed at 10%, 2%, 0.5% and 0%. Refer to section 3.2.1.2 for the test results. The manufacturer of the Hysol, Henkle, was also contacted to receive a recommendation on what percentage of microspheres should be used. Their recommendation was 0.5%. Therefore, all cylinder and insert testing was conducted using a 0.5% mixture which yielded good results. While this was not the root cause of the failure, it was deemed to be a significant other finding.

V. Conclusion

The root cause of the condition was an improper preparation of the outer surface of the inserts causing an adhesive bond line failure between the Hysol Epoxy and the metal of the insert. Testing was conducted to determine what bonding procedure would produce acceptable strength of the inserts based off of analysis and calculations. Reduction in torque of some of the screws is necessary to achieve a 2.0 FoS on several of the inserts.

The following summarizes the results of the insert/cylinder pull testing:

- The off nominal grooves did not affect the strength of the bond
- The "no undercut" versions performed slightly better in all sizes
- Even though the brief has undercuts, the FoS is high enough that we got screw breaks on all samples and could not fail the insert
- Cycling to the total load did not affect the pull strength

A B-basis estimate was applied to the data as a knock down factor to determine the final torque values.

- MSPV no undercut – 951 (which equates to a torque of 8)
- Neck no undercut – 1099 (which equates to a torque of 11)
- Brief undercut – 1564 (which equates to a torque of 15)
- Waist no undercut – 1145 (which equates to a torque of 14)
- Hatch no undercut – 1043 (which equates to a torque of 8)

Significant other findings were: 1.) that the diameter of the blind holes at the MSPV, PPRV and Hatch were too small to allow the predetermined bond line thickness of .005" to be achieved 2.) The pre-load tension that torqueing the fasteners places on the inserts is significantly higher than the tension from the pressure load of the suit and was not included in the insert safety factor calculations and 3.) An improper amount of glass microspheres were used in the epoxy which degraded its strength.

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Acknowledgments

The authors acknowledge the Advanced Exploration Systems (AES) program for funding the Z-2 effort.