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Shearographic Non-Destructive Evaluation of the Space Shuttle

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ABSTRACT

Preliminary results of shearographic inspections of the shuttle external tank (ET) spray-on foam insulation (SOFI) and solid rocket booster (SRB) Marshall sprayable ablative (MSA-2) epoxy-cork thermal protection systems (TPS) and remote manipulator system (RMS) honeycomb are presented. Debonding SOFI or MSA-2 damage the orbiter belly tile and exposes the ET/SRB to thermal loading.

Previous work with the ET/SRB showed promising results with shearography. The first area investigated was the jack pad close-out, one of many areas on the ET where foam is applied at KSC. Voids 0.375 inch were detected in 1.75 inch thick foam using a pressure reduction of less than 0.4 psi. Of primary interest are areas of the ET that directly face the orbiter tile TPS. It is estimated that 90% of tile TPS damage on the orbiter "belly" results from debonding SOFI during ascent. Test panels modeling these areas were manufactured with programmed debonds to determine the sensitivity of shearography as a function of debond size, SOFI thickness, and vacuum. Results show a Probability of Detection (POD) of .95 or better for of debonds with a diameter equal to the SOFI thickness at less than 0.4 psi pressure reduction. Preliminary results are also presented on inspections of MSA-2 and the remote manipulator system (RMS) honeycomb material.

1. PROBLEM DESCRIPTION

1.1 External tank (ET)

The ET thermal protection is provided by SOFI on the launch pad and during the ascent portion of the flight. Four types of SOFI are used: NCFI in the aft dome and CPR everywhere else except for KSC close-outs. BX-250 and PDL foam are used for KSC Close-outs. Many KSC close-outs are poured with the ET vertical, where the foam expands unevenly causing voids. Surface contamination on the substrate may cause debonds.

Debonding SOFI causes most of the damage to the orbiter belly tile and exposes the ET to point thermal loading. At present no non-destructive techniques for evaluation of TPS on the ET have been approved for use at KSC. Only pull tests on representative test panels are conducted to determine the integrity of the SOFI bond to the aluminum substrate of the ET. Of the techniques available, laser shearography provides good detectability and sensitivity to the areas of concern and provides sufficient immunity to environmental conditions, such as vibration, to be used in the field. Results with Shearography have detected debonds with a diameter approximately half of the SOFI thickness with less than 0.4 psi pressure reduction.

The first application is the jack pad area. This is one of many areas which foam is applied at KSC as opposed to during manufacture of the ET. This area is also one of many areas on the ET to which unique geometry and access require a dedicated procedure. ET systems engineering have catalogued the areas on the tank with the most recurrent TPS debonding problems. The list that follows is prioritized in order of greatest concern:

1. Jack Pad Close-Out
2. SOFI Acreage Repairs, especially on the +Z side (facing the Orbiter)
3. Nose Cone:

a. New Composite Nose Cone & Ogive
b. Nose Cone Ablative Repairs

4. Aft hardpoint close-out, 20 ft^2 on the -Z side
5. Umbilical Area:
   a. Pyrotechnic can close-out
   b. Recirculation Line close-out
   c. Repairs
6. Upper Strut Fairing close-out
7. Bolt Heads at Flanged Joint
8. Corrugated InterTank area
9. All Transition Areas
10. SOFI Acreage

1.2 Solid rocket booster (SRB)

The SRB forward section, consisting of the nose cone, frustum and the forward skirt, and the aft skirt have MSA-2 TPS, an epoxy-cork material. KSC applies K5NA as a close-out to other areas such as the three field joints. Pull tests, similar to those done on the ET, qualify both the MSA-2 and the K5NA. KSC applies K5NA to replace the MSA-2 from these test areas and to repair any damaged areas. Since the SRB is reused, all TPS is reapplied for each flight.

MSA-2 has a history of debonding but not separating from the SRB. One common location of debonding is at the frustum bolts, which is often visually detected. All K5NA material is suspect for debonding.

1.3 Robotic manipulator system (RMS)

The remote manipulator system (RMS) is made by Spar Aerospace Limited. It is mounted at hard points on the sill longeron of the midbody of the orbiter. The RMS performs vital mission operations, e.g. deploying payloads, and provides a work platform for extra-vehicular activity. Ground processing of the RMS is performed in place at the vertical assembly building (VAB) and in the orbiter processing facility (OPF).

The RMS consists of three joints: shoulder, elbow, and wrist. The composite structure between the joints is composed of 0.020 inch thick kevlar exterior facesheet, 0.210 inch thick nylon-adhesive honeycomb, and 0.090 inch thick graphite-epoxy inner facesheet. The kevlar facesheet and nylon-adhesive honeycomb are not structurally significant; this portion functions to cushion the graphite-epoxy against impacts, abrasions, etc.

Accepted inspection techniques for the RMS honeycomb structure are currently limited to visual and tactile methods. The inspector sights down the length of the cylindrical structure looking for bubbles, and lightly presses on the bubble to confirm the debond. Recently, engineers detected a large debond (exceeding 6 inches) on the RMS installed on OV-103/STS 63, prompting concern for all RMS's. Pulse-echo ultrasonic testing (UT) did not corroborate the debond.

2. SHEAROGRAPHY

2.1 Theory of operation

In shearography the test object is illuminated with coherent laser radiation and the light scattered from the surface is collected and passed through some kind of a shearing optic before the image is focused on the detector. The shearing optic splits the scene into two identical images and displaces the images in space relative to each other before they are focused on the detector. The result is that each resolution element of the detector receives energy from two distinctly different locations on the surface being imaged. Because this image shear has a magnitude and a direction it is often referred to as the shearing vector[1].

When the object under inspection of a shearographic system vibrates or undergoes bulk motion the pair of points contributing to the speckle at a single resolution element on the CCD tend to move together. In this way the phase relationship at that element remains relatively constant and the shearographic system becomes largely insensitive to environmental vibrations and rigid-body motions.

When an object is being inspected with a shearographic system and a sub-surface defect is present, stressing of the object will cause a localized surface deflection in the vicinity of the flaw. This local surface deflection will cause the two points that contribute to the speckle phase information at a resolution element on the detector to undergo an out-of-plane motion relative to each other. The relative motion between the paired points alters the phase relationship of the light reaching the element on the CCD and causes a change in the intensity response of that element. Because the difference in relative motion between the paired points is referenced to the magnitude of the image shear, the information contained in a shearogram is a scaled modular measure of the slope of the localized surface deflection along the direction of the image shear. Therefore, with shearography the fringe patterns represent regions of deformation gradient and not deformation amplitude as in the case of holographic systems.

Because a shearographic system is sensitive to the gradient of the out-of-plane surface deflection along the direction of image shear it is prudent to inspect the same area with several different orientations of the shear vector[2]. Asymmetric debonds, for example a seam debond, may not be adequately resolved if the shear vector is aligned with the long axis of the debond, but may show up very well with the shear vector perpendicular to the long axis of the flaw.

2.2 Benefits/Advantages

KSC has many locations for which an NDI system which can successfully detect a debond or void is needed. Shearography satisfies all the following desirable properties for Non-Destructive Inspection.

- Non-contact or Low-load contact with good sealing against rough surfaces of the TPS
- Exterior (TPS) side Inspection only
- Good Sensitivity to debonds
- Portable and Quick Setup (after some changes to the delivered system)
- High Inspection Rates (limited by stressing method, field of view and resolution requirements)

2.3 Description of system

The current Shearography System being implemented at KSC consists of the following: 1) a 750 mW Krypton-Ion laser, (2) a shearographic camera using a birefringent shearing optic, (3) an image processor, (4) an acoustic horn and controller, (5) a heat gun for thermal stressing, and (6) a vacuum hood with an integral camera and controller.

The laser is tuned to a wavelength of 641 nm which provides excellent reflectivity off of the SOFI. Both vacuum and acoustic controllers permit automatic testing to permit high inspection rates once test parameters are established.

The light from the laser is fed to the camera head by fiber optics. The camera head contains the CCD detector, shearing optics and controls to adjust the size and position of the spot of laser illumination being projected on to the surface. The field of view and focus of the camera can be controlled remotely. The controller processes the images containing the speckle phase information and displays the results at video rates.

3. KSC TESTING WITH SHEAROGRAPHY

3.1 Historical reports

Laser Technology Incorporated (LTI) and Marshall Space Flight Center (MFSC) have successfully tested the ET SOFI and the SRB MSA-2 with shearography. LTI received a set of test panels from MSFC and performed a blind test. All programmed debonds as small as one inch in two inches of SOFI were detected. Pressure reduction stressing of 5 inches or less of water provided adequate surface deflection. When debonds were so large as to create leak paths, acoustic excitation of up to 120 dB was substituted for vacuum stressing.

LTI tested an entire cone shaped SRB Forward Section with a 75 inch base diameter and 78 inch height. LTI observed the programmed debonds prior to MSA-2 application. A test chamber provided pressure reduction stressing of up to 2 psi (nominally less than 0.2 psi). LTI also used acoustic excitation of 120 dB and thermal stressing. Vacuum stressing was the most sensitive detecting debonds as small as 0.375 inch in diameter. Acoustic stressing detected debonds as small as 0.75 inch in diameter. Thermal stressing in conjunction with peak value detection imaging provided results similar to acoustic stressing. Shearography detected all preplanned debonds and 8 unplanned debonds. [3]

3.2 Jack pad close-out

The ET jack pad is a 4.5 inch square located near both aft bipod struts. Ground Support Equipment (GSE) connected to the Jack Pad at 4 attach bolt locations guides the ET to mate to the Solid Rocket Boosters (SRB). After mating KSC technicians apply PDL foam to the area. SOFI is the surrounding material and Aluminum is the substrate.

This close-out has had a history of debonds and voids culminating with both jack pad close-outs completely debonding and separating from the ET in April 1994 during STS 59/OV-105 ascent. Partial debonding has occurred numerous other missions. The problematic nature of this close-out prompted some kind of inspection prior to flight and shearography was the only NDI method available at KSC. This area is also one of many areas on the ET to which unique a geometry and access require a dedicated NDI procedure.

The test panels and defects were configured as closely as possible to the ET flight article. A 11 inch by 9 inch surface was sprayed with BX-250 and a 4.5 inch square was removed from the center. Fourteen panels were created. Twelve panels were used to test the a new close-out foam configuration in which the 4.5 inch square is replaced with four 1 inch diameter holes in order to reduce the surface area of the close-out. These panels were destructively inspected to determine the benefits of the new application technique. The remaining two panels (panel 10 and panel 12) were used to simulate debonds and voids using the established close-out configuration. Balloons ranging from 0.375 and 1.5 inch diameter glued to the substrate simulated voids. Two pieces of Teflon tape, placed face to face, simulated debonds.

Both test panels were sent to LTI, who had facilities to adequately test the panels. LTI knew only how the defects were created. The test articles were inspected using pressure reductions of 2, 5, and 10 inches of water with vertical and horizontal shear vectors.

LTI found 3 strong indications and 3 weak indications in panel 10. The strong indications correctly located the 3 programmed flaws of 0.75, 1.0 and 0.375 inch. The 3 weak indications corresponded to porosity or collection of voids with diameters between 0.125 and 0.25 inch. This porosity is located at the SOFI/BX-250 interface, which represents the perimeter of the close-out. The perimeter of the close-out has an adhesive applied to it before the BX-250 close-out foam is applied. LTI verified this porosity in panel 10 by destructive evaluation.

LTI found 2 strong indications and 5 weak indications in panel 12. KSC destructively inspected this panel. One strong and two weak indications corresponded to a 1.5 by 0.785 inch face to face Teflon debond. This indication was obscured by a nearby strong indication that turned out to be porosity or a collection of voids with diameters between 0.125 and 0.25 inch within one inch of the debond. This porosity was an unintentional defect introduced by the foam application process. Another weak indication correlated to a 0.375 inch diameter void. The final two weak indications corresponded to porosity at the SOFI/BX-250 adhesive interface[4].

Though there was not a direct one-to-one correlation between programmed flaws and shearograpically indicated flaws, all the flaws were detected. In addition, the unintentional flaws, introduced by the problematic foam application process were detected . This effort was terminated when the manufacturer of the ET decided to go to the new close-out configuration on a permanent basis. Nevertheless, the ability of shearography to detect debonds and voids was demonstrated and the next logical step was to characterize the sensitivity of shearography for the majority of the remaining areas of concern.

3.3 SOFI Test Panels

There were three test panels fabricated for this investigation. It was desirable to have a larger set of panels to increase the data set, however, a large variety of shapes and sizes of debonds were used. Every effort was made to maximize the information content of each panel.

3.3.1 SOFI Test Panel Construction

Each test panel was constructed from a 24-inch square aluminum substrate with a nominal thickness of 0.125 inch. The substrate was prepared with a two-part epoxy primer by Martin Marietta corporation[5]. Prior to applying the programmed debonds the primer was prepared to a water-break-free surface by cleaning with distilled water and a freon wash.

The programmed debonds were prepared by the Teflon sandwich method in which two thin sheets of Teflon are cut to the desired shape, placed face-to-face and covered with a thin layer of tape to maintain debond integrity. The debonds were placed close enough to each other on the test panels to maximize the number of debonds per panel but not so close as to interfere with each other during testing.

Programmed debonds consisted of symmetric and asymmetric geometry's. Circular and square debonds were created ranging from 0.5 inch to 2 inches in 0.25 inch increments. There are also seam/strip debonds and "L" shaped debonds to determine the dependency of delectability on shear vector orientation. Also incorporated in the test panels are annular debonds and groups of debonds placed in close proximity to determine the ability of the system to spatially discriminate flaws which may be separate but closely spaced. A resolution debond was constructed from a triangle approximately 12 inches in height with a 4 inch base. This debond was used to help determine the a detectability threshold for SOFI depth verses flaw extent.

The test panels were sprayed with standard SOFI equipment used at KSC to a nominal thickness of 3 inches. Subsequently, the panels were planed off to a thickness of 1.5 inches.

3.3.2 SOFI Test Panel Inspection

Each panel was inspected with two field of views with four orientations of the shear vector in each view. The first view consisted of the entire 24 inch square panel. Using this field of view the entire panel was inspected using a vertical shear vector, a shear vector 45 degrees off of vertical, a horizontal shear vector and a shear vector 135 degrees clockwise off of vertical. The field of view was then reduced to an area which sub-divided the test panel in to nine, four inch square sub-areas with some overlap between adjacent sub-areas. Each of the nine sub-areas where then inspected, again, with the four shear vector orientations. This process was carried out for each of the three test panels at a fixed SOFI thickness.

Two to three inspectors were present during all testing and the panels were tested in random order. A scale was developed for use in grading the detection of the flaws. The grades were assigned with a value of 1 to 10 and the following criteria was used:

1. A perceived non-uniform disturbance in the image when observed under dynamic stress (metaphysical detection).
2. A non-uniform disturbance in the image observed under static stress.
3. An apparent separation of two areas (derivative) under dynamic stress warrant future investigation.
4. A surface deflection sufficient to cause single phase step resulting in uniformly bright doublet with no secondary fringes. Considered to be a detection of a flaw.
5. A surface deflection sufficient cause the formation of a double bullseye i.e. one complete set of fringes. (Light / dark pair)
6. A surface deflection sufficient to cause the formation of two sets of fringes.
7. A surface deflection sufficient to cause the formation of three sets of fringes.
8. A surface deflection sufficient to cause the formation of four sets of fringes.
9. A surface deflection sufficient to cause the formation of five sets of fringes.
10. A surface deflection sufficient to cause the formation of six or more sets of fringes.

For the purposes of flaw identification a grade of 4 or higher is considered to be a detection. A grade of 3 would be cause for additional testing e.g. by zooming in on an area of grade 3 the image is enhanced and the area may then be upgraded to 4 if it meets the criteria. This represents a typical maintenance or production inspection where the largest field of view is selected for maximum isnpection rates and any anamoly is zoomed in on to better characterize it.

When the inspection of all panels were completed the SOFI was then reduced by a quarter of an inch and the entire test procedure was repeated. This process continued until the SOFI was reduced to a thickness of 0.5 inch. The nominal thickness of the SOFI on the external tank is 1 inch and as such extra data was taken at that thickness. This is discussed in more detail below.

3.3.3 Additional Testing

Data at all thicknesses and views were typically performed at with 1 inch of water vacuum. Full panel views were performed at a nominal laser power of 500 mw and area testing was performed at 100 mw. Additional testing at the nominal foam thickness of 1 inch included vacuums of 1, 5, 10, and 15 inches of water in the full panel views and 1 and 10 inches of water in the small area testing. No detectability enhancement was observed for various vacuum levels for the SOFI. Shown below in FIGURE 1 is a typical shearogram showing debonded areas in 1 inch of SOFI at a vacuum of 1 inch of water

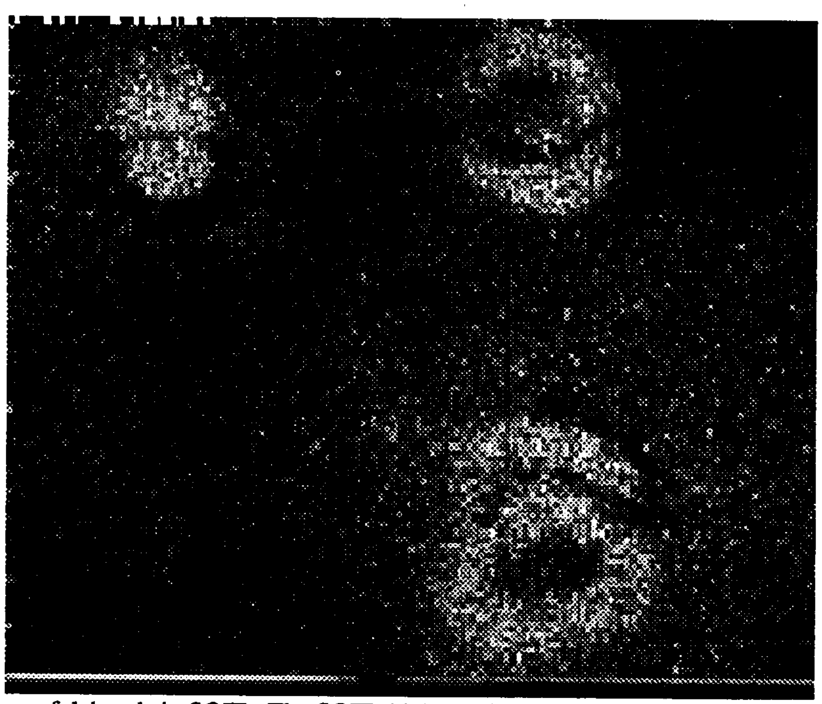

FIGURE 1: A shearogram of debonds in SOFI. The SOFI thickness is 1 inch and a vacuum of 1 inch of water has been applied. The debond in the upper left corner is a 1 inch square, the debond in the upper right corner is a 1.5 inch circle and the debond in the lower right corner is a 2 inch circle. There is a 0.5 inch debond present in the lower left corner but it is not quite visible in this image.

3.3.4 Results of SOFI testing

The results of the SOFI testing indicate that debonds with dimensions along the direction of the shearing on the order of the foam thickness were easily detectable and flaws with dimensions on the order of the foam thickness were often detected and a significant number of even smaller defects were observed. The shearing optics in the camera used in testing had a 0.5 degree shearing angle, a limited number of images were taken with 1 degree shearing optics. The 1 degree camera did not provided any additional detections, but did provide better fringe visibility. Preliminary data showing defect detection as a function of defect size and SOFI thickness are shown below in CHART 1.

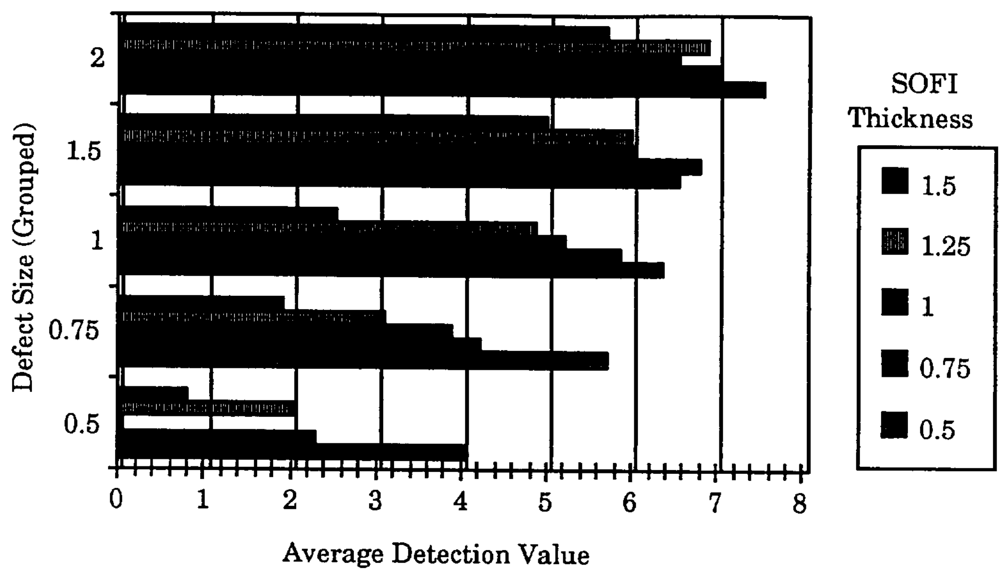

CHART 1: Average detection values of debonds in SOFI at a vacuum of 1 inch of water. Values of 4 or greater are detects.

The inspection of the SOFI test panels was very extensive resulting in a data base of over 600 images and nearly a 1000 datum. The testing began in November of 1994 and was just recently concluded in March of 1995. A probability of detection (POD) analysis data shows a POD of 0.95 or greater for defects with a diameter equal to the thickness of the foam. A complete report containing the entire POD analysis, all data and a detailed description of the experiment is expected to be completed in January of 1996.

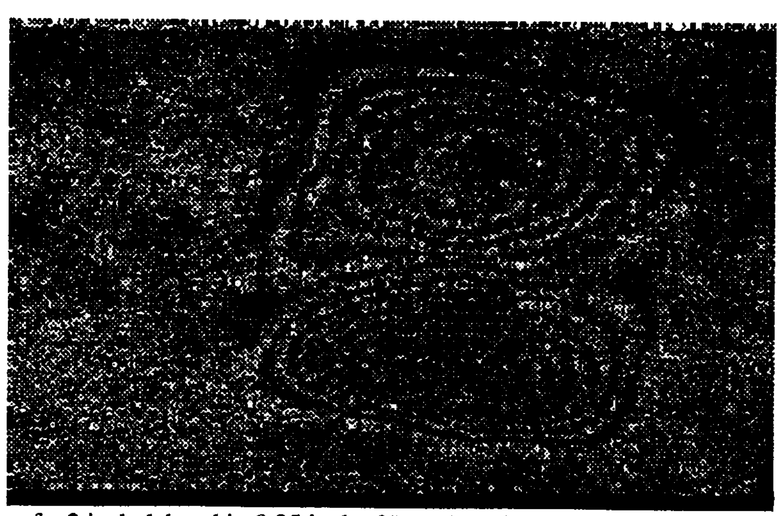

FIGURE 2: Shearogram of a 2 inch debond in 0.25 inch of K5NA cork-epoxy material at a vacuum of 1 inch of water.

3.4 K5NA SRB ablative material

A 24 inch square test panel consisting of K5NA ablative material 0.25 inch thick on an aluminum substrate was available and was tested using shearography. The K5NA material reacted well to thermal and acoustic stressing, however, vacuum stressing provided the best and most repeatable results. The authors have no knowledge of the method used to program the debonds on the panel and therefore the results shown below are provided only to indicate the possible effectiveness of laser shearography in detecting debonds in K5NA material. With a pressure drop of 1 inch of water defects ranging from less than 0.25 inch to 2 inches in extent were detected. Shown below in FIGURE 2 is a shearogram of the 2 inch defect containing many fringe pairs.

Post-flight evaluation of STS-73 SRB frustum BIO75 occurred in October 1995. The inspection was intended to verify the system would function adequately in a difficult field environment and to determine the shearography system's ability to detect the visually indicated debonds. Inspectors visually detected twelve locations of debonds, most of which were associated with bolt heads. Shearography corroborated all debonds and at one location indicated debonds, not identified visually, at the two bolt heads adjacent to each side.

3.5 Robotic Manipulator System (RMS) Inspection

Shearographic inspection of RMS, P/N: 51140F5-5, serial number -202 (Manufacturer date: May 1993) and serial number -201 (Manufacturer date: April 1979) occurred at two different times. The RMS hung in the GSE for s/n 201 and in the transportation dolly for s/n 202, providing access to approximately 75 % of the honeycomb structure. Incorporating a mirror will permit inspection of the remaining exposed structure. Initially, thermal stressing identified the defects. Next, automated acoustic testing provided greater sensitivity and a higher inspection rate. The field of view was about nine inches square, partly limited by the curvature of the 13.5 inch outer diameter of the RMS. Images are stored either on a VCR SVHS tape or in a the hard drive as a TIFF file. Video taping of the live image provides a better interpretation of the defects.

Several visually detected bubbles were only surface irregularities and were not debonds. Thermal stressing detected debonds as small as 0.5 inch; however, the acoustic stressing provided sensitivity as small as an individual honeycomb cell, the maximum sensitivity required. The thermal stressing required only a short 2-3 second heating period distributed evenly over the field of view and 30 seconds afterward to detect any debonds. Automated acoustic stressing operated at 110 to 120 decibels and a frequency sweep between 2 and 15 kilohertz. Acoustic test time was 2 seconds with 2 to 4 sweeps per test. With acoustic stressing shearographic inspection of the entire RMS takes four hours.

Shearography detected five debonds in s/n 202 as shown in the table:

Defect #	Width (inch)	Circumferential Length (degrees)	Notes
1	5.0	75-160	visually detected
2	0.75	20	cluster of small defects
3	0.5	15	
4	2.0	150	cluster of small defects
5	0.5	15	
6	5.0	60	
7	0.5	15	
8	0.375	10	2 each defects
9	4.0	20	cluster of small defects
10	2.0	20	
11	1.5	20	
12	8.0	75	cluster of small defects
13	4.0	75	cluster of small defects

Shearography detected five debonds in s/n 201 as shown in the table:

Defect #	Width (inch)	Circumferential Length (degrees)	Notes
1	0.75	20	at joint where honeycomb ends
2	4.0	20	suspect honeycomb to graphite-epoxy debond
3	4.0	320	at joint where honeycomb ends
4	2.0	150	at joint where honeycomb ends
5	2.0	145	at joint where honeycomb ends

Post-test image enhancement improves the quality of the image. FIGURE 3 below is a shearogram of Debond 1 described above. As an option, Pseudocoloring can improve the identification of the debond.

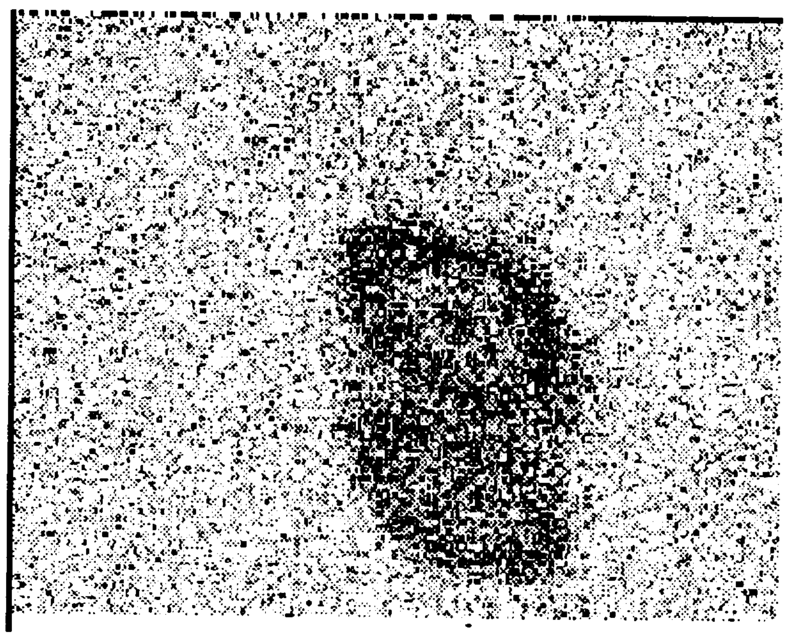

FIGURE 3:An image enhanced shearogram of Defect 1 found on the RMS s/n 201

A ten flight interval inspection of this honeycomb was rescinded by the Design Center when no NDI method was available to inspect this area of the RMS. Though shearography is not a certified inspection procedure, system engineers will use the results to determine the integrity of the honeycomb. These known debonds are not considered mission threatening, nor even structurally significant, at this time. Until the Design Center develops accept/reject criteria, shearography will inspect all RMS on a ten flight interval to monitor/detect any debonds.

4. ET Implementation Plan

4.1 ET Flight Vehicle

Based on these preliminary investigations shearography seem a promising NDI technique for the ET TPS. In order to incorporate this new non-certified NDI technique in to KSC operations the following Implementation Plan is being proposed. It is believed that utilizing shearography as part of the normal vehicle flow will reduce, if not eliminate the problems of debonding TPS.

- Complete report on the ET test panels to determine POD curves on SOFI. Determine the impact of not testing the flight vehicle.

- Coordinate the results of all aforementioned testing with the Design Center. Determine maximum stressing levels. Determine negligible/acceptable defect/debond size. Determine method to verify sensitivity of shearography inspection of KSC close-outs and incidental damage of the rest of the ET TPS due to handling or operations.

- Fabricate all interfacing equipment and specific support equipment for testing the ET or SRB in the VAB.

5. Conclusions

Shearography is an excellent NDI technique for TPS inspection of the ET and the SRB. Vacuum stressing provides a maximum deflection of six fringes before the entire SOFI expands. Vacuum stressing levels are very low levels (nominally < 0.4 psi). Inspection of seam debonds demonstrated the importance of using at least two shear vectors (0° and 90°) at any location.

Implementation of shearography should greatly reduce damage to the orbiter belly tile resulting from debonding ET SOFI. Any reduction in tile damage translates to a large cost savings for the Space Shuttle program. The accurate detection of defects permits foam application improvements as well as assessing handling and maintenance induced damage. Reliable detection of flaws on the ET and SRB contributes not only to cost savings but also to the safety of those who fly aboard the Space Shuttle.

Shearographic inspection of composites used for structure on the orbiter requires development. The more rigid composite structures are more sensitive to acoustic stressing, particularly in the ultrasonic range. KSC is in the process of acquiring a new, more portable system and a test chamber. The new system is designed towards the structural applications of the orbiter. Given the abundant use and many types of composites on the Orbiter, an efficient and effective NDI technique will enhance safety and reduce processing costs.

6. References

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