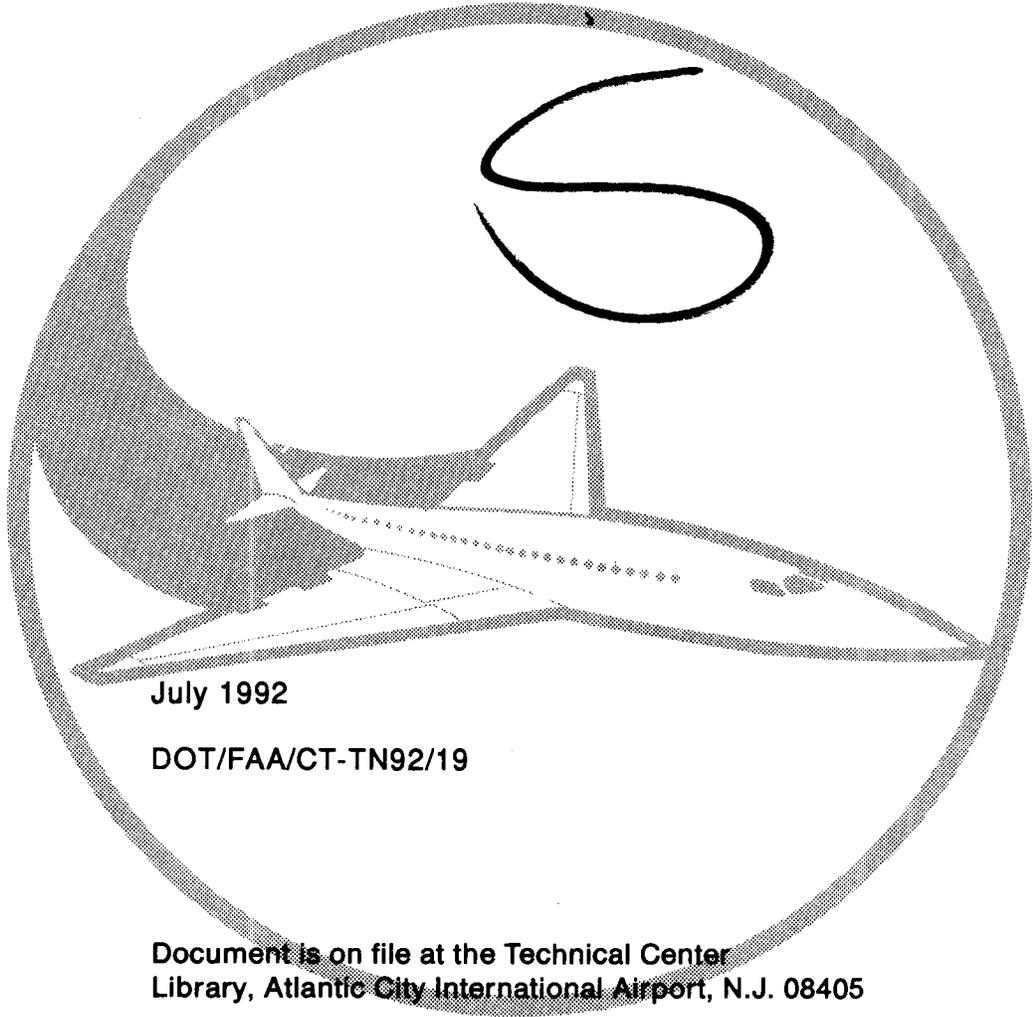


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Shearographic Inspection of a Boeing 737



July 1992

DOT/FAA/CT-TN92/19

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16. Abstract Under a Cooperative Research and Development Agreement between VNTSC and Henson Aviation, Inc., operator of USAir Express, a shearographic demonstration inspection of the fuselage of a Boeing 737 aircraft was performed at a USAir repair station at Winston-Salem, NC, during August 1991. The inspection compared the effectiveness of shearography with currently mandated methods in detecting disbonds in the fuselage. Adhesive bonding is utilized in modern aircraft fuselages, frequently in combination with rivets. As aircraft age, bond failure may become a major problem, since it may promote fatigue cracking, moisture intrusion, and subsequent corrosion. Any of these events may cause cabin pressure loss and, sometimes, catastrophic fuselage failure. The shearographic method of detecting disbonds depends on the deformation of the aircraft skin under varying pressurization. When illuminated by coherent light, the phase relationship and intensity of the light reflected from any two points of the skin changes as a result of this deformation. Surface changes down to 0.00025 millimeters can be detected and displayed as a real-time image of the field of view. Comparison of successive images as the pressure changes permits interpretation of the condition of a bond. For this demonstration, 31 disbonds were found by shearography; 25 were confirmed by ultrasound. Of the remainder, six were disbonds on structure where the Sondicator cannot perform reliably; one was a false positive; in addition, there was one Sondicator false positive confirmed by reference to a drawing and by observation. The demonstration indicated potential advantages of shearography over currently used inspection techniques, namely, improved reliability in the detection of disbonds in the fuselage and reduced down-time of the aircraft with concomitant reduced inspection costs.					
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EXECUTIVE SUMMARY

Under a Cooperative Research and Development Agreement between the Volpe National Transportation Systems Center and Henson Aviation, Inc., operator of USAir Express, a shearographic demonstration inspection of selected portions of a Boeing 737 aircraft fuselage was performed at a USAir repair station in Winston-Salem, NC, during August 1991. This report describes the instrumentation and inspection procedure, and presents the results that were obtained. The demonstration indicated potential advantages of shearography over currently used inspection techniques, namely, improved reliability in the detection of disbonds in the fuselage, and reduced down-time of the aircraft with concomitant reduced inspection costs. The report concludes that additional demonstrations utilizing shearography are required to confirm the capabilities of this promising inspection tool.

INTRODUCTION

Adhesive bonding is utilized in modern aircraft fuselages, frequently in combination with rivets. As aircraft age, bond failure may become a factor, which, in turn, can promote fatigue cracking, moisture intrusion, and subsequent corrosion.

In support of the FAA's Aging Aircraft Program, the Volpe Center reviewed candidate nondestructive inspection procedures which might be more reliable than currently mandated techniques, while also reducing the inspection time and associated costs. In order to evaluate these techniques in an operational environment, VNTSC entered into a Cooperative Research and Development Agreement with USAir, to select, jointly with the air carrier, the most promising technique and to compare its performance with existing methods during routine inspections of aircraft.

An inspection for disbonds was conducted on a Boeing 737-200 aircraft at the carrier's repair station at Winston-Salem, NC, from August 21 to 23, 1991. The inspection concentrated on comparing the effectiveness of shearography with currently mandated methods in detecting disbonds in the fuselage.

The shearographic method of detecting disbonds depends on the deformation of the aircraft skin under varying pressurization. When illuminated by coherent light, the phase relationship and intensity of the light reflected from any two points of the skin changes as a result of this deformation. Surface changes down to 0.00025 millimeter can be detected and displayed as a real-time image of the field of view. Comparison of successive images as the pressure changes permits interpretation of the condition of a bond.

THE AIRCRAFT

The aircraft, a Boeing 737-200, was manufactured in 1970 for All Nippon Airlines. It entered U.S. service in 1980.

At the time of this inspection, the aircraft was out of service for a landing gear replacement. Its service history indicated that 50,394 flight hours and 55,816 taxi, takeoff and landing cycles had been achieved.

A previously mandated visual inspection by the air carrier disclosed that all identified disbonds had been repaired by rebonding and/or riveting. When the repair station's maintenance foreman was questioned concerning the use of bonding agents, he indicated that larger disbonded elements, such as skin panels, were rebonded in addition to being fastened with buttonhead rivets, whereas smaller disbond areas were riveted only. For this reason special attention during the inspection was given to locations where buttonhead rivets were observed.

INSTRUMENTATION

The shearographic equipment was provided and operated by Laser Technology, Inc. Two illumination systems were available: a tripod-mounted system (Figure 1), usable only on the hangar floor; and a fixed-focus system (Figure 2), which could be attached directly to the aircraft for inspection of portions of the fuselage accessible only by scaffolding. The shearographic image was viewed, processed and recorded electronically. Specifications of the equipment are presented in Appendix A.



Figure 1 Tripod-Mounted Illumination System

INSPECTION PROCEDURE

The inspection was performed in accordance with a procedure jointly prepared by the FAA Technical Center and the Volpe center (see Appendix B). Data were recorded on a Body Station Template (Figure 3) by referring to the Boeing Structural Repair Manual (Appendix C).

Before setup of the shearography equipment, selected surfaces were spray-painted with dye penetrant developer to increase their reflectivity. Although shearographic images may be obtained for untreated surfaces, this increased reflection permitted a larger field of view for a given illuminating power level. In order to record the field of view covered by a particular shearogram, an image of the illuminated area was initially recorded (Figure 4). A crayon mark, which corresponded to the upper right-hand corner of this image, was then made on the fuselage to serve as an index point for the next adjacent image. Where the shearogram indicated the presence of a disbond, the skin was annotated as shown on the Figure and the shearogram (Figure 5) was recorded.

A USAir inspector then performed an ultrasonic examination of the area, using a Model S-3 Sondicator.



Figure 2 Fixed-Focus Illumination System

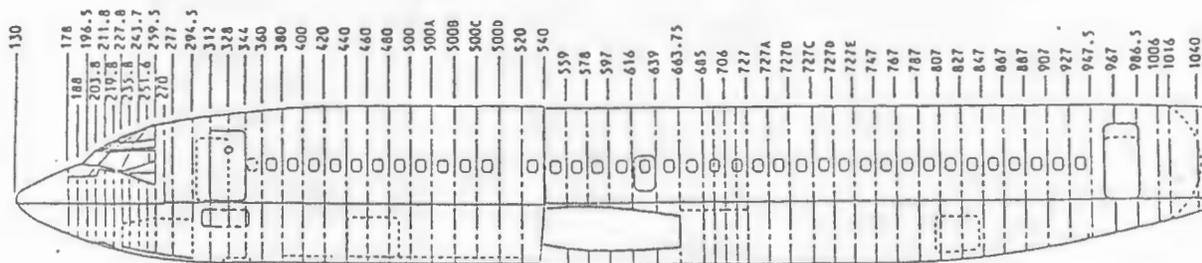


Figure 3 Body Station Template for Recording Inspection Results

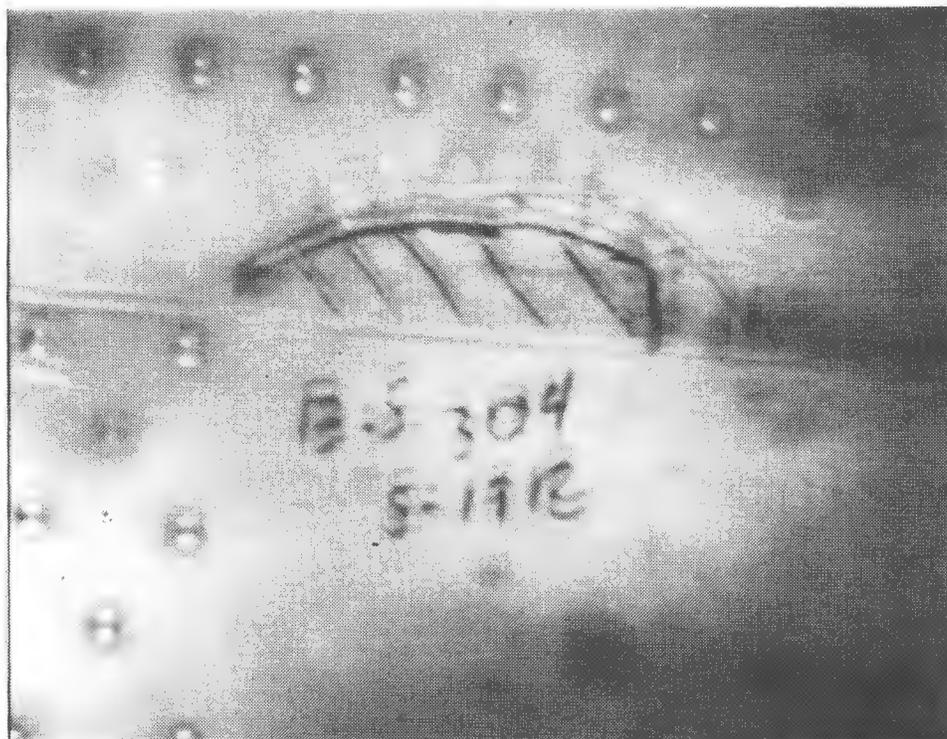


Figure 4 Disbond in Repaired Area.

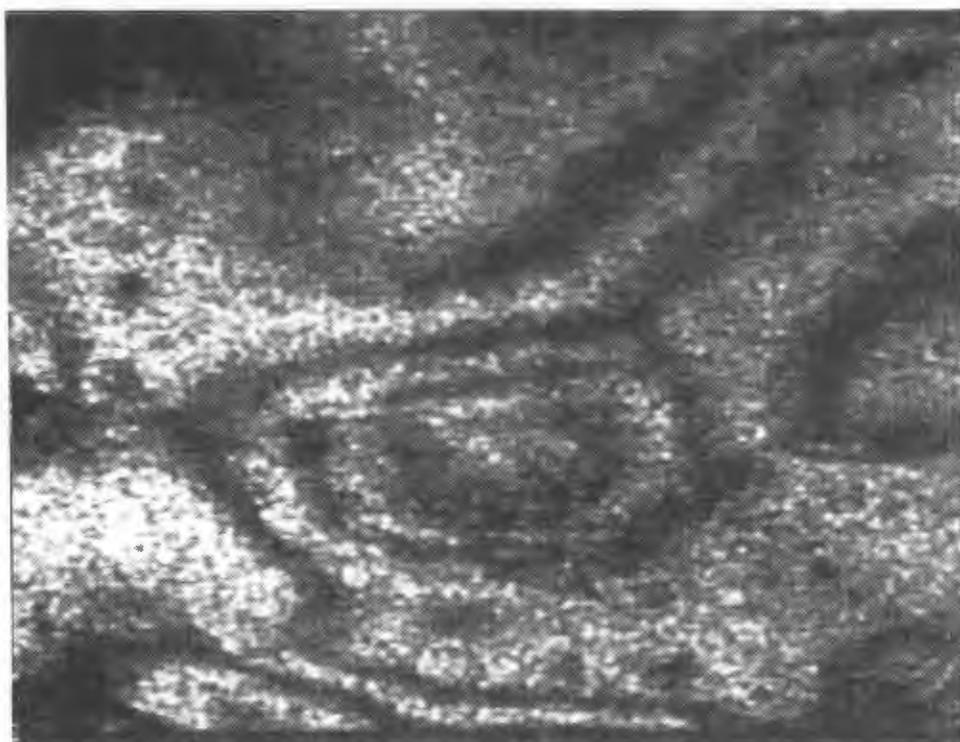


Figure 5 Shearogram Associated with the Disbond Shown in Figure 4

PRESSURIZATION

To pressurize the aircraft and introduce cyclic pressure variations, an auxiliary air supply was used. Cyclic pressure variation was controlled manually by maintenance personnel over the pressure range between 2 and 2.4 PSI above ambient.

To reduce skin surface vibrations of the aircraft caused by noise from the compressor, the compressor was left outside the hangar and a long connecting hose was used. Even after removal of the compressor, air exhausting from the aircraft created a bothersome hiss.

The inspection was intended to cover as much of the aircraft as possible during the available 24-hour period. The fixed-focus system could cover an area of about 14x11 inches, whereas the coverage of the tripod-mounted system was proportional to the distance from the target with maximum distance being governed by the intensity of the illumination and the ambient background. Parts of the window belt and upper stringers on the right-hand side of the aircraft were inspected using the fixed-focus system. Parts of the left- and right-hand side and bottom of the aircraft were inspected using the tripod-mounted system with two fields of view: 30x24 inches for coarse real-time observation, 10x8 inches for recording. Figure 6 shows inspection coverage of the aircraft during the 24-hour period was approximately twenty percent.

RESULTS

Interference fringes around rivets observed in a shearogram were found to be evidence of disbonding. Absence of such fringes was found to indicate that the bond had maintained its integrity. In an unriveted area such as at a tear strap, the shearogram, for a good bond, clearly displayed the outline of the tear strap (Figure 7). A disbond was indicated when the outline of the tear strap was ragged or displaced (Figure 8).

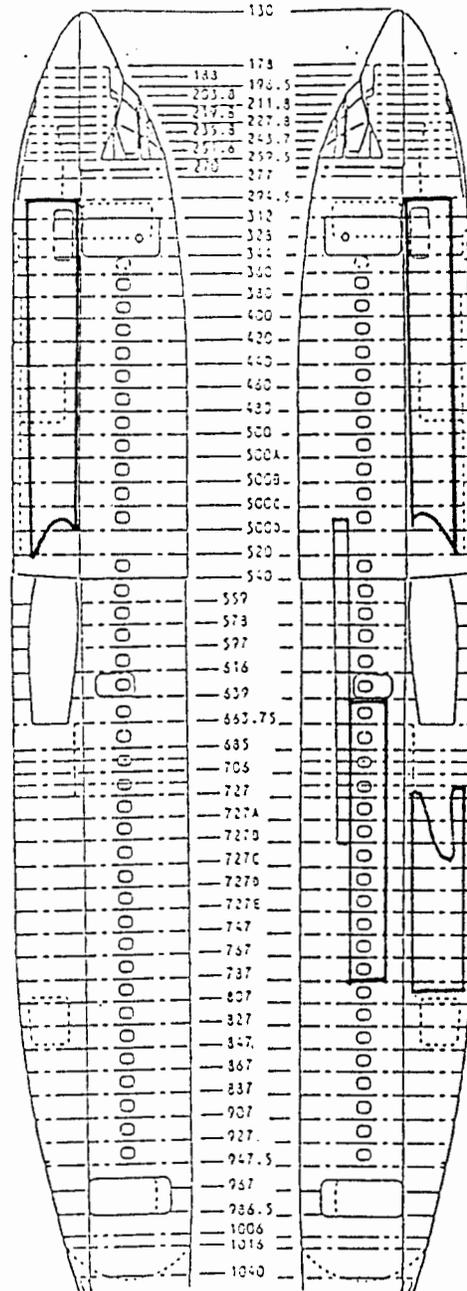


Figure 6 Left and Right Side of the Aircraft Showing Inspection Coverage

Most observed disbonds were related to repairs where the top row of rivets of a lap joint had been replaced, leaving the two adjacent rows of rivets intact. In such a case, disbonds frequently extended from the panel edge into the lap, as in Figure 4.

Sometimes the disbonds extended all the way to the other side of the lap; at other times, only the upper row of rivets was affected. Correlation between shearography (outer double line) and ultrasound (cross-hatched area) is also indicated in Figure 4. The fringe pattern from which the disbond in Figure 4 was determined is shown in Figure 5. Since the Sondicator could not detect disbonds shorter than one inch, only disbonds longer than this are reported here for comparison between shearography and ultrasound.

For the areas of the fuselage examined, thirty-one disbonds were found by shearography. Twenty-five were confirmed by Sondicator. Of the remainder, five were disbonds on repaired riveted lap joints where the Sondicator cannot perform reliably; one was a disbond on a riveted stringer which the Sondicator did not detect for the above reason. In addition, there was one Sondicator false positive confirmed by reference to a drawing and by observation. These results are presented in Table 1.



Figure 7 Intact Tear Strap Bond

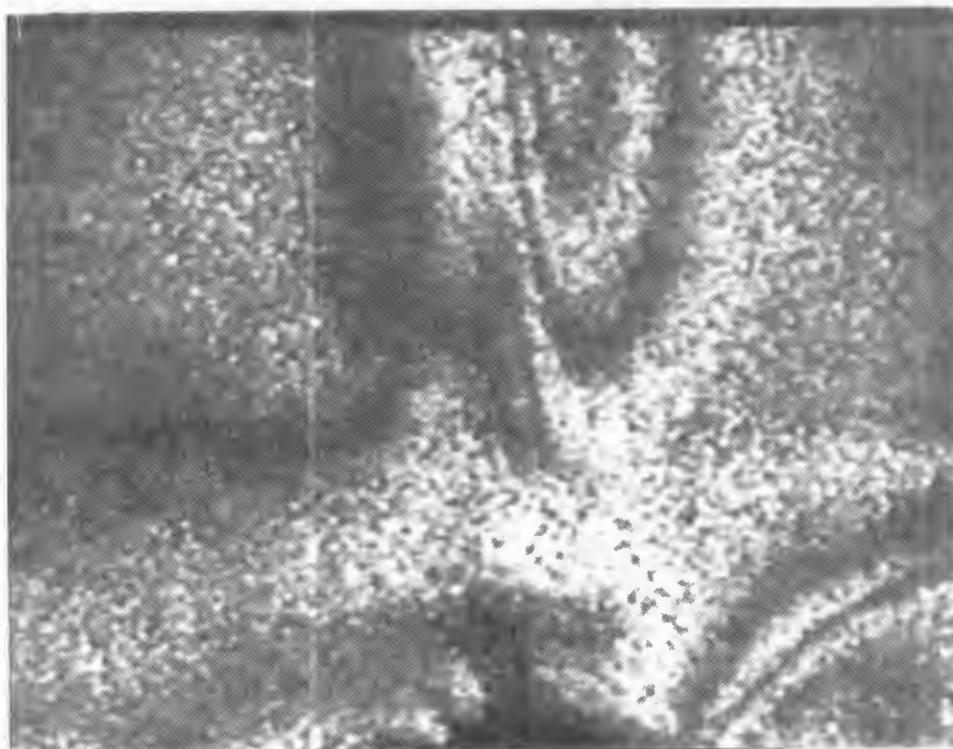


Figure 8 Degraded Tear Strap Bond

Table 1 Shearographic and Sondicator Findings

DISBONDS, LEFT SIDE OF AIRCRAFT				
LOCATION BS and S Note 1	LENGTH A, B, or C Note 2	TYPE	At Repair	Sondicator
BS252-257 S 24 L	C	Lap	Yes	Yes
BS259.5 S18-25L	C	Lap	Yes	Yes
BS271-277 S 24 L	C	Lap	Yes	No
BS 279 S 19 L	A	Lap	Yes	Yes
BS 282 S 24 L	A	Lap	Yes	No
BS316-321 S 24 L	C	Lap	Yes	Yes
BS320-326 S 24 L	C	Lap	Yes	Yes
BS 328 S 19 L	A	Lap	Yes	Yes
BS 338 S 24 L	A	Lap	Yes	No
BS 360 S 23 L	A	Stringer	Yes	No
BS 380 S20-21L	C	Tear Strap	Yes	Yes
BS380-420 S 19 L	C	Lap	Yes	No
BS 400 S 23 L	B	Tear Strap	Yes	Yes
BS 420 S 23 L	B	Tear Strap	Yes	Yes

Notes:

1. "BS" denotes Bulkhead Station number; "S" denotes Stringer number; "L" or "R" denotes left or right side of aircraft.
2. "A" denotes shorter than 5 inches; "B" denotes 5-10 inches; "C" denotes longer than 10 inches.
3. Sondicator false positive at BS 380-420, S 19 L.

Table 1 (continued)

DISBONDS, RIGHT SIDE OF AIRCRAFT				
LOCATION BS and S	LENGTH A, B, or C	TYPE	At Repair	Sondicator
BS 259.5 S 20 R	A	Lap	Yes	Yes
BS 259.5 S 24 R	A	Lap	Yes	Yes
BS 259.5 S 21 R	A	Butt	Yes	Yes
BS 259.5 S 21 R	A	Butt	Yes	Yes
BS 270 S 22 R	C	Tear Strap	Yes	Yes
BS 270 S 22-23 R	B	Tear Strap	Yes	Yes
BS 297 S 19 R	A	Lap	Yes	Yes
BS 304 S 19 R	A	Lap	Yes	Yes
BS 322 S 19 R	A	Lap	Yes	No
BS 330 S 19-24 R	C	Tear Strap	Yes	Yes
BS 358 S 19 R	A	Lap	Yes	Yes
BS 359 S 22 R	A	Stringer	Yes	Yes
BS 360 S 17 R	B	Tear Strap	No	Yes
BS 360 S 19-23 R	B	Butt	Yes	Yes
BS361-368 S 19 R	C	Lap	Yes	Yes
BS 500C S 10 R	A	Lap	Yes	Yes
BS 908 S 19 R	A	Butt	Yes	Yes

POTENTIAL PAYBACK

Three factors were considered in estimating the potential payback of shearography as an inspection tool: labor hours, aircraft down-time, and equipment cost. For inspection performed by conventional means, the first two factors are of importance, since equipment costs are usually less than \$10K and are amortized over many inspections. Labor hours and aircraft down-time estimated for currently mandated inspection procedures are derived from Boeing Service Bulletins (References 1 and 2) and summarized in Table 2 ("Elapsed Time" is defined as labor hours divided by recommended crew size).

Table 2 Inspection Operations Currently Mandated

Operation	Labor-Hours	Elapsed Time (Hours)
External Visual Inspection	516	132
Internal Visual Inspection	578*	92
Ultrasonic Inspection	80	40
Eddy Current Inspection	50	25
Total	1224	

* Includes 350 man hours by a crew of 10 required to access and restore airplane interior.

Since the listed operations are essentially performed concurrently in three shifts, aircraft down-time (days) is assumed to equal the longest Elapsed Time, divided by 24. From discussions with the carrier's staff, accelerated (salary, benefits and overhead) hourly labor cost is \$30; daily down-time cost (aircraft unavailable for revenue service) is \$15K (an approximate figure given by USAir). From Table 2, computed labor cost (1224 hours) is \$36.7K, aircraft down-time cost (6 days) is \$90K; total \$126.7K.

From observations during the partial inspection of the aircraft and discussions with the air carrier's staff, it became apparent that shearography could improve the reliability of the inspection and substantially reduce the inspection time. Members of the carriers staff indicated that probably both the internal visual and ultrasonic inspections of the aircraft could be dispensed with and the time for external visual inspection reduced by a factor of two. On this basis, an estimate of the potential payback of shearography is presented in Table 3.

As before, these operations are assumed to be performed concurrently at respective labor costs (308 hours) of about \$9K and aircraft down-time (3 days) cost of \$45K.

Total savings, using shearography, amount to about \$72K.

Table 3 Inspection Operations Using Shearography

Operation	Labor Hours	Elapsed Time
Shearographic Inspection	258	66
Eddy Current Inspection	50	25
Total	308	91

In this case, however, equipment costs must be considered. If the equipment is to be purchased (\$290K), the cost could be recovered in four inspections with subsequent savings of \$72K per inspection. Equipment rental, including three certified operators (\$10.5K per day), \$31.5K, with immediate savings of approximately \$40K.

CONCLUSIONS

The principal potential benefits indicated by the demonstration of shearography are improved reliability and reduced aircraft down-time, compared with currently mandated techniques. To make shearography generally applicable and acceptable, it will be necessary to perform demonstrations during other mandated inspections of the Boeing 737 and other types of aircraft. Concurrently, it would be advantageous to improve various facets of the technology such as might include expansion of the field of view, automation of data acquisition and interpretation, and reduction of equipment cost.

REFERENCES

1. Boeing Service Bulletin 737-53A1039, "Fuselage Skin Lap Joint Inspection and Repair."
2. Boeing Service Bulletin 737-53-1076, "Fuselage-Circumferential Butt Splices and Bonded Doublers - Inspection, Repair and Modification."

APPENDIX A
SPECIFICATIONS OF SHEAROGRAPHIC INSTRUMENTATION

Specifications for the equipment provided by Laser Technology, Inc., are as follows.

<u>Model</u>	<u>LTI 9200</u>	<u>LTI980D</u>
	Tripod-Mounted	Fixed-Focus
Laser	Argon Ion	Diode
Laser Output Power	200mW	80mW
Effective Output Power	80mW	80mW
Size (inches LxWxH)		
Optical Head	12x4x5	16x16x18
Electronics	22x22x24	22x22x24
Power		
Laser	110V @ 20A	110V @ 10A
Electronics	110V @ 10A	110V @ 10A
Cable Length (ft)	33	33
Field of View	25°x22°	14x11 in.

APPENDIX B

SHEAROGRAPHIC INSPECTION PROCEDURE
(FOR 737 DEMONSTRATION INSPECTION)

Date: June 3, 1991

SUBJECT: INSPECTION OF BOEING 737 FOR DISBONDING OF TEAR STRAPS, CIRCUMFERENTIAL BUTT SPLICES, AND SKIN LAP JOINTS

BACKGROUND

This document sets forth a procedure which may provide an improved alternative to the currently mandated inspections which are difficult and time consuming. It is designed to be carried out in such a manner that a comparison may be made and evaluated between the effectiveness of the existing inspections and the potential shearographic alternative.

REFERENCES

Boeing Service Bulletins 737-53A1039, 737-53-1036, and 737-53-1124.
FAA Airworthiness Directives 89-16-05 and 91-08-12.
737 Boeing Nondestructive Test Manual, Document D6-37239, Subjects 51-00-00, 51-10-2, 51-10-06, 53-30-00, 53-30-01 53-30-3, 53-30-4.

I PLANNING INFORMATION

The inspection may be carried out on any aircraft listed under "Effectivity" in the referenced service bulletins.

Description

The inspections for disbonding and delamination called out in the referenced Boeing service bulletins will be carried out in addition to the shearography inspections described herein.

Auxiliary air conditioning unit modified for switch actuated proportional pressurization will be installed to appropriate connection on aircraft.

A shearographic inspection will be performed on the following:

1. Bonded doublers above stringer 26 between Body Stations (BS) 259 and 1016.
2. Skin lap joints between (BS) 259 and 1016 left and right side.
3. Butt splices and major cutouts between (BS) 259 and 1016 left and right side.
4. Keel between (BS) 259 and 1016 left and right side.

Manpower: two operators

Estimated time for the shearographic inspection:
All bonded doublers 12 hours
All skin lap joints 8 hours
All butt splices and major cutouts 6 Hours

II ACCOMPLISHMENT INSTRUCTIONS

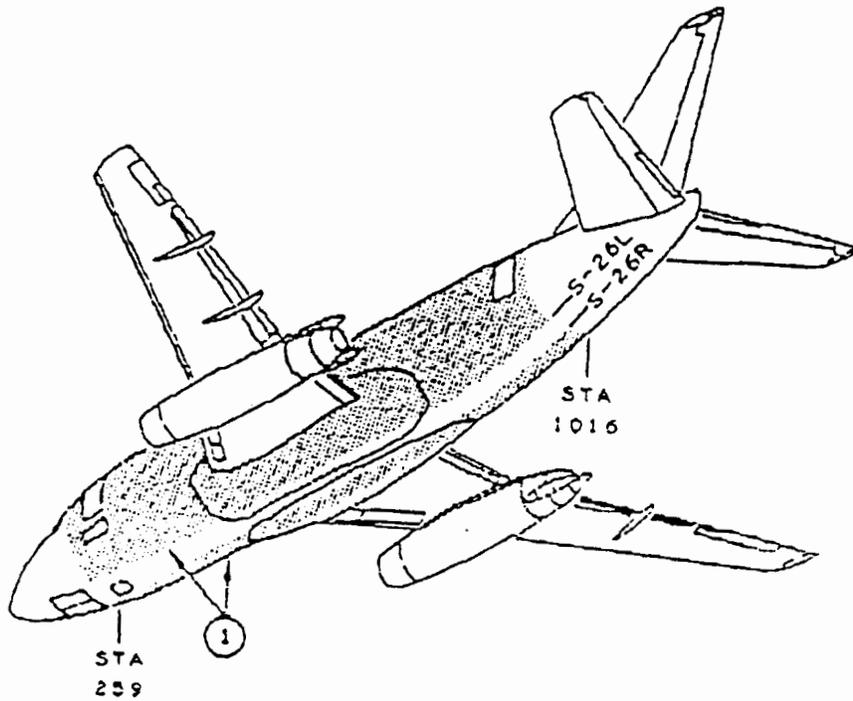
NOTES: 1. The following paragraphs outline the general accomplishment instructions. The suggested sequence of operations and detailed accomplishment instructions are indicated by circle notes on the figures.

2. On the figures, unless otherwise specified:

- All linear dimensions are in inches.
- Tolerance on linear dimensions other than rivet and bolt edge margin is ± 0.03 .
- Tolerance on rivet and bolt edge margin is ± 0.05 .

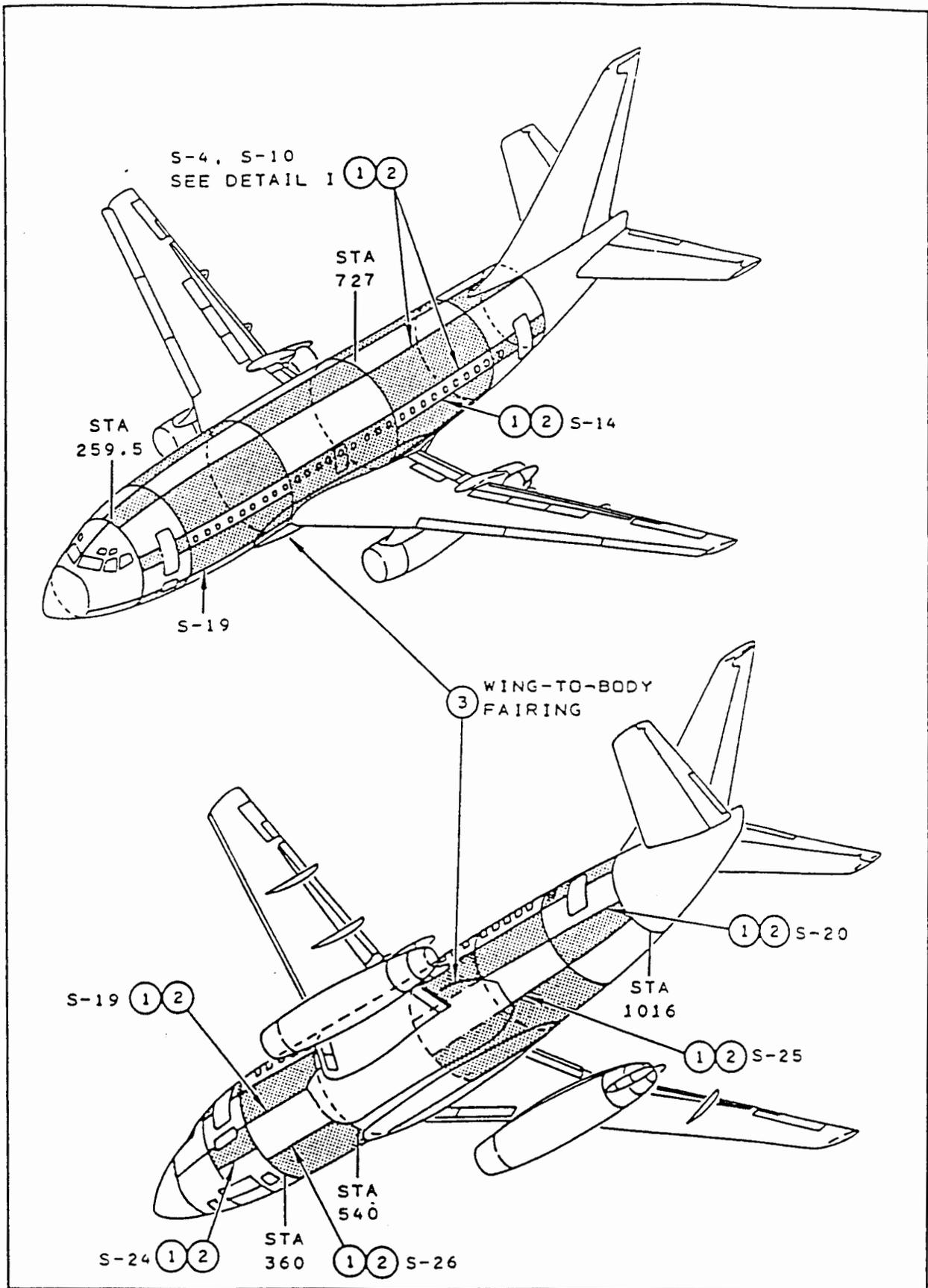
Inspection

1. Remove wing and body fairings on left and right sides. Retain attachment hardware for reattachment unless otherwise noted.
2. Install auxiliary air conditioning to unit modified for switch actuated proportional pressurization to appropriate connection on aircraft.
3. Perform an ultrasonic inspection of all tear strap doublers for disbonds.
4. Perform a close visual inspection of all skin lap joints and circumferential skin butt splices between (BS) 259 and 1016 left and right side.
5. Perform an ultrasonic inspection of all window belt doublers for disbonds.
6. Perform a shearographic inspection of the following:
 1. Bonded doublers above stringer 26 between Body Stations (BS) 259 and 1016.
 2. Skin lap joints between (BS) 259 and 1016 left and right side.
 3. Butt splices and major cutouts between (BS) 259 and 1016 left and right side.
 4. Keel between (BS) 259 and 1016 left and right side.



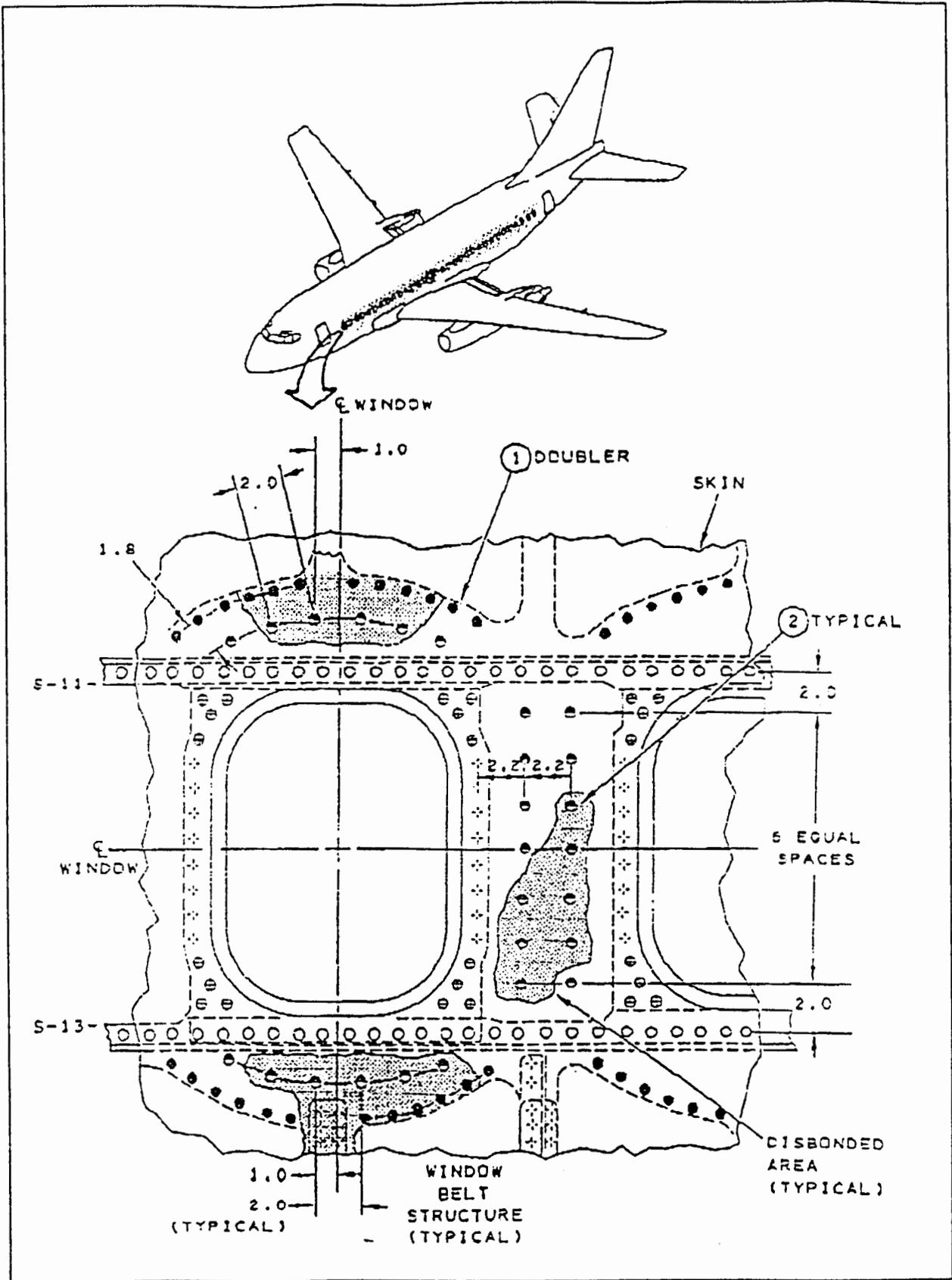
- 1 Conduct ultrasound inspection of tear straps above stringer 26 except window belt panels
- 1 Conduct shearographic inspection of tear straps above stringer 26 except window belt panels

Figure 1



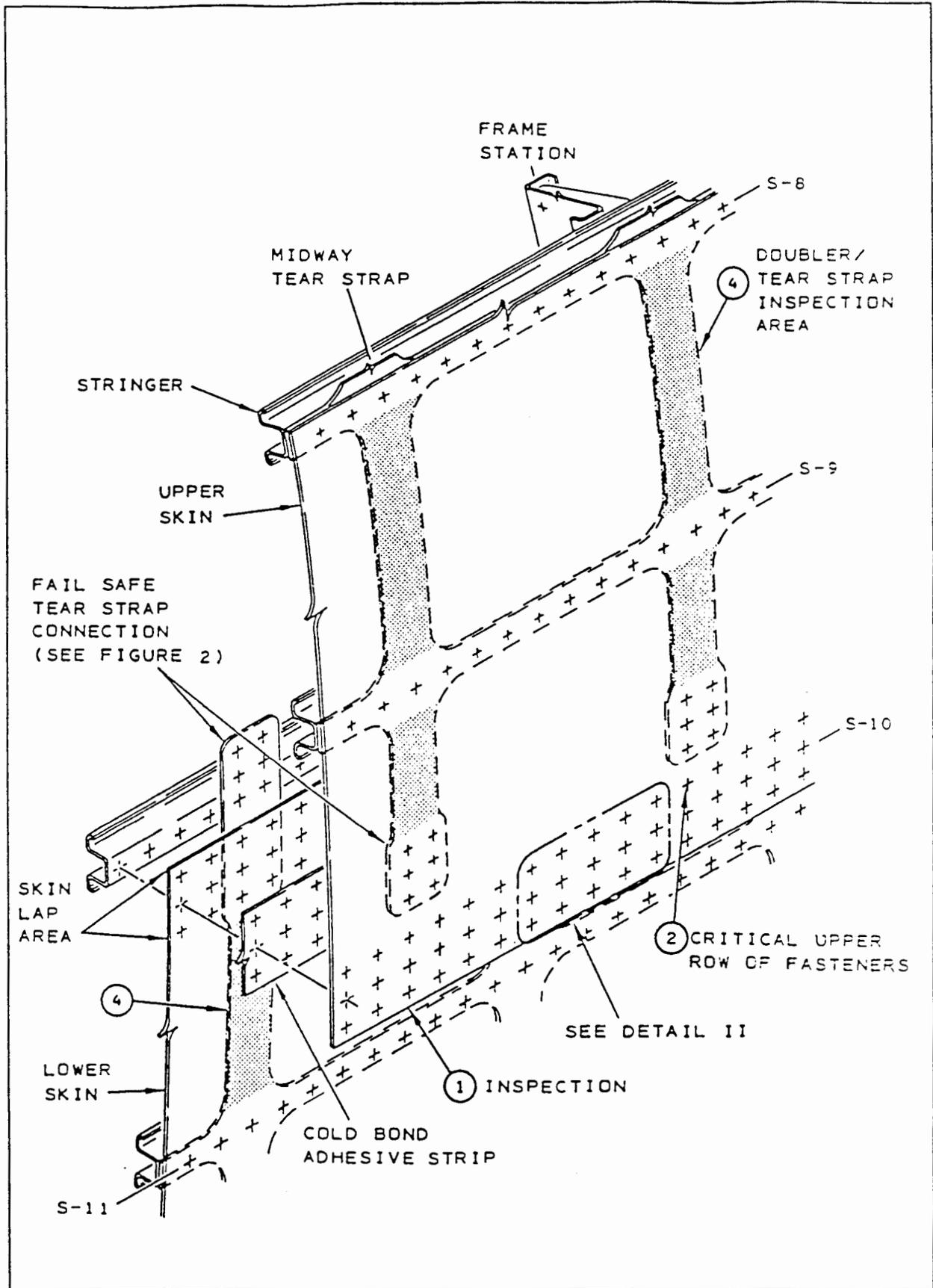
1 2 Lap Joint and Tear Strap inspection

Figure 2



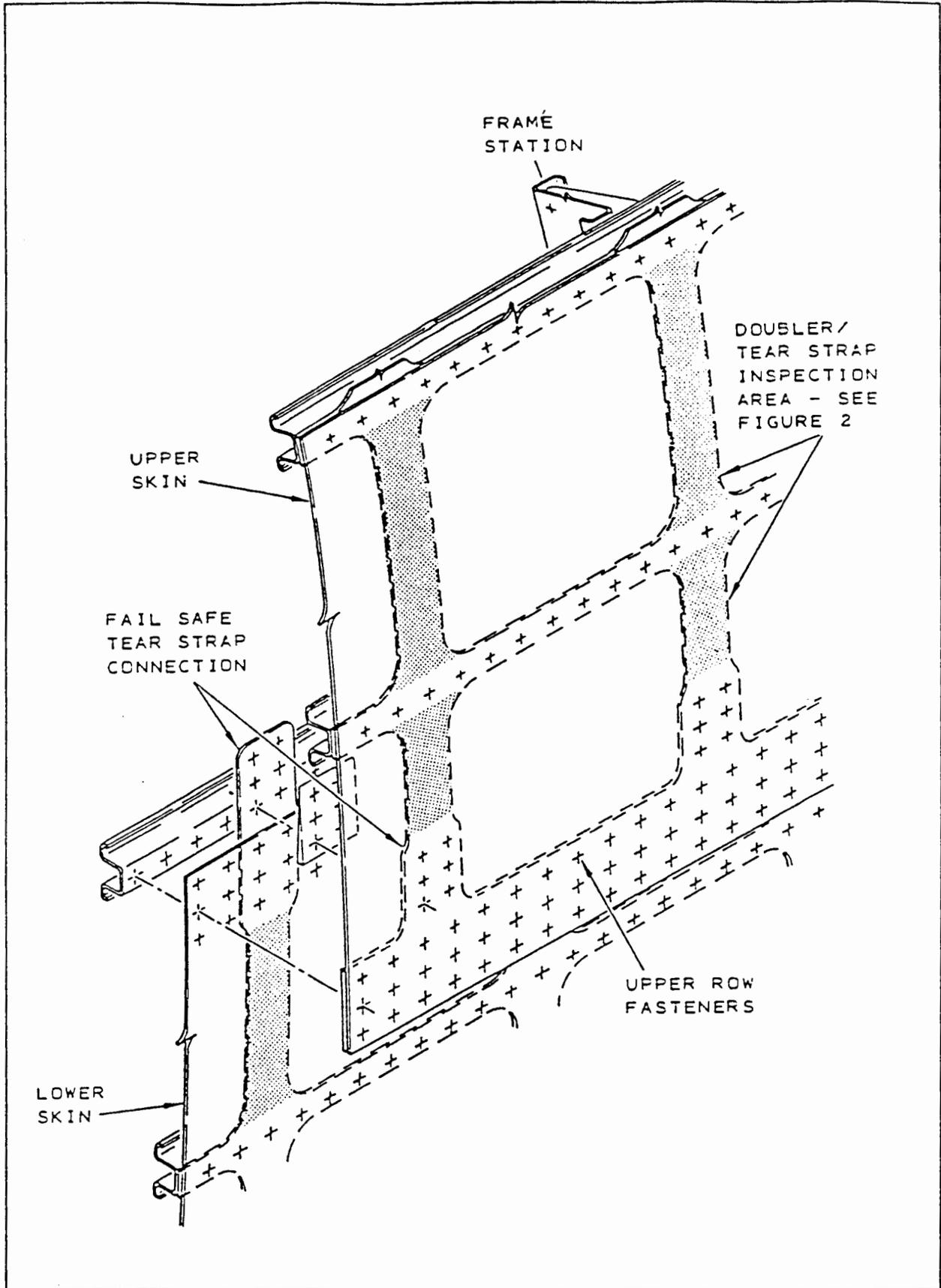
- 1 Conduct ultrasound inspection of window belt panels
- 1 Conduct shearographic inspection of window belt panels

Figure 3



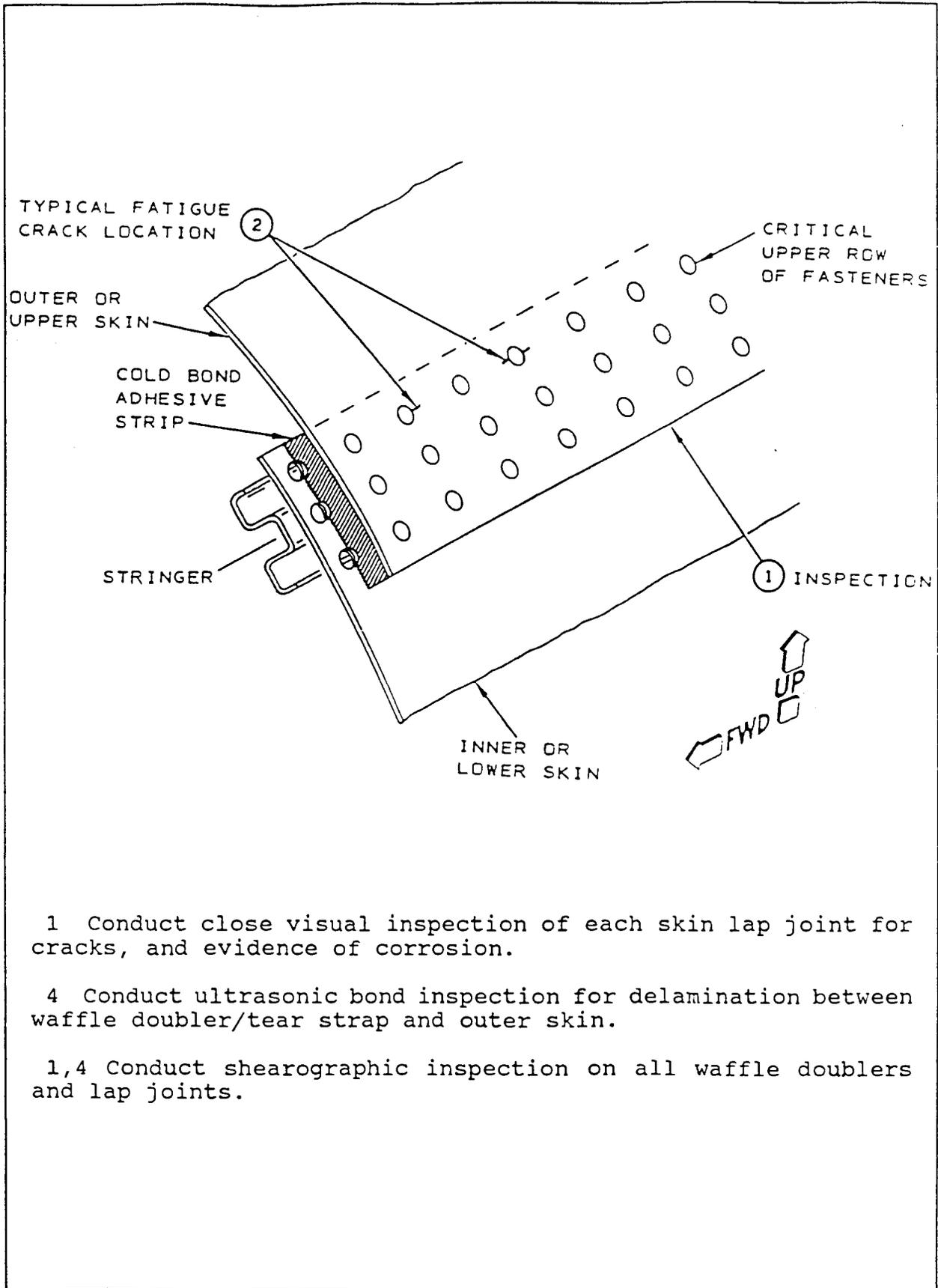
Lap Joint and Tear Strap inspection, Detail 1, Group 1.

Figure 4



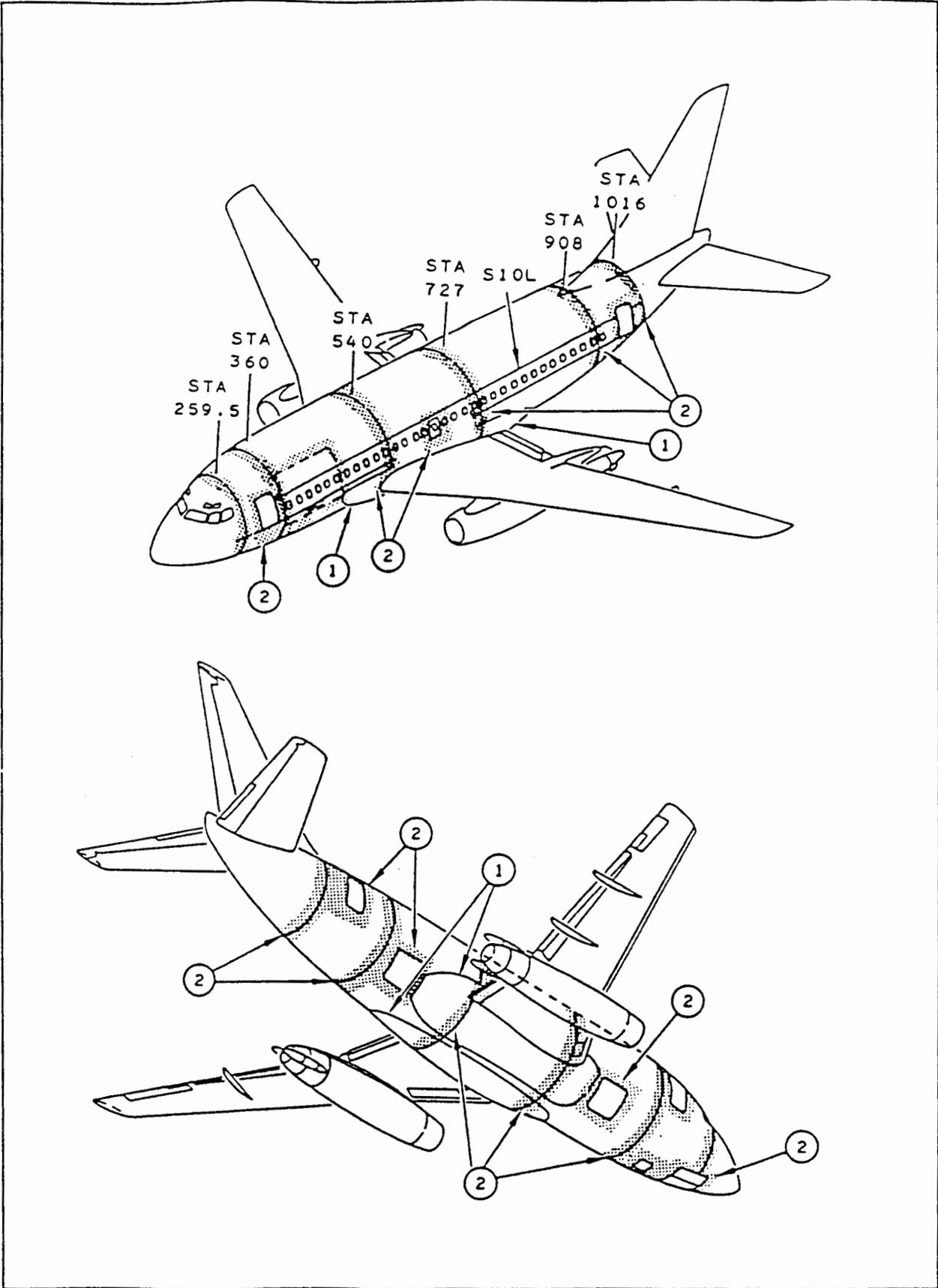
Lap Joint and Tear Strap inspection, Detail 1, Group 2.

Figure 5



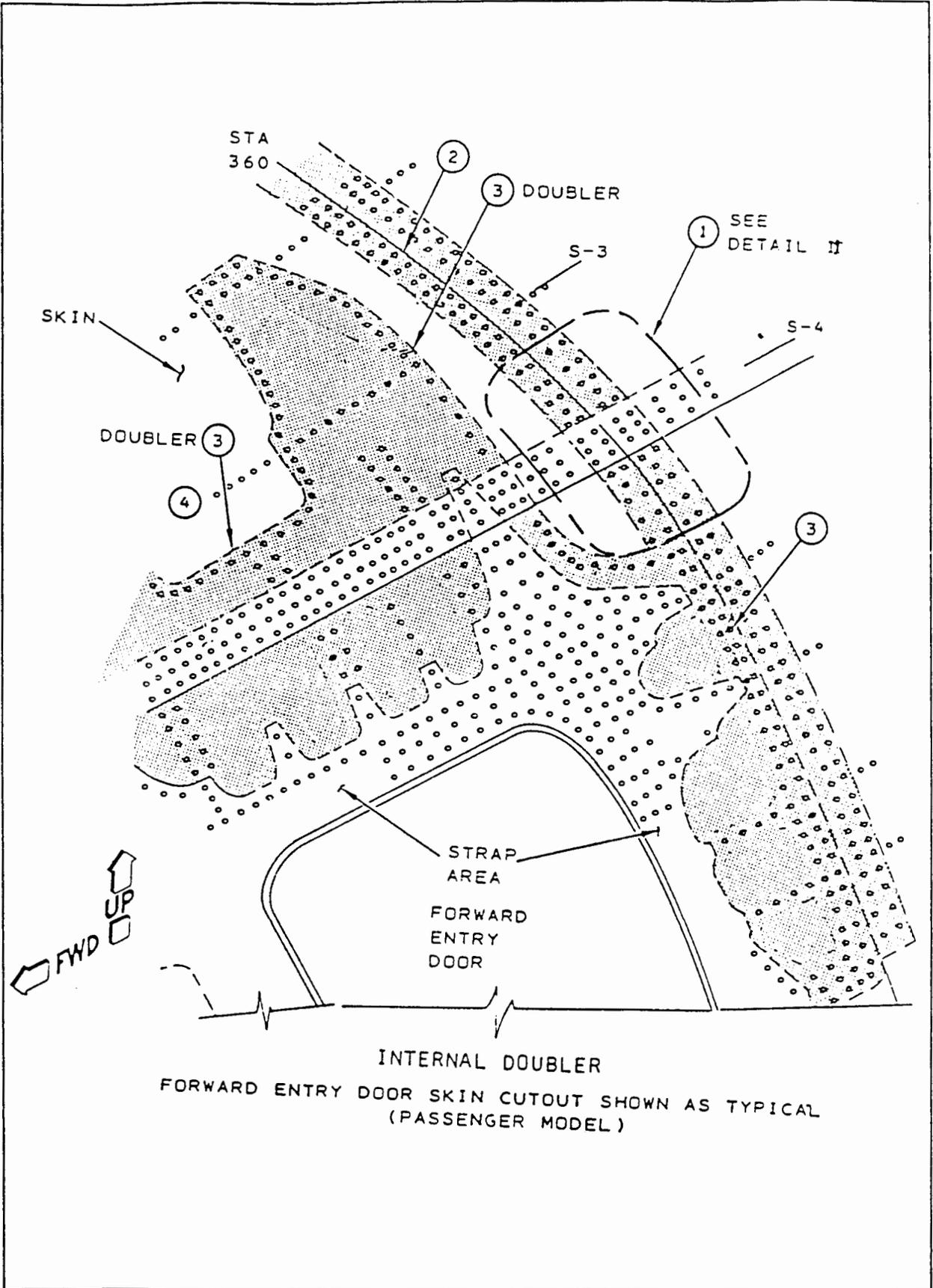
Lap Joint and Tear Strap inspection, Detail 2.

Figure 6



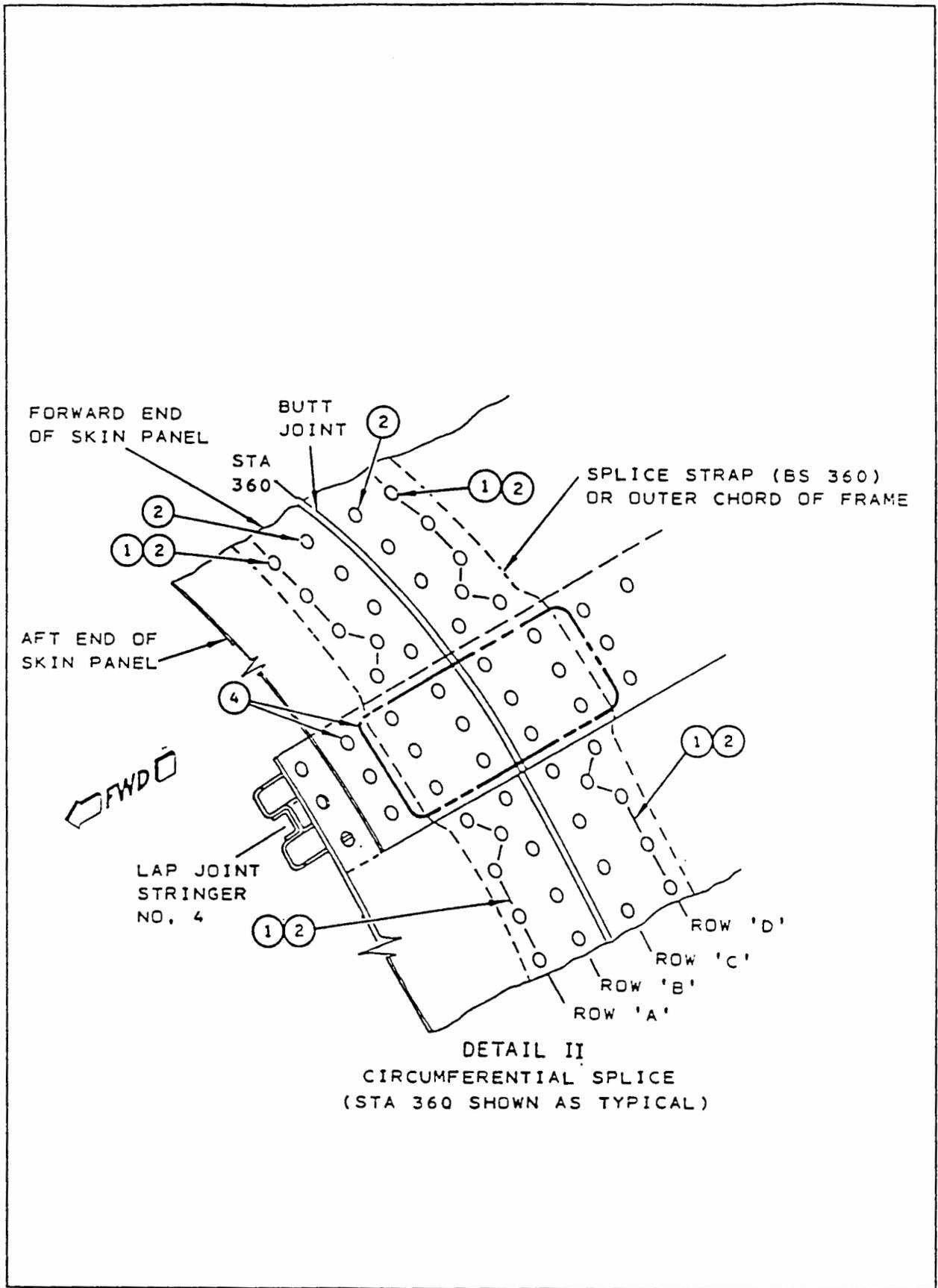
Butt splice inspection, General

Figure 7



Butt splice inspection, Detail 1

Figure 8

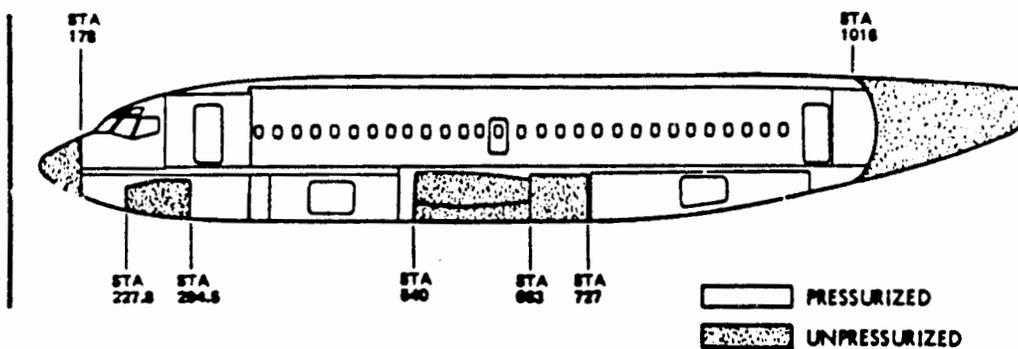


Butt splice inspection, Detail 2

Figure 9

APPENDIX C
BOEING STRUCTURAL REPAIR MANUAL, SELECTED PAGES

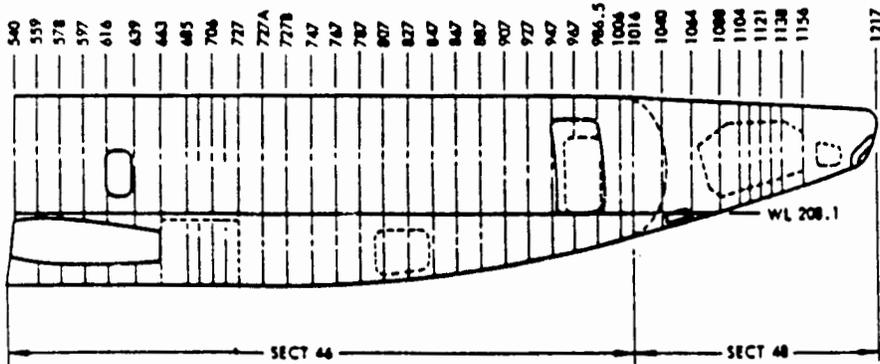
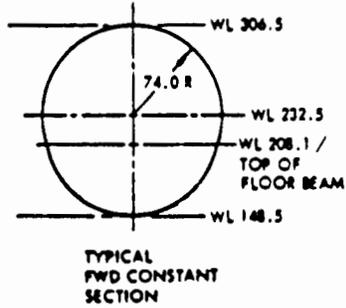
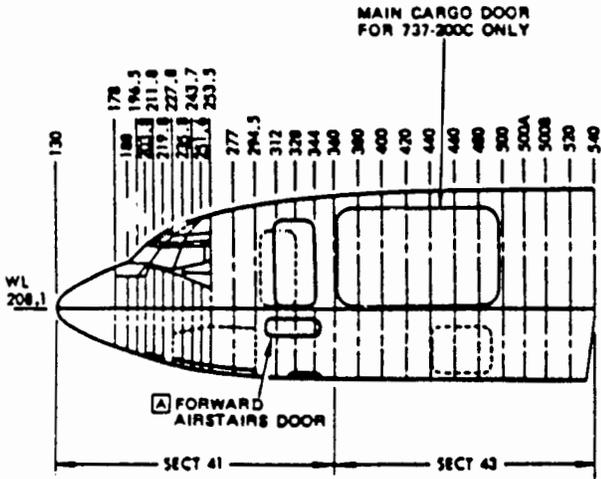
737 **BOEING**
STRUCTURAL REPAIR



737 SRM
Aug 1/74

Pressurized Region Diagram
Figure 1

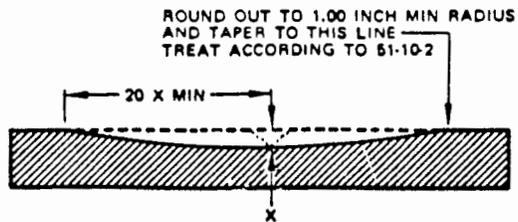
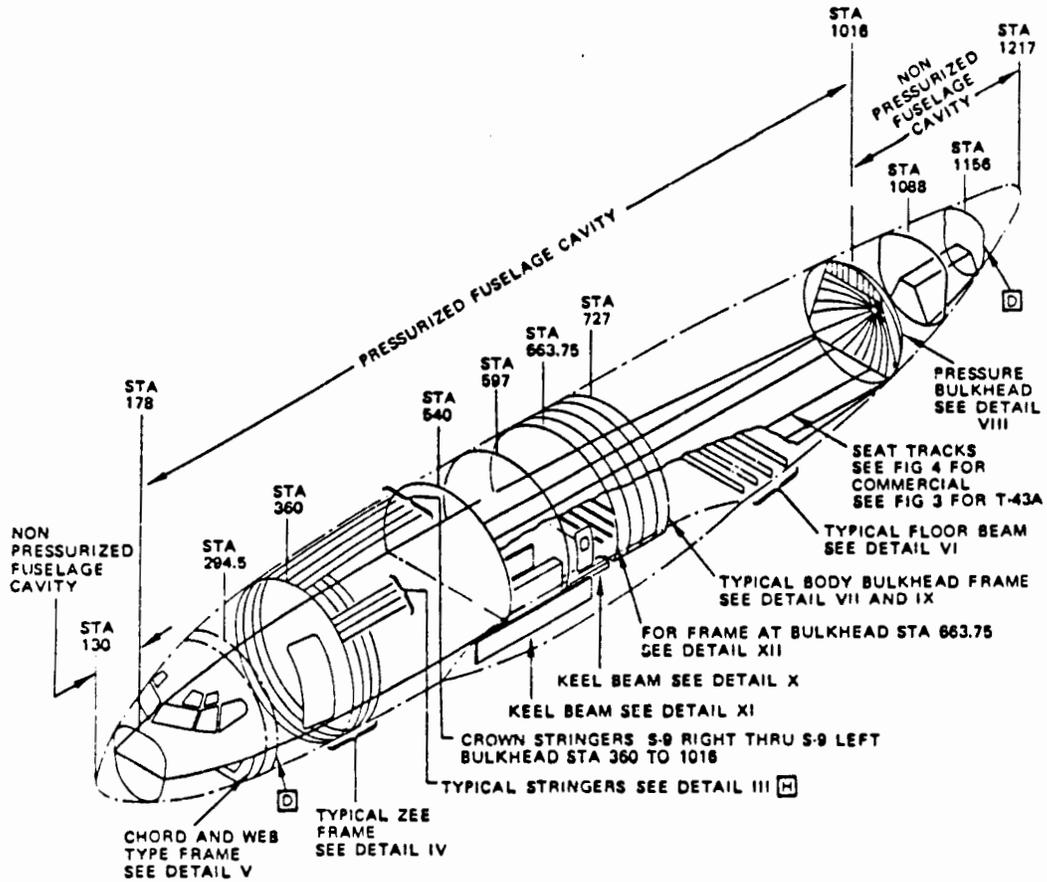
53-00-2
Page 1



△ FORWARD AIRSTAIRS AND FORWARD AIRSTAIRS DOOR ARE NOT INCLUDED IN CUM LINE NUMBERS
 726, 727, 734, 745, 754, 768, 782, 798, 788,
 770, 778, 780, 781, 786, 788, 791, 792, 794,
 796, 798

Fuselage Station Diagram - 737-200, 737-200C
 Figure 2 (Sheet 1)

BOEING
737 
STRUCTURAL REPAIR

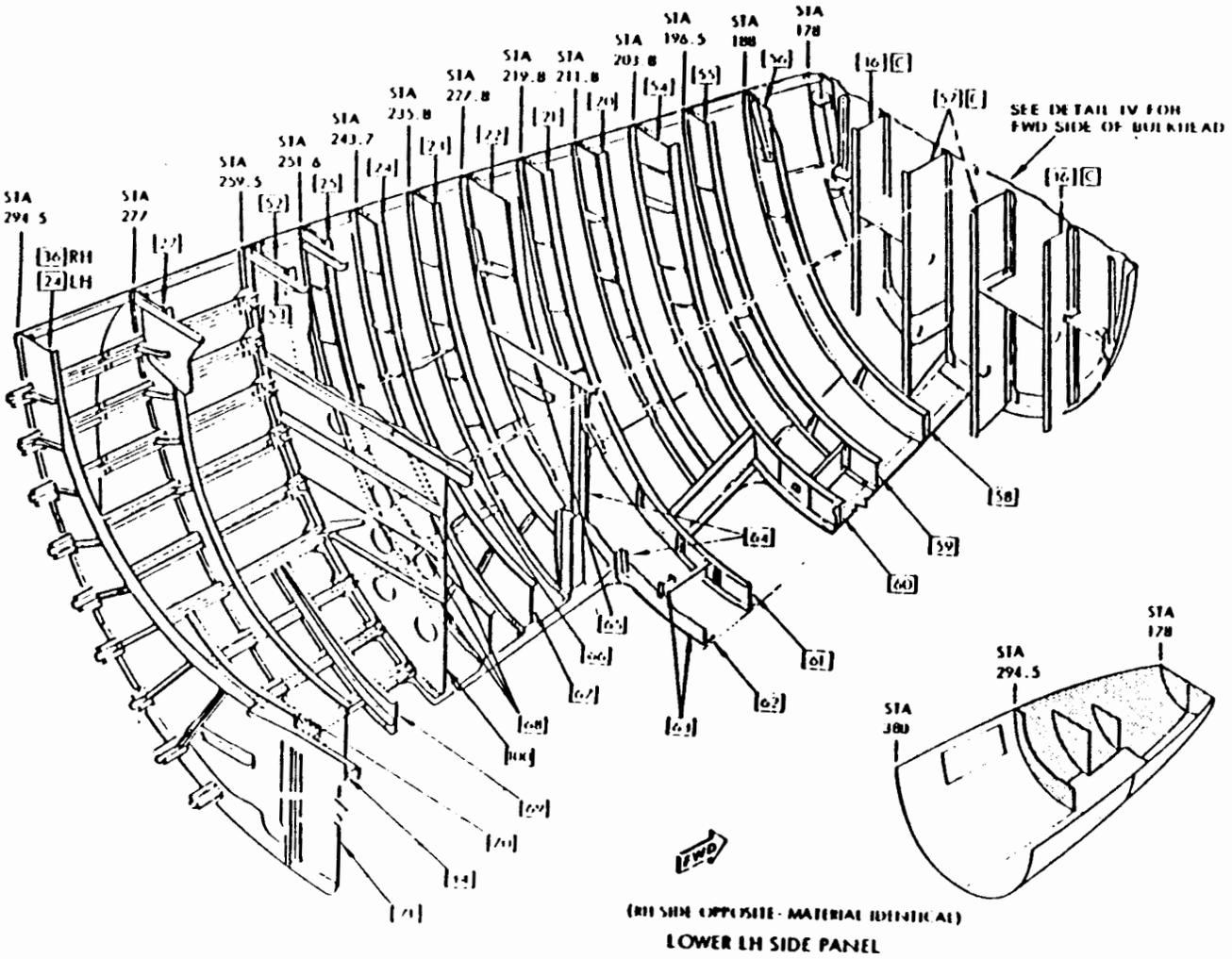


SECTION THROUGH DAMAGE
 DETAIL I

Allowable Damage - Main Frame
 Figure 1 (Sheet 3)

SRM CMN
 Feb 1/84

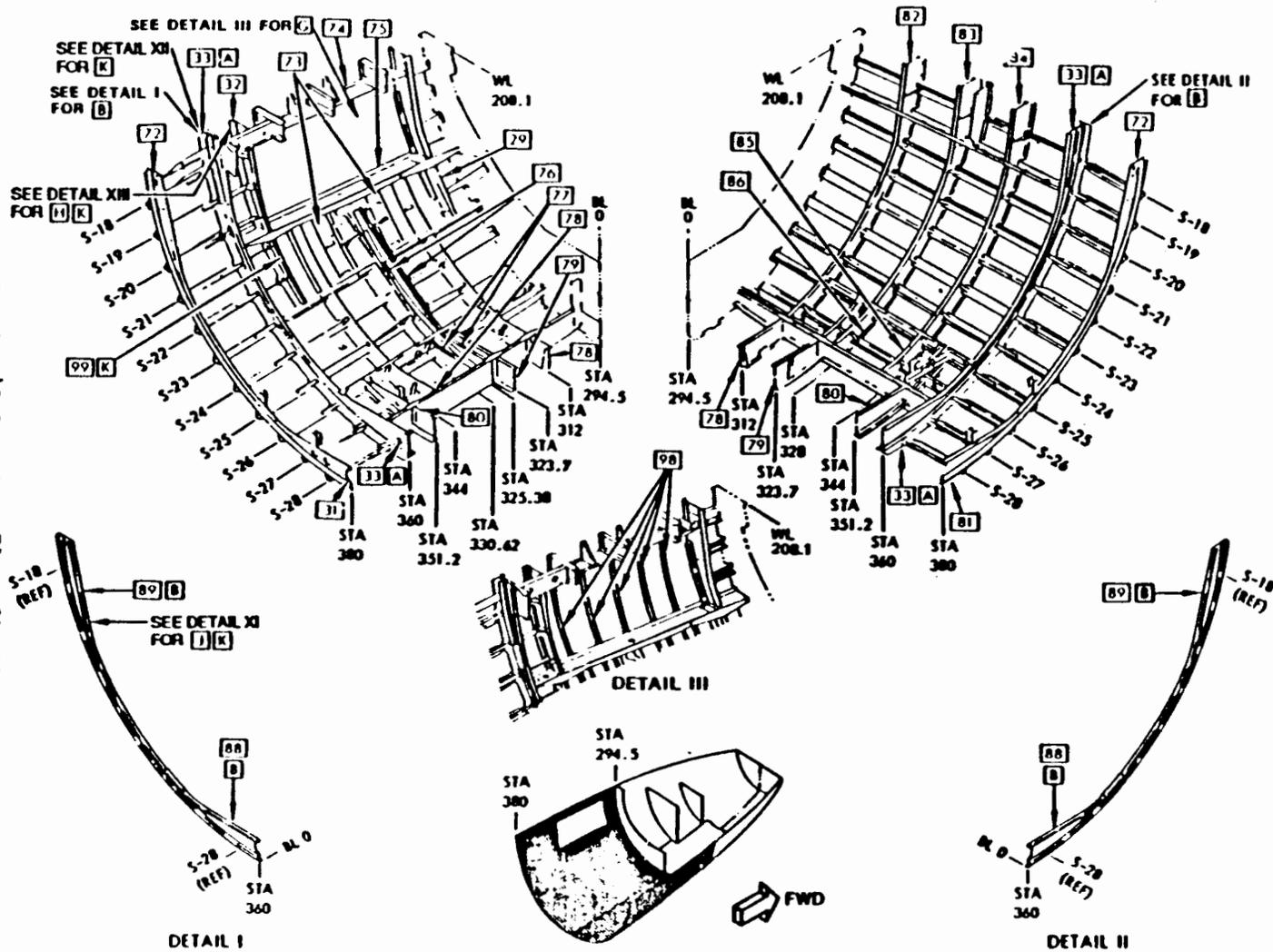
53-10-1
 Page 3



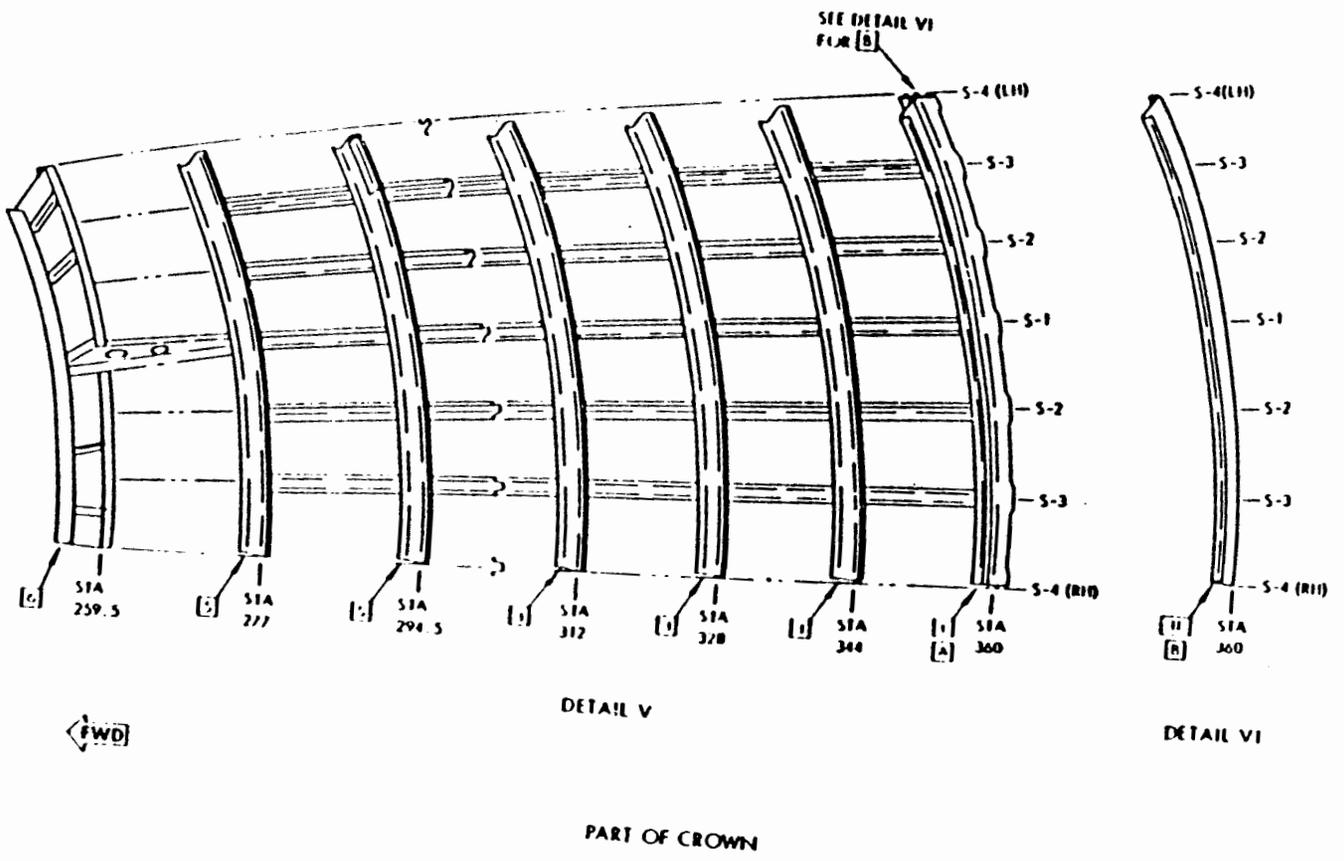
Section 41 Structure Identification
Figure 1 (Sheet 10)

737 SRM
Feb 5/90

Section k1 Structure Identification
Figure 1 (Sheet 11)



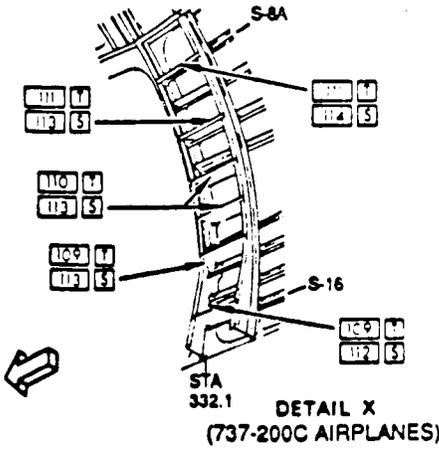
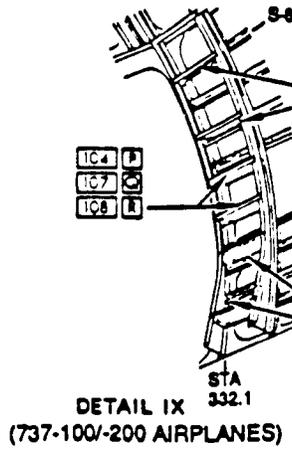
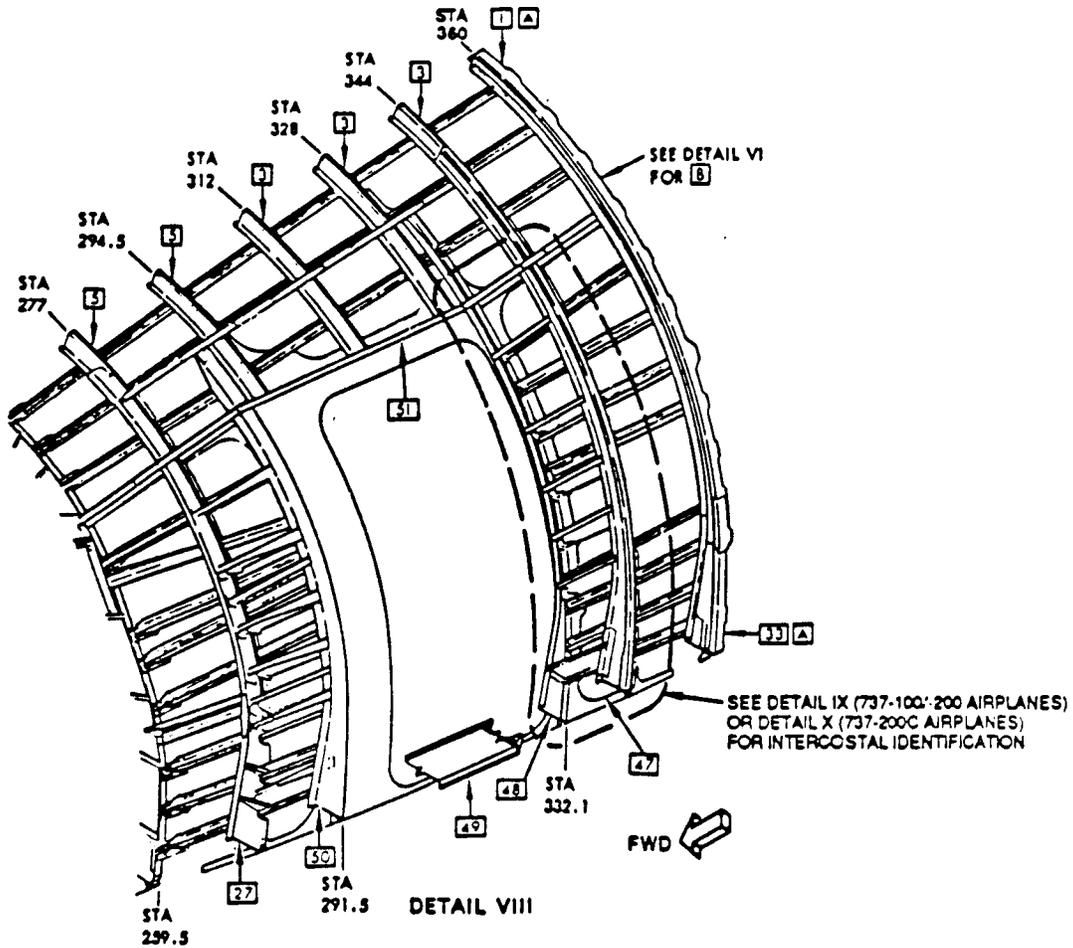
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Section 41 Structure Identification
 Figure 1 (Sheet 13)

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Section 41 Structure Identification
 Figure 1 (Sheet 15)

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