NATIONAL TRANSPORTATION SAFETY BOARD
Office of Research and Engineering
Materials Laboratory Division
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Report No. 99-74

SEQUENCING GROUP STUDY
ON EXPLOSION OF CENTER WING FUEL TANK OF A TEST AIRPLANE

A. RELATED ACCIDENT

Place	:	East Moriches, New York
Date	:	July 17, 1996
Vehicle	:	Boeing 747-131, N93119
NTSB No.	:	DCA96-M-A070
IIC	:	Al Dickinson, AS-10

B. COMPONENTS EXAMINED

Wing center section and associated fuselage structure from a test airplane in Bruntingthorpe, United Kingdom.

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D. DETAILS OF THE EXAMINATION

1.0 TEST INTRODUCTION AND BACKGROUND

Between July 28 and August 2, 1997 a series of tests were carried out in Bruntingthorpe, England on an out-of-service 747 in support of the ongoing investigation into the crash of TWA Flight 800. The test discussed in this report involved the ignition and explosion of a propane/air mixture in the center wing fuel tank. The tests were carried out under the direction of the NTSB with the direct assistance of the Defense Evaluation and Research Agency (DERA) and Federal Bureau of Investigation (FBI). The documentation of the damage patterns after the explosion of the fuel/air mixture in the center wing fuel tank was conducted as a group activity with technical representatives from some of the parties to the TWA Flight 800 investigation. Additional technical support was provided by Boeing to assist in setting up the airplane for testing.

Group members were as follows: Al Dickinson, Deepak Joshi, and Jim Wildey from NTSB, Warren Steyaert and Jack Winchester from Boeing, Dennis Santiago from the International Association of Machinists, Dan Rephlo from TWA, and Steve Green from the Air Line Pilots Association. This report has been reviewed by the group members and represents a consensus of the participants.

2.0 TEST AIRPLANE DESCRIPTION

2.1 In-service Background

The test airplane was a Boeing 747-100 in a basic passenger configuration. The airplane was production line number 105 and available records indicate that the airframe had experienced 19,333 flights and 75,391 flight hours. The primary structural configuration of the Wing Center Section (WCS) of the test airplane was similar to the TWA Flight 800 Boeing 747-100 as discussed below. During the time period that the test airplane was built, a 7178 aluminum alloy was used for the side of body web. This was a different material than on the TWA Flight 800 airplane, which had a 7075 aluminum alloy. The water injection system on the test airplane had been deactivated and the water bladders had been removed from the forward dry bay between the front spar and spanwise beam #3. Unlike the TWA airplane, portions of the original water injection system installation structure remained installed. These included plumbing and systems support brackets. Two intercostals that span between spanwise beam #3 and the front spar were cut and bent out of the way. Cursory visual examination of the WCS showed no obvious evidence of structural damage from fatigue or corrosion.

During filling of the #2 main fuel tank with water during test preparation, minor seepage of water occurred between the vertical flange of the left lower side of body rib chord and rib web in the bay between spanwise beam #2 and the midspar.

2.2 Status/Damage Following Earlier Tests

Portions of the structure had been damaged and other modifications had been made to accomplish prior testing. These portions of damaged structure and modifications are noted in order to subsequently assess the potential impacts to the results of the current test.

During earlier tests, explosive charges significantly damaged the aft fuselage. The damaged portion of the fuselage aft of the STA[1] 1480 bulkhead was removed. The remaining portion of the STA 1480 bulkhead was structurally damaged and was not fully attached to the adjoining fuselage. The body landing gear remained attached to the STA 1480 bulkhead.

There was no apparent visual damage to the floor support structure immediately forward of the front spar although the floor panels were removed on both sides of the airplane between BL 33 to 75, from STA 1000 to 820.

Since earlier testing damaged the forward cargo door, it could not be closed or latched. For the test involving the propane/air explosion, the door was restrained in a near-closed position by a tether to floor beam structure. Overpressure venting into the forward cargo compartment during the propane/air explosion test resulted in failure of the floor structure that was used to secure (by tether) the cargo door. The door was then free to open and vent the overpressure from the compartment.

There were no seats forward of the WCS front spar, and the remaining floor panels forward of STA 820 in this area were attached to the floor beams and seat tracks.

There were no cargo containers in the forward cargo compartment. This could have affected the way the pressure vented from the WCS and the possible interaction of the vented pressure with the structure in the forward fuselage.

2.3 Status/Damage during Preparation for Center Fuel Tank Explosion Testing

During preparation for the explosion testing of the center fuel tank, portions of the floor structure were modified for test hardware and instrumentation.

[1] STA refers to fuselage station, which is measured in inches from a zero datum point near the nose of the airplane.

All of the floor panels over the top of the WCS from just aft of STA 980 (front spar) to STA 1241 (aft of the rear spar) were cut out and removed from between the longitudinal floor beams.

In the region of the environmental control system duct penetrations through the Left Buttock Line (LBL) and Right Buttock Line (RBL) 57.5 longitudinal floor beams, the upper chord and portion of floor beam web was cut through and the upper portion of the floor beam was removed. This resulted in a portion of floor beam from STA 1120 to STA 1177 that did not have a full depth floor beam supporting the wing upper panel.

The spar mounted fuel pumps and valves were removed from both the WCS rear spar and the outboard wing front and rear spars. The majority of the fuel system plumbing within the wing center section was disconnected. The vent tubing elbow with the dive valve (float valve) that connects to the WCS vent stringers was disconnected so that the vent stringers were open to the WCS interior.

In order to make it easier to reconstruct the wing center section components after the fuel/air explosion, lines of different colors were painted on each of the internal spanwise beams, the rear spar, the front spar, and the side of body ribs.

3.0 TEST SET-UP DESCRIPTION

3.1 AIRCRAFT WEIGHT AND BALANCE

Since the TWA Flight 800 event occurred during flight, the stresses in the WCS of the accident airplane were associated with approximately 1 g flight loads. In order to partially represent those loads for this test, the inboard main tanks were each filled with 47,000 pounds of water (total of 94,000 pounds in the airplane). This was approximately 6,000 gallons in each of the #2 and #3 main tanks. This water weight was greater than the fuel weight in the inboard main tanks on TWA800, and the extra weight increased the side-of-body wing bending moment. The total weight of the test airplane was estimated at 236,000 pounds.

In addition, the two potable water tanks on the front spar were filled with 1000 pounds of water. This provided inertial restraint if the front spar failed forward.

There were 10 sets of 3 seats over the WCS. These seats were filled with about 176 pounds of sandbags in each seat to represent passengers. This represents about 1/3 the passenger loading for TWA Flight 800, and as such would not provide a similar inertial restraint for upper panel of the WCS. All but two sets of seats were located in the outside rows resulting in relatively little mass over the mid portion of the WCS.

There were no cargo containers in the forward cargo bin, no aft curtain, few ceiling panels, and few sidewall panels.

There were no sidewall panels, ceilings, carpet, seats (other than those documented), or overhead bins on the main deck and the upper deck. Some of the insulation over the WCS was missing. The cockpit door was missing. Some or all main deck entry doors were open or not attached to the aircraft. Some lavatories and galleys were not in the TWA Flight 800 configuration or were not installed. Some windows were missing.

3.2 AIRCRAFT SUPPORT

The aircraft was supported on wooden towers built directly inboard of each nacelle. Each tower was constructed of timbers 5 inches by 10 inches by 8 feet long stacked in a square approximately 8 feet square. The inboard tower was centered at approximately wing station 614 and the outboard tower was centered at approximately wing station 1000. The primary support interface of each tower with the wing was made by setting the last timber parallel with and directly under the front and mid spars. The load distribution between inboard and outboard supports could not be determined.

Jacking of the aircraft was accomplished by filling the wing gear struts with pressurized nitrogen. The maximum height measured, per the strut placard, was 29 inches. After the towers were in place, the struts were depressurized and the final height measured, per the strut placard, was 19.5 inches. The gears were then chocked to prevent the aircraft from rolling backward.

With the aft half of the airplane missing, the load on the nose gear was disproportionately high, estimated at 64,000 pounds. This condition induced loads in the body, including the keel beam structure, which were not representative of an actual flight condition. A tower was constructed to catch the airplane if the nose gear collapsed during the test. A gap of approximately 6 inches was left between the tower and the airplane.

An additional tower was constructed under the keel beam at STA 1480. If the wings failed, the body would drop approximately 18 inches to this tower. This would allow the failure sequence to be completed but minimize the collateral damage that would occur due to a large drop and would allow for easier inspection of the lower surfaces.

With the wing supported by the towers and with 94,000 pounds of water in the main fuel tanks, the bending moment at the side of body approached 50 percent of the 1 g loading relative to the TWA Flight 800 event. In order to reach a more representative loading, it would have been necessary to apply additional jacking to the wing and balancing restraint to the fuselage. This was judged not to be practical under the circumstances.

3.3 Instrumentation

Pressure transducers were installed in each cell of the center wing fuel tank. In order to support some of the sensors in the tank, cables were strung between the upper and lower panels. There were several cables in each bay of the tank and they may have slightly affected the failure sequence.

4.0 EVALUATION OF CENTER WING FUEL TANK EXPLOSION TRIAL DAMAGE

4.1 General Post-Test Description

On August 2, 1997, a propane/air vapor mixture was ignited in the right rear compartment of the wing center section of the previously described test airplane. The explosion produced significant damage to the airplane including ejecting parts from the airplane through the top of the fuselage. Large portions of the wing center section were fractured, disrupting wing and body continuity, and allowing portions of the wing center section and adjoining structure to be distributed throughout and around the aircraft. Many pieces of structure, interiors, systems, etc. were piled on top of the wing center section lower skin panel. No evidence of soot accumulation or fire damage was noted in the wing center section.

Subsequent to the explosion of the center wing fuel tank, an evaluation was made regarding the stability of the aircraft and shoring was put in place under the fuselage forward of the wing center section. The remaining structure was also reviewed for stability to allow personnel to gain access. After the airplane was stabilized, parts were removed from the wing center section cavity, forward cargo hold, main deck, and on the ground around the airplane. The major pieces of the center section were laid out on the ground for reconstruction. A comprehensive photo record was also generated. Appendix A contains sketches of the fracture patterns and appendix B photographs of the structure.

4.2 Damage Evaluation by Subcomponent

4.2.1 Wing Center Section Upper Skin Panel

The upper panel of the WCS was broken into approximately 35-40 pieces ranging in size from less than one square foot to one large piece that extended almost to each side of body rib and from spanwise beam No. 1 (SWB1) to the rear spar.

The majority of the upper panel separated from the WCS with the following exceptions:

1. LBL 75 to LSOB[2], SWB2 to midspar
2. LBL 86 to LSOB, SWB1 to rear spar
3. RBL 98 to RSOB, SWB3 to midspar
4. RBL75 to RSOB, just aft of the midspar to SWB1
5. RBL 98 to RSOB, just aft of front spar to SWB3

Other smaller pieces of upper panel remained attached to the double plus chord in local areas. The outboard 12 to 24 inches of most of the upper stringers remained attached to the splice fittings at both side of body double plus chords. The one major exception was at the right side of body, from SWB1 to the rear spar. In this region, the skin flange of the double plus chord was no longer attached. The fastener hole elongation in the lower horizontal flange of the double plus chord indicated upward movement of the upper skin panel relative to the right side of body rib. A large portion of the stringer remnants and stringer end splice fittings on the right side (primarily aft of SWB2) showed either bolt/hole failures at the stringer to end fitting connection or at the end fitting connection to the double plus chord. All of the stringer end fittings on the left side remained attached to the double plus chord. The left hand stringer remnants (primarily aft of the midspar) remained relatively straight from the side of body and some of the fasteners attaching the stringer end splice fittings sheared at the lower horizontal flange.

The majority of the skin flange of the rear spar upper chord remained attached to the upper skin panel. The skin panel fractured through the rivet line at SWB1. Most of the fasteners that attached the SWB1 upper chord to the skin remained intact in the SWB1 upper chord. The majority of the midspar upper chord skin flange remained attached to the skin panel. Portions of 6 out of 10 tension fittings common to the floor beams remained attached on the upper side of the panel. Only 3 out of 10 tension fittings on the lower side of the panel remained attached to the skin.

Short intermittent portions of the SWB2 upper chord skin flange remained attached to the skin with 8 of the 10 floor beam tension fittings remaining attached on the upper surface of the skin panel while 7 of the 10 fittings on the underside of the panel remained attached to the skin.

Most of the SWB3 upper chord skin flange remained attached to the skin with 8 of the 10 floor beam tension fittings remaining attached to the upper surface of the skin panel while 6 of the 10 remained attached to the underside of the panel.

The majority of the front spar upper chord skin flange remained attached to the upper panel. Only some skin flange portions of 15 upper shear ties at stiffener locations remained attached. Where the skin to shear tie fastener remained in the

[2] LSOB refers to the left side of body rib. RSOB refers to the right side of body rib.

hole, some fasteners showed mainly residual forward deformation, but there were instances of no deformation forward or aft.

Little forward/aft residual deformation was found on the skin panel pieces. Residual spanwise curvature tended to be primarily on larger pieces. At least one piece had residual deformation with the inboard and outboard ends bent up relative to the center. Smaller pieces tended to have less deformation. Fractures on inboard and outboard edges did not tend to be on specific BL locations, did not have high radius of curvature compressive fractures, and were more consistent with bending type fractures.

Only short segments of full height stringers remained on the skin panel, and some skin flange portions of the stringers remained on the panel primarily toward the forward end of the upper panel. Most of the stringer to skin panel attachments toward the aft end of the WCS upper panel exhibited rivet shear failures. Generally, only the skin flange portion of the longitudinal floor beam lower chords remained attached to the skin panel with the rest of the floor beam separated.

Three panel crack/fracture lines propagated through the pre-existing holes generated at LBL110, S-9 to S-10. Cracks/skin fractures also propagated through the pre-existing hole generated at LBL 85, S-4 to S-5.

4.2.2 Wing Center Section Lower Skin Panel

The entire lower skin panel remained attached to the airplane along at least one edge but had internal fractures separating the lower panel into 3 major portions:

1. front spar to midspar, LSOB to RSOB
2. midspar to rear spar , LBL90 to RSOB with smaller piece from LBL9 to LBL50 just aft of midspar
3. S-7 to rear spar, LBL9 to LSOB

The forward portion of the panel (item 1, above) separated from the airplane at LSOB and at the front spar. The vertical flange of the midspar lower chord remained attached to the midspar, and the horizontal flange remained with the skin lower panel. The fracture between the skin segments at the midspar was primarily through failure of the skin flange of the lower chord to the right of the keel beam and through a combination of fastener failure and chord failure to the left of the keel beam. The lower chord of SWB2 was relatively intact from LBL57 to the RSOB, and the lower skin intercostals (lower beams) from RBL33 to RSOB were still partially attached to what remained of SWB2 and the lower stringers. The lower chord of SWB3, including some web, remained on the lower skin from LSOB to LBL15, skin flange only from LBL15 to RBL 57, and both flanges of chord from RBL57 to the RSOB. The skin flange of the front spar lower chord remained attached over the entire length.

The SWB1 lower chord remained attached to the lower panel and large portions of the beam remain partially attached on the right side on portion 2 of the lower skin panel.

The lower stringers on the forward portion of the panel were generally not fractured. Eight of the stringers that were riveted to the skin panel (in lieu of bolts) separated from the skin as a result of fastener shear over the majority of the stringer length.

From S-15 to S-21, the panel showed fairly constant spanwise radius of curvature from the LSOB to RSOB with the middle of the panel bowed down. Forward of S-21, the panel also showed inboard/outboard curvature but had an area locally above the keel beam that was sharply bent upward at the forward edge with a crease in the panel at S-21 from RBL21 to LBL12. The locally bent up area extended from LBL35 to RBL55 and was centered about the keel beam. Aft of S-15, the panel was bowed down on both left and right sides near LBL and RBL 60 with reversing curvature over the top of the keel beam (as if the panel had been draped over the keel beam). Aft of SWB1, the panel showed less curvature.

No cracks or skin failures originated or propagated through the pre-existing holes generated in the lower panel at either the LBL78, S-3 to S-4 location, or at the RBL65, S-10 to S-11 location.

The lower panel failed at the left side of body from the front spar to the midspar through a combination of tension/bending fracture of the skin, shear fracture of the side of body lower panel splice bolts, and shear pull-out of the lower side of body splice plate.

4.2.3 LEFT SIDE OF BODY RIB (LSOB)

The LSOB remained intact from the midspar to the rear spar. There was a web crack starting from the lower chord running up and aft approximately fourteen inches to the midspar attach stiffener. It ran up through the forward fastener holes and ran forward at about twenty inches below the upper chord at a 45 degree angle to the upper edge of the web. Fasteners common to the upper web and double plus chord aft of SWB2 failed in combined tension and shear. From SWB2 to the front spar, the double plus chord attach flange was fractured. The lower chord of LSOB was undamaged. The LSOB web between the midspar to the front spar was generally displaced outboard approximately three inches along the cracked edge only. There was also outward bowing of the web indicative of an outward acting overpressure. The web and stiffeners between SWB2 and the front spar were generally straight. The midspar web attach flange was separated approximately ten inches above the lower edge. The SWB2 web attach flange remained attached from the bottom to approximately 25 inches below the upper end. It had a distinct buckling wave also consistent with crippling due to an outward acting overpressure. The SWB3 web attach flange fractured from top to bottom. The SWB1 web attach flange remained intact. Sections of front spar, midspar, SWB1, and rear spar remained attached to the LSOB.

4.2.4 RIGHT SIDE OF BODY RIB (RSOB)

The RSOB remained intact from the rear spar to the midspar. The lower chord vertical flange from the midspar to the front spar was cracked in the radius and remained attached to the RSOB (the skin was bowed down approximately twelve inches at SWB3). There was a web crack that ran vertically between twelve to sixteen inches aft of the front spar from six inches above the lower edge of the web to twenty-four inches below the upper edge of the web, intersecting another crack from the front spar aft and up to the SWB3 upper chord. The double plus chord web attach flange radius contained a crack that ran aft to approximately fourteen inches aft of SWB2.

The SWB3 web attach flange fractured from top to bottom. Portions of the front spar, SWB2, midspar, SWB1, and rear spar remained attached to the RSOB. The web from SWB3 to the midspar contained evidence of outward bowing with fairly constant curvature consistent with outward acting overpressure.

4.2.5 REAR SPAR

Rear Spar Sections That Remained Attached to the Airplane

A three foot section from LSOB to LBL 98 of the rear spar remained attached to the LSOB (it included the pickle fork fitting). The lower end of this section was bent aft to a maximum of approximately four inches at the inboard end. A five-inch portion of this web at the inboard end was curled aft.

A four foot section (RSOB to RBL 85) of the rear spar remained attached to the RSOB (it included the pickle fork fitting). The inboard end of this section at the lower chord exhibited no evidence of bending, and a portion of the inboard edge of the web was bowed and bent slightly aft.

Rear Spar Sections that were not Attached to the Airplane

A large section from LBL 11 to RBL 85 and from the lower chord to the upper chord remained partially in the tank and partially in the right wing gear wheel well with numerous web cracks and stiffener fractures. The lower and upper chord web attach flanges remained attached to this piece. Although this section was in the airplane, it was not attached to any other aircraft structure and was bowed aft. At RBL 82 and approximately 20 inches above the lower chord was the location of the hole associated with the initiation of the propane/air vapor mixture. Three cracks intersected this hole (see section 4.4).

From LBL 11 to LBL 98 the rear spar broke into six pieces. All of these pieces (items 3, 354, 355, 357, 351, 356, and 361)[3] were found near the center wing fuel tank area on the ground. The stiffeners on these pieces were either separated or cracked. Assembly of the web pieces formed a dome shape in the aft direction centered at LBL 45.6 and midway between the upper and lower chords. The upper chord and lower chord web attach flanges remained attached to these pieces.

The BL 0 rib attach flange remained mostly attached to the rear spar. The upper end was bent forward and the BL 0 web attach flange was fractured and not attached.

4.2.6 SWB1

SWB1 separated into approximately seven large sections and numerous small sections. The upper chord fractured at RBL 98 and LBL 106. Mainly the lower portion of the web and the horizontal stiffeners remained attached from RSOB to RBL 106. Approximately four to twelve inches of lower web remained attached to the lower chord from the LSOB to the RSOB.

A large section from RBL 50 to RBL 11 and from upper to lower chords was separated and was found laying aft face down in the bay between SWB1 and the rear spar. This piece was trapped under the large portion of the midspar. The access door in this section remained attached with no punctures. The upper shear ties and tension fittings remained attached. The stiffeners remained attached.

Sections from BL 0 to LBL 49 broke into an upper and lower piece, consisting of web and partial stiffeners. The access door was not attached and these two sections were found lying together in the tank. The upper half of the web from LBL 91 to the LSOB remained attached at the upper left hand corner to LSOB and was bent aft about 70 degrees with the inboard web tabs curled aft and the inboard edges of the tabs curled forward. The web was generally bowed aft. Some portions of the web attached to the LSOB contained impact deformation from contact with fastener heads on the LSOB, consistent with a very high pressure load on the forward side of SWB1 near the LSOB.

From RBL 112 to RBL 50, the web broke into numerous pieces (items 140, 142, 146, 134, 139, 147, and 135). Generally, the edges of cracks were jagged with curls. There was a fragment hole less than 0.5 inch in diameter (see section 4.4) with three cracks running through it (at RBL 78 and approximately 28 inches[4] above the lower

[3] Item numbers refer to various sketches in appendix A.
[4] Geometrical considerations indicated that the 28-inch height of this hole corresponded to the 20-inch height of the hole in the rear spar associated with the ignition of the propane/air vapor.

chord). Around this area there was a general pattern of forward deformation in this area. All the pieces were bent in various directions.

From LSOB to LBL 50, the web broke into numerous small sections (items 137, 136, 131, and 138). Generally, these pieces were grossly deformed with no apparent pattern. Fractures in this area did not intersect the holes previously created in the structure.

Generally, there were no stiffeners attached to the web.

4.2.7 MIDSPAR

The midspar broke into five large sections out of which two remained attached to the center tank structure. The two sections that remained attached accounted for about 90 percent of the spar. The three smaller pieces that separated from the airplane (items 127, 128, and 129) were from the left side, including two that were adjacent to the LSOB.

The largest piece of the midspar (about LBL 57 to RSOB) remained in the tank and was displaced aft about 3.5 feet. This section remained attached to RSOB, and the upper end of the spar was tilted aft approximately 30 degrees at LBL 57. This piece of the midspar was relatively undeformed from RBL 95 to the RSOB. The remaining portion of the web was bowed in the aft direction over most of its length, with the most aft portion of this bowing located approximately at BL 0. Associated with the bowing in the aft direction was a fracture in the upper chord of the spar at RBL 95 and a fracture in the lower chord at RBL 69. The aft bowing in the midspar was inboard of these fractures.

The bowing deformation on the left end of the largest piece of the midspar was slightly in the forward direction, reversed from the bowing deformation over most of the spar piece.

Generally, the vertical stiffeners remained attached to the large piece of the web with the upper and lower shear ties fractured. Examination of the shear tie and associated skin panel attachment areas showed that initial motion of the top of the right side of the midspar was in the forward direction. The right access door remained attached with no damage. The left access door remained attached and was punctured by portions of the SWB1 access door. The aft side of the midspar web contained no apparent damage associated with initiation of the propane/air vapor explosion.

A second large section from LBL 69 to the LSOB consisted of the lower half of the web and the lower chord. This section remained attached to the airplane, and one of the pieces that separated from the airplane was located at the outboard end of this piece. The web and chord on this piece was bowed in the forward direction, including forward deformation in the lower left corner of the spar. The vertical stiffener at LBL 105 was also bowed in the forward direction a sufficient amount to cause a buckling fracture of the stiffener at its midpoint. The outboard lower end of the web on this piece (about 10 inches in height) was separated from the LSOB vertical stiffener. The midspar web attach flange at this location was bowed forward as well as the vertical flange of the lower LSOB paddle fitting in the lower left corner of the midspar. The fasteners common to the ten-inch flange exhibited shear failures. The fasteners common to the paddle fitting exhibited tension failures. Vertical stiffeners of this section were severely damaged. No punctures or significant cracks in the web were observed.

A third large section of the midspar was from the top half of the spar and was located above most of the large piece attached to the LSOB. This piece (item 127) extended from LBL 57 to LBL 105. This is the midspar web upper half with the upper chord vertical flange remaining attached. No punctures or significant cracks in the web were observed. Forward bowing was noted in the upper chord and web of this piece.

The final two pieces of the midspar (items 128 and 129) were small pieces of web and LSOB vertical stiffener midspar web attach flange. The LSOB flange was fractured 35 inches below the upper edge.

4.2.8 BL 0 RIB

Rear Spar to SWB1

This segment of the BL 0 rib remained essentially intact, having failed through the chords at the top, bottom, and aft edge, and through most of the SWB1 attach fasteners (fastener heads fractured in tension) at the forward edge. The rib was bowed to the right, centered at about 10 inches aft of SWB1. The upper chord was fractured and the web was cracked (7 inches long) at this location, and the lower chord was fractured approximately at the same location. The angle extrusion attaching the rib to SWB1 was deformed consistent with the rib having moved to the right. The bolts attaching the upper and lower chords to panel stringers were also sheared consistent with the rib having moved to the right.

SWB1 to Midspar

This segment of the BL 0 rib broke into three large pieces (items 148, 149, and 151). These pieces show general bowing to the right consistent with an overpressure in that direction. The upper chord and the lower chord skin attach flanges were partially or totally separated (remained on skin panels). The upper chord was fractured midway between SWB1 and the midspar. The lower chord was fractured at the same location. The web crack ran from the same location as the upper chord crack and the web crack ran down approximately 33 inches intersecting with a horizontal crack that ran from the midspar to SWB1. The web was bent left approximately 80 degrees and the bend line was located at the upper chord crack location. Most of the stiffeners remained attached.

The fasteners attaching the forward edge of the web to the extruded angle attaching the rib to the midspar were sheared laterally consistent with the rib having been forced to the right. The bolts attaching the upper and lower chords to panel stringers were also sheared consistent with the rib having moved to the right.

4.2.9 SWB2

SWB2 was generally broken into a large number of small pieces, especially between LBL 34 and the LSOB. No evidence of overall bowing in the pieces was found. Most pieces of the left side of SWB2 were found forward of the beam location, including some in the forward cargo compartment. A few pieces were found aft of the beam, including a large piece from the center (item 105) that was found lying on its aft side with the lower chord approximately in its proper location (STA 1100). Approximately 28 percent of the spanwise beam 2 pieces were recovered from the forward cargo compartment.

A section of the web and horizontal stiffener remained attached to the airplane from RBL 98 to RSOB. The stiffener attaching the SWB2 web to the RSOB was fractured in the radius from 15 inches to 45 inches above the lower chord and was bent aft at the midpoint. The lower chord and section of the web from 4 inches to 40 inches in height remained attached to the lower chord, which remained attached to the lower skin. This is from LBL 57 to the RSOB (see lower skin panel documentation for intercostals).

The center portion of SWB2 separated as a larger piece (item 105) from LBL 50 to RBL 75. This section remained in the tank but not attached to the airplane. It contained most of the upper shear ties and tension fittings between RBL 17 to LBL 34. The manufacturing access door remained attached along the upper and outboard sides and the two vertical stiffeners. Fasteners from lower outboard corner running to the lower inboard corner and up to the upper inboard corner failed primarily in shear. The left access door (item 109) was intact, but not attached to SWB2. The left side of the left access door attach flange fractured at each fastener location from fastener shear tear-out, then the door rotated forward causing bending deformation and fractures on its right side.

Sections from LSOB to the left access door fractured into numerous pieces (including items 118, 112, 125, and 124). All of the fractures in this area were jagged, and the web was bent in various directions with no stiffeners attached.

4.2.10 SWB3

SWB 3 was fragmented into approximately 15 larger pieces that were 2 square feet or more and approximately 60 additional smaller pieces whose positions were verified while laying out the parts on the ground. These smaller pieces were as small as 4 inches by 4 inches. There were at least 150 additional pieces of the web that were much smaller and could not be identified for location. A large percentage of these pieces were approximately 10 square inches. The majority of these pieces (about 63 percent) were recovered in the forward cargo compartment (as far forward as STA 480), with some pieces in the forward main cabin. No apparent overall bowing deformation was noted in the pieces of SWB3.

The upper chord was fractured into 9 pieces that ranged from 12” to 60” long. The portion of the upper chord from LBL 70 to 115 had the free flange still attached with only one major impact mark. The remaining upper chord had the free flange of the chord broken off. None of the skin flange of the chord remained on the upper chord. It was confirmed (by matching witness marks on the front spar to features in SWB3 upper chord) that at least the right side of SWB3 (see front spar discussion) rotated forward about its lower edge, impacting the front spar. Only one portion of the lower chord vertical flange that extended from LBL 9 to RBL 83 was identified.

The LBL 9 lower tension fitting remained attached to the beam, and the tension bolt hole had elongation on the forward side of the hole. There were three lower stiffener shear ties recovered that exhibited hole elongation on the forward side of the hole. At nine shear tie locations on the lower panel, shear tie fasteners still remained in the lower skin panel. These fasteners showed some small forward/aft deformation but were relatively straight. There were five recovered upper chord shear ties. The upper skin to shear tie fasteners exhibited head tension failures and the bolt shanks remained straight. The floor beam tension bolt in the SWB3 tension fitting at LBL 33 and 57 showed tension failure with some inward bending. The shear tie fastener holes in the upper skin panel showed forward elongation and witness marks at the majority of the bolt holes, consistent with the upper edge of SWB3 moving forward.

4.2.11 Front Spar and Lower Pressure Bulkhead

The WCS front spar separated into 6 major sections. The portions from LBL 94 to the LSOB and from RBL 87 to the RSOB remained attached to the aircraft and were heavily bent forward on the inboard edges and wrapped around the fuselage ring chord. Compression damage to the fuselage skin panel (see 4.2.14) attached to the ring chord was consistent with the ring chord being forced forward. Another major portion on the right side extended from LBL 20 to RBL 66 and was rotated forward and was found lying in the forward cargo compartment just forward of its original location. The right potable water tank was still attached to this front spar section and was crushed. Another section of the front spar extended from RBL 66 to RBL 87.

On the left side of the front spar, two sections separated from the airplane. One extended from LBL 20 to LBL 80 and the other from LBL 80 to LBL 94.

The lower pressure bulkhead from RBL 75 to RBL 9 remained attached to the fuselage ring chord and separated from the front spar. The bulkhead bowed forward approximately 60 degrees rotating around the ring chord near RBL 75, and the deformation/rotation decreased going inboard to RBL 9 where the pressure bulkhead remained relatively straight vertically. From RBL 9 to LBL 41, the pressure bulkhead remained attached to the front spar and remained relatively straight vertically. At RBL 9, the vertical splice strap on the forward face of the spar was slightly bent forward on the upper end whereas the strap at LBL 9 remained flat. The pressure bulkhead from LBL 41 to LBL 55 remained attached to the front spar, and the web and stiffeners remained relatively straight. The pressure bulkhead from LBL 55 to LBL 78 remained attached to the fuselage ring chord and was rotated forward around the ring chord.

The stiffeners on the aft side of the front spar segments had multiple impact marks and paint transfer marks from impact with portions of SWB3. Most of the stiffeners were partially crushed, and the free flange of the stiffeners had buckled, consistent with a direct forward translation of most of SWB3 into the front spar. However, on the front spar segment from RBL 66 to RBL 87, the aft face of the three stiffeners had horizontal impact marks and black transfer from sealed fastener heads on the forward side of SWB3. One set of impact marks was located approximately 8 inches below the upper skin inner surface, and a second set was located about 10.75 inches below the upper skin inner surface. The black marks occurred between the impact marks. The segment of front spar from LBL 20 to RBL 66 had some of the same impact marks on the stiffener on the right side of the segment but diminishing to the left, and the distance below the skin inner was not consistent.

There were numerous web penetrations in the front spar segments and paint transfer marks on the aft side of the web (paint was applied to the spanwise beams prior to the explosion to aid in reconstruction).

The large section of front spar from LBL 20 to LBL 60 was bowed vertically forward at the mid height of the web as much as 20 inches and also showed distinctive lateral (inboard/outboard) bending and curvature. The segment from RBL 66 to RBL 87 was also bowed forward 11 inches at the mid-height of the beam with a fairly constant radius of curvature.

The large portion of front spar from LBL 20 to RBL 66 (that had the right water bottle attached) remained relatively straight vertically, and the portion to the right of the water bottle was bowed forward. The portion to the right of the water bottle was also bowed forward vertically near the mid height. The stiffeners on this segment were deflected laterally and crushed against the web at numerous locations.

4.2.12 Keel Beam

The keel beam was recovered in several major segments consistent with having failed in three separate regions:

1. Failure just aft of keel extensions (STA 1000) leaving the extensions from that location forward intact.
2. Failure 20" aft of SWB3 resulting in separation of a number of fragments (upper chord, web, and lower chord) between the front spar and SWB3.
3. Failure between the rear spar and STA 1350 bulkhead resulting in a fracture of the upper chord at the rear spar, lower chord at STA 1350, and buckling failure of the web (rear spar to STA 1350). The keel beam was intact between this failure zone and the one behind SWB3. The keel beam was also intact aft of this failure zone to the STA 1480 bulkhead.

The keel beam upper chord from the front spar to 20 inches aft of SWB3 remained partially attached to the lower skin panel. The keel extension splice remained intact at LBL 9 with the lower chord fractured 13 inches aft of the front spar (downward bending as if the keel beam aft of the fracture rotated down). The keel extension at RBL9 fractured aft of the aft bolt location in the splice (also downward bending). The lower chords and lower horizontal web from near the front spar to near STA 1060 separated from the airplane.

The tension fitting at RBL9 on the underside of the panel at SWB3 remained attached to the panel whereas the LBL9 fitting on the underside had a tension failure of the bolt, and the bolt had an outboard residual deformation at the top of the bolt. The base of the RBL9 fitting on the topside of the skin was only partially in place with the base of the tension fitting failed through the bolt hole. The tension fittings on the top of the lower skin panel were attached to the skin at SWB2 and SWB1, and the tension bolts fractured at the midspar with the fittings remaining attached to the midspar.

The web of the keel beam at STA 1060 (aft of SWB3) was heavily buckled along RBL9. The lower chord of the keel beam on the left side at this location was broken into smaller pieces just as the web was fragmented into smaller pieces. The upper chord had fastener tensile separations from the lower skin panel aft to STA 1100 on the right side. The keel beam and tension fittings were intact on both the left and right sides from STA 1100 to the rear spar near STA 1241. Fractures and deformation to the keel beam in the area aft of SWB3 were consistent with downward bowing of the beam.

Aft of the rear spar, the keel beam lower chord was intact to STA 1350. The keel box web above the lower chord had multiple fractures and was separated back to just forward of STA 1350. The upper chord of the keel beam was fractured away from the

BL 0 web and was bent down at the rear spar to STA 1350. The keel beam from STA 1350 to STA 1480 was intact (based upon limited visual inspection capability). The keel beam fractures and deformation around STA 1350 were consistent with downward loading of the portion of the keel beam forward of this location.

4.2.13 Floor Beams Forward of Front Spar

STA 980
- Missing from LBL 98 to RBL 98
- Remaining lower chord at ends deflected forward with webs also bent
- Stanchion severed on both sides

STA 960
- Fractured at LBL 98 and RBL 98 at stanchion with some of middle portion suspended by wiring
- Stanchion intact on both sides

STA 940
- Fractured at LBL 86 and RBL 75 and no longer in place
- Portions inboard of fracture deflected forward
- Stanchions intact

STA 920
- Web is fractured at numerous locations and both upper and lower chord bent at various locations but beam is still in place
- Stanchion intact
- Floor beam intact outboard of stanchion

STA 900, STA 880, STA 860

Upper chord and web failures on both sides just inboard of stanchion
Upper chord bowed down at RBL and LBL 75

STA 840, STA 820, STA 800
- Upper chord and web failure at LBL 75 with upper chord bowed down
- Right side of floor beam intact

STA 780 and forward
- Floor beams intact

4.2.14 Fuselage

Fuselage Forward of STA 1000

The fuselage monocoque structure forward of STA 1000 was relatively undamaged except locally within a zone thirty inches forward of the front spar in the lower lobe.

The fuselage above S19 remained intact on both the left and right sides of the fuselage. From S19L to S38L and from S19R to S38R, the fuselage skin and stringers were bent and crushed forward due to the forward movement of the front spar that remained attached to the ring chord. The skin panel was crushed forward approximately 7 inches near S35L and approximately 5 inches near S36R. The ring chord and attaching skin panel was also rotated forward from S38L to S44L and from S38R to S44R.

The lower lobe frame at STA 980 had the inner chord of the frame deflected forward from S30L to S45L and from approximately S45R to S30R. The remainder of the STA 980 frame is intact.

Local damage was noted to the lower cargo frames at STA 960 and STA 940 near the cargo track end stops at BL 27 and BL 45.

Fuselage Aft of STA 1000

The frames at overwing stub beams from STA 1020 to STA 1120 had the inner chord buckled at S22L and S22R. The frames were not attached in the region from S4L to S4R and from STA 1060 to STA 1100. The skin panel had a large tear from STA 1005 to STA 1130 that extended from S4R to BL0 at both ends. Five approximately 6 inch by 6 inch punctures occurred at the following locations:

1. STA 1030, S4L-S5L
2. STA 1110, S3L
3. STA 1130, S1L-S2L
4. STA 1130, S1R-S2R
5. STA 1165, S8R

A piece of upper WCS skin panel (10 inch by 20 inch) was wedged under S8L at approximately STA 1110.

A large hole was generated in the upper skin with the flap bent up along S2R. The flap of skin extended from STA 1220 to STA 1280 and extended down to S6R.

4.2.15 Shear Tie Study

Most of the bolt shanks remaining in the shear ties at the upper end of the stiffeners for the various spanwise beams and spars were straight.

Front Spar Upper Chord Shear Ties/Tension Fittings indicated forward motion.
Front Spar Lower Chord Shear Ties/Tension Fittings remained stationary.

SWB3 Upper Chord Shear Ties/Tension Fittings indicated forward motion.
SWB3 Lower Chord Shear Ties/Tension Fittings indicate no relative movement, except forward motion at RBL 85.

SWB2 Upper Chord Shear Ties/Tension Fittings indicated slight forward motion. LBL 98 to LSOB remaining web indicates forward motion restricted by upper chord.
SWB2 Lower Chord Shear Ties/Tension Fittings remained stationary. LSOB paddle fitting vertical flange bent forward at inboard edge 30 degrees.

MS Upper Chord Shear Ties/Tension Fittings indicated slight forward motion on the right side, and the left side was not determined.
MS Lower Chord Shear Ties/Tension Fittings indicate no relative movement except LBL11 keel beam bolt, indicating forward motion.

SWB1 Upper Chord Shear Ties/Tension Fittings not determined in upper skin panel. Shear ties indicate no relative movement.
SWB1 Lower Chord Shear Ties/Tension Fittings indicated web moved aft on the left side. The right side remained stationary.

BL0 Upper Chord Shear Ties have cracking on left side of shear tie indicating movement to the right between RS and SWB1.
BL0 Lower Chord Shear Ties not determined.

4.3 Failure Sequence

The failure sequence has been summarized with respect to the progression of the overpressure resulting from the propagation of the propane/air explosion. In this manner the failures could be directly related to the loads which would have been present to drive them. Failure sequence was generally derived from the evaluation of the following data: (1) the location from which parts were recovered, (2) general deformations, cracking patterns, etc., (3) metallurgical identification of crack propagation directions, and (4) understanding of the fundamental structural arrangement, internal loads and stress considerations.

It should be noted that the failure sequence summarized below represents the most rationale match to the multiple considerations used for criteria listed at the start of this section. The team attempted to identify multiple supporting evidence for any one step in the sequence. However, in some cases sequential failure steps may have occurred virtually simultaneously. In a few cases, adjacent steps may even be transposed in order. Nevertheless, the team believed that any such uncertainty or variation would not affect the general trend of the overall breakup sequence.

4.3.1 *Ignition and initial pressurization of aft right tank bay*. The initiation of the propane/air vapor within the aft right bay of the center fuel tank created a small hole in the web of the rear spar. Some fragment(s), resulting from the method used to ignite the tank, also penetrated SWB 1. The web around the hole in SWB 1 was severely deformed in the forward direction and broken into smaller pieces, creating a larger hole, about 12 to 18 inches in diameter.

4.3.2 *Progression of pressure to aft left cell*. The BL 0.0 centerline rib between the aft right and aft left bays contained no evidence of a pressure differential that may have deformed it to the left, away from the bay that was ignited. This indicates that the pressure propagated rapidly to the left and that a pressure gradient capable of deforming the rib to the left was never developed.

4.3.3 *Generation of high pressure aft of the midspar on the left side*. There is multiple failure evidence of a very early, very intense, localized overpressure to the left side of the left bay between SWB 1 and midspar. The left side of the midspar (outboard of LBL 70) is bowed forward, with stiffeners buckled. This forward bowing extends partially onto the large piece of the midspar that remained attached to the RSOB. Due to this overpressure, the midspar cracked horizontally approximately at midheight and vertically at about LBL 63. The lower skin to LSOB joint was also fractured below this area, and the skin was blown downward.

4.3.4 *Initiation of venting*. At some point early in the sequence, pressure in the aft right bay grew large enough to cause the upper skin of the tank above this bay to fracture, causing the large piece of upper skin to be blown upward. The right end of this piece of skin penetrated the upper fuselage, then the piece fell back into the main cabin. This pressure also bowed the right side of the rear spar in the aft direction, causing fractures through the hole associated with ignition. Pressure in the left rear bay also reached levels sufficient to cause the left portion of the rear spar to be bowed in the aft direction and fractured. Venting associated with these tank breeches started at the right rear, and the decrease in pressure associated with this venting pulled the pieces of the BL 0.0 centerline rib to the right, and most of SWB1 to the rear.

4.3.5 *Initiation of the failure of SWB2*. The intense overpressure on the aft side of the midspar opened the left side of the midspar. This opening in the midspar allowed the intense overpressure to progress forward, and the left side of SWB2 (left of about LBL 34) was fragmented into pieces that were forcibly propelled forward.

4.3.6 *Progression of upper skin panel failure*. As the internal beams (rear spar, SWB1, midspar, etc.) began failing, the upper panel and longitudinal floor beams became progressively unsupported and began to be blown upward, typically failing near the side of body and at multiple location in between. The upper skin panel failures would have been closely sequenced with respective beam failures such that panel failure would occur almost simultaneous with beam failure before significant pressure venting could occur.

4.3.7 *Progression of the lower skin panel deformation and failure*. As in the case of the upper skin panel, when the spars and spanwise beams began to fail, the lower panel was deformed downward under the pressure. The rear portion of the lower skin panel (aft of the midspar) was visibly draped over the still intact keel beam. The forward portion of the panel contained a more uniform downward deformation indicating that the keel beam was separated or fractured as this portion of the damage occurred.

4.3.8 *Initial keel beam failure between STA 1240 and 1350*. As the failure of spars and spanwise beams progressed forward, support for the keel beam was increasingly removed, finally resulting in an overstress shear and bending fracture of the keel beam between the rear spar (STA 1240) and the landing gear bulkhead at STA 1350 as a result of loads induced by the pressure on the lower skin panel.

4.3.9 *Completion of SWB2 and midspar failure*. After the forceful damage to the left side of SWB2, the continued pressurization on both sides of the remainder of this beam did not generate a significant forward acting force to propel the right side of this beam in the forward direction. Due to venting aft, a sufficient aft-acting pressure gradient was developed on most of the remainder of the right side of SWB2, rotating it aft. This same venting pulled the major portion of the midspar aft causing it to be bowed rearward over much of its length.

4.3.10 *Failure of SWB3*. The full pressure gradient was applied to SWB3 (the tank end) causing it to separate from the upper panel and rotate forward into the front spar with such force it fragmented in to relatively small pieces, which were generally blown forward.

4.3.11 *Failure of the front spar*. Following impact from SWB3 and being loaded by the vented tank pressure, the front spar failed at the attachment to the upper panel, rotating forward. The motion of the center portion of the front spar was impeded by the potable water bottles, and the center front spar section ended up lying over onto the cargo floor. The regions outboard of the potable water bottles and inboard of the pickle fork fittings were generally blown into the forward cargo compartment.

4.3.12 Completed failures of the keel beam. As failure of supporting spars and beams progressed on toward the front spar, the downward load on the keel beam from the internal pressure on the lower skin panel caused the keel beam to fail in bending aft of SWB3 (multiple failure of both the upper and lower chords as well as webs).

Downward rotation associated with this failure also resulted in failure of the keel beam extension just aft of the front spar.

4.3.13 *Completion of upper panel failure*. As failure of supporting spars and beams progressed up to and including the front spar, the failure of the upper panel due to pressure followed closely in parallel.

4.3.14 *Initial failure of side of body ribs*. Initially, failure occurred along the upper plus chord web attach leg (either in web or leg) between the midspar and front spar. The initial failure was due to pressure loads acting on the side of body ribs (bowed outward) that forced the upper and lower surfaces apart as well as tended to rotate open the joint at this location (both left and right ribs similar).

4.3.15 *Failure of lower panel at left side of body joint*. Due to pressure acting on the now unsupported lower panel, the panel failed in tension (some bending) just inboard of the left side of body joint over most of the chord.

4.3.16 *Final failure of right side of body opening #3 main tank*. The now cantilevered lower skin panel failed the right lower side of body Tee chord (in bending), opening up the main tank from the midspar to near the front spar.

4.4 Assessment of the Effect of Holes Created by Earlier Testing

During the examinations after the propane/air vapor explosion testing, the structure in the vicinity of each of the holes created by earlier testing was evaluated to determine any effects of the presence of the holes on the breakup pattern or sequence. This evaluation included the hole created during the initiation of the propane/air vapor explosion (listed as hole 5, below).

Upper skin panel (Hole 1) (S-9 to S-10, LBL112)

Three fractures propagated through the hole. Two of the fractures progressed diagonally through the hole and visually appeared to be continuous through the hole. The other fracture is perpendicular to the other fractures and is propagating on the inboard side of the hole. It was undetermined if the cracks initiated at the hole or propagated into the hole.

SWB#3 Web (Hole 2) (LBL116 and 25” below the upper panel)

The hole was encompassed by approximately five segments of spanwise beam web. There were multiple cracks propagating into or out of the hole with no obvious pattern of fracture directions. Segments and fracture types are not visually different in nature than the rest of SWB#3. It could not be determined if cracking associated with this hole was generated by pressure from the fuel tank explosion or by impacts of SWB3 with the front spar.

Lower Skin Panel (Right Side)(Hole 3A)

There were no visual indications of fractures propagating into or out of the hole. (The hole was largely covered by sealant prior to the explosion of the propane/air vapor in the center fuel tank.)

Lower Skin Panel (Left Side)(Hole 3B)

There were no visual indications of fractures propagating into or out of the hole in the lower skin panel.

A hole in the upper skin panel was associated with hole 3B in the lower skin panel. This upper skin panel hole had four fractures propagating into or out of the hole. Two of the fractures were oriented laterally and appeared to be continuous through the hole. The other two fractures were oriented chordwise and also appear to be continuous through the hole. At least some of these cracks appeared to have initiated from the hole.

Rear Spar Web (Left Side)(Hole 4)

There were four fractures that propagated into or out of this hole. The four fractures were oriented vertically and horizontally and appeared to be continuous through the hole. The hole was located in the portion of the web that was bulged rearward, indicating that the cracks initiated from the hole.

Rear Spar Web (Right Side)(Hole 5)

The hole associated with the initiation of the propane/air vapor explosion was located in the thinnest portion of the spar web. However, the web on each side of the hole location contained much thicker areas associated with manufactured holes in the web. The vertical position of hole 5 was approximately level with the top of the thicker web areas. The web was fractured vertically upward and downward and horizontally to the right through this hole.

Rearward bulging was found in the rear spar above hole 5 and inboard of the hole. The presence of this bulging indicates that the rear spar retained substantial integrity as pressure rose in the aft rear compartment following initiation of the propane/air vapor mixture. The vertical fracture through hole 5 is consistent with lateral tension stresses created as the rear spar bulged in the aft direction. The lack of bulging deformation to the lower part of the spar is consistent with constraint provided by the thicker web material near hole 5 and with fracture initiating from the hole as pressure increased.

SWB1 contained a small hole associated with hole 5. The web of SWB1 around this hole was severely deformed in the forward direction and broken into smaller pieces, creating a larger hole, about 12 inches to 18 inches in diameter. This larger hole also appeared to be associated with hole 5 in combination with effects from ignition of the propane/air vapor mixture.

4.5 Comparison to TWA800 Failure Modes and Breakup Sequence

There are both similarities and obvious differences when comparing the failure modes and breakup sequence of the Bruntingthorpe test airplane to the TWA Flight 800 airplane. For both airplanes, it is apparent that many of the local deformations and failure modes are driven by overpressure from either the fuel/air vapor or propane/air vapor explosion. However, the Bruntingthorpe test airplane had a significantly more dynamic and destructive effect on the wing center section structure than was found on the TWA Flight 800 airplane, largely as a result of some combination of the explosive energy, pressure rise rates, and peak pressures experienced during the test. Some of these differences were predictable because the Bruntingthorpe airplane test was conducted at sea level ambient pressure while the TWA Flight 800 explosion occurred at a much higher altitude. The exact propane/air mixture used and the specific type and location of ignition might have contributed significantly to differences as well.

Other factors could have contributed to the different damage patterns on the Bruntingthorpe and TWA Flight 800 airplanes. The Bruntingthorpe airplane was unpressurized whereas the fuselage of the TWA flight 800 airplane was pressurized. The Bruntingthorpe airplane body loading and wing bending loads were different than the TWA Flight 800 airplane. Also, the different payload, the lack of cabin pressure above the center section, and the partially compromised floor beam structure of the Bruntingthorpe airplane may have contributed to differences in the failure of the wing upper panel.

The Group members agreed that the following items are some of the more significant comparisons between the Bruntingthorpe airplane and the TWA Flight 800 airplane:

1) At Bruntingthorpe, failure of the WCS structural box was immediately catastrophic leaving no question that such an in-flight event would result in the airplane also immediately separating into four major components (left wing, right wing, forward body, and aft body). In TWA Flight 800 the significant initial failures were more confined to the forward WCS structure, and the wings were not immediately separated from the majority of the wing center section or the aft fuselage.

2) At Bruntingthorpe, venting of the expanding gasses occurred aft through the rear spar, upward as the upper panel disintegrated, forward through front spar, and

probably locally through the lower panel. In TWA Flight 800 the significant failure venting was confined to the forward direction, through the front spar and to some degree through the most forward upper skin area.

3) At Bruntingthorpe, failure of the keel beam resulted from overpressure loads as the keel beam supporting structure was progressively lost from the rear spar proceeding forward. In TWA Flight 800 the keel beam failure resulted from overpressure loads as the keel beam supporting structure was lost at the forward end and the body disintegration applied further loads on the keel beam extension area forward of the front spar.

4) At Bruntingthorpe the test airplane setup as well as the keel beam failure sequence (discussed above) probably precluded any real possibility of failure propagating from the WCS to the fuselage lower lobe as in TWA Flight 800.

5) At Bruntingthorpe the bowing deformations and damage patterns on the internal beams and upper and lower skins is clear evidence of a very intense pressure peaking event (located on the left side between the midspar and SWB1) at a substantial distance from the tank ignition. The examination of the TWA Flight 800 wreckage has not revealed comparable evidence.

6) In both Bruntingthorpe and TWA Flight 800, SWB3 failed at the connection to the upper wing panel, rotated forward, and impacted the front spar. The front spar then also failed at the attachment to the upper panel and rotated forward being impeded in the central area by the mass of the water bottles. At Bruntingthorpe SWB3 was fragmented into many smaller pieces whereas in TWA Flight 800 it was recovered in relatively larger pieces. Also the front spar stiffeners showed significantly greater level of overall crushing damage at Bruntingthorpe whereas the stiffeners in the TWA Flight 800 airplane showed primarily local crushing damage.

7) At Bruntingthorpe, numerous WCS fragments ended up in the forward cargo compartment and even into the E&E bay. In TWA Flight 800, no WCS spar or spanwise beam pieces were found in the yellow zone where the majority of the forward fuselage parts were recovered.

8) At Bruntingthorpe, there was compression damage to the fuselage skin panel forward of the ring chord where it attaches to the front spar. In TWA Flight 800, there was no indication of corresponding damage.

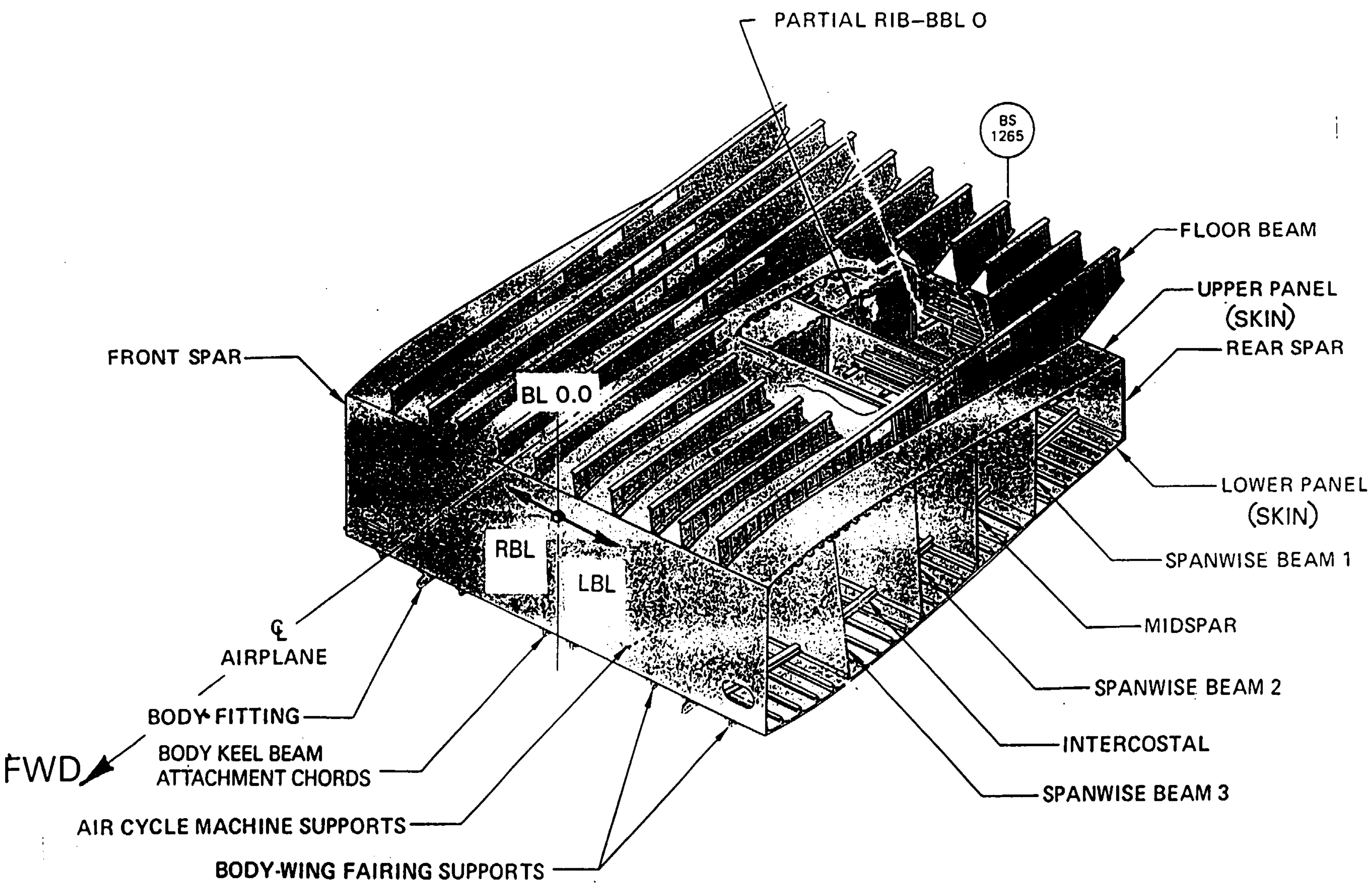
9) At the structural element level there are similarities between Bruntingthorpe and TWA Flight 800, which can probably be attributed to the failure modes on both airplanes being driven by overpressure loading. Examples are the manner in which spanwise beam vertical stiffeners failed, separating away the free flanges, local pillowing of thinner webs, etc.

For the Bruntingthorpe airplane there is a known ignition source of a specific nature and location, whereas in TWA Flight 800 the nature and location of ignition have not yet been determined. Because of the many differences between the test conditions of the Bruntingthorpe airplane and the conditions associated with the TWA Flight 800 accident, caution should be exercised when comparisons are used to support or refute various scenarios.

[signed]	*[signed]*
Deepak Joshi Structures Engineer	James F. Wildey II Supervisory Metallurgist

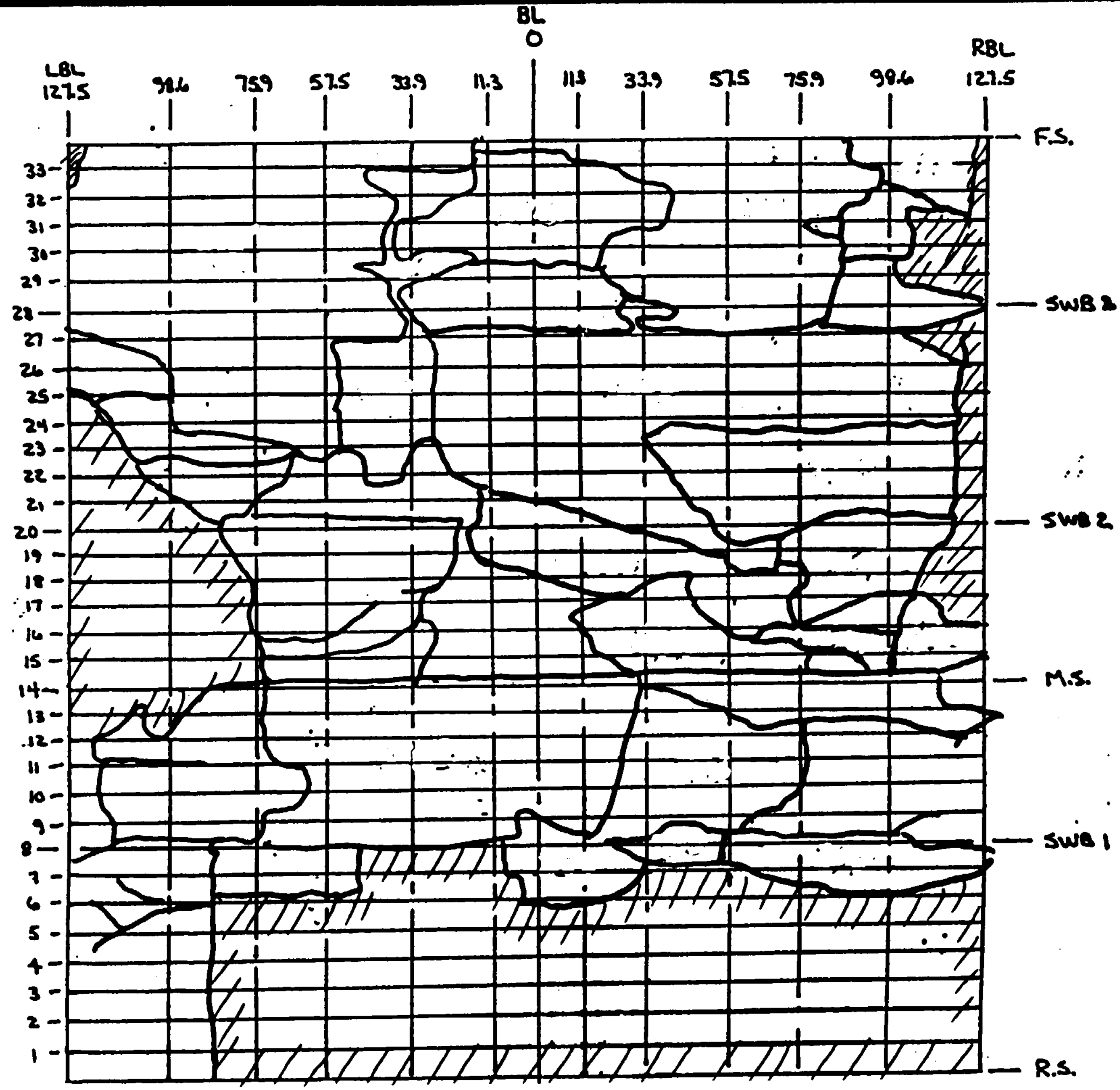
APPENDIX A

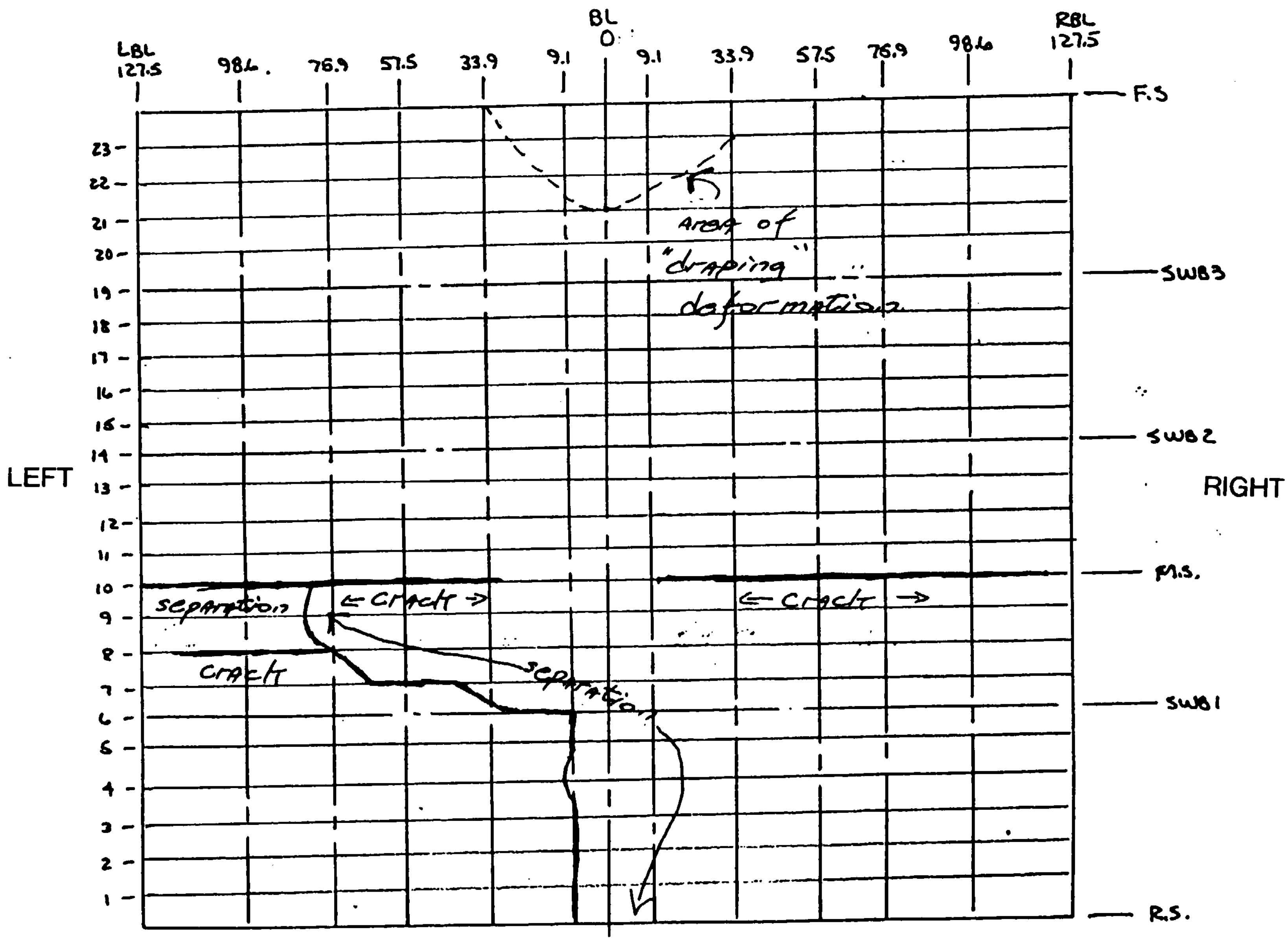
CENTER WING TANK - GENERAL CONFIGURATION



UPPER PANEL

LEFT





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98.6
76.9
57.5
33.9
9.1
9.1
33.9
57.5
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98.6
RBL
127.5
F.S
SWB3
SWB2
M.S.
SWB1
R.S.
LEFT
RIGHT
23
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1
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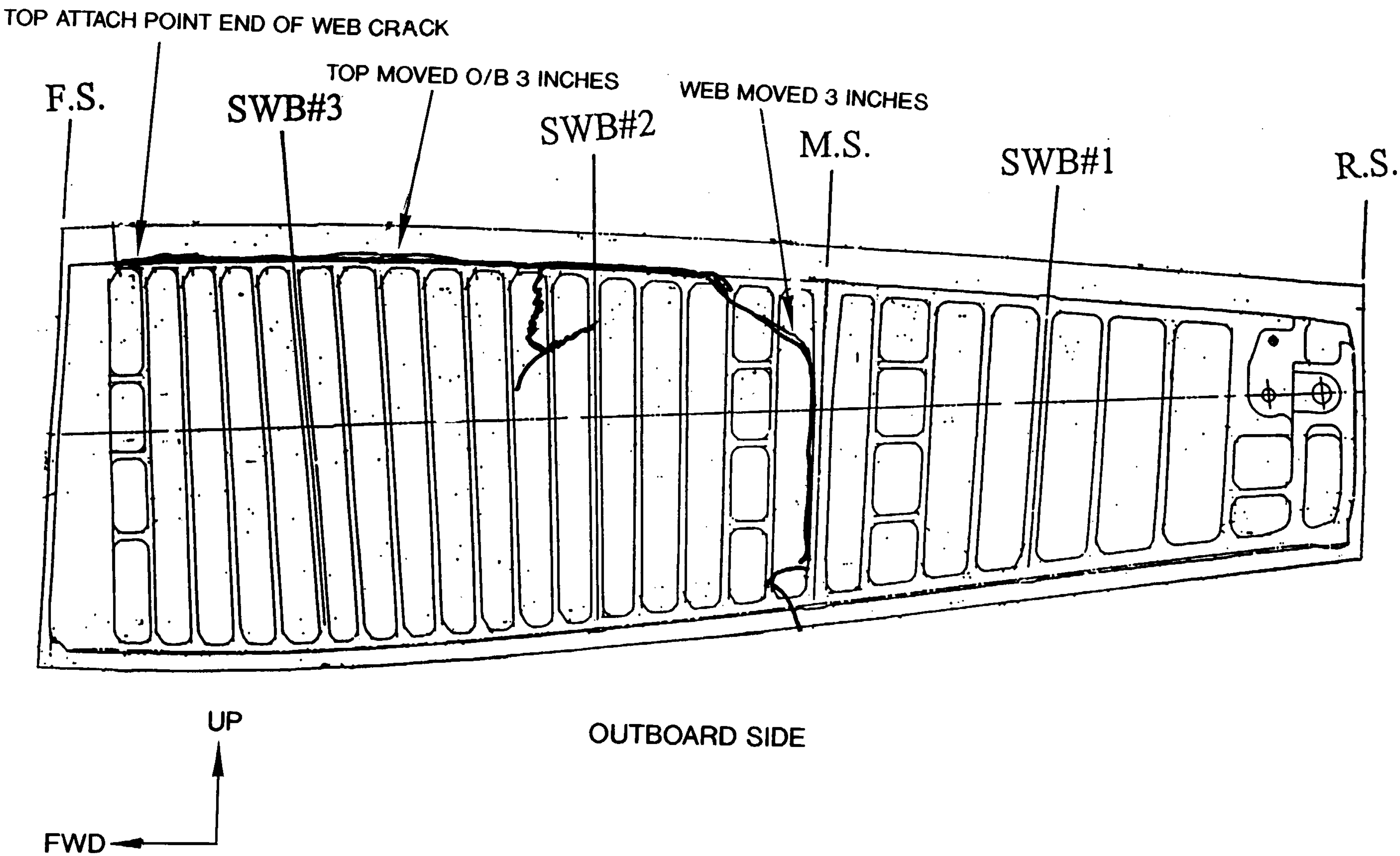
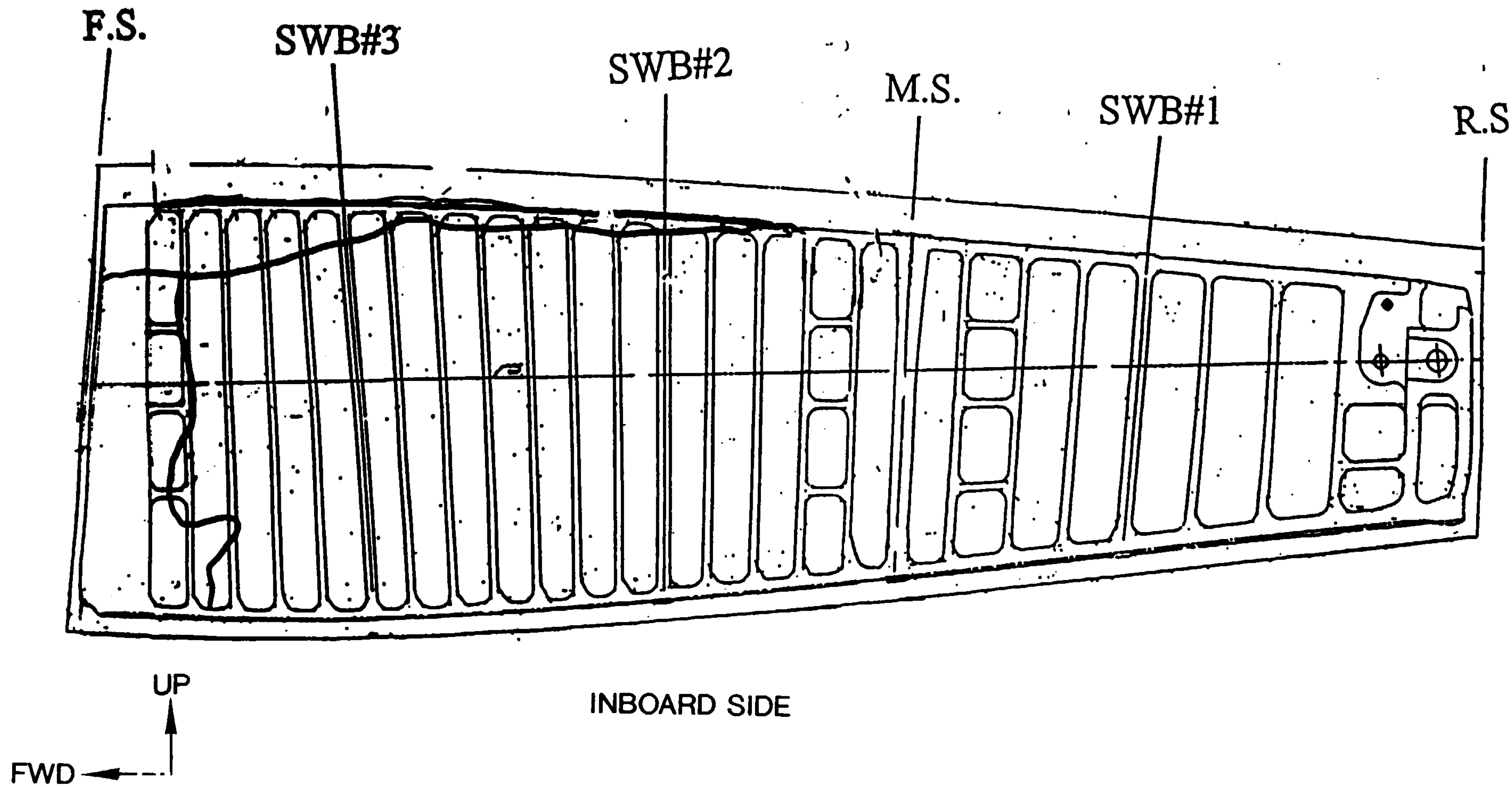
separation
← crack →
← crack →
crack
separation

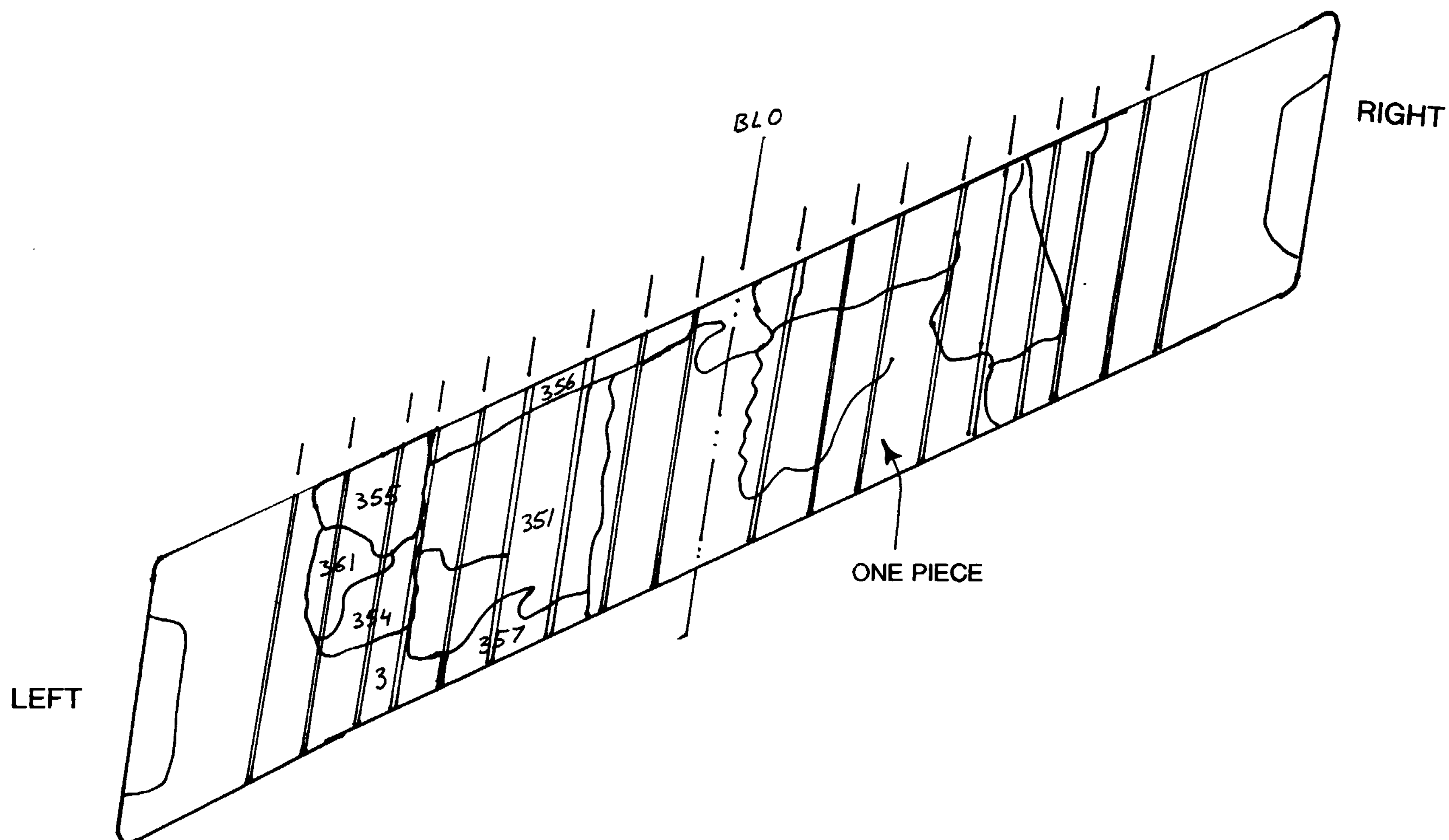
LOWER PANEL



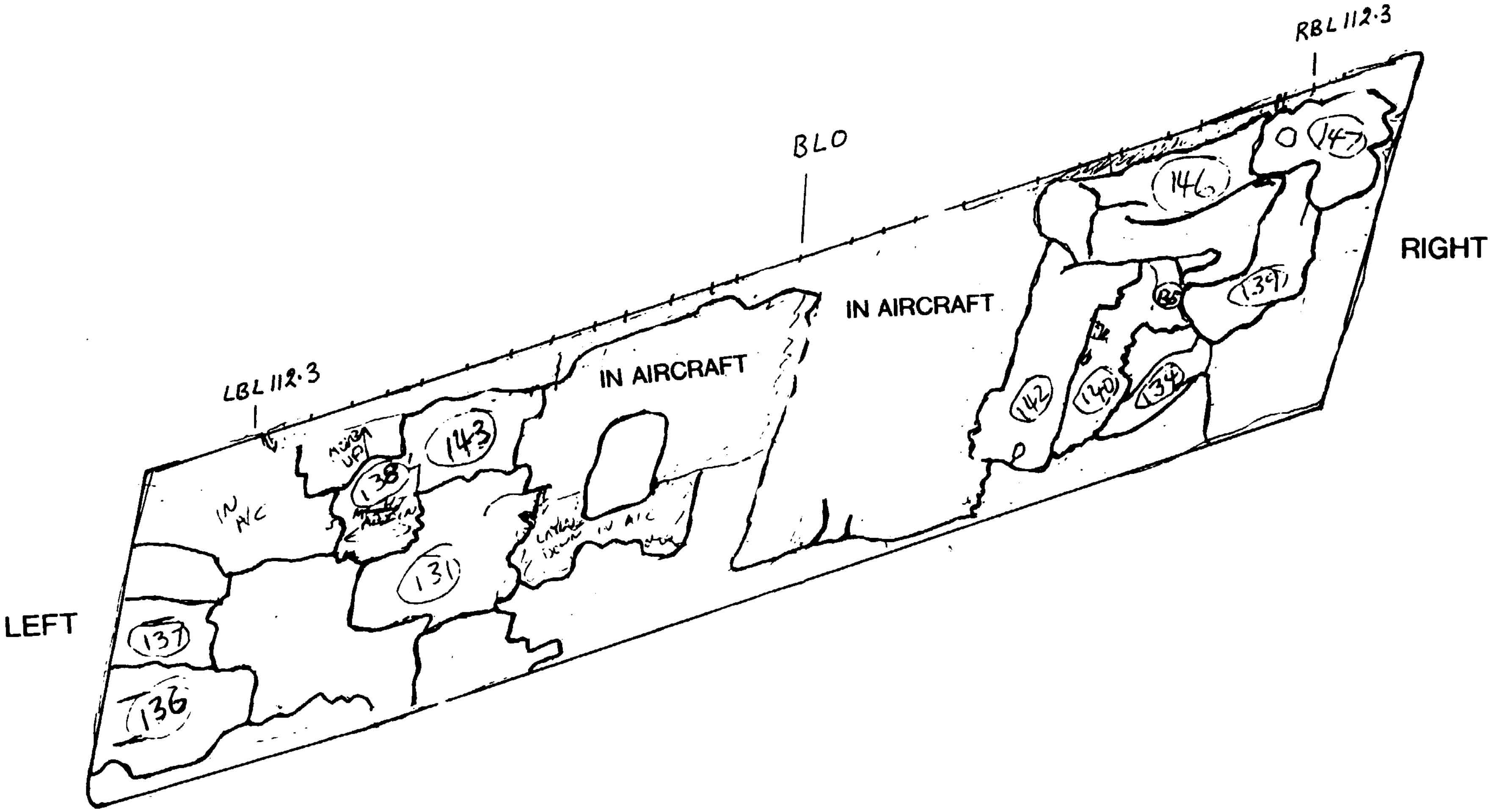
LEFT SIDE-OF-BODY RIB



RIGHT SIDE-OF-BODY RIB

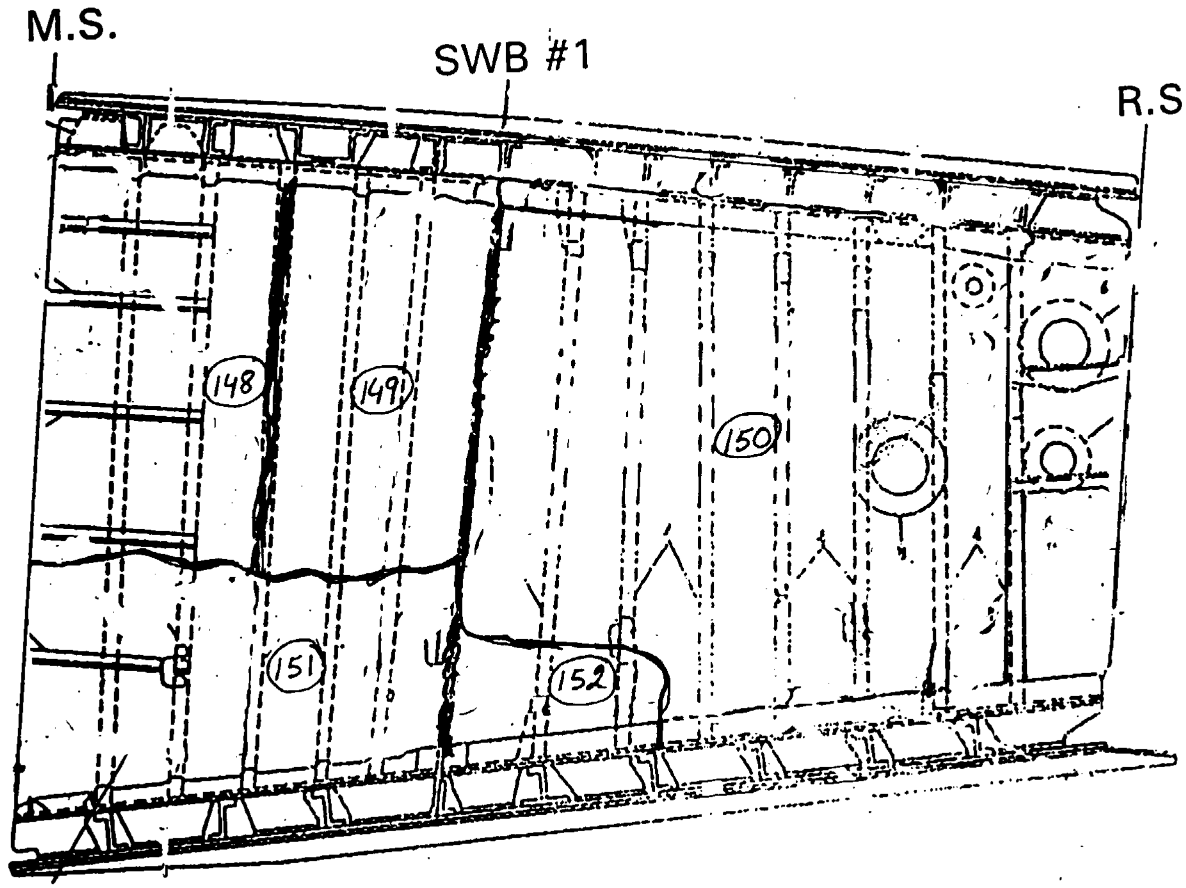


REAR SPAR



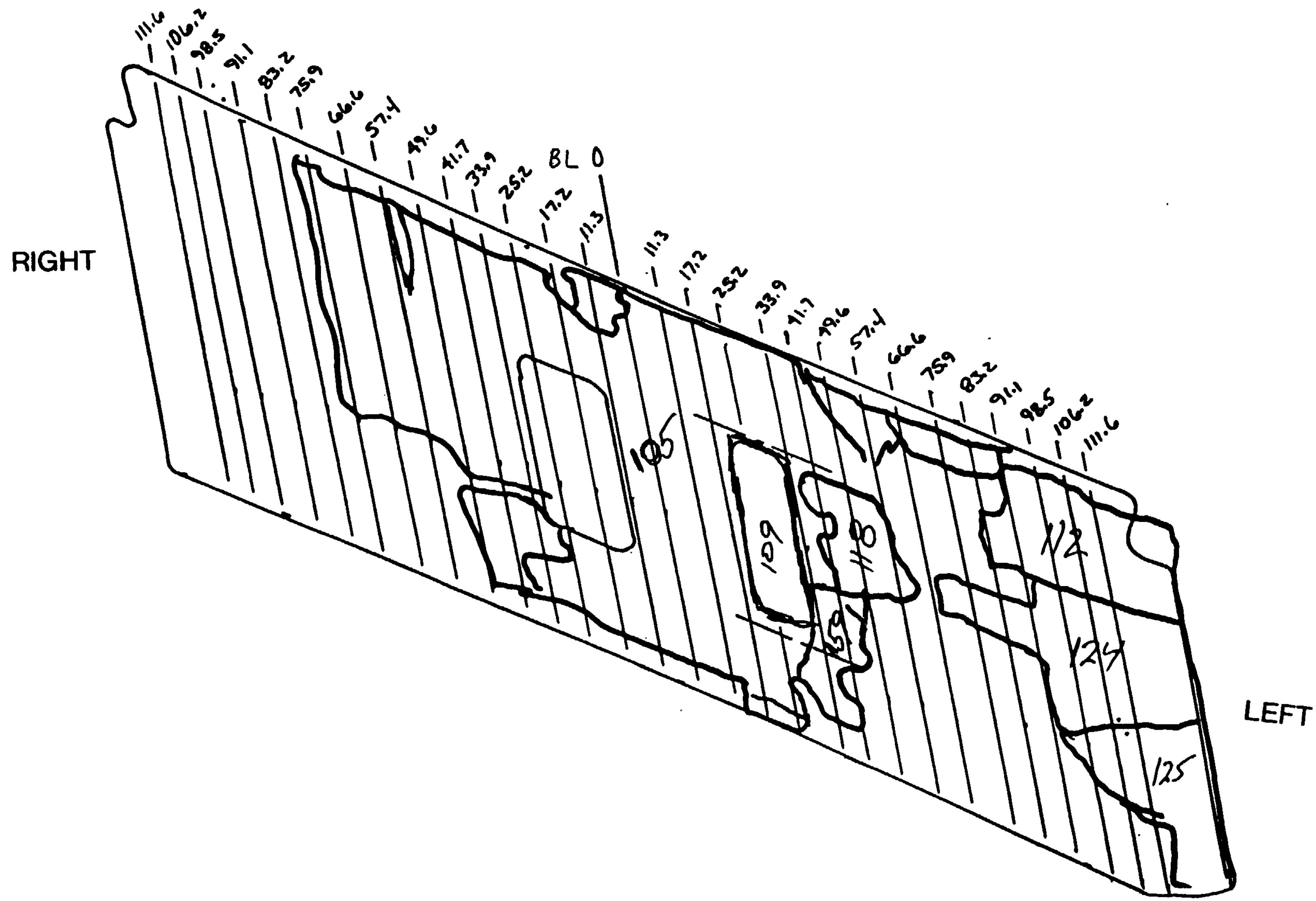
SPAN WISE BEAM 1

CENTER WING TANK - BL 0.00 RIB

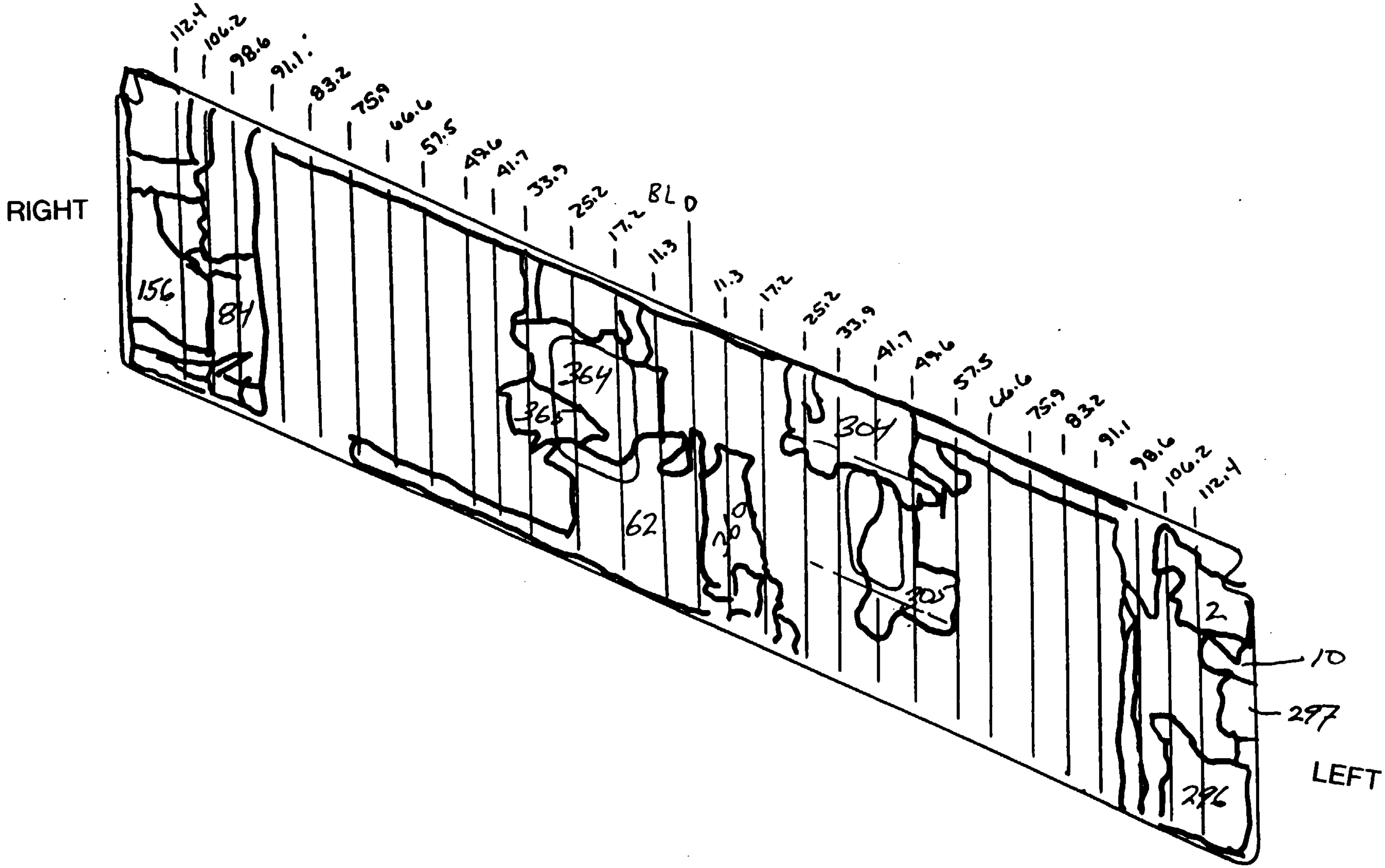


UP

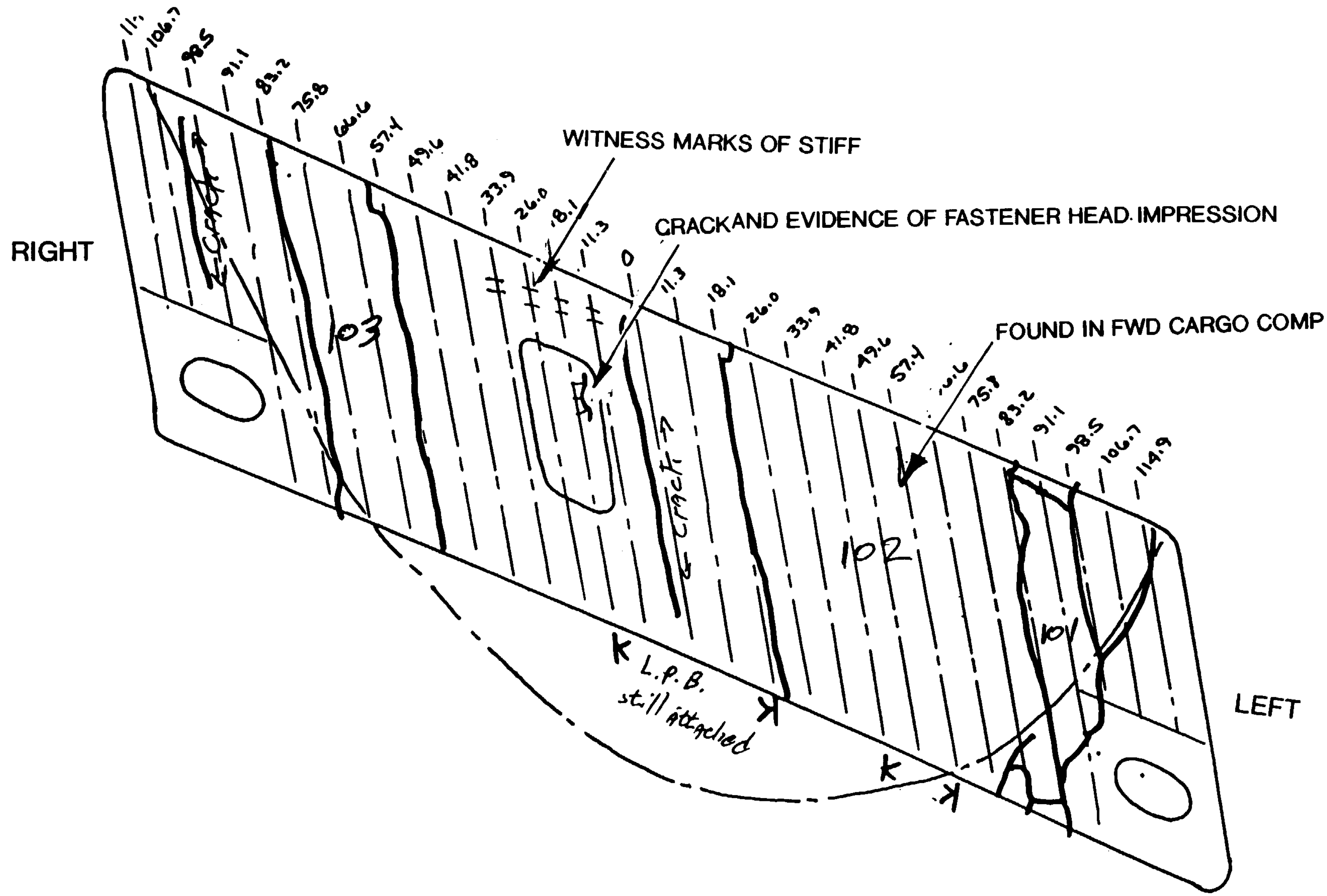
FWD



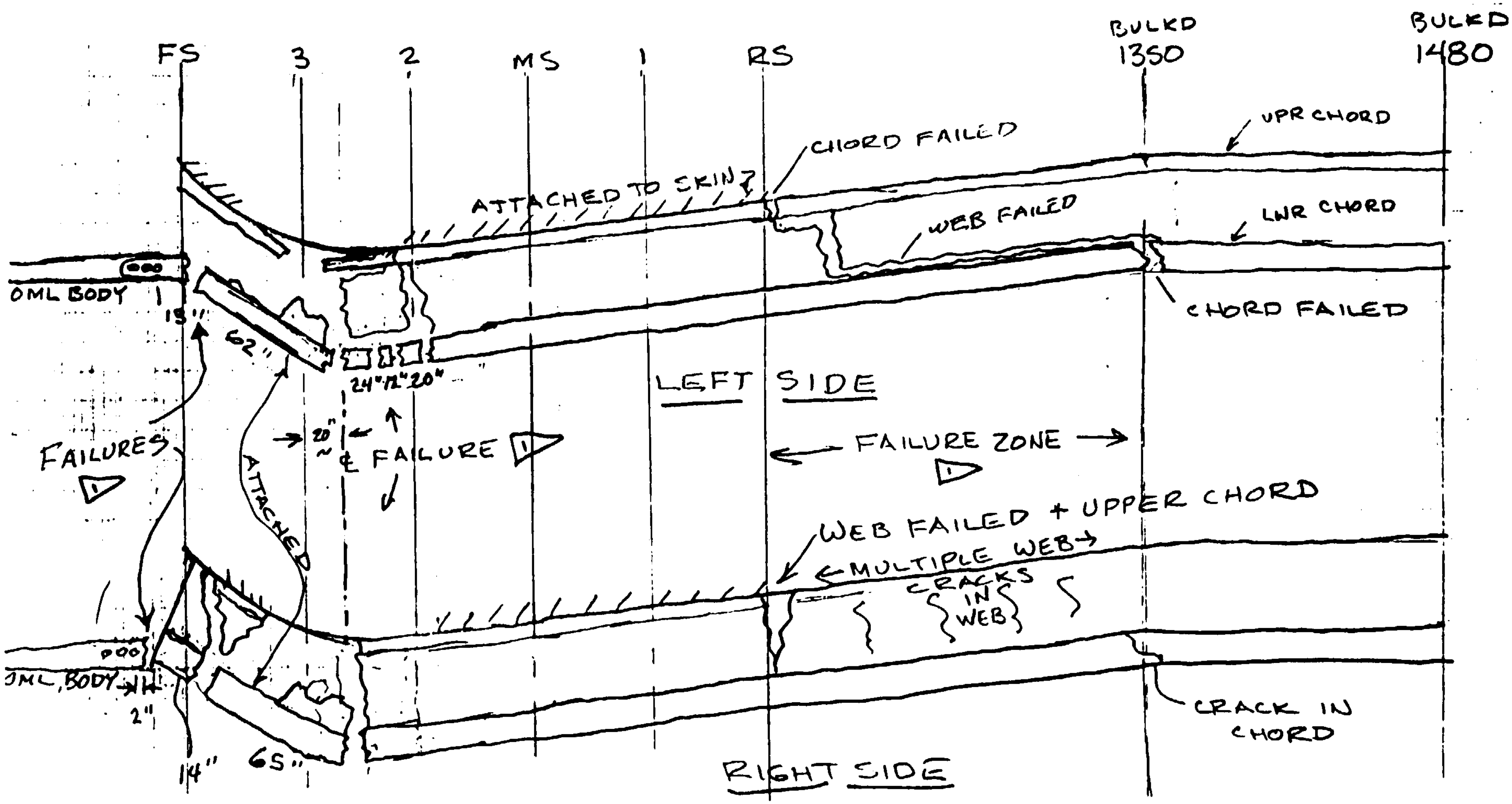
SPANWISE BEAM 2



SPANWISE BEAM 3


WITNESS MARKS OF STIFF
CRACK AND EVIDENCE OF FASTENER HEAD IMPRESSION
FOUND IN FWD CARGO COMP
RIGHT
LEFT
103
102
101
crack
crack
L.P.B. still attached

FRONT SPAR


FS
3
2
MS
1
RS
BULKD 1350
BULKD 1480
UPR CHORD
CHORD FAILED
ATTACHED TO SKIN
WEB FAILED
LWR CHORD
OML BODY
CHORD FAILED
15"
62"
24" 12" 20"
LEFT SIDE
FAILURES
20"
℄ FAILURE
FAILURE ZONE
ATTACHED
WEB FAILED + UPPER CHORD
MULTIPLE WEB
CRACKS IN WEB
OML BODY
2"
CRACK IN CHORD
14"
65"
RIGHT SIDE

KEEL BEAM

APPENDIX B

1. VIEW OF THE TEST SET-UP

2. CLOSE-UP VIEW OF THE TEST SET-UP

3. VIEW SHOWING SET-UP OF INTERIOR WITH SEATS & SAND BAGS

4. VIEW OF EXPLOSION IN TEST SET-UP

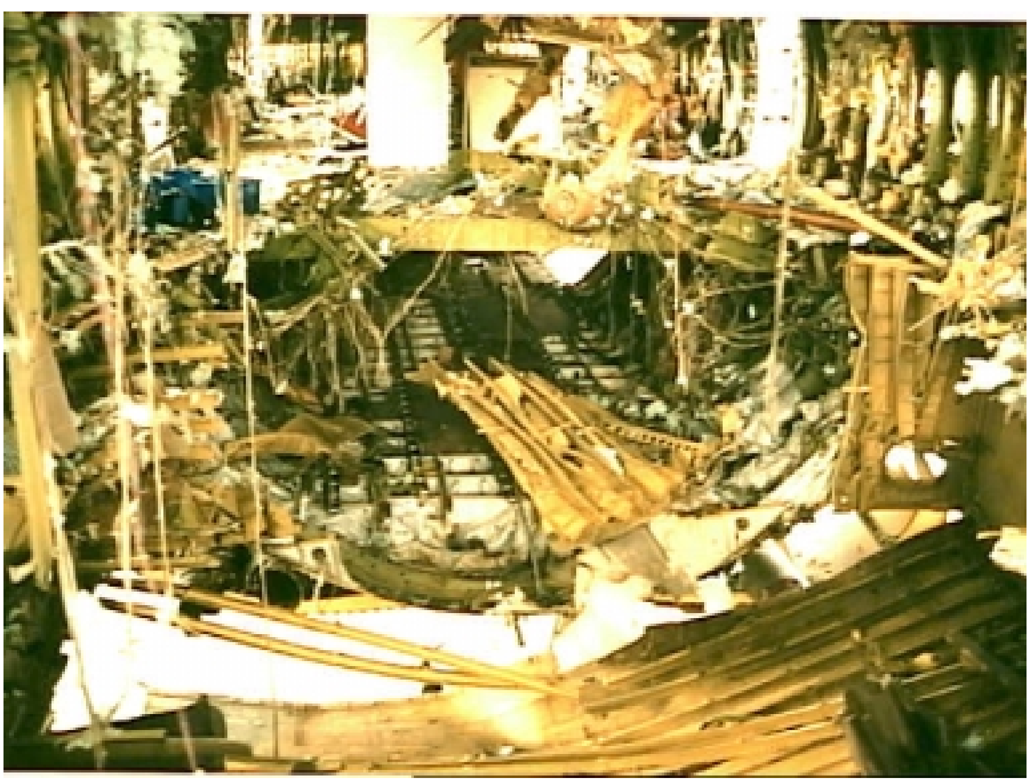
5. CLOSE-UP VIEW OF THE TEST SET-UP AFTER EXPLOSION

6. VIEW SHOWING DAMAGE OF WING CENTER TANK AFTER EXPLOSION

7. CLOSE-UP VIEW OF THE DAMAGE TO WING CENTER SECTION

8. VIEW SHOWING DEFORMATION OF THE UPPER SKIN

9. VIEW SHOWING DEFORMATION OF THE LOWER SKIN



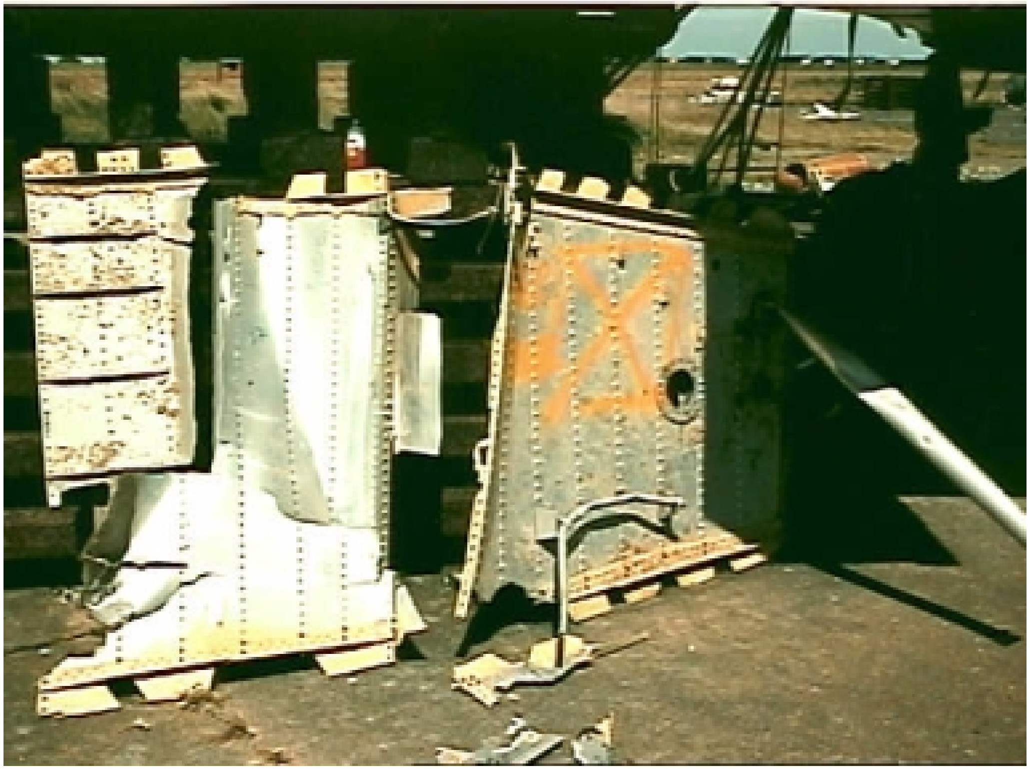
10. VIEW SHOWING SECTIONS OF FRONT SPAR PUSHED FORWARD

11. VIEW SHOWING DEFORMATION & DAMAGE TO SWB#3

12. VIEW SHOWING DEFORMATION & DAMAGE TO SWB#2

13. VIEW SHOWING DAMAGE TO MID SPAR

14. DEFORMATION OF SWB#1



15. DEFORMATION AND DAMAGE OF B.L.0 RIB

16. DEFORMATION OF REAR SPAR

17. VIEW SHOWING DAMAGE TO RSOB RIB

18. VIEW SHOWING DAMAGE TO LSOB RIB