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A Record of All Marker Bands Found in the Upper Rivet Rows of 2 Adjacent Bays From a Fuselage Lap Splice Joint

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Introduction

As part of the NASA Langley Research Center's Airframe Structural Integrity Program (ASIP), detailed destructive examinations were performed on a riveted fuselage lap splice joint structure containing widespread fatigue damage (WFD). A major goal of the ASIP program is to develop fracture mechanics-based prediction methodology for fuselage lap splice joints. As part of this work, detailed fractographic characterization of WFD is required. The following report documents the progression of fatigue cracking in the lap splice joint panel by characterizing the fracture surface marker bands. This accurate characterization of WFD is required before damage tolerant based models can be developed for fuselage structure life prediction.

The objective of this study was to create a data base of fracture surface marker band locations that will be used to determine the growth kinetics of fatigue cracks emanating from rivet holes contained in a lap splice joint. The position of all marker bands present on the fatigue fracture surfaces in the upper rivet rows of two adjacent bays in a fuselage lap splice joint were recorded. Future work will use the quantitative fractography performed in this study to determine fatigue crack growth rates, associated range of stress intensity (ΔK), and crack front shapes.

Background

A full scale fuselage test article was subjected to 60,000 load cycles (pressurizations) to study the effect of widespread fatigue damage in fuselage structures. Every 10,000 cycles coded marker block loading sequences were used to mark the fracture surfaces of the fatigue cracks propagating within the panel. The loading sequences consisted of series of underloads combined with a series of full pressurizations. The combination of loads and underloads marked the fracture surfaces with marker bands that could later be used to reconstruct the fatigue crack growth history of selected regions within the test article.

Thirty rivet holes comprising the upper rivet rows from two adjacent bays (bays #3 and #4) from a fuselage lap splice joint were examined for the purpose of this study (*Fig. 1*). Optical and scanning electron microscopy (SEM) were used to locate the marker bands.

The upper rivet row of Bay #3 contained 29 cracks in 15 rivet holes ranging in size from 0.307 mm (0.012 in) to 4.890 mm (0.192 in). A summary schematic detailing the destructive examination results including crack location, crack length, crack morphology (not to scale), crack type, and initiation site are presented in *Figure 2*. No crack linkup occurred in this bay.

The upper rivet row of Bay #4 contained 24 cracks in 15 rivet holes ranging in size from 0.769 mm (0.030 in) to 12.954 mm (0.510 in). A summary schematic detailing the destructive examination results including crack location, crack length, Crack morphology (not to scale), crack type, and initiation site are presented in *Figure 3*. Crack linkup occurred between rivet holes 8 and 9.

Procedure

Every fracture surface was obscured by oxides and it became necessary to properly clean them before marker bands could be located. The cleaning process required acetone, an acetone-based plastic cement (butyl acetate was used in this study), and acetate replica film. The following procedure was used for cleaning. Equal parts of acetone and plastic cement were mixed. The mixture was applied to both the replica film and the fracture surface. Then the replica film was applied firmly to the fracture surface so that the mixture bonded the two together. The mixture was dried in air for ten minutes and the replica film was removed. Next, the specimen was cleaned by placing it in an acetone bath agitated with an ultrasonic cleaner. This process was typically repeated 4-10 times before the fracture surface was adequately cleaned. Considerable time was saved by cleaning the specimen twice between acetone baths.

After the specimens were properly cleaned, optical microscopy was the primary tool used to search for and locate the marker bands. Magnifications of 400X to 600X were used a majority of the time. The 400X magnification worked better because more of the fracture surface could be seen, and fewer fine focus adjustments were required while searching. Although marker bands are visible with SEM, they were more difficult to find than with optical microscopy. Marker band surface contrast under bright field optical conditions were much easier to detect compared to SEM techniques.

Unique marker blocks were used to create distinct marker bands at regular intervals of 10,000 cycles (*Fig. 4*). A marker block consists of a repeated sequence of underload crack growth followed by full pressurization crack growth. Typically, 10 full pressurizations were alternated with 100 "underloads" to give the marker bands their characteristic "stripes" under reflected light.

Marker band locations were recorded in two dimensional space with an (X,Y) coordinate system. A reference point that could be readily identified with optical microscopy and SEM was chosen as the coordinate origin and a (0,0) coordinate value was assigned to it. Points along the marker bands were then identified relative to the origin (see Appendices A and B).

Results

In the upper rivet row of bay #3, at least one set of marker bands was found in 15 out of 24 fatigue fracture surfaces (Table 1). No marker bands were found on 9 fatigue fracture surfaces. All marker bands were found in the outer skin of the fuselage lap splice joint. The most commonly found marker bands were the 40K(12 found) and 50K(11 found) sets. Six 30K sets were also found while no 10K or 20K sets were found. A summary of all marker band coordinates and crack shapes for bay #3 are listed in Appendix A.

In the upper rivet row of bay #4 at least one set of marker bands was found in 19 out of 29 fatigue fracture surfaces (Table 1). No marker bands were found on 10 fatigue fracture surfaces. All marker bands were found in the outer skin of the fuselage lap splice joint. The most commonly found marker bands were the 30K(12 found) and 40K(16 found) sets. Nine 50K sets were found and two 20K sets were found. No 10K sets were found. A summary of all marker band coordinates and crack shapes for bay #4 are listed in Appendix B.

Although nine 50K cycle sets were found in bay #4, 10 sets of 50K marker bands went undetected where they logically should have existed. Due to increasingly high growth rates at the longer crack lengths, the marker bands became very large in 6 of these 10 cases. The light reflected from the marker bands was too diffuse for them to be adequately defined. This phenomenon was most prevalent in the cracks that linked up in the center of the bay where this phenomenon occurred on 3 cracks emanating from 2 rivet holes.

Concluding Remarks

The purpose of this examination was to determine the growth kinetics of multiple fatigue cracks emanating from rivet holes contained in a fuselage lap splice joint. Two adjacent bays removed from a full scale fuselage test article that had received 60,000 pressure cycles were examined. Optical and scanning electron microscopy were used to perform quantitative fractography on fatigue fracture surfaces that had been marked with coded marker bands at intervals of 10,000 cycles. Fifty-three fatigue cracks emanating from thirty rivet holes were examined. Thirty-four out of these fifty-three cracks were found to have at least one set of marker bands. A total of sixty-eight sets of marker bands were recorded. These data will be useful in understanding the initiation, growth, and linkup processes of fatigue cracks in lap splice joints that exhibit WFD. Ultimately these data will be used in the development of life prediction methodology required by the ASIP. Future work will determine crack growth rates and associated stress intensity factors as well as crack front shapes at various stages of propagation.

Table 1

Marker Bands Found in the Upper Rivet Row of Bay#3

Specimen #	20K	30K	40K	50K
3J1(Aft)		X	X	X
3J1(Fwd)				X
3J2(Aft)			X	
3J2(Fwd)		X	X	X
3J4(Aft)		X	X	X
3J4(Fwd)			X	X
3J5(Fwd)				X
3J7(Fwd)			X	X
3J9(Aft)				X
3J11(Fwd)			X	
3J12(Aft)			X	X
3J13(Fwd)		X	X	X
3J13(Fwd)			X	
3J15(Aft)		X	X	
3J15(Fwd)		X	X	X

Table 2

Marker Bands Found in the Upper Rivet Row of Bay#4

Specimen #	20K	30K	40K	50K
4J1(Aft)		X	X	
4J2(Aft)			X	
4J2(Fwd)			X	X
4J3(Fwd)		X		
4J4(Fwd			X	X
4J5(Fwd)		X	X	
4J5(Aft)		X	X	X
4J6(Fwd)		X	X	X
4J6(Aft)				X
4J7(Fwd)			X	
4J8(Aft)	X	X	X	
4J8(Fwd)		X	X	
4J9(Fwd)		X	X	X
4J10(Aft)		X	X	
4J12(Aft)				X
4J14(Fwd)		X	X	X
4J14(Aft)			X	X
4J15(Aft)	X	X	X	
4J15(Fwd)		X	X	

Appendices A and B

Appendices A and B summarize the location of all marker bands found on all 34 fracture surfaces in the upper rivet rows of bay #3 and bay #4, respectively. This information consists of marker band and crack front coordinates superimposed on a schematic. The schematic illustrates a cross section of the outer skin layer of the fuselage lap splice joint that includes half of the countersink portion of each rivet hole. Arrows and brackets highlight initiation sites and initiation regions respectively. Numerical marker band and crack front coordinates are reported in millimeters as well as in inches. The positive X and Y directions are marked on each figure along with the origin of the coordinate system. The number of bands refers to the number of marker bands counted with optical microscopy at the point corresponding to the given coordinates. Comments when given refer to the condition and clarity of the marker bands as determined by optical microscopy. Comments when not given denote an average condition that was nonetheless resolvable with optical microscopy.

Specimen numbers are coded as follows: The first character is a single digit number representing the bay number. The second character corresponds to the rivet row in the panel that was removed from the test article. In this study only the upper rivet row (row J) was observed in both bays. The third character is a one or two digit number that signifies the rivet number. As seen in *Figure 2* and *Figure 3*, the upper rivet rows in these bays are numbered from one to fifteen in the aft direction. Finally, crack growth is noted to be in the forward or aft direction.

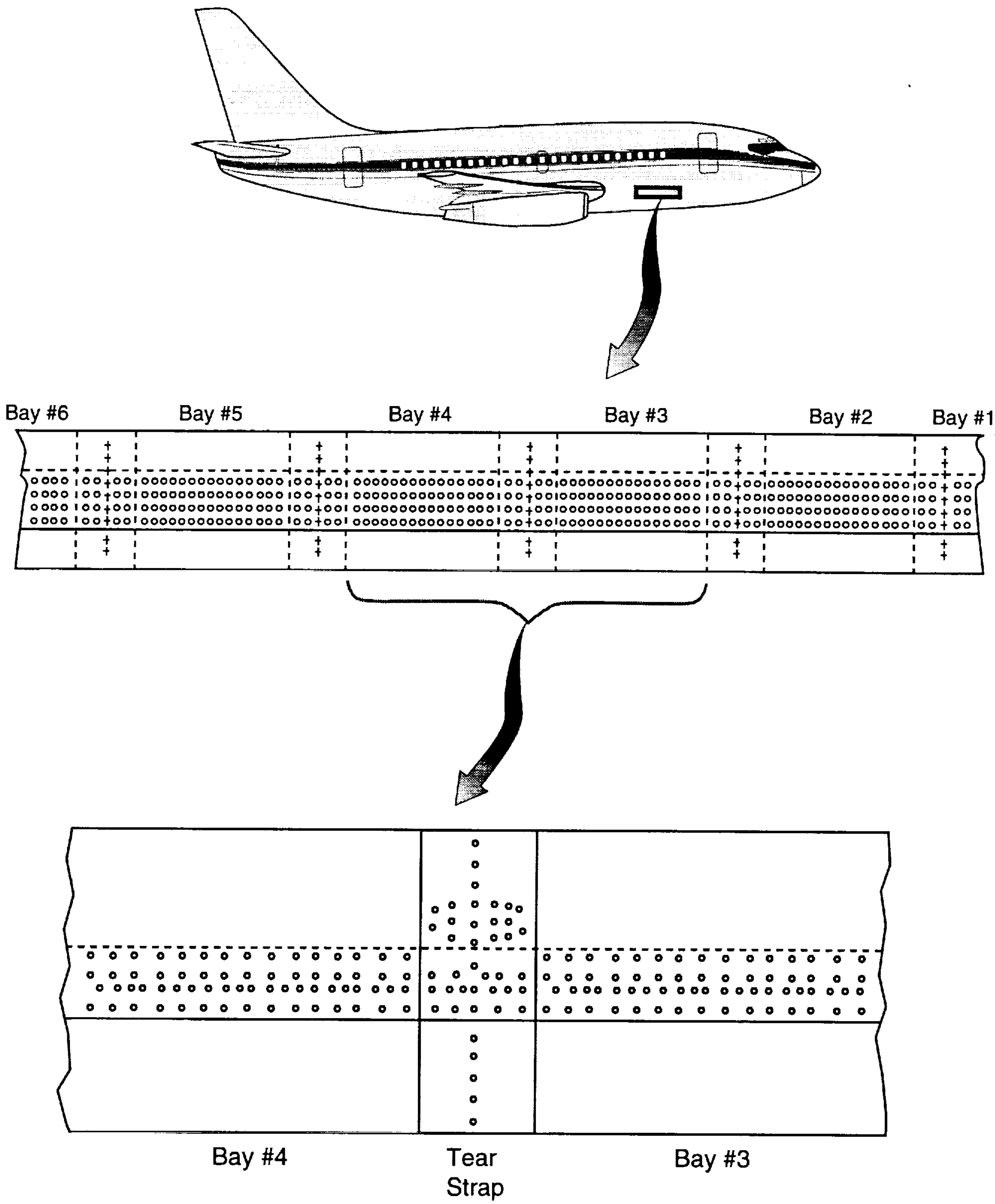
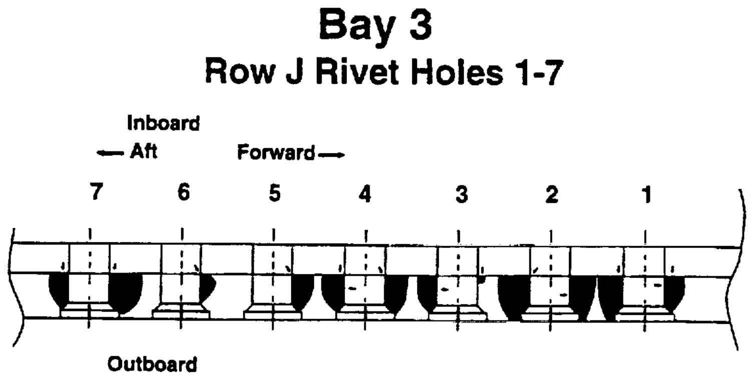
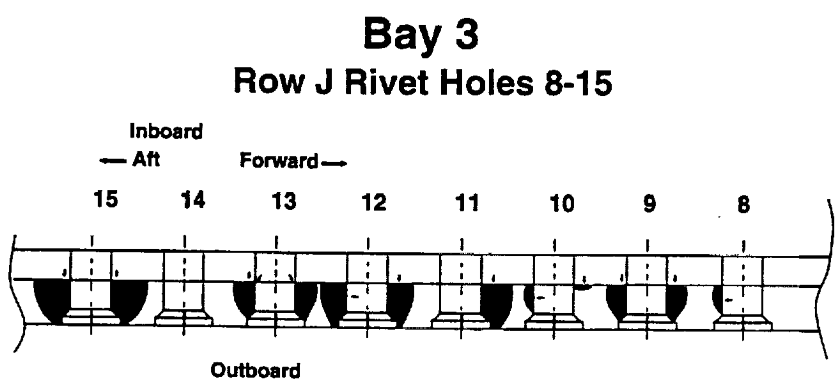


Fig. 1 Bay #3 and Bay #4 from the widespread fatigue panel.



Hole #	Location	Length mm (in)	Type	Initiation site
1 (Aft)	Outer Skin	4.733 (0.186)	Fretting	Inner skin / outer skin
1 (Fwd)	Outer Skin	2.550 (0.100)	Fretting	Inner skin / outer skin
2 (Aft)	Outer Skin	2.300 (0.091)	Through	Inboard corner
2 (Fwd)	Outer Skin	4.222 (0.166)	Through	Not determined
3 (Aft)	Outer Skin	1.625 (0.064)	Countersink	Counterbore
3 (Fwd)	Outer Skin	1.071 (0.042)	Fretting	Inner skin / outer skin
4 (Aft)	Outer Skin	1.833 (0.072)	Countersink	Multiple
4 (Fwd)	Outer Skin	2.439 (0.096)	Countersink	Inboard corner
5 (Fwd)	Outer Skin	1.737 (0.068)	Countersink	Inboard corner
6 (Fwd)	Outer Skin	0.662 (0.026)	Countersink	Inboard corner
7 (Aft)	Outer Skin	1.419 (0.056)	Countersink	Inboard corner
7 (Fwd)	Outer Skin	2.500 (0.098)	Fretting	Inner skin / outer skin

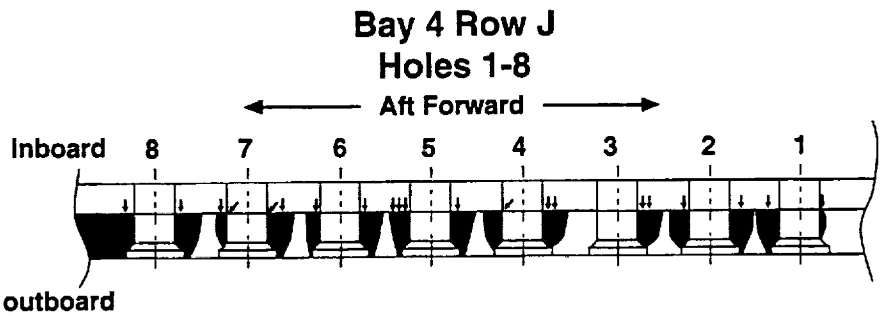
a) Rivet holes 1-7.



Hole #	Location	Length mm (in)	Type	Initiation site
8 (Aft)	Outer Skin	0.742 (0.029)	Countersink	Center of counterbore
9 (Aft)	Outer Skin	1.737 (0.068)	Countersink	Inner skin / outer skin
9 (Fwd)	Outer Skin	1.130 (0.044)	Countersink	Inner skin / outer skin
10 (Aft)	Outer Skin	0.905 (0.036)	Countersink	Center of counterbore
10 (Fwd)	Outer Skin	0.307 (0.012)	Fretting	Inner skin / outer skin
11 (Aft)	Outer Skin	4.160 (0.164)	Countersink	Inner skin / outer skin
12 (Aft)	Outer Skin	3.220 (0.127)	Through	Center of counterbore
12 (Fwd)	Outer Skin	4.890 (0.192)	Through	Inner skin / outer skin
13 (Aft)	Outer Skin	2.030 (0.080)	Countersink	Multiple
13 (Fwd)	Outer Skin	2.500 (0.098)	Countersink	Inner skin / outer skin
15 (Aft)	Outer Skin	3.040 (0.120)	Through	Inner skin / outer skin
15 (Fwd)	Outer Skin	2.980 (0.115)	Through	Inner skin / outer skin

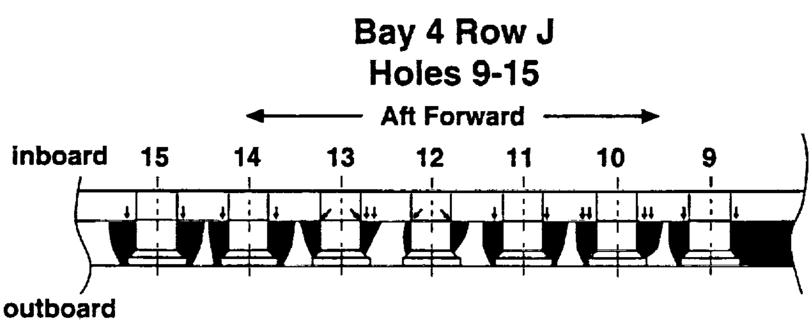
b) Rivet holes 8-15.

Fig. 2. Schematic of Bay #3 upper rivet row.



Hole #	Location	Length mm(in)	Type	Initiation site
1 (Aft)	Outer skin	2.893 (0.114)	Fretting	Inner skin/Outer skin
1 (Fwd)	Outer skin	0.769 (0.030)	Fretting	IS/OS
2 (Aft)	Outer skin	0.905 (0.036)	Fretting	IS/OS
2 (Fwd)	Outer skin	2.814 (0.111)	Fretting	IS/OS
3 (Fwd)	Outer skin	2.427 (0.096)	Fretting	IS/OS multiple
4 (Aft)	Outer skin	2.497 (0.098)	Fretting	IS/OS multiple
4 (Fwd)	Outer skin	2.700 (0.106)	Countersink	Inboard corner
5 (Aft)	Outer skin	5.334 (0.210)	Fretting	IS/OS multiple
5 (Fwd)	Outer skin	5.279 (0.207)	Fretting	IS/OS
6 (Aft)	Outer skin	2.714 (0.107)	Fretting	IS/OS
6 (Fwd)	Outer skin	3.848 (0.152)	Fretting	IS/OS
7 (Aft)	Outer skin	1.113 (0.044)	Fretting	IS/OS, inboard corner
7 (Fwd)	Outer skin	3.310 (0.130)	Fretting	IS/OS, inboard corner
8 (Aft)	Outer skin	Linkup with 4J9 (Fwd)	Fretting	IS/OS
8 (Fwd)	Outer skin	12.954 (0.510)	Fretting	IS/OS

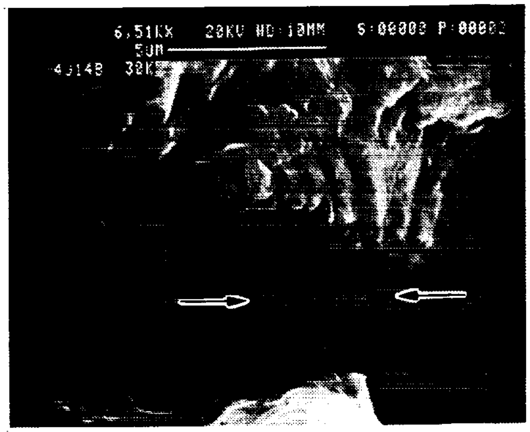
a) Rivet holes 1-8.



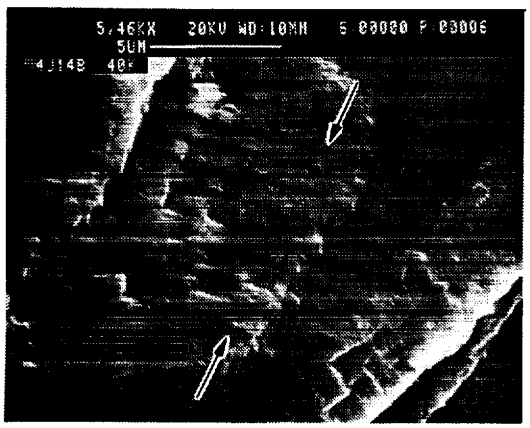
Hole #	Location	Length mm(in)	Type	Initiation site
9 (Aft)	Outer skin	8.265 (0.325)	Fretting	Inner skin/Outer skin
9 (Fwd)	Outer skin	Linkup with 4J8(Aft)	Fretting	IS/OS
10 (Aft)	Outer skin	4.194 (0.165)	Fretting	IS/OS multiple
10 (Fwd)	Outer skin	3.042 (0.120)	Fretting	IS/OS multiple
11 (Aft)	Outer skin	5.397 (0.212)	Fretting	IS/OS
11 (Fwd)	Outer skin	5.675 (0.223)	Fretting	IS/OS
12 (Aft)	Outer skin	1.874 (0.074)	Countersink	Inboard corner
12 (Fwd)	Outer skin	2.460 (0.097)	Countersink	Inboard corner
13 (Aft)	Outer skin	1.835 (0.072)	Countersink	Inboard corner
13 (Fwd)	Outer skin	1.102 (0.043)	Fretting	IC,IS/OS multiple
14 (Aft)	Outer skin	2.995 (0.118)	Fretting	IS/OS
14 (Fwd)	Outer skin	2.810 (0.111)	Fretting	IS/OS
15 (Aft)	Outer skin	8.559 (0.337)	Fretting	IS/OS
15 (Fwd)	Outer skin	6.959 (0.274)	Fretting	IS/OS

b) Rivet holes 9-15.

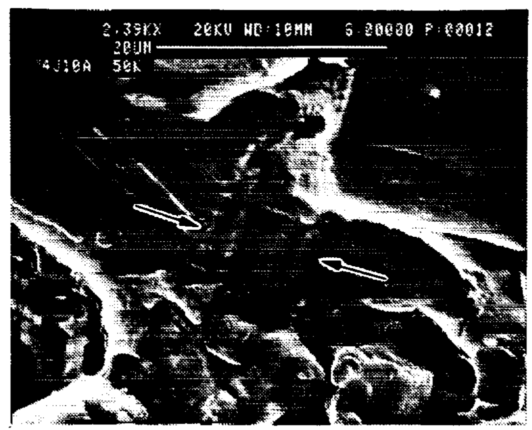
Fig. 3. Schematic of Bay #4 upper rivet row.



a)



b)

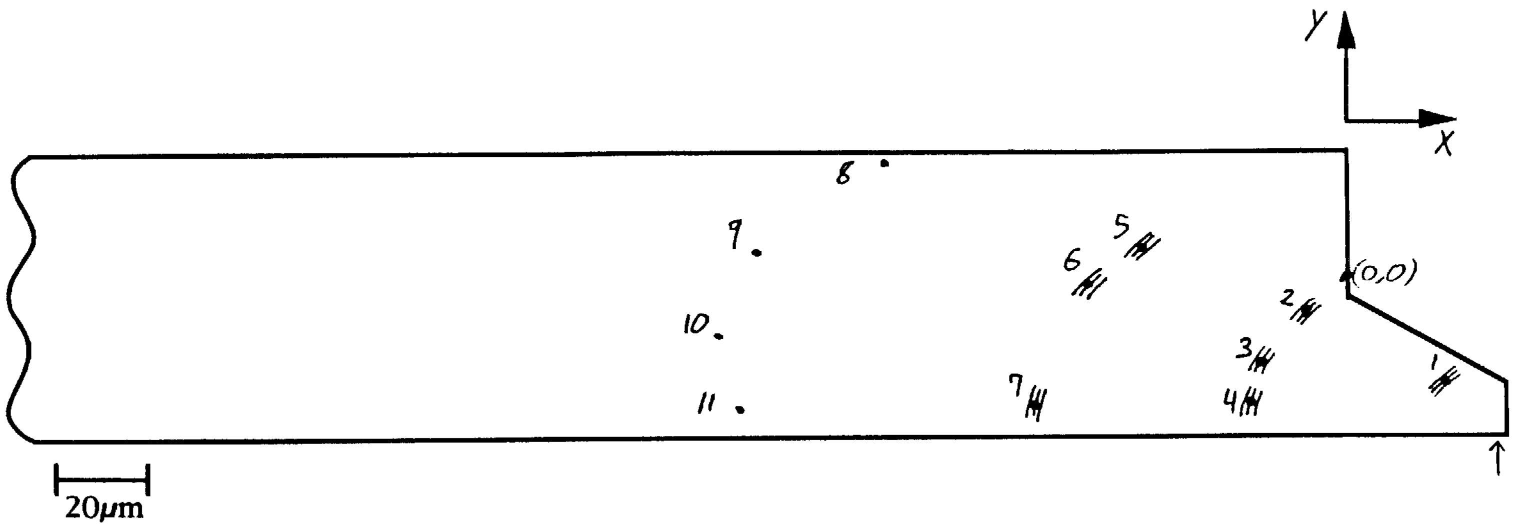


c)

Fig. 4. SEM micrographs of: a) 6 marker bands between arrows comprising a 30 K set of marker bands. b) 10 marker bands between arrows comprising a 40 K set of marker bands. c) 4 marker bands between arrows comprising a 40 K set of marker bands.

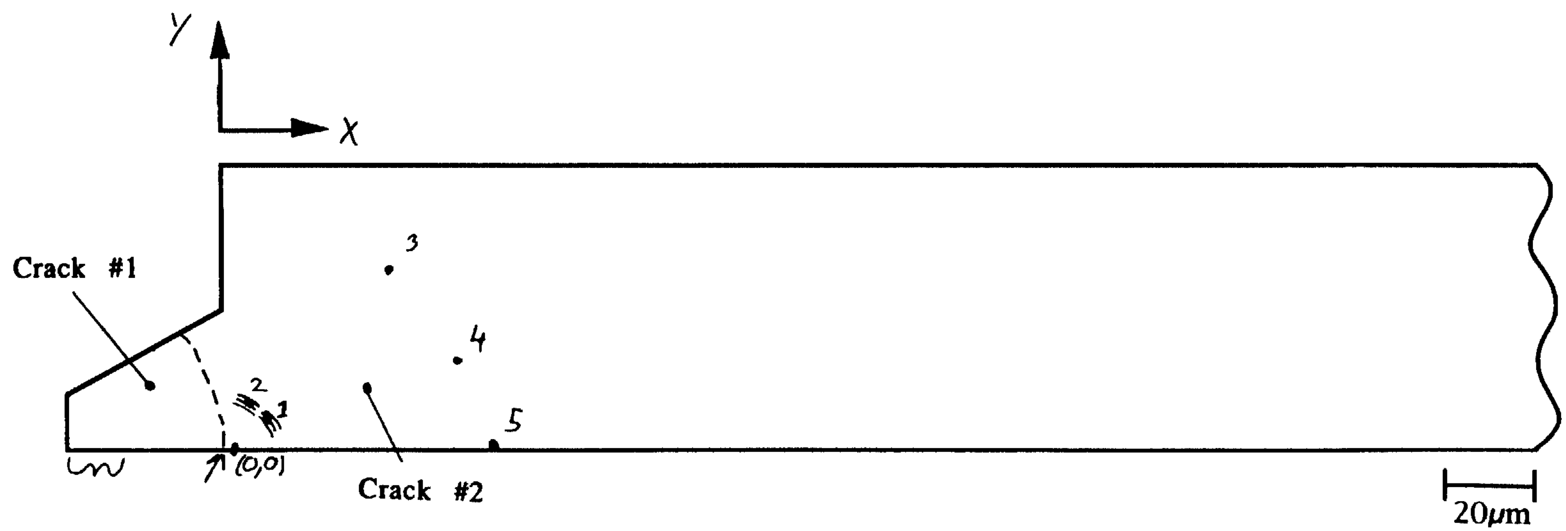
Appendix A

Bay #3 Marker Bands



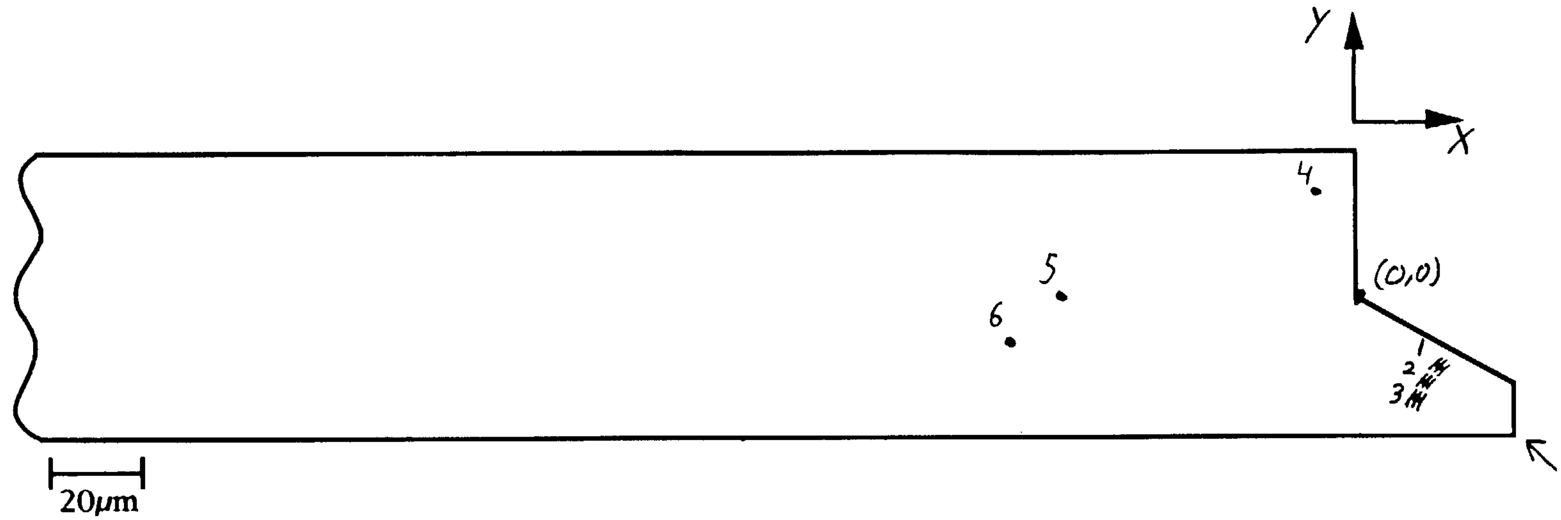
#	Coordinates (mm) [in]		# of Bands (cycles)	Comments
1	(0.55,-0.6)	[0.022,-0.024]	3(30K)	Fair
2	(-0.265,-0.2)	[-0.010,-0.008]	9(40K)	Good
3	(-0.4875,-0.5)	[-0.019,-0.020]	9(40K)	Poor
4	(-0.5375,-0.6825)	[-0.021,-0.027]	9(40K)	Poor
5	(-1.13,0.2075)	[-0.051,0.008]	4(50K)	Good
6	(-1.425,0.0)	[-0.056,0.000]	4(50K)	Poor
7	(-1.725,-0.655)	[-0.068,-0.026]	4(50K)	Good-Fair
8	(-2.61,0.6225)	[-0.103,0.025]	Crack Front	
9	(-3.3125,0.1583)	[-0.130,0.006]	Crack Front	
10	(-3.53,-0.325)	[-0.139,-0.013]	Crack Front	
11	(-3.63,-0.725)	[0.143,-0.028]	Crack Front	

Figure A1 - Rivet hole schematic: Upper rivet row, hole number 3J1, fatigue crack growth is in the aft direction.



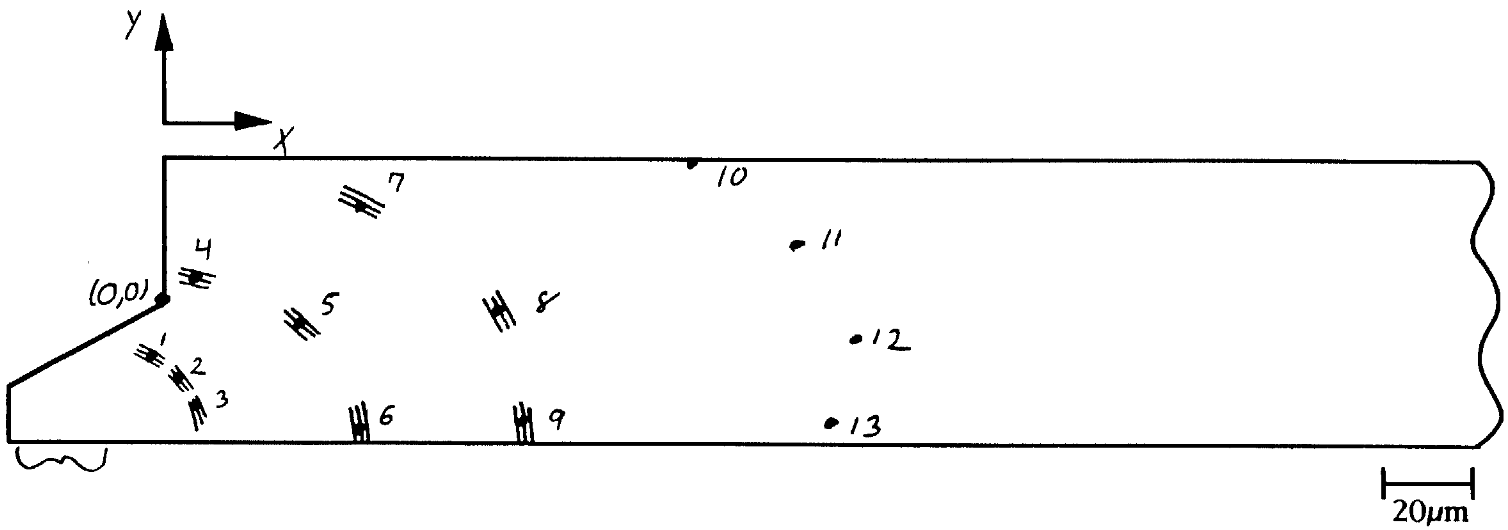
#	Coordinates (mm)	[in]	# of Bands (cycles)	Comments
1	(0.2,0.15)	[0.008,0.006]	4(50K)	
2	(0.0875,0.2625)	[0.014,0.041]	4(50K)	
3	(0.85,1.0)	[0.033,0.039]	Crack Front	
4	(1.2,0.5)	[0.047,0.020]	Crack Front	
5	(1.45,0.0)	[0.057,0.000]	Crack Front	

Figure A2 - Rivet hole schematic: Upper rivet row, hole number 3J1, fatigue crack growth is in the forward direction.



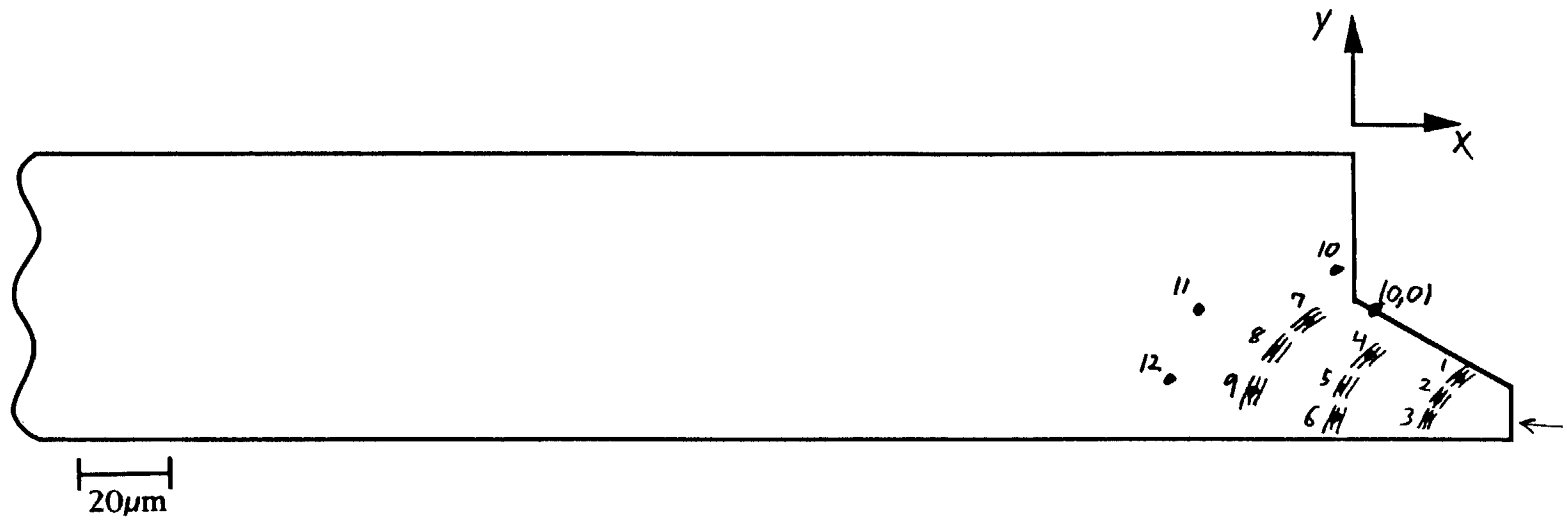
#	Coordinates (mm) [in]	# of Bands (cycles)	Comments
1	(0.4425,-0.3925)[0.017,-0.015]	9(40K)	
2	(0.35,-0.48) [0.014,-0.019]	9(40K)	
3	(0.3175,-0.5525)[0.013,-0.022]	9(40K)	
4	(-0.233,0.581) [-0.009,0.023]	Crack Front	
5	(-1.65,0.0) [-0.065,0.000]	Crack Front	
6	(-1.94,-0.271) [-0.076,-0.011]	Crack Front	

Figure A3 - Rivet hole schematic: Upper rivet row, hole number 3J2, fatigue crack growth is in the aft direction.



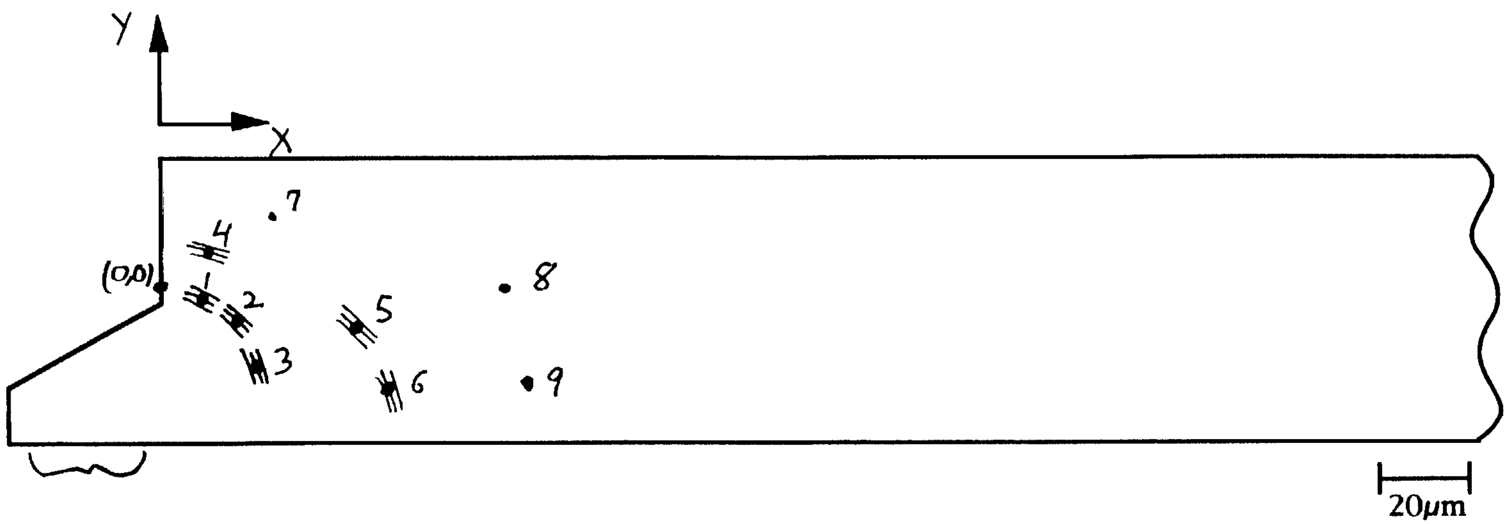
#	Coordinates (mm)	[in]	# of Bands (cycles)	Comments
1	(0.05,-0.3)	[0.002,-0.012]	3(30K)	Poor
2	(0.1125,-0.4125)	[0.004,-0.016]	3(30K)	Fair-Good
3	(0.2125,-0.525)	[0.008,-0.021]	3(30K)	Poor-Fair
4	(0.1625,0.125)	[0.006,0.005]	4(40K)	Fair
5	(0.75,-0.1325)	[0.030,-0.005]	4(40K)	Good
6	(0.9875,-0.7125)	[0.039,-0.028]	4(40K)	Fair
7	(1.0875,0.5)	[0.043,0.020]	5(50K)	
8	(1.8375,-0.05)	[0.072,-0.002]	5(50K)	
9	(2.005,-0.625)	[0.079,-0.025]	5(50K)	Fair
10	(2.95,0.85)	[0.116,0.033]	Crack Front	
11	(3.55,0.35)	[0.140,0.014]	Crack Front	
12	(3.85,-0.24)	[0.152,-0.009]	Crack Front	
13	(3.72,-0.6)	[0.146,-0.024]	Crack Front	

Figure A4 - Rivet hole schematic: Upper rivet row, hole number 3J2, fatigue crack growth is in the forward direction.



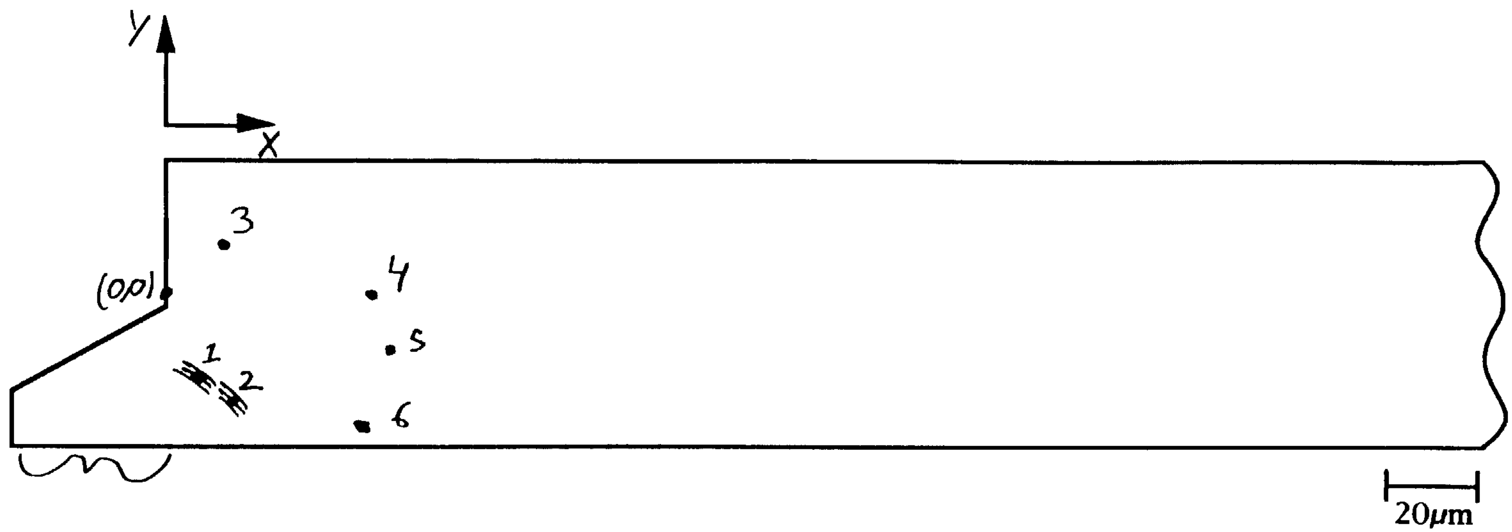
#	Coordinates (mm)	[in]	# of Bands (cycles)	Comments
1	(0.45,-0.3875)	[0.018,-0.015]	6(30K)	Fair
2	(0.3125,-0.475)	[0.012,-0.019]	6(30K)	Fair
3	(0.2675,-0.5375)	[0.011,-0.021]	6(30K)	Poor
4	(-0.0125,-0.2375)	[-0.0005,-0.009]	9(40K)	Poor
5	(-0.1875,-0.425)	[-0.007,-0.017]	9(40K)	Fair
6	(-0.2,-0.5875)	[-0.008,-0.023]	9(40K)	Good
7	(-0.375,-0.0625)	[-0.015,-0.002]	4(50K)	Good
8	(-0.5625,-0.225)	[-0.022,-0.009]	4(50K)	Fair
9	(-0.65,-0.4)	[-0.026,-0.016]	4(50K)	Fair
10	(-0.225,0.25)	[-0.009,0.010]	Crack Front	
11	(-1.0,0)	[-0.039,0.000]	Crack Front	
12	(-1.135,-0.35)	[-0.045,-0.014]	Crack Front	

Figure A5 - Rivet hole schematic: Upper rivet row, hole number 3J4, fatigue crack growth is in the aft direction.



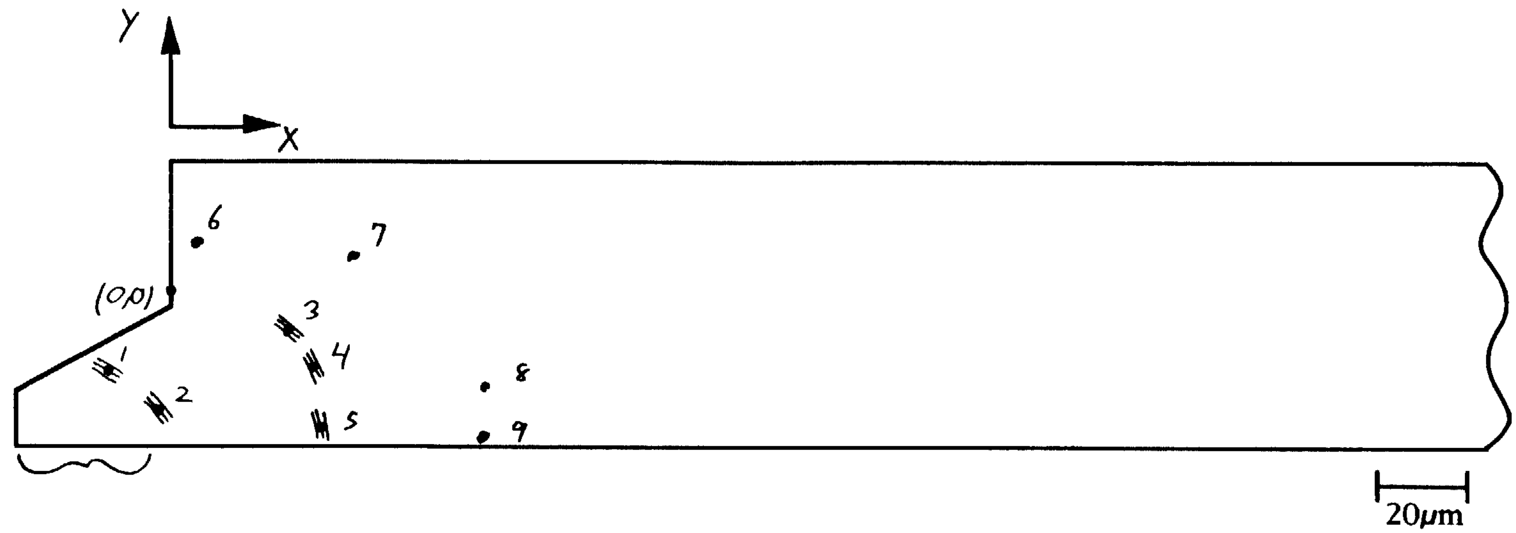
#	Coordinates (mm)	[in]	# of Bands (cycles)	Comments
1	(0.2325,-0.025)	[0.009,-0.001]	9(40K)	Poor
2	(0.32,-0.17)	[0.013,-0.007]	9(40K)	Good
3	(0.5125,-0.405)	[0.020,-0.016]	9(40K)	Fair
4	(0.2125,0.225)	[0.008,0.009]	4(50K)	
5	(1.095,-0.175)	[0.043,-0.007]	4(50K)	Fair
6	(1.1625,-0.45)	[0.046,-0.018]	4(50K)	Good
7	(0.4,0.595)	[0.016,0.024]	Crack Front	
8	(1.95,0.0)	[0.077,0.000]	Crack Front	
9	(2.005,-0.5)	[0.080,-0.020]	Crack Front	

Figure A6 - Rivet hole schematic: Upper rivet row, hole number 3J4, fatigue crack growth is in the forward direction.



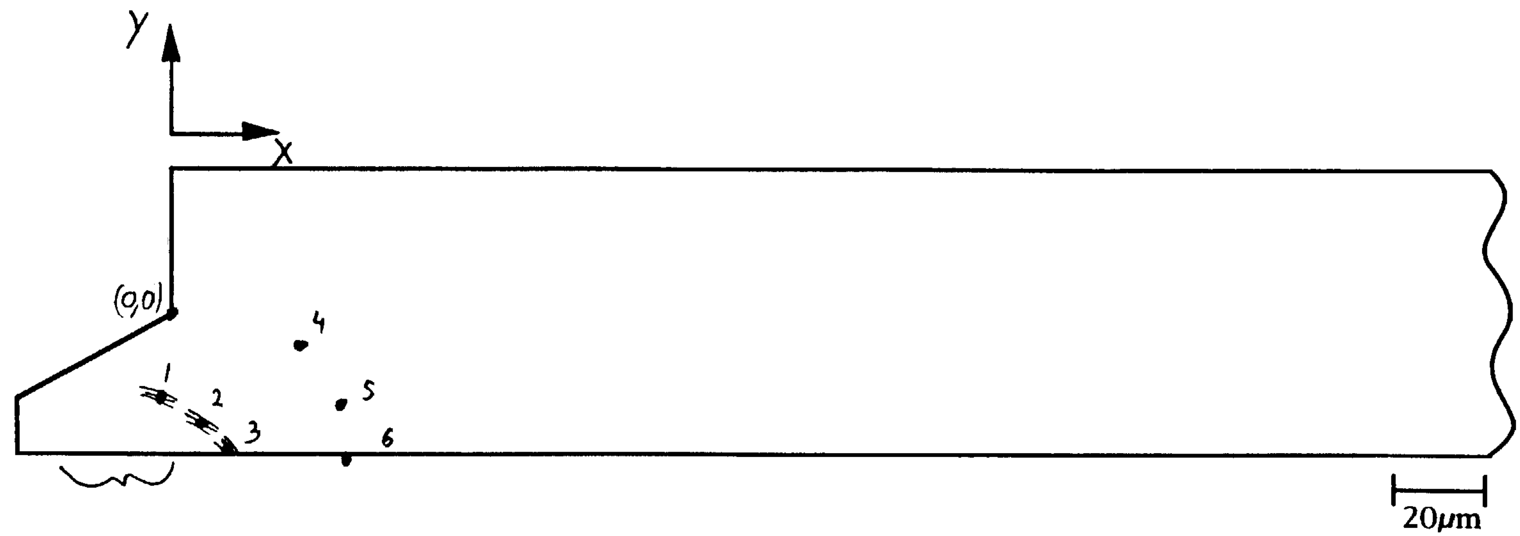
#	Coordinates (mm) [in]		# of Bands (cycles)	Comments
1	(0.4425,-0.425)	[0.017,-0.017]	4(50K)	
2	(0.5125,-0.595)	[0.020,-0.023]	4(50K)	
3	(0.25,0.225)	[0.010,0.009]	Crack Front	
4	(0.95,0.0)	[0.037,0.000]	Crack Front	
5	(1.225,-0.33)	[0.048,-0.013]	Crack Front	
6	(1.04,-0.73)	[0.041,-0.029]	Crack Front	

Figure A7 - Rivet hole schematic: Upper rivet row, hole number 3J5, fatigue crack growth is in the forward direction.



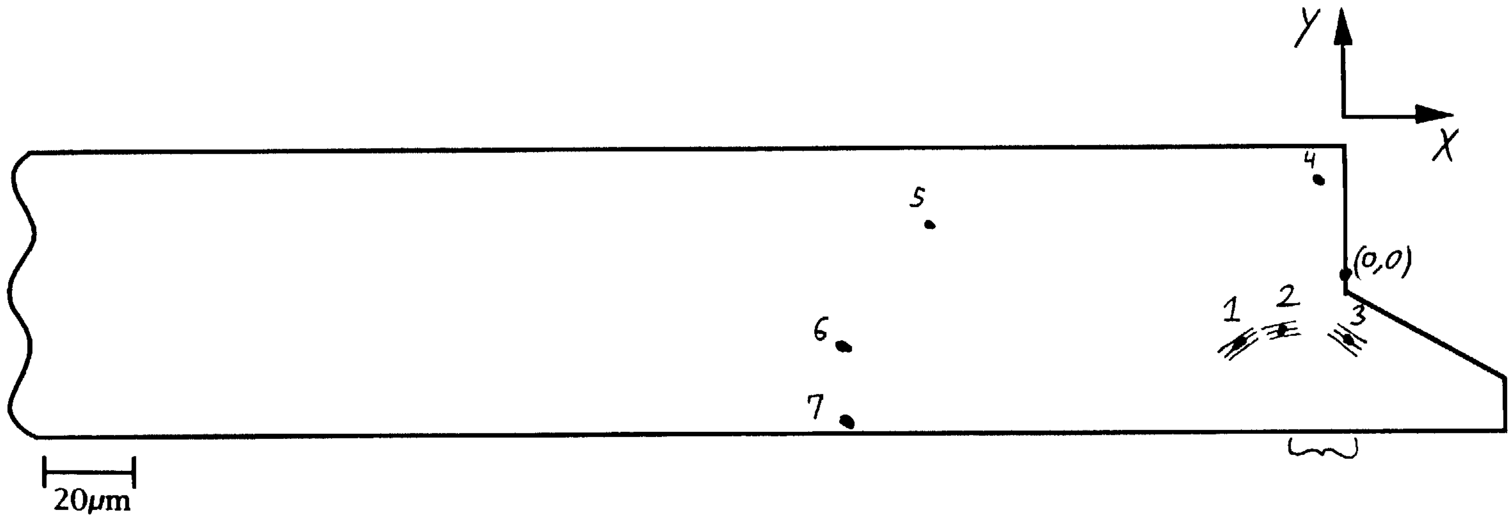
#	Coordinates (mm) [in]	# of Bands (cycles)	Comments
1	(-0.3125,-0.4125)[-0.012,-0.016]	9(40K)	
2	(-0.0625,-0.625) [-0.002,-0.020]	9(40K)	
3	(0.6175,-0.2125)[0.024,-0.009]	4(50K)	
4	(0.775,-0.4125) [0.031,-0.016]	4(50K)	
5	(0.825,-0.75) [0.032,-0.030]	4(50K)	
6	(0.12,0.29) [0.005,0.011]	Crack Front	
7	(1.0,0.24) [0.039,0.009]	Crack Front	
8	(1.75,-0.5) [0.069,-0.020]	Crack Front	
9	(1.71,-0.85) [0.067,-0.033]	Crack Front	

Figure A8 - Rivet hole schematic: Upper rivet row, hole number 3J7, fatigue crack growth is in the forward direction.



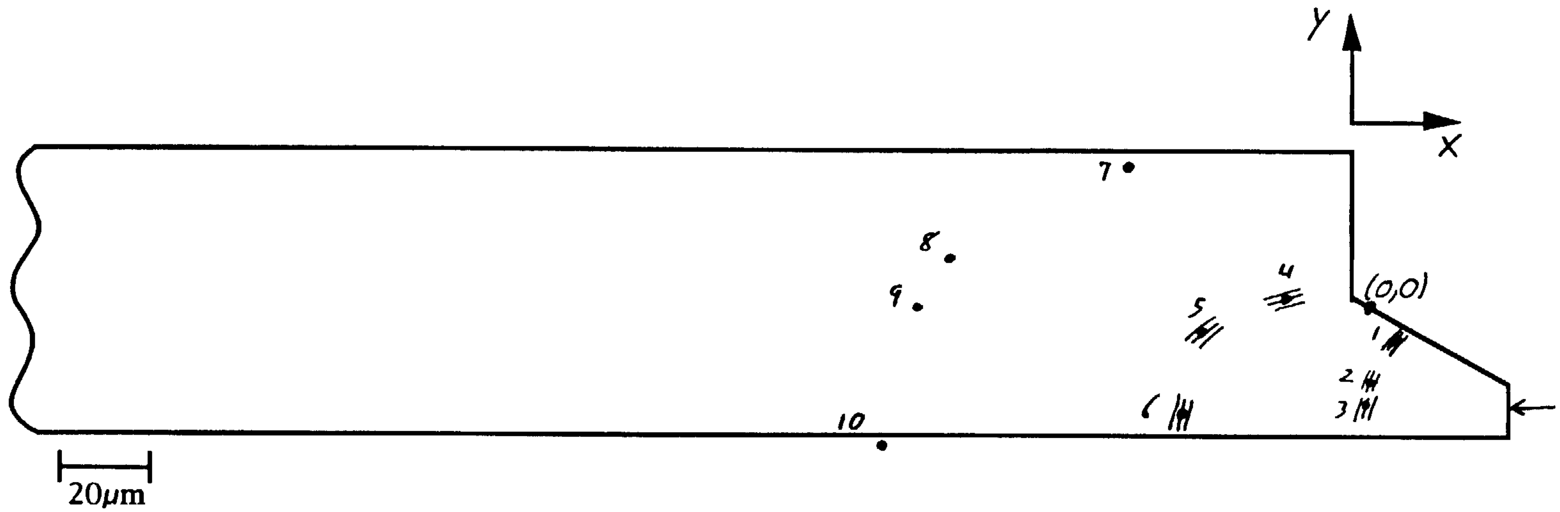
#	Coordinates (mm) [in]	# of Bands (cycles)	Comments
1	(-0.0875,-0.455) [-0.003,-0.018]	4(50K)	
2	(0.1625,-0.6025)[0.006,-0.024]	4(50K)	
3	(0.2725,-0.8125)[0.011,-0.032]	4(50K)	
4	(0.7,-0.2) [0.028,-0.008]	Crack Front	
5	(0.91,-0.5) [0.036,-0.020]	Crack Front	
6	(0.98,-0.91) [0.039,-0.036]	Crack Front	

Figure A9 - Rivet hole schematic: Upper rivet row, hole number 3J9, fatigue crack growth is in the aft direction.



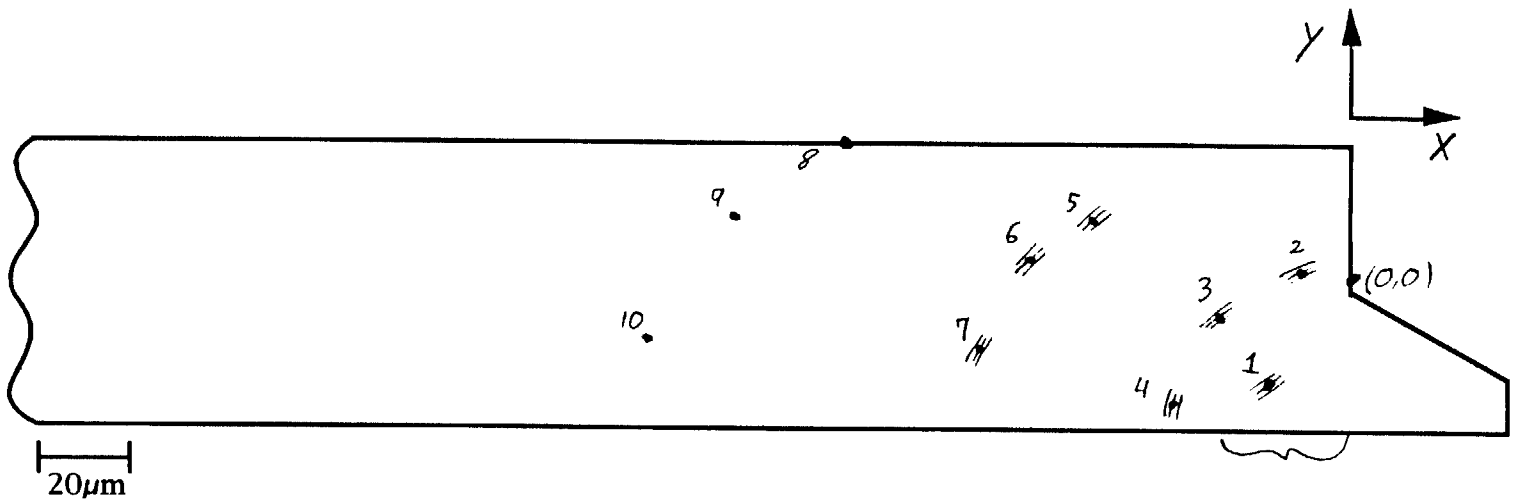
#	Coordinates (mm) [in]		# of Bands (cycles)	Comments
1	(-0.6075,-0.375)	[-0.024,-0.015]	9(40K)	
2	(-0.33,-0.355)	[-0.013,-0.014]	9(40K)	
3	(0.0,-0.4375)	[0.000,-0.017]	9(40K)	
4	(-0.157,0.52)	[-0.006,0.020]	Crack Front	
5	(-2.35,0.3)	[-0.092,0.012]	Crack Front	
6	(-2.85,-0.4)	[-0.112,-0.016]	Crack Front	
7	(-2.82,-0.8)	[-0.111,-0.031]	Crack Front	

Figure A10 - Rivet hole schematic: Upper rivet row, hole number 3J11, fatigue crack growth is in the forward direction.



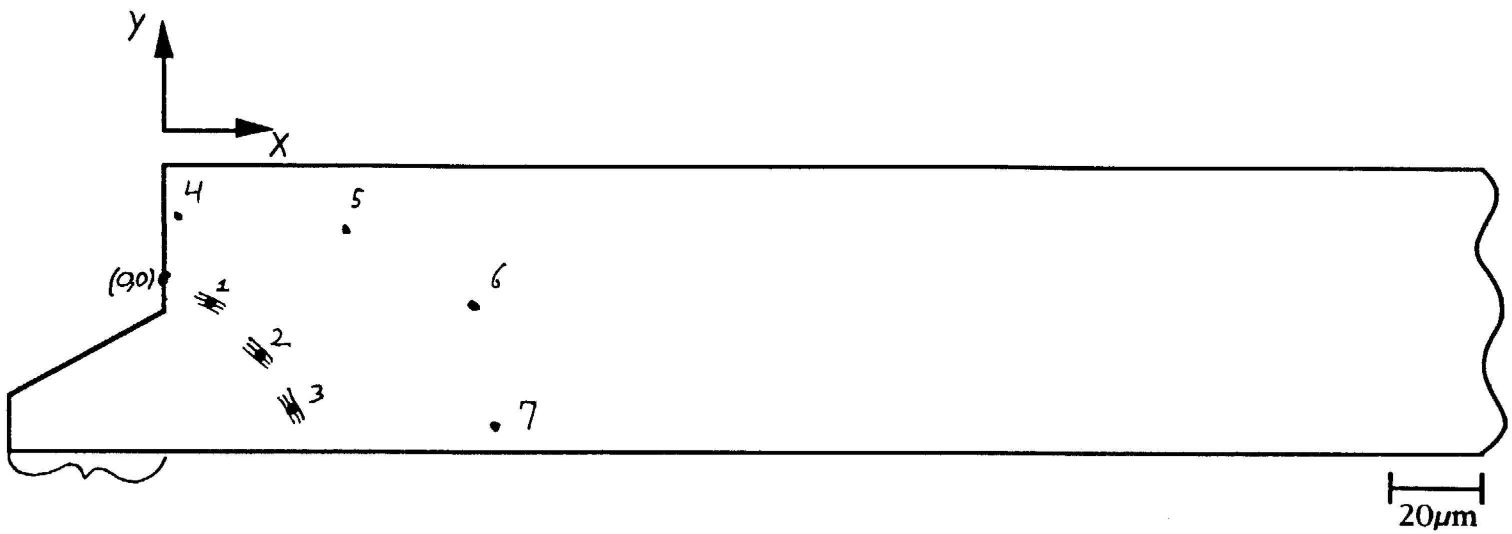
#	Coordinates (mm) [in]	# of Bands (cycles)	Comments
1	(0.0825,-0.1725)[0.003,-0.007]	9(40K)	Poor
2	(-0.05,-0.3875) [-0.002,-0.015]	9(40K)	Poor
3	(-0.05,-0.4875) [-0.002,-0.019]	9(40K)	Poor
4	(-0.55,0.0375) [-0.022,0.001]	4(50K)	Good
5	(-1.0,-0.125) [-0.039,-0.005]	4(50K)	Good
6	(-1.1375,-0.6) [-0.045,-0.024]	4(50K)	Fair
7	(-1.385,0.775) [-0.055,0.031]	Crack Front	
8	(-2.375,0.275) [-0.094,0.011]	Crack Front	
9	(-2.575,0.0) [-0.101,0.000]	Crack Front	
10	(-2.75,-0.775) [-0.108,-0.031]	Crack Front	

Figure A11 - Rivet hole schematic: Upper rivet row, hole number 3J12, fatigue crack growth is in the aft direction.



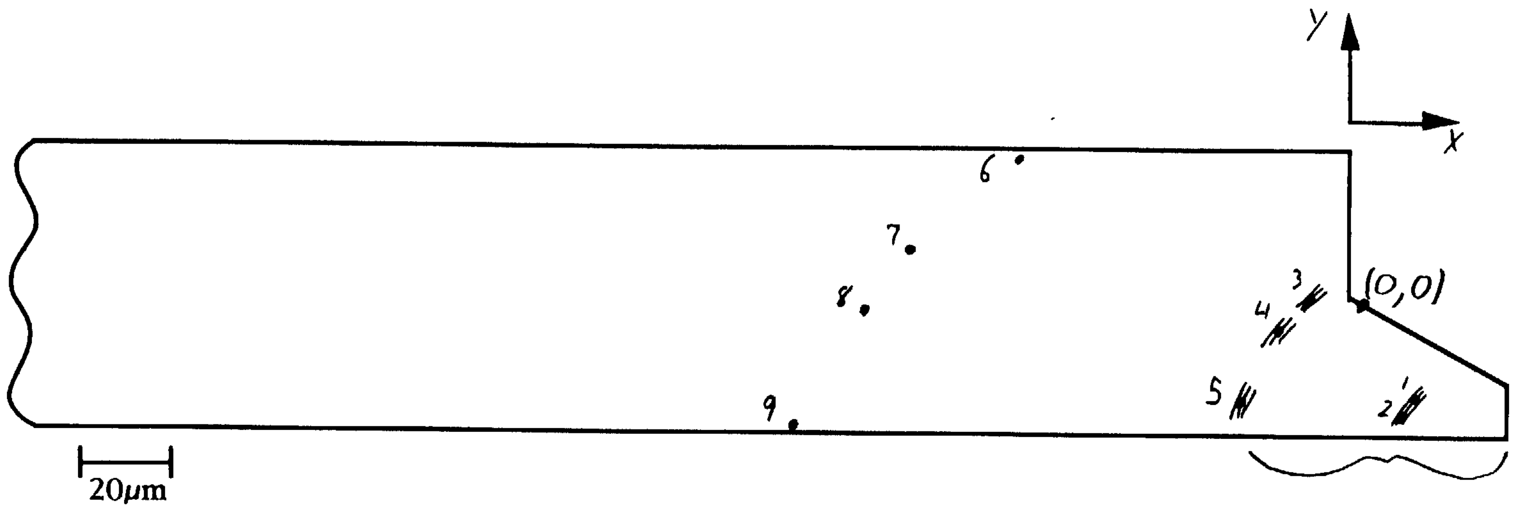
#	Coordinates (mm) [in]	# of Bands (cycles)	Comments
1	(-0.4325,-0.5675)[-0.017,-0.022]	3(30K)	Good
2	(-0.2625,0.0125)[-0.010,0.0005]	9(40K)	Fair
3	(-0.75,-0.225) [-0.030,-0.009]	9(40K)	Good
4	(-0.995,-0.6625) [-0.039,-0.026]	9(40K)	Fair-Poor
5	(-1.45,0.33) [-0.057,0.013]	4(50K)	Good-Fair
6	(-1.7875,0.125) [-0.070,0.005]	4(50K)	Good
7	(-2.1075,-0.4) [-0.083,-0.016]	4(50K)	Fair
8	(-2.82,0.73) [-0.111,0.029]	Crack Front	
9	(-3.48,0.35) [-0.137,0.014]	Crack Front	
10	(-3.97,-0.38) [-0.156,-0.015]	Crack Front	

Figure A12 - Rivet hole schematic: Upper rivet row, hole number 3J12, fatigue crack growth is in the forward direction.



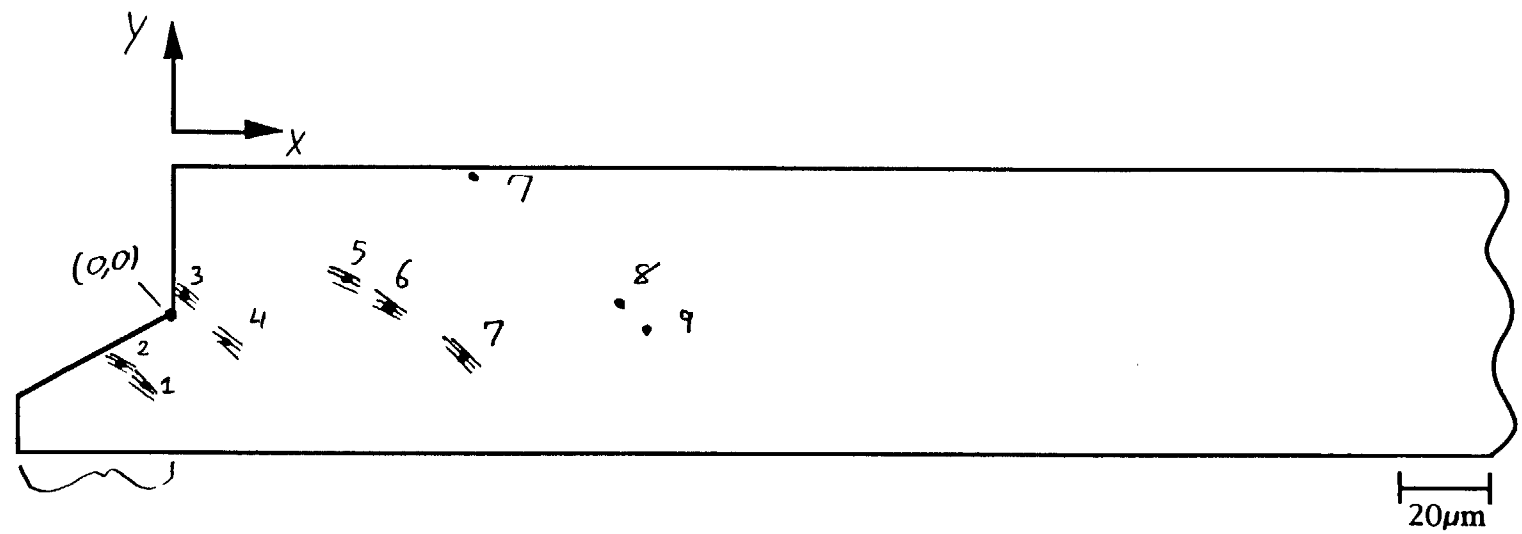
#	Coordinates (mm)	[in]	# of Bands (cycles)	Comments
1	(0.25,-0.1175)	[0.01,-0.005]	9(40K)	Good-Fair
2	(0.525,-0.3375)	[0.020,-0.013]	9(40K)	Fair
3	(0.7375,-0.675)	[0.029,-0.266]	9(40K)	Fair
4	(0.08,0.36)	[0.003,0.014]	Crack Front	
5	(1.02,0.3)	[0.040,0.011]	Crack Front	
6	(1.72,-0.2)	[0.068,-0.008]	Crack Front	
7	(1.85,-0.78)	[0.073,-0.031]	Crack Front	

Figure A13 - Rivet hole schematic: Upper rivet row, hole number 3J13, fatigue crack growth is in the forward direction.



#	Coordinates (mm)	[in]	# of Bands (cycles)	Comments
1	(0.2375,-0.5)	[0.009,-0.020]	3(30K)	
2	(0.175,-0.64)	[0.007,-0.025]	3(30K)	
3	(-0.325,0.0)	[-0.013,0.000]	9(40K)	
4	(-0.525,-0.1625)	[-0.021,-0.006]	9(40K)	
5	(-0.7125,-0.55)	[-0.028,-0.022]	9(40K)	
6	(-1.95,0.79)	[-0.077,0.031]	Crack Front	
7	(-2.55,0.28)	[-0.100,0.011]	Crack Front	
8	(-2.84,-0.05)	[-0.112,-0.002]	Crack Front	
9	(-3.2,-0.7)	[-0.126,-0.028]	Crack Front	

Figure A14 - Rivet hole schematic: Upper rivet row, hole number 3J15, fatigue crack growth is in the aft direction.

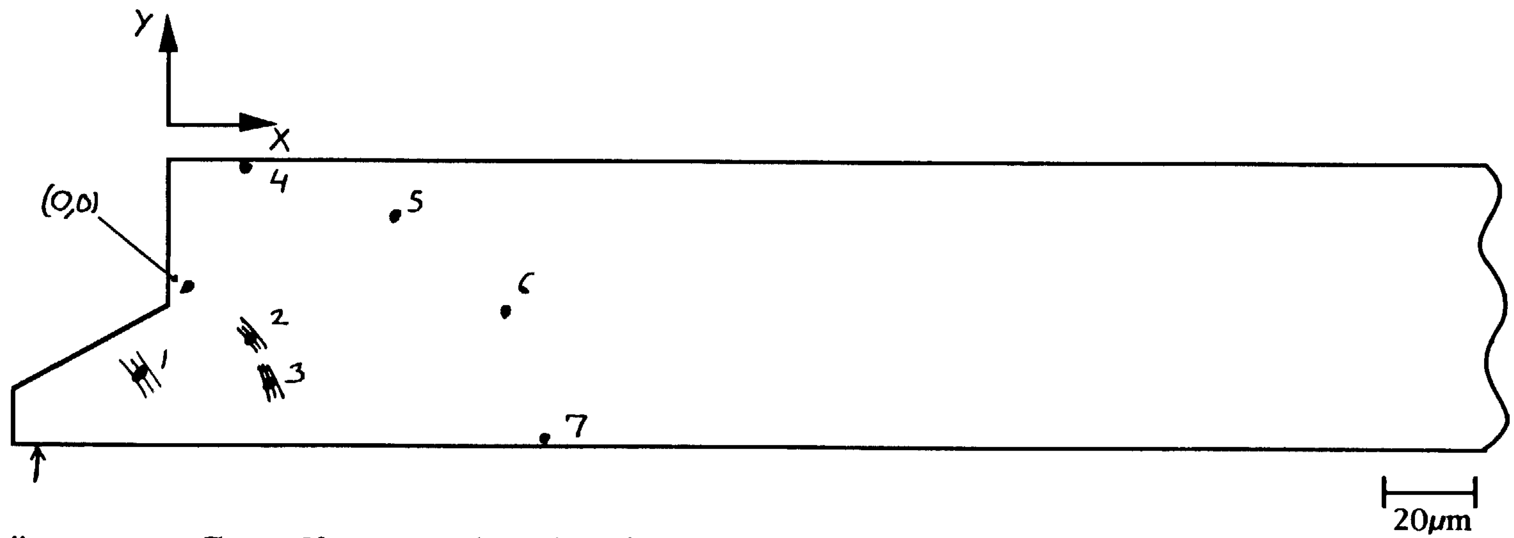


#	Coordinates (mm)	[in]	# of Bands (cycles)	Comments
1	(-0.15,-0.37)	[-0.006,-0.015]	3(30K)	Poor
2	(-0.29,-0.2625)	[-0.011,-0.010]	3(30K)	Poor
3	(0.135,-0.0375)	[0.005,-0.001]	9(40K)	Fair
4	(0.3,-0.175)	[0.012,-0.007]	9(40K)	Fair-Good
5	(0.9825,0.225)	[0.039,0.009]	4(50K)	Good
6	(1.1875,0.095)	[0.047,0.004]	4(50K)	Good
7	(1.625,-0.2325)	[0.064,-0.009]	4(50K)	Good-Fair
8	(1.67,0.8)	[0.066,0.031]	Crack Front	
9	(2.5,0.25)	[0.098,0.010]	Crack Front	
10	(2.7,-0.03)	[0.106,-0.001]	Crack Front	

Figure A15 - Rivet hole schematic: Upper rivet row, hole number 3J15, fatigue crack growth is in the forward direction.

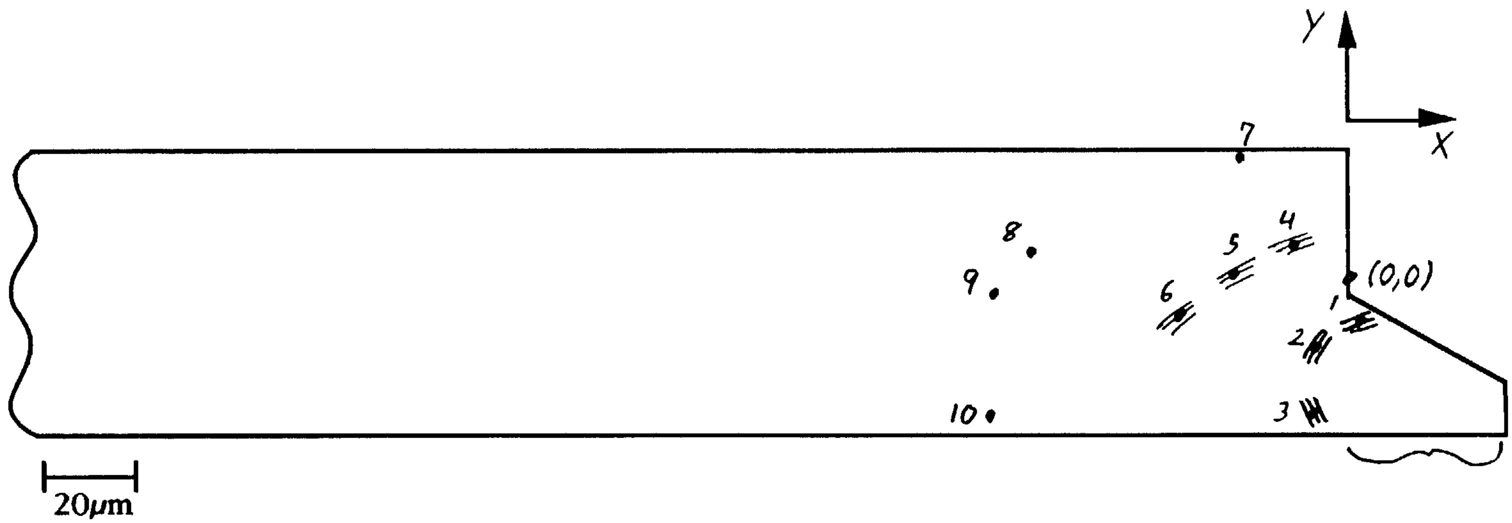
Appendix B

Bay #4 Marker Bands



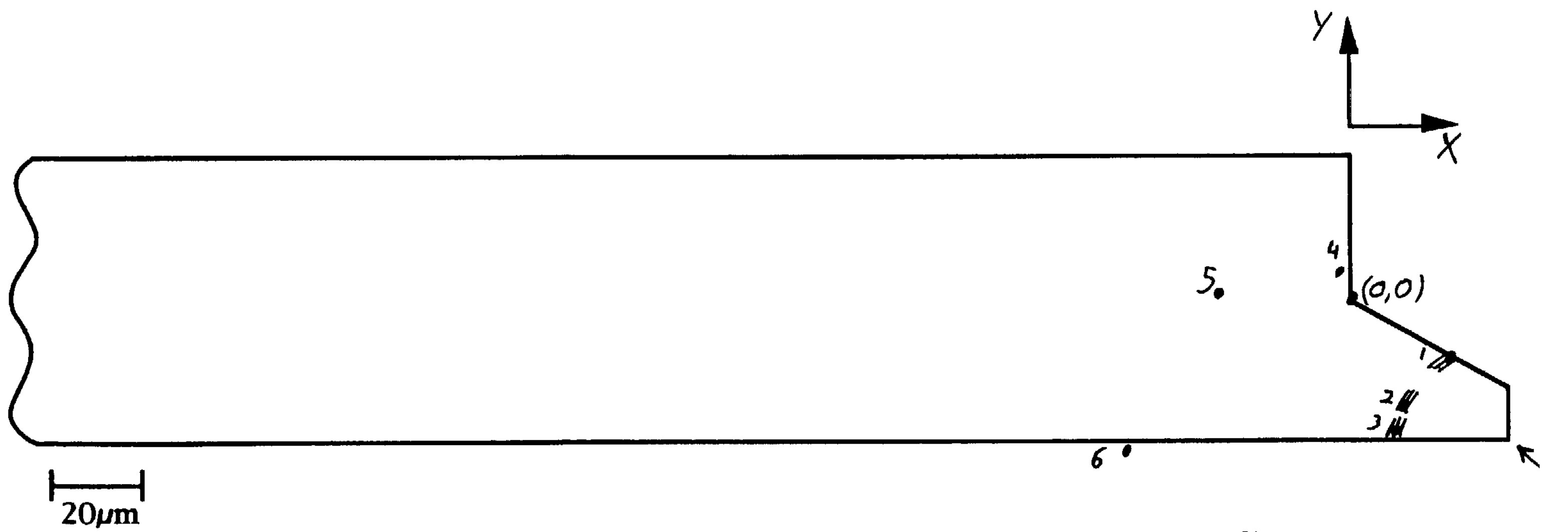
#	Coordinates (mm)	[in]	# of Bands (cycles)	Comments
1	(-0.27,-0.463)	[-0.011,-0.018]	6(30K)	
2	(0.35,-0.275)	[0.014,-0.011]	9(40K)	
3	(0.045,-0.525)	[0.018,-0.021]	9(40K)	
4	(0.3,0.65)	[0.012,0.026]	Crack Front	
5	(1.13,0.39)	[0.044,0.015]	Crack Front	
6	(1.8,-0.11)	[0.071,-0.004]	Crack Front	
7	(1.97,-0.85)	[0.078,-0.033]	Crack Front	

Figure B1 - Rivet hole schematic: Upper rivet row, hole number 4J1, fatigue crack growth is in the aft direction.



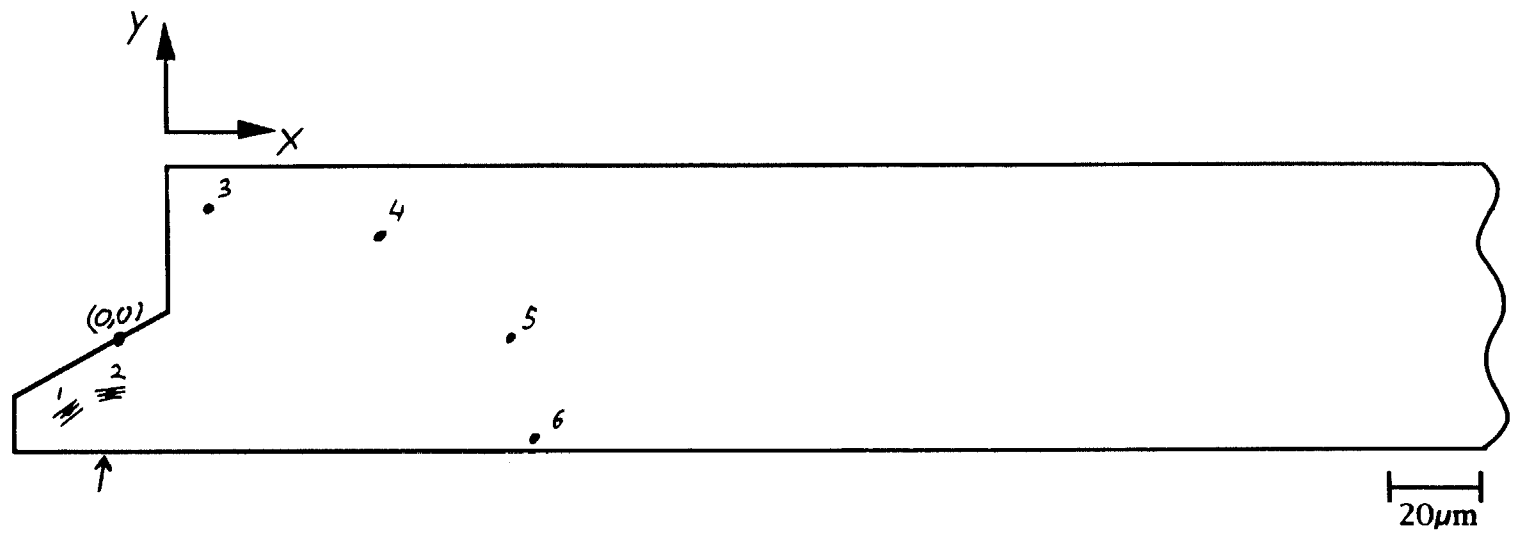
#	Coordinates (mm)	[in]	# of Bands (cycles)	Comments
1	(0.090,-0.210)	[0.004,-0.008]	10(40K)	
2	(-0.235,-0.45)	[-0.009,-0.018]	10(40K)	
3	(-0.200,-0.8125)	[-0.008,-0.032]	10(40K)	
4	(-0.330,0.170)	[-0.013,0.007]	4(50k)	
5	(-0.6875,-0.075)	[-0.027,-0.003]	4(50k)	
6	(-0.9625,-0.2625)	[-0.038,-0.010]	4(50k)	
7	(-0.62,0.62)	[-0.024,0.024]	Crack Front	
8	(-1.77,0.1)	[-0.070,0.004]	Crack Front	
9	(-2.05,-0.15)	[-0.081,-0.006]	Crack Front	
10	(-2.1,-0.92)	[-0.083,-0.036]	Crack Front	

Figure B2 - Rivet hole schematic: Upper rivet row, hole number 4J2, fatigue crack growth is in the forward direction.



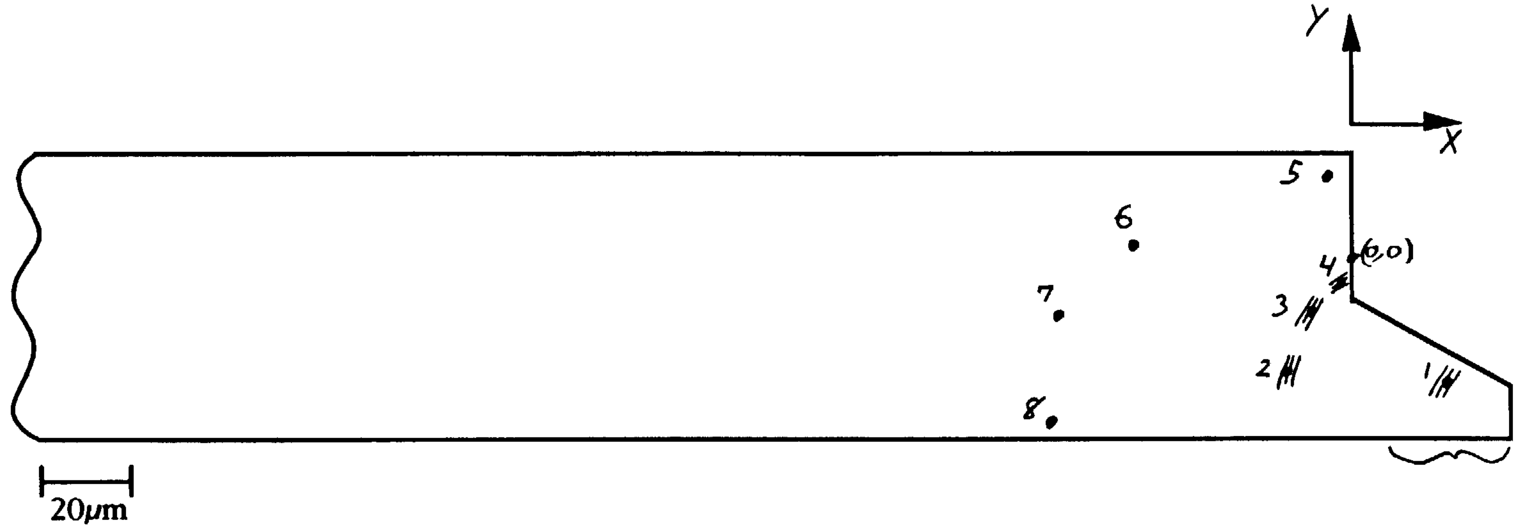
#	Coordinates (mm)	[in]	# of Bands (cycles)	Comments
1	(0.5625,-03125)	[0.022,-0.012]	10(40K)	Good
2	(0.300,-0.575)	[0.012,-0.023]	10(40K)	Good
3	(0.255,-0.775)	[0.010,-0.031]	10(40K)	Fair
4	(-0.07,0.18)	[-0.003,0.007]	Crack Front	
5	(-0.75,0.0)	[-0.029,0.000]	Crack Front	
6	(-1.29,-0.85)	[-0.041,-0.033]	Crack Front	

Figure B3 - Rivet hole schematic: Upper rivet row, hole number 4J2, fatigue crack growth is in the aft direction.



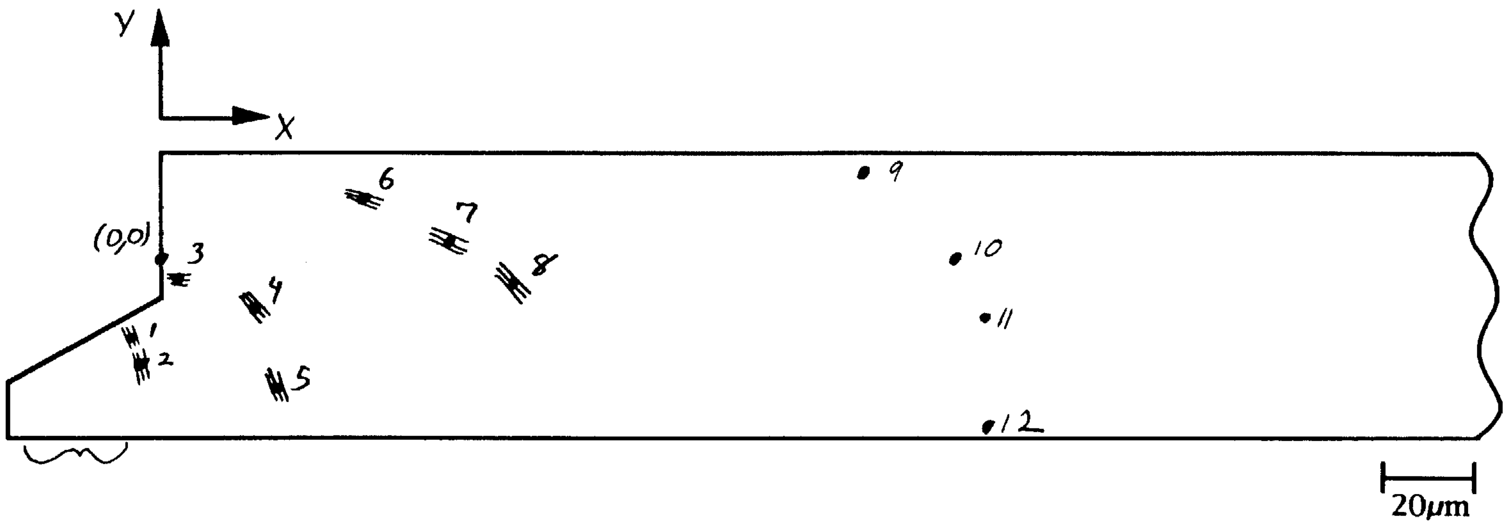
#	Coordinates (mm)	[in]	# of Bands (cycles)	Comments
1	(-0.068,-0.275)	[-0.003,-0.011]	6(30K)	Fair
2	(-0.288,-0.323)	[0.011,-0.013]	6(30K)	Fair
3	(0.47,0.72)	[0.019,0.028]	Crack Front	
4	(1.43,0.6)	[0.056,0.024]	Crack Front	
5	(1.95,0.0)	[0.077,0.000]	Crack Front	
6	(2.08,-0.5)	[0.082,-0.020]	Crack Front	

Figure B4 - Rivet hole schematic: Upper rivet row, hole number 4J3, fatigue crack growth is in the forward direction.



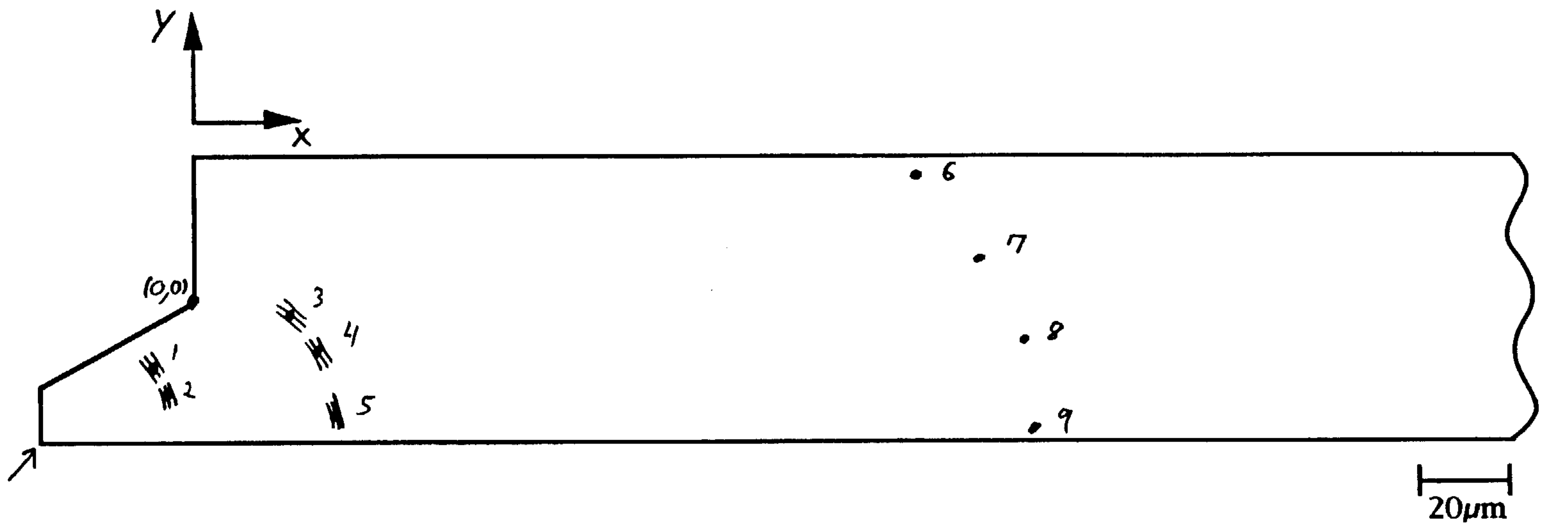
#	Coordinates (mm)	[in]	# of Bands (cycles)	Comments
1	(0.525,-0.5675)	[0.021,-0.022]	10(40K)	
2	(-0.3625,-0.500)	[-0.014,-0.020]	4(50K)	
3	(-0.250,-0.1875)	[-0.010,-0.007]	4(50k)	
4	(-0.0125,0.0125)	[-0.0004,0.0004]	4(50K)	
5	(-0.15,0.58)	[-0.006,0.023]	Crack Front	
6	(-1.21,0.2)	[-0.048,0.008]	Crack Front	
7	(-1.65,-0.2)	[-0.065,-0.008]	Crack Front	
8	(-1.72,-0.9)	[-0.068,-0.035]	Crack Front	

Figure B5 - Rivet hole schematic: Upper rivet row, hole number 4J5, fatigue crack growth is in the forward direction.



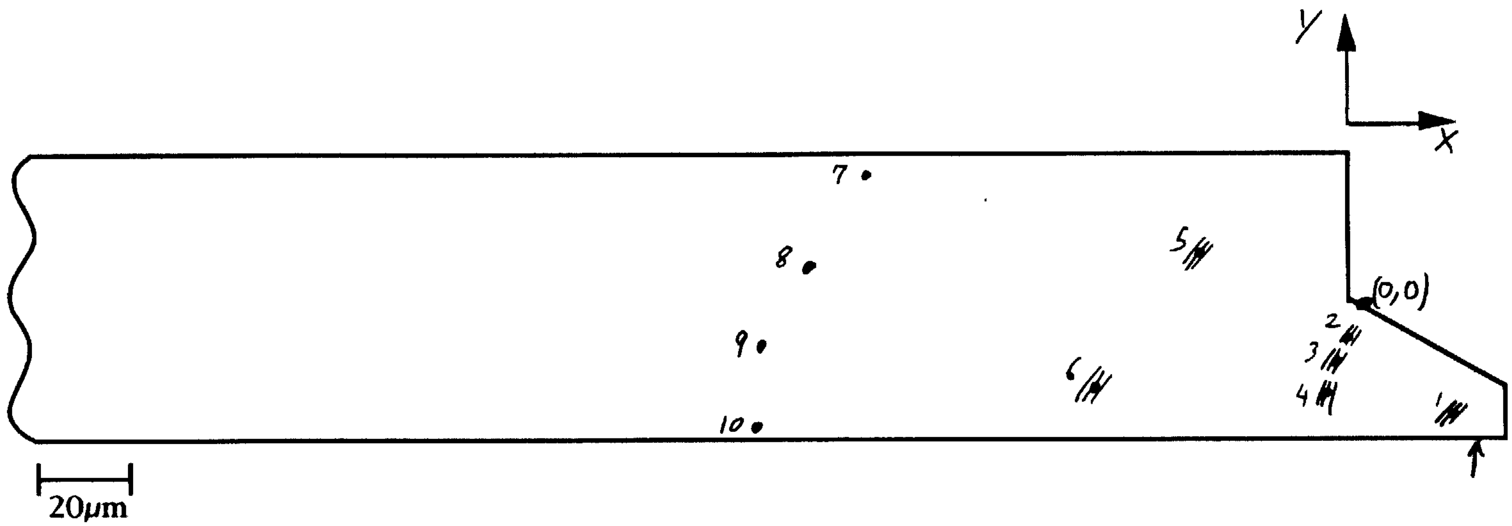
#	Coordinates (mm)	[in]	# of Bands (cycles)	Comments
1	(-0.238,-0.413)	[-0.009,-0.016]	6(30K)	Good
2	(-0.163,-0.5375)	[-0.006,-0.021]	6(30k)	Very Good
3	(0.050,-0.075)	[0.002,-0.003]	9(40K)	Poor
4	(0.483,-0.260)	[0.019,-0.010]	9(40K)	Fair
5	(0.563,-0.663)	[0.022,-0.026]	9(40K)	Good
6	(1.100,0.35)	[0.043,0.013]	4(50K)	Fair
7	(1.600,0.1375)	[0.063,0.005]	4(50K)	Good
8	(1.950,-0.0875)	[0.077,-0.003]	4(50K)	Fair
9	(3.93,0.53)	[0.155,0.021]	Crack Front	
10	(4.45,0.0)	[0.175,0.0]	Crack Front	
11	(4.6,-0.3)	[0.181,-0.012]	Crack Front	
12	(4.65,-0.9)	[0.183,-0.035]	Crack Front	

Figure B6 - Rivet hole schematic: Upper rivet row, hole number 4J5, fatigue crack growth is in the aft direction.



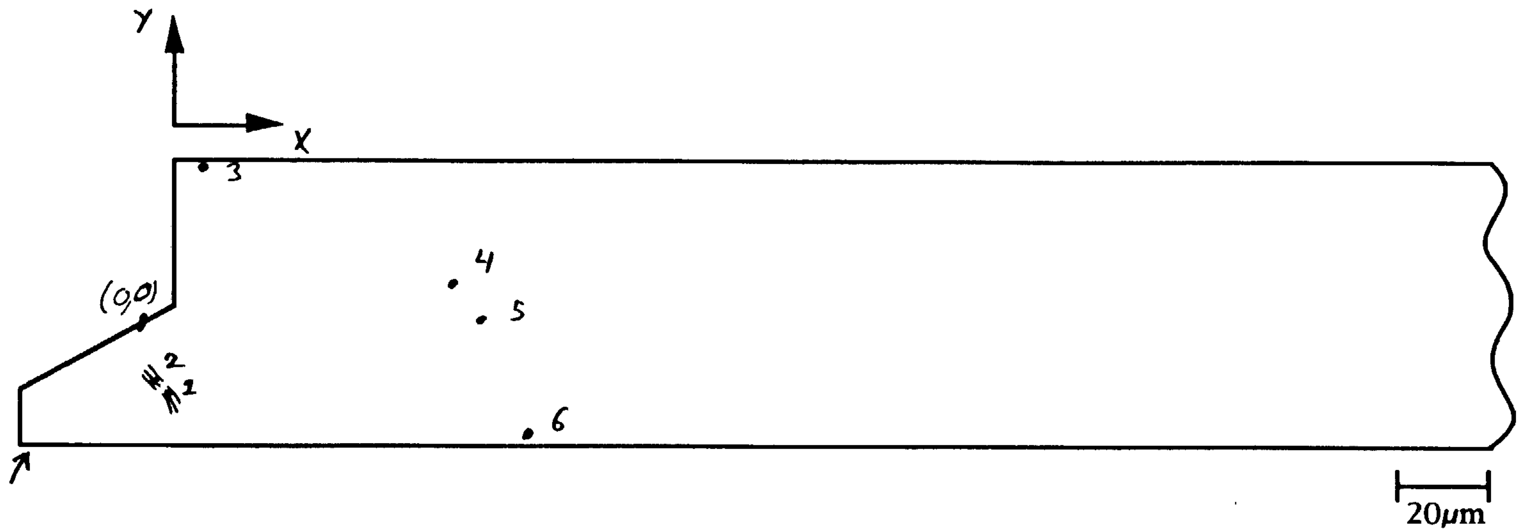
#	Coordinates (mm)	[in]	# of Bands (cycles)	Comments
1	(-0.334,-0.217)	[-0.013,-0.009]	6(30K)	
2	(-0.142,-0.493)	[-0.006,-0.019]	6(30K)	
3	(0.509,-0.050)	0.020,-0.002]	9(40K)	Good
4	(0.676,-0.258)	[0.027,-0.010]	9(40K)	Good-Fair
5	(0.793,-0.635)	[0.031,-0.025]	9(40K)	Fair
6	(4.0,0.77)	[0.157,0.030]	Crack Front	
7	(4.4,0.2)	[0.173,0.008]	Crack Front	
8	(4.6,-0.2)	[0.181,-0.008]	Crack Front	
9	(4.6,-0.75)	[0.181,-0.029]	Crack Front	

Figure B7 - Rivet hole schematic: Upper rivet row, hole number 4J5, fatigue crack growth is in the forward direction.



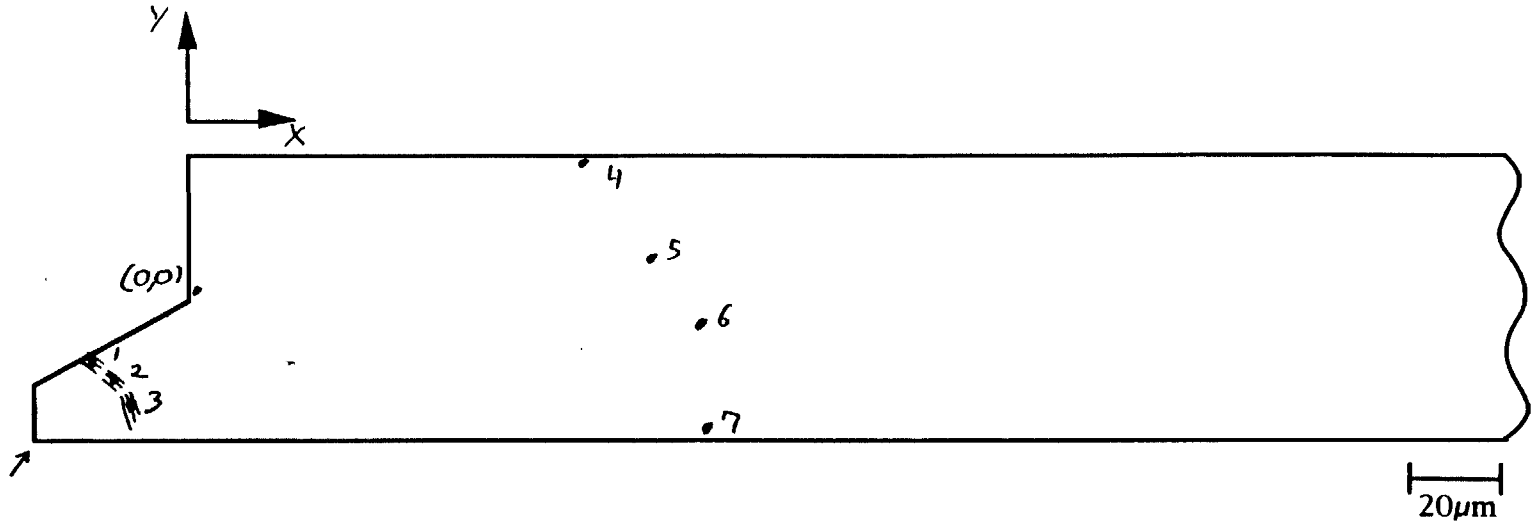
#	Coordinates (mm)	[in]	# of Bands (cycles)	Comments
1	(0.550,-0.550)	[0.022,-0.022]	6(30K)	
2	(-0.025,-0.175)	[-0.001,-0.007]	9(40K)	Poor
3	(-0.075,-0.250)	[-0.003,-0.010]	9(40K)	
4	(-0.130,-0.4575)	[-0.005,-0.018]	9(40k)	
5	(-0.875,0.2875)	[-0.034,0.011]	4(50K)	Fair-Good
6	(-1.4375,-0.4375)	[-0.057,-0.017]	4(50K)	Fair-Good
7	(-2.7,0.69)	[-0.106,0.027]	Crack Front	
8	(-3.03,0.2)	[-0.119,0.008]	Crack Front	
9	(-3.34,-0.2)	[-0.131,-0.008]	Crack Front	
10	(-3.35,-0.8)	[-0.132,-0.031]	Crack Front	

Figure B8 - Rivet hole schematic: Upper rivet row, hole number 4J6, fatigue crack growth is in the forward direction.



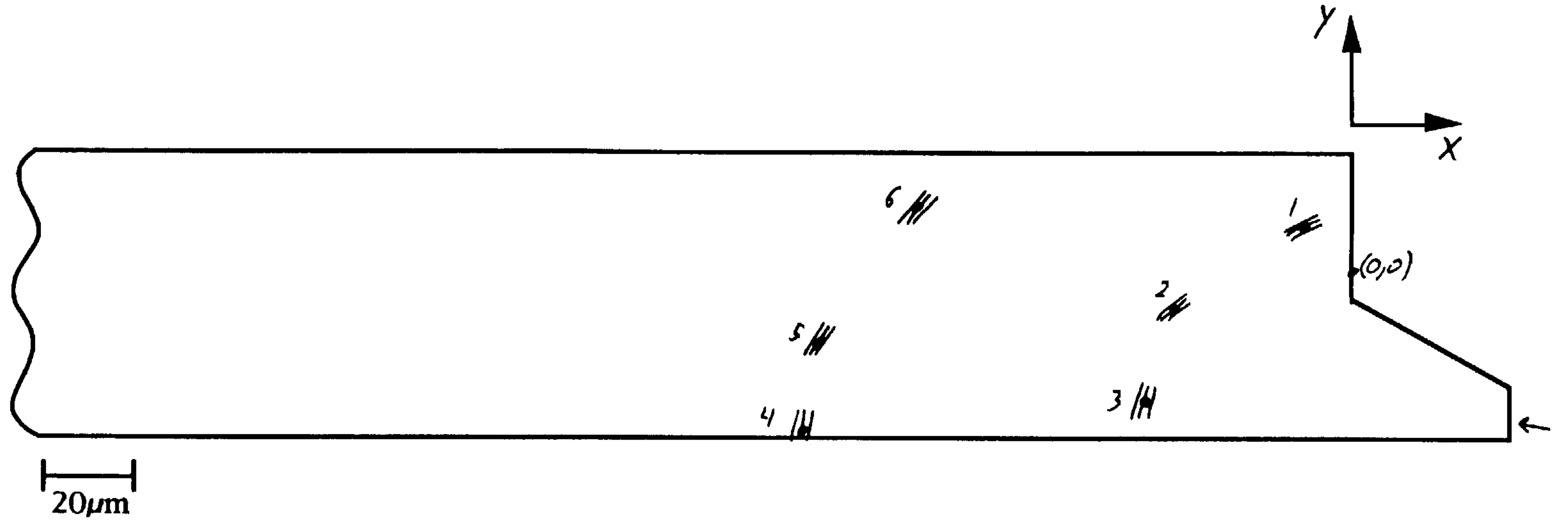
#	Coordinates (mm)	[in]	# of Bands (cycles)	Comments
1	(0.095,-0.3625)	[0.004,-0.014]	4(50K)	Fair
2	(0.0175,-0.27)	[0.001,-0.010]	4(50K)	Fair
3	(0.25,0.83)	[0.010,0.033]	Crack Front	
4	(1.7,0.2)	[0.067,0.008]	Crack Front	
5	(1.91,0.0)	[0.075,0.0]	Crack Front	
6	(2.1,-0.65)	[0.083,-0.026]	Crack Front	

Figure B9 - Rivet hole schematic: Upper rivet row, hole number 4J6, fatigue crack growth is in the aft direction.



#	Coordinates (mm)	[in]	# of Bands (cycles)	Comments
1	(-0.575,-0.4875)	[-0.023,-0.019]	9(40K)	
2	(-0.4625,-0.5625)	[-0.018,-0.022]	9(40K)	
3	(-0.325,-0.7125)	-0.013,-0.028]	9(40K)	
4	(2.2,0.72)	[0.087,0.028]	Crack Front	
5	(2.5,0.2)	[0.098,0.008]	Crack Front	
6	(2.85,-0.2)	[0.112,-0.008]	Crack Front	
7	(2.86,-0.69)	[0.113,-0.027]	Crack Front	

Figure B10 - Rivet hole schematic: Upper rivet row, hole number 4J7, fatigue crack growth is in the forward direction.



#	Coordinates (mm) [in]	# of Bands (cycles)	Comments
1	(-0.250,0.2375) [-0.010,0.010]	6(30K)	
2	(-1.000,-0.250) [-0.039,-0.010]	6(30K)	
3	(-1.1425,-0.925) [-0.045,-0.036]	6(30k)	
4	(-3.0625,-0.950) [-0.121,-0.037]	9(40K)	
5	(-2.9875,-0.425) [-0.118,-0.017]	9(40K)	
6	(-2.425,0.3375) [-0.095,0.015]	9(40K)	

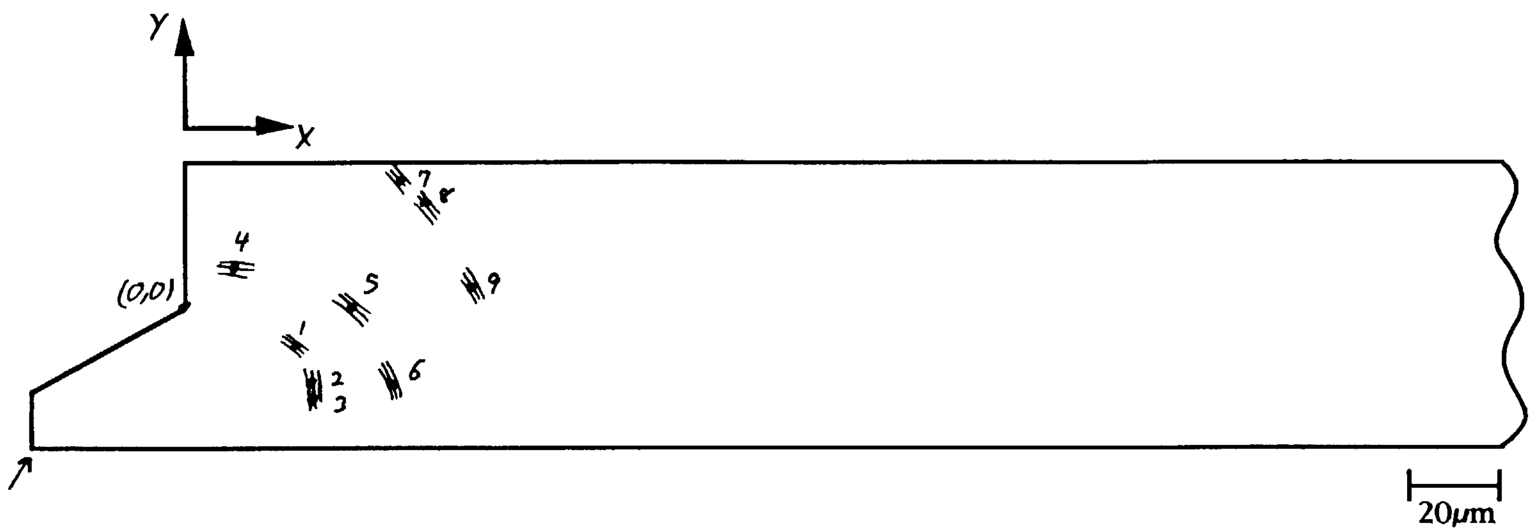
* Crack front not available.

Figure B11 - Rivet hole schematic: Upper rivet row, hole number 4J8, fatigue crack growth is in the forward direction.

#	Coordinates (mm)	[in]	# of Bands (cycles)	Comments
1	(-0.275,-0.5375)	[-0.011,-0.021]	3(20K)	Good
2	(0.175,0.150)	[0.007,0.006]	6(30k)	Fair
3	(0.6875,-0.150)	[0.027,-0.006]	6(30k)	Poor
4	(0.820,-0.475)	[0.032,-0.019]	6(30k)	Fair-Poor
5	(1.3875,0.6125)	[0.054,0.024]	9(40K)	Fair
6	(2.2375,0.000)	[0.088,0.000]	9(40K)	Good
7	(2.400,0.525)	[0.097,0.021]	9(40K)	Poor

* No crack front. Crack linked up with 4J9B.

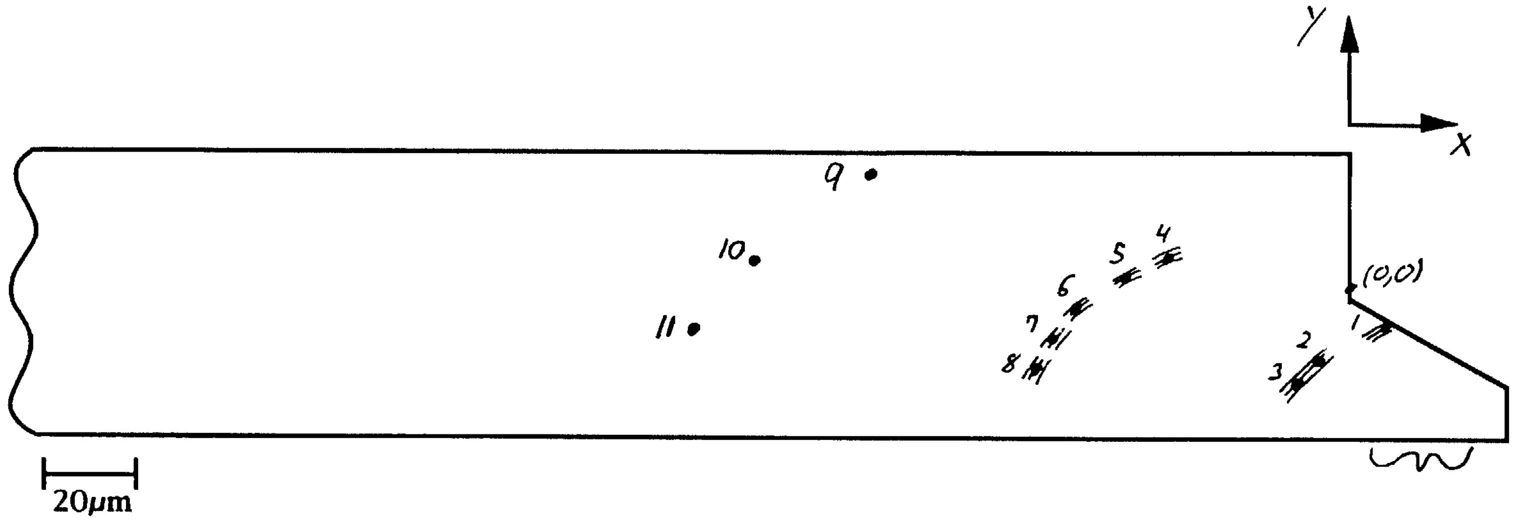
Figure B12 - Rivet hole schematic: Upper rivet row, hole number 4J8, fatigue crack growth is in the aft direction.



#	Coordinates (mm) [in]	# of Bands (cycles)	Comments
1	(0.5875,-0.1875)[0.023,-0.007]	6(30K)	Good-Fair
2	(0.6625,-0.4425)[0.026,-0.017]	6(30K)	Good-Fair
3	(0.695,-0.475) [0.027,-0.019]	6(30K)	Fair-Poor
4	(0.2675,0.2425) [0.010,0.010]	9(40K)	Good
5	(0.8925,-0.0125)[0.035,-0.0004]	9(40K)	Poor
6	(1.1125,-0.4125)[0.044,-0.016]	9(40K)	Good
7	(1.1625,0.7375) [0.046,0.029]	4(50K)	Fair
8	(1.25,0.5875) [0.049,0.023]	4(50K)	Very Good
9	(1.570,0.125) [0.062,0.005]	4(50K)	Very Good

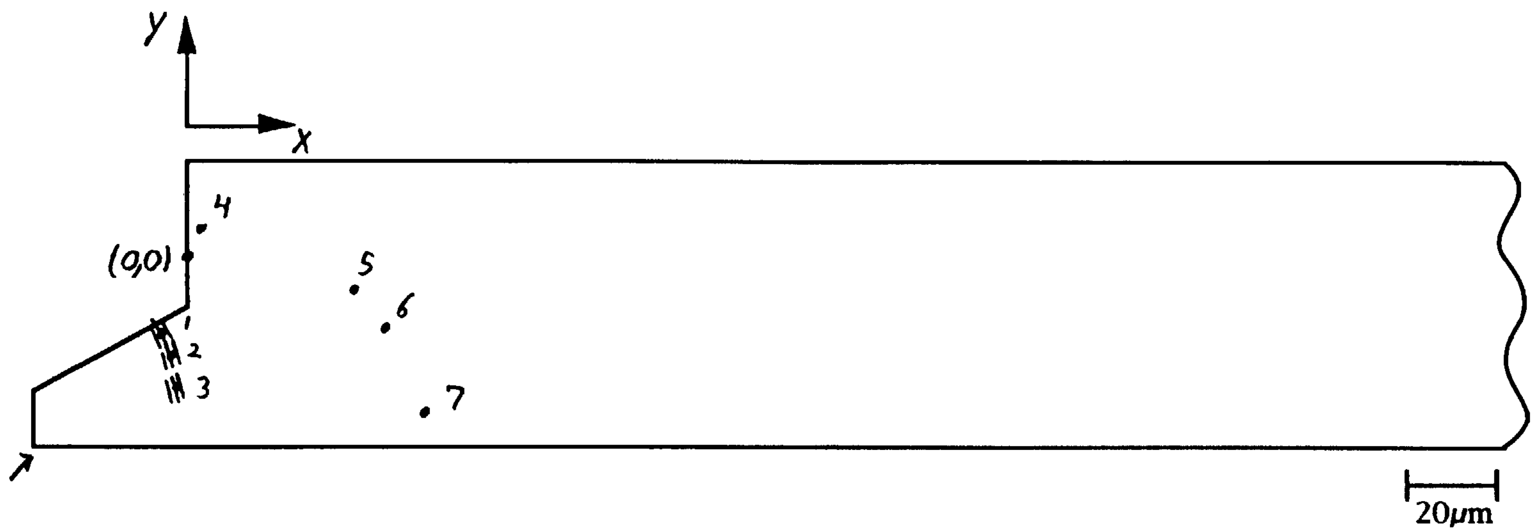
* No crack front. Crack linked up with 4J8A.

Figure B13 - Rivet hole schematic: Upper rivet row, hole number 4J9, fatigue crack growth is in the forward direction.



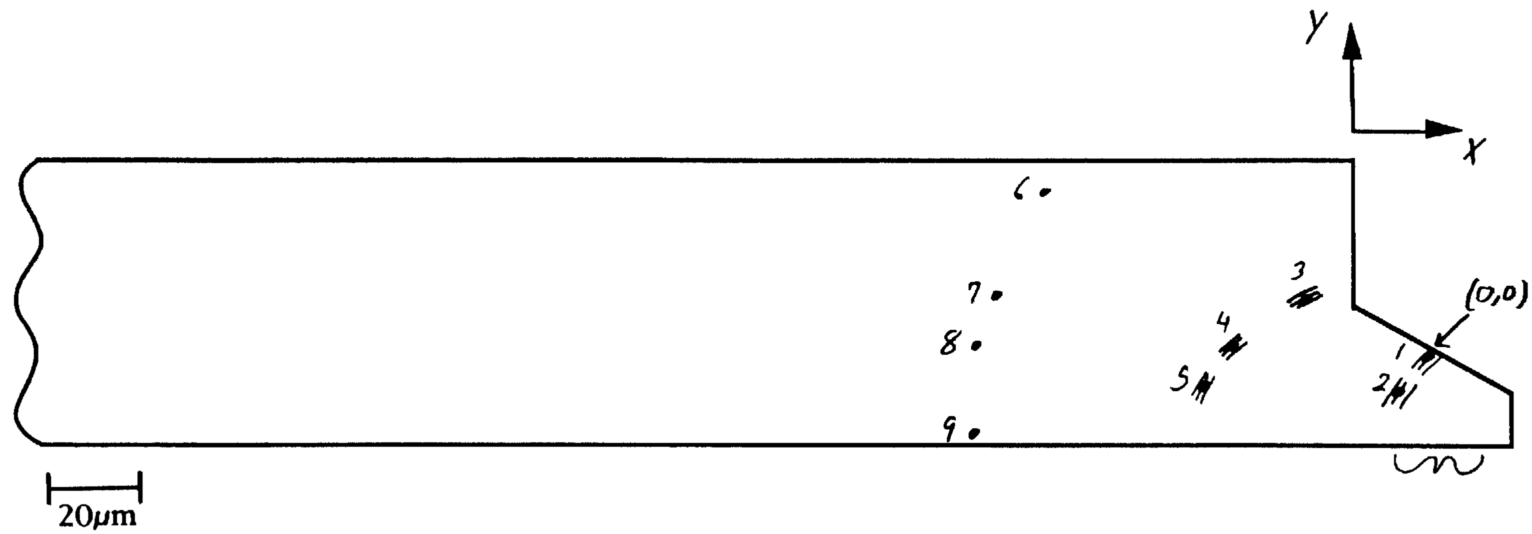
#	Coordinates (mm)	[in]	# of Bands (cycles)	Comments
1	(0.2175,-0.175)	[0.009,-0.007]	9(40K)	Good
2	(-0.1875,0.375)	[-0.007,0.015]	9(40K)	Fair
3	(-0.2875,-0.500)	[-0.011,-0.020]	9(40K)	Fair
4	(-1.7375,-0.4175)	[-0.068,-0.016]	4(50K)	Good
5	(-1.6625,-0.275)	[-0.065,-0.011]	4(50K)	Good
6	(-1.5125,-0.0875)	[-0.060,-0.003]	4(50K)	Good
7	(-1.2375,0.080)	[-0.049,0.003]	4(50K)	Fair
8	(-1.000,0.200)	[-0.039,0.008]	4(50K)	Fair-Poor
9	(-2.65,0.67)	[-0.104,0.026]	Crack Front	
10	(-3.28,0.2)	[-0.129,0.008]	Crack Front	
11	(-3.68,-0.2)	[-0.145,-0.008]	Crack Front	

Figure B14 - Rivet hole schematic: Upper rivet row, hole number 4J10, fatigue crack growth is in the aft direction.



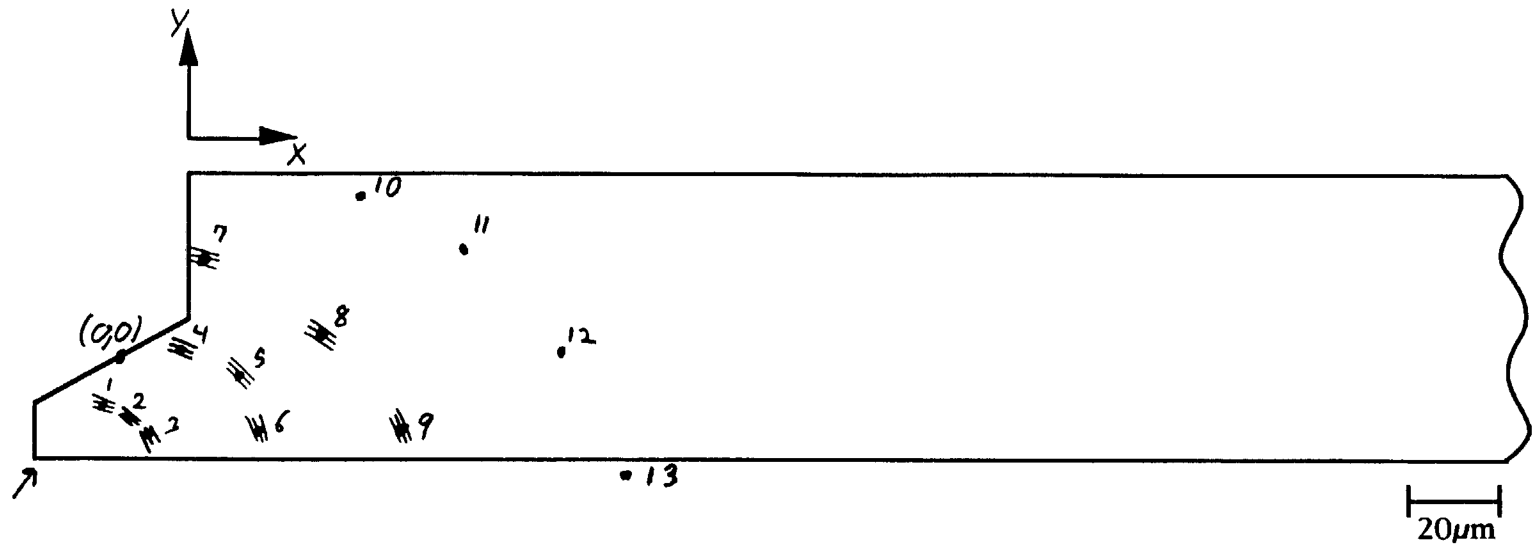
#	Coordinates (mm) [in]		# of Bands (cycles)	Comments
1	(-0.1625,-0.375)	[-0.006,-0.015]	4(50K)	Poor
2	(-0.1125,-0.500)	[-0.005,-0.020]	4(50K)	Good
3	(-0.0875,-0.5625)	[-0.003,-0.022]	4(50K)	Poor
4	(0.04,0.14)	[0.002,0.006]	Crack Front	
5	(0.89,-0.2)	[0.035,-0.008]	Crack Front	
6	(1.05,-0.4)	[0.041,-0.016]	Crack Front	
7	(1.24,-0.87)	[0.049,-0.034]	Crack Front	

Figure B15 - Rivet hole schematic: Upper rivet row, hole number 4J12, fatigue crack growth is in the aft direction.



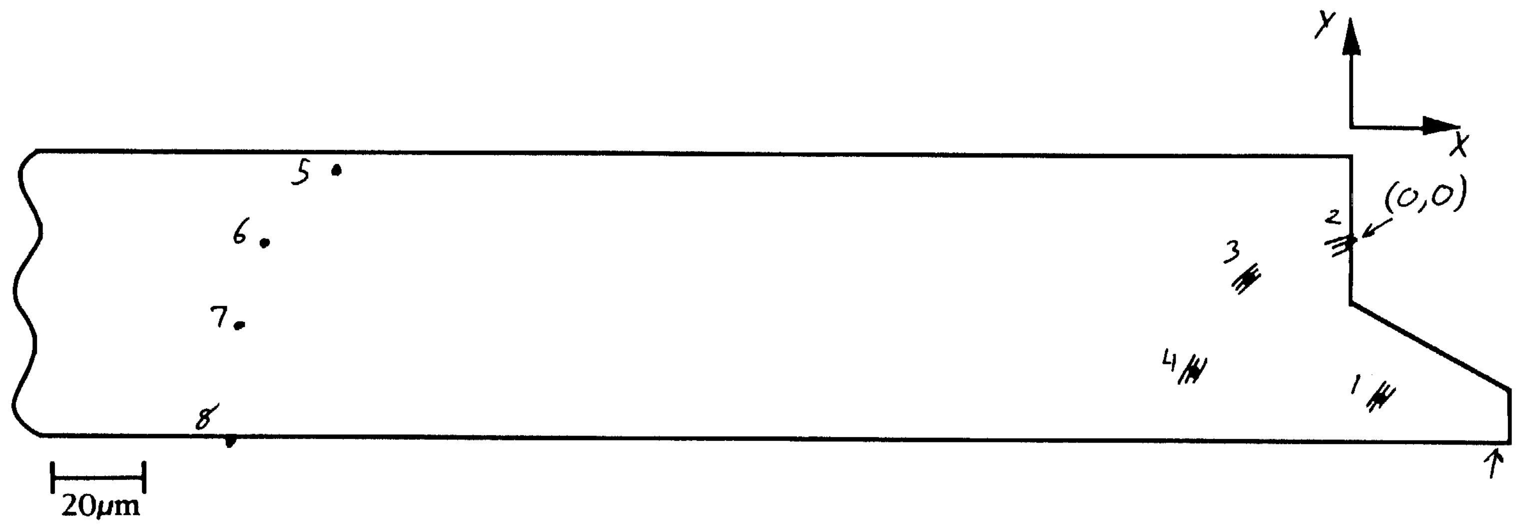
#	Coordinates (mm)	[in]	# of Bands (cycles)	Comments
1	(0.000,-0.025)	[0.000,-0.001]	9(40K)	Fair
2	(-0.1625,-0.150)	[-0.006,-0.006]	9(40K)	Fair
3	(-0.6875,0.3025)	[-0.027,0.012]	4(50k)	Very Good
4	(-1.1125,0.000)	[-0.044,0.000]	4(50K)	Fair-Good
5	(-1.250,-0.2125)	[-0.049,-0.008]	4(50K)	Fair
6	(-2.15,0.85)	[-0.085,0.033]	Crack Front	
7	(-2.45,0.3)	[-0.096,0.012]	Crack Front	
8	(-2.59,0.0)	[-0.102,0.0]	Crack Front	
9	(-2.66,-0.65)	[-0.105,-0.026]	Crack Front	

Figure B16 - Rivet hole schematic: Upper rivet row, hole number 4J14, fatigue crack growth is in the aft direction.



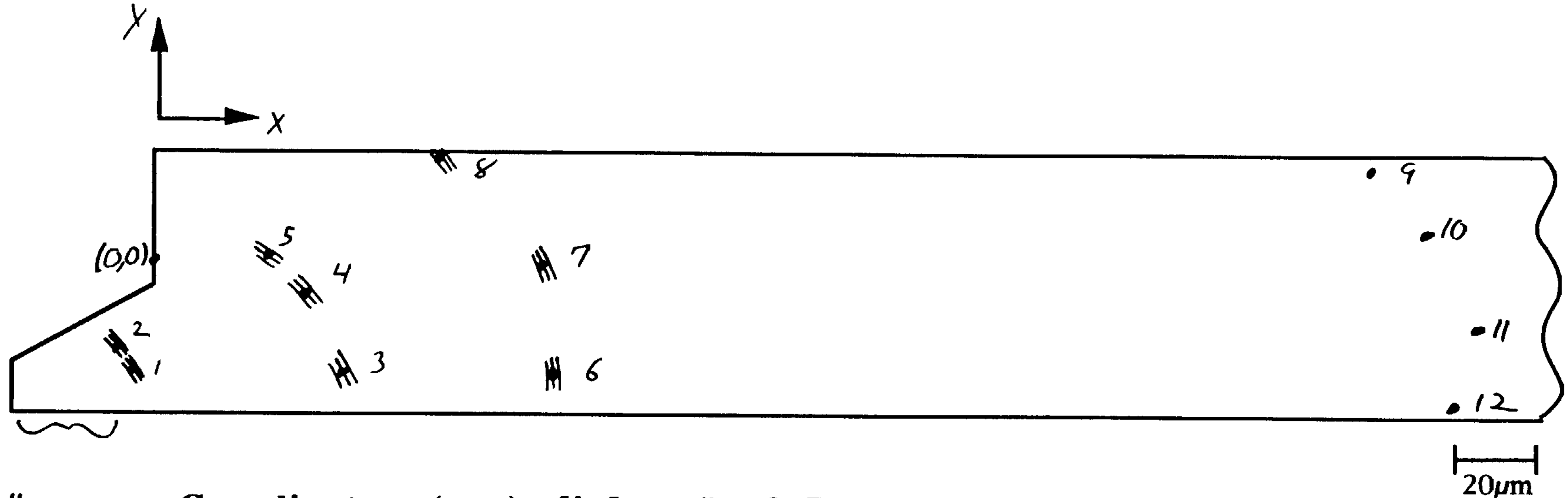
#	Coordinates (mm)	[in]	# of Bands (cycles)	Comments
1	(-0.0625,-0.255)	[-0.002,-0.001]	6(30K)	Very Good
2	(0.050,-0.2875)	[0.002,-0.011]	6(30K)	Fair
3	(0.160,-0.395)	[0.006,-0.016]	6(30K)	Good
4	(0.325,-0.0625)	[0.013,-0.002]	9(40K)	Good
5	(0.064,-0.150)	[0.025,-0.006]	9(40K)	Very Good
6	(0.750,-0.350)	[0.030,-0.014]	9(40K)	Fair
7	(0.475,0.5325)	[0.019,0.021]	4(50K)	Poor
8	(1.125,0.125)	[0.044,0.005]	4(50K)	Fair
9	(1.550,-0.3125)	[0.061,-0.012]	4(50K)	Very Good
10	(1.28,0.83)	[0.050,0.035]	Crack Front	
11	(1.86,0.6)	[0.076,0.024]	Crack Front	
12	(2.4,0.0)	[0.094,0.0]	Crack Front	
13	(2.73,-0.7)	[0.107,-0.028]	Crack Front	

Figure B17 - Rivet hole schematic: Upper rivet row, hole number 4J14, fatigue crack growth is in the forward direction.



#	Coordinates (mm)	[in]	# of Bands (cycles)	Comments
1	(0.153,-0.860)	[0.006,-0.034]	6(30K)	Fair-Poor
2	(0.000,0.000)	[0.000,0.000]	4(40K)	Incomplete set (P)
3	(-0.576,-0.200)	[-0.023,-0.008]	9(40K)	Good
4	(-0.710,-0.835)	[-0.028,-0.033]	9(40k)	Good
5	(-5.75,0.3)	[-0.226,0.012]	Crack Front	
6	(-6.1,0.0)	[-0.240,0.000]	Crack Front	
7	(-6.32,-0.5)	[-0.249,-0.020]	Crack Front	
8	(-6.3,-1.15)	[-0.248,-0.045]	Crack Front	

Figure B18 - Rivet hole schematic: Upper rivet row, hole number 4J15, fatigue crack growth is in the forward direction.



#	Coordinates (mm)	[in]	# of Bands (cycles)	Comments
1	(-0.165,-0.650)	[-0.006,-0.026]	3(20K)	Good
2	(-0.3125,-0.565)	[-0.012,-0.022]	3(20K)	Fair-Poor
3	(1.1375,-0.66)	[0.045,-0.026]	6(30K)	Poor
4	(0.9925,-0.200)	[0.039,-0.008]	6(30K)	Poor
5	(0.650,0.250)	[0.026,0.010]	6(30K)	Poor
6	(2.500,-0.7175)	[0.098,-0.028]	9(40K)	Good
7	(2.375,-0.0625)	[0.093,-0.002]	9(40K)	Fair
8	(1.7125,0.6375)	[0.067,0.025]	9(40K)	Poor
9	(7.4,0.6)	[0.291,0.024]	Crack Front	
10	(7.7,0.2)	[0.303,0.008]	Crack Front	
11	(8.0,-0.2)	[0.315,-0.008]	Crack Front	
12	(7.9,-0.82)	[0.311,-0.032]	Crack Front	

Figure B19 - Rivet hole schematic: Upper rivet row, hole number 4J15, fatigue crack growth is in the aft direction.

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A full scale fuselage test article was subjected to 60,000 load cycles (pressurizations) to study the effect of widespread fatigue damage in fuselage structures. Every 10,000 cycles coded marker block loading sequences were used to mark the fracture surfaces of the fatigue cracks propagating within the panel. The loading sequences consisted of series of underloads combined with a series of full pressurizations. The combination of loads and underloads marked the fracture surfaces with marker bands that could later be used to reconstruct the fatigue crack growth history of selected regions within the test article. Thirty rivet holes comprising the upper rivet rows from two adjacent bays (bays #3 and #4) from a fuselage lap splice joint were examined for the purpose of this study. Optical and scanning electron microscopy (SEM) were used to locate the marker bands.

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