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FATIGUE ANALYSIS OF MULTIPLE SITE DAMAGE AT A ROW OF HOLES IN A WIDE PANEL

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ABSTRACT

This paper is concerned with predicting the fatigue life of unstiffened panels which contain multiple site damage (MSD). The initial damage consists of through-the-thickness cracks emanating from a row of holes in the center of a finite width panel. A fracture mechanics analysis has been developed to predict the growth, interaction, and coalescence of the various cracks which propagate in the panel. A strain-life analysis incorporating Neuber's rule for notches, and Miner's rule for cumulative damage, is also employed to predict crack initiation for holes without initial cracking. This analysis is compared with the results of a series of fatigue tests on 2024-T3 aluminum panels, and is shown to do an excellent job of predicting the influence of MSD on the fatigue life of nine inch wide specimens. Having established confidence in the ability to analyze the influence of MSD on fatigue life, a parametric study is conducted to examine the influence of various MSD scenarios in an unstiffened panel. The numerical study considered 135 cases in all, with the parametric variables being the applied cyclic stress level, the lead crack geometry, and the number and location of MSD cracks. The numerical analysis provides details for the manner in which lead cracks and MSD cracks grow and coalesce leading to final failure. The results indicate that MSD located adjacent to lead cracks is the most damaging configuration, while for cases without lead cracks, MSD clusters which are not separated by uncracked holes are most damaging.

*This research was performed while K. Buhler and E. J. Moukawsher were graduate students at Purdue University.

INTRODUCTION

The problem of Multiple-Site Damage (MSD) in aging aircraft has motivated development of a computer program to predict the fatigue life of a panel containing a row of holes with an arbitrary arrangement of small cracks [1-3]. A typical MSD specimen which the program is designed to analyze is shown in Fig. 1. Here a row of open holes are assumed to contain various combinations of initial radial through-thickness cracks. Small cracks located at multiple holes are referred to as multiple-site damage (MSD), while the term "lead crack" is used to describe a large crack connecting two or more holes. This section overviews the computational algorithm, and summarizes a set of experiments conducted to verify the ability to predict the effect of MSD on fatigue life. Additional details of the analysis and experiments are provided in Refs. 1-3. Once the predictive capabilities of the algorithm are established, subsequent sections describe results from a parametric analysis performed to study the effects of various crack combinations on the fatigue life of a 31.0 inch wide panel containing 30 open holes.

Description of the Crack Growth Algorithm

The crack growth algorithm is conceptually quite simple. Given the initial specimen geometry (dimensions and hole layout), MSD configuration (location and lengths of cracks), and loading conditions (constant amplitude load only), the cracks are grown incrementally until they link together or the panel fails. The first step is to calculate the stress intensity factors for all cracks. One crack tip is then assumed to advance a small amount, and the cycles required for this increment of growth are calculated. The remaining cracks are then grown a distance corresponding to this cyclic interval by employing a user selected fatigue crack growth model to relate the cyclic stress intensity factor and fatigue crack growth rate. After each incremental growth the current crack geometry is compared to one of several failure criteria to determine whether the panel fails. For holes which are initially uncracked, cumulative damage is summed at these locations in conjunction with a Neuber notch analysis. Miner's rule is applied to determine when a crack is initiated at these holes. When this strain-life analysis determines that "crack initiation" has occurred at a given hole, a crack equal to Dowling's "transition" crack length [4] is introduced, and the crack growth calculations continue at that location. This routine is repeated until the failure criterion is satisfied. Throughout the analysis storage arrays are used to monitor the crack tip properties (stress intensities and growth rates), and changing panel configuration (as cracks link together).

A form of the compounding method is used to determine the stress intensity factors for the various MSD specimen cracks. The cracks are treated as either edge, center or radial hole cracks [5]. Cracks which link together are considered as either center or edge cracks (the holes are ignored). Once the crack type is designated (initiated by the user and automatically updated with crack growth) an initial solution for ΔK is calculated for each crack. The final cyclic stress intensity factor employs an interaction factor which is based on the Kamei-Yokobori K solution [6] for two interacting cracks.

Several different failure criteria have been incorporated into the program including:

- a. K exceeds the critical stress intensity factor (K_C) for the material

- b. The crack growth rate exceeds a user specified amount
- c. The total crack length exceeds a user specified amount
- d. The net section stress in the uncracked ligament exceeds the tensile yield stress of the material
- e. The ligament between two adjacent cracks yields by a criterion proposed by Swift [7].

Swift's ligament yield criterion accounts for the significant plastic zone ahead of long lead cracks which limit the ability to carry additional load. Failure of the panel is predicted when the plastic zone at the tip of the lead-crack reaches a point where it 'touches' the plastic zone of the nearest approaching crack tip from the adjacent holes. If this condition occurs, then the panel fails as the large lead crack 'unzips' through the remaining row of holes.

Experimental MSD Fatigue Tests

A series of experimental tests were conducted with nine inch wide 2024-T3 aluminum panels to verify the program analysis. The 0.09 inch thick specimens contained a single row of 8 to 11 open holes with a 0.16 inch diameter. Some specimens contained large lead cracks (obtained by cutting the ligament between two or more central holes), and all specimens contained small radial MSD cracks (on the order of 0.05 to 0.10 inches long) at two or more of the remaining holes. These specimens were cycled to failure using a constant amplitude loading spectrum with an R ratio of 0.01 and at a frequency of 5 hertz. Measurements of the growth and coalescence of initial fatigue cracks, as well as cycles required to develop cracks at initially uncracked holes, were recorded and compared with results of the LEFM based numerical analysis. Figure 2 compares measured and predicted crack growth for a typical MSD specimen, while Fig. 3 summarizes measured and predicted life for the 12 tests conducted. A separate set of experiments with similar precracked MSD specimens indicated that the Swift [7] ligament yield criterion gave a good estimate of residual strength for those test specimens. Further details of the test results are included in Refs. 1-3.

PARAMETRIC STUDY OF A WIDE PANEL WITH MSD

Having established confidence in the ability to analyze the influence of MSD on fatigue life, it was decided to employ the numerical model for a parametric study of the influence of various MSD scenarios in an unstiffened panel. To conduct this study, a 31.0 inch wide panel containing 30, 3/16 inch diameter holes was selected as the test model. This size panel was chosen to allow analysis of many different MSD/lead crack combinations. Two basic crack configurations were considered in this study: panels containing a 'lead' crack in the presence MSD cracks growing from other holes, and panels containing arbitrary combinations of MSD without a lead crack. Typical examples of the starting crack configurations are shown in Fig. 4. The main goal here was to determine how reasonably expected MSD

scenarios affect the life of a large panel. Furthermore, trends in the crack growth and coalescence were sought.

Parameters Associated With MSD

A summary of the parameters investigated are shown in Table 1. Some parameters were fixed to limit the total number of feasible combinations, with the main variables being the applied loading and the crack geometries. The assumed stress-strain and fatigue material properties were extracted from Ref. 1. The 0.2% yield strength was determined to be 54.3 ksi, while the ultimate strength was 60.0 ksi. Additionally, the material da/dN versus ΔK relationship was experimentally determined and converted to a mathematical representation consisting of a series of line segments [1].

The initial crack geometry defines the size of the initial cracks and their location relative to the holes and other cracks. To bound the number of combinations to a reasonable maximum, the initial sizes and configurations were limited to a selection which were considered reasonably expectable. As the initial predictions were analyzed some configurations were refined to focus on critical areas. Two basic crack sizes were selected to resemble typical MSD fatigue cracks growing from a hole. The lengths of these two radial cracks were 0.05 inches and 0.1 inches, and they were placed at opposite sides of a hole (Fig. 5) to approximate the general randomness of fatigue crack lengths which normally stem from differing initiation periods.

The panels were divided into five zones, each containing six holes (Fig. 4), to enable an ordered approach to the placement of the various crack combinations. Three different lead crack configurations were selected, and in all cases the lead cracks were located in zone three (which was centered in the panel). The different lead crack configurations are shown in Fig. 6. For each lead crack type, various combinations of other cracks were started at holes in the other zones. Both symmetrically and nonsymmetrically placed cracks in the overall panel were studied. Examples of the starting configurations with lead cracks are shown in the top part of Figs. 7 and 8. For the cases without lead cracks, various numbers of cracked holes in each zone were considered. An example is shown at the top of Fig. 9. The clusters of cracks in each zone were positioned in adjacent holes, and also with uncracked holes between the cracked ones. Additionally, a cluster of six cracked holes was moved to various locations in the panel and the resulting fatigue behavior considered.

Constant amplitude cyclic loading was applied to the parametric models. Typical fuselage hoop stresses, which are generated from internal pressurization, are reported in the literature as ranging from 10.0 to 15.0 ksi [8-10]. This study considered the following three maximum applied cyclic loads: 10.0, 12.5 and 15.0 ksi. The variations in the applied loading was seen to greatly affect the fatigue lives of the cracked panels.

DISCUSSION OF RESULTS

The results from the study are presented in three forms. Tables 2 and 3 present the total panel lives for specific cases considered, as well as the number of cracked holes in each zone. Figures 7-9

show example crack tip propagation plots for all the holes in the panel, and include plots for panels with or without lead cracks. Above the main plot is a figure which illustrates the initial panel crack configuration. Figures 10 and 11 are bar charts of the total panel life versus the number of cracked holes. These charts include results for all the three applied loading cases.

Typical Crack Growth Trend in Panels Containing a Lead Crack

The parametric study revealed a typical crack growth trend which leads to the panel failure. This is best described for the panels containing lead cracks by considering Fig. 7. This panel contained a type 1 lead crack with cracks growing from all other holes in zone 3. No other holes in the panel were initially cracked. The propagation plot shows dominant crack growth from the holes on the left side of the lead crack. The crack on the right side of hole 14 grows quickly in the presence of the lead crack tip to the left of hole 15. These cracks link after about 19,000 cycles resulting in a much longer crack with its left tip on the left side of hole 14, and the right end still uncracked at hole 16. This process continues with the crack growth accelerating through the other MSD cracks in holes 13 and 12.

While the initial cracks on the left of the lead crack have been linking, the cracked holes on the right side of the lead crack (holes 17 and 18) have grown comparatively slower. These cracks have not been so strongly influenced by the lead crack which does not extend past the right side of hole 16. After hole 12 and 13 link at 26,000 cycles, there is a period up until 30,500 cycles where only the cracks from holes 17 and 18 grow in a slow stable manner. At this point none of the other holes in the panel contain cracks. During this time the uncracked holes are accumulating "initiation" damage until 30,500 cycles when a crack initiates at the right side of hole 16. This results in a large central crack extending from holes 12 to 16. At this stage the large central crack has reached a critical length where unstable extension occurs. This causes the central crack to link with the cracks growing from holes 17 and 18 almost immediately after the initiation at hole 16, which results in an even longer central crack which is temporarily stopped by the uncracked holes 12 and 19. Within another 1,000 cycles the cracks in the remaining uncracked holes begin to initiate causing the excessively large central crack to instantly 'unzip'. This is only temporarily halted by further uncracked holes which are remotely located from the center of the panel. Once the unzipping process starts, cracks rapidly initiate in the remaining holes causing the panel to fail.

Typical Crack Growth Trend in Panels Containing No Lead Crack

Figure 9 is a sample crack propagation plot for a panel without an initial lead crack. For this case the panel contained a pair of adjacently cracked holes in each of the five zones. The plot shows the cracks between the pairs of cracked holes growing and linking after about 47,000 loading cycles. The resulting longer cracks grow and link with the adjacent holes after about 64,000 cycles. Following this, cracks start to initiate at previously uncracked holes, and the panel soon fails. Reference 11 further describes similar trends for various other configurations.

The patterns described above suggest that regardless of the initial crack configuration, crack growth and coalescence will tend to result in a much larger crack, which will control the failure of the panel as it extends through other holes. Additionally, the number of cycles required to fail the panel after the larger crack has reached some critical length is a small portion of the total panel life, and is affected by

the initiation times of the initially uncracked holes. Based on this pattern the life of the panel is dependent on how long it takes for a particular crack configuration to generate the larger critical crack. The next section discusses the effects of the various configurations, and the different applied loads.

Effects of Different Crack Configurations on Panels Containing a Lead Crack

For the lead cracked panels a series of predictions were made with varying numbers of other holes cracked. The number of cracked holes remotely located from the lead crack ranged from 0 to 12, and was selected to simulate the initial onset of a MSD scenario. For each crack configuration, predictions were made for the three different cyclic load levels (10, 12.5, and 15.0 ksi). Referring to Table 2, the results show that the type of lead crack and the magnitude of applied load have a great effect on the total panel life. For the 10.0 ksi applied load case, the panel with the type 1 lead crack and 8 other cracked holes (MSD334) had a total life of 73,021 cycles. By comparison, the same case with the type 2 lead crack (MSD335) had a life of 40,921 cycles which is approximately 40 percent less than the life of the type 1 case. Similarly, the same case with the type 3 lead crack (MSD336) had a total life of 30,616 cycles, which is approximately 25 percent less than the type 2 life.

The magnitude of the applied loading also has a large effect on the panel lives. For example the life of the panel containing the type 1 lead crack with 8 other cracked holes (MSD334), ranged from 73,021 cycles for 10.0 ksi applied load, to 7,054 cycles for the 15.0 ksi load. Similarly the type 3 lead crack case (MSD336) ranged from 30,616 cycles to 2,988 cycles. The fatigue life for the panel when loaded at 15 ksi was approximately 10 percent of the life when loaded at 10 ksi.

Table 2 also indicates that moving the same number of cracked holes remote from the lead to various zones has a negligible effect on the total panel life. For example moving three other cracked holes to different zones in the type 1 lead crack panel (MSD316, MSD322), causes the total life to vary from 91,291 cycles to 91,281 cycles. This is due to the dominance of the lead crack controlling the panel life.

The apparent dominance of the lead crack on the panel lives motivated several predictions where holes located closely to the lead crack were initially cracked. A typical example is shown in Fig. 8. As expected the lives are markedly reduced in these cases. For example, referring to Table 2 (MSD326, MSD332), the panel life for the type 2 lead crack case containing 4 other cracked holes is more than halved when the four other holes are located in zone 3 (adjacent the lead crack) compared to the MSD being located in the other zones, remote from the lead crack location. Furthermore, predictions were made where a cluster of three cracked holes were located on the immediate left side of the lead cracks. This cluster was separated from the lead crack by both one and two initially uncracked holes. (Refer to Fig. 8 example). Table 2 shows that for this situation the magnitude of the effect on the total lives depends on the type of lead crack. For example, for the type 1 lead crack (MSD322), the panel life for three other initially cracked holes remotely located from the lead crack was 91,281 cycles. This compares to 55,821 cycles when a cluster of three cracked holes was separated from the lead crack by two uncracked holes (MSD340), and 52,721 cycles when the cluster was separated from the lead by one uncracked hole (MSD343). The same comparison for the type 2 lead crack case resulted in 46,935 cycles for the remote crack locations, compared to 45,250 cycles for the two hole separation, and 42,299 cycles for the single hole separation (results not included in Table 2). A similar result for the type 3 lead crack case as the type 2 case occurred. Figure 8 shows how the cracks coalesce to form the controlling large central crack. The

close proximity of the cluster of three cracks to the lead crack tends to reduce the time taken to generate large central crack, which in turn reduces the total panel life.

Figure 10 is an example bar chart of the total panel life versus the number of cracked holes remotely located from the lead crack. From this figure it is apparent that:

- a. there is a large reduction in the panel life with increasing applied load,
- b. the lives of the panels loaded at 10.0 ksi decrease quite considerably as the number of initially cracked holes increases, but by comparison the lives for the panels loaded at 12.5 ksi and particularly 15.0 ksi are not as sensitive to the number of initial cracked holes.

In summary the lives of these panels are strongly controlled by the type of lead crack, the location of the other MSD relative to the lead crack, and the magnitude of the applied loading.

Effects of Different Crack Configurations on Panels Without a Lead Crack

A similar crack growth pattern for panels with lead cracks was found to be applicable to the panels without lead cracks. The cracks grow and coalesce to form a large central crack which rapidly extends to panel failure. Predictions were made for increasing numbers of cracked holes. In some cases the cracked holes were clustered together while in others they were separated by uncracked holes. Additionally, predictions were made for a cluster of six initially cracked holes which were moved about the panel. Some specific results for these cases are listed in Table 3.

The results show that the panel lives are strongly influenced by the number of cracked holes clustered together. Referring to Table 3, the results from case numbers MSD406 and MSD402 show that there is a considerable difference in panel lives when the cracked holes are adjacent to one another as opposed to being separated by an uncracked hole. For example, if a total of 15 cracked holes are initially clustered together in groups of three, the panel life was 50,336 cycles. When the same number of holes are separated by an uncracked hole, the panel life was 79,407 cycles, which is 58% greater than for the clustered case.

Figure 11 is a bar chart of the total panel life versus the number of clustered holes in these panels. Similarly to the lead crack case, the plot shows the large reduction in the panel life as the applied loading increases. Additionally, it shows that for a particular applied load there is some minimum number of cracked holes which may be clustered together after which the total panel life is insensitive to additionally cracked holes. Referring to the bar chart, for a load level of 10.0 ksi, the panel life is about the same when there are clusters of 4 and 6 holes. For a load level of 12.5 ksi the chart shows that the panel life is insensitive to additional MSD once three holes are cracked, while for a load of 15.0 ksi two holes is the critical minimum.

Finally, within the limitations of this simplified study, it is worth noting that the most damaging case leading to the shortest panel life consisted of a lead crack in the presence of cracks at all the other holes in the immediate vicinity and subject to a 15.0 ksi applied load. For this case the total panel life was 1,270 cycles, which compares with the least damaging case which was a panel containing no lead crack

and several separately located cracked holes, remotely loaded at 10.0 ksi. The panel life for this case was 124,025 cycles, which is two orders of magnitude higher.

A Note On Predicted Crack Initiation Times

As explained, the predictive program applies a cumulative damage rule to determine when cracks initiate at uncracked holes. At zero life the initial accumulated damage is assumed to be zero, and is subsequently summed to 1.0 before cracks are initiated. In reality, the accumulated damage is not zero when the MSD problem starts. While it is possible to initialize the accumulated damage to some value between 0.0 and 1.0, there is no reasonable basis to select or calculate an appropriate value. It does, however, seem reasonable that since MSD is associated with aging aircraft subjected to thousands of pressurization loading cycles, then initially uncracked holes in any type of predictive scenario will probably have an accumulated damage closer to 1.0 than 0.0. (In this study 0.0 was selected and applied consistently throughout). Furthermore, since the application of Miner's rule to predict crack initiation is generally considered to have a large scatter band, it was not deemed necessary to fine tune it by adjusting the initial accumulated damage.

CONCLUSIONS

This paper described the development of a computer program to predict the fatigue crack growth, coalescence, and ultimate failure of a flat, unstiffened panel with a row of holes containing MSD. The numeric analysis was verified by a series of experimental test results which agreed well with the predictions. The program was then used to study the fatigue behavior of a wide panel containing many open holes and various crack configurations.

Within the limitation on considering every conceivable crack case, several conclusions were drawn from the parametric study. For panels with a lead crack plus MSD:

- a. MSD fatigue growth and coalescence forms a large crack which causes the panel to fail. Crack initiation delays the unstable extension of the longer cracks.
- b. The lead crack type has a strong effect on the fatigue life.
- c. MSD located immediately adjacent to a lead crack presents the most damaging crack configuration.
- d. The maximum applied cyclic stress greatly affects the total panel fatigue life.

For panels without lead cracks:

- a. A similar fatigue crack growth pattern as for the lead crack case applies.

- b. Panels containing clusters of cracked holes not separated by uncracked holes present the most damaging crack configuration.

REFERENCES

1. E.J. Moukawsher, "Fatigue Life and Residual Strength of Panels With Multiple Site Damage", M.S. Thesis, School of Aeronautics and Astronautics, Purdue University, May 1993.
2. E. J. Moukawsher, A. F. Grandt, Jr., and M. A. Neussl, "A Fatigue Analysis of Panels With Multiple Site Damage," *1992 USAF Structural Integrity Program Conference*, San Antonio, Texas, December 1-3, 1992
3. E. J. Moukawsher, A. F. Grandt, Jr. and M. A. Neussl, "Analysis of Panels with Multiple Site Damage," AIAA Paper No. 94-1459, *AIAA SDM Conference*, Hilton Head, SC, April 18-21, 1994.
4. N. E. Dowling, "Notched Member Fatigue Life Predictions Combining Initiation and Propagation," *Fracture of Engineering Materials and Structures*, Vol. 2, 1979, pp. 129-138.
5. D. P. Rooke and D. J. Cartwright, "Compendium of Stress Intensity Factors," *Her Majesty's Stationery Office*, London, 1976.
6. A. Kamei and T. Yokobori, "Two Collinear Asymmetrical Elastic Cracks," *Report of the Research Institute for Strength and Fracture of Materials*, Tohoku University, Vol. 10, Section 1-4, pp 41-42, December 1974.
7. T. Swift, "Effect of MSD on Residual Strength", from a presentation given at the U.S. Air Force Symposium on Multi-Site Damage, February 1992.
8. T. Swift, "Widespread Fatigue Damage Monitoring Issues and Concerns", 5th International Conference on Structural Airworthiness of New and Aging Aircraft, June 1993.
9. P. Tong, R. Grief, L. Chen, D.Y. Jeong, "Damage Tolerance of Fuselage Panels With Widespread Fatigue Damage", ICAF Conference, Stockholm Sweden, June 1993.
10. R.J. Bucci, H.J. Konish, "Test/Evaluation Protocols for Corrosion Damage Assessment - C/KC135 Corrosion Fatigue Round Robin Test Program", Report 57-93-24, October 1993.
11. K. Buhler, "A Study of Fatigue Crack Growth of Panels Containing Multiple Site Damage," M.S. Thesis, School of Aeronautics and Astronautics, Purdue University, December 1993.

Table 1. Parameters Associated With The Numeric Study

FIXED PARAMETERS:	
Panel Width	31.0 inch
Panel Thickness	3/32 inch
Material	2024-T3 Aluminum Alloy
Hole Diameter	3/16 inch
Hole Pitch	1.0 inch
MSD Lengths	0.05, 0.1 inch
VARIABLES:	
Applied Load	10.0, 12.5, 15.0 ksi
Lead Crack Geometry	three different configurations
MSD Locations	total 135 cases considered

Table 2: Highlights of Specific Results For Panels Containing Lead Cracks and MSD

CRACK CONFIGURATION								PANEL LIFE (CYCLES)		
LEAD CRACK TYPE	TEST REFER. NO.	TOTAL NO. OTHER CRACK HOLES	ZONE 1 NO. OF CRACK HOLES	ZONE 2 NO. OF CRACK HOLES	ZONE 3 NO. OF CRACK HOLES	ZONE 4 NO. OF CRACK HOLES	ZONE 5 NO. OF CRACK HOLES	LOAD: 10.0 KSI	LOAD: 12.5 KSI	LOAD: 15.0 KSI
1	MSD316	3	1	1	2	1	-	91,291	29,192	8,393
1	MSD322	3	1	1	2	-	1	91,281	-	-
1	MSD325	4	1	1	2	1	1	86,306	28,088	8,060
1	MSD331	4	-	-	6	-	-	32,414	10,034	3,082
1	MSD334	8	2	2	2	2	2	73,021	24,437	7,054
1	MSD340	3	-	3	2	-	-	55,821	23,606	8,438
1	MSD343	3	-	2	3	-	-	52,721	22,911	8,106
2	MSD326	4	1	1	2	1	1	45,578	13,133	3,241
2	MSD332	4	-	-	6	-	-	15,250	5,358	1,270
2	MSD335	8	2	2	2	2	2	40,921	12,051	2,988
3	MSD336	8	2	2	4	2	2	30,616	9,020	2,360

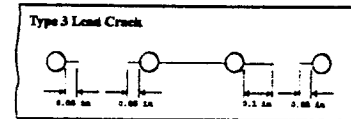
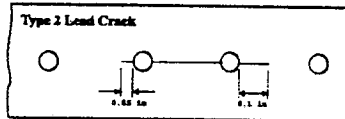
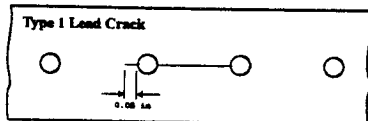
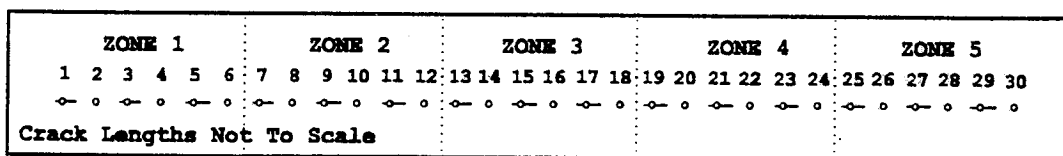


Table 3. Highlights of Specific Results For Panels Containing MSD Without a Lead Crack

CRACK CONFIGURATION								PANEL LIFE (CYCLES)		
TEST REFER. NO.	TOTAL NO. OF CRACK HOLES	ZONE CRACK CONFIG	ZONE 1 NO. OF CRACK HOLES	ZONE 2 NO. OF CRACK HOLES	ZONE 3 NO. OF CRACK HOLES	ZONE 4 NO. OF CRACK HOLES	ZONE 5 NO. OF CRACK HOLES	LOAD: 10.0 KSI	LOAD: 12.5 KSI	LOAD: 15.0 KSI
MSD401	30	GROUP	6	6	6	6	6	41,596	20,394	11,478
MSD406	15	GROUP	3	3	3	3	3	50,336	21,797	12,237
MSD402	15	APART	3	3	3	3	3	79,407	37,992	20,668
MSD405	10	GROUP	2	2	2	2	2	67,010	27,369	12,981
MSD403	10	APART	2	2	2	2	2	97,727	40,146	20,956
MSD404	5	APART	1	1	1	1	1	124,025	54,066	27,986

Note: GROUP = clusters of initially cracked hole grouped together.
 APART = cracked holes initially separated by one or more uncracked holes.



Example: MSD402 - Cracked holes separated by uncracked holes.

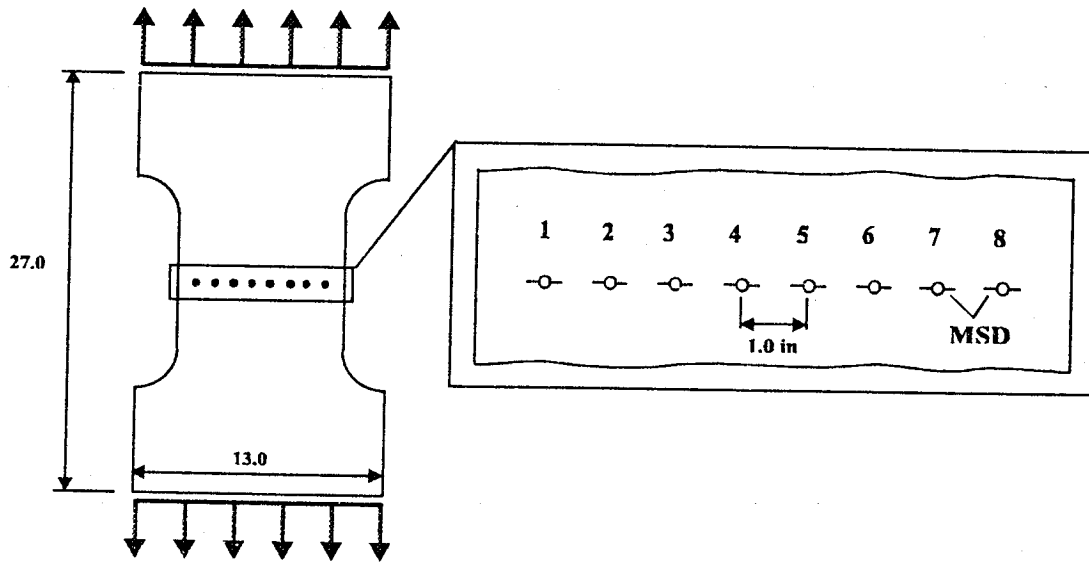


Figure 1. Typical fatigue specimen with cracks at all holes.

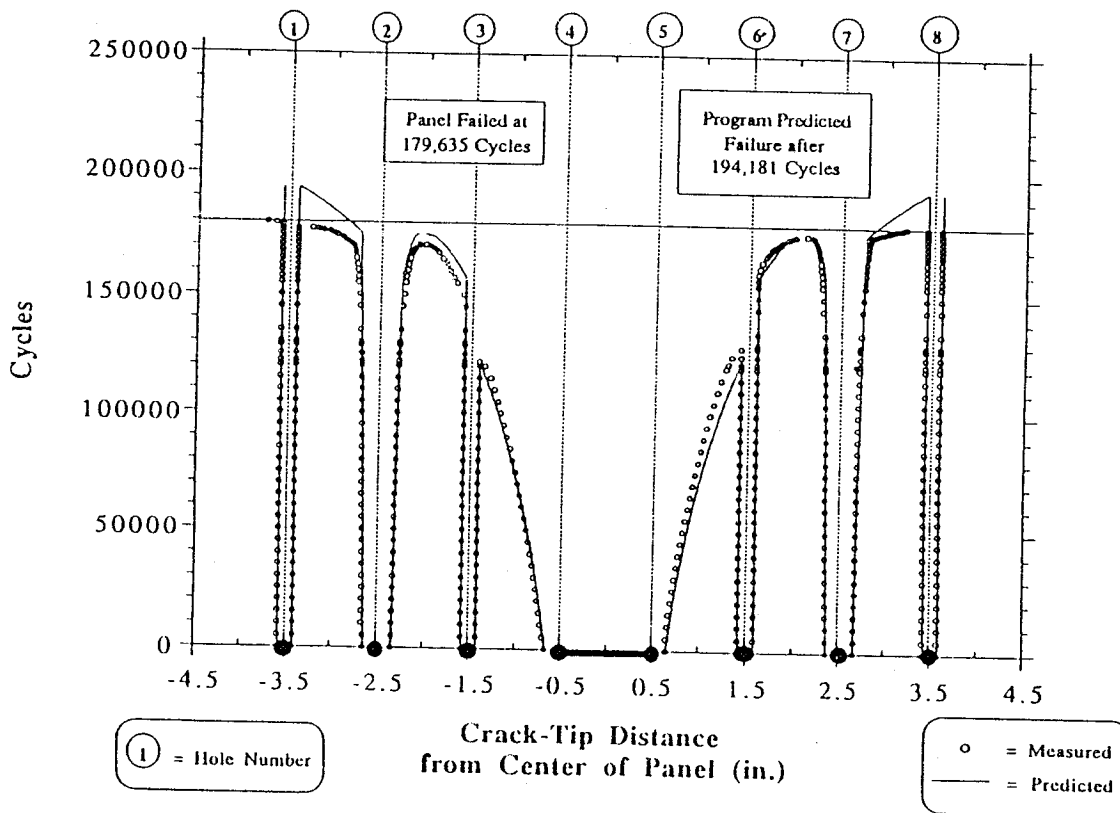


Figure 2. Sample comparison of measured and predicted MSD crack propagation diagram.

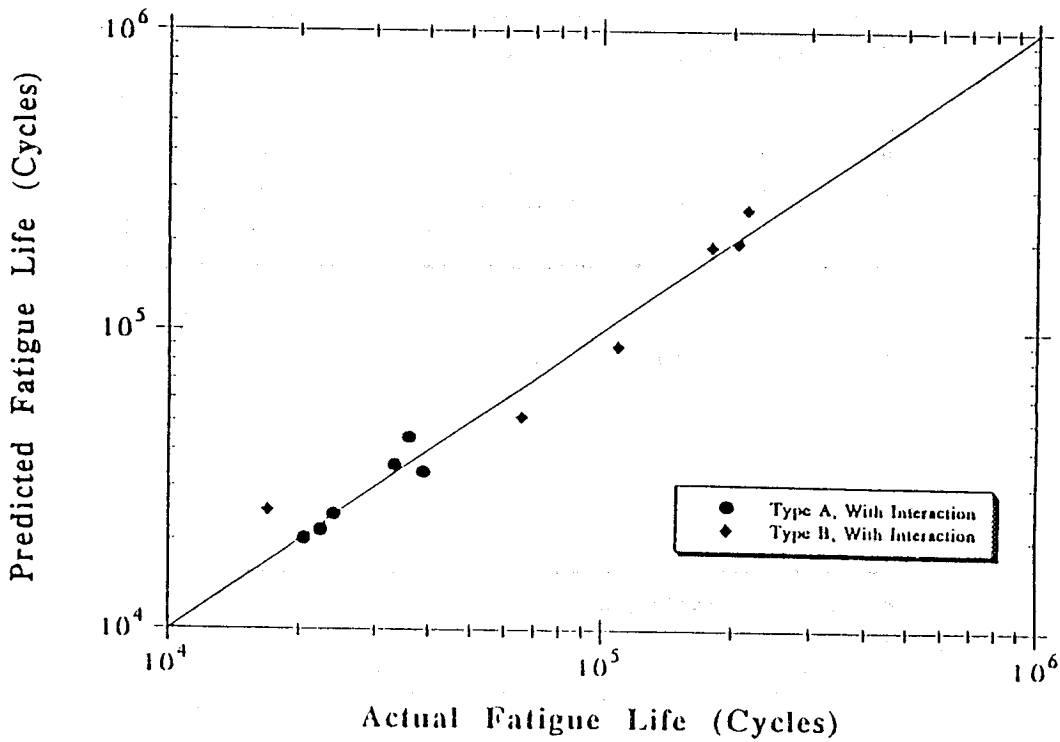
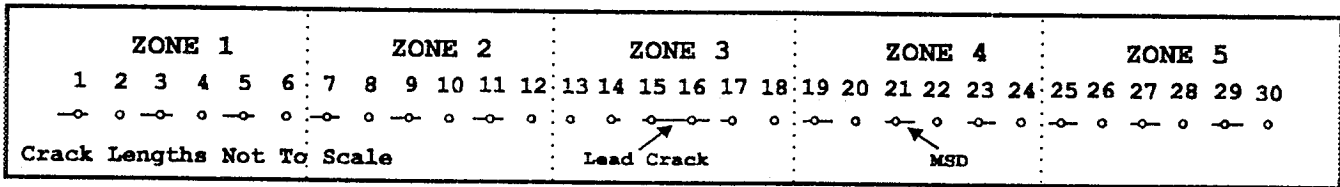
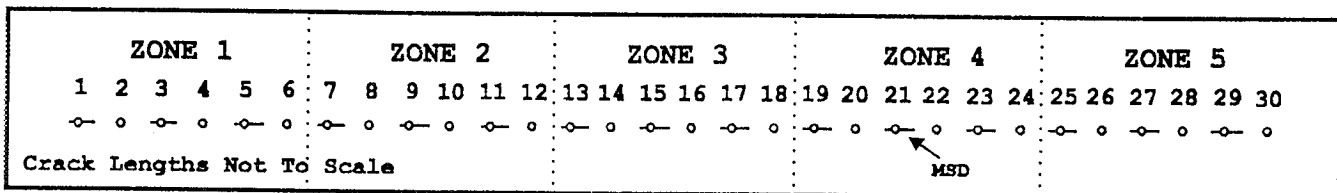


Figure 3. Predicted versus actual fatigue lives for 12 test specimens.



Example of a cracked panel containing MSD and a lead crack.



Example of a cracked panel containing MSD at every alternate hole.

Figure 4. Typical starting configurations considered in numeric study.

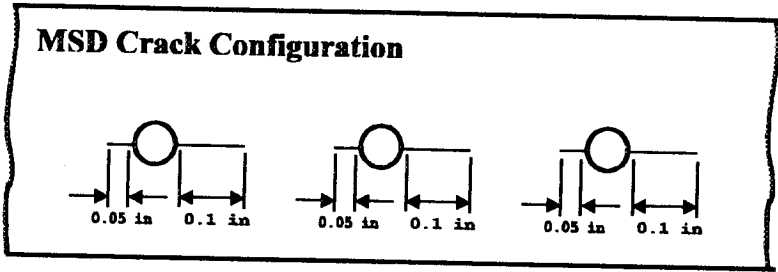


Figure 5. Details of MSD crack configuration.

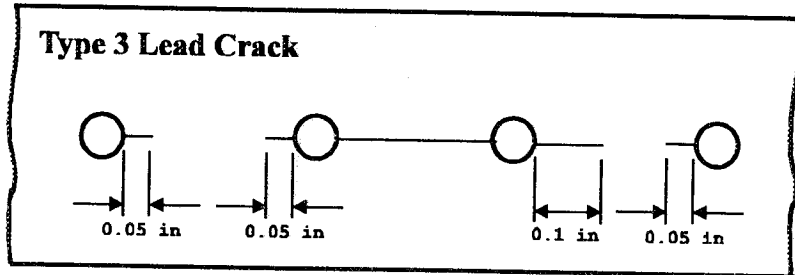
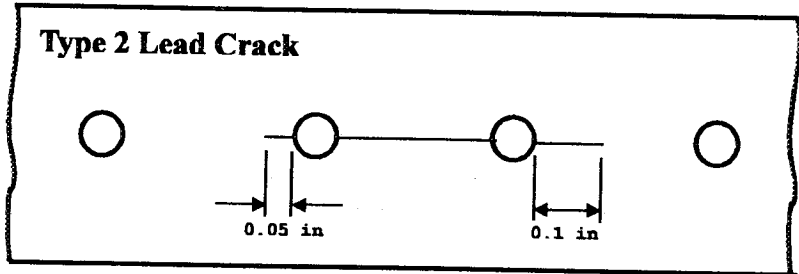
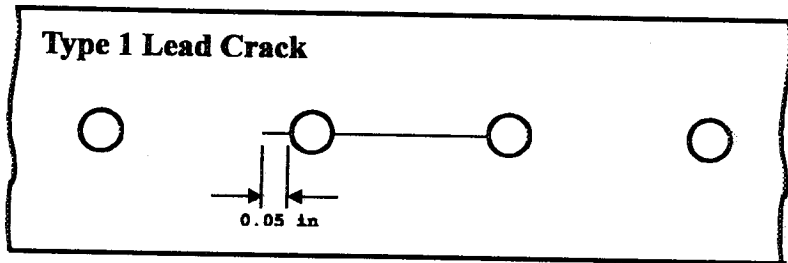
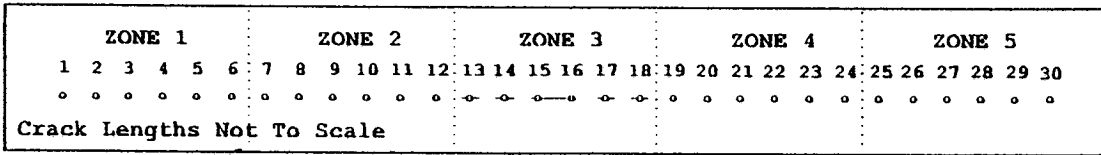


Figure 6. Details of the lead crack configurations.



Initial Crack Configuration

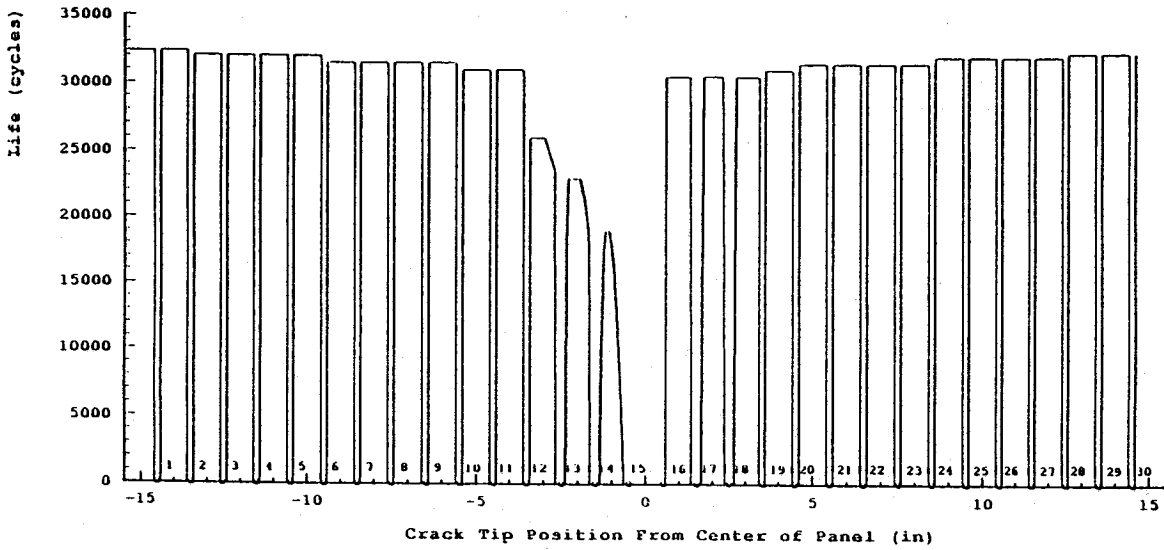
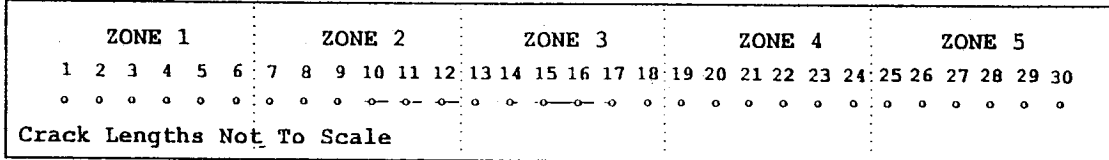


Figure 7. Sample crack propagation diagram for a panel containing a lead crack.



Initial Crack Configuration

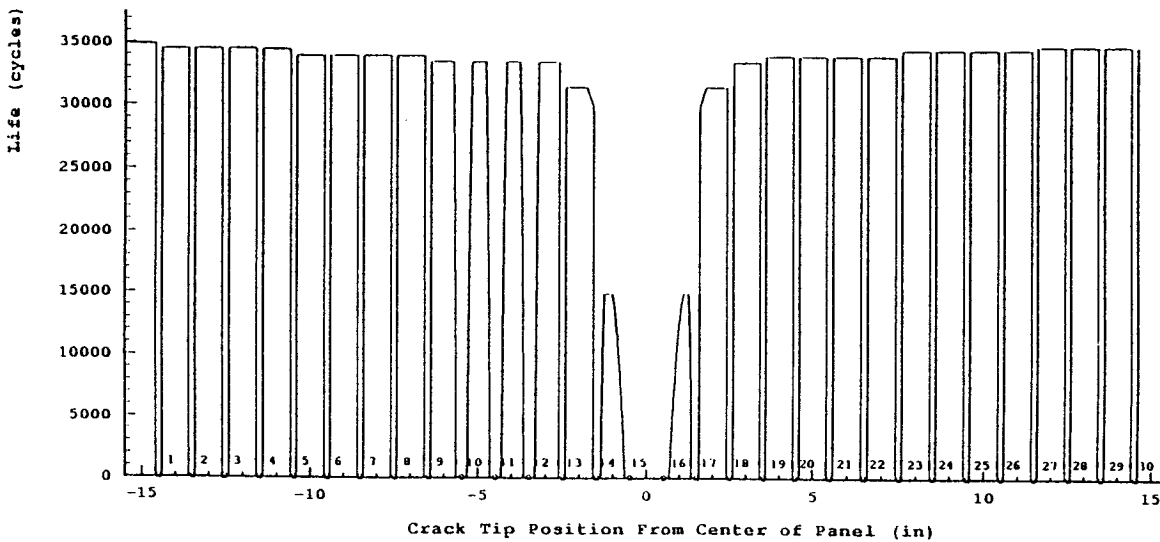


Figure 8. Sample crack propagation diagram for a panel containing a lead crack and adjacent MSD.

ZONE 1						ZONE 2						ZONE 3						ZONE 4						ZONE 5					
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o

Crack Lengths Not To Scale

Initial Crack Configuration

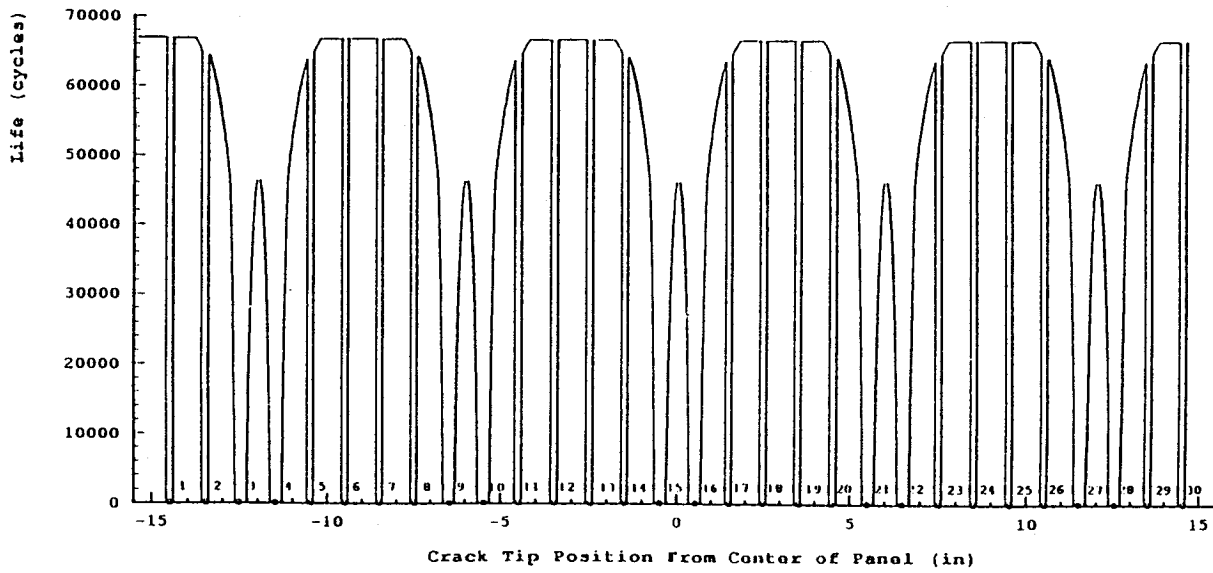


Figure 9. Sample crack propagation diagram for a panel containing pairs of holes with MSD.

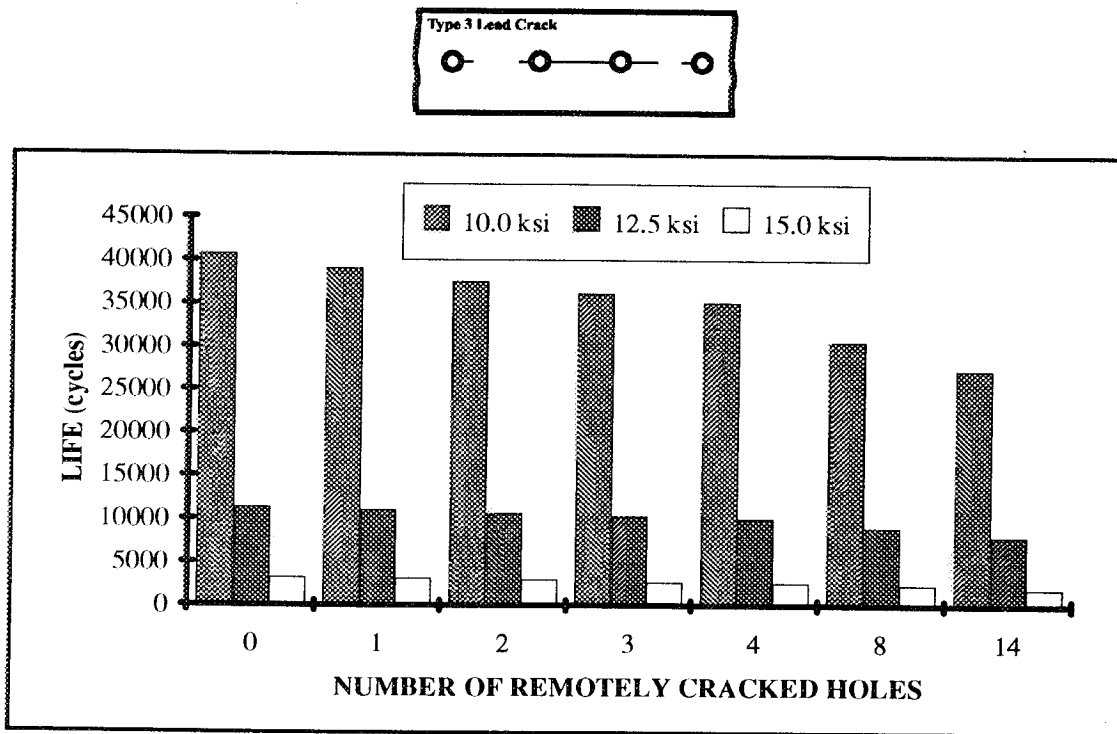


Figure 10. Total panel life versus number of cracked holes remotely located from the lead crack for the type 3 lead crack.

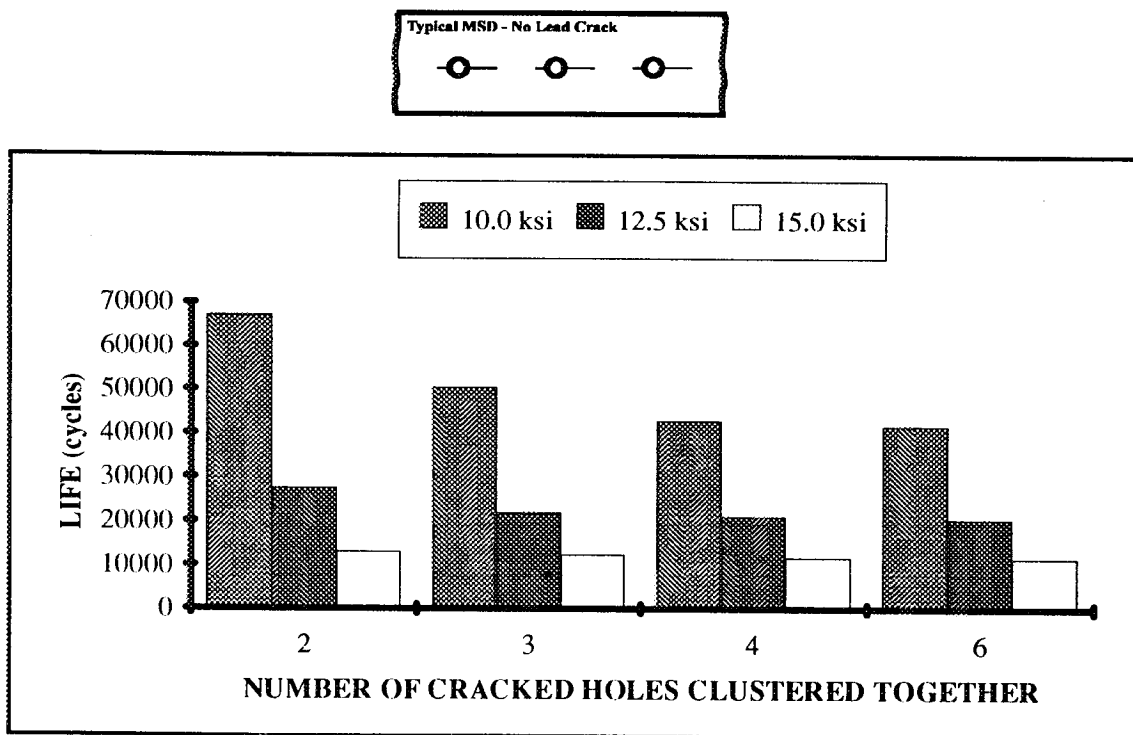


Figure 11. Total life versus number of clustered holes for panels containing no initial lead crack.