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EFFECTS OF VARIATIONS IN COLDWORKING REPAIR
PROCEDURES ON FLAW GROWTH AND STRUCTURAL LIFE

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Structural Integrity Branch
Structures and Dynamics Division

April 1984

Final Report for Period November 1979 - December 1980

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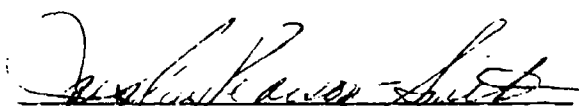
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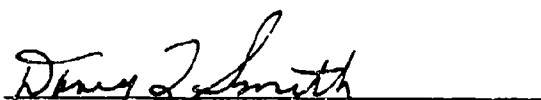
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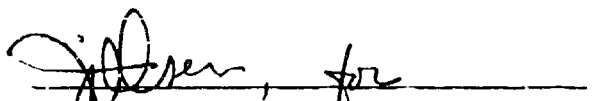
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component with the potential of thousands of person-hours for replacement and refurbishment.

The purpose of this research effort was to investigate the effect of out-of-tolerance cold hole expansion on flaw growth and structural life. To accomplish this goal, specimens were prepared and fatigue tested under spectrum loading conditions to failure. Typical discrepancies found in structures undergoing repair were simulated for this effort. They are:

1. holes not coldworked.
2. holes mistakenly reamed too large following coldwork, and
3. holes mistakenly drilled too large to be coldworked.

Crack length measurements were periodically obtained during the spectrum test and the resultant fatigue lives were noted. Crack growth behavior and fatigue lives for the holes with discrepant preparation were compared to those of properly prepared specimens. The data indicate that a properly repaired structure gives a significant improvement in fatigue life. The data from holes drilled too large following proper coldwork also indicate a benefit from the repair. The fatigue lives from the specimens with one hole which was not coldworked were significantly shorter than those of properly repaired holes but were longer than the baseline, unrepaired structures. This increase in life is attributed to localized change in stress (strain) path due to the coldworking in neighboring holes. This "shielding" effect leads to increased structural fatigue life in spite of the discrepant repair.

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FOREWORD

This technical report was prepared by Lt Jackie Pearson-Smith and John Potter. The work for this report was done in the Structures and Dynamics Division, Flight Dynamics Laboratory, AFWAL, Wright-Patterson AFB, Ohio during the period of November 1979 through December 1980.

Lt Pearson-Smith wishes to take this opportunity to thank those who gave her endless encouragement and contributed substantially to the accomplishment of this work: Dr Frank Adams, Mr Harold Stalnaker, and Mr Jack Smith all of the AFWAL Flight Dynamics Laboratory.

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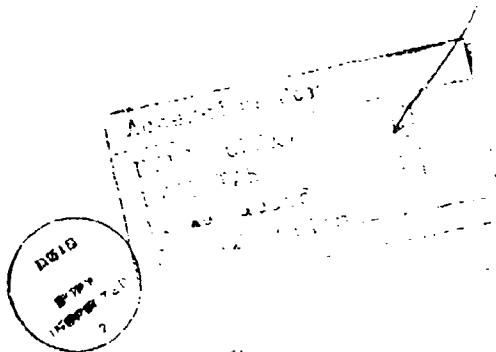


TABLE OF CONTENTS

SECTION		PAGE
I	INTRODUCTION	1
II	TEST METHODS AND PROCEDURES	3
	1. Load History	3
	2. Specimen Fabrication	3
	3. Test Equipment	6
III	DISCUSSION AND RESULTS	7
	1. Residual Stress Measurement Results	7
	2. Fatigue Life Study Results	9
	3. Crack Growth Study Results	13
	4. Hole Spacing Effects	17
IV	CONCLUSIONS	20
V	RECOMMENDATIONS	21
	REFERENCES	22

LIST OF ILLUSTRATIONS

FIGURE		PAGE
1	Test Specimen Geometry	4
2	Measured Stress Distribution at Coldworked Holes	8
3	Fatigue Life of Type I (one hole) Specimens	11
4	Fatigue Life of Type II (three hole) Specimens	12
5	Crack Growth Behavior of Type I Specimens	14
6	Crack Growth Behavior of Type II Specimens (cracking from one side of hole)	15
7	Crack Growth Behavior of Type II Specimens (cracking from opposite sides of hole)	16
8	Effect of a Row of Notches on Stress Concentration Factor	18

SECTION I
INTRODUCTION

Fastener holes are areas of high stress and potential crack initiation sites. They are, therefore, a source of loss in structural fatigue life. One of several techniques developed to enhance the fatigue life of a fastener hole is coldworking (Reference 1). The coldworking process consists of expanding and yielding the material around a fastener hole in a structural member by pulling an oversized mandrel through the hole. This results in a permanent increase in hole diameter. Expanding a hole leaves an area of compressive residual hoop stresses around the hole edge. These compressive residual stresses surrounding the hole provide protection against fatigue from applied tensile loads. Coldworking fastener holes is a relatively common practice not only on newly fabricated structures, but also as a life extension modification on older aircraft such as the F-4.

A potential problem identified with coldworking as a life extension modification was first recognized by Ogden ALC, MMSRA, Hill AFB, Utah. Defective coldworked holes were found on F-4s which had undergone life extension modifications. The potential problem was a detrimental interaction between the residual stress field of the coldworked holes and a defective hole. This problem was brought to the attention of the Structural Integrity Branch of the Flight Dynamics Laboratory at AFWAL, WPAFB, Ohio, with a request to conduct an exploratory development program to systematically evaluate the fatigue life of coldworked holes.

Coldworking fastener holes is a modification which can be unreliable in the field due to human error and structural complications. While coldworking a structural component during the manufacturing stage is a relatively simple task, it can be difficult as a repair operation. Problems arise during repair or scheduled maintenance since some holes are not easily accessible to the technician with a coldworking gun. Also, fastener holes may no longer be of uniform size due to previous cleaning procedures (such as reaming) or because of damage caused by removal of fasteners. These defective holes lead to inconsistent

amounts of hole expansion during coldworking. Therefore, it is probable that several holes in a structure may not obtain the desired benefits from coldworking.

Common instances where holes do not receive coldworking benefits are:

1. a hole missed while coldworking a row of holes;
2. a hole too large to be coldworked with a regular sized mandrel because of earlier damage from reaming or damage from removal of a fastener; and
3. a hole which after being coldworked properly, is reamed larger than recommended relieving a substantial amount of the desired residual stresses.

Two questions arise: (1) what effect does a noncoldworked hole have on the residual stresses and therefore fatigue life, of neighboring holes which have been coldworked properly, and (2) what is the effect upon the fatigue life of a discrepant hole (noncoldworked or improperly coldworked hole) due to the state of stresses associated with nearby coldworked holes? The objective of this test program was to investigate these questions. This was done by measuring the residual stress pattern near fastener holes and by studying the fatigue behavior of coupon specimens containing both coldworked and noncoldworked holes.

The goal of this program was to determine the factors that affect the life of one row of open coldworked holes with a discrepant hole. Simulating a complex structural component to evaluate the above challenges involves numerous and complicated factors. A structural component experiences loads not only parallel to the row of fastener holes, but also loads perpendicular to the same row. Hole spacing must be considered along with differences in the amount of load transfer. For this program no-load-transfer specimens were used with one row of fastener holes parallel to the load axis. The specimens were tested to failure and the fatigue life and crack growth behavior were recorded. This report describes the type of specimens, test equipment, testing techniques, and results obtained from the program.

SECTION II

TEST METHODS AND PROCEDURES

1. LOAD HISTORY

A variable amplitude fighter load history described in References 2 and 3 was used in this investigation. This load history was a truncated composite baseline history. Studies have shown it to be an accurate and conclusive load history (Reference 3). The load history is made up of flight-by-flight segments which are repeated in 1000 flight hour blocks. This history was applied until failure or until 140 repeats of the 1000 hour sequence occurred.

2. SPECIMEN FABRICATION

Two geometries of test specimens were made from 0.25 inch thick 7075-T651 aluminum. Figure 1 shows these specimens which were designated Type I (one hole) specimens, and Type II (three hole) specimens. The distance between fastener hole centers was 0.75 inches. This hole spacing is prevalent on the underside of the F-4 wing. Below is a list of the specimens tested.

<u>Test Designation</u>	<u>Number of Specimens</u>	<u>Hole Configuration</u>
Type I-A	3	One hole not coldworked
Type I-B	3	One hole coldworked
Type I-C	3	One hole reamed too large after coldworking
Type II-A	3	Three holes not coldworked
Type II-B	5	Three holes coldworked
Type II-C	3	Two outside holes coldworked-inside hole reamed too large after coldworking
Type II-D	6	Two outside holes coldworked-inside hole too large to be coldworked
Type II-E	5	Two outside holes coldworked-inside hole not coldworked

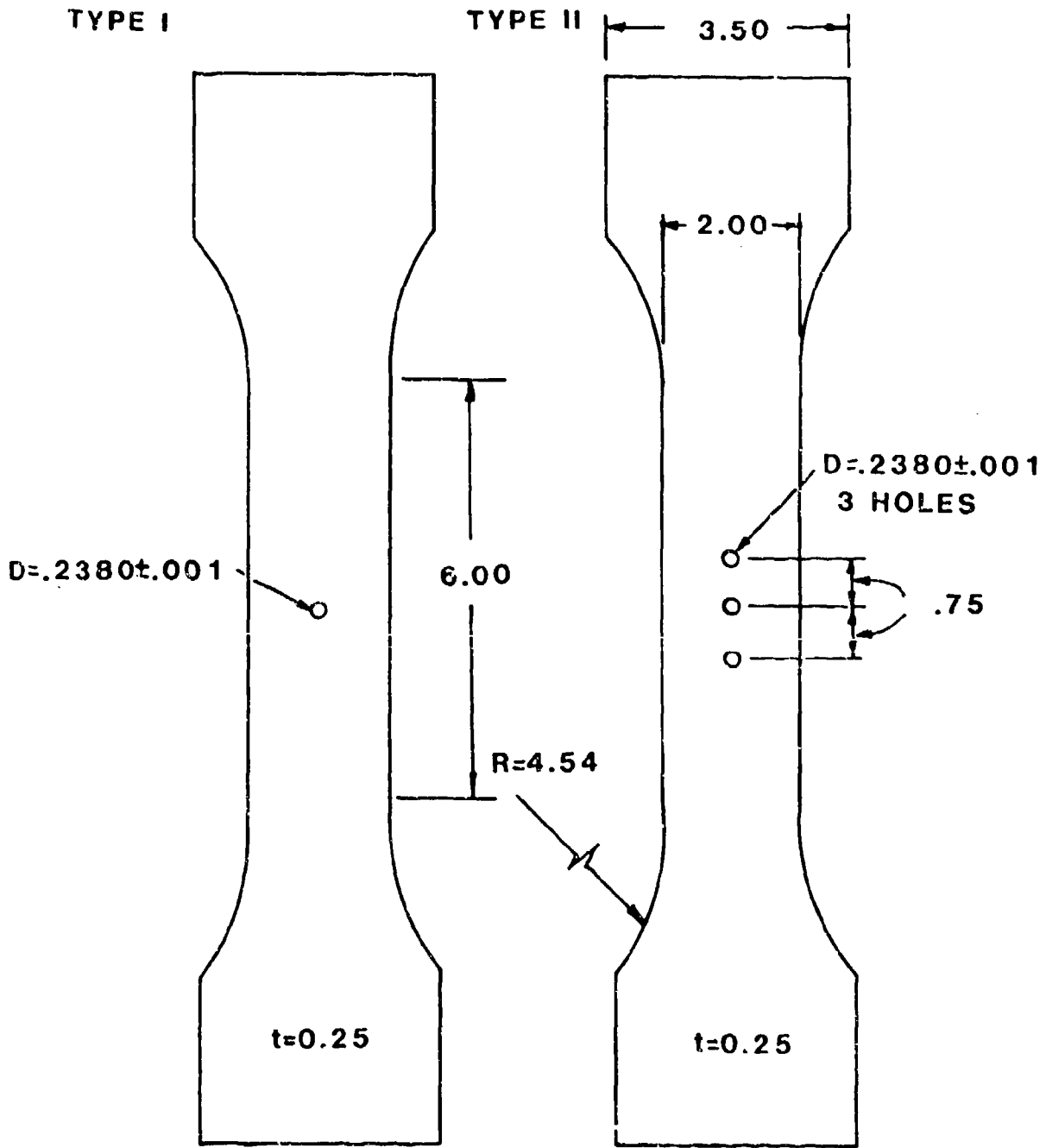


FIGURE 1 TEST SPECIMEN GEOMETRY

Fastener holes were coldworked using an Enerpac coldworking gun manufactured by Fatigue Technology Inc. (formerly Industrial Wire and Metal Forming Inc.). The initial hole diameter was between $.2350 + .003 - .000$. Mild steel sleeves with a $.008$ inch measured wall thickness were used with a dry film lubricant applied to the surfaces. The installation parameters used were specified in McDonnell Douglas process specification No. 19172. A mandrel was pulled through the sleeved hole with the hand operated hydraulic gun. After the mandrel was pulled through, the sleeve was removed, thus leaving a permanent increase in hole diameter. The amount of permanent expansion was determined by measuring the increase in hole diameter.

After coldworking, holes were reamed to remove marks left by the sleeve, as specified in McDonnell Douglas process specification No. 19172.

Three types of discrepant holes were simulated. To simulate a hole that was missed during the coldworking process, the hole was simply not coldworked. Holes that were to be too large to be coldworked were simulated by initially over drilling to a diameter of $.2460 + .004 - .000$ inches; with a hole of this diameter, the prescribed mandrel and sleeve could not plastically expand during the coldworking process. The third type of discrepant hole was produced by oversized reaming after coldworking. The procedure for coldworking was properly executed, but these holes were final-reamed to $.2600 + .003 - .000$ inches. This final diameter is far larger than a correctly reamed hole.

During the subsequent fatigue tests, crack lengths were measured with the aid of a binocular zoom microscope at 40X. The specimens were polished and mylar tape (200 divisions to the inch) was placed outside the fastener hole. Fastener holes were not preflawed to start cracking. Crack growth data was obtained following the application of every 1000 simulated flying hours.

3. TEST EQUIPMENT

A 100 KIP dynamic capacity closed-loop servocontrol load frame was used to subject test specimens to the fighter load history. The command signals (load levels) were stored in a 4000 byte memory digital programmer, and then fed to the load servo-controller. The applied loads were monitored through an independent computerized data system.

SECTION III

DISCUSSION AND RESULTS

The increased fatigue life observed with coldworked holes as compared to a noncoldworked hole is directly related to the compressive residual stresses immediately outside the fastener holes. However, there is an area of tensile residual stresses further away from the hole because of the necessary equilibrium of forces. It was first speculated that a coldworked hole surrounded by coldworked holes would be an extremely critical crack initiator. Not only would a discrepant hole experience the tensile stresses from an applied load, but also those tensile residual stresses from neighboring coldworked holes. This study, which included fatigue life tests and x-ray diffraction measurements, was designed to determine what effect tensile residual stresses from neighboring coldworked holes. This study, which included fatigue life tests and x-ray diffraction measurements, was designed to determine what effect tensile residual stresses from neighboring coldworked holes have on a discrepant hole and what effect a discrepant hole has on the fatigue life of that structure.

1. RESIDUAL STRESS MEASUREMENT RESULTS

By directly measuring the residual stresses outside Type I (one hole) specimen which is coldworked, certain effects of coldworking become easy to identify. Nondestructive measurements were taken with a Fastress Automatic Stress X-Ray Analyzer using the technique in References 4 and 5. The stresses were measured by an x-ray beam measuring .06 inch in diameter. It was found that a zone of beneficial compressive residual stresses for a Type I specimen extended 0.10 inches from the edge of the coldworked hole. This is illustrated in Figure 2. The accompanying tensile residual stresses were not measurable beyond 0.15 inches from the hole edge. This was due to the inability of the dual beam x-ray diffraction system to measure stresses in an area with metallurgical "preferred orientation." Measurements were possible near the hole edge because the cold working had destroyed the typical x-ray preferred orientation found in aluminum alloys. The two outside holes were coldworked leaving the middle hole uncoldworked. There was no

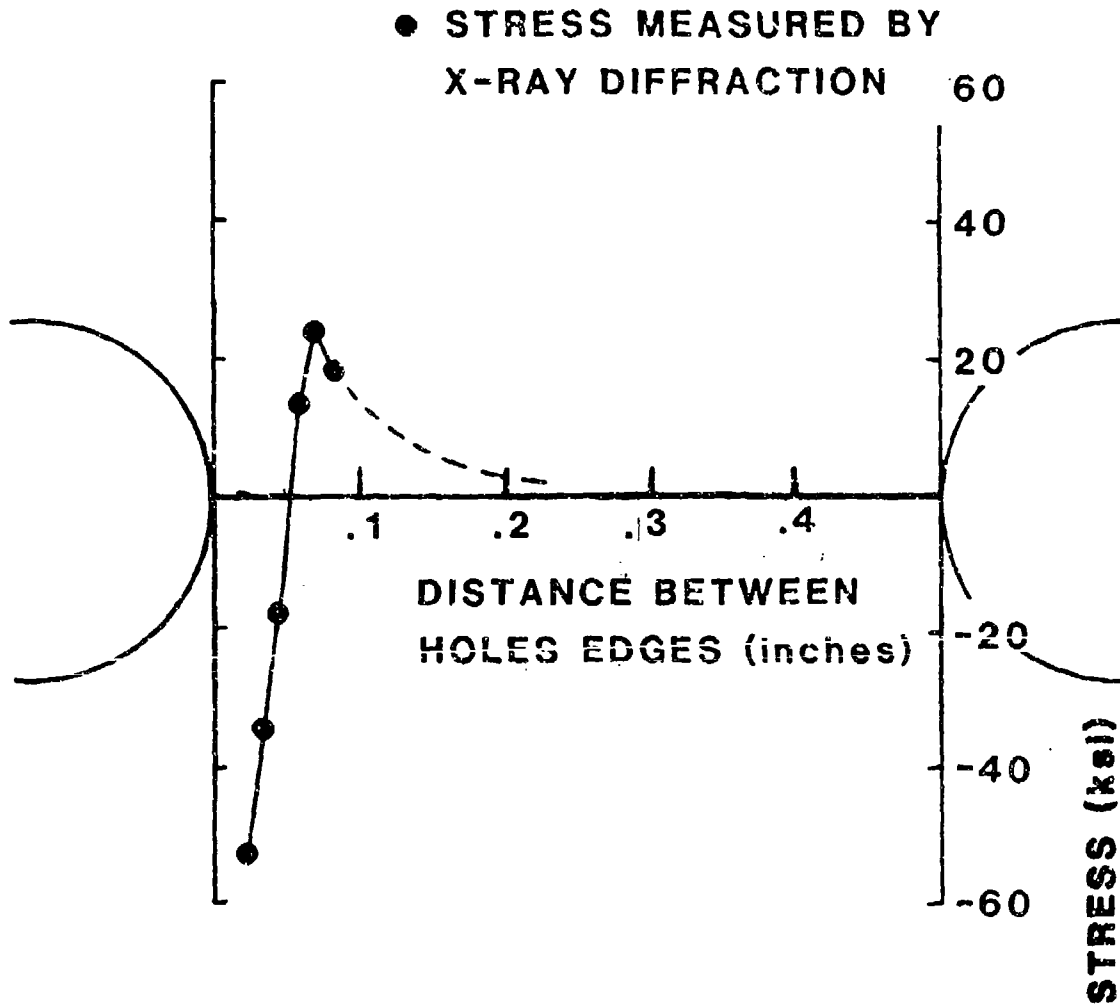


FIGURE 2 MEASURED STRESS DISTRIBUTION AT
COLDWORKED HOLES

difference between the coldworked residual stress distributions measured in the Type I and Type II specimens. Having a discrepant hole in a row of coldworked holes does not appear to change the residual stress pattern around the coldworked hole. It was, therefore, not anticipated that the discrepant hole would degrade the fatigue life of the coldworked hole. The result of the Fastress X-Ray measurements clearly illustrates that the residual stresses from a coldworked hole having a 1.5% permanent expansion falls off far in advance of reaching the discrepant hole edge. Based on these results, a critical loss in fatigue life for a discrepant hole next to a coldworked hole was also not anticipated.

2. FATIGUE LIFE STUDY RESULTS

The fatigue test results from this program are shown in Table 1. Figure 3 illustrates the fatigue life data and the log-mean fatigue life of each of the Type I specimen groups. Within the Type I specimens, the B specimens (properly coldworked holes) have the longest lives, outlasting the A specimens (noncoldworked hole) by nearly six times. This indicates a significant increase in life due to the coldworking process. The specimens in test series C showed approximately the same results as the properly coldworked "B" coupons. These results indicate that even out-of-specification post reaming of properly coldworked holes will produce adequate structural fatigue life behavior. An original concern was that loss in life would result from relieved compressive residual stresses caused by the removal of cold expanded material during the out-of-specification reaming process. This concern does not appear to be warranted.

Figure 4 illustrates the fatigue life results of the type II specimens. As in the Type I specimens, the properly coldworked coupons (Series II-B) had log-mean fatigue lives which were many times longer than the baseline non-coldworked specimens (II-A). Further, the out-of-specification reamed specimens (II-C) produced lives approximately the same as the within-spec coldworked coupons. An examination of the series II-D and II-E specimens compared to the II-B and II-C series reveals their life to be far less than the II-B and II-C series, but substantially more than the II-A non-coldworked specimens. This

TABLE 1
SUMMARY OF FATIGUE TEST RESULTS

Test Series	Specimen #	Test Lives (x1000 flight Hours)	Notes	Log Mean Average
Type I-A	G-4	20		21
	G-5	21		
	G-6	22		
Type I-B	F-1	123		113
	F-2	99		
	F-3	118		
Type I-C	H-1	116		117
	H-2	112		
	H-3	124		
Type II-A	B-1	18		18.3
	B-2	18		
	B-6	19		
Type II-B	E-1	148	Stopped - no growth	167
	E-2	453	Stopped - no growth	
	E-4	102		
	E-5	205		
	E-6	94		
Type II-C	A-5	157		164
	A-6	231	Failed outside test section	
	A-7	122	Failed outside test section	
Type II-D	D-1	40		32
	D-2	27		
	D-3	30		
	D-4	40		
	D-5	25		
	D-6	33		
Type II-E	C-2	39		38
	C-3	39		
	C-4	67		
	C-5	25		
	C-6	32		

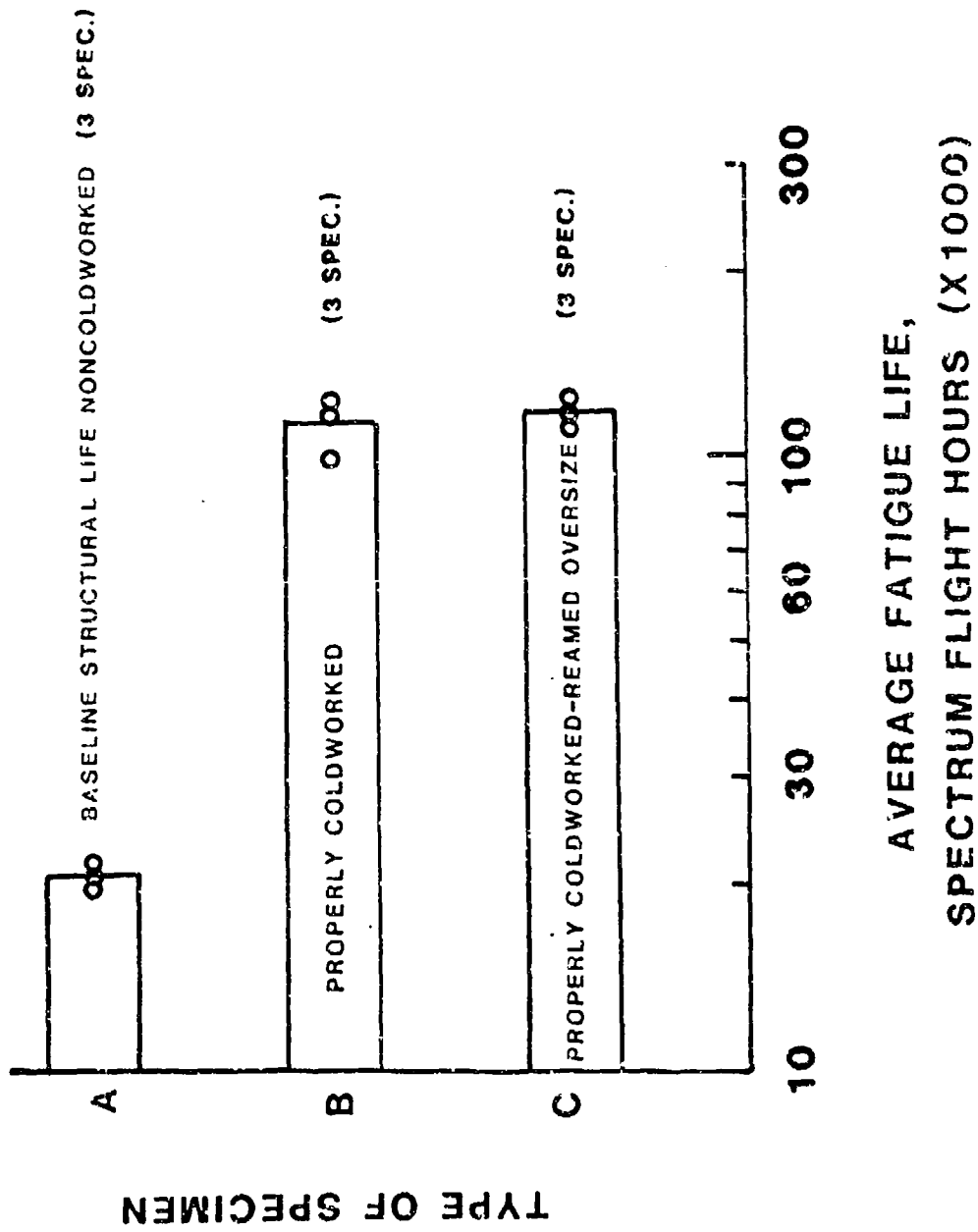


FIGURE 3 FATIGUE LIFE OF TYPE I (ONE HOLE) SPECIMENS

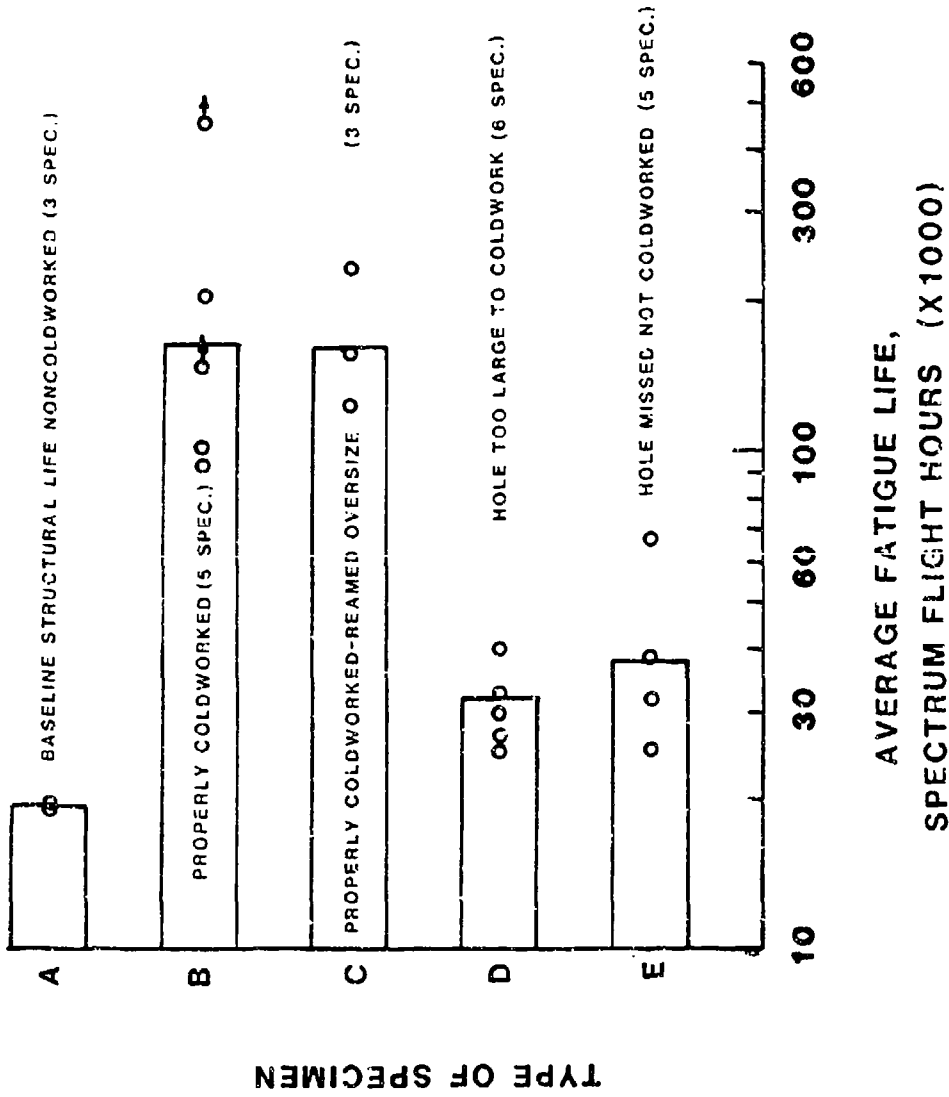


FIGURE 4 FATIGUE LIFE OF TYPE II (THREE HOLE) SPECIMENS

indicates that there is an apparent increase in fatigue life in a specimen with a noncoldworked hole surrounded by coldworked holes when compared to specimens with all noncoldworked holes. The average lives of II-D specimens were lower than those of the II-E specimens because of a higher stress concentration at the edge of the smaller hole.

With the use of the zoom microscope, cracks in the series II-D and II-E specimens were not visible in any of the outside properly coldworked holes; all cracks had originated from the center discrepant hole. This behavior contrasts with that of the Type II-A, II-B, and II-C series which had cracking in the outside holes only.

Several conclusions can be drawn from these tests. The problem that originally started this investigation was the worry that a poorly prepared hole would fail very prematurely because of the tensile residual stress field from the neighboring coldworked hole. This was determined not to be a critical situation. Discrepant hole Type II C, D, and E specimens have average lives which are longer than the life of A specimens without coldworking. It is apparent that there is a beneficial interaction between holes due to the state of stresses of the coldworked holes. Secondly, there was no noticeable detrimental effect in the life of a coldworked hole beside a discrepant hole since cracking did not occur in the coldworked hole.

3. CRACK GROWTH STUDY RESULTS

Figures 5, 6, and 7 were based on crack measurements taken after each 1000 hour repeat of the fighter load history. Since the holes were not pre-flawed, cracks were found growing from one or opposite sides of the holes. Figure 5 illustrates the crack growth of Type I specimens where cracks initiated from opposite sides of the hole. Figures 6 and 7 illustrate the crack growth of Type II specimens with one side and opposite sides of the hole cracked respectively.

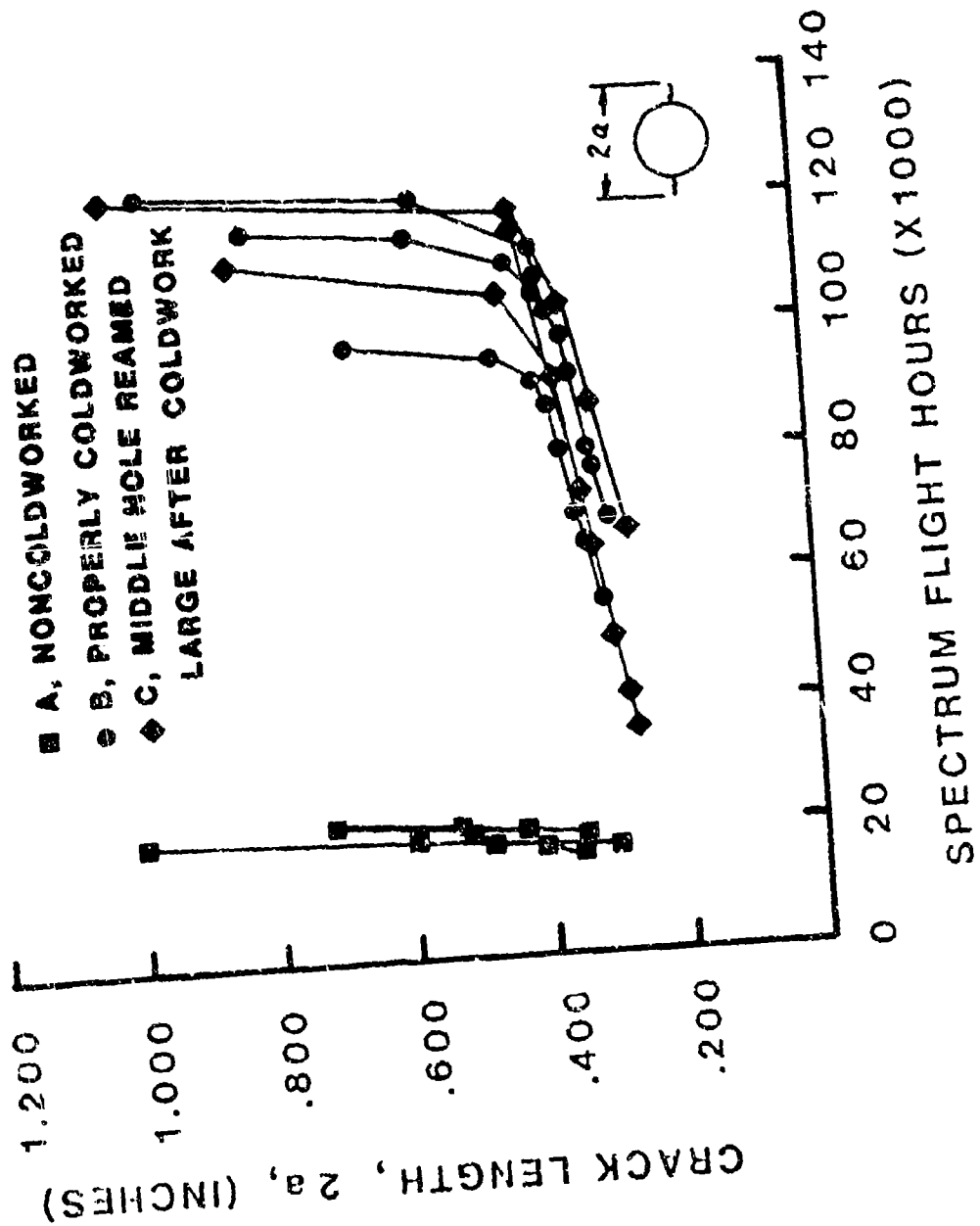


FIGURE 5 CRACK GROWTH BEHAVIOR OF TYPE I SPECIMENS

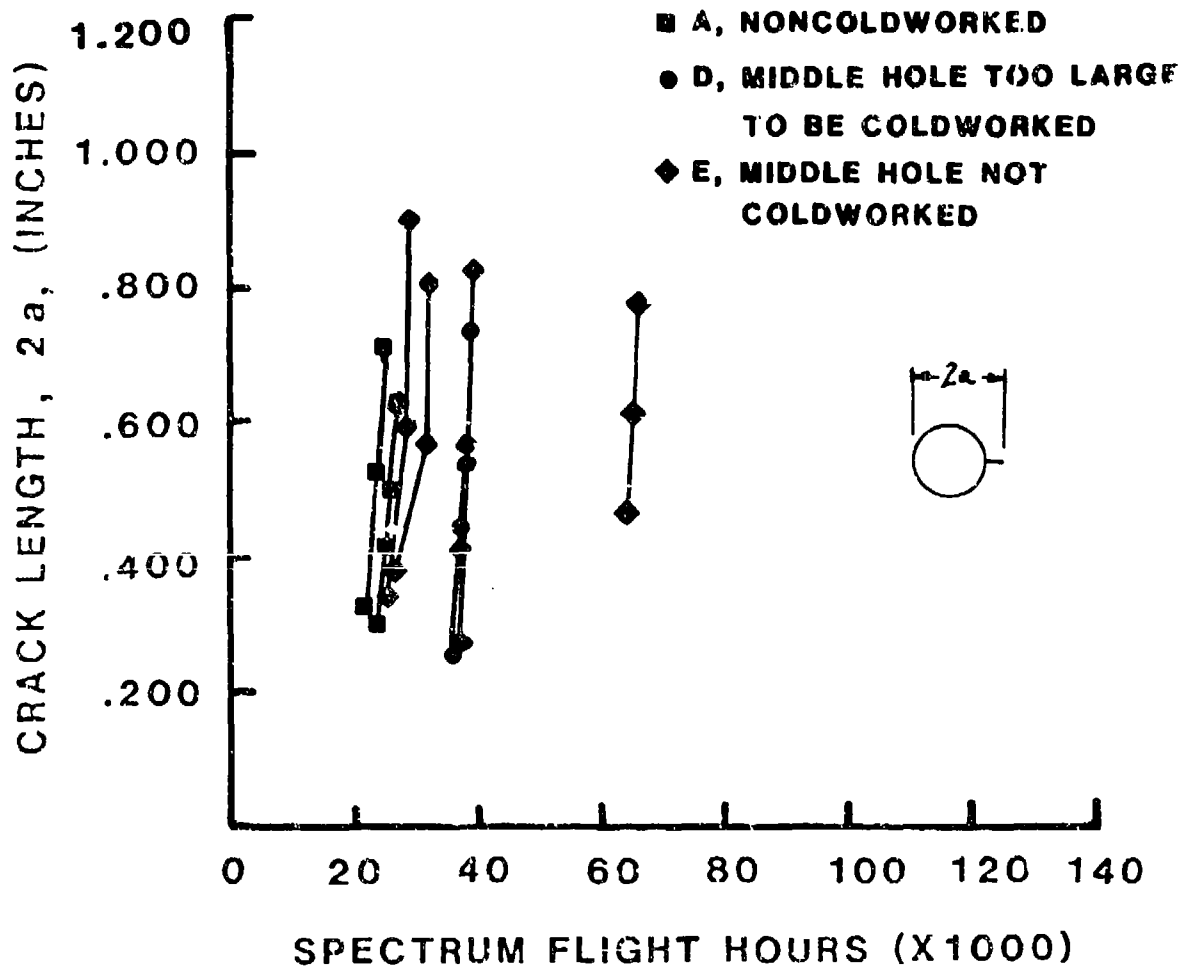


FIGURE 6 CRACK GROWTH BEHAVIOR OF TYPE II SPECIMENS (CRACKING FROM ONE SIDE OF HOLE)

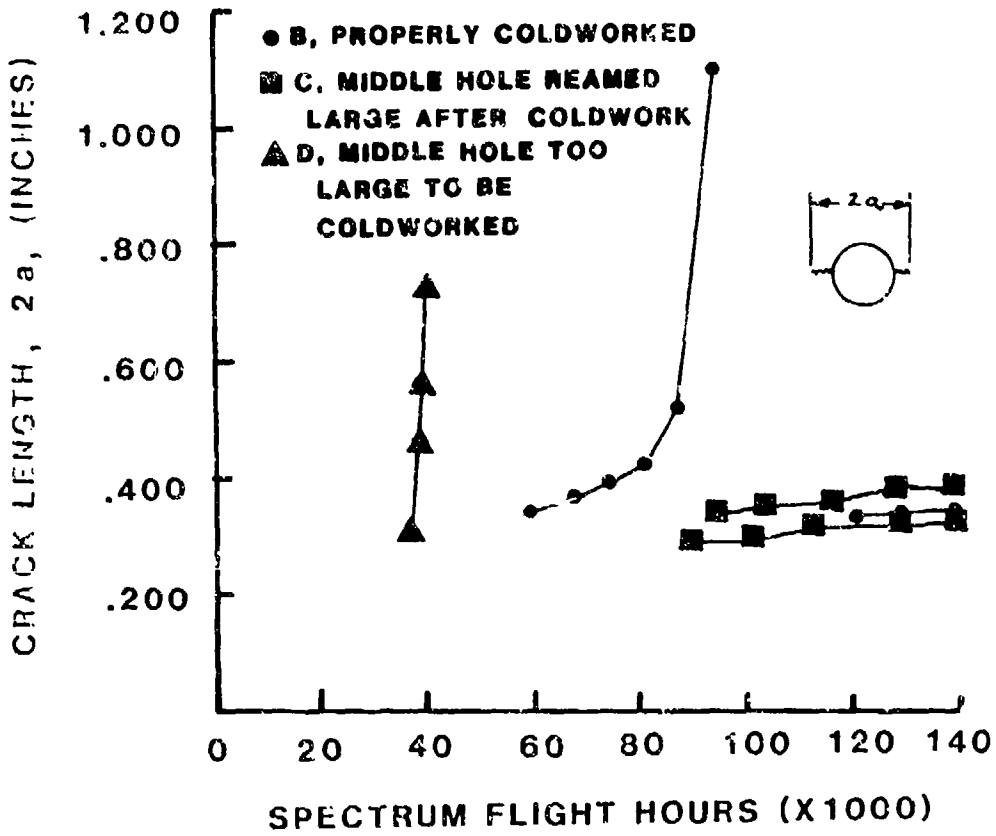


FIGURE 7 CRACK GROWTH BEHAVIOR OF TYPE II SPECIMENS
 (CRACKING FROM OPPOSITE SIDES OF HOLE)

The coldworked holes of specimens Type 1B, 1C were seen to crack initially at a predictably slow rate in the compressive residual stress region. Once outside of this region, the crack grows at nearly the same rate as those in A specimens noncoldworked.

No significant difference could be determined in crack initiation time or crack growth rate between the single coldworked hole and the hole reamed large after coldworking.

In Type II specimens, cracks initiated from the discrepant middle hole in all specimens except for A specimens (3 noncoldworked holes), where cracks were only observed in the outside holes. A look at the data from Type II specimens (Figures 6 and 7) reveals very little change in crack growth rate as compared to Type I specimens (Figure 5). However, a longer time to crack initiation is evident in Type II specimens. Apparently, the tensile residual stresses outside of the coldworked holes had no detrimental effect on the crack growth of a noncoldworked hole beside it. Crack growth data from the middle hole in C specimens were not significantly different than that observed in Type IA or Type IIA specimens (no coldworked holes). In specimens Type IIE and IID, there were no signs of increased crack growth rates, indicating that there was little or no effective tensile residual stresses due to neighboring coldworked holes. In turn, the properly coldworked holes show little or no signs of cracking during the fatigue test. Therefore, no detrimental effect is apparent on the state of stress of a coldworked hole due to a discrepant hole beside it as seen in the crack growth curves.

4. HOLE SPACING EFFECTS

The data from Figure 4 indicates that the Type IID and IIE specimens which had one hole not-coldworked had fatigue lives which were at least 50% longer than IIA specimens where none of the holes were coldworked. This fatigue life increase occurred even though each set of specimens experienced identical loading conditions. Photoelastic results are available in the Peterson (Reference 6) handbook for a wide variety of structural geometrics. Peterson's results for a row of notches is shown in Figure 8. These results indicate that the center of

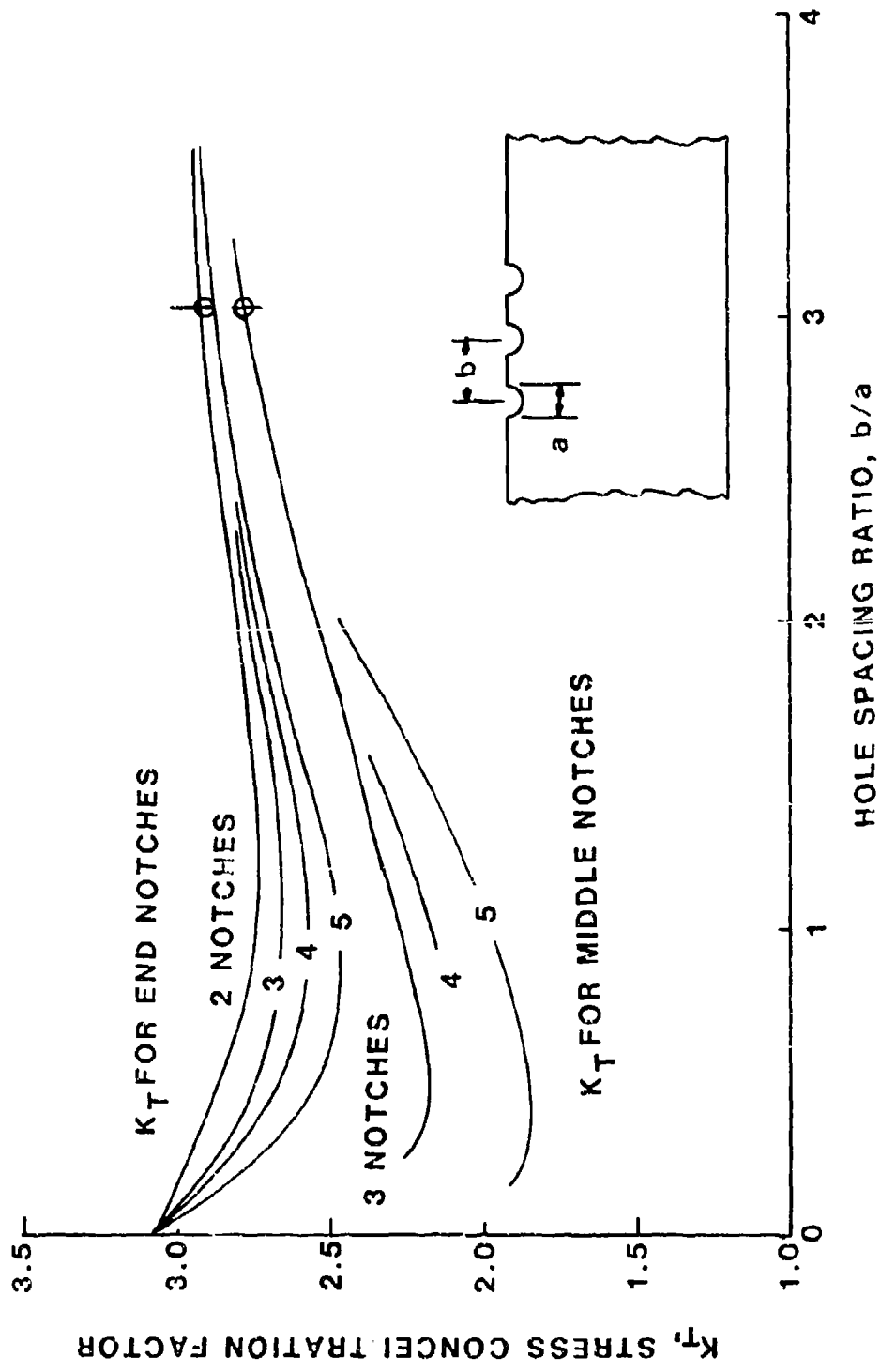


FIGURE 8 EFFECT OF A ROW OF NOTCHES ON STRESS CONCENTRATION FACTOR

three-in-a-row holes would have an elastic stress concentration factor of 2.72 compared to 2.88 for the end notches. The Type IIA specimens all failed at the end holes whereas the IID and IIE specimens all failed at the center holes. The difference in stress concentration factors between the end holes and middle holes is greater than five percent. The data by Potter, Gallagher, and Stalnaker (Reference 7) for a similar F-4 load history would indicate a similar increase in fatigue life for a 5% reduction in stress (analogous to a 5% change in stress concentration factor). Thus, the improvement in fatigue life for test series IID and IIE specimens is consistent with the elastic stress shielding of a row of fastener holes.

SECTION IV

CONCLUSIONS

The results of this investigation indicate that there is a minimal reduction in fatigue life attributable to a defective discrepant hole in a structure with the following configuration:

1. one row of coldworked fastener holes and,
2. an applied load parallel to the row of fasteners.

The residual stresses extending from coldworked holes do not interact with a discrepant hole to substantially reduce its life.

The discrepant hole does not affect the residual stresses of a coldworked hole so that the coldworked hole would fail before the defective hole.

The life of a component containing a discrepant hole among properly coldworked holes, will be no worse than that of a noncoldworked structural component. In fact, the structural life is usually enhanced.

The relative increase in structural fatigue life of a discrepant hole in an otherwise properly coldworked structure is due to a "shielding" effect.

SECTION V
RECOMMENDATIONS

The following are recommendations for further study:

1. A new specimen should be designed such that the loading will be perpendicular to the row of fastener holes. A defective hole should be placed in a row of coldworked holes in a manner similar to what was done with Type I and II specimens. A life study should be done to determine if there are any interactions between defective and coldworked holes in this stress field.

2. A similar study should be done with a specimen having 3 rows of coldworked holes. A defective hole should be placed in the middle of the three rows, simulating a more complicated structure. This proposed study should be made to determine the prime cause of failure in the defective hole.

3. An investigation should be conducted to better understand the "shielding" effect when coldworking is present. Specimens with different hole spacing should be manufactured to determine the hole spacing at which "shielding" no longer affects the life of a defective hole. Methods of actually measuring the "shielding" effect should also be evaluated.

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