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Analytical Tools for Residual Stress Enhancement of Rotorcraft Damage Tolerance

Volume 2: Materials, Components, and Life Enhancement Verification

April 2015

Final Report

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16. Abstract

There are several methods for improving the damage tolerance life of metals commonly used on rotorcraft. These methods have been used conservatively for many years without adequate practical, reliable, and validated analytical methods for fracture mechanics analyses to account for the total benefits. This program examined one life improvement method (i.e., cold working) on open hole specimens and loaded hole specimens of aluminum structures.

Sikorsky Aircraft Corporation designed and manufactured the test articles and provided life enhancement verification of the methods currently used in the rotorcraft industry. This volume describes these procedures.

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LIST OF ABBREVIATIONS AND ACRONYMS

BEASY	A boundary element software code that is able to account for frictional surfaces.
CHOLE4	An in-house SAC code that solves closed-form equations for cold-worked holes
FASTRAN	A fracture and crack growth code
FRANC2DL	Fracture Analysis code is an academic software code that uses FEA on 2D models
FRANC3D	Fracture Analysis code is an academic software code that uses FEA on 2D models and boundary elements on 3D models for fracture mechanics
2D	Two-dimensional
DTA	Damage tolerance analysis
EDM	Electrical discharge machining
FEA	Finite element analysis
FTI	Fatigue Technologies Incorporated
HE	Hill Engineering
MSU	Mississippi State University
SAC	Sikorsky Aircraft Corporation
SIF	Stress intensity factor
VMC	Vertical machining center

EXECUTIVE SUMMARY

Sikorsky Aircraft Corporation (SAC) designed and manufactured test specimens for determining the effects of life enhancement techniques on rotorcraft materials. SAC designed test coupons for open hole and loaded hole tests. SAC also designed and manufactured nested angle component specimens to test the life enhancement techniques on an actual rotorcraft component. The parts were designed, manufactured, and cold worked at SAC and later notched and assembled at Hill Engineering.

SAC examined the current methodology of analyzing the life enhancements used in rotorcraft manufacturing. The CHOLE4 program is an in-house SAC program that solves the closed-form equations to derive a residual stress field to incorporate into a finite element analysis (FEA) model or NASGRO® solution. A FEA is performed to determine the loads and stress fields, which are then used in fatigue or damage tolerance analyses. NASGRO allows the addition of residual stresses in some of its K solutions, but these residual stresses can also be included using data tables. Another method whose use is currently expanding in this area is the BEASY program, which is a boundary element software code that is able to account for frictional surfaces. Future releases of BEASY may be able to account for many aspects of the component level tests that have not been examined—such as friction, head fixity, fastener preload, and load redistribution. Extending from the BEASY analysis and testing, these items should be further examined for effects on cold working and other life enhancement techniques.

This program originally planned to examine several different methods of life enhancement. Because of the reduction in the program's scope, only cold working was examined.

1. INTRODUCTION

This program studied the use of analytical techniques to help quantify the effects of life enhancement techniques, specifically the cold working of holes. Specimens were manufactured for open hole tests and loaded hole tests with holes cold-worked. The holes were cold-worked to 3% to ensure that the holes would crack. Electrical discharge machining (EDM) notches were also introduced into the specimens at Hill Engineering (HE). These results are elaborated on in volume 3 of this study [1].

For the component level test, a nested angle specimen was used. Tests on these specimens verified many of the additional complexities associated with actual aircraft parts. These results are also shown in volume 3.

1.1 PURPOSE

The development of a consistent and validated analytical approach for predicting the influence of residual stress treatments will allow damage tolerance analysis (DTA) to be used more widely in rotorcraft structures. The purpose of the research was to establish current DTA capabilities for rotorcraft as well as opportunities for improvement. Practical DTA methods were applied in a typical rotorcraft development environment. These methods were developed to advance previous research and provide practical, reliable, and validated analytical methods for crack growth analyses that account for the effects of residual stress-based life enhancement processes such as cold-worked holes. The objectives were:

- design and manufacture aluminum coupons of increasing complexity to generate the data needed to review analysis predictions
- review current analysis methods abilities in accounting for stress fields resulting from residual stress treatments
- experimental validation of commercial-off-the-shelf analysis methods to predict crack growth in bodies containing residual stresses
- baselining DTA design tool capability for rotorcraft components
- quantifying the capability of existing damage tolerance techniques to properly account for the benefits of existing and new life enhancement processes for rotorcraft applications

1.2 BACKGROUND

The current methods baseline program was conducted by the Sikorsky Aircraft Corporation (SAC) at its Stratford, CT and Fort Worth, TX facilities. SAC supplied both production and engineering support. Test articles were manufactured for open hole, loaded hole, and fastened lap joint configurations. The fastened lap test article was designed to closely mimic common fielded configurations. All of the materials used in the manufacture of the test articles were production materials commonly used in many rotorcraft products. All life enhancement work (cold working) was done at SAC using the Fatigue Technologies Incorporated (FTI) split sleeve method. The

FTI method is commonly used on aerospace structures. A nested angle single lap configuration, developed at SAC [2], was used to represent the fastened lap joint found in many production aircraft. SAC's CHOLE4 code was applied to determine the residual stress field generated by the FTI cold working and reaming process. Early in the program analyses, through the use of NASGRO® version 6.1 and CHOLE4, it was determined that some level of relief from the standard FTI process was required for slow crack growth from small crack-starter notches. The cold working intensity was subsequently reduced to 3% instead of the standard 4–4.5%. This work is described in [3 and 4].

1.3 RESEARCH OBJECTIVES

The objective of this program was to provide an improved method of accounting for life enhancement techniques commonly used in rotorcraft production. Some of the complexities of the actual aircraft parts were investigated, including frictional contact between joints and on the fastener, load transfer, head fixity, and bending loads.

2. MATERIALS

2.1 ALUMINUM ALLOY 7075-T6 SHEET (BARE AND CLAD)

7075-T6 is a high-strength aluminum alloy commonly used in the manufacture of aerospace structures. The alloy was chosen for the open and loaded hole tests because of its extensive application in rotorcraft as well as for its data availability in the NASGRO material database.

2.2 ALUMINUM ALLOY 7075-T6511 EXTRUSION

The fastened joint test article was constructed of 7075-T6511 extruded aluminum. The T6511 heat treatment is a common standard for aerospace 7075 extrusions. This alloy was chosen for the nested angle component tests because: (1) it is used extensively in rotorcraft structural configurations, (2) this alloy has been used on several nested angle tests in other programs, and (3) of its extensive application in rotorcraft and data availability in the NASGRO material database.

3. MANUFACTURING DESCRIPTIONS

3.1 GENERAL MACHINING NOTES

All machining was done using a Bridgeport vertical machining center (VMC). Castrol Syntilo™ 9930 10% concentration cutting/cooling fluid was used. Edge deburring was done using an aluminum oxide abrasive drum on a drill press. The drum was a compliant article producing a radius edge in lieu of a hard chamfer.

3.2 NESTED ANGLE DETAIL MANUFACTURING

The nested angle details were machined from Alcoa extruded 7075-T6511 die numbers AND10133-1202 and AND10133-1601. The extrusions were purchased from Castle Metals® and were of the material specification AMS-AA-A-200/11. The detail lengths were cut using a band

saw. The corners of the extruded cross sections were radiused to facilitate assembly. The radii were produced using a high-speed steel radius cutter. The grip ends of the angle sections were left as saw cut. The opposite ends, in the splice zone, were machined using a two-fluke carbide end mill. The legs of the extrusions were milled to the required length using the same two-fluke carbide end mill.

Fastener holes were initially produced using a hand drilling operation similar to that of aircraft assembly procedures. It was determined that the hand drilling could not produce the desired consistency. Subsequent fastener holes were produced using the VMC. A drilling operation was followed by a reaming procedure. Two large grip holes were produced in the mounting regions of the angles. The large .750-inch diameter holes were generated using a circle reaming process and were deburred; the fastened holes were surface sanded but not deburred.

The fastener holes in the residual stress specimens were cold-worked using an FTI split sleeve cold expansion cutting tool (part CBSD-4-4-N-1), a split sleeve cold expansion cutting tool (part CBSR-4-4-N-1),), a split sleeve cold expansion gage (part CBMG-4-4-N), a split sleeve cold expansion sleeve (part CBS-4-4-N-16F), a split sleeve cold expansion mandrel (part CBM-4-4-N-1-30-V1), a split sleeve cold expansion nose cap (part MEN-14A-0601F), and a 0.1875” split sleeve cold expansion cutting tool (part CBR-4-4-N-1). Figure 1 shows the equipment used in the process.

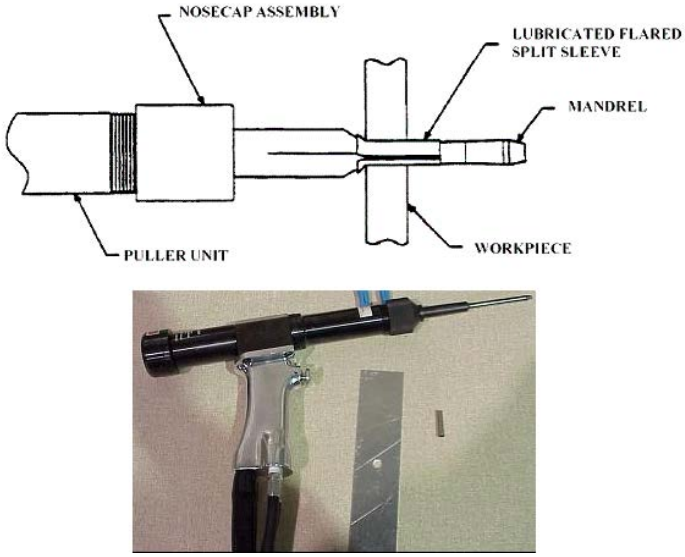


Figure 1. Cold Working Unit

The sleeve split was positioned at either the 6 o’clock or 12 o’clock (+/- 5°). Specimens were line-reamed to the final diameter as a matched set. A standard Hi-Lok® go/no-go inspection tool was used to inspect the final diameters. Matched sets with required Hi-Lok pins and collars were supplied without final deburr or EDM notching to HE. Figure 2 shows the cold working done on the nested angle specimens.

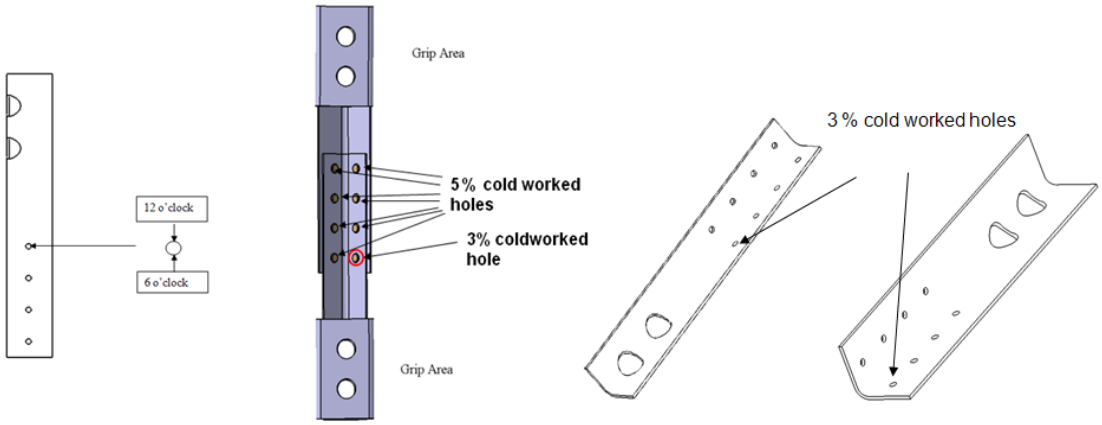


Figure 2. Cold Working on Nested Angle Specimens

Hi-Lok fasteners were sent to HE for assembly of the nested angle specimens. HL-20-6-3 (3/16") fasteners and HL86-6 stainless steel collars were delivered along with the two cold-worked and non-cold-worked angle pieces for EDM notching and assembly. The exact specifications are detailed in [4]. Figure 3 shows some drawings from the specifications.

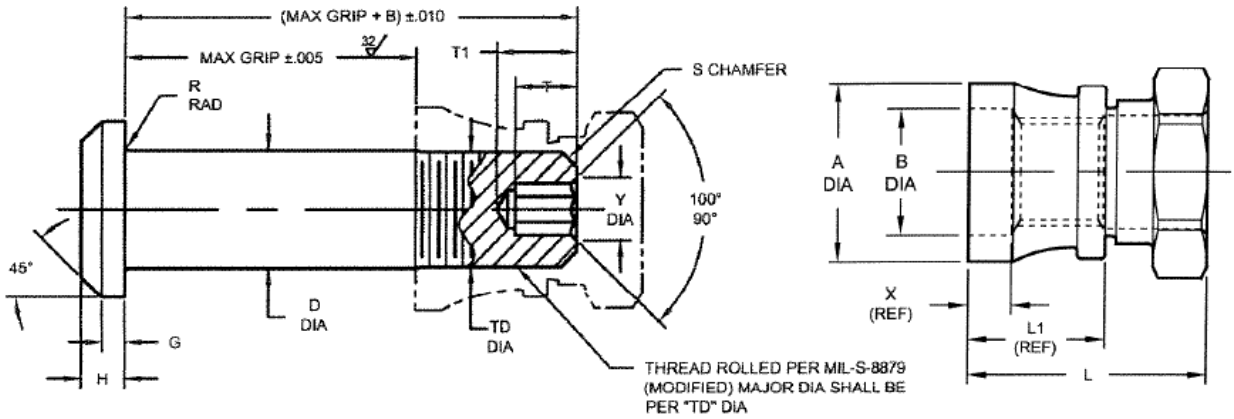


Figure 3. Fastener and Collar for Nested Angle Specimens

3.2.1 Open Hole/Loaded Hole Specimens

Specimens were rough saw-cut and finished machined from previously heat-treated plate stock. Specimens were profile-cut to shape using a two-flute end mill. Large flat surfaces of specimens were generated using a 4-inch diameter, 6-insert face mill turning at 800 rpm. Holes were drilled and reamed using the VCM. Cold working and deburring were done, where required, using the same process as that used for the nested angle specimens.

Open hole specimens were all individually manufactured. Loaded hole specimens were manufactured in pairs. The loaded hole pairs were initially joined at the small end, opposite the grip region. Holes were drilled while the pairs were joined. The pairs were cut into two specimens using the VMC. All cold working was done after separation of pairs.

4. LABORATORY TEST SPECIMEN DESIGN

4.1 OPEN HOLE SPECIMENS

Three different test specimens were designed for testing the advantages of cold working (figure 4). The previous program [4] examined an open hole with cold working. In that program, the cold-worked holes required reaming and notching several times before they cracked. For this program, the cold worked holes were reamed to the maximum value allowed by specification and cold-worked to only 3%.

The first specimens designed were for the open hole tests. A total of 99 specimens of the open hole type was delivered. Two different thicknesses were tested. Several non-cold-worked and several cold-worked (to 3%) holed specimens were tested (see table 1).

If the EDM notches do not facilitate crack growth, the hole could be further reamed or the EDM notch size increased. This notching was not done at SAC.

Table 1. Open Hole Specimens

Material	Condition	B, Thickness, in.	Number of Specimens	
			Cold-Worked	Non-Cold-Worked
Al 7075-T6	Clad	.08	15(a)	2(a)
Al 7075-T6	Bare	.08	15(a)	2(a)
Al 7075-T6	Clad	.19	15(a)	2(a)
Al 7075-T6	Bare	.19	15(a)	2(a)
Al 7075-T6	Clad	08	4(b)	2(b)
Al 7075-T6	Bare	08	4(b)	2(b)
Al 7075-T6	Clad	.19	4(b)	2(b)
Al 7075-T6	Bare	.19	4(b)	2(b)

Note: (a) = Length and width: 12” x 3.5”, (b) = Length and width: 3.5” x 1.75”

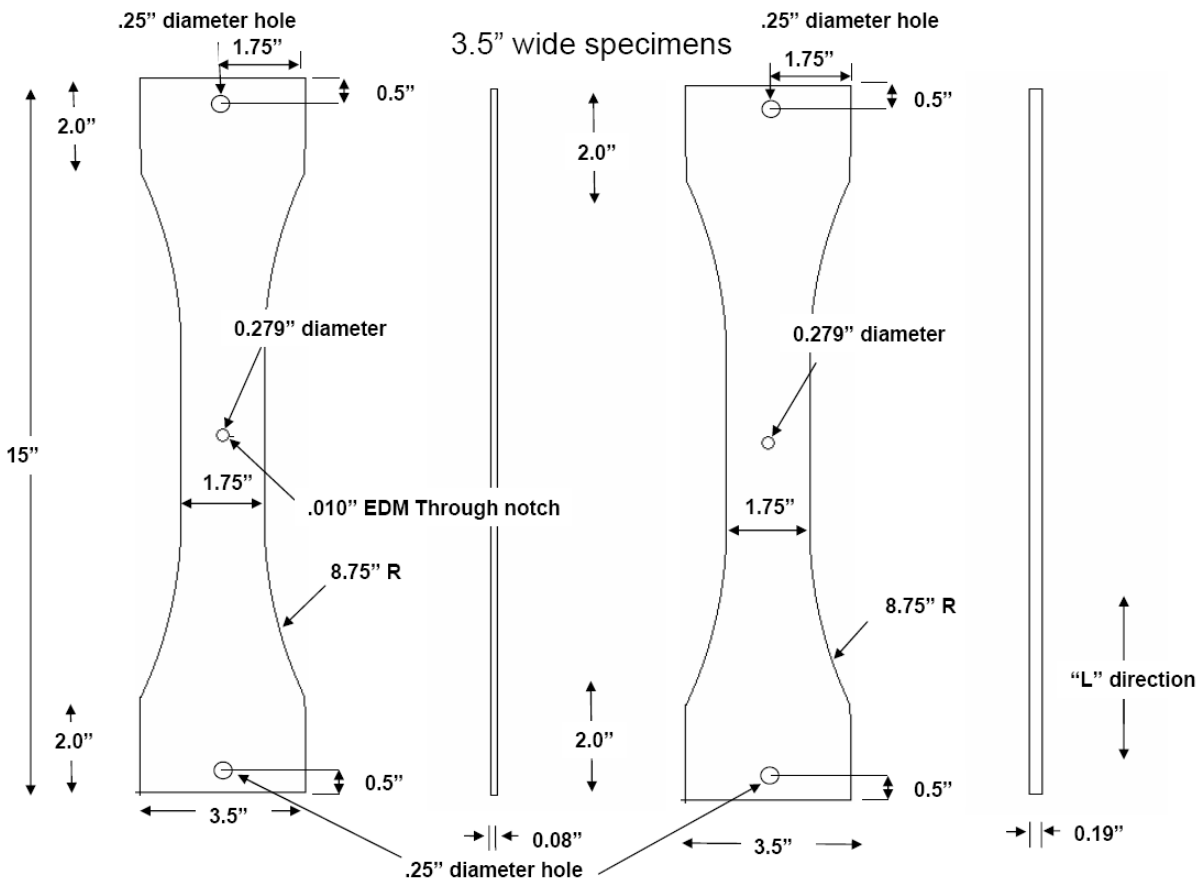


Figure 4. Open Hole Design

A FRANC2DL model shows excellent correlation with the NASGRO K solution. The stress intensity factors (SIF) for this model are almost identical to that of the NASGRO K solution TC03 (see figure 5).

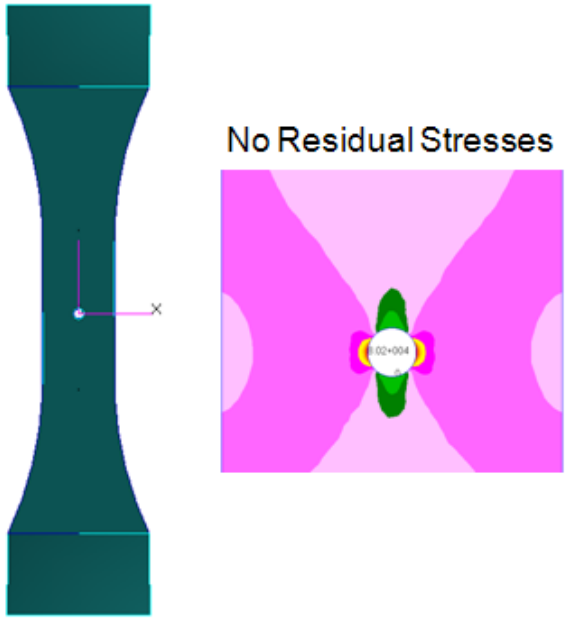


Figure 5. Open Hole Model

Constant-amplitude loading was used on the open hole specimens. The analysis shows an increase of about 10 times the life without cold working. It also shows that, once the crack gets past a certain size, it grows very quickly.

Figure 6 shows results for the .08-inch-thick specimen. For the test, the loading increased to allow the part to fail after a specific number of cycles. Therefore, the analysis is almost the same for the .19-inch-thick specimens, which are not shown.

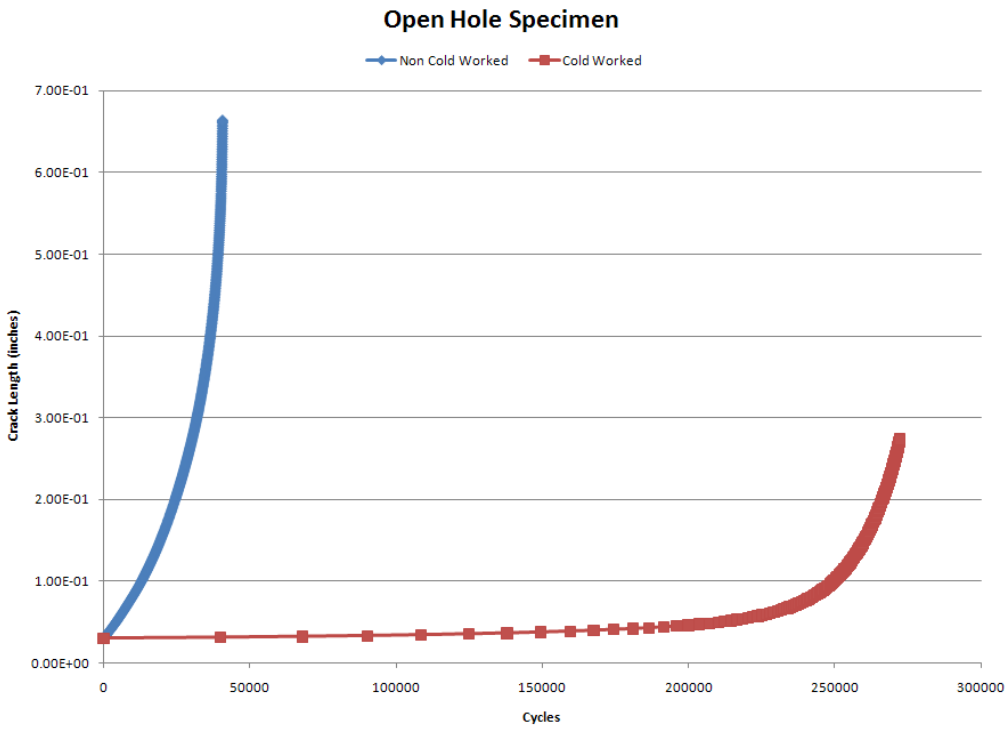


Figure 6. NASGRO Run for Open Hole for .08-Inch-Thick Specimen (TC-13)

A total of 16 residual stress coupons was also delivered to determine the residual stresses of the cold-worked holes (figure 7 shows a sample residual stress coupon). These specimens were cold-worked and the residual stresses determined by cutting open the specimen. A test was then performed to show the actual residual stress field. This is documented in volume 1 of this report [5].

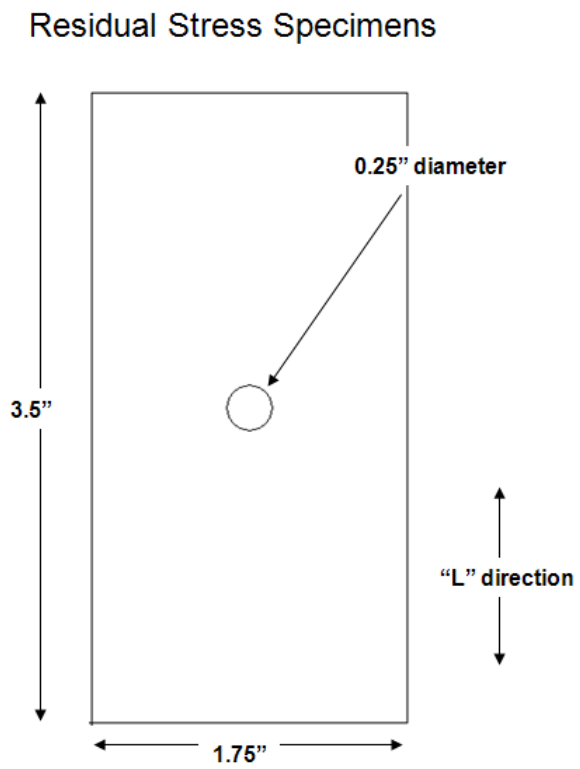


Figure 7. Residual Stress Coupon

4.2 LOADED HOLE SPECIMENS

The second set of specimens designed were for the loaded hole tests. A total of 48 loaded hole specimens—24 with a .08-inch thickness and 24 with a .19-inch thickness—was delivered to HE. Cold working was done at SAC, although EDM-notching was not done there.

Figure 8 shows the design of the loaded hole, which is similar to the open hole. The parts were cut in half and each side was used as a specimen. Specimens were then cold-worked, labeled, and shipped to HE. Figure 9 shows a bearing-only model run in FRANC2DL that was actually tested.

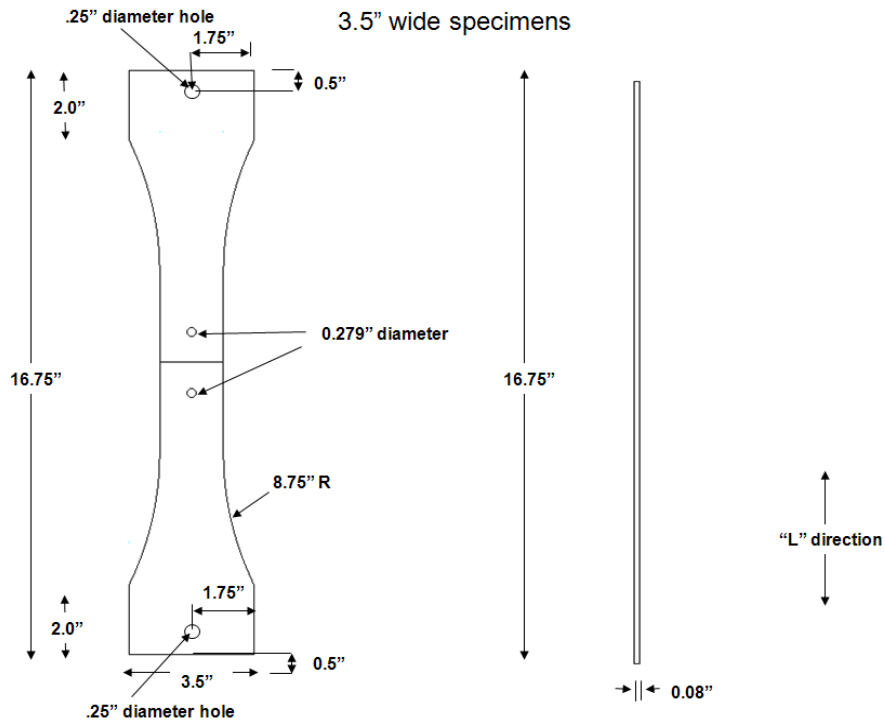


Figure 8. Loaded Hole Design

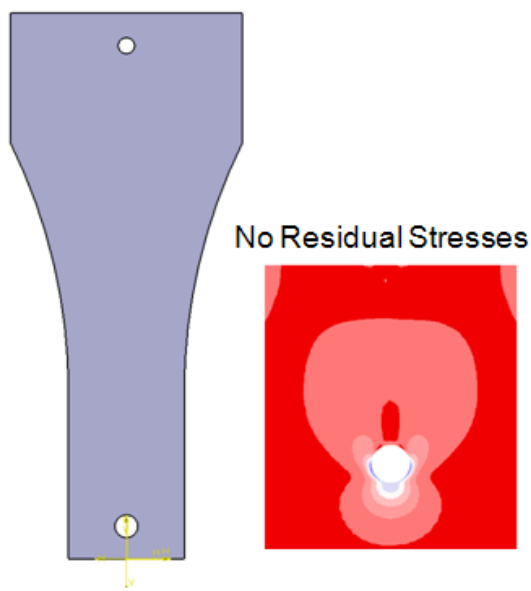


Figure 9. Loaded Hole Model

The stress model from Mississippi State University (MSU) agrees with the FRANC2D model, as shown in figure 10.

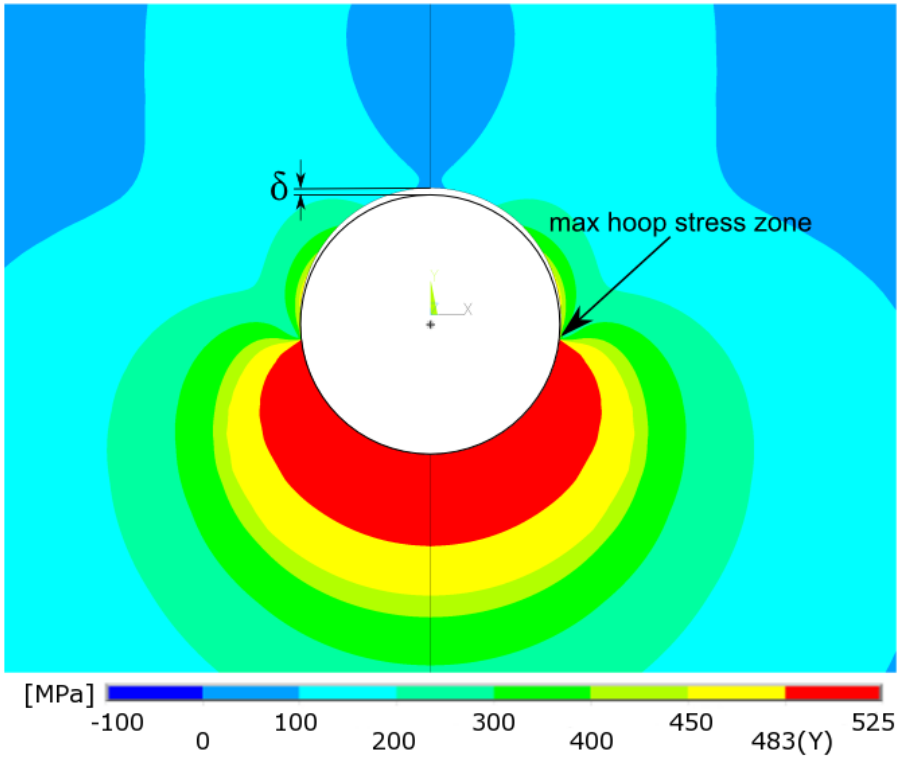


Figure 10. MSU Model von Mises Stresses

NASGRO does not provide the option of running a bearing load with residual stresses directly. NASGRO solution TC13 does not account for bearing loads. Figure 11 shows a comparison with pure bearing NASGRO solution TC03 and cold working TC13 models.

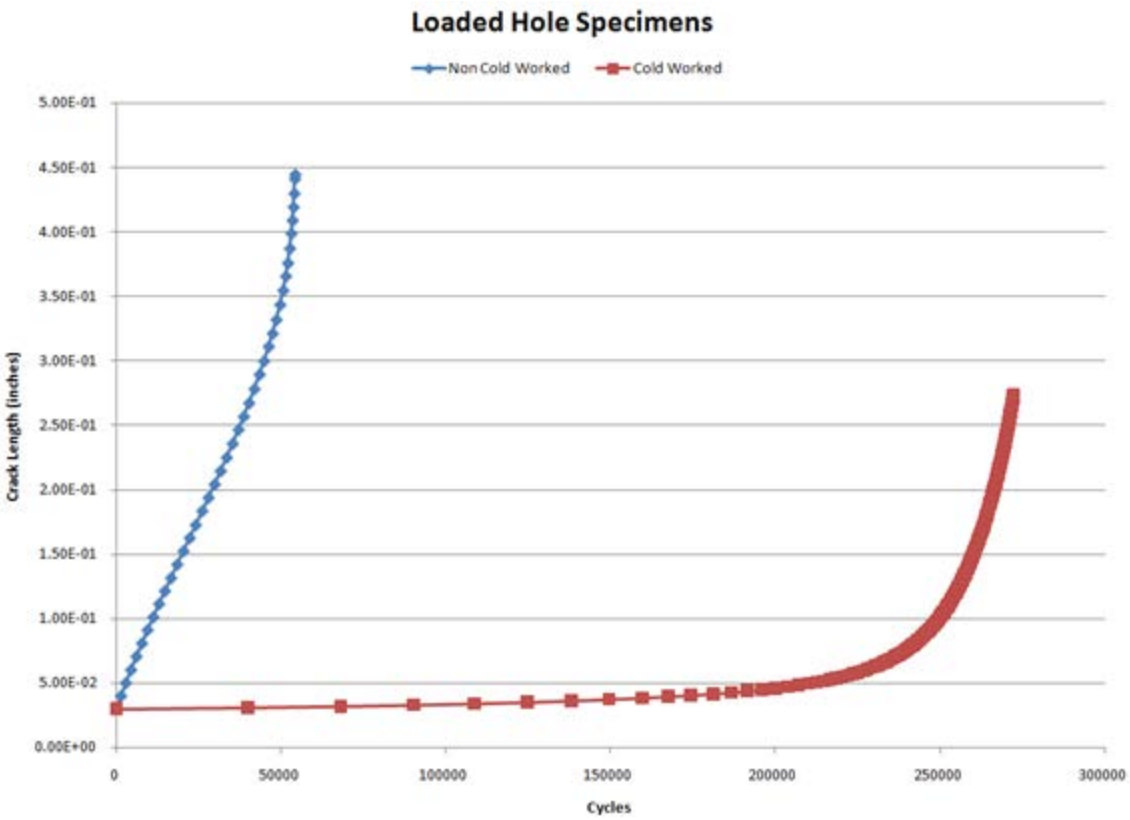


Figure 11. Loaded Hole NASGRO Analysis (.08-inch-thick specimen)

Running this FRANC2DL model with a pure bearing load shows the additional drop in SIF not seen in the NASGRO model; this is shown in figure 12. The direction of the crack growth is also quite different from FRANC2DL because NASGRO assumes the crack will grow directly to the edge. Figure 12 shows the stress intensities without any residual stresses.

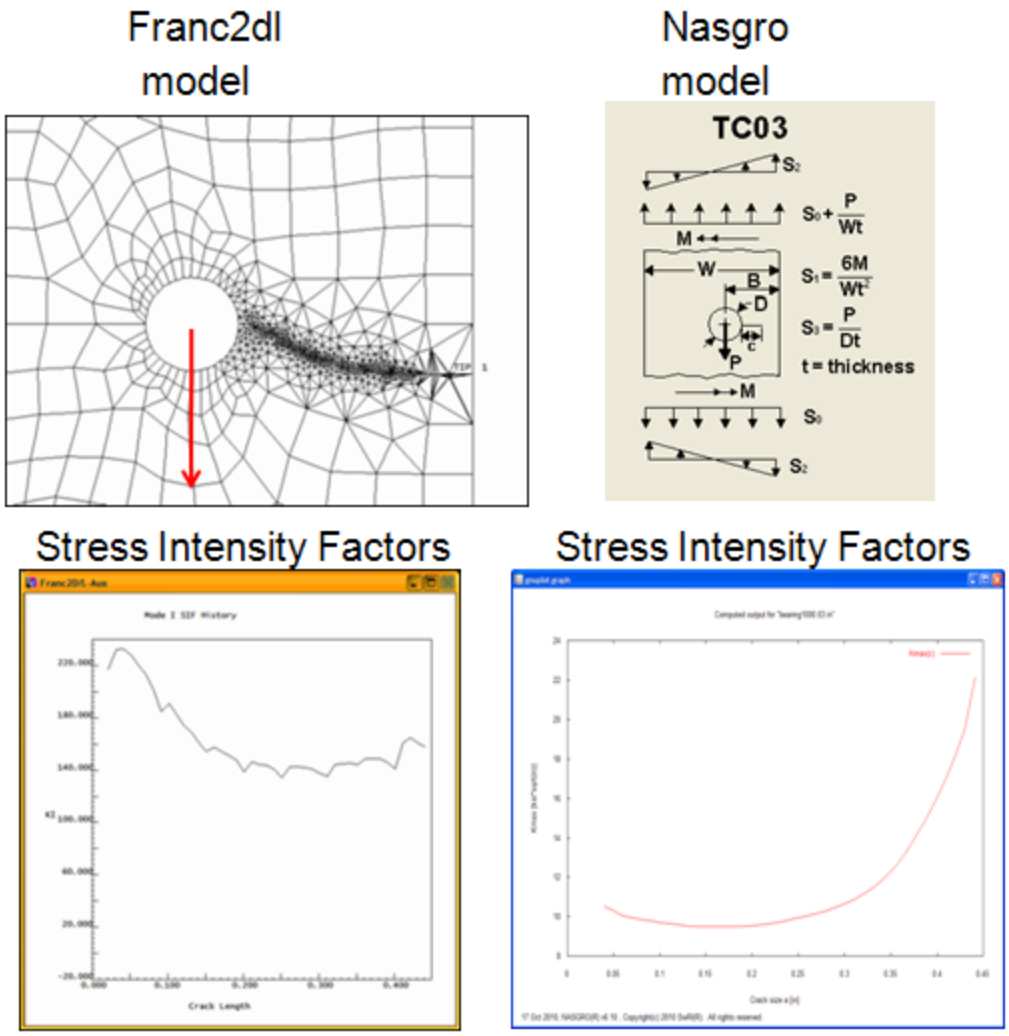


Figure 12. Stress Intensity Solutions From FRANC2DL and NASGRO

Using the principle of superposition, the FRANC2DL results can be put into a residual stress computation in NASGRO. This slowing down of the crack can be very important for inspections, repairs, and rotorcraft health and usage monitoring systems.

This slowing down is also seen in the nested angle specimens. However, these specimens had only 20% bearing loads on the critical fastener. Several other factors may also cause the crack to slow down as it grows. This is discussed in section 4.3.

The test data from the loaded hole tests shown in volume 3 [1] testing show the slowing down effects of the crack growth; figure 13 shows those effects for three different tests. Figure 14 shows crack growth rates from loaded hole specimen tests.

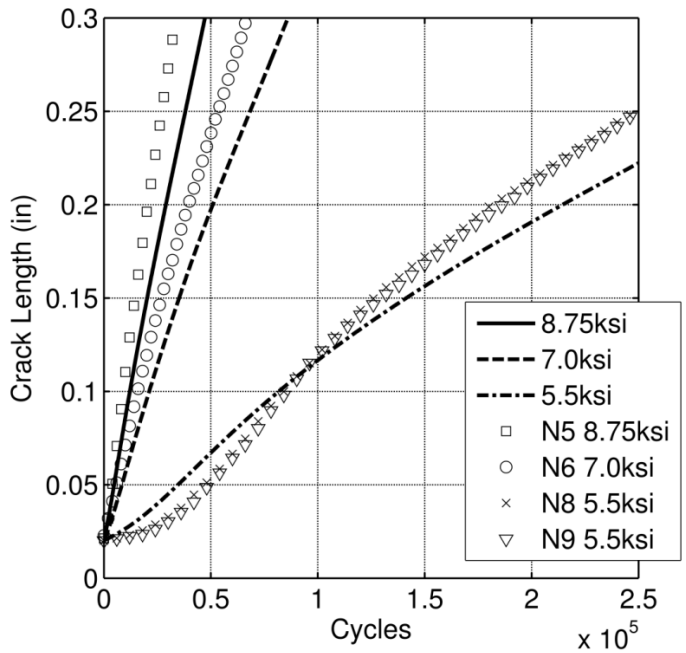


Figure 13. HE Crack Growth for Loaded Hole and As-Machined Coupons Tested

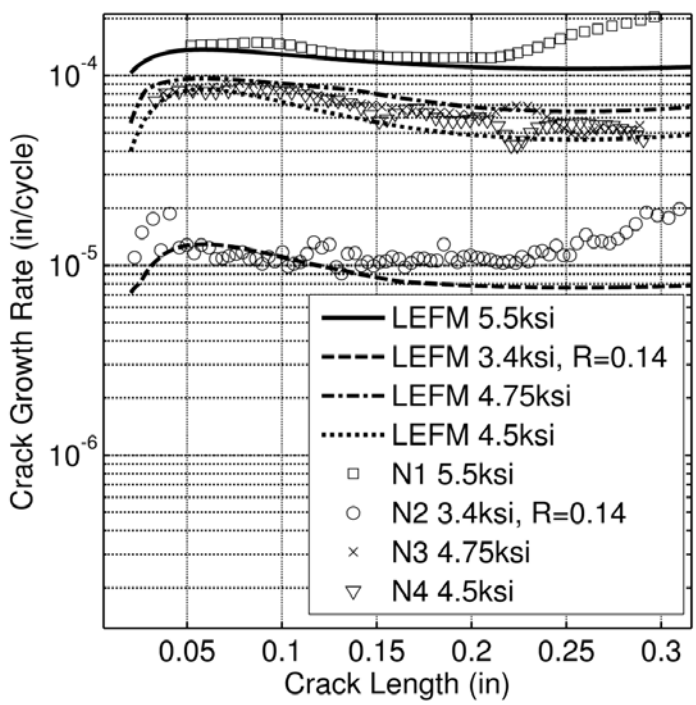


Figure 14. Crack Growth Rates From Loaded Hole Specimen Tests

4.3 NESTED ANGLE COMPONENT

A total of 40 specimens of the nested angle type was delivered and eight HL-20-6-3 Hi-Lok fasteners and eight HL86-6 collars were used to assemble the angles. The design of the angles is shown in figures 15 and 16.

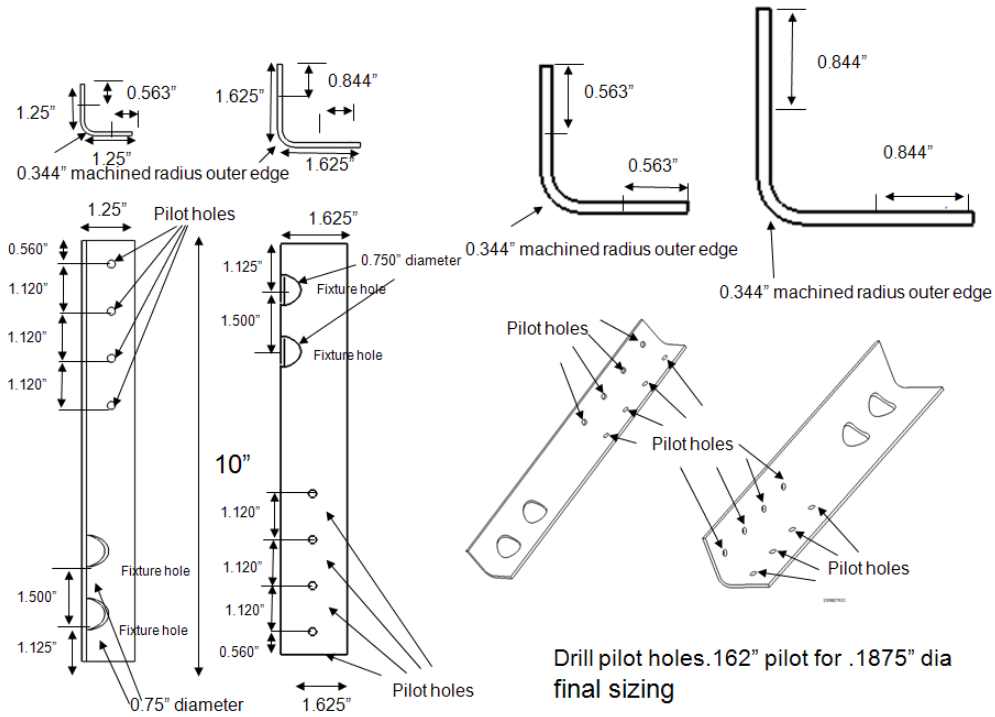


Figure 15. Nested Angle Design

The parts were designed for a test so that the center of gravity would be the same for each angle, thus removing as much bending as possible (figure 16). Bending was still apparent in the tests. This is shown in volume three [1].

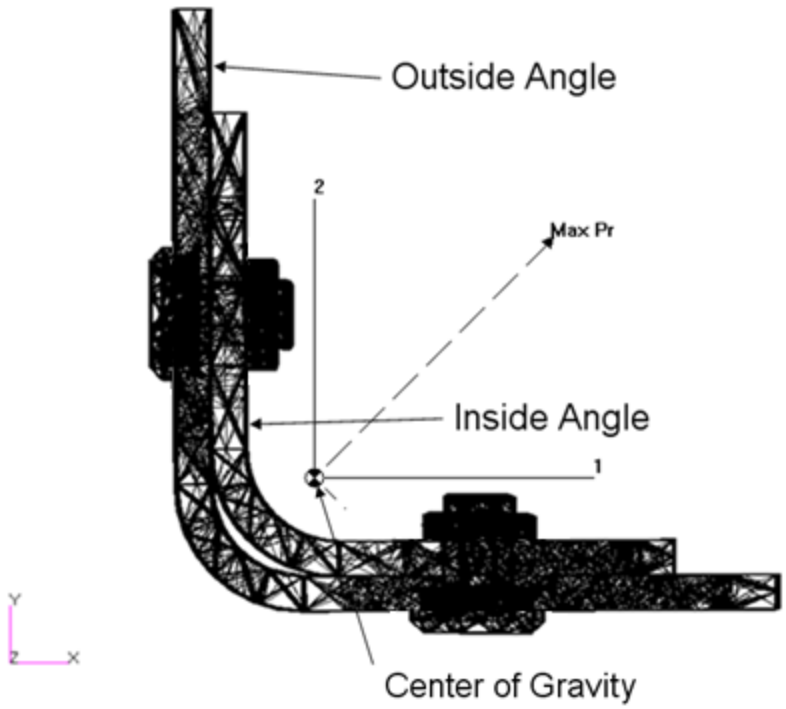


Figure 16. Nested Angle Loading to Avoid Bending

The grips were sourced from an in-house SAC program [6] and had been used for slightly thinner specimens (figure 17). Shims were needed to adjust for the thicker specimens (figure 18); these shims were produced at HE.

Figure 17. Test Grips

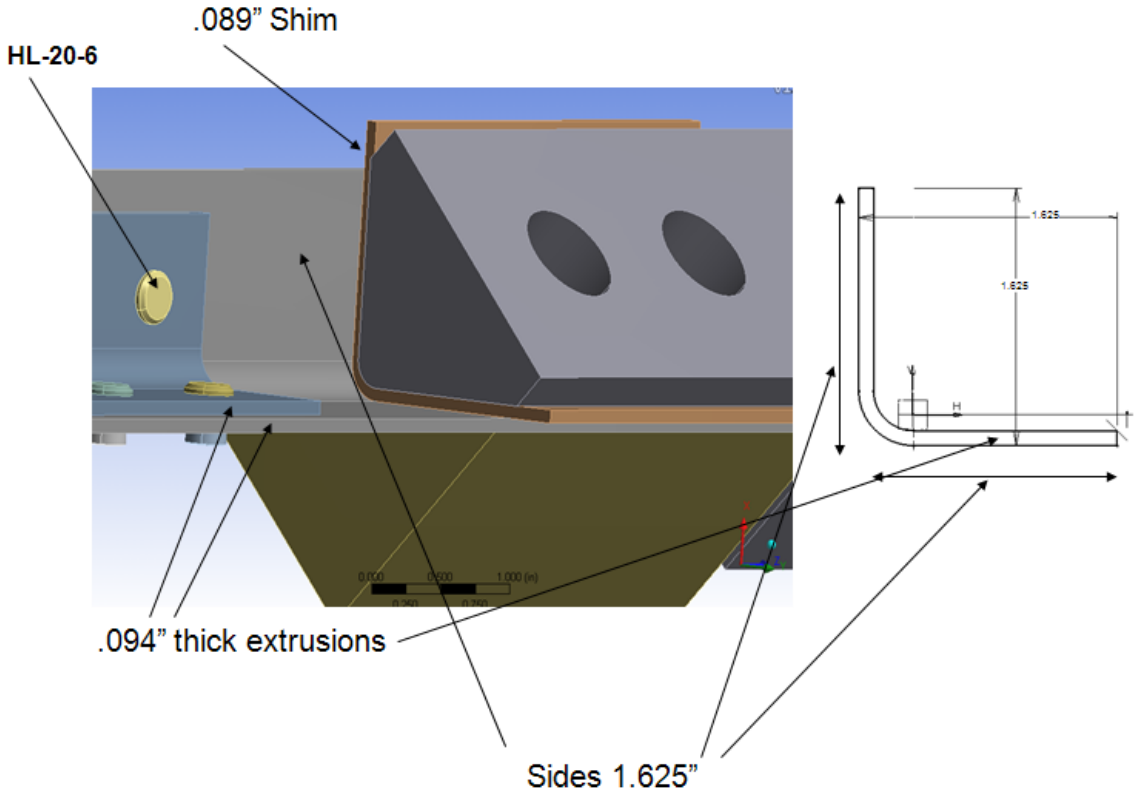


Figure 18. Shim Needed for Test With Thicker Specimens

The test setup (figure 19) is similar to several different specimen tests recently conducted by SAC. The main difference in these tests was the cold working.

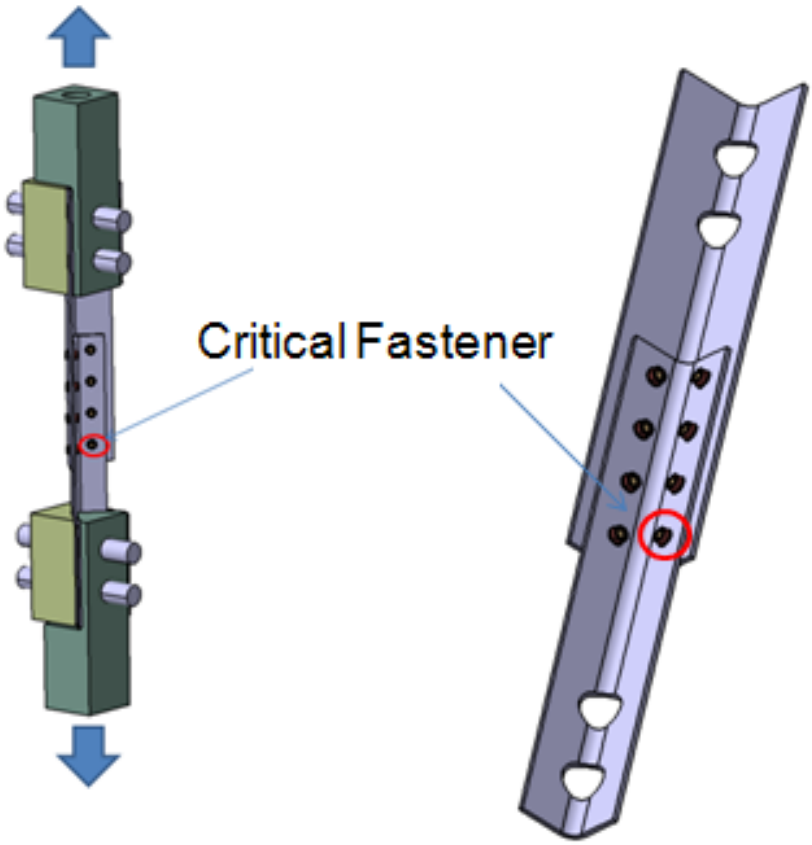


Figure 19. Test Setup

All but the critical fastener holes were cold-worked to 5%. The critical holes were cold-worked to 3% but only on the smaller angle. The other side had identical stresses; by reducing the cold working to 3% for only one hole, the crack should have initiated and grown from the critical fastener hole. Figure 20 shows the tables for determining the percentage of cold working.

Cold working per SS 5098 Rev1, page 26
work sheet reflects corrected table error in spec

Start dia.	Mandrel dia.	Sleeve thk	Interference Inches	Interference %
0.169	0.165	0.0064	0.0088	5.21%
		0.0058	0.0076	4.50%
	0.1646	0.0064	0.0084	4.97%
		0.0058	0.0072	4.26%
0.171	0.165	0.0064	0.0068	3.98%
		0.0058	0.0056	3.27%
	0.1646	0.0064	0.0064	3.74%
		0.0058	0.0052	3.04%
			Avg	4.12%
			Max	5.21%
			Min	3.04%

Cold working for 3% nominal interference

Start dia.	**Mandrel dia.**	**Sleeve thk**	**Interference Inches**	**Interference %**	
0.1730	0.165	0.0064	**0.0048**	**2.77%**	
		0.0058	**0.0036**	**2.08%**	
	0.1646	0.0064	**0.0044**	**2.54%**	
		0.0058	**0.0032**	**1.85%**	
0.172	0.165	0.0064	**0.0058**	**3.37%**	
		0.0058	**0.0046**	**2.67%**	
	0.1646	0.0064	**0.0054**	**3.14%**	
		0.0058	**0.0042**	**2.44%**	**delta**
			Avg	**2.61%**	**1.51%**
			Max	**3.37%**	**1.84%**
			Min	**1.85%**	**1.19%**

All Dimensions nominal

Start dia.	Mandrel dia.	Sleeve thk	Interference Inches	Interference %
0.17	0.166	0.006	0.008	4.73%

Start dia.	Mandrel dia.	Sleeve thk	Interference Inches	Interference %
0.1725	0.166	0.006	0.004	2.31%

Figure 20. Percentage of Cold Working for Fastener Holes

5. LIFE ENHANCEMENT VERIFICATION

The current method of evaluating a problem like the nested angle would be to do a two-dimensional (2D) FEA analysis. The analysis would not account for friction, preload, or fastener bending and a separate free body model for each part would be used, as shown in figures 21 and 22.

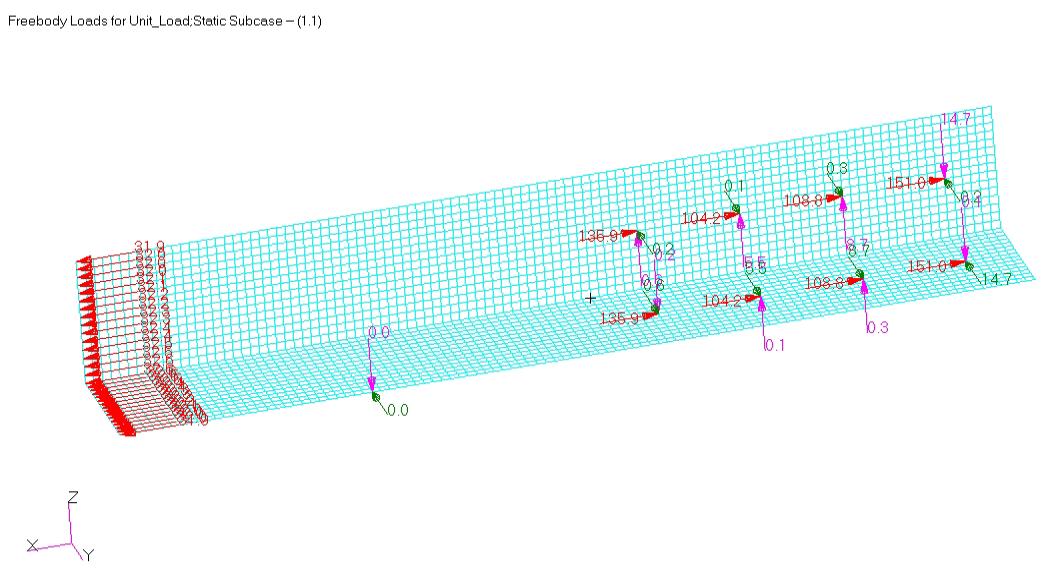


Figure 21. Free Body Loads for Large Angle

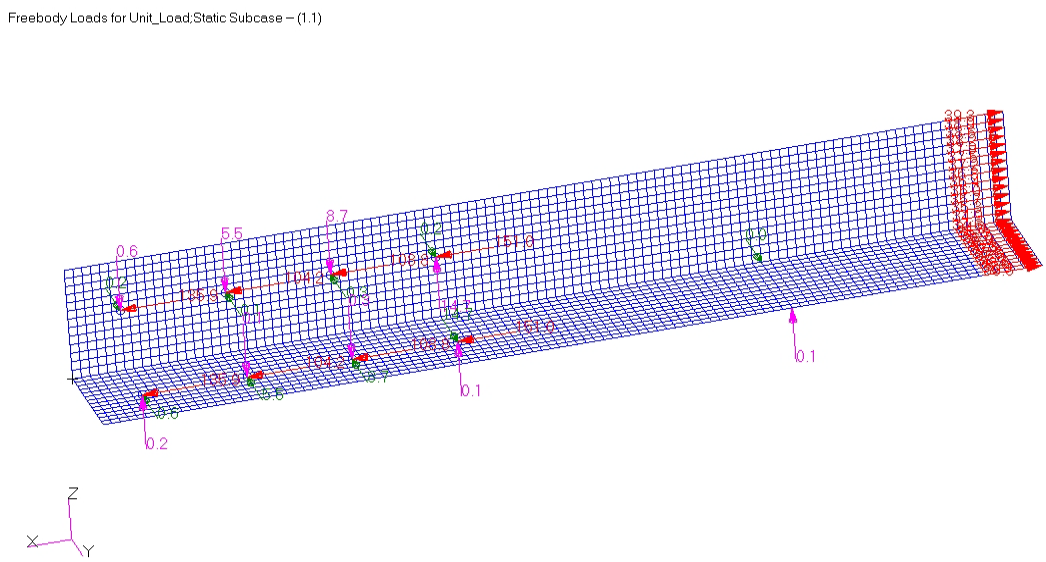


Figure 22. Free Body Loads for Smaller Angle

The loads from the model would then be entered into a NASGRO K solution (TC03), which has no way to account for residual stresses; thus, a data table solution would need to be used.

The loads from the loads models are used to develop a stress model (figure 23) to determine the stress concentration areas. This model indicated that the crack would grow at a slight angle, but the NASGRO K solution assumed it would grow directly to the edge.

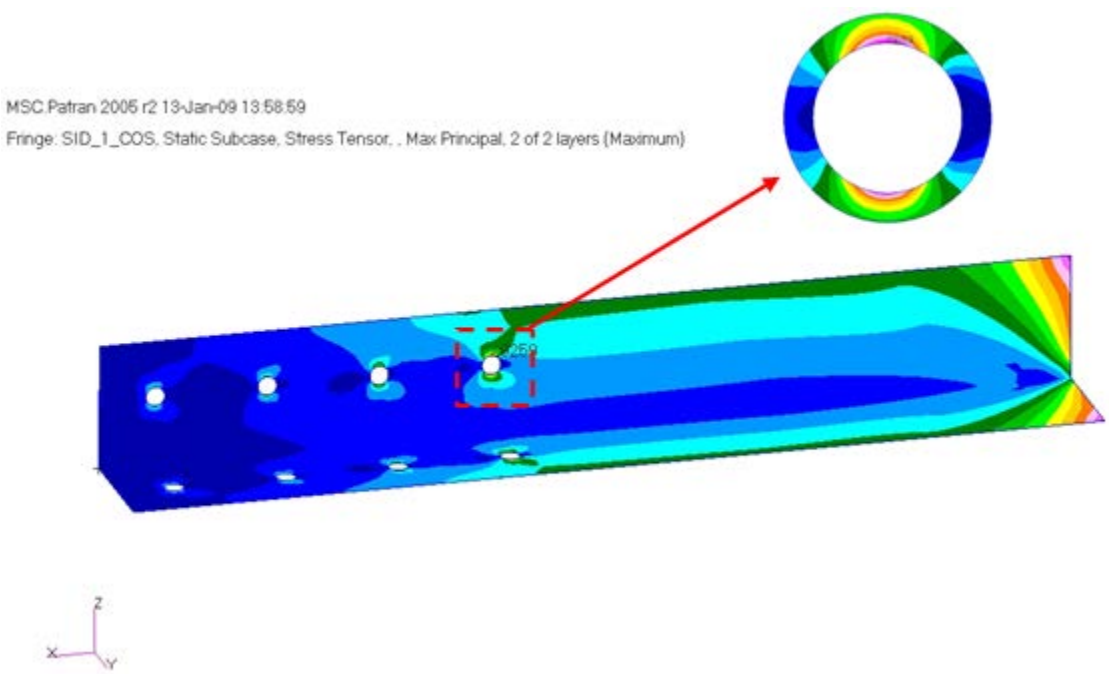


Figure 23. Stress Model

The stresses can then also be entered into a NASGRO data table analysis to determine crack growth.

5.1 CHOLE4 COMPUTER PROGRAM

Once the problem has been defined, loads and stresses derived, then accounting for the cold working effects would include a CHOLE4 analysis. CHOLE4 is a Sikorsky computer program that solves closed-form equations to determine the residual stress field around cold-worked holes. The program accounts for the stress relief after final reaming. Figure 24 shows a chart of the CHOLE4 program for 3%, 4%, and 5% of cold working before reaming. These charts are for the .25-inch-diameter holes used on the open hole and loaded hole specimens. The nested angle specimens used .1875-inch-diameter holes.

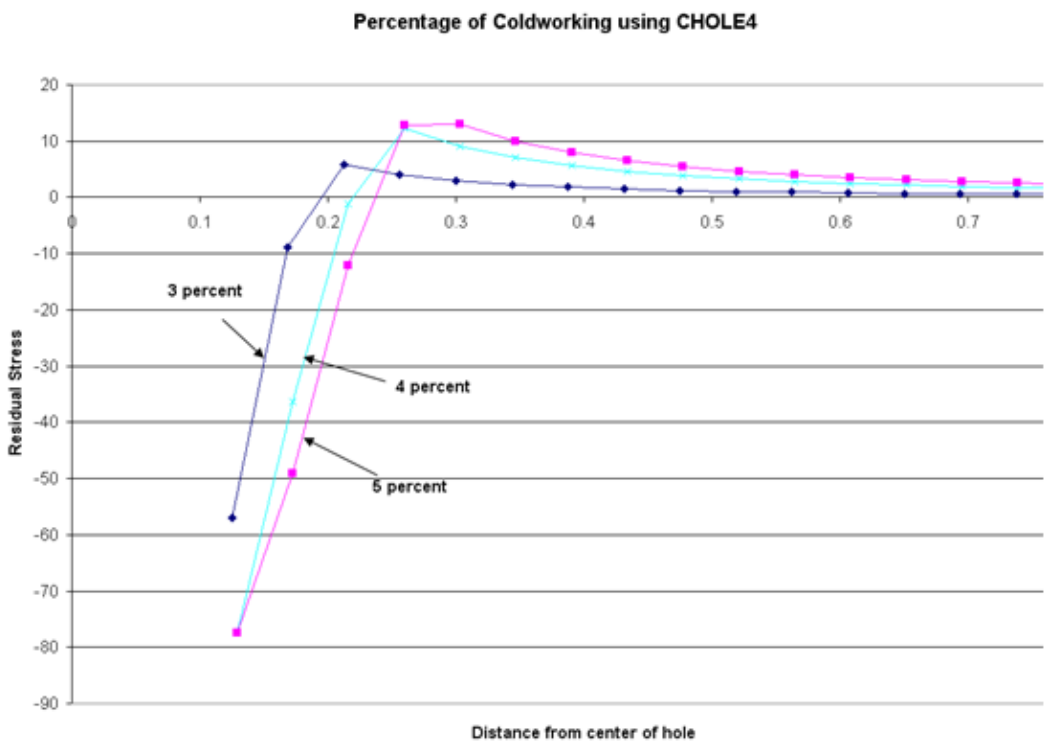


Figure 24. CHOLE4 3%, 4%, and 5% Cold Working

Figure 25 shows how the program adjusts the stresses for the final ream. The model runs out to one inch from the center of the hole.

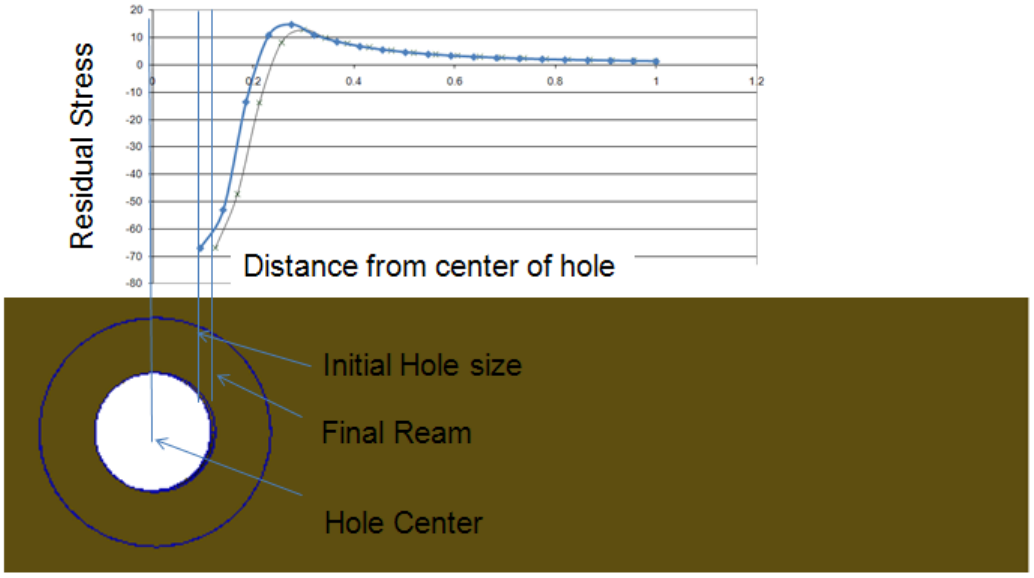


Figure 25. CHOLE4 Reaming Parameters

Once the CHOLE4 results are entered into NASGRO, the crack growth results can be calculated in NASGRO. Figure 26 shows a possible final result for a .01-inch initial flaw and loading to cause an 80,000-cycle crack growth life. The actual results and the NASGRO analyses are presented in figure 27. The potential problem in this case is the very short crack growth life after the crack grows to an inspectable length, such as .05 inch.

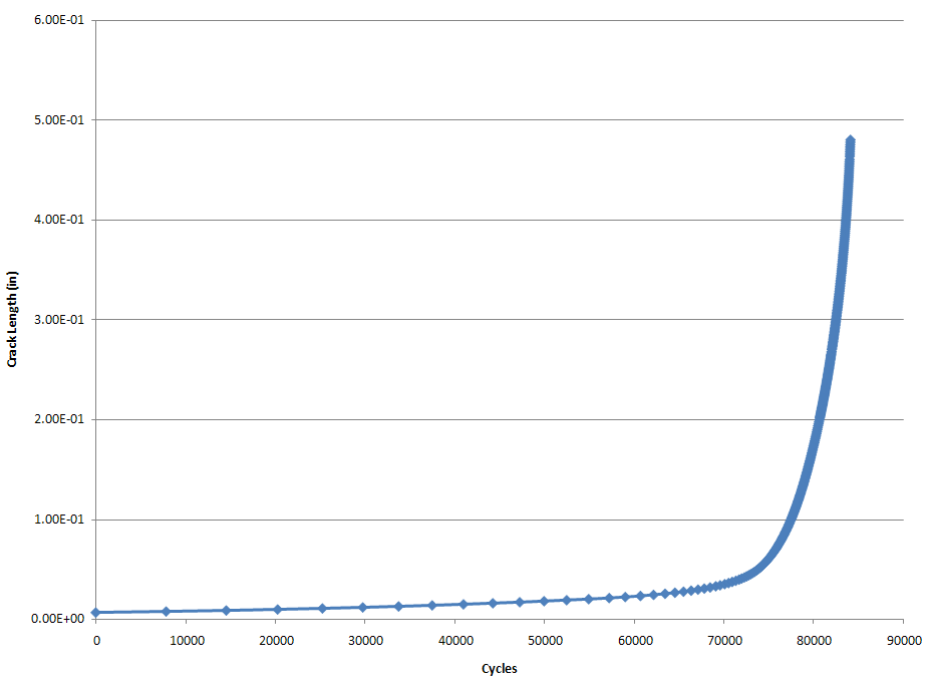


Figure 26. NASGRO Results for .01-inch Initial Flaw

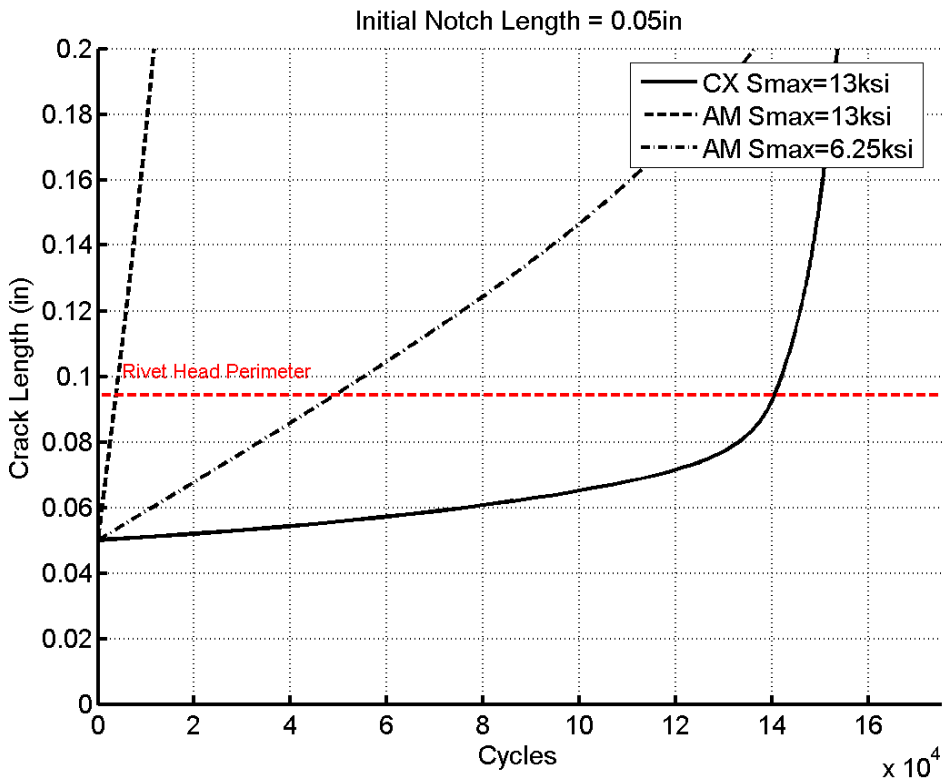


Figure 27. HE NASGRO Crack Growth Analysis

5.2 INDUSTRY STANDARD FRACTURE MECHANICS SOLUTIONS

The nested angle specimen analysis shows how much more complex an actual part can be for fracture mechanics solutions.

NASGRO 6.0 was used to evaluate the solutions to the problems. NASGRO was not able to account for the significant slowing down of the crack using NASGRO solution TC03. This was because of large bearing loads in the specimen, as discussed in section 3.2. In addition, the crack does not occur straight across the actual part as NASGRO assumes.

For the nested angle specimens, either TC03 or TC09 NASGRO solutions can be used. However, neither of these solutions account for residual stresses. These two models are shown in figure 28. These K solutions are described in [7].

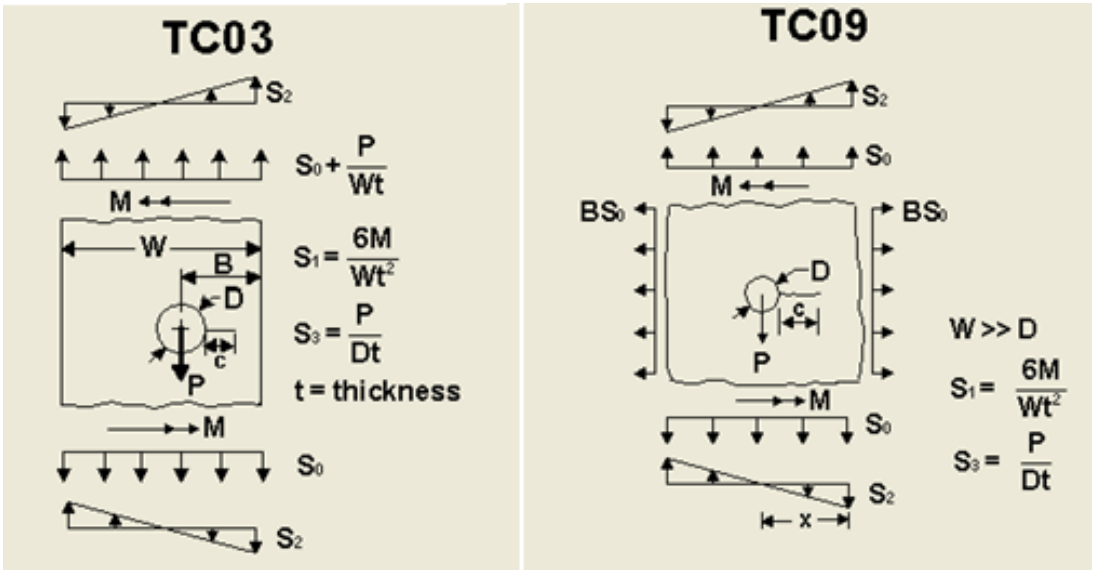


Figure 28. NASGRO Models

The expected crack growth using this type of analysis has the usual crack growth shape. The slowing down could be due to the friction in combination with the preload, fastener head fixity, and fastener bending.

A BEASY model was created to try to model these effects. The crack was grown on the faying surface with known friction. The friction case is not a simple model when combined with crack growth since there is iteration on both the contact solution (load steps are used to get a proper convergence on the contact solution) and the crack growth.

Figure 29 shows the effects of friction. As the friction increases, the maximum stress at the side of the hole decreases. The maximum stress moves away from the hole at an angle. The test data indicate that the crack initiates away from the hole and grows into the hole. This has also been seen in similar tests.

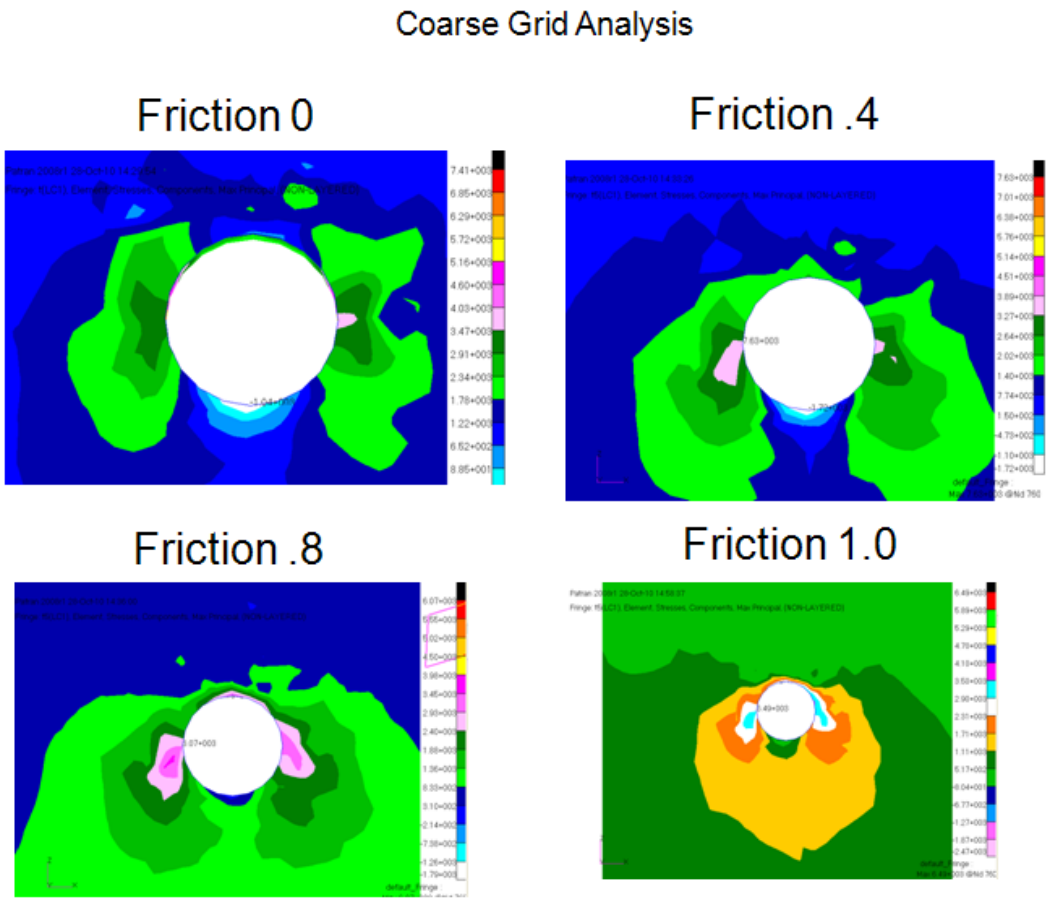


Figure 29. Friction Analysis

After comparing some of the HE analyses, it was concluded that, under the same loading conditions, there is a life improvement of more than 10 times for the nested angle component at the critical fastener.

The actual test data show the crack slowing down after initiation. As shown in figure 30, the crack initiates slowly, then slows down and levels off for nearly 100,000 cycles, before increasing.

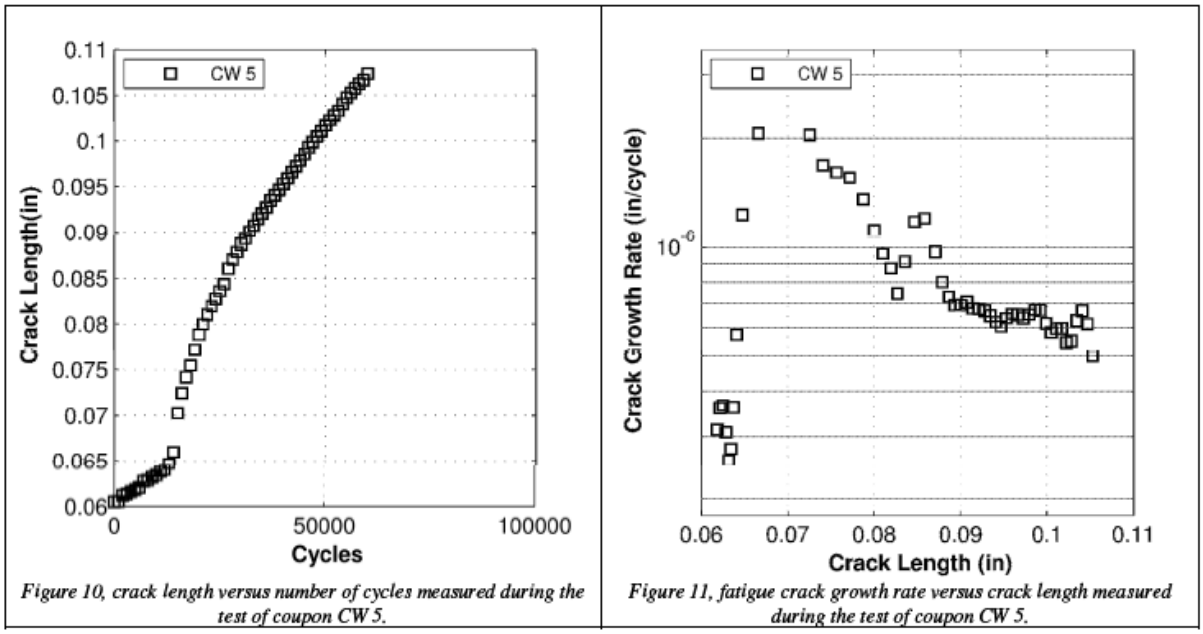


Figure 30. Data From Nested Angle Tests

The nested angle specimens were then tested with hand-tightened fasteners (figures 31 and 32). Specimens were torqued to approximately 10 in. lbs. These specimens do not show the slowing down seen in the normally torqued fasteners. This shows the significant effect of friction on crack growth.

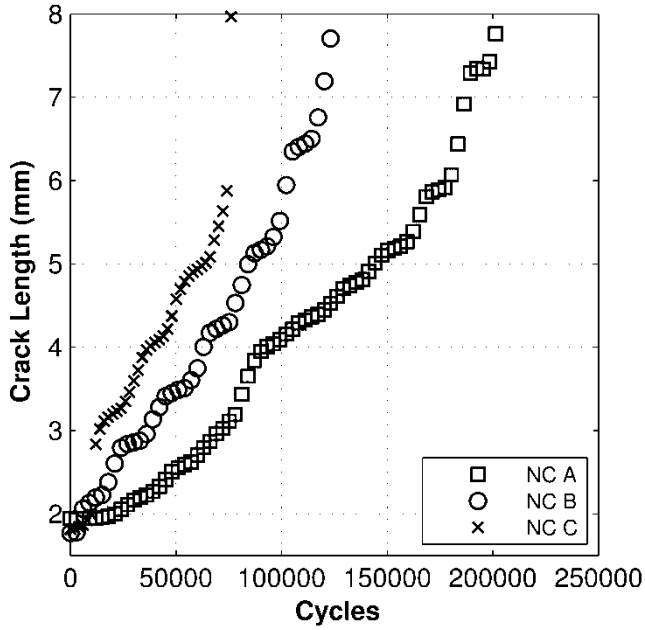


Figure 31. Non-Cold-Worked Specimens Tested With Hand-Tightened Fasteners

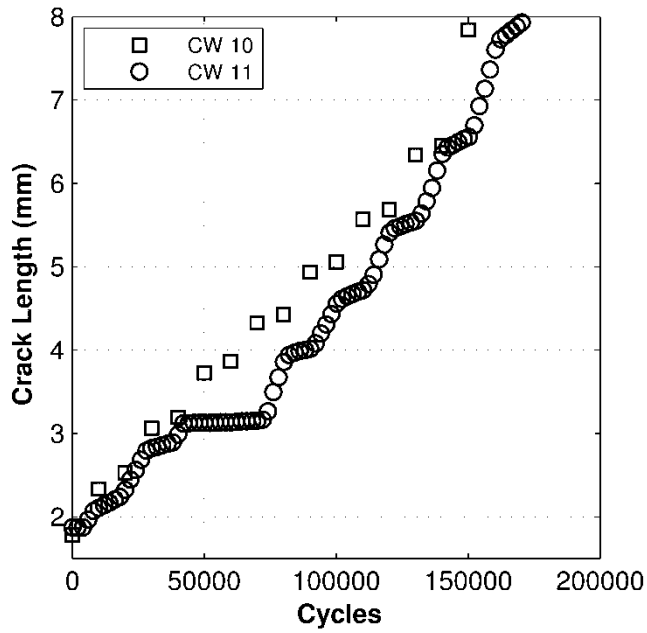


Figure 32. Cold-Worked Specimens Tested With Hand-Tightened Fasteners

6. ROTORCRAFT STRUCTURAL COMPONENT

The rotorcraft structural component selected was the nested angle component designed in section 4.3. This component is common to many aircraft such as the Erickson Sky Crane (figure 33). The nested angle configuration has been tested in several other similar programs, so there is a significant amount of non-cold-worked test data available from similar tests [6].

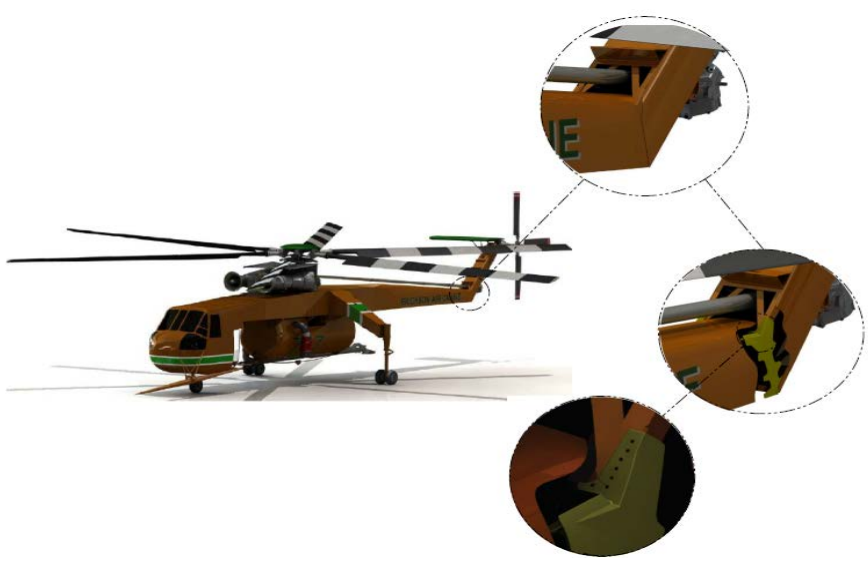


Figure 33. Erickson Sky Crane

Figure 34. Nested Angle Configuration on Sky Crane

7. DISCUSSION OF RESULTS

For this program, it was assumed there was little, if any, friction between the plates. The model also assumed that the side of the head of the fastener was unimportant (figure 35).

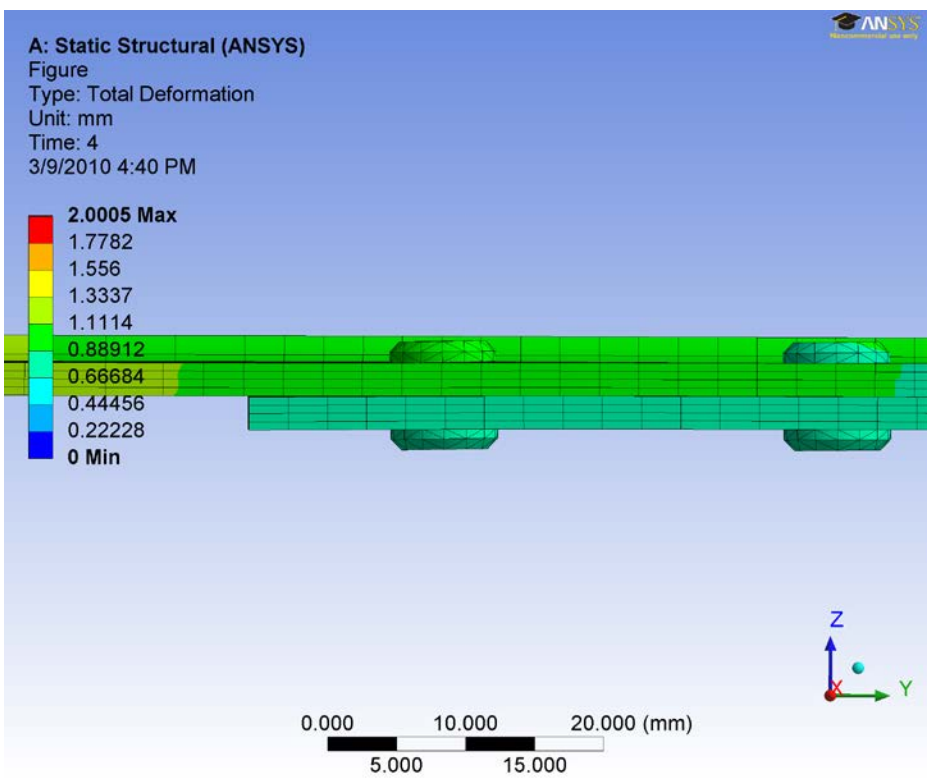


Figure 35. MSU Nested Angle Ansys Model

The MSU model showed that with preload and friction, the stresses were highest on the faying surface away from the bearing load (figures 36 and 37). The top surface shows the largest stresses are toward the bearing load.

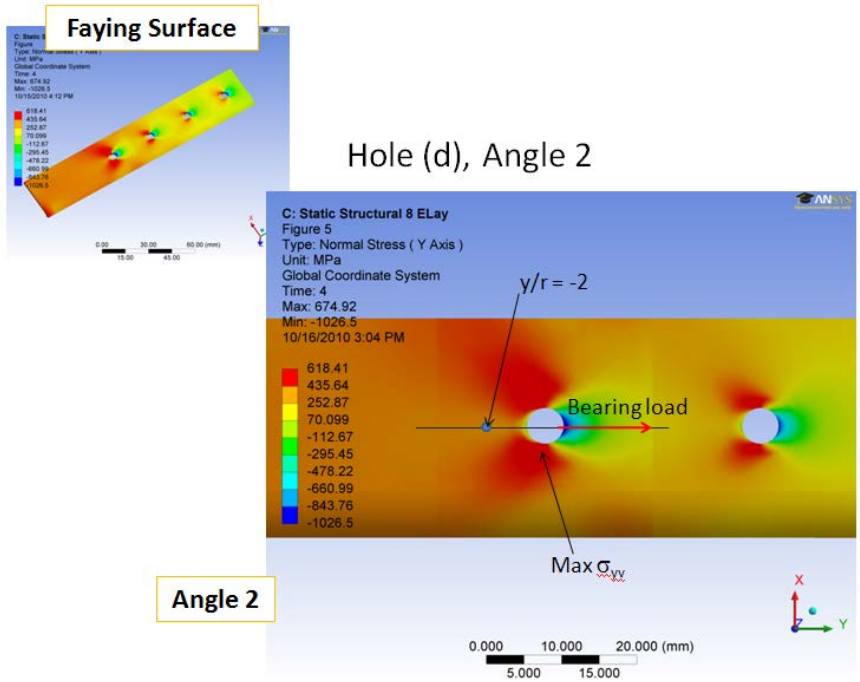


Figure 36. MSU Model Syy Faying Surface

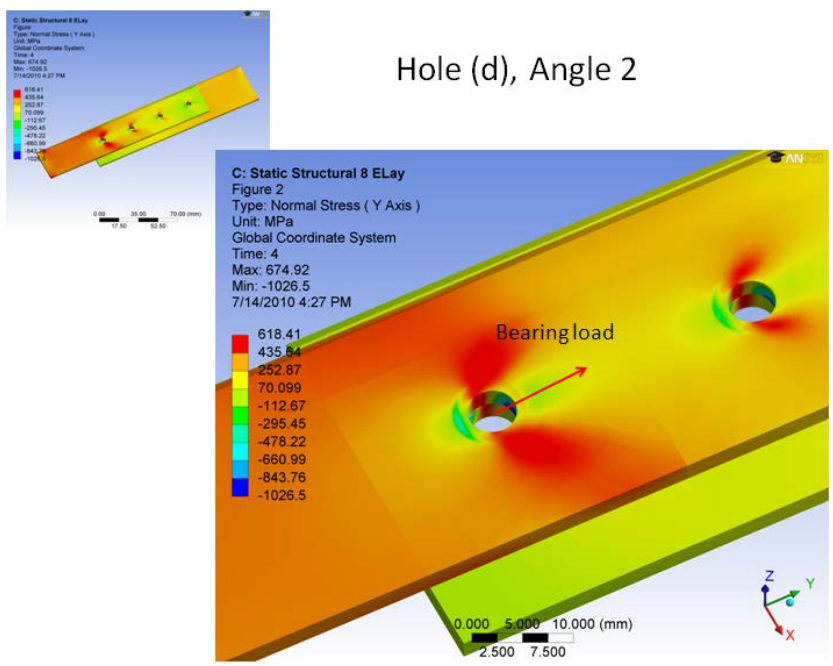


Figure 37. MSU Model Syy Top Surface

A 2D FRANC2DL model (figure 38) shows only the maximum stress and shows the stress maximum on the bearing side. The crack grows almost directly to the edge from the three o'clock position.

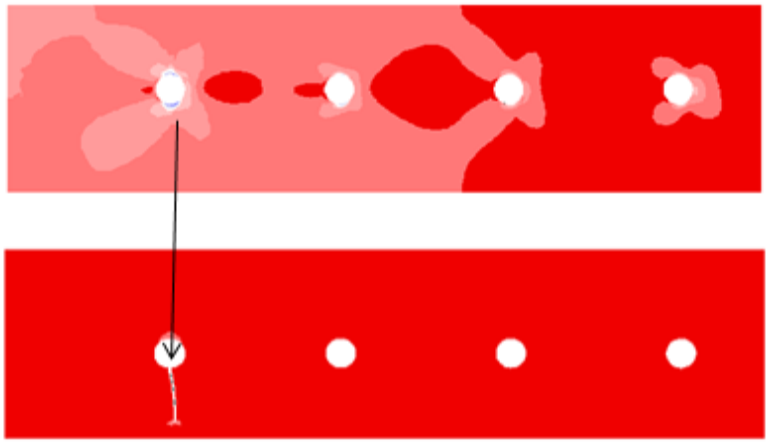


Figure 38. 2D Model of Nested Angle

The BEASY model was created from a small section of the whole model. As a boundary element program, the density of the mesh is not as important as an FEA model. The BEASY model creates internal nodes as needed to better model the stress state. Triangular elements are the same as quad elements since the nodes are only used to define the boundary. There is no stiffness difference as there is in FEA.

The BEASY model is separated into zones. The groups must be named zone 1, zone 2, zone 3, etc. Each zone must contain the nodes and elements that complete the volume. A contact region can then be defined with a friction coefficient. If it is not defined, the BEASY model will assume bonded contact.

Once the BEASY model calculates the SIFs, these factors can be entered into NASGRO.

The test was originally run with preloaded fasteners. However, the problems with the test caused the crack to grow with hand-tightened fasteners only. There are some results for the normally tightened fasteners. Figure 39 shows the BEASY model with no preload. Without the preload, the stress concentrations were at the sides of the hole, as shown in figure 40.

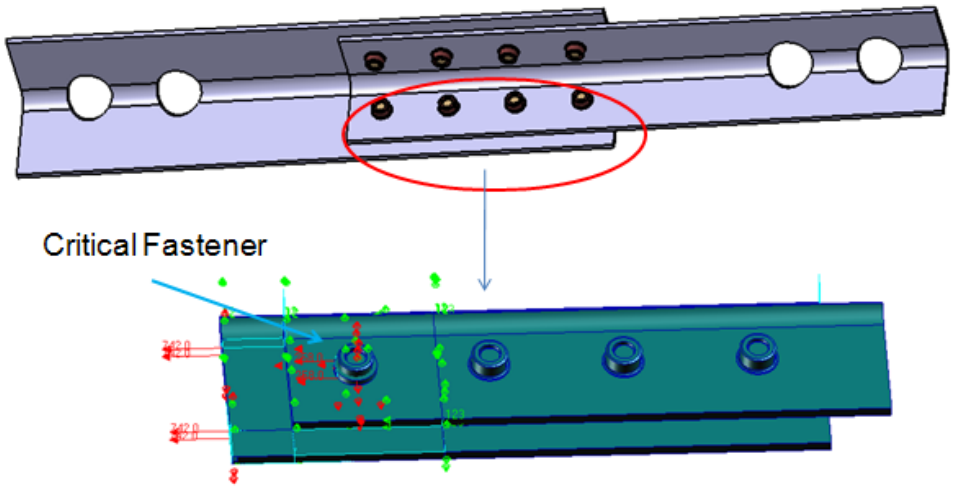


Figure 39. BEASY Model of Nested Angle Critical Fastener

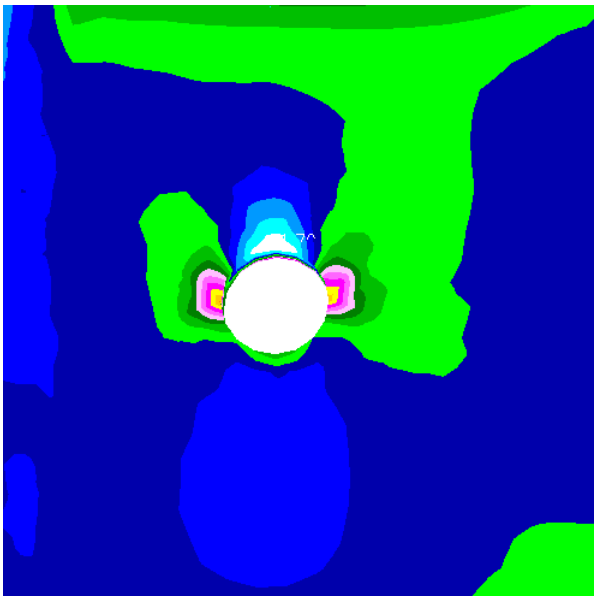
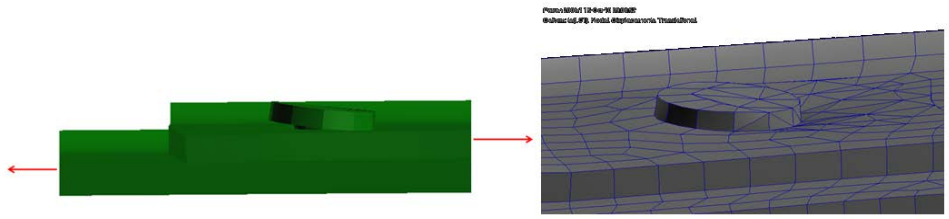


Figure 40. Faying Surface Maximum Principal Stress Without Friction

Fastener bending and fixity also affect crack growth. Under the normal FEA, these effects are not taken into account. Figure 41 (a) shows the effect of fastener bending without preload and with preload. Without preload, the fastener pulls away from the part. With preload, the fastener digs into the part. The amount of preload and the friction coefficient are significant factors in crack growth life.



(a) (b)

Figure 41. Fastener Bending Without Preload

Running the BEASY model without friction gives a very conservative answer and has the maximum stress intensity at the 3 o'clock or 9 o'clock position. Figure 41 (b) shows the model used without friction. When friction is introduced into the model, the crack surface becomes much more complicated.

To get the BEASY to remesh the surfaces, the model was used without friction and each crack growth increment was run separately. Figure 42 shows the distorted crack with friction—and the crack after it had grown through the thickness without friction.

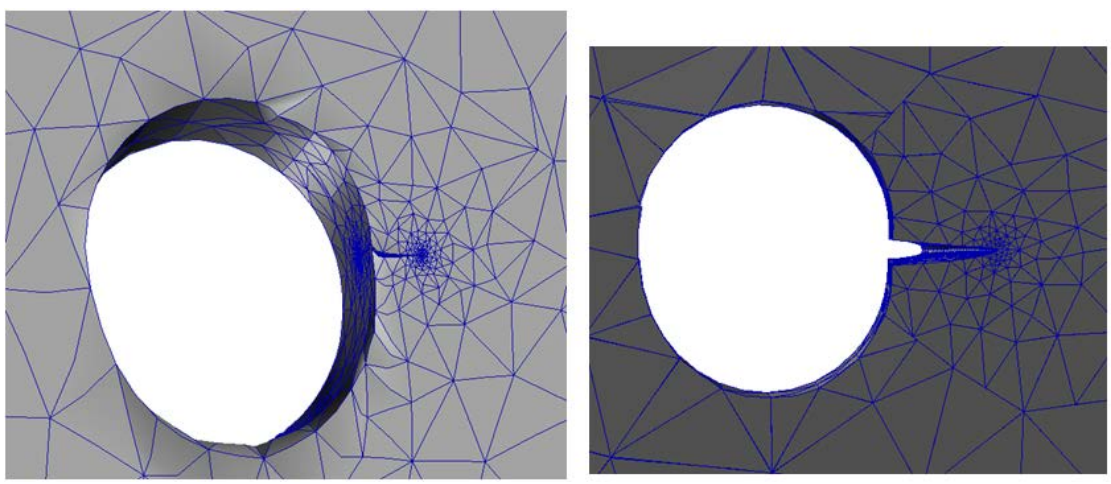


Figure 42. Friction and Without Friction BEASY Models

The friction model shows a reduction in the SIFs as friction is increased. This shows that the crack would grow slower with friction, but this does not show the slowing down of the crack growth after the crack initiates. These tests were run at the most coarse modeling and still took several days to run.

In figure 43, the stress intensity decreases as the friction coefficient increases. For this test, several different friction coefficients were used. A friction coefficient of .2 seems to be too low while a friction coefficient of .8 seems to be too high compared to the results.

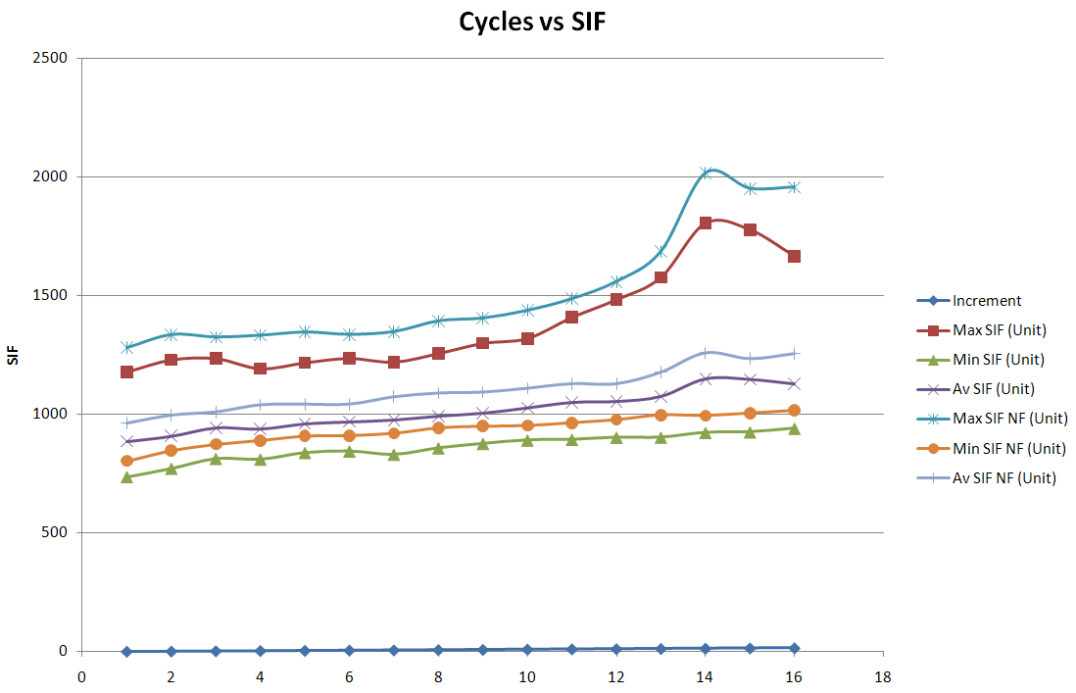


Figure 43. Friction Decreases the SIF (BEASY Analysis)

A FRANC3D model was also generated (figure 44). However, FRANC3D does not take contact into consideration; therefore, friction cannot be modeled in the current version of FRANC3D. The model does show the transfer of loading from one side of the specimen to the other as the crack grows. This may also be part of the reason for the slowing down of the crack.

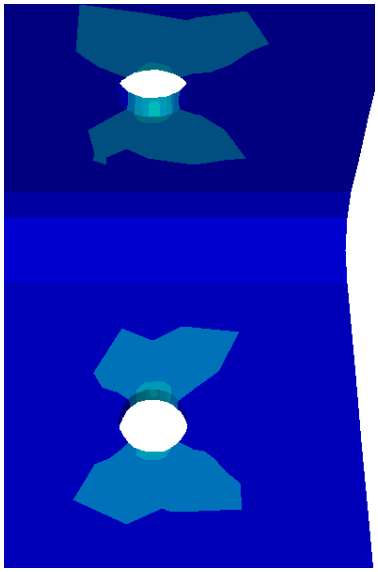


Figure 44. FRANC3D Model

The use of FASTRAN and ANSYS software in performing the analysis is described in the analysis volume.

8. CONCLUSION

Cold working parts showed an increase in the crack growth life for all coupons tested in this program. The simple open and loaded hole models show a significant improvement in life. However, the more complex loading in a nested angle may not have as significant an improvement. To account for the actual life improvement of the rotorcraft parts, the modeling must account for the complexities of parts.

This project provided insight into a nested angle configuration used in the rotorcraft and aircraft industries. The friction between the plates, 3-dimensional or 2-dimensional analyses, fastener preload, head fixity, and load redistribution—which are significant factors in the DTA—were all considered. These factors were also impacted by the introduction of cold working effects. To completely account for the true cold working benefits, the analysis must account for these factors examined in this program. However, further testing and analysis is needed to determine to what extent these factors affect crack growth life. There are several software companies that are currently working on newer versions of analysis tools to account for these effects. Some may be successful. However, the time to run the model, complexity of the analysis, and verification and validation will need to be addressed.

9. REFERENCES

1. Hill, M.H., Van Dalen, J.E., Stuart, D.H., Minotti J.R., Jr., “Analytical Tools for Residual Stress Enhancement of Rotorcraft Damage Tolerance—Volume 3: Residual Stress Measurements, Crack Growth Testing, and Linear Elastic Fracture Mechanics Analyses,” FAA Report DOT/FAA/TC-13/36, V3, April 2015.

2. FTI Document #98617, “Split Sleeve Cold Expansion and ForceTec Insert Installation in Conjunction with ECP4087 and 4088,” March 8, 2004.

3. LaRue, J.E., Daniewicz, S.R., “Predicting the Effect of Residual Stress on Fatigue Crack Growth,” International Journal of Fatigue, ScienceDirect, July 14, 2006.

4. Newman, J.C., Jr., Daniewicz, S.R., LaRue, J., Le, D., “FASTRAN Analyses of Coupons With Residual Stresses Due to Overloads and Cold-worked Holes,” 9th Joint FAA/DoD/NASA Aging Aircraft Conference.

5. Newman, J.C., Jr., Daniewicz, S.R., Ismonov, S., “Analytical Tools for Residual Stress Enhancement of Rotorcraft Damage Tolerance—Volume 1: Stress and Crack Growth Analysis,” FAA Report DOT/FAA/TC-13/36, V1, August 2014.

6. Urban, M.R., Bauer, G., Meyer, T.G., Ghoshal A., Welsh, G.S., Bordick, N., “Integrated Statistical Stress Life Analysis Methodology Utilizing Local Stress Fields,” Presented at

the American Helicopter Society 66th Annual Forum, Phoenix, Arizona, May 11–13, 2010.

7. NASGRO® Fracture Mechanics and Fatigue Crack Growth Software Reference Manual, Version 6.1, 2010.