RESIDUAL STRESS EFFECTS ON SAFE-LIFE OF WELDED STRUCTURES

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ABSTRACT

This paper presents the results of a study of the effects of residual stresses on crack-growth safe-life of the weld joints. This study effort covered residual stress measurement techniques investigation, fatigue crack-growth prediction methodology evaluation and testing of weld joints. A computer program , CRKGRO/DAMAGE was modified to account for the effects of residual stress on fatigue crack growth, in order to use on safe-life prediction of welded ground support equipment.

KEYWORDS

Residual stress, fatigue crack growth, safe-life analysis

INTRODUCTION

Welding processes often induce significant residual stresses in structural components joined by welds. Ground lifting equipment is a typical example. Because of their sizes, stress relief is not always possible. Hence, residual will be always existed in the weld joints which will affect the fatigue crack initiation time and crack propagation rates. It is well known that the compressive residual stress retard the fatigue crack growth rates hence improve the fatigue life of a structure. Many manufacturing processes have been used to intentionally induce compressive residual stresses at the critical region of a structures. These include cold-working the fastener holes of aircraft wings, autofretage the cannon barrel, shot penning the machine parts, etc. However, whenever there are compressive residual stresses, tensile residual stress are always existing. adjacently by the law of equilibrium. Tensile residual stress can be profoundly detrimental to the safe-life of the welded structures by initiating stress corrosion cracking and/or accelerating crack rates under cyclic loading. Hence, in order to determine the effect of residual stresses on safe-life of the welded structures, it is necessary to: (1) Measure residual stresses and (2) perform a crack growth safe-life analysis that incorporate residual stress.

The current practice for ground support lifting and handling equipment requires an annual proof test. Recent efforts have been initiated by range safety organization in the United States(Range Safety Regulation, 1995) to replace the annual proof test with 100% nondestructive evaluation (NDE) of all single-failure-point (SFP) components and SFP weld joints. Figure shows the flow chart of periodic test/NDE requirements for the ground handling equipment. The benefits of NDE and safe-life analysis over proof testing are reduced cost and elimination of unnecessary damage to the structure.

Since lifting/handling equipment are very large welded structures, the effects of welding residual stress must be accounted for to enhance the reliability of safe-life analysis and to facilitate the formulation of rational acceptance/rejection criteria for NDE
This paper presents a partial result of a research and development (R&D) project conducted at The Aerospace Corporation with two primary objectives : to investigate reliable residual stress measurement technique(s) and to predict the effects of residual stress on safe-life of welded structures

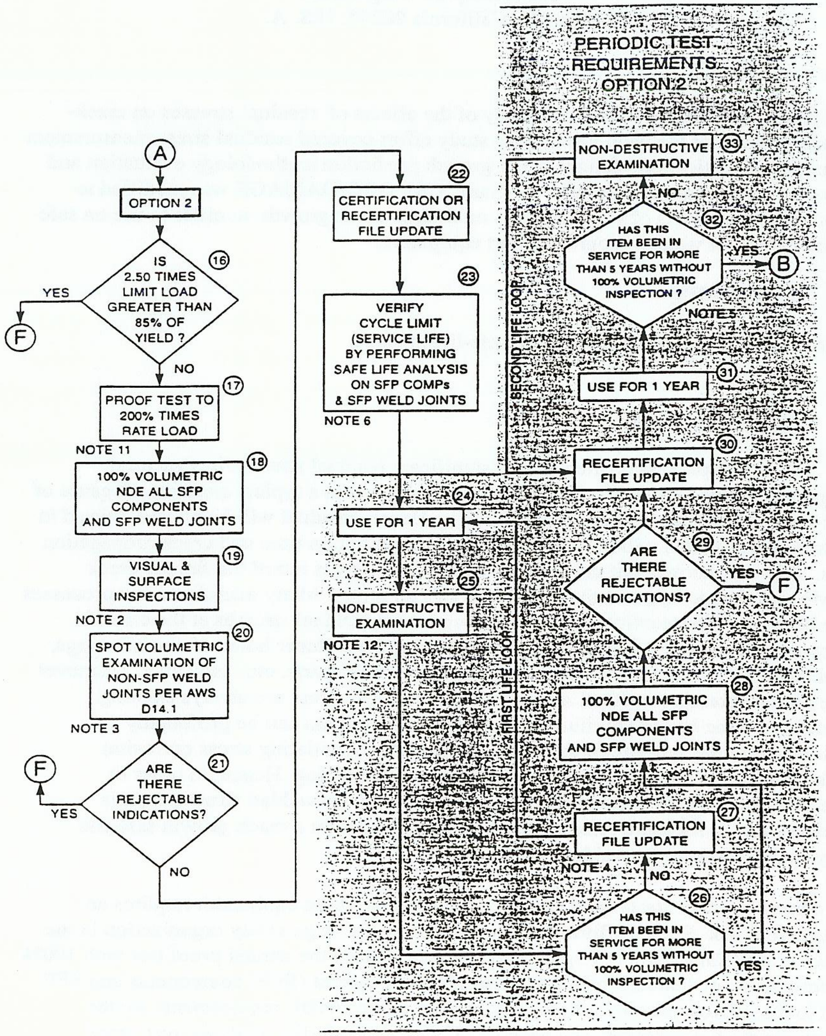


Figure 1. Ground Handling Equipment Periodic Test /NDE Requirement Flow-Diagram

RESIDUAL STRESS MEASUREMENT TECHNIQUES

The determination of residual stresses is usually experimentally by first measuring the residual strains. The residual stresses are then calculated from the measured strains. Available measurement techniques along with their relative advantages and disadvantages, are listed in Table I. The most common practices in industry are sectioning, hole-drilling, and x-ray diffraction methods.

Table 1. Residual Stress Measurement Techniques

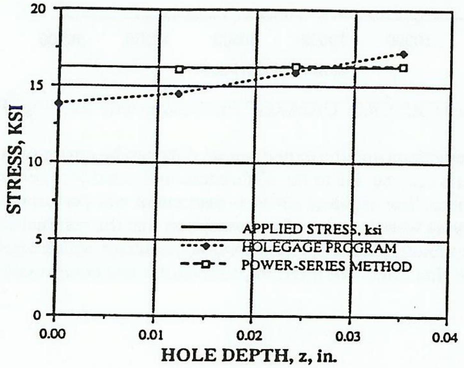
Method	Advantages	Disadvantages
Mechanical (1)	Simple Inexpensive Through-thickness profiling	Destructive Gross average stresses
Hole Drilling	Fast Portable Inexpensive	Semi-destructive Limited hole depth
X-ray Diffraction	Nondestructive (2) Fast Portable	Surface stresses only Sensitive to grain size, preferential orientation
Neutron Diffraction	Nondestructive Through-thickness profiling Fast	Expensive Requires nuclear reactor
Magnetic	Nondestructive Fast	Materials must be ferromagnetic Standard required
Ultrasonic	Nondestructive Portable Fast	Standard required Sensitive to grain size, preferential orientation

(1) Includes sectioning, layer removal, boring out, etc.

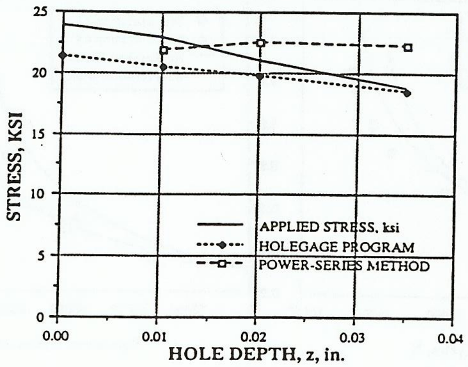
(2) Destructive depth profiling possible with electropolishing

Two methods were selected for further evaluation, hole-drilling and x-ray diffraction. A standard practice for hole drilling residual stress measurement is published by the American Society for Testing and Materials(ASTM 1985). However, variuos refinements have been developd beyond the residual stress calculation procedures contained in ASTM standard. where the residual stress distribution is assumed to be uniform across the hole depth.

In this R&D effort, two calculation schemes were investigated. The first method uses a power series to represent the stress distribution, and is based onm the stress-strain conversion coefficients provided in (Nickola, 1986) The second method utilizes the computer code. HOLEGAGE (Hampton, 1991). developed based on finite element procedures discussed in (Schajer 1988) Plots of the analytically predicted residual stresses are shown in Figure 1. For the constant stress field, the power series method predictions are very close to the actual stresses. The HOLEGAGE code appears to be more suitable for the linearly varying stress field, with a maximum error of approximately 12%.



(a) CALCULATED RESIDUAL STRESSES WITH A CONSTANT STRESS FIELD



(b) CALCULATED RESIDUAL STRESSES WITH A LINEAR STRESS FIELD

Figure 2. Calculated Residual Stresses Using Power Series Method and HOLEGAGE Code

A similar Standard for residual stress measurements using x-ray diffraction is currently being developed by ASTM. The major difference between the x-ray diffraction and hole-drilling methods is that the former technique is non-destructive. However, the x-ray technique can only determine residual stresses in a shallow layer close to the surface. The x-ray diffraction method was selected to measure residual stress in the welded specimens described later in the fatigue rack growth test section. Residual strains were measured using the $\sin^2\eta$ technique with Cr K_α radiation. The measured residual stress in the weld is approximately ± 8 ksi .

CRACK GROWTH SAFE-LIFE PREDICTION METHODOLOGY

It is well known now that tensile residual stresses accelerate fatigue crack growth rates and compressive residual stresses retard the growth rates. In a crack growth safe-life analysis, these effects are accounted for by superposition of the residual stress intensity K_{res} and the stress intensity due to the externally applied loads, K_o, i.e.,

$$\mathbf{K} = K_{res} + K_{o.}$$

The fatigue crack growth rate is then based on the relationship expressed as :

$$da/dN = F(R, \mathbf{K})$$

$$R = \mathbf{K}_{min} / \ \mathbf{K}_{max}$$

where $\mathbf{K}_{min}$ and $\mathbf{K}_{max}$ is the minimum and maximum resultant stress intensity, respectively.

There are quite few methods proposed by the investigators in the past. An approach to the calculation of residual stress intensity was proposed by Chang (Chang, 1986), where only the residual stress at the instantaneous crack tip is used to determine K_{res}. Good correlation of analytical predictions with experimental data was shown . A second approach for calculating K res is the weight function technique. The weight function is an integral of the residual stress distribution over the crack length.(Nelson, 1982, Bandini, 1991). gives details of studies which incorporated the weight function method.

Due to its simplicity, the approach proposed by Chang (Chang, 1986) was implemented by incorporating a RESIDUAL subroutine into an existing computer code, CRKGRO/DAMAGE. (Harmon,1989). CRKGRO/ DAMAGE was developed based on CRKGRO (Chang, 1981). to add the capability in considering the crack growth under arbitrary thermal loading for hypersonic air vehicle application.. The flow-diagram of CRKGRO/DAMAGE is shown in Figure 3.

Test data in (Bandini, 1991) were used to validate the modified DAMAGE/ code. Figure 4 shows the correlation results. The safe-life prediction assuming there is no residual stress over predict the crack growth life thus it is un-conservative. When residual stress is considered, the un-conservatism is eliminated and the correlation with the test data is much improved.

FATIGUE CRACK GROWTH TESTS AND DATA CORRELATION

In order to verify the analytical methodology, fatigue crack growth tests were conducted. The 4-in. wide center-crack specimens were prepared from ASTM A-53 Grade hot-rolled steel bar stock. Two specimens were tested in the as-welded condition. Before cycling testing, residual stresses were measured by x-ray diffraction technique as described previously Two welded specimens were stress-relieved at 1150°F. for eight hours to eliminate welding residual stresses. Constant amplitude fatigue pre-cracking was performed to grow the fatigue crack approximately 0.25 in. from an initial Electro discharge machining (EDM) notch. The specimens were then tested to failure under constant amplitude load cycling between 0 and 25 ksi, with periodic crack length measurement records.

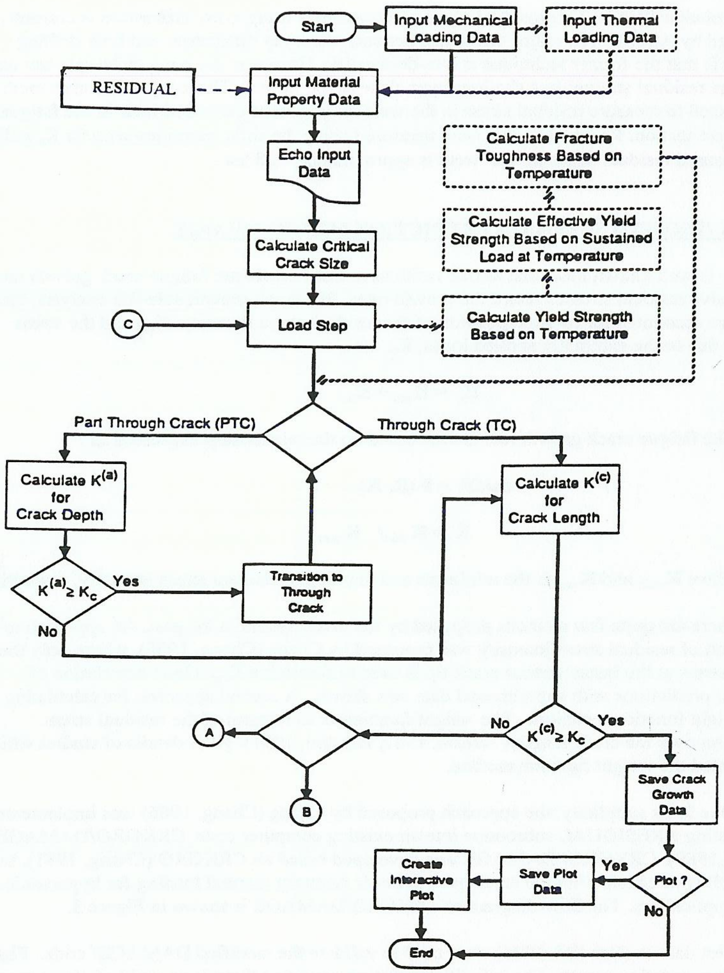


Figure 3. Modified CRKGRO/DAMAGE Code Flow Diagram

Analytical predictions were made by first establishing a da/dN-ΔK curve using crack growth data from the stress-relieved specimens only. Crack growth predictions were then made using the stress-relieved da/dN curve with either tensile or compressive residual stress measured by the x-ray diffraction technique. The analytical predictions were compared with test data shown in Figures 5. a and 5. b for tensile and compressive residual stresses , respectively. In Figure5.a, the difference between analytical predictions with and without residual stresses is small due to the low magnitude (8ksi) and distribution of measured tensile residual stresses.
The two predictions fall within the scatter band of the experimental data up to approximately 60,000 cycles. After 60,00 cycles, the experimental data showed that the crack growth rates decelerate, indicating a relaxation of the residual stresses. The results for compressive residual stress in Figure 5.b shows similar trends. The difference in analytical predictions with and without residual stress is larger than those shown in Figure 5.a due to the distribution of the compressive residual stresses. The predictions with residual stress follow the test data very closely up to 60.000 cycles. Again, the effect of residual stress relaxation on crack growth is evident from the increase in experimental crack growth rates after 60.000 cycles.

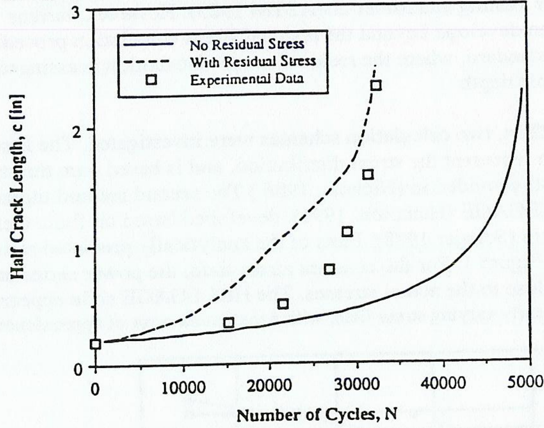
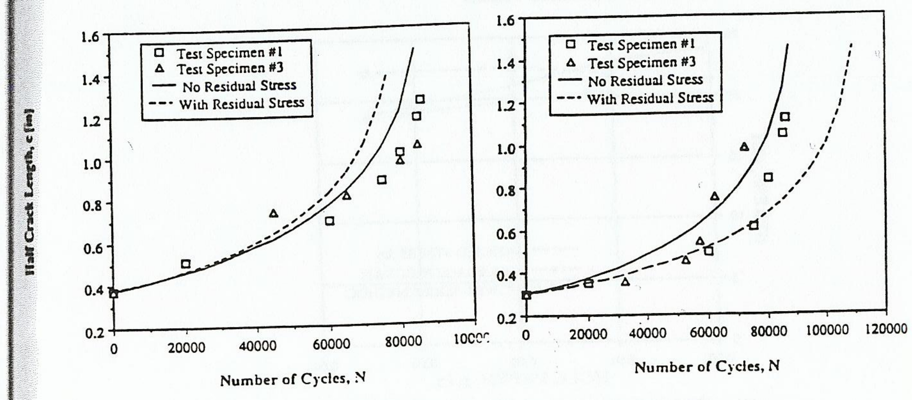


Figure 4 Correlation of Modified CRKGRO/ DAMAGE Predictions with Existing Test Data

The differences in analytical predictions and the experimental data can be attributed to two major factors. The scatter in the test data may be due to the differences in the residual stress distributions of the individual welded specimens. The residual stress measurement was performed on only unnotched specimens. The analyses were based on the assumption that the residual stress distributions are identical to the unnotched ones. The second major factor which cause the differences is the potential relaxation effect observed for both tensile and compressive residual stresses.



(a) (b)

Figure 5. Correlation of Current Test Data With Modified CRKGRO/DAMAGE Predictions

This phenomenon has been observed by many investigators including Chang(Chang, 1986) and Bandini (Banidini, 1991). Methodologies for predicting theses do exist, but incorporating them requires a large experimental data base, which is beyond this R&D effort. However, the largest difference in the experimental data and analytical predictions is 35% which is considered acceptable from a fatigue crack-growth (safe-life) analysis point of view, considering that a scatter factor of four (4) is generally applied.

CONCLUSIONS

In the study of the residual stress effects on fatigue crack growth (safe-life),The following conclusions are drawn:

1. There is a need to develop more convenient techniques to measure residual stresses and their distributions. The current techniques used are most destructive method. Only the x-ray diffraction is non-destructive. But this method can only measure the residual stresses at the surface or near the surface.

2. The simple way of superimposing only the residual stress at the crack tip to the applied stress seems to provide acceptable analytical results from application point of view.

3. The effect ofresidual stress relaxatio on crack growth needs to be investigated more in order to provide better analytical fatigue crack growth predictions Before the relaxation effect can be accurately predicted, it is recommended that in the safe-life prediction of welded ground support lifting and handling equipment, the detrimental tensile residual stress should be included in the analysis, but the beneficial compressive residual stress should be ignored in order to have conservative predictions.

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