PREDICTING FATIGUE LIFE IMPROVEMENT IN COLD EXPANDED FASTENER JOINTS

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Abstract

This work investigates the effectiveness of applying the cold expansion process to a fatigue-aged fastener joint. Experimental tests were conducted using low load transfer joint specimens made of 2024-T351 aluminium plate. Cold expansion was applied at 0, 25, 50, and 75 percent of the baseline fatigue life. The improvements in fatigue life were substantial, the factors ranging from 1.7 to 3.6, depending on the degree of fatigue ageing prior to cold expansion.

A strategy for predicting fatigue life improvement is proposed. The analysis is based on the damage tolerance methodology and consists of two parts: (a) determination of the residual stresses induced by cold expansion using a closed-form solution, and (b) calculation of crack growth life under flight load spectrum using fracture mechanics theory. The predicted crack growth life was validated by test.

The results of this investigation indicate that: (a) fatigue life can be improved significantly by cold expansion process applied at 25-50% of the baseline life; (b) it is possible to predict the life improvement using a crack growth approach combined with baseline test data.

1 Introduction

Mechanically fastened joints are highly susceptible to fatigue cracking since the main source of fatigue damage is fastener holes. A study of in-service fatigue failures in aircraft structures revealed that about 70% of fatigue cracks originated from the holes of riveted or bolted joints [1]. With the trend towards longer service lives and the continued desire for reduced weight, problems of fatigue failure will likely increase. Consequently, a great deal of attention has been paid to life enhancement techniques which offer improved fatigue performance of aircraft structures.

It is well known that the cold expansion process offers considerable life improvement. The process is a mechanical method of strengthening metallic components by expanding the hole diameter, creating a radial plastic flow of material, thereby producing a high residual compressive stress zone around the hole. The residual stress zone acts to reduce the crack growth rate around the hole, thereby increasing the fatigue life of the component. However most fastener holes are not cold expanded at build. In many cases cold expansion is applied when an aircraft is already part-way through its service life, e.g. at the first maintenance, in order to extend its life. This strategy is often used as insurance for life extension and it is particularly important to improve the cost effectiveness of operating ageing aircraft. Therefore, there has been a drive to investigate the economic benefits of part-life cold expansion [2-6].

For damage tolerance design, the capability of extending crack growth life or being able to repair cracked holes is very desirable. Buxbaum & Huth [1] investigated cold expansion of joint specimens using both constant amplitude and standardised spectrum loadings. Cold expansion was applied to fatigue-aged specimens after loading to a predefined crack size. They found that the gain in fatigue life due to cold expansion was dependent on the degree of precycling and the crack lengths before cold expansion. Cook [4] also investigated the repair of cracked fastener holes by cold expansion. He looked at low load and medium load transfer joints in four types of aluminium under the FALSTAFF loading at two different peak stress levels. The results showed that the optimum enhancement in life occurred with cracks of less than about 1 mm present, but cold expansion was still effective at crack lengths up to 3 mm.

Both of the above investigations looked at the effect of cold expansion after precycling to a predefined crack size. Work has also been carried out to investigate cold expansion applied at a portion of the component's service life [5-6]. In this case the aim was to examine the effectiveness of cold expansion that is applied at various stages of the total fatigue life of a component, irrespective of any fatigue cracks that may exist due to the fatigue ageing. This simulates the practical situation of life enhancement for in-service aircraft that were not cold expanded on production and have expended a portion of their service lives prior to cold expansion.

The first part of this paper presents the fatigue tests that were carried out on low load transfer joint (LLTJ) specimens made of 2024-T351 aluminium with cold expansion applied at different percentages of the baseline life.

The second part of this paper presents an effective method for fatigue life prediction. Crack growth life was calculated by using an existing solution for the cold work induced residual stresses and a computer code for predicting crack growth. The predicted results agreed well with the test.

2 Experimental Testing

The low load transfer joint (LLTJ) specimens, illustrated in Fig. 1, were made of 2024-T351 aluminium plates. This material was chosen for its common use on aircraft lower wing skins in low load transfer situations, e.g. span-wise skin to spar and skin to stringer attachment. In this case, LLTJ specimens are defined as those that have a load transfer between the members of less than 10% of the total axial load [7].

The FTI split sleeve cold expansion method was used in this study. This process results in a zone of residual compressive stress that extends approximately one radius from the edge of the hole. The average nominal expansion ratio was 4.1%. The average retained expansion ratio is about 2.8%. The plain hole diameter (6.35 mm) results in a slight clearance fit when used with a 1/4'' Hi-Lok fastener. For the cold worked specimens, the final hole size range (6.32 - 6.33 mm) results in fastener fits varying from a net fit to a slight interference fit.

The FALSTAFF spectrum used in this study is a standard flight-by-flight loading sequence representing the stresses on the lower wing surface near the wing-to-fuselage joint in tactical aircraft. The 24 complete sequences represent 200 flights. In this study the tests were conducted with a peak net stress of 300 MPa.

The specimens were tested under five different conditions: plain hole (NCx), cold expansion at build (Cx), Cold expansion at 25%, 50%, and 75% of the baseline life (part-life Cx). The test condition and results are presented in Table 1. The mean lives and the life improvement factors (LIF) for different part-life cold expansion are presented in Fig. 2. Details can be seen in [5-6].

Table 1. Summary of the test results.

Test condition	Flights before Cx	Total life (Mean flights)
Plain hole	N/A	9865
Cx at build	0	34004
Cx at 25% life	2400	35137
Cx at 50% life	5000	23961
Cx at 75% life	7400	16769

The results indicate that part-life cold expansion can provide significant improvements in fatigue life but the amount of benefit is dependent upon the degree of fatigue ageing and the lengths of existing cracks when the specimen is cold expanded. The optimum time for cold-expansion is around 25% of the service life. This result is consistent with the conclusions made in [2-3].

3 Method for Predicting Fatigue Life with Cold Expansion Effect

Fatigue tests are time consuming and expensive. With the effect of cold expansion, the fatigue life could be 3-10 times longer making experimental tests even more undesirable. Since the ultimate aim of fatigue research is to develop quantitative methods for predicting service life in structures, the main objective of this study is to explore an effective method for predicting the life improvement due to cold expansion process.

3.1 Definition of total fatigue life

There are two approaches used to design against fatigue in aircraft, i.e. the Safe Life and the Damage Tolerance methods. The safe life method calculates the crack free service life based on the stress-life relationship and the Miner's law, and is hence an initiation based approach; the damage tolerance approach assumes manufacture defects exist and calculates service life required to grow small flaws to a detectable size and the life from first detection to fracture failure. Since the mid 1960s, design against fatigue in civil aircraft has moved steadily from a universal safe life approach to the damage tolerance approach. Today, all safety critical parts of large transport fixed wing aircraft, with the exception of the landing gear, must be designed using a crack growth approach [8, 9]. For military aircraft, the US Air Force has moved to damage tolerance design since the mid 1970s.

A schematic diagram of the damage tolerance concept is given in Fig. 3. Based on this concept, the total fatigue life is:

$$N_f = N_i + N_p \qquad (1)$$

In equation (1), N_i is the life to grow a micro crack, a_i, to a minimum detectable crack size, a_d, and N_p is the life to grow a_d to the fracture critical crack size, a_{cr}. Usually N_i is referred as the crack initiation life, or safe life because no inspection is required during this period. Recently, there has been work on predicting the crack initiation life by the small crack growth theory using the equivalent initial flaw size (EIFS) as the starting crack size [10-11]. According to Newman's work on open hole and joint specimens made of 2024-T3, the typical EIFS in aluminum alloys representing manufacture defects is about 0.006 mm [10]. Since this flaw size is within the short crack region, analysis based on the linear elastic fracture mechanics (LEFM) theory will not give the correct solution. It was our intention to calculate N_i using the short crack theory, but there has been a difficulty with the currently available software packages in simulating short crack growth. Therefore, for the crack initiation life, i.e. small crack growth from 0.006 to 0.25 mm, experimentally measured life was used in Eq. (1) in order to find the total fatigue life. Work on modeling small crack growth is currently in progress, which will be reported to the ICAS Congress in August.

The macro-crack growth life, N_p, is the life available for damage tolerance by inspection. Experimental tests show that it is during this part of the life that cold working is most effective for life extension. Therefore, the present work has concentrated on predicting the crack growth life of macrocracks. The starting crack length is 0.25 mm. The method for predicting crack growth life with cold expansion effect is presented in Sections 3.3 and 3.4.

3.2 Life improvement due to cold expansion

The life improvement factor (LIF) is defined as the ratio of the total fatigue life of Cx specimen to the total life of NCx specimen. The following assumptions were made:

(a) The total fatigue life is defined as:

$$N_f = N_{pre\text{-}flight} + N_i + N_p \qquad (2)$$

Where $N_{pre\text{-}flight}$ is the life spent prior to cold expansion, N_i and N_p are defined in section 3.1.

(b) N_i is determined by control test.

(c) Two baseline tests are required. These are the total fatigue life of NCx specimen (N_f^{NCx}), and the total life of Cx at build specimen (N_f^{Cx}).

(d) Define the damage ratio as $D = N_{init}^{Cx} / N_{init}^{NCx}$, where N_{init}^{Cx} and N_{init}^{NCx} are crack initiation lives, with and without cold expansion, respectively. From the test results, the lives to crack initiation, for the NCx and Cx specimens, were 7400 and 25900 flights respectively. The damage ratio is therefore 3.5. Assuming the same cumulative damage law governs the damage accumulation for both specimens, it is hence inferred that the amount of damage caused by one flight to the NCx specimen is 3.5 times of that to the Cx specimen, i.e. $D=3.5$ for this case.

3.3 Residual stress calculation

There are three methods for determining cold expansion induced residual stresses: experimental, numerical, and analytical methods. The third option often employs closed-form solutions and is easier for engineering application.

There are many closed-form solutions available in the literature. The Hsu-Forman [12] and Rich-Impellizzeri [13] models are well known and suitable for plane stress and plane strain conditions, respectively. Ball's model [14] builds upon the Hsu-Forman model by including elastic-plastic unloading, therefore it generalises the solution by including any potential reverse yielding. A parameter to account for the Bauschinger effect was introduced in the unloading formula to modify the reverse yield zone. Chang's model [15] was developed based on the elastic-plastic solution of a pressurised thick-walled cylinder assuming perfectly plastic material and plane strain condition. Many researchers have tested all four models with a mixture of success and disappointment: no one model is suitable for general application. The thickness of the specimen in this study was 6 mm, which fits in neither the plane stress nor the plane strain condition. Therefore, modification was necessary in order to use these models. A comparative study of these models was carried out based on the life prediction results of three independent tests. Necessary modifications were suggested for the application of these models [16].

For an open hole specimen made of 6-mm thick 2024-T351 aluminium plate, the residual stress distributions described by these models are given in Fig 4, which shows considerable differences described by each model in terms of reverse yield zone size and the maximum residual stress. Measured residual stress distribution is also included in Fig. 4 showing a good agreement with the Ball's model. The measurement was done by Priest et al [17] using the X-ray diffraction technique. Same material and dimensions to the open hole specimen used in this study were used except that the specimens in [17] were much wider than that of this study. However, this should not affect the local residual stress distribution induced by cold expansion. Therefore, the Ball's model was used in this study.

3.4 Predicting crack growth

To account for the effect of residual stresses on crack propagation, the method used in this study involves the superposition of the respective stress intensity factors of applied and residual stress fields. This is based on the premise that, since the stress intensity factor is derived from the linear elastic fracture mechanics, the superposition principle would apply. Therefore, the effective stress intensity factor, K_{eff}, is determined by:

$$K_{eff} = K_{appl} + K_{res} \qquad (3)$$

Where, K_{appl} is the stress intensity factor due to applied stresses, and K_{res} the stress intensity of residual stress field. For a given residual stress distribution, K_{res} can be found by either integration or the weight function approach.

A Paris type law using the effective stress intensity range, ΔK_{eff}, can then determine the crack growth rate, da/dN:

$$\frac{da}{dN} = f(\Delta K_{eff}) \qquad (4)$$

The AFGROW computer code [18] was employed for the above calculation. AFGROW has the facility to calculate the residual stress intensity and to work out the effective stress intensity according to Eq. (3). The users can input the residual stress distribution through a dialog window. The residual stress intensity factor is then calculated by either the weight function method or the Gaussian integration. The latter was used in the present calculation. The NASGRO equation for crack growth rate was used for Eq. (4), which was developed by the NASA and ESA organizations, and is well described in [18].

For a fastener hole with slight interference fit, the load transfer through the fasteners also influences the crack growth life. The calculation of stress intensity factor (SIF) requires the knowledge of SIF solutions of the bypassing load and transferred load at the fastener to be considered. AFGROW code can calculate both SIF's and superpose the two solutions. Users need to provide the amount of the bearing load into the input menu.

For a flight-by-flight loading sequence, it is important to take account of the overload retardation effect. The Willenborg model was used to simulate this effect.

4 Results of the Prediction

4.1 Crack growth life

To validate the aforementioned analysis method, two groups of open hole specimens, cold expanded and non-cold expanded, were tested in addition to the joint specimens. This was because that both crack initiation (to a detectable size) and crack propagation are easier to measure for the open hole specimens. During the tests on the open hole specimens, the crack growth was periodically measured and recorded. The crack growth lives were predicted using the AFGROW code and the residual stress models of Ball and Chang. As shown in Fig. 5, the predicted crack growth histories for both Cx and NCx specimens agreed well with the test results.

Since the joint specimens were made of the same material and had similar dimensions to the open hole specimen, Ball's model was used for residual stress calculation. The influence of the bearing load on the stress intensity is also taken into account. According to the detail stress analysis for the LLTJ specimen used in this study, the total load transfer by the two fasteners is about 8% of the applied load. Therefore, depending on the degree of fastener fit (i.e. ranging from a net fit to slight interference fit), one fastener could transfer the load between 4% and 8%.

The predicted crack growth life was 8400 flights (from 0.25 mm crack to final fracture). It was found that there was little difference between the predicted crack growth lives at different load transfer levels between 4% and 8%. For the joint specimens the crack lengths were only measured before and after cold-expansion being applied. Macrocracks longer than 0.25 mm were found only in the 75% pre-cycled specimens. The mean measured crack growth life of 9369 flights (for the 75% part-life Cx case) is reasonably close to the predicted result of 8400 flights. The ratio of the predicted life to the test result is 0.90.

4.2 Fatigue life improvements

The life improvement factors for the part-life cold expanded joint specimens were calculated based on the aforementioned assumptions.

(1) 25% part-life Cx specimen. No cracks were detected at the time of cold expansion at 25% life. Cracks of significant lengths (0.3-0.45 mm) were only found at about 75% fatigue life. At 25% life any initial damage growth should have been removed by the cold work and reaming process. Therefore these specimens can be assumed to be the same as the "cold expanded at build" specimens when the test is resumed. Therefore, the total life is:

$$N_f = 25\%\ pre\text{-}flights + N_f^{Cx}$$
$$= 2400 + 34000 = 36400\ (flight)$$

(2) 50% part-life Cx specimen. Microcracks of significant length had already been formed before cold-expansion. They were not totally removed by the cold-work and reaming process, and thus continued to grow once the test was resumed. According the test results (75% part-life control test), these specimens need 2400 more flights to get into the macrocrack (0.25 mm) initiation stage if the test had not been stopped and the specimen had not been cold expanded. After cold-expansion, 8400 flights were needed (i.e. 2400 x D) to reach the crack initiation stage. Therefore:

$$N_f = 50\%\ pre\text{-}flights + Part\ of\ initiation\ life + N_p$$
$$= 5000 + 8400 + 8400 = 21800\ (flight)$$

(3) 75% part-life Cx specimen. For the 75% pre-flights specimens, macrocracks (typically 0.3-0.45 mm) had been formed before the cold expansion and they still existed after cold working and reaming. The typical crack size after cold working was 0.25 mm. Therefore, the total life is

$$N_f = 75\%\ pre\text{-}flights + N_p$$
$$= 7400 + 8400 = 15800\ (flight)$$

Fig 6 shows the comparison of the test and the predicted results for the part-life cold expanded specimens. The life improvement factor (LIF) is also indicated in Fig 6.

5 Discussions and Conclusions

The objective of this study was to assess the effectiveness of applying cold expansion to fatigue-aged fastener holes. It was shown that part-life cold expansion provides significant life improvement in low load transfer joints. The amount of benefit is dependent upon the degree of fatigue ageing. The greatest improvements were achieved when the specimens were cold expanded early in the fatigue life and these improvements can exceed those obtained by cold expanding on production. For aircraft that were not cold expanded on production, the results of this investigation would suggest that the best life improvement can be achieved by applying cold expansion at approximately 25% of its service life.

The effect of part-life cold expansion on total life improvement was also quantified by analysis. It was proposed that the fatigue-crack initiation part of the methodology is based on the damage tolerance approach. However, due to the difficulty in predicting short crack growth this part of the life is currently based on test. Therefore, to predict the total fatigue life improvement, two baseline fatigue tests are required using non-cold expanded and cold expanded at build specimens, respectively. The total life improvement of a part-life cold expanded specimen can then be estimated by calculating the crack growth life from a known crack length, and add it to the baseline crack initiation life obtained from the test. The significance of this quantitative analysis is that it should help in making decisions on whether and when to apply cold expansion during the service life of a component. The analysis can be done largely by computer simulation along with two baseline fatigue tests using plain and cold expanded specimens. This should be cost effective.

The prediction of fatigue crack growth history was validated by experimental tests on the open hole specimens with and without cold expansion. Crack growth life prediction for the joint specimen was also confirmed by one test (75% part-life cold expansion case). Good results were achieved for both open hole and joint specimens by using a suitable closed-form model for calculating the cold expansion induced residual stresses, and a computer code based on linear elastic fracture mechanics.

Future work includes: (1) prediction of crack initiation life using short crack theory; (2) evaluation of the interaction effect of the two plastic zones, introduced by tensile overload and cold expansion process, respectively.

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References

[1] Buxbaum, O and Huth, H. Expansion of cracked fastener holes as a measure for extension of lifetime to repair. *Eng. Fracture Mechanics*, Vol. 28, 689-698, 1987.

[2] Reid, L. Split sleeve cold expansion as a rework process for previously cold expanded holes. Proc of *ICAF'93*, Stockholm, Sweden, Jun 7-11, 1993.

[3] Wagner, R V, Reid, L, Easterbrook E T and Rufin, A C. Beneficial effects of split sleeve cold expansion™ on the fatigue lives of pre-cycled cold expanded structure. *Proc USAF Aircraft Structural Integrity Program Conference*, San Antonio, TX, December 1-3, 1992.

[4] Cook, R. Repair of cracked holes using cold expansion. *Computer Methods and Experimental Measurements for Surface Treatment Effects*, Ed. M H Aliabadi and C A Brebbia, Computational Mechanics Publications, 1997.

[5] Gaerke, JG & Zhang, X. Fatigue life extension through cold expansion. *Proc CEAS Forum on Life Extension - Aerospace Technology Opportunities*, Cambridge, UK, 23-25 March 1999, Paper 28.

[6] Gaerke, J G. *Fatigue Life Extension Through Cold Expansion*. MSc Thesis, College of Aeronautics, Cranfield University, 1998.

[7] *Fatigue of Aluminium Alloy Joints with Various Fastener Systems, Low Load Transfer*. ESDU Item No. 89046, Engineering Sciences Data Unit International plc, 1989.

[8] Bristow, J & Minter, R. The meaning of life. *Proc CEAS Forum on Life Extension - Aerospace Technology Opportunities*, Cambridge, UK, 23-25 March 1999.

[9] JAR Regulations Section 25.571, Large Transport Aircraft - Damage Tolerance.

[10] Newman Jr, J C, Harris, C E, James, M A & Shivakumar, K N. Fatigue-life prediction of riveted lap-splice joints using small-crack theory. Proc. 19th Symposium of International Committee on Aeronautical Fatigue (ICAF 97), June 1997, Edinburg, pp. 523-552.

[11] Everett Jr., R A & Elber W. The significance of small cracks in fatigue design concepts as related to rotorcraft metallic dynamic components. Proceedings of RTO Meeting of Applied Vehicle Technology, RTO Proceedings 24, RTO-MP-24, Corfu, Greece, Paper 1, 1999.

[12] Hsu, Y C and Forman, R G, Elastic-plastic analysis of an infinite sheet having a circular hole under pressure. *ASME J. Applied Mechanics*, Vol. 42, 347-352 (1975).

[13] Rich, D L and Impellizzeri, L F. Fatigue analysis of cold-worked and interference fit fastener holes. *Cyclic Stress-Strain and Plastic Deformation Aspect of Fatigue Crack Growth*, *ASTM STP 637*, Amer. Soc. for Test and Mat. 153-175 (1977).

[14] Ball, D L, Elastic-plastic stress analysis of cold expanded fastener holes. *Fatigue Fract. Engng. Mater. & Struct*., Vol. 18, 47-63, 1995.

[15] Chang, J B. Prediction of fatigue crack growth at cold-worked fastener holes. *J. of Aircraft*, Vol 14, 903-908, 1977.

[16] Wang, Z & Zhang X. A comparative study of closed-form residual stress models for predicting crack growth life of cold-worked fastener holes. Report, College of Aeronautics, Cranfield University, Jan 2000.

[17] Priest, M, Poussard, CG, Pavier, MJ & Smith DJ. An assessment of residual stress measurements around cold-worked holes. *Experimental Mechanics*, 1995, 361-366.

[18] Harter J A. *AFGROW Users Guide and Technical Manual*. AFRL-VA-WP-1999-3016, Air Force Research Laboratory, Wright-Patterson, OH, Feb 1999.

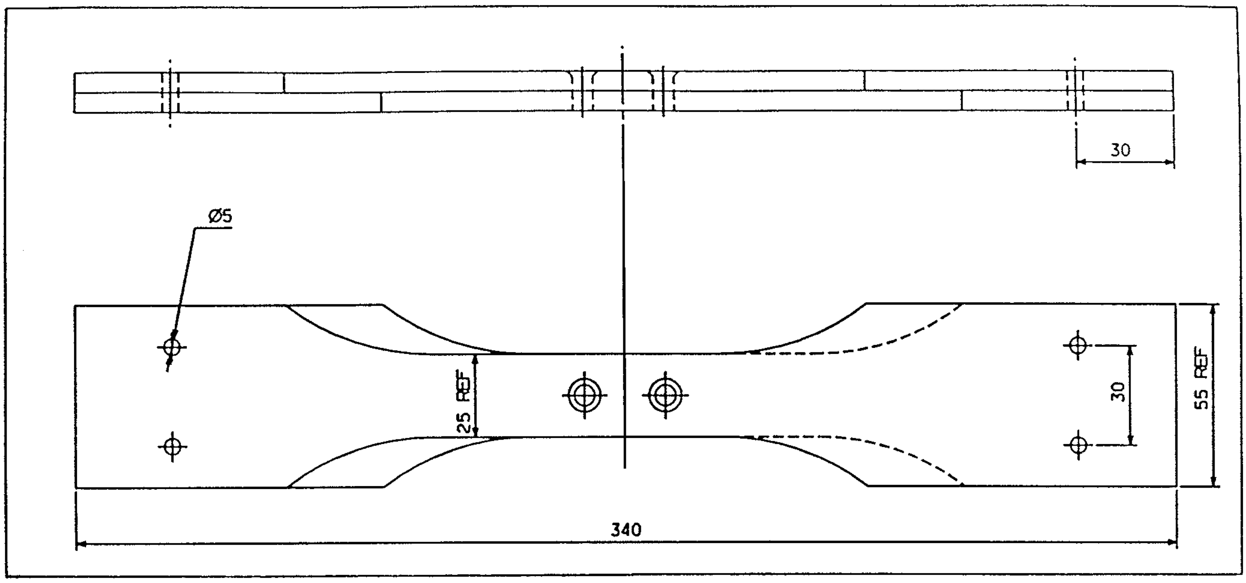

Fig. 1 Low Load Transfer Joint (LLTJ) Specimen.

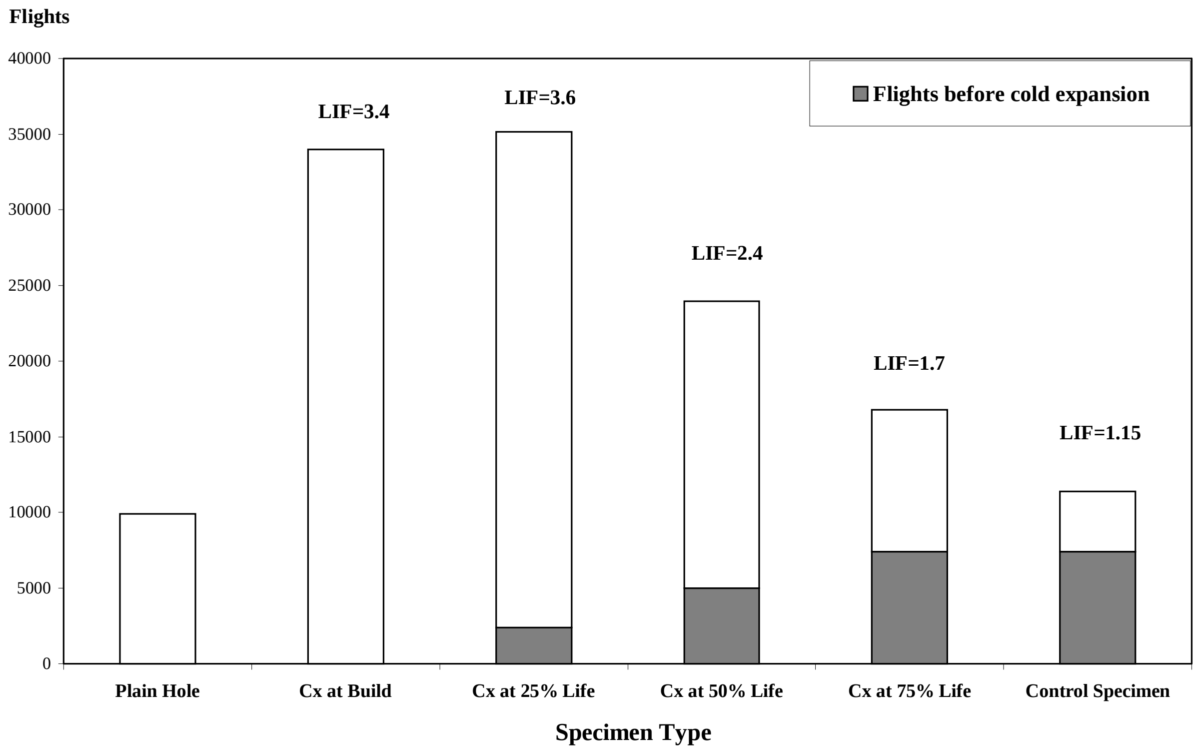

Fig. 2 Test result of part-life cold expanded LLTJ specimens.
LIF (Life Improvement Factor =N_{Cx}/N_{NCx})

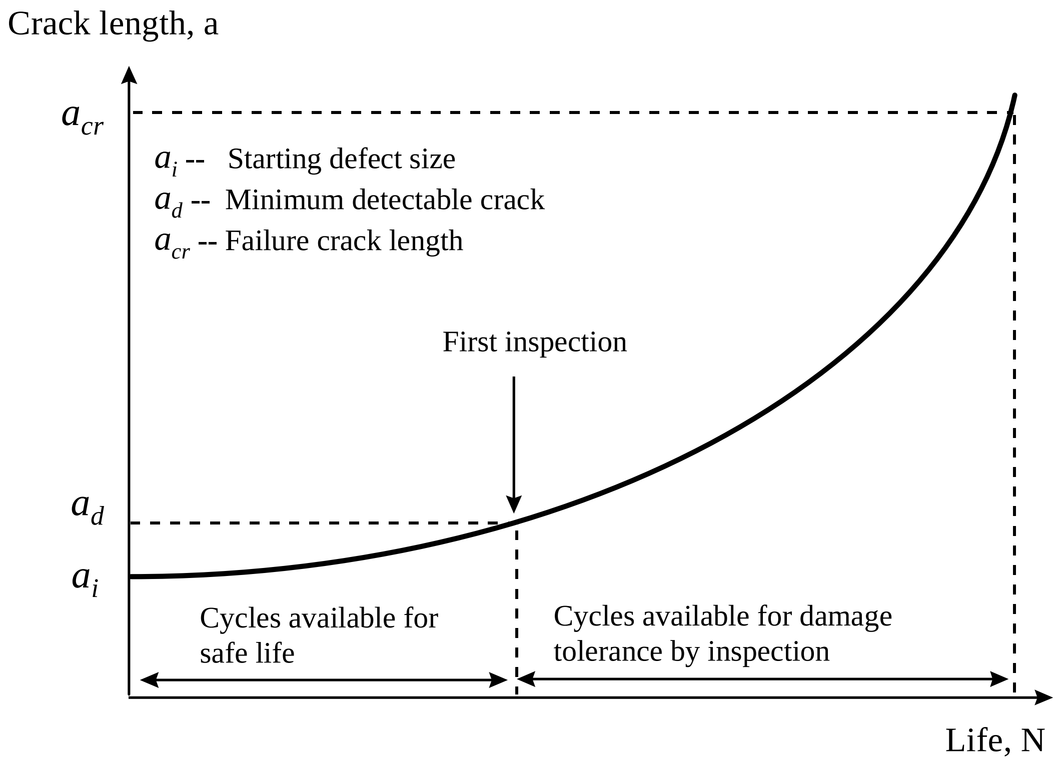

Fig. 3 Prediction of fatigue life by damage tolerance approach.

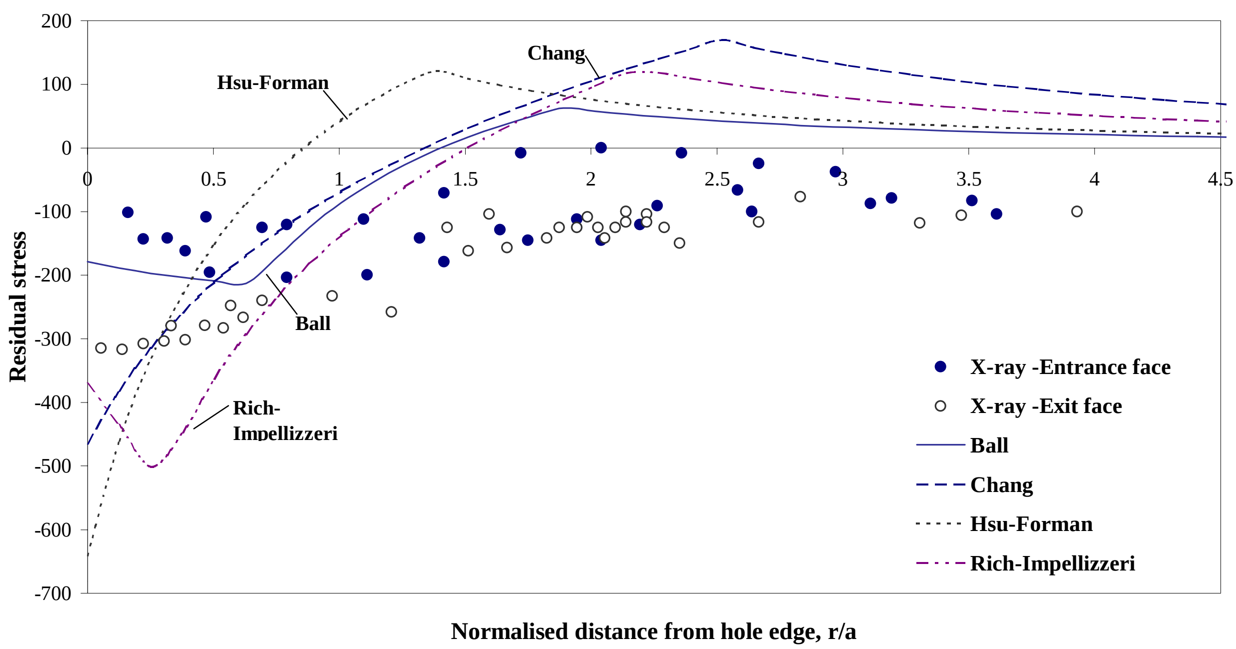

Fig. 4 Residual stress distributions determined by different closed-form models.

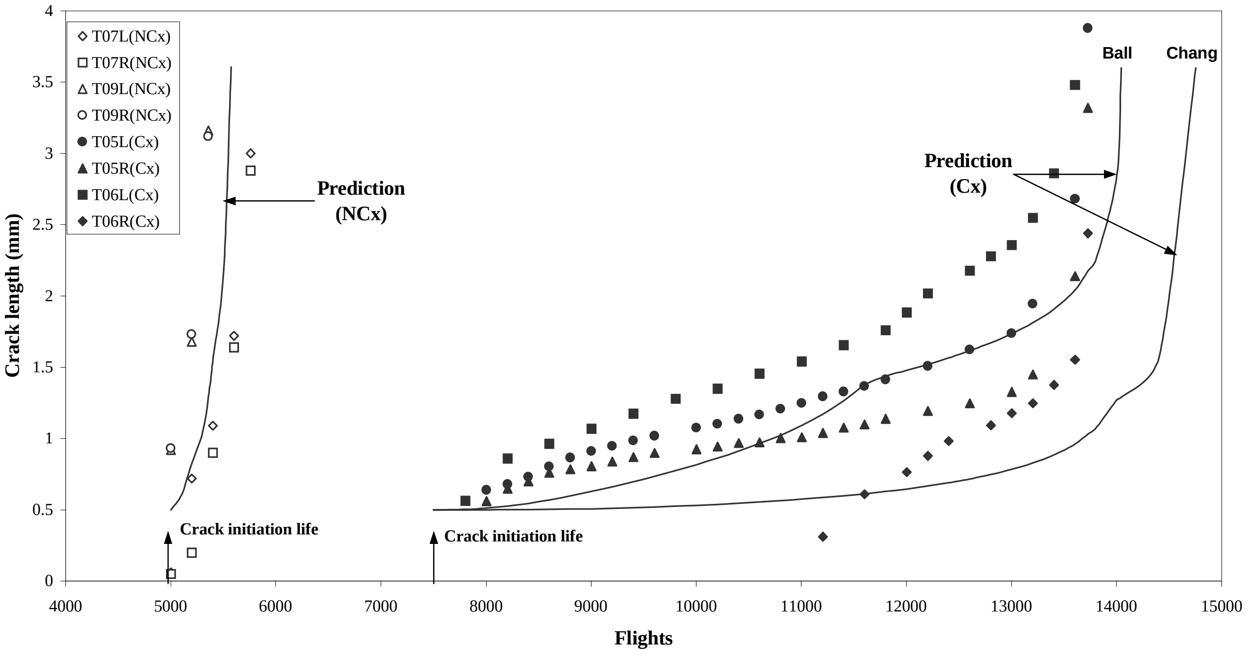

Fig. 5 Simulation of crack growth histories by AFGROW using two different residual stress models.

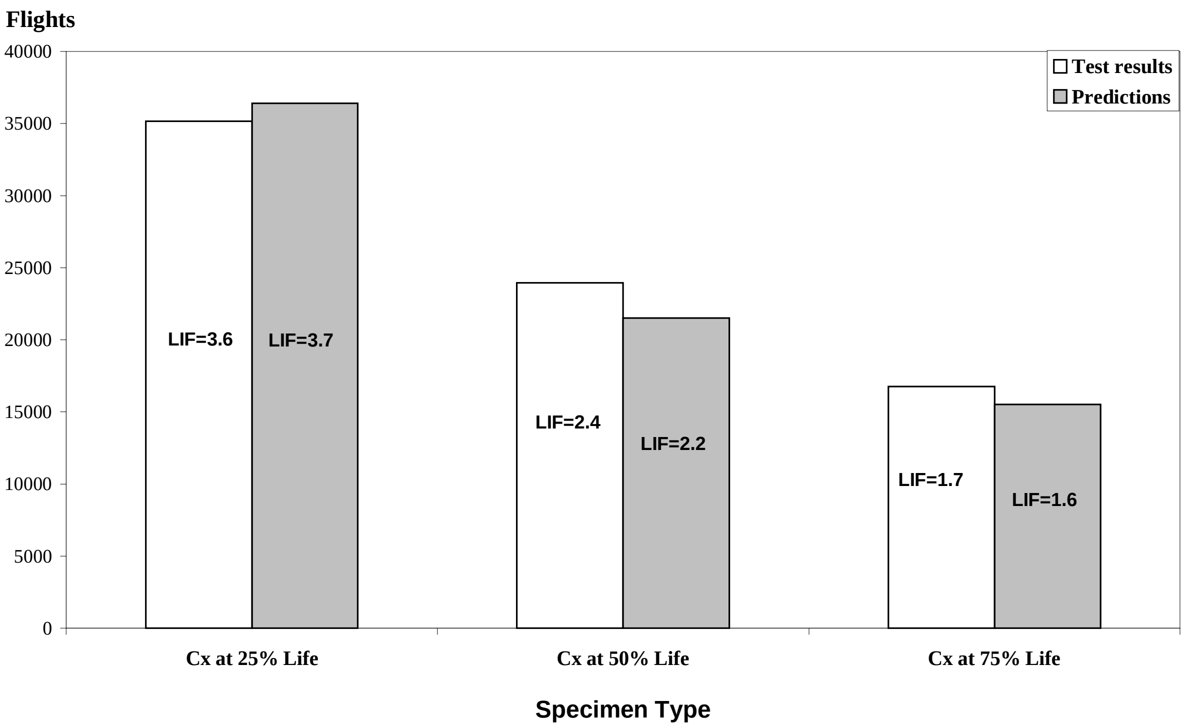

Fig. 6 Comparison of life improvement factor (LIF) between test and predicted results