FATIGUE EVALUATION OF THICK MONOLITHIC ALUMINUM STRUCTURES REPAIRED USING COMPOSITE BONDED DOUBLERS

Master Degree in Applied Science
Mechanical Engineering

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Sherbrooke (Québec), CANADA

May 2001
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ABSTRACT

The composite repair of metallic aircraft structures is a proven technology used in many repair applications on both military and commercial aircraft. Composite bonded repairs to metallic aircraft structures are generally used for fatigue enhancement, crack patching, as well as in different kinds of damage repairs.

A critical step in the design of a composite patch repair is the determination of the load transfer required by the doubler to reduce the crack growth or to delay the onset of crack initiation. This is traditionally performed using crack initiation or crack growth methods in which the composite doubler is assumed to reduce the magnitude of the stress cycles. Once the preliminary design is completed there is a requirement to conduct more detailed and accurate life assessment of the repaired structure. For a complex repair geometry this can only be done by including the full effect of the bonded repair into the analysis.

An alternative to improve fatigue prediction accuracy is to use finite element based methods to include the complex 3D stress distribution effects resulting from the application of a bonded composite doubler. The trade off between the conventional method and the finite element methods is the gain in life estimation accuracy versus analysis complexity and time needed to perform the analysis.

A classical research approach has been adopted for the project. A literature review has been conducted to become acquainted with the crack initiation and crack growth prediction methods in composite bonded repair situations and to gather experimental data for validation purposes. Test data generated by DERA and the USAF has been used to evaluate crack growth and crack initiation analysis tools. Both classical and FEA based fatigue analysis have been evaluated for accuracy. From the evaluation, a list of deficiencies has been developed, and a new methodology proposed to improve the fatigue life prediction for thick cracked aluminum structures. The new methodology provides a good compromise between accuracy and complexity in the analysis of bonded repair designs. A new set of data was generated, due to the lack of experimental crack growth data available for typical CF-18 materials and spectrum loading. The proposed methodology has been evaluated against existing and new test data generated for the project. The designed test coupons had a centre section of 6.35 mm (0.25 inch) of thickness and were made of 7050-T7451 Aluminum. Coupon testing was realized using spectrum loading representative of CF-18 usage.

This project has been realized in collaboration with the Canadian Department of National Defence (DND), Martec Limited and the Université de Sherbrooke.
ÉVALUATION EN FATIGUE DE STRUCTURES D’ALUMINIUM ÉPAISSES
RÉPARÉES À L’AIDE DE MATÉRIAUX COMPOSITES

La réparation de structures métalliques à l’aide de matériaux composites est une technologie qui a déjà fait ses preuves autant dans le milieu aéronautique civil que militaire. Les réparations en composites collées sont généralement utilisées pour l’amélioration en fatigue, la réparation de fissures, ainsi que pour la réparation de différents types de dommages.

Une étape critique dans la conception d’une réparation est la détermination du transfert de charge requis pour retarder l’initiation ou la propagation de fissures. Ceci est habituellement effectué à l’aide de méthodes de prédiction d’initiation ou de propagation de fissures, où l’on assume une réduction des contraintes égale au transfert de charge calculé. Une fois la conception préliminaire effectuée, un besoin se présente afin d’évaluer plus en détails la vie de la structure réparée. Pour une géométrie complexe, les effets complets de la réparation doivent être inclus dans l’analyse.

Afin d’améliorer la précision des prédictions, la méthode d’analyse par éléments finis peut être utilisée pour inclure les effets 3D résultant de l’application d’un composite. L’amélioration des prédictions (en comparaison à la méthode d’analyse traditionnelle) est cependant étroitement reliée à la complexité et au temps nécessaire pour exécuter l’analyse.

Une approche classique a été adoptée pour le projet de recherche. Une revue de littérature a été effectuée pour se familiariser aux méthodes de prédiction d’initiation et de propagation de fissures, ainsi que pour recueillir des données de test expérimentaux déjà existantes. Des résultats de tests provenant de DERA et de USAF ont été utilisés pour évaluer les logiciels retenus pour le projet. Ces logiciels ont été évalués sous plusieurs critères, et une nouvelle méthodologie d’analyse a été proposée. Cette nouvelle méthodologie fournit un bon compromis entre l’exactitude et la complexité de l’analyse effectuée. Un test expérimental de validation a été de plus entrepris en raison du manque de données expérimentales disponibles pour les matériaux et chargement typiques du CF-18. La méthodologie proposée a été évaluée à l’aide des résultats expérimentaux trouvés en phase préliminaire et ceux générés pour le projet. Les échantillons de test ont une section centrale de 6.35 mm (0.25 pouce) d’épaisseur et ont été fait d’aluminium (7050-T7451). L’essai a été effectué utilisant un chargement représentatif de l’utilisation des CF-18.

Ce projet a été réalisé en collaboration avec le Département de la Défense Nationale, Martec Limitée, ainsi que l’Université de Sherbrooke.
ACKNOWLEDGMENTS

I wish to thank Major Normand Landry, Major André Fillion, and Captain Karen Eiblmeier from DND as well as Mr. Ken McRae from National Research Council (NRC) for their time, involvement and contribution to the research project. Additional thanks to Quality Engineering Test Establishment (QETE) people, especially Marko Yanishevsky and Alain Douchant regarding their judicious advices for the validation test.

I would also like to thank the personnel from the Université de Sherbrooke who helped me during my research: Claude Aubé for the machining of all the parts required for the test installation, and Marc Demers (my ambassador at the university) for his help in understanding the test components and software packages. Finally, thanks to my professor Dr. Kenneth Neale for his trust, for leaving us the freedom to express creatively our ideas, and for having been there when I most needed support.

I wish to extend my thanks to all of Martec’s personnel for their encouragement, and for the nice working environment in the aerospace group. Thanks to Dr. James Warner, Martec’s President, who has supported this research project. Thanks to Dr. Josef Eiblmeier for his help in the FEA field, for the “How to Design a Composite Repair” course, and for the “warnings” when the project was not progressing sufficiently fast. Special thanks to my supervisor (the last but not the least) Mirko Zgela for his technical contribution and direction when I stumbled. He wrote the basic ideas of the research project and contributed greatly to make it materialize.

I dedicate this document to my family who provided me support and encouraged me to persevere with determination. Finally, I would like to thank my girlfriend Sofie, for her love and understanding, who tolerated so long my overloaded schedule, knowing what this thesis meant to me.
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<td>2D</td>
<td>Two Dimensional</td>
</tr>
<tr>
<td>3D</td>
<td>Three Dimensional</td>
</tr>
<tr>
<td>(a)</td>
<td>Half Crack Length</td>
</tr>
<tr>
<td>(\alpha,\text{CTE})</td>
<td>Coefficient of Thermal Expansion</td>
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<td>Air Force Institute of Technology</td>
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<tr>
<td>(\beta)</td>
<td>Beta Factor</td>
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<tr>
<td>BEM</td>
<td>Boundary Element Method</td>
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<td>CFG</td>
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<td>CG</td>
<td>Crack Growth</td>
</tr>
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<td>CI</td>
<td>Crack Initiation</td>
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<td>CMC</td>
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<tr>
<td>(da/dN)</td>
<td>Crack Growth Rate</td>
</tr>
<tr>
<td>DERA</td>
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<tr>
<td>(\Delta)</td>
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<td>(\varepsilon)</td>
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<td>(E)</td>
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<td>Function of ( )</td>
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<td>FS</td>
<td>Fuselage Station</td>
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<tr>
<td>$K_{\text{min}}$</td>
<td>Minimum Stress Intensity Factor</td>
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<td>$\Delta K_{\text{th}}$</td>
<td>Threshold Value of $\Delta K$ below which $da/dN = 0$</td>
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<tr>
<td>LIF</td>
<td>Life Improvement Factor</td>
</tr>
<tr>
<td>$\nu$</td>
<td>Poisson’s Ratio</td>
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<tr>
<td>$N$</td>
<td>Number of Cycles</td>
</tr>
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<td>NASA</td>
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<td>Quality Engineering Test Establishment</td>
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<tr>
<td>$R$</td>
<td>Stress Ratio</td>
</tr>
<tr>
<td>RAAF</td>
<td>Royal Australian Air Force</td>
</tr>
<tr>
<td>$S$</td>
<td>Patch-to-Panel Stiffness Ratio, or Symmetrical</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>Stress</td>
</tr>
<tr>
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<td>$\Delta T$</td>
<td>Difference between Cure and Ambient Temperatures</td>
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<tr>
<td>$\Psi$</td>
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<td>Bending and Thermal Correction Factor</td>
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1.0 INTRODUCTION

1.1 Bonded Repairs of Metallic Aircraft Structures

The composite repair of metallic aircraft structures is a proven technology used in many repair applications on both military and commercial airliners. This type of repair is composed of a reinforced fibre & epoxy resin (doubler), an adhesive and a substrate material. The repair consists in bonding the composite doubler to the substrate materials using a high performance adhesive.

Composite bonded repairs to metallic aircraft structures are generally used for fatigue enhancement, crack patching, as well as in different kinds of damage repairs (such as corrosion damages or machining defects). Generally, the bonded doubler repair is installed to reduce the stresses at a critical location, to reduce the stress intensity factor and opening at the crack tip, or to restore the static strength and stiffness of a damaged part.

There are many advantages of using bonded composite repairs instead of conventional metallic bolted or riveted repairs. Some of these advantages are

a) minimal access and tooling required;
b) no corrosion hazard (Silane);
c) applied easily in the field;
d) no fretting induced fatigue (no mechanical fasteners); and,
e) load eccentricity reduced (thinner doublers).

Key features of bonded repairs are that no additional holes are required for fastener installation, which can generate significant stress concentrations and create other fatigue cracks or lower edge distance problems. They also exhibit better efficiency in reducing the crack tip opening; the bonded doubler acting like a short spring to resist crack tip opening as compared to the conventional doubler where the material between the fasteners can stretch to allow extension of the crack. Bonded composite repairs are usually cheaper than their bolted metallic counterpart.
1.2 Research Activities on Composite Bonded Repair at Martec Limited

Martec Limited (Aerospace Group) has been extensively involved in the design, analysis and installation of composite bonded repairs of metallic aircraft structures for many years. Over the last few years, the following repairs have been conducted:

a) Design and installation of a technology demonstrating boron patch on a CC-130 aircraft lower wing skin. This repair was designed as a crack patching repair to reduce the growth of a fatigue crack originating at a fastener hole;

b) Design of a carbon epoxy bonded doubler to improve the fatigue life of the FS470.5 bulkhead at the critical location referred to as X-19;

c) Design of a boron doubler reinforcement to repair a lower wing skin damage to a CT-114 aircraft;

d) Design and installation of a fatigue improvement bonded doubler for the CF-18 FS470.5 bulkhead at section X-24 adjacent to the X-19 location;

e) Design and installation of carbon epoxy bonded doublers for crack patching at the web taper area Y453 of CF-18, left hand and right hand sides;

f) Design and installation of a boron doubler for crack patching at the CF-18 longeron area Y470; and,

g) Design and installation of a boron epoxy bonded doubler for cracked skin repair at the CF-18 engine intake location Y453.

Martec has also conducted research in the thermal analysis of composite bonded doubler repairs [ROBERGE 98], in process improvements, and in fatigue prediction of structures that have been repaired with bonded doublers. As part of a collaborative program into fatigue prediction of bonded repairs, Martec Limited has initiated a research project in collaboration with the Department of National Defence, and the Université de Sherbrooke. This project has been conducted at the Université de Sherbrooke, under the auspices of the Partnership Program for Masters and Doctoral Studies in the Workplace (PPMDSW).
1.3 Problem Statement

A critical step in the design of a composite patch repair is the determination of the load transfer required by the patch to reduce the crack growth or to delay the onset of crack initiation. This has been traditionally performed using crack initiation or crack growth analysis in which the patch is assumed to reduce the overall mean stress level. The appropriate in-service load spectrum is then scaled down to match the patch load transfer. For preliminary design this method is considered acceptable since it provides a quick means of estimating the load transfer requirement and patch size. Once the repair has been implemented there is a requirement to perform a more detailed and accurate life assessment of the repaired structures. For a complex geometry, such as the thick monolithic structures of the CF-18 main carry through wing bulkhead, this can only be done by including the full effect of the bonded repair into the analysis. For accurate prediction, the effects that need to be included are:

a) the influence of the fatigue load condition on the load transfer provided by the patch;

b) the complex strain profile modification resulting for the addition of the patch to the original structure; and,

c) the increased load taken by the doubler as the fatigue crack progresses underneath the bonded doubler.

Current life estimation methods do not include these effects and will result in significant errors in the fatigue life prediction. To account for these unquantified deficiencies, a large safety factor needs to be applied to the fatigue life estimation results with inherent penalties on the aircraft service life. One alternative to the current method is to use finite element based techniques to include the effects stated above into the analysis. The trade off between the two approaches is the gain in accuracy versus the analysis complexity and time required to perform the analysis. As part of Martec research activities into composite patching repair technology, a project has been conducted to improve on the current life estimation technique for thick monolithic structure by applying finite element based methods in practical repairs situations to assess their efficiency against more classical analytical methods.
1.4 Research Project Objectives

The objectives of this research project were as follows:

a) to improve our understanding of fatigue life estimation techniques for repaired structure with composite bonded doubler;

b) to develop a systematic and improved methodology for the evaluation of the fatigue life of thick monolithic structures repaired using bonded composite doublers;

c) to quantify the inaccuracy of using simplify classical life estimation methods as opposed to more complex FE based methods for bonded repair situations; and more generally,

d) to improve the bonded repair design process.
2.0 BACKGROUND

2.1 Fatigue Analysis of Bonded Repairs

Two methods have been traditionally used to analyze composite repairs: analytical closed form solutions, and finite element based analysis [BAKER 88]. The closed form solutions are often employed to obtain a first approximation of the repair geometry. This approach is simpler than the FEA based approach, and can provide sufficient accuracy in many simple repair situations.

When the damaged structure is more complex, the use of more complex FEA methods becomes necessary in order to obtain accurate results, especially in thick section repairs where 3D effects are significant.

The closed form solutions are generally good for one or two dimension problems. On the other hand, the numerical methods are most of the time based on commercial codes or in-house codes developed for the design and analysis of specific repairs. The following sections present a summary of the closed form and numerical methods found in the literature.

2.1.1 Repair Design using Closed Form Solutions

The closed form design solutions are always developed assuming some simplifying assumptions. The assumptions can be: identical Poisson’s ratios for the cracked structure and repair material; no thermal residual stresses induced during adhesive curing; negligible effect of out-of-plane displacement (for one-sided repair); or, plane stress state (no stress variation across the thickness) [BAKER 88].

One-dimensional models were first developed to analyze repairs such as isotropic stiffeners bonded to isotropic structures. More complex models were introduced later on for the analysis of composite repairs to metallic structures. Several analytical methods and closed-form solutions are found in the literature [BAKER 88; DUONG 97; HART-SMITH 99; HART-SMITH 00; RATWANI 79; ROSE 81; ROSE 82; ROSE 87; WANG 98; WANG 99]. These models became more and more complex, including effects such as thermal residual stresses, and secondary bending moment effects.
generated by the out-of-plane displacement of a one-sided repair [BAKER 88; HART-SMITH 99; RATWANI 79; WANG 98].

The best known closed form solution is the Rose Model [ROSE 82]. This model has been developed for one-sided or double-sided repairs for which no out-of-plane displacement is allowed. A one-dimensional idealization was used, which ignores the stress variation across the thickness, and assumes that the cracked plate and repair materials are isotropic with identical Poisson’s ratio.

The Rose Model was initially developed considering the external load only, and ignoring the thermal stresses. This was based on the assumption that the total force at the crack plane can be obtained by superposition. Rose found [ROSE 82] that the stress in the substrate (when no thermal stresses are present in the repaired structure) is given by:

\[ \sigma_0 \approx \sigma \left(1 + S\right)^{-1} \]

(2-1)

where \( S \) is the patch-to-skin stiffening ratio and is given by:

\[ S = \frac{h_R E_R}{h_p E_p} \]

(2-2)

Rose concluded that the stress intensity factor (SIF) is limited by an asymptotic upper bound given by:

\[ K_\infty = \sigma_0 \sqrt{\Omega} \]

(2-3)

where:

\[ \Omega = \sqrt{\left(1 + \frac{1}{S}\right) \frac{h_R h_p E_p}{G_A}} \]

(2-4)

In the above equations, \( E_R \) and \( E_p \) are respectively the Young’s modulus of the repair material and of the substrate, while \( h_R \) is the thickness of the doubler used. The substrate thickness is equal to \( h_p \) for
single-sided repairs and \(2h_p\) for double-sided repairs. Finally, the constants \(h_A\) and \(G_A\) are the adhesive’s thickness and shear modulus.

The effect of thermal residual strains has been included in the Rose Model assuming a correction to the stress magnitude in the substrate structure. By superposition, the stress in the substrate is then given by:

\[
\sigma_0 \approx \left[ \sigma + (\alpha_r - \alpha_p) \Delta T \cdot E_p \cdot S \right] \cdot (1 + S)^{-1}
\]  

(2.5)

where:

- \(\Delta T\) = Difference between operating temperature and curing temperature
- \(\alpha_r\) = Coefficient of thermal expansion of the repair material
- \(\alpha_p\) = Coefficient of thermal expansion of the cracked plate

The previous relation presented for the evaluation of the stress intensity factor is still valid because the thermal residual stress effect is included only in the substrate stress equation.

The use of the Rose model can be very useful when a crack growth prediction needs to be performed rapidly. However, the designer should know its limitations. Among these, the use of a constant stress intensity factor can lead to a crack growth prediction that is far from the real result. Also, stress variation through the thickness and bending moment (present in non-supported one-sided repair) are not included in the model.

2.1.2 Repair Design using Numerical Methods

The numerical methods used in literature for the design of composite bonded repair on isotropic structure are generally based on Finite Element Analysis (FEA). 2D or 3D analyses are performed, depending upon the repair scenario. The following references present various numerical analyses done using most of the time in-house codes [BAKER 78; BAKER 84a; BAKER 84b; BAKER 88; CHUE 94; JONES 81; JONES 84; PARK 92; WANG 98].

Recently, two-dimensional techniques were developed using the Mindlin plate theory [NABOULSI 96; RENAUD 97; SUN 96]. The two-dimensional Mindlin plate element includes a transverse shear deformation capability. It assumes a linear variation of the displacement field along
the plate’s thickness. This method allows the modelling of non-symmetrical repairs as it can include the effect of the secondary bending moment. The differences between the three methods presented in the references are related to the adhesive modelling.

2.1.3 Bending Moment Resulting from Non-Symmetrical Repairs

The influence of a secondary bending moment resulting from the application of an adhesively bonded repair on a cracked structure has first been evaluated by Ratwani [RATWANI 79]. The developed model is based on the assumption that the bending is induced by the force released from the cracked structure to the bonded repair.

As presented by Ratwani, the force released at the crack plane is taken partly by the cracked structure in the form of stress singularities ahead of the crack tips, and the remaining force is transmitted to the repair through the adhesive. His conclusion was that the net internal unbalanced force between the repair and the cracked structure at the crack plane will cause the bending.

Ratwani showed that the stress intensity factor that included the influence of bending moment is given by:

\[
K_p^* = \left(1 + BC\right) K_p
\]  

(2-6)

where \(K_p\) is the stress intensity factor in a cracked adhesively bonded structure, restrained in the out-of-plane direction, with a half crack length \(a\) and subjected to an applied stress \(\sigma\). The factor \((BC)\) for induced bending moment is given by:

\[
BC = \frac{a \ h_p \left(h_p + h_R\right)}{I} \left(1 - \frac{K_p}{K_S}\right) y_{max}
\]  

(2-7)

where:

- \(a\) = Half crack length
- \(h_p\) = Cracked plate thickness
- \(h_R\) = Bonded repair thickness
- \(I\) = Moment of inertia of the section (Plate/Repair Combination)
\[ K_S = \text{SIF of the equivalent non-repaired cracked plate} \]
\[ y_{\text{max}} = \text{Distance of plate unpatched side from section neutral axis} \]

As shown in the previous equation, the bending correction factor should increase indefinitely as the crack length \( a \) increases \(( a \to \infty \text{ & } K_p/K_S \to 0 \)\). Another interesting fact is that the ratio \( K_p/K_S \) is independent of the applied stress. Consequently, the bending correction factor should also be independent of the stress applied on the structure. Moreover, the equation presented above indicates that the bending effects are minimal for a small crack, and are zero for a non-cracked structure (ignoring that \( K_p/K_S \) is not defined for a non-cracked structure).

Wang and Rose [WANG 98] demonstrated that the out-of-plane bending of a one-sided repair is induced by the shifting of the neutral plane away from the mid-surface of the cracked plate, rather than by the force released at the crack plane, as assumed by Ratwani. They also concluded that the secondary bending induced by the load-path eccentricity has a detrimental effect on the efficiency of the bonded reinforcement.

The interest of the Wang and Rose paper [WANG 98] was to provide a theoretical and numerical analysis of one-sided repairs that take into account the out-of-plane effect. A FEA has been carried out to verify the closed form solution proposed by Wang and Rose. The analyses performed were geometrically linear. The effect of nonlinear deformations was not included in that research project.

The analytical solution for the bending correction is presented in reference [WANG 98]. As the bending effect is not the principal subject of the present work, this development has been omitted. It is important to keep in mind that this analytical model has been developed assuming linear behaviour only. In a recent publication, Wang and Rose [WANG 99] recommended the use of a geometrically nonlinear analysis combined with the Reissner plate-bending model, in order to consider the nonlinear effect present in a one-sided bonded repair.

Hart-Smith [HART-SMITH 2000] presented his research on the analysis of bending deformations of one-sided repaired structures using bonded doublers. He performed a comparison between nonlinear and linear predictions using both closed-form and finite element analyses. Using the linear and nonlinear methods, Hart-Smith presented predictions for out-of-plane vertical central displacement
and bending moment for bonded splice and bonded doubler. The nonlinear analyses indicated that the transverse deflections are limited and do not exceed the initial eccentricity in load path (distance between load path and neutral axis of section). It has been found that the linear predictions grossly over-estimate the out-of-plane deflection and induced bending moment at the crack location.

The major conclusions of Hart-Smith’s work on the analysis of the out-of-plane bending effect for one-sided patch repair are as follows:

a) The deflection will not exceed what is needed to align the centroid of the skin/patch combination adjacent to the crack with the line of action of the remotely applied loads.

b) Comparisons have been drawn between nonlinear and linear analyses and the inescapable conclusion reached was that linear analyses for the deflected shape of one-sided repair are quite inappropriate.

c) Any nonlinear techniques will yield plausible predictions. On the other hand, none of the linear methods come close enough to reality to permit their application for one-sided repair problems.

d) The linear analysis results can be less than, equal to, or greater than the nonlinear analysis results, as a function of material properties, geometry, and applied load.

Hart-Smith pointed out that "there is not sufficient awareness of the fact that the nonlinear analysis can be far more than a refinement of a linear solution", and that "sometimes the two results are like night and day." Furthermore, linear analysis of the bending deformations may have led many engineers to false perceptions of the phenomenon, since far more linear analysis are conducted than nonlinear ones.

Hart-Smith did not recommended a particular method to use, as both close-form and FE nonlinear analysis methods have their own advantages. He suggested the use of nonlinear closed-form methods for initial one-sided patch design, and the use of nonlinear FE methods for more complex and detailed analysis.
2.1.4 Thermal Residual Strain Effect

During the curing process of composite doublers, residual strains (and stresses) are generated in the substrate material due to the different Coefficient of Thermal Expansion (CTE) between the composite repair material and the metallic substrate. From a fatigue standpoint, these thermal residual strains can reduce the benefit of the repair by increasing the substrate stress level, since the thermal effect induces tension strains into the metallic substrate. The thermal residual stresses will affect the crack growth essentially by changing the stress ratio \( R \) seen by the crack in the substrate.

**Thermal Residual Stresses in Structure Free to Expand**

The thermal residual stresses in a structure repaired using a bonded doubler were approximated by many authors [BAKER 88; HART-SMITH 99; ROSE 82] as:

\[
\sigma_p \approx E_p \Delta T \frac{(\alpha_p - \alpha_R)}{1 + E_p t_p / E_R t_R}
\]  

(2-8)

This equation provides a good estimate of the thermal residual stresses present in the repaired structure if it is free to expand (during the patch installation process), and is not submitted to out-of-plane displacement. In practice, in the case of thick structures, this relation is only valid for supported structures or for double-sided repairs, as the stress distribution in the substrate will vary through the thickness.

The equation above can be developed as follows. During the cool down process, the patch/plate assembly shrinks as demonstrated in Figure 2.1.
Figure 2.1: Shrinkage During Cooling Down Process

where:
\( \varepsilon_R \) = Deformation of the patch material when not constrained = \( \alpha_R \Delta T \)
\( \varepsilon_p \) = Deformation of the metallic substrate when not constrained = \( \alpha_p \Delta T \)
\( \varepsilon_T \) = Deformation of the patch/plate assembly

At the equilibrium point, the load in the patch keeping the plate in tension is the same as the load in the plate keeping the patch in compression. This can be written as:

\[
\sigma_R t_R + \sigma_p t_p = 0 \quad (2-9)
\]

\[
\Rightarrow (\varepsilon_R - \varepsilon_T)E_R t_R + (\varepsilon_p - \varepsilon_T)E_p t_p = 0 \quad (2-10)
\]

Since \( \varepsilon_R = \alpha_R \Delta T \) & \( \varepsilon_p = \alpha_p \Delta T \), equation (2-10) becomes:

\[
(\alpha_R \Delta T - \varepsilon_T)E_R t_R + (\alpha_p \Delta T - \varepsilon_T)E_p t_p = 0 \quad (2-11)
\]

\[
\Rightarrow \varepsilon_T = \frac{\alpha_R E_R t_R + \alpha_p E_p t_p}{E_R t_R + E_p t_p} \Delta T \quad (2-12)
\]
As the stress in the metallic substrate is given by \( \sigma_p = (\varepsilon_p - \varepsilon_T)E_p \), it can be found that:

\[
\sigma_p = \left( \alpha_p \Delta T - \frac{\alpha_R E_R t_R + \alpha_p E_p t_p}{E_R t_R + E_p t_p} \right) E_p
\]

(2-13)

After some manipulations:

\[
\sigma_p = E_p \Delta T \frac{(\alpha_p - \alpha_R)}{1 + E_p t_p / E_R t_R}
\]

(2-14)

Equation (2-14) was presented by Baker [BAKER 88] and was proposed in a methodology for the determination of the thermal residual stress intensity factor \( K_T \). Baker suggested the use of the following equation:

\[
K_T \equiv \sigma_T \sqrt{\pi a}
\]

(2-15)

where \( \sigma_T \) is the thermal residual stress (as given by the preceding relation). Note that this equation is of the same form as the one for the SIF of a through crack in an infinite dimension plate. Baker verified the equation (2-15) with experimentally measured stress intensity factors, and suggested the use of this equation when cracks are small.

Rose [ROSE 82] also considered the effect of thermal residual stresses as mentioned in the development of the well-known Rose Model. The Rose model assumes that:

\[
K \approx \sigma_0 \sqrt{\Omega}
\]

(2-16)

where:

\[
\sigma_0 \approx \left[ \sigma + (\alpha_R - \alpha_p) \Delta T \cdot E_p S \right] \sqrt{1 + S}
\]

(2-17)

\[
S \ (\text{Patch to Panel Stiffness Ratio}) = \frac{t_R E_R}{t_p E_p}
\]

(2-18)
The contribution of the temperature variation to the stress in the metallic substrate is then:

$$\sigma_{T,R} = (\alpha_R - \alpha_p) \Delta T \cdot E_p t_R E_R / \left( t_p E_p + t_R E_R \right)$$  \hspace{1cm} (2-19)

$$\Rightarrow \sigma_p = E_p \Delta T \frac{(\alpha_p - \alpha_R)}{1 + E_p t_p / E_R t_R} \hspace{1cm} (2-20)$$

It is important to note that this relation is the same as the one proposed by Baker (equation (2-14)). Rose also suggested that the stress intensity factor due to the thermal residual stress increases as the crack grows to reach a constant asymptotic value. The Rose Model calculates this maximum value, and consequently is not a function of the crack length.

**Thermal Residual Stresses in Structure Not Free to Expand**

The thermal residual stresses and strains will vary substantially between repair specimens that are heated uniformly without any restraint, and real repairs submitted to significant restraints. The thermal residual stresses evaluation using a “not restrained” boundary condition will lead to conservative results, but can also make the difference between accepting or rejecting a certain repair design, from a fatigue point of view. An accurate prediction of the thermal residual stresses will be required for the real life repair in order to obtain an accurate fatigue crack growth prediction.

The influence of constraints induced by a surrounding structure has been evaluated in a previous Martec Limited research project [ROBERGE 98]. A two step approach was proposed to determine the thermal residual strains induced in the substrate material. First, a thermal analysis is conducted with FE methods for an unpatched configuration in order to obtain the thermal strain in the substrate structure. Then, a second thermal analysis is conducted, but this time with the presence of the bonded repair. Using these two analyses, the equation (2-21) is proposed for the thermal residual strain evaluation. Knowing the thermal residual strain in the substrate, the thermal residual stress can easily be derived.

$$\text{Strain}_{\text{Thermal Residual}} = \text{Strain}_{\text{Thermal Patch}} - \text{Strain}_{\text{Thermal Unpatch}} \hspace{1cm} (2-21)$$
where:

\[
\text{Strain}_{\text{Thermal Patch}} = \text{Thermal strain in substrate for a patched configuration}
\]

\[
\text{Strain}_{\text{Thermal Unpatch}} = \text{Thermal strain in substrate for an unpatched configuration}
\]

The surrounding structure effect in the evaluation of the thermal residual stress under the bonded repair has also been evaluated using an effective coefficient of expansion \( \alpha_R' \) [BAKER 88; JONES 80]. Both studies presented analytical expressions of \( \alpha_R' \) based on an uncracked circular plate reinforced with a concentric circular patch. The effective coefficient of expansion was principally dependent of the “patch to panel radius ratio”, and the support conditions at the edge of the plate (solutions for free and fixed edges are presented).

**Additional Thermal Residual Stress Models**

Recently, Albat [ALBAT 98] proposed modified models to evaluate the effect of thermal residual stresses based on the work of Hart-Smith and Rose. Relations were presented to account for an edge crack repaired with an anisotropic patch, and to include the effect of a disbond at crack vicinity.

### 2.2 Crack Growth Propagation Models

For the last forty years, many researchers have probed the fatigue crack propagation process. From these investigations, several empirical and theoretical crack growth models were suggested. Most of them are of the form of equation (2-22) showing that the crack growth rate is a function of the stress applied on the cracked structure and of the half crack length \( a \) (or total crack length for edge crack, as usually accepted in literature):

\[
\frac{da}{dN} = f(s, a)
\]  

(2-22)

In the next sections, the commonly used crack growth models are presented. Their differences and deficiencies are also given in order to highlight the progress observed in the fatigue crack growth predictions.
2.2.1 Paris Equation

One of the most simple and widely used crack propagation model is the Paris equation, developed by Paris and Erdogan [PARIS 63], such as:

\[
\frac{da}{dN} = A \Delta K^n
\]  \hspace{1cm} (2-23)

where:

\[
\frac{da}{dN} = \text{Fatigue crack growth rate}
\]

\[
\Delta K = \text{Stress intensity factor range (} \Delta K = K_{\text{max}} - K_{\text{min}} \text{)}
\]

\[
A = \frac{da}{dN} \text{ when } \Delta K = 1 \text{ (material constant)}
\]

\[
m = \text{Paris Exponent (material constant)}
\]

Knowing material constants \(A\) and \(m\), a crack growth prediction can be performed for a specific problem. As the material constants are dependent of the environment, temperature and stress ratio, the Paris equation should only be used for problems occurring in the same conditions as the ones in which the material constants were derived. This equation is simple to use and can provide a first order crack growth prediction.

2.2.2 Walker Equation

The Walker equation [WALKER 70] can be seen as an enhancement of the Paris equation and account for the effect of the Stress Ratio \(R\). It has been observed that an increase of the mean stress level, for the same \(\Delta K\), results in a higher crack propagation rate. The Walker equation is given by:

\[
\frac{da}{dN} = C \left[ \Delta K \left(1 - R \right)^{(m-1)} \right]^n
\]  \hspace{1cm} (2-24)

where:

\[
C = \frac{da}{dN} \text{ when } R=0 \text{ and } \Delta K = 1 \text{ (material constant)}
\]
\[ n = \text{Paris exponent (material constant)} \]
\[ m = \text{Walker exponent (material constant)} \]
\[ R = \text{Stress ratio (} s_{\text{min}} / s_{\text{max}} \text{)} \]

It can be noted that for a Walker exponent value of \( m = 1 \), the Walker equation becomes the Paris equation. The appearance of means to take into account the Stress Ratio was required for crack growth prediction problems submitted to non-constant amplitude loading. The Walker exponent essentially controls the shift in crack growth rate data.

2.2.3 Forman Equation

The Forman equation [FORMAN 67], named after Dr. Royce Forman, was an improvement to the Walker equation that included means to account for high \( \Delta K \) levels. Effectively, as \( K_{\text{max}} \) approaches \( K_c \) (at \( \Delta K = K_c - K_{\text{min}} \)), local fracture is observed which leads to an acceleration of crack growth. This phenomenon corresponds to the third and last regime of crack growth as shown in the Figure 2.2, and is followed by the failure of the cracked component.

![Fatigue Crack Growth Response](Figure 2.2: Fatigue Crack Growth Response)
The formulation of the Forman equation is shown below:

\[
\frac{da}{dN} = \frac{C \Delta K^n}{(1 - R) K_C - \Delta K}
\]

(2-25)

where:

\[C = \frac{\frac{da}{dN} \cdot (K_C - 1)}{\Delta K} \text{ when } R=0 \text{ and } \Delta K=1 \text{ (material constant)}\]

\[n = \text{Paris exponent (material constant)}\]

\[R = \text{Stress ratio } \left(\frac{s_{\text{min}}}{s_{\text{max}}}\right)\]

\[K_C = \text{Fracture toughness}\]

As specified in the AFGROW user’s guide [HARTER 99], the weakness of the Forman equation lies in a lack of flexibility in modelling data shifting as a function of the stress ratio \(R\). Effectively, there is no parameter to directly adjust the \(R\) shift. The amount of shifting is only controlled by the fracture toughness of a given material.

2.2.4 Elber Crack Growth Model

Elber [Elber 71] modified the Paris equation by replacing the stress intensity range by an effective Stress Intensity Factor (SIF) range based on crack closure measurements. He introduced the concept of crack closure for the first time in 1971, proposing a new explanation of stress ratio \(R\) effect on crack growth rate.

From fatigue tests performed at positive stress ratio, Elber observed that the crack closed during the unloading, before the value of minimum stress was reached. He noted also that the crack opened again only when a certain stress was reached during the load application. As a function of the stress ratio, Elber empirically derived the effective SIF relation that include the crack closure effects as follows:

\[\Delta K_{\text{eff}} = U \cdot \Delta K\]

(2-26)
where:

$$U = a + \beta \cdot R$$  \hspace{1cm} (2-27)

The variables $a$ and $\beta$ are constant for a given material. Introducing the effective SIF relation into the Paris equation (previously presented), the Elber equation is obtained:

$$\frac{da}{dN} = C \left(\Delta K_{\text{eff}}\right)^n$$  \hspace{1cm} (2-28)

2.2.5 NASGRO Equation

The NASGRO equation is the result of the combined work of Forman and Newman of NASA, Shivakumar of Lockheed Martin, de Koning of NLR and Henriksen of ESA. It was first published by Forman and Mettu [FORMAN 92], and was later integrated in NASGRO Version 3.0. This model takes into account the stress ratio ($R$) effect, a crack growth acceleration for high $\Delta K$ levels, and a retardation effect near threshold (first crack growth regime, as shown previously in Figure 2.2). Therefore, the three crack growth regimes are included in the NASGRO equation, presented below:

$$\frac{da}{dN} = C \left[ \left( \frac{1-f}{1-R} \right) \Delta K \right]^n \left( \frac{1 - \frac{\Delta K_{\text{th}}}{\Delta K}}{1 - \frac{K_{\text{max}}}{K_{\text{crit}}}} \right)^p$$  \hspace{1cm} (2-29)

The constants $C$, $n$, $p$ and $q$ are empirically derived. It should be noted that $n$ corresponds to the Paris exponent, but on the other hand $C$ is not the Paris constant. The NASGRO equation includes a crack opening function $f$ that incorporates the effect of $R$, derived by analyses for plasticity-induced crack closure [Newman 84]:

19
\[ f = \frac{K_{ep}}{K_{max}} = \begin{cases} \max(R, A_0 + A_1 R + A_2 R^2 + A_3 R^3) & R \geq 0 \\ A_0 + A_1 R & -2 \leq R < 0 \\ A_0 - 2 A_1 & R < -2 \end{cases} \] (2-30)

The coefficients are given by:

\[ A_0 = \left( 0.825 - 0.34\alpha + 0.05\alpha^2 \right) \left[ \cos \left( \frac{\pi}{2} \frac{S_{\text{max}}}{\sigma_0} \right) \right]^{\frac{1}{a}} \] (2-31)

\[ A_1 = \left( 0.415 - 0.071\alpha \right) \frac{S_{\text{max}}}{\sigma_0} \] (2-32)

\[ A_2 = 1 - A_0 - A_1 - A_3 \] (2-33)

\[ A_3 = 2 A_0 + A_1 - 1 \] (2-34)

In the previous equations, \( \alpha \) is the plane stress/strain constraint factor, and \( S_{\text{max}}/\sigma_0 \) is the ratio of the maximum applied stress to the material flow stress. These values are provided in the NASGRO material database for over 300 materials and are fitted parameters for the crack opening function \( f \).

The threshold stress intensity factor range, \( \Delta K_{ih} \), is approximated by the following empirical equation:

\[ \Delta K_{ih} = \Delta K_0 \left( \frac{a}{a + a_0} \right)^{\frac{1}{2}} \left( \frac{1 - f}{(1 - A_0)(1 - R)} \right)^{C_{ih}} \] (2-35)

where:

- \( \Delta K_0 = \) Threshold stress intensity range at \( R = 0 \)
- \( a = \) Crack length
- \( a_0 = \) Intrinsic crack length (0.0015 inch)
- \( f = \) Newman closure function
- \( C_{ih} = \) Threshold coefficient (empirical constant)
The values for $\Delta K_0$ and $C_{sk}$ are provided by the NASGRO material database. The NASGRO equation accounts for the thickness effect by the use of the critical stress intensity factor, $K_{crti}$:

\[
\frac{K_{crti}}{K_{lc}} = 1 + B_k e^{ -\left( \frac{A_k t}{t_0} \right)^2 }
\]  \hspace{1cm} (2-36)

where:

$K_{lc}$ = Plane strain fracture toughness

$A_k$ = Fit parameter

$B_k$ = Fit parameter

$t$ = Thickness of cracked structure

$t_0$ = Reference thickness (plane strain condition)

The plane strain condition $t_0$ is given by:

\[
t_0 = 2.5 \left( \frac{K_{lc}}{\sigma_{ys}} \right)^2
\]  \hspace{1cm} (2-37)

The values for $A_k$ and $B_k$ are provided by the NASGRO material database.

2.2.6 Harter T-Method

The Harter T-Method was formerly known as the “Point-by-Point Walker Shift Method” developed in 1983 by James A. Harter [HARTER 99]. This method essentially presents a way to interpolate and extrapolate crack growth data using a limited amount of tabular crack-growth rate test data.

Starting with existing crack-growth data, the Harter T-Method utilizes the Walker equation on a point-by-point basis to extrapolate and interpolate data for any $R$ value. Hence, it calculates crack growth rate shifting as a function of stress ratio. It is simply a way to interpolate and extrapolate data in log-log scale by using an exponential form.
From the Walker equation:

$$\frac{da}{dN} = C \left[ \Delta K \left( 1 - R \right)^{(m-1)} \right]^n$$  \hspace{1cm} (2-38)

the following relation is observed, for a given crack growth rate:

$$\Delta K_1 \left( 1 - R_1 \right)^{(m-1)} = \Delta K_2 \left( 1 - R_2 \right)^{(m-1)}$$  \hspace{1cm} (2-39)

This equality can be rewritten as:

$$m = 1 + \left[ \log_{10} \left( \frac{\Delta K_1}{\Delta K_2} \right) / \log_{10} \left( \frac{1 - R_2}{1 - R_1} \right) \right]$$  \hspace{1cm} (2-40)

The $m$ value is non-dimensional and has no real physical meaning. It is simply a mathematical means of controlling the shift of the crack growth rate data as a function of stress ratio ($R$).

The Harter T-Method needs a minimum of two sets of experimental data obtained for two different stress ratios. It is necessary to input the stress intensity data ($\Delta K$) at each $R$ at equal crack growth rate values. The method will then calculate the $m$ constants for all $da/dN$ values.

The Harter T-Method uses the $\Delta K$ for $R=0$ and $m$ at all crack growth rates values available to recreate the $da/dN - \Delta K$ curve for any $R$ desired using the following relation (valid for a given $da/dN$):

$$\Delta K = \Delta K_{R=0} \left( 1 - R \right)^{(1-m)}$$  \hspace{1cm} (2-41)

For a given $R$, the Harter T-Method, will calculate a $da/dN - \Delta K$ curve until the $\Delta K$ value exceeds the current $\Delta K$ value of interest. Then, a logarithmic interpolation is performed between the last two points in the $da/dN - \Delta K$ curve to give the current crack growth rate.
It is usually difficult to obtain crack growth rate data over sufficient crack growth range and $R$-values to use simple interpolation methods to accurately model material behaviour. The Harter T-Method comes in hand to solve this problem since it requires less experimental data to represent well the material behaviour.

2.3 Research on Thick Structure Repairs

A special attention has been accorded to the work done for composite bonded repairs on thick structures as this corresponds to the type of repairs designed and installed by Martec Limited. Also, crack growth data was required to validate a new methodology of analysis for thick structures repaired using bonded composite doublers.

The first composite repairs of thick cracked aircraft structures were performed by the RAAF [BAKER 78; BAKER 84b; JONES 84]. The repair, a boron/epoxy patch, was designed for a cracked area of landing gear wheels of the Macchi and Mirage III. The patches were laid up in a steel mould to match the profile of the metallic structures. The wheels were made of a magnesium alloy. In parallel to these repairs, an experimental study and a numerical analysis were done. The test specimens consisting of rectangular blocs with a semi-elliptic crack were repaired with boron/epoxy patches, and were tested under a unidirectional loading. A finite element analysis was also performed to predict the stress intensity factor of the repaired specimen.

Ten years ago, DERA undertook a research program to assess the performance of carbon/epoxy and boron/epoxy bonded repairs to thick aluminum structures [POOLE 91; POOLE 94]. They performed fatigue tests using 2024-T3 aluminum coupons, 12.4 mm thick, containing elliptical surface cracks and through cracks. The patched and unpatched specimens were subjected to FALSTAFF loading or constant amplitude loading.

Recently, the Air Force Institute of Technology (AFIT) also undertook a fatigue test using rectangular coupons with centre through cracks [SCHUBBE 97; SCHUBBE 99]. These coupons were made of 2024-T3 aluminum alloy, and were submitted to a constant amplitude loading. The AFIT investigated the effects of coupon thickness, and patch size on fatigue crack growth rate. Only one-sided repairs were used, and they consisted of a unidirectional boron/epoxy doubler.
3.0 PROJECT METHODOLOGY

The following chapter presents the methodology that had been initially defined in the project statement of work, and explains how the research project was conducted. The different project parts are as follows:

a) Literature Review;
b) Collation of Existing Crack Initiation and Crack Growth Data;
c) Evaluation of Existing CI and CG Analysis Tools;
d) Identification of Deficiencies;
e) Development of New Methodology; and,
f) New Methodology Validation.

3.1 Literature Review

The pertinent papers dating from 1993 to recent years have been collected using the CISTI search engine (Canada Institute for Scientific and Technical Information).

The papers related to crack initiation and crack growth estimation techniques for thick metallic structures with or without a bonded composite repair were reviewed. Papers on composite bonded repair of aircraft structures were also collected for general information.

3.2 Collation of Existing Crack Initiation and Crack Growth Data

The literature review presented limited experimental results to allow the validation of a new methodology of analysis for thick structures. Complete crack growth curves were required to be used as project test cases.

The literature review allowed the identification of the main players in composite repair design. These researchers have been contacted in order to find pertinent crack initiation and crack growth data for thick structures repaired with a bonded composite doubler.
3.3 Evaluation of Existing CI and CG Analysis Tools

After the test cases data were defined, the evaluation of the available crack initiation and crack growth prediction tools began. The analysis software packages chosen for the evaluation are listed below and will be described in the following chapter.

a) CI89/CG90 (Boeing St-Louis);
b) AFGROW (Air Force Research Laboratory);
c) FRANC2D/L (Cornell Fracture Group & Kansas State University);
d) FRANC3D (Cornell Fracture Group); and,
e) NISA/ENDURE (EMRC).

The software packages presented above are representative in terms of capability of the available crack initiation and crack growth software on the market. Among these, there are DOS based programs, Windows NT programs, and complex numerical analysis tools based on finite element and boundary element methods.

3.4 Identification of Deficiencies

After the tool learning, their characteristics were identified in order to highlight the strengths and weaknesses of all CI/CG tools. Different criteria have been evaluated, such as user interface features, crack growth models available, type of materials and loading that can be used, and time required to perform an analysis. An evaluation matrix has been derived to perform this evaluation.

It has been found that some software packages were good only for fracture mechanics analysis, or to perform crack growth predictions. Particular capabilities have been also observed (nonlinear analysis, thermal loading, orthotropic material, etc.).

3.5 Development of New Methodology

After the tool familiarization and the identification of their deficiencies, the development of a new methodology of analysis was undertaken.
The improved methodology allows the use of a combination of the previous software packages to find a compromise between analysis complexity and accuracy of the fatigue life prediction. The developed methodology also included the additional effect of thermal residual stresses due to adhesive curing, or the secondary bending effect for a single-sided repair.

3.6 New Methodology Validation

The last project portion consisted in the validation of the new methodology of analysis developed for thick cracked structures repaired using bonded composite doublers. The crack growth predictions calculated with the new methodology of analysis have been compared to the conventional method predictions, and to the experimental data for the test cases chosen.
4.0 CRACK INITIATION AND CRACK GROWTH TOOLS

4.1 CI89 and CG90

The crack initiation CI89 code and crack growth CG90 code developed by Boeing St-Louis are widely used on the CF-18 for structural life prediction. When the crack initiation code predicts a failure, it is assumed that a flaw of 0.25 mm (0.01 inch) has developed in the structure. To complete the fatigue life analysis, the remaining time from crack initiation to failure is calculated using CG90 with an initial flaw length of 0.25 mm. The total life of the structure can therefore be estimated.

4.1.1 CI89

CI89 [KLOHR 90] performs fatigue crack initiation analysis using a line-by-line load spectrum. It employs the cumulative damage crack initiation theory, which accounts for prior load history in the determination of fatigue damage. Neuber’s rule along with the cyclic stress-strain characteristics of the material is used to determine the stress and strain at a root of a notch.

The damage resulting from the spectrum application is evaluated using the strain-life curve of the material. The numbers of cycles for several strain amplitudes are given in the material file using a tabular representation. Crack initiation life for various stress levels is determined by the program where the crack initiation life is defined as the number of cycles required to develop a 0.25 mm crack.

The computer program C_FILTER89 is used as a pre-processor to eliminate intermediate load points in the fatigue spectrum and to produce a spectrum in a format compatible with CI89. The filtering routine removes all loads that are not peaks or valleys. Additionally, the program has the ability to truncate the output peak-valley spectrum.

4.1.2 CG90

CG90 [MCAIR 91] is a program which calculates crack growth life from some given initial flaw size to failure. Input part dimensions and flaw geometry are entered interactively in this text based program. Loading history and material properties are specified by data files.
The user must choose from available geometries to perform a crack growth fatigue life analysis. Several geometries are available, such as: surface flaw in a plate; centre crack in a plate; through crack at a hole, and; corner crack at a hole. The stress intensity factor due to the residual stress may be superimposed on the stress intensity factor resulting from applied stress.

4.2 AFGROW

The crack growth life prediction program AFGROW (Air Force GROW) [HARTER 99], is the latest version of a program that was previously known as MODGRO. It is the result of over 15 years of work, mainly funded by the U.S. Navy and U.S. Air Force. The AFGROW graphical user interface is presented in Figure 4.1.

![AFGROW Graphical User Interface](image)

**Figure 4.1: AFGROW Windows Graphical User Interface**

4.2.1 AFGROW Model Geometry

The standard cracked geometries available in AFGROW consist of several models for which closed form or tabular stress intensity factor solutions are available. Solutions for several geometries are built into the code, hence the user only needs to define the geometrical parameters of the problem.
In addition to the available solutions, the users can input their own solutions through the “User-Defined Beta” module. The user defined stress intensity solutions are introduced in the form of beta factors at various crack lengths. The beta factors ($\beta$) are defined as follows:

$$\beta = \frac{K}{\sigma \sqrt{\pi a}}$$  \hspace{1cm} (4-1)

4.2.2 Crack Initiation Prediction

The initiation part of AFGROW has been designed to work in conjunction with the rest of the software as an additional capability. When used, it will provide an initiation prediction (in cycles) which will be added to the cycles calculated for subsequent crack growth life.

The fatigue initiation life is calculated using Neuber’s Rule, the Cycling Stress-Strain Equation and the Strain Life Equation. The two latest are curve fits to actual fatigue test data, and the equation parameters are available for numerous aerospace materials. It should be noted that the crack initiation method used in AFGROW is the same one as used in CI89. The main difference resides in the fact that the life is evaluated with a strain life equation, instead of a strain life curve generated from a tabular format.

4.2.3 Crack Growth Prediction Models

A total of five fatigue life prediction models are available in AFGROW:

a) Walker Equation;
b) Forman Equation;
c) NASGRO Equation;
d) Harter T-Method; and,
e) Tabular Lookup.
These life prediction models are described in detail in the Section 2.2, except for the Tabular Lookup model. This model uses the Harter T-Method, and asks the user to enter the $\frac{da}{dN}$ vs. $\Delta K$ data manually for at least two stress ratios ($R$).

4.2.4 Additional Features

An important option available is the consideration of residual stresses. Using a Gaussian integration method or a weight function method, AFGROW will calculate the residual stress intensity factors with the user defined residual stress. The user can also manually input the residual stress intensity factors as a function of the crack length. This option is useful when considering the thermal residual stress resulting from the composite patch curing process.

There are three retardation models available in AFGROW: Generalized Willenborg, Closure, and Wheeler models. Each model has an adjustable parameter that is used to tune the model to fit actual test data obtained from coupon testing.

4.3 FRANC2D/L

FRANC2D/L [SWENSON 96] is an extension of FRANC2D originally developed by Cornell University for the analysis of crack growth. The major difference between the two software packages is the layered capability of FRANC2D/L, which allows the user to model riveted and adhesively bonded structures such as lap joints and bonded repairs. Kansas State University has been funded by NASA, as part of the Aging Aircraft Program, to extend the code to simulate crack growth in layered structures.

The software allows the performance of linear elastic fracture mechanics (LEFM) analysis with automatic remeshing as the crack grows. Only two dimensional structures can be modelled with FRANC2D/L. The FRANC2D/L user interaction window is presented in Figure 4.2 showing a model for the analysis of a centre through crack in a rectangular plate.
Figure 4.2: FRANC2D/L User Interaction Window

4.3.1 Geometry Construction

Before performing a FRANC2D/L analysis, the CASCA program must be used to create the model geometry [SWENSON 97]. It is a code for the modelling of two-dimensional finite element meshes.

Any two-dimensional geometry can be modelled, as long as it is flat. For layered structures, each layer is created individually with CASCA and then assembled using the “Castofrane” translator supplied with FRANC2D/L.
4.3.2 Finite Element Model Generation

The available elements in CASCA are six-node triangles and eight-node quadrilaterals with quadratic shape functions. FRANC2D/L has a pre-processing module, which defines the remaining information required for the FE analysis: the materials, loads, and boundary conditions.

Isotropic and orthotropic materials are available for bonded repairs and the substrate material. The joints between the layers can be of two types: fasteners or adhesive. The fasteners are applied at model nodes and require a stiffness value. The adhesive is applied between the layers to connect, and requires only a shear modulus and a thickness value.

The available boundary conditions and loading are: node constraint in the X or Y direction, point or edge displacement, point load, distributed load, and thermal load.

4.3.3 Fracture Mechanics Analysis

The fracture module of FRANC2D/L uses two-dimensional linear elastic fracture mechanics (LEFM) concepts. The stress intensity factors, which govern the fracture process in the LEFM context, are calculated using the displacement correlation or modified crack closure techniques.

Before performing a fracture mechanics analysis, a crack needs to be added to the model. The crack is introduced using six-node triangular elements, and the side nodes of crack tip elements are shifted to quarter-point locations. This technique has the advantage of incorporating the crack tip stress singularity in the solution, and is commonly used in fracture mechanics analysis.

During an automatic crack propagation analysis, the meshing must be modified at each propagation step to reflect the current crack configuration. The remeshing strategy adopted in FRANC2D/L deletes the elements in the vicinity of the crack tip, moves the crack tip, and then inserts a new mesh to connect the new crack to the existing mesh.

The crack will propagate in the direction predicted by one of three propagation theories implemented in FRANC2D/L. The theory adopted in the present research project is the default propagation theory.
the sigma theta max theory. This approach minimizes the mode II stress intensity during propagation. For each propagation step, the crack will grow by a constant user defined length.

4.3.4 Crack Growth Prediction

FRANC2D/L has only one crack growth model: the Paris model. Within FRANC2D/L, only mode I values of the stress intensity ranges are used for the fatigue life prediction.

The Paris model is a simple way to obtain a fatigue life prediction but is often not appropriate for some types of analysis. To perform a more complex analysis, it is suggested to extract $\Delta K$ vs. $a$ data computed by FRANC2D/L, and to use this information with a more sophisticated crack growth model.

4.4 FRANC3D

FRANC3D [CFG 98a] is a FRacture ANalysis Code for the simulation of arbitrary non-planar 3D crack growth. The code was developed by the Cornell Fracture Group at Cornell University (CFG). Crack growth simulation is the main feature of FRANC3D, along with capabilities for the modelling of multiple, non-planar, arbitrary shaped cracks which can be surface cracks, internal cracks or cracks in material interfaces. Crack geometry is not restricted to planar surfaces and crack fronts can take any geometrical shape. Stress intensity factors along the crack fronts are determined by numerical results. The 3D solid section of FRANC3D uses the Boundary Element Method (BEM).
4.4.1 Geometry Construction

Before performing a FRANC3D analysis, the geometry to analyze has to be constructed using the Object Solid Modeller (OSM) software [CFG 98c]. The OSM graphical user interface is similar to the FRANC3D user interaction window presented in Figure 4.3.

OSM allows importation of several FEM geometry files such as ANSYS, NASTRAN, PATRAN and ABAQUS files. The imported model must be solid, and must form a closed region. OSM will extract the outer element faces in order to build the solid geometry.

After importation, some rebuilding is sometimes needed for the surfaces that constitute the boundaries of the solid. For example, if an extremely refined FE model is imported, each individual outer surface generated will need at least one element per surface for the meshing to be performed in FRANC3D. Given that the time required by the BEM to solve an analysis is highly sensitive to the
number of elements used, a model generated from a FE refined model can become impossible to solve with limited computer resources.

Once a closed 3D solid has been built with OSM, a FRANC3D input geometry file can be created. The OSM program is only used to build the geometry's surfaces.

4.4.2 Boundary Element Model Generation

FRANC3D is used to create a mesh as well as to specify the materials, loads, and boundary conditions. FRANC3D has options to subdivide the surfaces of a model, but cannot perform changes to the model's geometry (generated by OSM). The user should then make sure that the model built with OSM is correct before beginning the meshing.

Before the model can be meshed, the edges must be subdivided into line segments. The nodes from edge subdivisions subsequently become mesh nodes. The meshing can be done step-by-step using the options and the meshing algorithm, or otherwise using the automatic meshing option. An "arbitrary region surface meshing" option is also available, which allows the user to adjust the meshing transition capabilities, and to specify manually the position of some inside nodes as required. Only triangular and quadrilateral elements are available, with a choice of first or second order elements.

The only material available in the FRANC3D version 1.15 is isotropic. The elastic modulus, the Poisson's ratio, the density, and the fracture toughness need to be specified. The boundary conditions available are: displacements, tractions and pressures. These conditions are attached to the topological faces, edges and vertices of the model.

4.4.3 Fracture Mechanics Analysis

The current technique implemented in FRANC3D for the propagation of 3D cracks first requires the calculation of the Stress Intensity Factors (SIFs) along the crack front. The SIFs are generated using the displacement correlation method. The propagation directions are then evaluated at discrete points along the crack front using 2D plane strain equations.
Once the SIFs have been calculated along the crack front and the propagation direction is found, two inputs are required to determine the new crack front: a maximum growth increment, and a Paris-type exponent. The equation used to determine the position of the nodes along the new crack front was derived using the Paris relation. It is given by:

\[
\Delta a_i = \Delta a_{\text{max}} \left( \frac{\Delta K_i}{\Delta K_{\text{max}}} \right)^n
\]  

(4-2)

where:
- \(\Delta a_i\) = Crack increment at a certain crack front node
- \(\Delta a_{\text{max}}\) = Maximum crack increment, as defined by the user
- \(\Delta K_i\) = SIF variation calculated at a certain crack front node
- \(\Delta K_{\text{max}}\) = Maximum SIF variation calculated along crack front
- \(n\) = Paris exponent

Once the new crack front points are projected, they are fitted with a polynomial curve in order to get an algebraic crack front description. The local mesh is then rebuilt manually or using the automatic module, and a LEFM analysis is performed to find the new SIFs along the crack front. The propagation methodology is summarized in Figure 4.4.

Figure 4.4: Crack Propagation in FRANC3D
4.4.4 Crack Growth Prediction

There are three crack growth models available in FRANC3D: the Paris model, the NASGRO equation, and a hyperbolic sinusoidal function model. The Paris and NASGRO equations were presented in detail in the background section. The hyperbolic sine model has four empirical constants (A, B, C, and D) and is given by:

\[ \log\left(\frac{da}{dN}\right) = A \sinh\left(B(\log(\Delta K) + C)\right) + D \] (4-3)

4.5 NISA/ENDURE

ENDURE is the fatigue analysis module supplied with the EMRC family of programs [EMRC 98a]. Based on a finite element analysis performed with DISPLAY III as pre-processor (shown in Figure 4.5) and NISA II as solver, ENDURE is used to perform three types of analyses:

a) Crack Initiation Analysis;

b) Crack Propagation Analysis; and,

c) Fracture Mechanics Analysis.
4.5.1 Geometry Construction & FEM Generation

DISPLAY III is the pre and post-processor supplied with the EMRC family of programs [EMRC 98b]. It is used to build the geometry and the meshing as well as to specify the materials, loading, and the boundary conditions.

While DISPLAY III is used for modelling, NISA II is used as the solver. NISA was released in 1974 and was renamed as NISA II in 1986. It has been continually updated and modified to incorporate new capabilities along with the most recent technology in the finite element analysis field.

The basic NISA II package can perform linear and nonlinear static analyses, and supports a wide range of elements, material types, and boundary conditions. The following elements are available:
shell, membrane, solid, beam, spring, laminate composite, gap, cable, and many others. Some of them can be of first or second order. The second order elements will not only have nodes at each corner, but also in the middle of element edges, as shown in Figure 4.6 (for shell elements). Second order elements require more computation time, but this leads to an appreciable improvement of result accuracy.

![Figure 4.6: NISA II Shell Elements](image)

Isotropic and orthotropic materials are available for static linear and nonlinear analyses and additional types such as hyperelastic and elastoplastic can be used for material nonlinear analyses. It should be noted that, with ENDURE, only linear static analyses are supported when performing a fracture mechanics analysis.

The boundary conditions and loading available are: specified displacements, concentrated forces, pressure loads, gravity loads and thermal loads. Rigid links and kinematics constraints can also be included into the analysis.

4.5.2 Initiation Analysis

For the crack initiation analysis, ENDURE uses the principal stresses or the Von-Mises stresses calculated with NISA II. Of course, the geometry to analyze is modelled without considering the presence of any crack. The crack initiation analysis may be performed at given nodes, at highest stress location, or at user defined locations.
The stress-life (S-N) or strain-life (e-N) correlation can be used to perform a crack initiation analysis. ENDURE will then calculate the number of cycles required to initiate a detectable crack in the structure. A propagation analysis should follow to complete the fatigue life analysis of the structure.

4.5.3 Propagation Analysis

There are two ways to perform a crack propagation analysis with ENDURE. First, the user can use a non-cracked FE model generated with DISPLAY III (as for an initiation analysis), and perform a NISA II analysis. ENDURE will read the stresses at one node specified by the user, and will assume a crack at this location. Thereafter, the user will have to specify a type of K-Calibration to be used. The user has the choice of 15 standard configurations such as: keyhole specimen; through crack with corrections; edge crack in finite and infinite width plate; compact tension specimen, etc. ENDURE will use the standard configuration selected by the user to calculate the $K$ vs. $a$ values.

The second way to perform a propagation analysis is to provide manually a table of $K$ vs. $a$ values. The $K$ vs. $a$ values have to be specified for a unitary stress. This is similar to the use of beta factors defined in AFGROW.

When $K$ vs. $a$ values are determined (using either standard configurations or a table provided by hand), a life approximation can be computed with one of the following crack growth prediction models:

- a) PARIS Equation;
- b) FORMAN Equation;
- c) COLLIPRIEST Equation;
- d) WALKER Equation; and,
- e) ELBER Model.

A crack growth prediction can be obtained in terms of the number of cycles required to grow a crack from an initial length to a final specified length. A final crack length can also be found for some given initial crack length and number of cycles.
ENDURE does not have the remeshing capabilities of FRANC3D as the crack grows. For analyses it is assumed that the crack stays in the same plane, and keeps the same shape as the one specified in the K-Calibration section. ENDURE does not have the capability to self propagate a 3D crack under a complex 3D loading. However, ENDURE can perform crack growth prediction and fracture mechanics analysis for a 3D structure, which includes a composite doubler made of orthotropic material.

4.5.4 Fracture Mechanics Analysis

The ENDURE fracture mechanics module uses, as the two previous modules, the NISA II FEA results. However, for this specific analysis, a crack (2D or 3D) needs to be added in the FE model. As FRANC2D/L and FRANC3D do, ENDURE uses the Linear Elastic Fracture Mechanics (LEFM) principles.

The stress intensity factors, strain energy release rate, and J-integral values are computed using one of the following method as per selected by the user:

a) Crack Tip Opening Displacement (CTOD) Method;

b) Virtual Crack Extension (VCE) Method;

c) Modified Crack Closure Integral (MCCI) Method; and,

d) J-Integral Method.

When performing a fracture mechanics analysis, the FE model should use second order solid or shell elements at the crack vicinity. The main reason is that isoparametric elements with quarter-point nodes or mid-point nodes are required surrounding the crack front.

During the interactive question-answer session, the user will have to specify manually the nodes that define the crack front. Moreover, for each node present on the crack front, the user has to define the local crack front coordinate system. Altogether, six angles are required to relate the local coordinates to global coordinates.
4.6 Summary

A summary of the crack initiation and crack growth tools is presented in Table 4.1. The tools were marked by a cross when either the option in question is available, or if the author judged the tool good for the specific point evaluated. Non-applicable (NA) capabilities are also indicated in Table 4.1. As it is shown, some software packages are great for performing fracture mechanics analysis of complex 3D structures, but may not be the best choice for crack growth predictions. A combination of some CG and CI tools could then lead to better crack initiation or crack growth predictions.

<table>
<thead>
<tr>
<th></th>
<th>2D Analy.</th>
<th>3D Analy.</th>
<th>FEM, BEM</th>
<th>Orthotropic Material</th>
<th>Automatic Propagation</th>
<th>C.G. Prediction</th>
<th>NL</th>
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<td>CG90</td>
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<td>NISA/ENDURE</td>
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</tr>
</tbody>
</table>

Table 4.1: Crack Initiation and Crack Growth Tools Comparison
5.0 AVAILABLE CRACK GROWTH DATA FOR BONDED REPAIR

Existing crack initiation and crack growth data for thick section repaired using bonded doublers have been collected in order to validate a new methodology of analysis. Two sources of crack growth data have been found, and are presented in this section.

5.1 DERA Research

5.1.1 Motivation

The DERA experimental research program [POOLE 94] consisted of the fatigue testing of thick aluminum alloy coupons repaired using single-sided and double-sided bonded doublers. The repairs were made of either BFRP (boron fibre reinforced plastic) or CFRP (carbon fibre reinforced plastic). The focus of the DERA research was to:

a) Compare the performance of BFRP and CFRP repairs to cracked structures;

b) Investigate the effects of asymmetric single-sided repair of thick sections containing through cracks; and,

c) Investigate the effects of different doubler CTE on the coupons life.

5.1.2 Coupon and Patch Description

The fabricated coupons were machined from 12.4 mm thick 2024-T3 aluminum alloy plate and had final dimensions of 108 mm in width and 520 mm in length, as shown in Figure 5.1. A central through-thickness notch of 10 mm was initially added, and the coupons were pre-cracked to a total crack length ($2a$) of 20 mm or 40 mm.

Patched and unpatched specimens were tested at constant amplitude loading with a stress ratio ($R$) of 0.1 and a maximum stress ($\sigma_{\text{max}}$) of 55 MPa. BFRP and CFRP doublers were bonded to one side of the specimens containing 20 mm long cracks, and to both sides of specimens containing 40 mm long cracks. The composite patches were 108 mm wide and 180 mm long. Both ends of the doublers were tapered in thickness over 30 mm long. The BFRP patches were manufactured from Textron 5521
prepreg, and were made of 10 unidirectional plies. The adhesive was Redux 312/5 with a curing temperature of 120°C.

![Diagram of DERA Test Coupon Geometry]

Dimensions in mm

Figure 5.1: DERA Test Coupon Geometry

The material properties given in the DERA technical report for aluminum plate, boron patch and for the adhesive are provided in Table 5.1:
<table>
<thead>
<tr>
<th>Property</th>
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<th>BFRP</th>
<th>Redux 312/5</th>
</tr>
</thead>
<tbody>
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<td>Tensile Modulus $E$ (GPa)</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>$E_1, E_2 = E_3$ (GPa)</td>
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<td>208, 25.0</td>
<td></td>
</tr>
<tr>
<td>Shear Mod. $G_{12} = G_{13}, G_{23}$ (GPa)</td>
<td></td>
<td>7.24, 4.94</td>
<td></td>
</tr>
<tr>
<td>Poisson's Ratio $v$</td>
<td>0.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Poisson's Ratio $v_{12} = v_{13}, v_{23}$</td>
<td></td>
<td>0.167, 0.02</td>
<td></td>
</tr>
<tr>
<td>Thickness $h$ (mm)</td>
<td>12.4</td>
<td>1.34</td>
<td>0.15</td>
</tr>
<tr>
<td>CTE $\alpha_x$ ($^\circ$C)$^{-1}$</td>
<td>23e-6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CTE $\alpha_x, \alpha_y = \alpha_z$ ($^\circ$C)$^{-1}$</td>
<td></td>
<td>4.5e-6, 23e-6</td>
<td></td>
</tr>
</tbody>
</table>

Table 5.1: Material Properties for DERA Coupons

5.1.3 Test Results

The fatigue crack growth data obtained for the unpatched and patched (boron) specimens are summarized in Figure 5.2. Only data for BFRP are presented since the present work only addresses this type of material.
Figure 5.2: Fatigue Life of DERA Coupons

A summary of the coupons lives is presented in Table 5.2. It shows that the single-sided patch repair improved the baseline coupon life by a factor of 2.5, while the double-sided repair improved the coupon life by a factor of 50 (compared to unpatched coupon with initial crack length = 40 mm).

<table>
<thead>
<tr>
<th></th>
<th>Coupon Life (Cycles)</th>
<th>Life Improvement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unpatched Specimen</td>
<td>62000</td>
<td>---</td>
</tr>
<tr>
<td>Single Sided Repair</td>
<td>152000</td>
<td>2.5</td>
</tr>
<tr>
<td>Double Sided Repair</td>
<td>1100000</td>
<td>50</td>
</tr>
</tbody>
</table>

Table 5.2: Life Improvement from Patch Installation (DERA)
5.2 AFIT Research

5.2.1 Motivation

The Air Force Institute of Technology (AFIT) has also identified that few studies have addressed fatigue characteristics of repaired thick aluminum structures using bonded composite doublers [SCHUBBE 97]. The focus of the AFIT research was to:

a) Investigate panel thickness and patch size effects on fatigue crack growth rate;

b) Address secondary bending effects present in one-sided repairs; and,

c) Provide data to validate analytical and numerical solutions currently available.

An important conclusion of the research project is the fact that experimental results showed that crack growth rates increased with the increase in plate thickness in both un-repaired and repaired panels. In consequence, the life prediction models that do not take into account the thickness effect are consequently inaccurate.

5.2.2 Coupon and Patch Description

Three thickness (3.175 mm, 4.826 mm, and 6.350 mm) ranging from thin to thick panels were used. All specimens were cut from an aluminum 2024-T3 sheet such that the longitudinal (load) axis was aligned with the grain (rolled direction). These flat aluminum panels, 508 mm long and 153 mm wide, were repaired with a single-sided composite patch made of pre-cured unidirectional boron/epoxy, and bonded with FM73 film adhesive. Several configuration of patches were tested in order to investigate the effects of different patch design parameters on fatigue crack growth rates, such as doubler width, doubler length, and doubler to panel stiffness ratio.

Fatigue tests were conducted at constant amplitude loading ($R=0.1$), with a maximum stress of 120 MPa (17.4 ksi). Each test specimen was machined with a centre through crack of 12.7 mm (performed using the electrical discharge machining (EDM) technique). The initial notch was pre-cracked to 25.4 mm long before testing (baseline) or repaired with the boron/epoxy patches.
The results of only one test specimen were considered for the present work because all thick coupons tested had the same geometry, same kind of repair, were made of same material, and were tested in same conditions. The selected coupon has a thickness of 6.35 mm. The patch configuration consists of a full coupon width doubler, 102 mm long (138 mm including the patch taper area), as shown in Figure 5.3. The doubler is made of 18 plies, and has a patch to panel stiffness ratio of 1.045. The adhesive (FM73) has been cured at 121°C during one hour.

![Figure 5.3: AFIT Test Coupon Geometry](image)

The material properties given in the AFIT report for the aluminum plate and for the boron patch are presented in Table 5.3. As shown, few material properties were presented for the boron/epoxy patch, and no property was given for the adhesive used. The boron patch thickness has been calculated from the patch to panel stiffness ratio $S$, given in the reference [Schubbe 97] for the actual coupon configuration.
5.2.3 Test Results

The fatigue crack growth data obtained for the unpatched and boron patched specimens are summarized in Figure 5.4. Two patched coupons were tested with the repair configuration presented above.

![Figure 5.4: Fatigue Life of AFIT Coupons](image)

A summary of the coupons lives is presented in Table 5.4. It is shown that the single-sided patch repair improved the baseline coupon life by 413% for one specimen and by 452% for the second patched coupon.
<table>
<thead>
<tr>
<th></th>
<th>Coupon Life (Cycles)</th>
<th>Life Improvement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unpatched Specimen</td>
<td>8746</td>
<td>---</td>
</tr>
<tr>
<td>Patched Specimen (1)</td>
<td>36100</td>
<td>4.13</td>
</tr>
<tr>
<td>Patched Specimen (2)</td>
<td>39500</td>
<td>4.52</td>
</tr>
<tr>
<td>Average (Patched)</td>
<td>37800</td>
<td>4.32</td>
</tr>
</tbody>
</table>

Table 5.4: Life Improvement from Patch Installation (AFIT)

It is important to note that delamination problems were observed in the coupon’s centre region, as the crack was growing. A life prediction performed using complex FE methods, which do not include the delamination presence, should result in a greater life than what was observed experimentally.

5.3 Summary and Conclusions

As presented in this section, two sources of crack growth data were found. Both studies used 2024-T3 aluminum coupons with centre through crack, tested at constant amplitude loading. The DERA coupons were repaired with thinner patches, and were tested at lower stress levels than the AFIT experimental tests.

These studies were good as a starting-point for the improved methodology development, but were considered not representative of typical CF-18 material and loading. New crack growth data was then required for the full validation of the improved methodology of analysis for thick aluminum structures repaired with bonded composite doublers. A decision was therefore made to perform additional coupon testing to gather suitable validation data for crack growth.
6.0 VALIDATION TEST

6.1 Motivation

The literature search for crack initiation and crack growth data on thick structures repaired using bonded composite doublers provided results for 2024-T3 materials tested under constant low amplitude loading. No experimental results were found for typical CF-18 materials (7050-T7451) and fighter in-service spectrum loading. In order to validate our new methodology of fatigue prediction for thick aluminum structures repaired with bonded composite doubler, additional data was required. As such, a coupon test program was undertaken.

6.2 Objectives

The objective of the validation coupon testing was to gather validation crack growth data for 7050 aluminum alloy material, using a representative CF-18 wing root loading spectrum.

6.3 Validation Test Coupon

6.3.1 Coupon Geometry

The coupon geometry is shown in Figure 6.1 and Figure 6.2. The test section was designed to be 121 mm (4.75 inches) wide by 6.35 mm (0.25 inch) thick. A total of eight specimens were tested: two unpatched (baseline) and six patched (one-sided repair). The coupons were machined to have their longitudinal axis (load direction) aligned with the grain (rolling direction). A 2.54 mm (0.1 inch) long centre through notch was created at the centre of each coupon using the Electrical Discharge Machining (EDM) technique. The coupon manufacturing drawings are presented in Annex B.
6.3.2 Coupon Analysis

In order to define the coupon's geometry, a parametric study was performed using Pro-Engineer V.20 and Pro-Mechanica V.20 analysis software package. The latest uses the Pro-Engineer solid model as input geometry and constructs the meshing automatically using the p-element formulation. The test specimen design started as a flat rectangular plate configuration and progressed to become the geometry presented in Figure 6.1. A section widening was required to ensure that no failure would
happen at the attachment area. The Pro-Mechanica maximum stress contour plot of the coupon half model is shown in Figure 6.3.

![Coupon Analysis with Pro-Mechanica](image)

Figure 6.3: Coupon Analysis with Pro-Mechanica

The coupon model was restrained at the plane symmetry (crack location), and load was applied directly to the grip holes. This approach is conservative because in reality the bolts will not transfer the entire load. The friction between the grip plates and the coupons will contribute largely to the load transfer from the hydraulic jack to the coupon. The bolt loads were introduced to the FE model using bearing loads. These loads are greatest along the vector that defines the load direction, and taper toward the hole edges. The analysis was performed for the maximum load in the spectrum.

As the five bolts may not distribute the exact same load, a method suggested by [JARFALL 86] has been used to evaluate the load transmitted by each bolt. The results observed (starting from the coupon centreline) were that the first two bolts transfer 21.3% of the load, the middle bolt transfers 19.7%, and the two outer bolts transfer 18.9% of the load applied.

The numerical analysis showed that the maximum stress at the radius tangency was approximately 367 MPa (53.2 ksi), as shown in Figure 6.3. This corresponds to a stress concentration factor of 1.15 compared to a gross section stress of 319 MPa (46.3 ksi). The numerical analysis predicted a
maximum stress of 431 MPa (62.5 ksi) at the bolt holes. This corresponds to a stress concentration factor of 3.6 compared to the nominal stress at grip section of 119 MPa (17.2 ksi).

A fatigue analysis was also performed on the final coupon geometry assuming the presence of a non-detected crack in the critical area. This has been done using AFGROW in order to verify that the coupon failure will happen in the test section and not in the grip.

Assuming a corner crack of 0.5 mm by 0.5 mm at a bolt hole, a crack growth life 30 times higher than the one obtained at the test section was calculated for the baseline coupon. Assuming the same corner crack at the section radius, a life 9 times higher than the test section was obtained. As no crack should be present in these areas, it can be confidently assumed that the coupon failure would happen in the test section, and not at other stress concentration area.

6.3.3 Composite Patch Design and Analysis

The coupon composite patches were made of 16 plies of boron. They covered the complete coupons width (121 mm) and were 137 mm long. The patch manufacturing drawings are presented in Annex B. The boron patch lay-up is symmetrical and is made of the following stacking sequence:

\[
\begin{bmatrix}
0^\circ_2 & +45^\circ & 0^\circ_2 & -45^\circ & 0^\circ_2
\end{bmatrix}_s
\]

The repair has been designed based on numerous criteria. The patch lay-up was chosen in conformity to accept laminated design rules [NIU 92]. Among these are:

a) adjacent ply angles should not differ by more than 60\(^\circ\);

b) absence of groupings of more than six plies in the same orientation, and;

c) each 45\(^\circ\) ply should be balanced by a -45\(^\circ\) ply.

The doubler was also designed to ensure that the load to be transferred would not lead to failure of the patch. In addition, by being symmetrical, the presented sequence of 16 plies offers good margins of safety. The strength in the direction perpendicular to the load applied is assured by the four plies aligned at +45\(^\circ\) and -45\(^\circ\).
As to the adhesive transfer the loads between the composite and the metallic structure, it should be able to resist to the spectrum maximum load without any failure. Hence, the maximum shear strains and peel stresses in the adhesive were verified to be within the allowable values known for FM73 (as it is conventionally done for composite design repair). The margins of safety, defined as per equation (6.1), are presented in Table 6.1 for the adhesive and the bonded doubler.

\[
M.S. = \frac{\text{Safe Load}}{\text{Applied Load}} - 1
\]  

(6.1)

<table>
<thead>
<tr>
<th></th>
<th>Adhesive Shear Strain</th>
<th>Adhesive Peel Stress</th>
<th>Composite 0° Plies</th>
<th>Composite 45° &amp; -45° Plies</th>
</tr>
</thead>
<tbody>
<tr>
<td>Margin of Safety</td>
<td>1.29</td>
<td>2.1</td>
<td>0.96</td>
<td>0.20</td>
</tr>
</tbody>
</table>

Table 6.1: Margins of Safety of Bonded Repairs

Finally, the patch taper has been designed with a 4° drop-off. A drop-off is required to reduce the peel stresses in the adhesive at the ends of the composite patch.

6.3.4 Shot Peening

Although the coupon fatigue analysis indicated a fatigue free structure, a decision was made to shot peen the coupons in the critical area to avoid any possibility of fatigue failure. Shot peening has been performed at 0.008A intensity using 0.43 mm ceramic beads, as per Bombardier Aerospace shot peening standard process. The shot peened area is shown in Figure 6.4, and the detail drawing is presented in Annex B.
6.3.5 EDM Notch

The electrical discharge machining technique is commonly used to create an initial defect as similar as possible to a real crack. This technique can perform defects varying from 0.0318 mm to 0.254 mm, depending on the electrode type.

For the current project, rectangular shape copper electrodes (0.13 mm x 2.54 mm) were used to create the initial through notch. The EDM notch was performed as per the drawing provided in Annex B.

6.4 Patch Installation

The composite doublers were installed as per the Martec Process Specification [MARTEC 99] (Gritblast / Silane / BR127).

6.4.1 Adhesive Curing

The adhesive (FM73M OST) and the composite patches were cured at 85°C (185°F), for eight hours under a vacuum bag. The six coupons, the Boeing wedge test plates and the single lap shear test plates were installed on a massive 915 mm by 915 mm plate, and covered with a vacuum bag as shown in Figure 6.5.
6.4.2 Temperature Monitoring

The curing temperature monitoring was performed using thermocouples placed in contact with the coupons. During the curing, the oven temperature was adjusted to obtain a thermocouple reading within the curing tolerance: $[+10^\circ F, -0^\circ F]$. The cure cycle soak started when all thermocouples reached the curing tolerance, and the cooling began after the specified curing time.

The Silane and the BR127 were cured for three coupons simultaneously. The temperature monitoring was achieved by using five thermocouples located on the coupons.

The adhesive and the composite patch were cured for all test coupons simultaneously. Eleven monitoring thermocouples were installed for this operation. Two coupons were instrumented at several locations, and the remaining coupons had one thermocouple at a reference point. Figure 6.6 shows the patched test coupons following the installation of doublers.
6.5 **Bond Integrity Verification**

After the patch installation, C-Scans were performed to verify the bond quality. When there is a good bond quality, the signal will traverse the specimen easily, and will present a bright color as the C-Scan results. Dark regions are observed on C-Scans when the signal is blocked at a potential defect point through the specimen’s thickness. This can be the result of a delamination into the composite patch or a disbond in the adhesive. Figure 6.7 presents the C-Scans results for the 6 patched coupons. The C-Scan inspection was performed by NRC and the results indicated that all doublers were properly bonded.
6.6 Substrate and Doubler Material Properties

The material properties for Martec’sCoupon, boron/epoxy composite doubler, and for the adhesive are provided in Table 6.2. These properties were used for the finite element analyses presented later.
Table 6.2: Material Properties for MARTEC Coupons

<table>
<thead>
<tr>
<th>Property</th>
<th>7050-T7451 Al</th>
<th>Boron/Epoxy</th>
<th>BM73M OST</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile Modulus $E$ (GPa)</td>
<td>71.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$E_1, E_2 = E_3$ (GPa)</td>
<td></td>
<td>193, 18.6</td>
<td></td>
</tr>
<tr>
<td>Shear Mod. $G_{12} = G_{13}, G_{23}$ (GPa)</td>
<td></td>
<td>6.2, 5.5</td>
<td></td>
</tr>
<tr>
<td>Poisson’s Ratio $v$</td>
<td>0.33</td>
<td></td>
<td>0.33</td>
</tr>
<tr>
<td>Poisson’s Ratio $v_{12} = v_{13}, v_{23}$</td>
<td></td>
<td>0.21, 0.02</td>
<td></td>
</tr>
<tr>
<td>Thickness $h$ (mm)</td>
<td>6.35</td>
<td>2.11</td>
<td>0.51</td>
</tr>
<tr>
<td>CTE $\alpha_1, \alpha_2 = \alpha_3$ ($^\circ$C)$^{-1}$</td>
<td>23e-6</td>
<td></td>
<td>7.2e-5</td>
</tr>
<tr>
<td>CTE $\alpha_1, \alpha_2 = \alpha_3$ ($^\circ$C)$^{-1}$</td>
<td></td>
<td>4.5e-6, 23e-6</td>
<td></td>
</tr>
</tbody>
</table>

6.7 Spectrum Loading Description

The spectrum used for testing was the so-called IARPO3, generated for the CF-18 wing root attachment fitting. The spectrum has 16427 turning points per block and represents 300 flight hours. It has a maximum value of 4497 $\mu$e and a minimum value of -1431 $\mu$e.

All spectrum compressive lines were replaced by zero deformation values to avoid buckling. This simplifies considerably the test setup. Removing the compressive values has only a minimal effect on the fatigue life because the compressive loads only close the crack (loads perpendicular to the crack). This hypothesis has been verified using AFGROW for the baseline coupon and the fatigue life obtained using the clipped spectrum was different by roughly 5%. Furthermore, the anti-buckling guides would prevent the test coupon from buckling and cancel the out-of-plane displacement due to the eccentricity of the repair. This out-of-plane bending is nonlinear and is desired in the current work in order to verify how this effect can be included in the numerical analysis.

The IARPO3 spectrum has already been modified and is assumed to be representative of 300 flight hours of the CF-18. No additional truncation has been performed on the spectrum for the validation test. Each time a truncation is done on a spectrum, an experimental test should follow in order to compare the life resulting from the original and truncated spectrum.
6.8 Experimental Procedures

6.8.1 Test Methodology and Set Up

The coupons have been tested vertically using a test rig of the civil engineering department of the Université de Sherbrooke, as shown in Figure 6.8. The hydraulic jack used has a capacity of 250 kN and a maximum travel of ±200 millimetres. This jack can be used for dynamic tests at a frequency up to 10 Hz. A frequency of 2 Hz has been used for both pre-cracking and crack growth. The jack was controlled (load control) by a load cell of 250 kN and the MTS equipment and software packages presented in the next section. The jack installation included two ball joints to ensure a uniaxial load in the test section, and no residual moment in the jack itself.

![Figure 6.8: Validation Test Installation](image)

6.8.2 Data Acquisition Requirements

The controller and data acquisition TestStar II system was used to control the load applied to the hydraulic jack. The software TestWare SX generated the load signal representing the spectrum
loading. The hardware used consisted in a Pentium type computer. A diagram of the control system is presented in Figure 6.9.

Figure 6.9: Validation Test Control System Diagram
The crack growth was monitored and measured using two travelling microscopes. These instruments have a precision of 0.005 mm and 0.05 mm and are shown in Figure 6.10. For the patched coupons, the crack length was measured on the unpatched side. The crack length of baseline coupons was defined as the maximum length of both sides.

![Figure 6.10: Shop Microscopes](image)

6.8.3 Coupon Pre-Cracking

The first part of the test consisted of pre-cracking the coupons. This has been done at constant amplitude loading using a frequency of 2Hz. The maximum stress applied was 116 MPa (16.8 ksi), and the stress ratio \((R)\) was 0.1.

The maximum stress value has been chosen in order to obtain a pre-cracking session of approximately 40000 cycles (estimated with AFGROW). This rule of thumb is used to minimize plastic effects at crack tips and to avoid pre-cracking over several days.

The eight coupons were pre-cracked until a crack length \((2a)\) of 7.62 mm (0.3 in) was measured. Crack length was measured at each 1000 cycles using the two microscopes.
6.8.4 Validation Test

The validation test has been realized using the spectrum described previously at a frequency of 2Hz. As for the pre-cracking, the crack length was measured using the instruments shown in Figure 6.10. The crack length was measured at each 1000 cycles for the unpatched coupons and each 2000 cycles for the patched coupons to account for the difference in crack growth.

The cycling was performed until the coupons failed. The TestStar controller software was programmed to stop the test when an abnormal hydraulic jack displacement was observed. Hence, the test stopped automatically at coupon rupture.

6.9 Test Results

6.9.1 Coupon Pre-Cracking

Pre-cracking was performed until a total crack length ($2a$) of 7.62 mm (0.3 in) was obtained. Crack growth curves are presented in Figure 6.11 for crack lengths from 3.0 mm to 7.62 mm. These curves were “normalized” to an initial value of $2a = 3.0$ mm because the crack initiation (moment when a natural crack is observed) varied from 2000 cycles to 11000 cycles. These shifted curves show that the crack growth rates vary similarly for the crack length range studied (3.0 mm to 7.62 mm).
Figure 6.11: Coupon Crack Growth During Pre-Cracking

The maximum stress for the pre-cracking (116 MPa) has been chosen in order to obtain a pre-cracking period that is approximately equal to 40000 cycles per coupon. The number of cycles required to initiate a crack and to grow it to 7.62 mm is presented in next table for all test specimens.

<table>
<thead>
<tr>
<th>Coupon</th>
<th>Alfa (A)</th>
<th>Bravo (B)</th>
<th>Charlie (C)</th>
<th>Delta (D)</th>
<th>Echo (E)</th>
<th>Foxtrot (F)</th>
<th>Golf (G)</th>
<th>Hotel (H)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial Defect Length (mm)</td>
<td>2.7</td>
<td>2.7</td>
<td>2.8</td>
<td>2.7</td>
<td>2.8</td>
<td>2.8</td>
<td>2.8</td>
<td>2.8</td>
</tr>
<tr>
<td>Pre-Cracking Time (Cycles)</td>
<td>43540</td>
<td>41360</td>
<td>40150</td>
<td>42920</td>
<td>44860</td>
<td>49020</td>
<td>40940</td>
<td>42840</td>
</tr>
</tbody>
</table>

Table 6.3: Coupons Pre-Cracking Results

6.9.2 Validation Test

The cracks were propagated until the failure of the coupons occurs. Table 6.4 and Table 6.5 present the number of cycles to failure for the baseline specimens and for the repaired specimens. The crack growth curves are also presented below. A life improvement factor of 2.4 (average) has been obtained from the application of the repairs.
Figure 6.12: Fatigue Test Coupon Crack Growth

Table 6.4: Time to Failure for Baseline (No Repair)

<table>
<thead>
<tr>
<th>Cracking Time (Cycles)</th>
<th>Echo (E)</th>
<th>Hotel (H)</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>35074</td>
<td>33765</td>
<td>34420</td>
<td></td>
</tr>
</tbody>
</table>

Table 6.5: Time to Failure for Patched Coupons

<table>
<thead>
<tr>
<th>Cracking Time (Cycles)</th>
<th>Alfa (A)</th>
<th>Bravo (B)</th>
<th>Charlie (C)</th>
<th>Delta (D)</th>
<th>Foxtrot (F)</th>
<th>Golf (G)</th>
<th>Average (μ)</th>
<th>Standard Deviation (S_μ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>87516</td>
<td>76894</td>
<td>81475</td>
<td>82967</td>
<td>82220</td>
<td>84271</td>
<td>82557</td>
<td>3494</td>
<td></td>
</tr>
</tbody>
</table>
Six patched coupons were tested in order to have a representative statistical distribution. The standard deviation calculated (3500 cycles) is very small, considering the variability usually observed in fatigue testing.

6.10 Test Observations

During the testing, no disbonds were observed at the edges of the doublers, and all coupons failed at the test section. The decision to shot peen the coupons' radius was wise, and no crack initiation has been observed in that area.

The interesting point of the test is that the patch resisted the applied load until the maximum stress intensity factor was reached (approximately $2a = 90$ mm). Then the crack propagated dramatically, and caused the failure of the repair. This makes sense since the composite patch was not designed to support the highest spectrum loads, but only the maximum transferred load.

In conclusion, the validation test was a success, and now provides crack growth data for CF-18 material (7050-T7451) and loading, for repaired and unrepaired coupons.
7.0 IMPROVED METHODOLOGY DEVELOPMENT FOR FATIGUE EVALUATION

7.1 Conventional Fatigue Life Assessment Method

The conventional fatigue life assessment method is the primary technique used to assess the gain in fatigue life resulting from the application of a bonded repair over a cracked area. The load transfer is first evaluated using the FEM, or closed form solutions for a non-cracked configuration. According to the load transfer obtained, a scaled spectrum loading is then created to represent the loads seen by the repaired structure. The final step consists of performing a crack growth prediction using the scaled spectrum loading, and a conventional fatigue evaluation software, such as CG90 or AFGROW. These steps are schematized in Figure 7.1.

![Figure 7.1: Conventional Fatigue Life Assessment Method](image)

This method is easy to perform, but may lead to highly inaccurate crack growth prediction for many reasons. Among these, the increasing load transfer as a function of crack growth, and the thermal residual stresses generated by the curing process are not considered in the crack growth prediction.

7.2 FE Based Fatigue Life Assessment Method

The second approach is based on the use of FE tools (FRANC2D/L, FRANC3D and NISA/ENDURE) in order to include the full effect of the repair. These numerical tools perform linear elastic fracture mechanics (LEFM), and for a given applied stress, they calculate the
corresponding SIF for numerous crack lengths. The SIFs are then converted to beta factors (β) and used in a standard crack growth prediction software. This second approach is summarized in Figure 7.2.

![Figure 7.2: FE Based Fatigue Life Assessment Method](chart)

This method can take into account easily the load transfer increase as the crack grows, as well as the SIF variation across the thickness of the cracked structure.

### 7.3 Corrected FE Based Fatigue Life Assessment Method

The last analysis approach suggested in the present work is an improved version of the FE based methods, presented in the previous section. It consists of the inclusion of additional effects such as thermal residual stresses and secondary bending moments (for one-sided repairs), when required. When performing a crack growth prediction, these effects may be included using residual SIFs, corrections on beta factors, or corrections on spectrum loading. More details on the effects included in the analysis are presented in the next sections. This last approach is summarized in Figure 7.3.
This method has proven to give the best crack growth predictions, as it considers additional significant effects previously disregarded.

### 7.4 Out-of-Plane Displacements Effect

The bending moment resulting from the out-of-plane displacements of one-sided repairs is non-negligible and should be evaluated using nonlinear methods. In preliminary design, the out-of-plane displacements effect may be evaluated using nonlinear closed-form or nonlinear finite element analysis. The nonlinear closed-form analysis is relatively simple to perform, but it will be inadequate for complex 3D structures.

The improved methodology should be applicable to any kind of complex three-dimensional thick structures. The choice of using FEA in order to evaluate the secondary bending moment was evident. For this project, all nonlinear analyses have been performed using the NISA II solver.

None of the available fracture mechanics analysis software was able to include nonlinear effects during calculation of the SIFs. FRANC2D/L and FRANC3D simply do not have nonlinear capabilities, while ENDURE does not support nonlinear results calculated with NISA II. As such, there was a need to develop a correction scheme that will adjust the fracture mechanics analysis results to consider the nonlinear effects calculated separately using nonlinear finite element analysis.
7.4.1 Bending Correction Scheme Development

The total stress at the unpatched face of a one-sided repair problem results from the axial load applied on the cracked structure, and from the secondary bending moment due to the out-of-plane displacement, as shown in Figure 7.4.

![Image showing bending moment in one-sided repair](image)

Figure 7.4: Bending Moment in One-Sided Repair

The expression for the total stress at the unpatched side is then given by:

\[
\sigma_{\text{Total}} = \sigma_{\text{Axial Load}} + \sigma_{\text{Bending Moment}}
\]

(7-1)

This expression can be rewritten as:

\[
\sigma_{\text{Total}} = \sigma_{\text{Axial Load}} \left(1 + \Psi\right)
\]

(7-2)

where:

\[
\Psi \text{ (Bending Correction Factor)} = \frac{\sigma_{\text{Bending Moment}}}{\sigma_{\text{Axial Load}}} = \frac{\sigma_{\text{Total}} - \sigma_{\text{Axial Load}}}{\sigma_{\text{Axial Load}}}
\]

(7-3)
The total stress at the unpatched side is obtained from a static nonlinear analysis with boundary conditions best representing the physical problem studied. The stress due to the axial load is obtained from a static linear analysis in which the out-of-plane displacements were restrained.

In the fracture mechanics analysis, it is known that the stress intensity factor $K_I$ is proportional to the applied stress:

$$K_I \propto \sigma$$  \hspace{1cm} (7-4)

The bending correction factor defined previously can be used to calculate an effective stress intensity factor at the unpatched side of the repaired structure, by using the following equation:

$$K_{\text{eff}} = K_I \left(1 + \Psi \right)$$  \hspace{1cm} (7-5)

where:

$K_I$ = Stress intensity factor resulting from the axial load
$K_{\text{eff}}$ = Effective stress intensity factor at unpatched side

7.4.2 Bending Correction Factor for Variable Crack Length ($2a$)

When a crack must be included in the FE model, a modified approach has to be used to evaluate the correction factor. As it is known, the singularity present at the crack tip results in an infinite stress value. The methodology adopted to avoid this problem is to evaluate the bending correction factor at a point far from the crack location, as shown in Figure 7.5:
As the bending stresses may not be exactly the same at the centre and at the edge of the aluminum plate, the bending correction factor is first evaluated at both locations using a non-cracked model. The bending correction factor at the crack location is then derived using the following equation:

\[ \Psi_{\text{Centre}}(a) = \frac{\Psi_{\text{Centre}}(a = 0)}{\Psi_{\text{Edge}}(a = 0)} \times \Psi_{\text{Edge}}(a) \]  

(7-6)

where:

- \( \Psi_{\text{Centre}}(a) \) = Bending correction factor at crack location, function of crack length
- \( \Psi_{\text{Edge}}(a) \) = Bending correction factor at plate edge, function of crack length
- \( \Psi_{\text{Centre}}(a = 0) \) = Bending correction factor at crack location, for uncracked model
- \( \Psi_{\text{Edge}}(a = 0) \) = Bending correction factor at plate edge, for uncracked model

At maximum spectrum load, the correction factors can be computed, and a modified beta table that account for crack growth can be obtained as follows:
\[
\begin{bmatrix}
\beta'(a_1) \\
\beta'(a_2) \\
\beta'(a_3) \\
\vdots \\
\beta'(a_n)
\end{bmatrix} = \begin{bmatrix}
(1 + \Psi(\sigma_{\text{max}}, a_1)) \cdot \beta(a_1) \\
(1 + \Psi(\sigma_{\text{max}}, a_2)) \cdot \beta(a_2) \\
(1 + \Psi(\sigma_{\text{max}}, a_3)) \cdot \beta(a_3) \\
\vdots \\
(1 + \Psi(\sigma_{\text{max}}, a_n)) \cdot \beta(a_n)
\end{bmatrix}
\]  
(7-7)

7.4.3 Bending Correction Factor for Variable $\sigma$ and $a$

For a complex loading, a $\Psi(\sigma, a)$ table can be built for several $\sigma$ and $a$ values using the method presented in the previous section. This would result in a two dimensional correction matrix:

<table>
<thead>
<tr>
<th>$\sigma_1$</th>
<th>$\sigma_2$</th>
<th>$\sigma_3$</th>
<th>$\sigma_4$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Psi_{11}$</td>
<td>$\Psi_{12}$</td>
<td>$\Psi_{13}$</td>
<td>$\Psi_{14}$</td>
</tr>
<tr>
<td>$\Psi_{21}$</td>
<td>$\Psi_{22}$</td>
<td>$\Psi_{23}$</td>
<td>$\Psi_{24}$</td>
</tr>
<tr>
<td>$\Psi_{31}$</td>
<td>$\Psi_{32}$</td>
<td>$\Psi_{33}$</td>
<td>$\Psi_{34}$</td>
</tr>
<tr>
<td>$\Psi_{41}$</td>
<td>$\Psi_{42}$</td>
<td>$\Psi_{43}$</td>
<td>$\Psi_{44}$</td>
</tr>
</tbody>
</table>

Table 7.1: Bending Correction Factor Function of Stress Applied and Crack Length

The main problem of using a $\Psi(\sigma, a)$ correction table is the fact that most of the crack growth prediction software packages do not support variable betas ($\beta$) as the loading change (for a given crack length).

However, if it is found that the bending correction factors are influenced by the applied stress, the following method can be used. The modified beta table is first calculated, as shown in equation (7-7). For any applied stress and any crack length, the effective stress intensity factor at the unpatched plate side is given by:

\[
k_{\text{eff}} = K_I \left( 1 + \Psi(\sigma, a) \right)
\]  
(7-8)

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This equation is approximately equal to:

\[ K_{\text{eff}} \approx K_i \left( 1 + \Psi(\sigma_{\text{max}}, a) \right) \cdot \Phi(\sigma) \quad (7-9) \]

where \( \Phi \) is the stress correction factor, which is given by:

\[ \Phi(\sigma) = \frac{\left( 1 + \Psi(\sigma, a = 0) \right)}{\left( 1 + \Psi(\sigma_{\text{max}}, a = 0) \right)} \quad (7-10) \]

Hence, the current suggested method evaluates the effect of the applied stress for an uncracked configuration only. The stress correction factor presented above is only a function of the applied stress, as \( \Psi(\sigma_{\text{max}}, a = 0) \) is constant. The easiest way to consider \( \Phi(\sigma) \) in a crack growth analysis will be to scale the spectrum loading as follows:

\[
\begin{bmatrix}
\sigma_1 \\
\sigma_2 \\
\sigma_3 \\
\vdots \\
\sigma_n
\end{bmatrix} =
\begin{bmatrix}
\Phi(\sigma_1) \cdot \sigma_1 \\
\Phi(\sigma_2) \cdot \sigma_2 \\
\Phi(\sigma_3) \cdot \sigma_3 \\
\vdots \\
\Phi(\sigma_n) \cdot \sigma_n
\end{bmatrix}
\quad (7-11)
\]

Now that the mathematically correct formulation has been presented, a simplified approach is presented below for an uncracked configuration. The stress correction factor has been presented to be:

\[
\Phi(\sigma) = \frac{\left( 1 + \Psi(\sigma, a = 0) \right)}{\left( 1 + \Psi(\sigma_{\text{max}}, a = 0) \right)} = \frac{1 + \sigma_{\text{Total}}(\sigma) - \sigma_{\text{Axial Load}}(\sigma)}{1 + \frac{\sigma_{\text{Total}}(\sigma_{\text{max}}) - \sigma_{\text{Axial Load}}(\sigma_{\text{max}})}{\sigma_{\text{Axial Load}}(\sigma_{\text{max}})}}
\quad (7-12)
\]
Because the axial stress in the structure is proportional to the applied load, the following expression is obtained:

\[ \sigma_i' = \sigma_{\text{max}} \cdot \frac{\sigma_{\text{Total}}(\sigma_i)}{\sigma_{\text{Total}}(\sigma_{\text{max}})} \]  

(7-14)

where:

- \( \sigma_i \) = Spectrum stress at position “i”
- \( \sigma_i' \) = Modified spectrum stress at position “i”
- \( \sigma_{\text{max}} \) = Maximum spectrum stress
- \( \sigma_{\text{Total}} \) = Stress seen by the structure (found using a linear or nonlinear analysis)

This method reduces significantly the complexity of the problem and can be applied to a conventional crack growth software. Only a simple program or a spreadsheet is needed to find the modified spectrum stress values.

For the specific cases where the loading changes as the crack grows, the following method is suggested. The beta table is first built using the correction factors \( \Psi(\sigma_{\text{max}}, a) \). Next, series of spectrum files are created as presented previously, for numerous crack lengths corresponding to the range of interest (as shown in Figure 7.6). A crack growth prediction is then performed for all reduced crack ranges, and the number of cycles to failure is obtained by the summation of all the predictions.

\[ a_1 \rightarrow a_2 \rightarrow a_3 \rightarrow a_4 \rightarrow a_i \]

Spectrum 1  Spectrum 2  Spectrum 3  ...

Figure 7.6: Crack Growth Prediction Using a Variable Spectrum
7.5 Thermal Residual Stress Effect

7.5.1 Cracked Structures Free to Expand

For supported structures, such as double-sided repairs or one-sided supported repairs, the following relation can be used as a first evaluation of the thermal residual stress present in the substrate:

\[
\sigma_p = E_p \Delta T \frac{(\alpha_p - \alpha_R)}{1 + E_p t_p / E_p t_R}
\]  

(7-15)

This equation does not consider thermal variations across the specimen’s thickness, it neglects the presence of the adhesive, and is good only when the cracked structure is free to expand. For further investigations, a FE analysis must be performed. In that case, the thermal residual stress will be obtained directly from the application of the thermal loading simulating the cooling down process.

7.5.2 Cracked Structures Not Free to Expand

Supported structures restrained by surrounding structures represent most of the thick section repairs in an aircraft. CF-18 X-19 and X-24 repairs are included in this class of problems. As these structures are heavily supported, no appreciable out-of-plane displacement is observed, and the only effect that needs to be included in the crack propagation analysis is the thermal residual stress effect.

The approach suggested here for the evaluation of the thermal residual stresses is based on a previous Martec Limited research project [ROBERGE 98]. The following relation has been proposed for thermal residual strain evaluation (equation (2-21)). Knowing the thermal residual strain in the substrate, the thermal residual stress can easily be derived.

\[
\text{Strain}_{\text{Thermal Residual}} = \text{Strain}_{\text{Thermal Patch}} - \text{Strain}_{\text{Thermal Unpatch}}
\]

where:

\[
\text{Strain}_{\text{Thermal Patch}} = \text{Thermal strain in substrate for a patched configuration}
\]

\[
\text{Strain}_{\text{Thermal Unpatch}} = \text{Thermal strain in substrate for an unpatched configuration}
\]
7.5.3 Thermal Residual Stress Consideration in CG Prediction

When a repaired structure is submitted to out-of-plane displacements, the evaluation of the thermal effect is more complex. It was found that a single-sided repair submitted to thermal loads can be analyzed linearly using linear FE methods. However, the principle of superposition cannot be applied, and consequently the linear effect (thermal load) and nonlinear effect (secondary bending moment) cannot be added.

The only way to combine both effects is to use a nonlinear method. It is to be noted that a nonlinear closed form solution combining thermal and bending effects has not been developed.

The philosophy used to include the nonlinear thermal effect is very similar to the one presented for the nonlinear bending effect. It was earlier presented that, for a one-sided repair problem, the expression of the total stress at the unpatched side is given by:

\[
\sigma_{\text{Total}} = \sigma_{\text{Axial Load}} + \sigma_{\text{Bending Moment}}
\]  \hspace{1cm} (7-16)

Including the stresses at the unpatched side due to the thermal residual, the equation becomes:

\[
\sigma_{\text{Total}} = \sigma_{\text{Axial Load}} + \left( \sigma_{\text{Bending Moment}} + \sigma_{\text{Thermal Residual}} \right)
\]  \hspace{1cm} (7-17)

\[
\sigma_{\text{Total}} = \sigma_{\text{Axial Load}} \left( 1 + \Psi' \right)
\]  \hspace{1cm} (7-18)

where:

\[
\Psi' \ (\text{Bending \ & \ Termal Correction Factor}) = \frac{\sigma_{\text{Total}} - \sigma_{\text{Axial Load}}}{\sigma_{\text{Axial Load}}}
\]  \hspace{1cm} (7-19)

The methodology presented previously, that takes into account the bending correction factor \( \Psi \) for a crack growth prediction, can be used for the bending and thermal correction factor \( \Psi' \).
In cases where there is no out-of-plane displacement, the same methodology is applied. However, only the contribution of the thermal residual stresses will be required. It should be noted that out-of-plane displacements may be generated by neutral axis shifting, or by external out-of-plane loads. The developed methodology will be applicable for both cases, and the choice of a linear or nonlinear analysis will be carried out depending on the type of applied loads.
8.0  LINEAR ELASTIC FRACTURE MECHANICS OF TEST SPECIMENS

8.1  Modelling Strategy

This research required that a large numbers of FE runs be performed to account for the different crack scenarios, analysis types, and fracture mechanics analysis used. The following sections provide descriptions of the different models used pertinent to each fracture mechanics analysis code.

8.1.1  FRANC2D/L

The models used eight-node quadrilateral elements. However, six-node triangular elements were automatically added by the code when a transition mesh was required for the creation of a new crack. The coupons were modelled without considering the presence of the symmetry planes. The analyses were conducted supposing plane stress conditions.

The aluminum plates were modelled with an isotropic material, while the composite doublers were modelled with orthotropic material. The adhesive between the metallic structure and the composite patch transmits the loads in shear.

The lower plate edge has been restrained in the loading direction and one node located at the coupon edge has been restrained to avoid rigid body motion (as shown in Figure 8.1). The loading has been applied on the upper plate edge using nodal forces.
8.1.2 FRANC3D

The models were built using three and four-node shell elements (first order). Since FRANC3D uses the boundary element technique, only the model surfaces needed to be meshed. FRANC3D coupons models consisted of the half of the real geometry to analyze, exploiting the symmetry plane perpendicular to the crack (plane “xz” as per Figure 8.2). The symmetry plane parallel to the crack was not used because FRANC3D needs material on both side of the crack front to propagate the new crack.

The patch, the adhesive, and the aluminum plate were all modelled with isotropic materials, since FRANC3D cannot support anisotropic and orthotropic materials.
The nodes located at one model extremity were restrained in the loading direction, as shown in Figure 8.2. The nodes located on the symmetry plane were restrained in the y-direction. Finally, the nodes located on the bottom plane were constrained in z-direction to represent symmetry condition for double-sided repairs, or to stop out-of-plane displacement for single-sided repairs. Rigid body motion was avoided by putting these restraints at the model faces. The loading has been applied using pressure loads on the elements located at one model extremity, as shown in Figure 8.2.

![Diagram showing boundary conditions](image)

**Figure 8.2: FRANC3D Models Boundary Conditions**

8.1.3 NISA / ENDURE

The aluminum plate and the adhesive were modelled utilizing 20-node (second order) brick elements (NISA II element type #4). The composite doubler was modelled with laminated composite eight-node (second order) shell elements (NISA II element type #32). These shell elements were developed for the analysis of composites. The fracture mechanics analyses performed with NISA II / ENDURE were done exploiting a minimum of two coupons plane of symmetry. Only a quarter of the test coupon was needed for single-sided repairs and one eighth of the geometry for double-sided repairs.
The aluminum plate and the adhesive were considered to be isotropic, while the composite doublers were modelled as orthotropic with the laminated capability of composite shell elements. No material non-linearity has been considered in the present project.

Figure 8.3 presents the boundary conditions applied to the FE model. The displacements at one symmetry plane have been restrained in the y-direction and the displacements at the other symmetry plane have been restrained in the x-direction (as per Figure 8.3). The crack has been introduced by removing some constraints in the x-direction. This allows the crack to open when the loading is applied. As for FRANC3D, the displacements at the bottom surface were restrained in the z-direction to avoid nonlinear out-of-plane displacements for single-sided repairs. The same constraint was applied for double-sided repairs in order to exploit the third plane of symmetry of this kind of problem. The loading has been applied using pressure loads.

Figure 8.3: NISA Models Boundary Conditions
8.2 Convergence Studies

When performing a finite element or boundary element analysis, the meshing density has to be chosen in order to assure accurate results. Convergence is obtained when an element size decrease produces only a minor influence on the expected results. This does not imply that the model gives realistic results (the ones obtained experimentally), but it confirms that no additional modelling refinement will improve the accuracy of the numerical analysis.

Since numerous analyses had to be performed with many different FE models, it was not possible to perform a convergence study for each model analyzed. However, as all analyzed geometric shapes are similar (rectangular plate with single or double-sided repairs), a brief convergence study was done for each of the fracture software used. The mesh density was then translated to other models. The convergence study basically determined the element density required for the adhesive, doubler, and plate modelling.

The convergence criteria chosen is the maximum SIF, and was evaluated using a unit pressure. The chosen test case for the convergence studies is the validation test coupon.

8.2.1 Related Study on Convergence for One-Sided Repairs

A recent paper [UMAMAHESWAR 99] on the modelling strategies for single-sided repairs presents different methods to model one-sided repairs, with corresponding accuracy. For our study, nonlinear analyses were performed since it was determined that linear analyses would over-estimated the SIF values by over 20%. NISA version 6.0 was used for this research.

Umamaheswar used a model consisting of brick elements. He used eight-node brick elements of first order and used 4 elements through the thickness for the substrate, 2 for the adhesive, and 4 for the composite doubler.

He proposed the following modelling techniques:

a) Substrate and doubler: four-node shell elements; adhesive: spring elements;
b) Substrate and doubler: four-node shell elements; adhesive: eight-node brick elements; and,
c) Substrate, doubler and adhesive: eight-node elements (using only one brick through the thickness for the three constituents).

His conclusion was that the “single-brick” model (third method) was the best compromise to the expensive computational cost of numerous brick elements through the model thickness. The results obtained with this model were within 2% of those provided by the reference configuration.

8.2.2 FRANC2D/L Convergence Study

The FRANC2D/L convergence study was performed on the validation test coupon’s geometry. As indicated before, the SIF was used as convergence criteria. A unit pressure was applied on the model, and a crack length of 25.4 mm ($2a$) was used.

The cracked plate and the repair material were modelled using 2D eight-node shell elements, then no refinement across the thickness was required. Since all analyzed structures are rectangular with similar dimensions, this study provided guidelines to determine the mesh size for all FRANC2D/L analyses.

Figure 8.4 provides the SIF values obtained as a function of the number of nodes composing the model. The total number of nodes was used to compare the different refined models since it is directly proportional to the number of degrees of freedom, and hence accuracy.
As shown, a model made of over 7000 nodes gives results with less than 1% of error, and this was used for subsequent analyses.

8.2.3 FRANC3D Convergence Study

FRANC3D uses the boundary element method to perform fracture mechanics analysis of thick structures. A convergence study was difficult to perform since the BEM is highly influenced by the number of elements composing the model. When the number of unknown (in a boundary element analysis) reached a certain point, the time required to solve the problem increased exponentially.

A Cornell Fracture Group validation report of FRANC3D [CFG 98b] highlights the fact that the results accuracy is not only a function of the mesh size, but also of the crack element aspect ratio. Therefore, a particular attention has been brought to keep the crack elements similar to a square shape.

Under these assumptions, a convergence study was undertaken to assess the effect of the number of elements present across the cracked plate’s thickness. For this purpose, the validation test coupon model was used, with a crack length of 25.4 mm (2a), submitted to a unitary stress. Figure 8.5 presents the SIF predictions at the unpatched side, as function of the number of elements present in
the model. The four points (in Figure 8.5) were calculated for the patched configuration with one, two, three or four elements across the aluminum plate's thickness.

![Figure 8.5: FRANC3D Convergence Study](image)

As shown in the previous figure, a difference of only 0.13% has been obtained with the models consisting of 1860 and 2030 nodes (3 and 4 elements across the thickness). The configuration using four elements across the cracked plate’s thickness (approx. 2000 nodes) has been chosen as the reference modelling case.

### 8.2.4 NISA/ENDURE Convergence Study

NISA/ENDURE uses the FEA method to perform fracture mechanics analysis. For our analysis, the model was built with second order 20-node brick elements. Compared to eight-node bricks (first order), the 20-node brick elements require more computation time, but results in an appreciable gain in the analysis precision. Based on Umamaheswar’s paper [UMAMAHESWAR 99] it was anticipated that a reduced number of elements across the cracked plate’s thickness should be required to obtain convergence.

Figure 8.6 shows the SIF computed at the unpatched side as a function of the number of nodes. It can be noted that the convergence is obtained with few elements, and that a model with only two or three
elements across the plate’s thickness gives small errors (compared to an highly remeshed model). However, as it was planned to perform nonlinear analyses, the configuration with four elements across the plate’s thickness was chosen (composed of 32533 nodes for the validation test coupon FE model), even if a model with 22000 nodes provided enough accuracy.

![Graph showing convergence study](image)

**Figure 8.6: NISA/ENDURE Convergence Study**

### 8.3 FE Models Characteristics

Table 8.1 presents the number of nodes and elements for the 21 fracture mechanics analyses runs performed with FRANC2D/L, FRANC3D and NISA II for the DERA, AFIT and MARTEC coupons.
<table>
<thead>
<tr>
<th></th>
<th>FRANC2D/L</th>
<th></th>
<th>FRANC3D</th>
<th></th>
<th>NISA II / ENDURE</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td># Elem.</td>
<td># Node</td>
<td># Elem.</td>
<td># Node</td>
<td># Elem.</td>
<td># Node</td>
</tr>
<tr>
<td>AFIT Unpatched</td>
<td>3680</td>
<td>11305</td>
<td>1740</td>
<td>1016</td>
<td>5375</td>
<td>25892</td>
</tr>
<tr>
<td>AFIT Patched</td>
<td>4960</td>
<td>15209</td>
<td>3254</td>
<td>1942</td>
<td>6800</td>
<td>29960</td>
</tr>
<tr>
<td>DERA Unpatched</td>
<td>2400</td>
<td>7421</td>
<td>1830</td>
<td>1121</td>
<td>6264</td>
<td>30953</td>
</tr>
<tr>
<td>DERA Patched (1)</td>
<td>3600</td>
<td>11162</td>
<td>3126</td>
<td>1813</td>
<td>9909</td>
<td>41109</td>
</tr>
<tr>
<td>DERA Patched (2)</td>
<td>4800</td>
<td>14903</td>
<td>3242</td>
<td>1993</td>
<td>6777</td>
<td>28067</td>
</tr>
<tr>
<td>MARTEC Unpatched</td>
<td>2880</td>
<td>8865</td>
<td>1740</td>
<td>1040</td>
<td>4992</td>
<td>24715</td>
</tr>
<tr>
<td>MARTEC Patched</td>
<td>5120</td>
<td>15778</td>
<td>2478</td>
<td>1815</td>
<td>7776</td>
<td>32509</td>
</tr>
</tbody>
</table>

Table 8.1: FE Models General Information

The above table can be used for the verification of all FE models. It should be noted that the convergence study has only been performed with a repaired test specimen. The unpatched models contain less nodes and elements than the convergence criteria defined for a repaired configuration (plate + repair). However, the unpatched models contain the exact same number of nodes and elements as the cracked plates in the patched models.

8.4 MARTEC Coupons FE Model Validation

In order to verify the behaviour of FE models, a two step validation was performed. First, the curing process results in significant out-of-plane deformation from the un-matched CTE, and is ideal for the FEA verification. A temperature load can be applied to the FE model simulating the cooling process following the adhesive curing. Secondly, strain gauges were installed on repaired and non-repaired coupons in order to measure deformations under given applied loads. For same loading condition, the FEA predicted deformations can be compared to experimental values.

8.4.1 Displacement Based Validation

In order to validate the NISA FE model for our test coupons, the out-of-plane displacements obtained from the finite element analysis were compared with the displacements measured for two test specimens following the cure. The out-of-plane displacements were measured along the centre axis and the side axis as per Figure 8.7. Figure 8.8 and Figure 8.9 compare the curvatures obtained experimentally with those obtained from the FE analysis. As they show, the measured values match
extremely well the FEA predictions, indicating a good model behaviour. Figure 8.10 shows the comparison between the out-of-plane displacements obtained from the numerical analysis and the values measured on two test specimens, along the centre and side axis (as defined in Figure 8.7). Ideally, a straight line with a slope of one should be obtained.

Figure 8.7: Curvature of Validation Test Coupon
Figure 8.8: Curvature Along Centre Axis

Figure 8.9: Curvature Along Side Axis
8.4.2 Strain Based Validation

In order to validate the FE models, strain gauges were installed on two test specimens: one repaired and one non-repaired. Series of strain data were taken at different loads, resulting in stress levels varying from 0 to 183 MPa (26.5 ksi) for the patched specimen, and from 0 to 124 MPa (18.0 ksi) for the unpatched specimen. The strain gauge results were then compared to the FEA results for the maximum stress applied.

Unpatched Configuration

Four strain gauges were installed on one unpatched specimen at 51 mm (2.0 in) from the crack location (far from the stress concentration effect), as per Figure 8.11.
Two strain gauges were installed on the edge of the coupon (#2 & #4), while the two others were installed on the front and on the back (#1 & #3). This configuration allows to verify if there was any bending stresses induced by the coupon installation during the testing.

Ideally, the strain gauges #1 and #3 should give the same result, as well as the strain gauges #2 and #4. However, it is not possible to obtain the exact same results. Each strain gauge has its own resistance and precision, and they may not have been aligned perfectly with the load axis. Moreover, the strain gauge bond may not be of exact same quality for all strain gauges. The experimental and FEA results are presented in Figure 8.11.
<table>
<thead>
<tr>
<th>Strain Gauge #</th>
<th>Measured (με)</th>
<th>NISA (με)</th>
<th>Error (%)</th>
<th>FRANC3D (με)</th>
<th>Error (%)</th>
<th>FRANC2D/L (με)</th>
<th>Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1688</td>
<td>1700</td>
<td>0.73</td>
<td>1707</td>
<td>1.11</td>
<td>1699</td>
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<td>2</td>
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<td>1715</td>
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<td>0.57</td>
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<td>0.19</td>
<td>1699</td>
<td>0.66</td>
</tr>
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<td>4</td>
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<td>2.76</td>
<td>1715</td>
<td>2.47</td>
<td>1721</td>
<td>2.81</td>
</tr>
</tbody>
</table>

Table 8.2: MARTEC Unpatched Coupon Strain Results (124 MPa Stress)

**Patched Configuration**

A total of eight strain gauges were installed on the repaired coupon, as shown in Figure 8.12. The strain gauges #1 and #2 were installed on the composite patch, at the centre and near the edge. The strain gauges #3 and #4 were installed on the sides of the coupon. The strain gauges #5 and #8 were installed on the patched and unpatched coupon side, near the patch taper, on the metallic surface. The strain gauge #6 was installed on the unpatched side, at the same location as the strain gauge #2. Finally, the strain gauge #7 was installed on the unpatched face at a distance of 25.4 mm (1.0 in) of the crack.
The strain gauge results and the FEA nonlinear results are presented in Table 8.3. This time, only the NISA results are presented, as it is the only model that can approximate the nonlinear experimental results in a realistic way.

<table>
<thead>
<tr>
<th>Strain Gauge #</th>
<th>Measured (με)</th>
<th>NISA (με)</th>
<th>Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>2186</td>
<td>2000</td>
<td>8.50</td>
</tr>
<tr>
<td>4</td>
<td>2108</td>
<td>2000</td>
<td>5.11</td>
</tr>
<tr>
<td>5</td>
<td>2946</td>
<td>3031</td>
<td>2.89</td>
</tr>
<tr>
<td>6</td>
<td>2960</td>
<td>2907</td>
<td>1.78</td>
</tr>
<tr>
<td>7</td>
<td>2786</td>
<td>2640</td>
<td>5.22</td>
</tr>
<tr>
<td>8</td>
<td>2006</td>
<td>2065</td>
<td>2.94</td>
</tr>
</tbody>
</table>

Table 8.3: MARTEC Patched Coupon Strain Results (183 MPa Stress)
As shown, an important error is noted for strain gauges #3 and #4. These strain gauges were installed on the coupon sides in order to verify the presence of a non-desirable moment in the coupon. However, there is an important stress variation through the coupon’s thickness (shown by strain gauges #5 & #8), therefore a minor variation of the strain gauge position will lead to different results.

The strain gauges #5, #6 and #8 are in good agreement with the FEA results calculated with NISA, as one would have expected. A difference of 5% has been observed for the strain gauge #7. As it is shown in the previous figure, this strain gauge is located near the crack, and is then submitted to a local stress variation. Consequently, it is reasonable to have such difference noted in that area.

The experimental and FEA values at strain gauges locations #1 and #2 were not presented because an important difference between the predictions and the measured values was obtained. This can be explained by the fact that the strain gauges were bonded on the resin and not directly on the boron fibre. Also, the same technique used to install strain gauges on metallic surface was used to install the two strain gauges on the boron patch. This may have led to a low quality bond on resin. The gauge alignment with the fibre is critical and may have been the case for the difference. Finally, the doubler FE model consisted of one layer of composite shell elements, which do not allow movement between plies through the thickness (a certain movement should happen in reality).

8.5 Conclusion

In conclusion, the numerical results calculated are in good agreement with the strain gauge results obtained experimentally. This is a good indication that the coupon installation was well set-up and properly calibrated.
9.0 METHODOLOGY VALIDATION

9.1 Crack Growth Prediction Models

Prior to performing a crack growth prediction, a crack growth model is required. Different types of crack growth models are available, and for a given stress intensity factor variation (ΔK), they will provide the corresponding crack growth rate (da/dN).

For each test case analyzed, one crack growth model was chosen to perform the crack growth predictions. The following sections present the crack growth models used for the DERA, AFIT and MARTEC repair test cases.

9.1.1 Model for DERA Coupons

In addition to the CG results already presented for DERA unpatched and patched coupons in Section 5.1, crack propagations were performed (baseline coupon) for different stress ratios: 0.1, 0.4 and 0.6 [POOLE 94]. Figure 9.1 presents the experimental data and the tuned NASGRO equation for 2024-T3. As shown, the crack growth model reproduces very well the experimental data for the stress ratio used.
Figure 9.1: Crack Growth Model for DERA Predictions

Table 9.1 presents the NASGRO model parameters used for the crack growth predictions for the DERA coupons. These parameters were adjusted to fit the experimental data for the stress ratios available.

<p>| | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>E</td>
<td>10300 ksi</td>
<td>C</td>
<td>2.0e-7</td>
</tr>
<tr>
<td>ν</td>
<td>0.33</td>
<td>n</td>
<td>2.25</td>
</tr>
<tr>
<td>YLD</td>
<td>53 ksi</td>
<td>p</td>
<td>1.0</td>
</tr>
<tr>
<td>K1C</td>
<td>33 ksi·in^{1/2}</td>
<td>q</td>
<td>0.8</td>
</tr>
<tr>
<td>KC</td>
<td>66 ksi·in^{1/2}</td>
<td>Cth</td>
<td>-0.5</td>
</tr>
<tr>
<td>K1E</td>
<td>46 ksi·in^{1/2}</td>
<td>Alpha</td>
<td>1.0</td>
</tr>
<tr>
<td>DKo</td>
<td>4.5 ksi·in^{1/2}</td>
<td>Smax/S0</td>
<td>0.5</td>
</tr>
<tr>
<td>AK</td>
<td>0.2</td>
<td>Rhi</td>
<td>0.7</td>
</tr>
<tr>
<td>BK</td>
<td>2.0</td>
<td>Rho</td>
<td>-0.3</td>
</tr>
</tbody>
</table>

Table 9.1: NASGRO Equation Constants for DERA Predictions
9.1.2 Model for AFIT Coupons

The NASGRO equation has been used to perform the crack growth predictions of the AFIT coupons. This time, the model was adjusted to the experimental results for the unpatched specimen (R=0.1). The NASGRO equation parameters used for the predictions are presented in Table 9.2.

<table>
<thead>
<tr>
<th>E</th>
<th>10300 ksi</th>
<th>C</th>
<th>8.2e-9</th>
</tr>
</thead>
<tbody>
<tr>
<td>YLD</td>
<td>53 ksi</td>
<td>P</td>
<td>0.5</td>
</tr>
<tr>
<td>KIC</td>
<td>33 ksi-in-1/2</td>
<td>Q</td>
<td>1.0</td>
</tr>
<tr>
<td>KC</td>
<td>66 ksi-in-1/2</td>
<td>Th</td>
<td>1.5</td>
</tr>
<tr>
<td>K1E</td>
<td>46 ksi-in-1/2</td>
<td>Alpha</td>
<td>1.5</td>
</tr>
<tr>
<td>Dko</td>
<td>2.9 ksi-in-1/2</td>
<td>Smax/S0</td>
<td>0.3</td>
</tr>
<tr>
<td>AK</td>
<td>1.0</td>
<td>Rhi</td>
<td>0.7</td>
</tr>
<tr>
<td>BK</td>
<td>1.0</td>
<td>Rlo</td>
<td>-0.3</td>
</tr>
</tbody>
</table>

Table 9.2: NASGRO Equation Constants for AFIT Predictions

9.1.3 Model for MARTEC Coupons

For the MARTEC coupon crack growth predictions, the Harter T-Method was used for a number of reasons. First, not enough experimental data were available to efficiently adjust the NASGRO equation. A model improperly tuned can easily lead to significant error in crack growth predictions.

Second, the Harter T-Method computes crack growth according to test data collected for several stress ratios. Test data for 7050-T74 are available in the AFGROW material file for the Harter T-Method.

Finally, the crack growth rate curve at R=0 of the Harter T-Method has been compared to the experimental data present in the CG90 material file for 7050-T7451. The result is surprising: it seems that the two sets of experimental data emanate from the same source, as shown in Figure 9.2. The only appreciable difference is observed in the last section of the crack growth curve, when $K_{max}$ approach $K_C$. This zone usually represents a small part of the structure’s life.
9.2 Crack Growth Predictions for DERA Test Results

9.2.1 Conventional Method

The conventional method of analysis was first used to predict the crack growth of the test cases chosen. As mentioned in the improved methodology development section, this method consists of performing crack growth predictions using a scaled spectrum loading. The spectrum loading is scaled down according to the load transfer resulting from the application of a bonded repair. This load transfer is calculated using a non-cracked model.

The conventional method assumes that the load transfer does not vary as the crack grows. The thermal residual effect is neglected when a crack growth prediction is performed using this method.

To gather the information required for the load transfer equation, FE analyses (linear and nonlinear) were done for all test case geometries. The calculated stresses for DERA coupons are presented in Table 9.3.
<table>
<thead>
<tr>
<th></th>
<th>DERA (1 Patch)</th>
<th>DERA (2 Patches)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_{\text{max, unpatched}}$ (MPa)</td>
<td>55</td>
<td>55</td>
</tr>
<tr>
<td>$\sigma_{\text{max, patched}}$ (MPa)</td>
<td>59.7</td>
<td>33.3</td>
</tr>
<tr>
<td>Stress Reduction</td>
<td>-8.9%</td>
<td>39%</td>
</tr>
</tbody>
</table>

Table 9.3: FEA Predicted Maximum Stress for DERA Coupons

The FE nonlinear analysis for the DERA coupon repaired on one side showed a stress increase at the unpatched side, as if the presence of the patch did not decrease the stress level. This stress increase is due to the secondary bending moment present in one-sided repairs. The linear FE analysis performed for the two-sided repair coupon showed a stress reduction of 39%. The crack growth predictions performed using CG90 and AFGROW for the load transfer above are presented in Table 9.4.

<table>
<thead>
<tr>
<th></th>
<th>Cycles to Failure</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Experimental</td>
</tr>
<tr>
<td>Unpatched (2a = 20 mm)</td>
<td>62000</td>
</tr>
<tr>
<td>Unpatched (2a = 40 mm)</td>
<td></td>
</tr>
<tr>
<td>One Patch (2a = 20 mm)</td>
<td>152000</td>
</tr>
<tr>
<td>Two Patches (2a = 40 mm)</td>
<td>1100000</td>
</tr>
</tbody>
</table>

Table 9.4: Conventional Method Predictions for DERA Coupons

As it is shown, the conventional method predicted a life improvement factor (LIF) of almost five for the coupon repaired on both sides and no improvement for the one-sided repair specimen. In reality, the one-sided repair increased the coupon’s life by a factor of 2.5, and the double-sided repair increased the coupon’s life by a factor of almost 50. Analyses conducted using this technique are therefore extremely conservative. For the actual work, conservative results are presented in green and non-conservative results are presented in red.

9.2.2 FE Based Method

The following section presents the crack growth life calculated utilizing the second approach presented in Section 7.2. This approach consists in using the complex FE based methods to generate
beta tables (β vs. α), considering the applied load only. The out-of-plane displacements (for one-sided repair) and the thermal residual stresses are not considered at this point. The cycles to failure for all DERA test cases have been calculated with AFGROW using the NASGRO crack growth model, and the fracture mechanics analyses performed with FRANC2D/L, FRANC3D, and NISA/ENDURE.

<table>
<thead>
<tr>
<th></th>
<th>Experimental</th>
<th>FRANC2D/L / %</th>
<th>FRANC3D / %</th>
<th>NISA/ENDURE / %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unpatched Coupon</td>
<td>62000</td>
<td>64780 / 4.5</td>
<td>57650 / 7.0</td>
<td>64350 / 3.8</td>
</tr>
<tr>
<td>One Boron Patch</td>
<td>152000</td>
<td>2020700 / 1230</td>
<td>810200 / 433</td>
<td>592900 / 290</td>
</tr>
<tr>
<td>Two Boron Patches</td>
<td>1100000</td>
<td>&gt; 10000000 / 800</td>
<td>&gt; 10000000 / 800</td>
<td>&gt; 10000000 / 800</td>
</tr>
</tbody>
</table>

Table 9.5: FE Based Method Predictions for DERA Coupons

As it is shown, the predictions obtained using this method are outside of the experimental values. These results are non-conservative and could be very misleading. This indicates that this analysis method require to consider additional parameters in the analysis, such as thermal residual strain and secondary bending moment (for one-sided repairs).

9.2.3 Corrected FE Based Method

As it was shown in the previous section, the crack growth predictions performed using the FE based method are very different from the results obtained experimentally. This means that additional effects that were not yet considered have an important effect on the crack growth life.

For a double-sided repair, the only other (evident) effect that could be included in the crack growth prediction is the thermal residual stress effect. From a two-dimensional view point the thermal residual stresses (resulting from the adhesive curing) increase the mean stress level in the cracked structure. In other words, the thermal residual stresses do not affect the stress intensity factor variation (ΔK), but they affect the stress ratio (R).

For one-sided repairs, the out-of-plane displacement effect must also be included in the crack propagation analysis. This effect is due to the shifting of the section neutral axis, which tends to align
with the load axis as the load is increased. The out-of-plane displacement is a nonlinear phenomenon, which must be evaluated using nonlinear methods. The predictions using the corrected FE based method (including thermal and nonlinear bending effects) are presented in Table 9.6.

<table>
<thead>
<tr>
<th></th>
<th>Cycles to Failure</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Experimental</td>
</tr>
<tr>
<td>Unpatched Coupon</td>
<td>62000</td>
</tr>
<tr>
<td>One Boron Patch</td>
<td>152000</td>
</tr>
<tr>
<td>Two Boron Patches</td>
<td>1100000</td>
</tr>
</tbody>
</table>

Table 9.6: Corrected FE Based Method Predictions for DERA Coupons

The corresponding crack growth prediction curves are presented in Figure 9.3 for double-sided repair and in Figure 9.4 for single-sided repair specimens. For the coupon repaired on both sides, the best prediction has been obtained with the NISA/ENDURE software, presenting a difference of only 11% compared to the experimental results. Since the difference is very small, it can be concluded that the corrected FE based method worked very well for double-sided repair case with NISA/ENDURE.

For the one-sided repair configuration, FRANC3D seems to have given the best prediction with 16% of difference with the results obtained experimentally. On the other hand, the prediction performed with NISA/ENDURE was conservative by a notable difference of 31%. Because NISA/ENDURE gave the best prediction for a simpler problem (double-sided repair), this shows that an additional effect is still missing in the analysis for one-sided repair specimens. Upon reflection and observation of the rupture surface of the validation test coupon, it has been observed that the crack was growing faster at the unpatched side, as shown in Figure 9.5.
Figure 9.3: Corrected FE Based Method Predictions for DERA Two-Sided Repair Specimen

Figure 9.4: Corrected FE Based Method Predictions for DERA One-Sided Repair Specimen
9.2.4 Corrected FE Based Method including Crack Shape Effect

For thick specimens repaired on one side only, the crack will propagate according to the stress distribution across the thickness. The assumption that the crack fronts remain straight and parallel (as shown in Figure 9.6a) can consequently lead to an error in the crack growth prediction.

A first analysis was conducted supposing that the crack was growing at a constant angle of 45° (as shown in Figure 9.6b). A crack growth prediction was performed using the maximum SIF found for each crack length, and it led to a good prediction compared to the experimental results. However, it was found later (for this specific crack shape) that the maximum SIF was no longer located at the unpatched side, but it was now at the patched side. When taking the SIF at the unpatched side (considering also the bending correction factor), the crack growth prediction was now largely higher than the experimental results obtained. Hence, the hypothesis of a crack inclined at 45° was finally not the best assumption for the analysis of the single-sided repair problem.
A second approach was then developed in order to consider the crack shape effect. The validation test coupon showed that the crack started at a 0° angle, and increased constantly to become near 30° prior the coupon’s failure (similarly as shown in Figure 9.6c). A beta table has been built for a crack inclined at 0°, 26°, 44°, and an intermediate solution has been developed to represent the validation test observations, as shown in Figure 9.7.

Figure 9.6: Crack Shape Configurations for Crack Growth Predictions
Figure 9.7: Beta at Unpatched Side Fct. of Crack Inclination – DERA Coupon

Using the modified beta solution, which takes into account the crack front shape, the corrected FE based method provided a very good prediction, as shown in Table 9.7. The difference with the experimental data decreased from 31% to 11% considering the effect of the crack shape. Both predictions are presented in Figure 9.8.

<table>
<thead>
<tr>
<th>Cycles to Failure</th>
<th>Experimental</th>
<th>NISA/ENDURE / Diff. %</th>
<th>NISA/ENDURE &amp; Crack Shape / Diff. %</th>
</tr>
</thead>
<tbody>
<tr>
<td>One Boron Patch</td>
<td>152000</td>
<td>105400 / 31</td>
<td>135800 / 11</td>
</tr>
</tbody>
</table>

Table 9.7: Crack Shape Effect on Crack Growth Predictions for DERA Coupons
9.3 Crack Growth Predictions for AFIT Test Results

9.3.1 Conventional Method

As for DERA test cases, FE analyses were performed for the AFIT coupons. The calculated stresses for the unpatched coupon (linear analysis), and for the patched coupon (nonlinear analysis) are presented in Table 9.8.

<table>
<thead>
<tr>
<th></th>
<th>AFIT</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_{\text{max, unpatched}}$ (MPa)</td>
<td>120</td>
</tr>
<tr>
<td>$\sigma_{\text{max, patched}}$ (MPa)</td>
<td>116</td>
</tr>
<tr>
<td>Stress Reduction</td>
<td>3.4%</td>
</tr>
</tbody>
</table>

Table 9.8: FEA Predicted Maximum Stress for AFIT Coupons

The FE nonlinear analysis for the AFIT coupon repaired on one side showed a stress reduction of only 3.4%. The coupon out-of-plane displacements contributed dramatically to the reduction in the
load transfer at the unpatched side. The crack growth predictions performed using CG90 and AFGROW are presented in Table 9.9.

<table>
<thead>
<tr>
<th></th>
<th>Cycles to Failure</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Experimental</td>
</tr>
<tr>
<td>Unpatched Coupon</td>
<td>8750</td>
</tr>
<tr>
<td>Patched Coupon</td>
<td>36100</td>
</tr>
</tbody>
</table>

Table 9.9: Conventional Method Predictions for AFIT Coupons

As it can be calculated from Table 9.9, the conventional method predicted an average LIF of 1.07. In reality, the boron doubler increased the coupon’s life by a factor of 4.1. Once again, extremely conservative results were obtained.

9.3.2 FE Based Method

The Table 9.10 presents the crack growth predictions for the AFIT test case calculated using the FE based life assessment method. AFGROW has been used with the NASGRO equation to calculate the cycles to failure of the coupons.

<table>
<thead>
<tr>
<th></th>
<th>Cycles to Failure</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Experimental</td>
</tr>
<tr>
<td>Unpatched Coupon</td>
<td>8750</td>
</tr>
<tr>
<td>Patched Coupon</td>
<td>36100</td>
</tr>
</tbody>
</table>

Table 9.10: FE Based Method Predictions for AFIT Coupons

As concluded before (in DERA crack growth analysis), the predictions performed using the FE based method without considering the thermal and bending effects were non-conservative, and very far of the values obtained experimentally. This shows for a second time the importance of including these effects in a crack growth prediction for a repair.
9.3.3 Corrected FE Based Method

The predictions performed using the corrected FE based method are presented in Table 9.11. Again, as for the FE based Method, AFGROW has been used with the NASGRO equation to calculate the cycles to failure of the coupons.

<table>
<thead>
<tr>
<th></th>
<th>Cycles to Failure</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Experimental</td>
</tr>
<tr>
<td>Unpatched Coupon</td>
<td>8750</td>
</tr>
<tr>
<td>Patched Coupon</td>
<td>36100</td>
</tr>
</tbody>
</table>

Table 9.11: Corrected FE Based Method Predictions for AFIT Coupons

This method improved greatly the predictions (in comparison to the FE based method), but a difference of 48% (NISA/ENDURE) is still observed with the experimental results.

![Graph showing crack length vs number of cycles for experimental data and model predictions](image)

Figure 9.9: Corrected FE Based Method Predictions for AFIT Patched Coupon
As mentioned before, several material properties were not specified in the following reference [SCHUBBE 97]. In addition, it was known that the adhesive used was FM73, but no thickness and properties were given. Finally, the presence of disbonds (as noted in reference [SCHUBBE 97]) should necessarily lead to a faster crack growth than what has been predicted. All these factors are attributing to the difference between the predictions and the experimental results.

9.4 Crack Growth Predictions for MARTEC Test Results

9.4.1 Conventional Method

A FE linear analysis was performed for the unpatched coupons, while a FE nonlinear analysis was used for the repaired ones. The calculated maximum stress for both configurations is presented in Table 9.12.

<table>
<thead>
<tr>
<th></th>
<th>MARTEC</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_{\text{max, unp.}}$ (MPa)</td>
<td>319</td>
</tr>
<tr>
<td>$\sigma_{\text{max, patched}}$ (MPa)</td>
<td>284</td>
</tr>
<tr>
<td>Stress Reduction</td>
<td>11%</td>
</tr>
</tbody>
</table>

Table 9.12: FEA Predicted Maximum Stress for MARTEC Coupons

Without considering the thermal residual stress effect, the patched configuration showed a stress reduction of 11% at the coupon’s unpatched side. As for the previous test cases, the crack growth predictions were performed using CG90 and AFGROW, and are presented in Table 9.13.

<table>
<thead>
<tr>
<th></th>
<th>Cycles to Failure</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Experimental</td>
</tr>
<tr>
<td>Unpatched Coupon</td>
<td>34420</td>
</tr>
<tr>
<td>Patched Coupon</td>
<td>82560</td>
</tr>
</tbody>
</table>

Table 9.13: Conventional Method Predictions for MARTEC Coupons
As shown in Figure 9.10, the retardation parameter in CG90 and in AFGROW was very well tuned, and the predictions follow the experimental crack growth curve. The Harter T-Method (AFGROW) predicted the crack growth very well until 30000 cycles, then a certain difference is observed. It was not possible to tune the crack growth model for this specific range, because the Harter T-Method uses experimental data, and no constant or parameter can be adjusted by the AFGROW user. It is important to note that the Harter T-Method gave lower crack growth rates compared to what has been experimentally observed near the coupon failure.

The predictions calculated using CG90 are too conservative for both patched and unpatched coupons. CG90 has been developed and calibrated for F-18 crack analysis. The initial crack length of the validation test coupon (7.62 mm) is near the critical crack length value at which the cracked part (of the aircraft) should be replaced. This is probably the reason why CG90 predicted early failures, the initial crack being too large.

![Figure 9.10: CG90 & AFGROW Predictions for Unpatched MARTEC Coupons](image)
9.4.2 FE Based Method

This section presents the crack growth predictions for Martec’s validation test coupons, calculated using the second approach presented in Section 7.2. AFGROW has been used with the Harter T-Method to calculate the cycles to failure of the coupons.

<table>
<thead>
<tr>
<th></th>
<th>Cycles to Failure</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Experimental</td>
</tr>
<tr>
<td>Unpatched Coupon</td>
<td>34420</td>
</tr>
<tr>
<td>Patched Coupon</td>
<td>82560</td>
</tr>
</tbody>
</table>

Table 9.14: FE Based Method Predictions for MARTEC Coupons

For a third time the importance of the thermal and bending effects is shown. The predictions calculated without the consideration of these effects were completely out-of-range for the three complex FE methods used.

9.4.3 Corrected FE Based Method

The predictions performed using the corrected FE based method are presented in Table 9.15. As for the FE based Method, AFGROW has been used with the Harter T-Method to calculate the cycles to failure of the coupons.

<table>
<thead>
<tr>
<th></th>
<th>Cycles to Failure</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Experimental</td>
</tr>
<tr>
<td>Unpatched Coupon</td>
<td>34420</td>
</tr>
<tr>
<td>Patched Coupon</td>
<td>82560</td>
</tr>
</tbody>
</table>

Table 9.15: Corrected FE Based Method Predictions for MARTEC Coupons

The crack growth predictions are shown in Figure 9.11 for the unpatched coupon and in Figure 9.12 for the patched coupon. In this latest figure, only the Foxtrot coupon results are presented in order to clarify the figure. All the predictions obtained for the patched configuration are conservative, such as seen for the DERA coupon repaired on one side.

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Figure 9.11: Complex FE Based Method Predictions for Unpatched MARTEC Coupons

Figure 9.12: Corrected FE Based Method Predictions for Patched MARTEC Coupons
9.4.4 Corrected FE Based Method including Crack Shape Effects

As it has been presented in the DERA section, an analysis including a correction for the crack shape has also been realized for the MARTEC coupon. The validation test coupon showed that the crack started at a 0° angle, and increased constantly to become near 30° prior the coupon’s failure (as it was shown in Figure 9.6c). A beta table has been built for a crack inclined at 0°, 31°, 50°, and an intermediate solution has been developed to represent the validation test observations, as shown in Figure 9.13.

Figure 9.13: Beta at Unpatched Side Fct. of Crack Inclination – MARTEC Coupon

Using the modified beta solution, which takes into account the crack front shape, the corrected FE based method resulted in an improved crack growth prediction. The results are presented in Table 9.16. The difference with the experimental data decreased from 23% to 14%, but the prediction shifted to the non-conservative side.
Table 9.16: Crack Shape Effect on Crack Growth Predictions for MARTEC Coupons

<table>
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<th>NISA/ENDURE / Diff. %</th>
<th>NISA/ENDURE &amp; Crack Shape / Diff. %</th>
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<tr>
<td>One Boron Patch</td>
<td>82560</td>
<td>63900 / 23</td>
<td>94250 / 14</td>
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The new prediction is longer by 30000 cycles (representing a 47% difference with the previous prediction). The crack growth curve obtained considering the crack shape is definitely in better agreement with the results obtained experimentally. The major difference is obtained at the end of the prediction, where the same phenomenon presented for the unpatched configuration is observed. Before the coupon’s failure, the crack growth rate predicted using the Harter T-Method is smaller than the one observed experimentally. The difference between the experimental data and the prediction could then mainly be attributed to the crack growth model improperly tuned near the coupon’s failure. The predictions with and without the crack shape effect consideration are presented in Figure 9.14.

![Crack Shape Effect on Crack Growth Predictions for MARTEC Coupons](image_url)

Figure 9.14: Crack Shape Effect on Crack Growth Predictions for MARTEC Coupons
9.5 Conclusion

In conclusion, the corrected FE based methods showed an evident improvement compared to conventional methods when performing fatigue life evaluation. However, when using the complex FE based methods, the thermal and bending effects have to be considered in the analysis in order to obtain accurate results. The shape of the crack front is important for one-sided repairs when out-of-plane displacements are observed, and needs to be considered for best crack growth predictions. Finally, the use of NISA/ENDURE along with the consideration of all the effects cited above yields to the best crack growth predictions.
CONCLUSION

The literature review led to two sources of crack growth data generated by DERA and AFIT. However since this data is not representative of typical CF-18 materials and loading, a validation test has been conducted in order to validate a new methodology of analysis for thick aluminum structures repaired using bonded composite doublers.

Numerous crack initiation and crack growth software packages were learned and compared to one another during the project. These software packages are either classified as conventional methods or as complex numerical methods (FEM or BEM). In the current project, the tool characteristics have been identified, and it has been shown that each tool has strengths and weaknesses.

The inaccuracy of classical crack growth estimation techniques has been quantified using simple test cases. An improved methodology has been developed and validated for the evaluation of the fatigue life of thick monolithic structures repaired using bonded composite doublers. FE based methods including thermal and bending effects showed excellent fatigue life predictions for both single and double-sided repairs. The shape of the crack front was found important for one-sided repairs when out-of-plane displacements are observed, and this effect should be considered for best crack growth predictions.

As a first recommendation, it is clear that a 2D approach without bending and thermal considerations cannot be used for one-sided repair configurations in order to obtain accurate crack growth predictions. For best results in crack growth predictions of one-sided repair problems with out-of-plane displacements, the effect of crack shape should be included in the analysis. Finally, it is recommended to use the improved methodology for thick structures repaired using bonded composite doublers. A decision tree reflecting the developed methodology is presented at the end of this conclusion for crack patching and fatigue enhancement problems.

As for future work, it is recommended to investigate the effect of load reduction on the crack front shape in patched thick structures. It has been recognized that the crack front shape may influence considerably the crack growth predictions when important stress variations are observed across the cracked structure's thickness. Means to predict the crack front shape as the crack grows could be very useful in complex 3D repair cases.
As a final comment, this project was the first to involve the Université de Sherbrooke, Martec Limited, and the Canadian Department of National Defence (DND) in a partnership research program. The collaboration of every partner has been crucial, and led to a complete project of very high quality. It proved that the partnership approach is a good approach for companies and government agencies to develop new technologies, and at the same time, provide interesting and challenging work for graduate students.
Crack Initiation Prediction of Thick Monolithic Structure Repaired using Bonded Composite Doubles

- One Sided
  - Nonlinear Geometric &/ or Material Problem
    - Yes: Complete 3D FE Nonlinear Analysis
    - No: Structure Free to Expand
  - No: Thermal Effect Evaluated by Martec's Previous Work
- Double Sided
  - One or Double Sided Repair
    - Yes: Thermal Effect Evaluated with Standard FE Method
  - No: Spectrum is Scaled Down According to L.T.
- Crack Initiation Analysis Performed using calibrated CI89 (for DND) and Modified Spectrum

Figure 10.1: Decision Tree for Crack Initiation Predictions
Crack Growth Prediction of Cracked Thick Monolithic Structure Repaired using Bonded Composite Doubler

Fracture Mechanics Analysis of Repaired Structure, performed with NISA/EENDURE

One Sided

One or Double Sided Repair

Double Sided

Nonlinear Geometric & / or Material Problem

No

Structure Free to Expand

Yes

Yes

Complete 3D FE Nonlinear Analysis

No

Thermal Effect Evaluated by Martec's Previous Work

Thermal Effect Evaluated with Standard FE Method

\[
\begin{bmatrix}
\beta'(a_1) \\
\beta'(a_2) \\
\beta'(a_3) \\
... \\
\beta'(a_n)
\end{bmatrix} = 
\begin{bmatrix}
(1 + \Psi(\sigma_{\text{max}},a_1)) \cdot \beta(a_1) \\
(1 + \Psi(\sigma_{\text{max}},a_2)) \cdot \beta(a_2) \\
(1 + \Psi(\sigma_{\text{max}},a_3)) \cdot \beta(a_3) \\
... \\
(1 + \Psi(\sigma_{\text{max}},a_n)) \cdot \beta(a_n)
\end{bmatrix}
\]

\[
\begin{bmatrix}
\sigma_1 \\
\sigma_2 \\
\sigma_3 \\
... \\
\sigma_n
\end{bmatrix} = 
\begin{bmatrix}
f(\sigma_1) \\
f(\sigma_2) \\
f(\sigma_3) \\
... \\
f(\sigma_n)
\end{bmatrix}
\]

Crack Growth Analysis Performed using Standard Crack Growth Tools & Including Previous Calculated Effects

Figure 10.2: Decision Tree for Crack Growth Predictions
ANNEX A: VALIDATION TEST PLAN
A.1 INTRODUCTION

A.1.1 Background

For the purpose of developing Martec capabilities in the composite repair field, a joint research project has been initiated by Martec Limited, the Department of National Defence (DND) and the Université de Sherbrooke. The centre of interest of this project is the fatigue analysis of thick monolithic aluminum structures repaired with composite bonded doublers.

Following the second progress review meeting of the project, it was decided to undertake a fatigue test at the Université de Sherbrooke. The main objective of this fatigue test was to provide experimental data to validate a new methodology of analysis of thick aluminum sections repaired with a composite doubler. Testing was performed on 7050 aluminum alloy using a representative CF-18 wing root bending moment spectrum.

This appendix will define the fatigue test activities. Specifically, this plan will address the test objectives and test concepts, such as instrumentation and data acquisition requirements as well as the specific test procedures. In addition, the test plan will define internal and external support and will provide the necessary management information to assure the efficient conduct of the fatigue test.

A.1.2 Objectives

The objective of the fatigue test on thick structures repaired using composite bonded doublers was to gather validation data for crack growth, from a coupon made of 7050 aluminum alloy, using a typical CF-188 spectrum loading.

A.1.3 Test Item Description

The coupon geometry is presented in Figure A-1. A total of eight specimens were tested: two unpatched and six patched (one side). The coupons were tested vertically using the set-up and instrumentation presented in Section A.2.2 & A.2.3. The spectrum loading that was used is presented in Section A.2.4.
A.1.4 Test Team

The Martec test team was comprised of the following personnel:

Mr. J.F. Roberge     Aerospace Group     Engineer-In-Training     (819) 595-3526
Mr. M.B. Zgela       Aerospace Group     Technical Authority     (819) 595-3526

The Université de Sherbrooke test team used for technical and test activity support was as follows:

Dr. K.W. Neale       U. de S.             Titular Professor       (819) 821-7752
Mr. M. Demers        U. de S.             Research Engineer      (819) 821-8000 ext. 1921
Mr. C. Aubé          U. de S.             Technician             (819) 821-8000 ext. 2103

In addition to the team members cited above, the help of QETE was required for their knowledge in the conduct of experimental tests.
A.2 TEST CONCEPT

A.2.1 Coupon Geometry

The coupon geometry is presented in Figure A-1. All the dimensions provided are in inches. Each coupon was made of 7050 aluminum alloy and had the following external dimensions: 559 mm (22 in) long, 159 mm (6.25 in) wide, and 19 mm (0.75 in) thick. The coupons were machined to have their longitudinal axis (load direction) aligned with the grain (rolling direction). A 2.54 mm (0.1 in) long notch was added at the centre of the coupon using Electrical Discharge Machining (EDM).

A.2.2 Test Methodology and Set Up

The test coupons were installed vertically using one of the test frames of the civil engineering department. These structures consist of two vertical channels fixed on the concrete floor and one horizontal channel bolted on the vertical channels. The height of the horizontal channel was adjusted according to the length of the coupons and of the hydraulic jack.

The hydraulic jack that was used has a capacity of 250 kN and a maximum travel of ±200 millimeters. This jack can be used for dynamic tests using a frequency up to 10 Hz. It was planned to use a frequency of 2 Hz for the present experimental test. The jack was controlled using a load cell of 250 kN; the instrumentation is presented in Section A.2.3. The jack installation included two ball joints to assure a uniaxial load in the test section.

The first part of the test consisted of pre-cracking the coupons. The coupons were pre-cracked at constant amplitude loading ($R=0.1$) with a maximum stress of 117 MPa (17 ksi). The pre-cracking ended when a crack length ($2a$) of 7.62 mm (0.3 in) was measured. Then, six coupons were sent to Hull for the patch installation.

After the pre-cracking part, the patches were installed, and the patched and unpatched coupons were fatigue tested using the spectrum loading defined in Section A.2.4. They were tested until the failure of the coupons was obtained.
A.2.3 Data Acquisition Requirements

The controller and data acquisition Testar II system was used during the tests. This software controlled the load applied on the hydraulic jack. The software TestWare SX was used to generate the load signal representing the spectrum loading.

The hardware used consisted of a Pentium type computer. The computer hard drive was used to store the output data coming from Testar II.

During the fatigue test, the crack length was measured using a shop microscope. This measuring instrument has a precision of 0.05 mm and was used without stopping the tests. For the patched coupons, the crack length was measured on the unpatched side. For the unpatched coupons, the crack length was defined as the maximum found on both sides.

A.2.4 Spectrum Loading Definition

The spectrum loading chosen was the spectrum coming from the wing root fitting of the CF-18. This spectrum counts 16427 turning points per block and represents 300 flying hours. It has a maximum value of 4497 micro-strains. This spectrum was used as input signal for the validation test.

For the purpose of the project, the negative values of the spectrum have been replaced by null values to avoid buckling problems. This positive spectrum was also used later in the numerical analyses.

Anti-buckling guides could have been used to avoid buckling problems, but the test installation was much simpler considering only the spectrum positive values. Removing the compressive values would have had a minimal effect on the fatigue life because the compressive loads only close the crack (load perpendicular to the crack). Also, anti-buckling guides would have had the effect to cancel the out-of-plane displacement due to the eccentricity of the repair. This out-of-plane displacement is nonlinear and was required to evaluate the capabilities of the nonlinear tool (NISA).
A.3 TEST PLAN

A.3.1 Test Installation

As mentioned in Section A.2.2, the coupons were installed vertically using a test frame of the civil engineering department. The height of the horizontal channel was adjusted to obtain the hydraulic jack in his ¼ opened position.

The coupons were attached to the load cell (located between the coupon and the jack) and to the lower attachment part using two steel grips. These grips were machined at the Université de Sherbrooke. A total of 10 steel bolts of 25.4 mm of diameter were needed for the assembly.

Two ball joint systems were included into the installation: one is present in the lower attachment part, and the other one is included in the jack to horizontal channel attachment fitting.

The lower attachment part was bolted on a 50 mm thick steel plate, which was bolted on the 1.0 meter thick concrete floor of the civil engineering laboratory.

A.3.2 Load Cell Calibration

The load cell that was used was already calibrated by the manufacturer and did not require to be calibrated again. However to assure accurate results, the load cell was calibrated once before the crack initiation phase.

A.3.2 Applied Loads

As mentioned in Section A.2.4, the spectrum that was used was a CF-18 spectrum loading. In order to convert the spectrum strains to stresses, the following equation was used (assuming uniaxial loading):

\[ \sigma = E \cdot \varepsilon \]  \hspace{1cm} (A.3.1)

where:

\[ E = \text{Modulus of elasticity in tension of 7050 aluminum alloy.} \]
The resulting stresses were converted to equivalent loads using the following equation:

$$P = \sigma \cdot A$$  \hspace{1cm} (A.3.2)

where:

$$A = \text{Test section area (121 mm wide by 6.35 mm thick)}$$

The equivalent positive spectrum was introduced in the TestWare SX software in order to generate a Testar II spectrum loading file, which was used for the tests.

### A.3.4 Crack Length Monitoring

The crack length was measured using a shop microscope without stopping the tests. For the patched coupons, the crack length was taken on the unpatched side. For the unpatched coupons, the crack length was taken as the maximum found on both sides.

For both patched and unpatched coupons, the crack length was measured at each 1000 cycles. The monitoring was done until the failure of the coupons occurred.

### A.3.5 Dummy Specimen

In order to verify the test setup and the test installation, a dummy specimen made of 6061-T6 aluminum alloy was used. This specimen was machined at the Université de Sherbrooke and had the same dimensions as the coupon presented in Figure A-1.

Using the positive spectrum loading, the dummy specimen was fatigue tested until the coupon's failure occurred. This was performed to assure that no problem would happen with the test installation. The spectrum was scaled down in order to take into account the lower yield and ultimate strength of the 6061-T6 (compared to 7050).
A.4 MANAGEMENT ORGANISATION

A.4.1 External Support

DTA 3-8 / QETE made the following equipment available for testing:

- Material for eight coupons of 7050 aluminum alloy as per Figure A-1. QETE also performed the centre notches using the electrical discharge machining technique.

The Université de Sherbrooke made the following equipment available for testing:

- Test frame
- Hydraulic jack of 250kN & load cell
- Hardware & software packages necessary to test
- Steel grips (Qty 2)
- Dummy specimen

The SMS (Service de Mécanique Spécialisée) performed the machining of the validation test coupons.

A.4.2 Internal Support

Martec Limited was responsible for the patch installation and provided engineering support for all the test activities.

A.4.3 Test Schedule

All the tasks necessary to achieve the objectives cited in Section A.1.2 are presented in the schedule at the next page. This fatigue test was scheduled to be completed by the end of November 2000.
### Fatigue Evaluation of Thick Monolithic Aluminum Structures Repaired Using Composite Bonded Doublers
#### Validation Test Plan

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**Project: Fatigue Test**
**Date: Sat 5/5/01**
ANNEX B: PROJECT DRAWINGS
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LAMINATE LAY UP AS FOLLOWS:

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TWO LAYERS OF FM730O DSM ADHESIVE
3. SURFACE PREPARATION: Grit Blast, Silane, BR/27
4. SURFACE PREPARATION AS PER 8-25 INSTALLATION PROCEDURE
BIBLIOGRAPHY


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