Life extension of Structural Repairs – A statistical approach towards efficiency improvement

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Abstract: The life extension program of aircraft is taken up whenever aircraft’s intended life reaches close to its DSG (Design Service Goal). The Extended Service Goal (ESG) of an aircraft, in general, and structural repairs, in particular, is arrived at on the basis of F&DT (Fatigue & Damage Tolerance) analysis. Life extension program of aircraft consists of assessment of remaining life of all parts of the aircrafts including structural, mechanical, and electrical and avionics equipment and structural repairs. For life extension of stringer repair, as an example, it is required to re-assess the fatigue life of stringer in the presence of coupling under modified load spectrum. This is achieved by assessing the fatigue life of Web and Outer Flange (OF) part of stringers separately as per F&DT justification philosophy. Assessment of the fatigue life requires determination of stress concentration factor (Kt) for different combination of width, pitch, stringer thickness, coupling thickness and pad-up thickness of all stringer profiles available in different sections of fuselage. Determination of stress concentration factor for Web and Outer Flange of stringer profile covering entire ranges involves substantial number of Finite Element (FE) analysis. In order to optimise the number of FE runs, stress concentration factor is determined under worst repair factors combination (max. plate width; max. thickness; max. pitch; min. rivet dia.; and min. No. of rivets) resulting in conservative value. A parametric study of Web and Outer Flange data across stringer profiles were carried out and proven statistical techniques were used to find the optimal equation to predict stress concentration factor. This in turn reduced number of FE runs substantially for a given range of width, pitch, stringer thickness and so on. The use of optimal equation obtained through regression analysis is able to predict Kt within reasonable accuracy for a given range of inputs.

1. Introduction
Damage to aircraft structures is often caused by corrosion, erosion, incidents, accidents and mishaps. Sometimes modifications to aircraft structure require extensive structural rework. For example, the installation of winglets on aircraft not only replaces a wing tip with a winglet, but also requires extensive reinforcing of the wing structure to carry additional stresses [1].

Structural repair is defined as a design change to an aeronautical product intended to restore it to an airworthy condition and to ensure that the aircraft continues to comply with the design aspects of the airworthiness requirements used for the issuance of a Type certificate for that aircraft type after it has been damaged [2]. When a structural damage is detected, usually one of the following decisions is taken on the basis of severity of damage vis-a-vis structural repair manual:

- No-repair
- Cosmetic or sealing repair to correct minor damage.
Structural repair due to reduction of strength below the design limits

Un-economical for the repair leading to replacement

Structural repair plays a key role to ensure the structural integrity of aircraft throughout its intended operational life. When a group of lead aircraft approaches its DSG (Design Service Goal), life extension program of aircraft involving assessment of remaining life studies of all parts is taken up individually. Since structural repair also influences the structural integrity of aircraft, it is also mandatory to evaluate its life as per regulation. The Extended Service Goal (ESG) of an aircraft, in general, and structural repairs, in particular, is arrived at on the basis of F&DT (Fatigue & Damage Tolerance) analysis as well as tests under modified load spectrum.

The present paper provides an overview of methodology involved in the exercise of life extension of a typical structural repair under 3rd line item (from above) as an example to demonstrate how effectively the statistical approach helps in improving the efficiency substantially without compromising quality of results.

2. Structural Repair Manual

Structural Repair Manual (SRM) of aircraft provides general procedures, identification of structures, allowable damage limits and specific instructions for repair to those parts of the airframe that are most likely to be damaged [3].

SRM also gives the dimensional limit to the damage to aircraft structure and it provides the approved repair method or repair scheme and approved materials to be used to repair the damage occurred at different section as per ATA Chapters. Typical structural repairs that cover in SRM for fuselage are:

- External Structure – Skin
  - Skin Lightning Strike Repairs
  - External Skin Repairs (small, limited, unlimited, and conversion of temporary skin repairs)
  - External Skin Repair (Longitudinal joint, Circumferential joint)
  - Internal Skin repairs (small, limited, and conversion of temporary skin repairs)
  - Door Surround Skin Repair
  - Bush Skin Repair
  - Plug Repair

- Internal Structure
  - Stringer Repair
  - Frame Repair
  - Cross-beam Repair

Subsequent to catastrophic failure of aircraft happened in aviation history in the past due to inappropriate repairs (available in open literature), following conclusions/amendments were made:

- In-service repairs can influence the damage tolerance of aircraft significantly
- Fatigue justifications are required for existing repairs of oldest aircraft
- Damage tolerance certification of repairs has become mandatory
- In-service repairs are subjected to inspection programmes as per those for the original un-repaired structure
- Regulations for repair are introduced
- Life extension of repair is also to be taken up as a part of aircraft life extension program
3. Extended Service Goal (ESG)

When an aircraft is approaching the Design Service Goal limitation, it is either withdrawn from service or the lease of life is provided based on detail analysis and tests undertaken during the Extended Service Goal program.

The Extended Service Goal will enable customers to earn additional revenue by flying their aircraft for longer, as well as benefiting from the increased residual value of their fleet. In addition, operators will have the opportunity to upgrade their fleet to keep in-service aircraft at the highest level of efficiency.

Life Extension activities include a general review of the fatigue and damage tolerance analysis prepared for type certification, interpretation of full scale fatigue test findings, tear down results and Service Bulletin (SB) review with respect to extended service goals. As a part of life extension of aircraft exercise program, following items are taken up individually:

- Airframe
- Landing Gear
- Aero Engines
- Rotables
  - Mechanical equipment
  - Electrical & avionics equipment
- Perishable Items
  - Rubber seals and hoses
- Structural Repairs

With regard to structural repairs are concerned, the impact of the ESG loads on existing repairs in the fuselage structure are re-assessed for extended service goal requirements. Generally Fatigue & Damage Tolerance (F&DT) justification is performed for ESG requirements.

ESG exercise of a typical stringer repair is considered in the present paper to demonstrate the usefulness of statistical approach towards efficiency improvement.

4. Methodology for Stringer Repair

Stringers, running in the longitudinal direction of the fuselage, are internal structures of the aircraft (Figure 1) and are fastened to the fuselage through a series of rivets.

![Figure 1. Stringer location on aircraft fuselage](image-url)
As a part of life extension of stringer repair, it is required to re-assess the fatigue life of stringer in the presence of coupling under modified load spectrum (Figures 2 & 3)

![Damaged Stinger and Repaired with coupling](image1)

**Figure 2.** Repaired stringer with coupling

![Side view and Web & OF parts of a stringer](image2)

**Figure 3.** Side view of a stringer  
**Figure 4.** Web & OF parts of a stringer

Re-assessment of fatigue life is done for both Web and OF separately (Figure 4) as per F&DT justification philosophy. Determination of stress concentration factor ($K_t$) for a two plates system (for Web-stringer & coupling) or three plates system (for OF-skin, stringer & coupling) is one of the important parameters required for re-assessment of fatigue life under modified load spectrum.

As per the process for life extension program of stringer repair, it is required to determine $K_t$ for different combination of width, pitch, stringer thickness, coupling thickness, rivet diameter and pad-up thickness of all stringer profiles available in different sections of fuselage. Moreover, the recalculated fatigue life should cover all combination of repair scenarios possible for a given repair at different location of the fuselage.

For the given case in the present study, fuselage of a particular passenger aircraft contains 60 plus different stringer profiles with number of variations in geometry parameters.

There will be a range of values existing in 2 different stringer materials of the web over 60 plus stringer profiles. Similarly, same order of variations are existing in OF corresponding to profiles.

The determination of stress concentration factor of 2 plates joint model (Web) or 3 plates joint model (OF) covering entire ranges involves substantial number of FE runs. In order to optimise the number
of runs, stress concentration factor is determined under worst condition scenario based on parametric study of different parameters that affects stress concentration factor such as rivet diameter, width, pitch, stringer thickness, coupling thickness and in addition pad-up thickness in the case of OF. Typical worst scenario conditions that results in maximum stress concentration factor are maximum width, maximum pitch, maximum thickness combination of stringer & coupling (mean thickness), minimum rivets diameter and maximum pad-up thickness (in case OF only). In the process, the predicted life at most of the cases (locations) does not meet the target life due to use of conservative $K_t$ value obtained under worst condition scenario.

In the present paper, efforts were made to make use of relevant statistical modelling and analysis for possibility of bringing in efficiency enhancement in terms of reducing number of FE analysis substantially. Also upon successful statistical modelling of stringer data across profiles for an aircraft, the same can be horizontally deployed for other aircrafts for a given set of pre-defined values for each geometric parameter.

5. Statistical approach towards efficiency improvement

5.1. Overview of the approach:

Aircraft structure getting damaged during its service is inevitable. A multimillion dollar aircraft’s utilization after DSG is essential from cost optimization point of view and also to address gradual and rapid increase in volume of traffic. In such a situation, it is imperative that fatigue analysis is done for all internal and external components of aircraft and meet airworthiness requirement and qualify the aircraft for ESG. Fatigue life assessment was done using deterministic approaches. Instead of that, statistical approach in determining the stress concentration factor was used, which is more probabilistic in nature.

5.2. Statistical analysis:

Stringer data for aircrafts that were undergoing ESG captured over a period of time was taken up for a systematic study. This study included factors such as:

- Geometrical dimension of the stringer profile data
- Material used for coupling the damaged stringer
- Rivet diameter

The stringers have numerous profiles and various dimensional parameters like pitch, thickness, width that impacts stress concentration factor ($K_t$). The permutation and combination of these parameters ran into large number of data sets, hence stringers was chosen as the first part for this study as they are more in volume and present in every aircraft. Also upon successful statistical modelling of stinger data across profiles for an aircraft, the same can be deployed for other aircrafts for a given set of pre-defined dimensions for each parameter without the need for revalidation.

5.3. Objective of the statistical analysis of stinger data:

$K_t$ is determined for stringer (with coupling) corresponding to each profile to determine the fatigue life of the aircraft structure. In order to optimise number of FE runs, $K_t$ is determined under worst repair scenario which is a very conservative approach. In the process, the predicted life at most of the cases (locations) does not meet the target life due to conservative $K_t$ value. Instead, based on parametric study and statistical analysis, optimum equation for $K_t$ can be derived for a combination of geometry without compromising the level of accuracy of $K_t$ and also reduce number of FE runs and thereby improve efficiency of the team involved in re-assessing of stringer repair’s life through conventional approach.

Note: Regression analysis is a statistical technique that attempts to estimate the relationships among variables and relationship between a dependent and multiple independent variables (1Y and multiple
X’s). It provides cause and effect relationship between X’s (predictors) and Y (response) [4]. Understanding the relationship between X and Y can be further extended in having a meaningful use of the relation to predict the future.

Tools used:
MS Excel, OEM specific tools for $K_t$ generation for certain combination of geometrical parameters of web and outer flange and R tool was used for the statistical modelling, as it provides variety of analysis & is highly extensible.

5.4. Parametric study of stringer parts

![Comparison of Web Parameters for Two Aircrafts](image1)

**Figure 5.** Comparison for WEB (indicative numbers)

![Comparison of Outer Flange Parameters for Two Aircrafts](image2)

**Figure 6.** Comparison for OUTER FLANGE (indicative numbers)
5.5. Understanding key characteristics that impact $K_t$

In order to derive at an equation that predict the behaviour of $K_t$, it was important to understand which of the key characteristics that really impact from statistical angle.

All predictors were subjected to Hypothesis Test at every level of classification, i.e. does change in profiles, material, rivet pitch etc. impact $K_t$.

Via hypothesis test, it was evident that only geometrical dimensions impact $K_t$ for a given fastener diameter, whereas material of stringer/coupling and stringer profile does not impact $K_t$.

Prediction models were built using statistically qualified predictors. Available range of data was considered at minimum, average and maximum values for each parameters. $K_t$ was determined for two combinations: $Y = f(X_1, X_2, X_3)$ for Web and $Y = f(X_1, X_2, X_3, X_4)$ for OF, where $Y = K_t$.

- $X_1 = \text{Width}$
- $X_2 = \text{Pitch}$
- $X_3 = \text{Pad-up thickness (Skin)}$
- $X_4 = \text{Mean Thickness (Average thickness between stringer (S) and coupling (C))}$

5.6. Regression output for WEB

From table 1, it is evident that range of width is split into two. This is done to ensure that prediction accuracy doesn’t get compromised in order to accommodate the entire geometrical range for individual parameters.

| Fastener Diameter in mm | Width in mm [X1] | Pitch in mm [X2] | Mean Thickness in mm [X3] | Coefficient of determination ($R^2$) |
|-------------------------|------------------|------------------|---------------------------|----------------------------------|
| 4                       | 20, 30 & 40.9    | 20, 30 & 40      | 1.5, 3.1 & 4.6            | 99.89%                           |
| 4                       | 41 & 50          | 20, 30 & 40      | 1.5, 3.1 & 4.6            | 100%                             |
| 4.8                     | 20, 30 & 40.9    | 20, 30 & 40      | 1.5, 3.1, & 5.1           | 99.99%                           |
| 4.8                     | 41 & 50          | 20, 30 & 40      | 1.5, 3.1, & 5.1           | 99.99%                           |

Table 1. Outcome from regression for Web

| Source                         | DF | Sum of Squares | Mean Square | F Value | Pr > F |
|--------------------------------|----|----------------|-------------|---------|--------|
| Model                          | 3  | 25.80220       | 8.60073     | 115195  | <.0001 |
| Error                          | 14 | 0.00105        | 0.00007466  |         |        |
| Corrected Total                | 17 | 25.80325       |             |         |        |

Table 2. Regression model output for rivet diameter 4 mm

| Variable          | Parameter Estimate | Standard Error | t Value | Pr > |t| |
|-------------------|--------------------|----------------|---------|------|---|
| Intercept         | 4.49633            | 0.02255        | 199.38  | <.0001|
| Pitch             | 0.00567            | 0.00024944     | 22.72   | <.0001|
| Mean Thickness    | 0.94508            | 0.00161        | 587.37  | <.0001|
Figure 7. Model diagnostics

Inference:
- Result is achieved through multilinear regression with two-level-interaction between the predictors
- Co-efficient of determination $R^2$ was at close to 1, which implies best prediction.
- Overall P and individual P value of all predictors is < 0.05, which validates the hypothesis.
- It was possible to achieve < +/-1% error between observed and predicted for a given range of predictors, which is acceptable prediction from engineering accuracy point of view.
- Prediction accuracy % at less than +/-1 is critical considering that the fatigue life reduces exponentially with every decimal increase in prediction accuracy beyond +/-1%.
- Table 3 shows a typical comparison of predicted (using equation) and theoretical results (obtained through FE analysis) of Kt for different combination of width, pitch and mean thickness for the Web (4.0 mm rivet dia.) which are not a part of pre-defined data set.

| Width in mm [X1] | Pitch in mm [X2] | Mean Thickness in mm [X3] | $K_t$ predicted | $K_t$ through FE analysis | % Error |
|------------------|------------------|---------------------------|------------------|---------------------------|---------|
| 21               | 27               | 2.1                       | 4.88             | 4.86                      | 0.4%    |
| 25               | 27               | 4.1                       | 6.09             | 6.06                      | 0.4%    |
| 25               | 30               | 1.7                       | 4.95             | 4.96                      | -0.2%   |
| 27               | 27               | 2.3                       | 5.53             | 5.56                      | -0.5%   |
| 27               | 30               | 2.5                       | 5.69             | 5.72                      | -0.5%   |
5.7. Regression output for OUTER FLANGE

Table 4. Outcome from regression for OF

| Fastener Diameter in mm | Width in mm [X1] | Pitch in mm [X2] | Thickness (skin pad-up) in mm [X3] | Thickness - OF in mm [X4] | Coefficient of determination (R²) |
|------------------------|------------------|------------------|-----------------------------------|--------------------------|----------------------------------|
| 4                      | 21,30,40,9       | 21,30 & 40       | 1.6,3,6                           | 1.9,4.5                  | 99.71%                           |
| 4                      | 40,50            | 21,30,40,50      | 6,12                              | 1.9,3.5                  | 99.46%                           |
| 4.8                    | 21, 30 & 40      | 21,30 & 40       | 2.2,6,12                          | 1.9,4.5                  | 99.62%                           |

Inference:
- For the 3 plates system (OF), it was possible to achieve <+/− 2% error between observed and predicted for a given range of predictors.
- It is achieved through multilinear regression with two-level-interaction between the predictors.
- Containing error % at less than +/-1 is critical, but it was not possible to achieve in present exercise as it is a 3 plates system with additional predictor influencing the K_f.

Note: Similar to web, validation of observed and predicted K_f were carried out for outer flange for intermediate levels for each of the parameter and results were in line with pre-defined levels used for model building.

Table 5. Sample comparison of efforts resulting in saving due to statistical analysis approach

| Part | Effort w/o Improvement [Hours] | Effort with Improvement [Hours] | Total Efforts [Hours] | No. of FE runs | No. of FE runs using regression analysis | % saving in efforts |
|------|-------------------------------|-------------------------------|-----------------------|----------------|----------------------------------------|-------------------|
| Web  | 16                            | 4                             | 20                    | 106 runs       | 45 runs                                 | 57%               |
| OF   | 40                            | 56                            | 96                    | 230 runs       | 108 runs                                | 53%               |

For the given ESG program exercise for stringer repairs of an aircraft containing 60 plus profiles, 106 FE runs, based on the worst case scenario conditions were made which took 16 hours of efforts for re-calculation of fatigue life based on K_f results. Since FE analysis results in conservative K_f value due to consideration of worst case scenario conditions, some of locations did not meet the required target life. Therefore, additional efforts of 4 hours were spent in improving the results by re-calculating K_f in FE using actual geometry parameters at those locations. A total of 20 hours were spent to cover the entire profiles with all sort of geometry parameter combinations existing in the fuselage of the aircraft in the process of re-calculation of fatigue life. Percentage of effort saving is calculated based on the number of FE runs (45) required to carry out regression analysis to obtain the optimum equation compared to the number FE runs (106) made to obtain the conservative K_f value. The percentage effort saving stands at 57% for web. Efforts involved in the calculation of fatigue life is ignored as it involves excel based calculation sheet corresponding to all combinations of geometry parameters. Similar case of effort saving of 53% was witnessed for OF, which is very significant in terms of saving man hours & software usage.

6. Concluding Remarks
- Overview of methodology for life extension of stringer repair is outlined from aircraft industry practice point of view and F&DT justification is the basis for life extension of structural repairs.
• Statistical tool is used to develop regression analysis for prediction of $K_t$ based on limited number of FE runs required for determination of stress concentration factor
• The correlation between the predicted $K_t$ and $K_t$ obtained through FE analysis is found to be excellent with error well within 1% for Web for a given range of pre-defined data set
• The correlation between the predicted $K_t$ and $K_t$ obtained through FE run is found to be good with error well within 2% for OF for a given range of pre-defined data set
• Optimum equation for prediction of $K_t$ for both Web & OF is achieved through multilinear regression with two-level-interaction between the predictor
• Substantial benefit, in terms of reduction in number of FE runs and thereby huge time saving can be realized while carrying out similar exercise for other a/c program provided they are within pre-defined data set
• In the present study, the effect of secondary bending moment in joint model is ignored as per F&DT justification philosophy.
• Error percent between predicted $K_t$ and observed $K_t$ of up to 2% is not considered to be exceptionally good outcome in case of outer flange since the impact of fatigue life is considerable with increase in error percentage, this will be considered for further refinement and analysis.

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References
[1] Aircraft Metal Structural Repair, Aviation Maintenance Technician Handbook Volume 1, 2008
[2] AIRWORTHINESS ADVISORY CIRCULAR, AAC No. 2 of 2013 Dated 20th January, 2013, Government of India, Civil Aviation Department, Director General of Civil Aviation
[3] Structural repair manuals are customer specific, hence online references alone can be used.
[4] Understandable statistics concepts and methods by Brase