Design and Stress Analysis for Aircraft Structure Repair Beyond Specification

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Abstract: The airline structure design engineers often need to design repairs to restore structural integrity for conditions not covered in the Structural Repair Manuals (SRM) provided by the OEM. This is normally called repair beyond specification. Reasons for having to modify a SRM repair include: variations in local structural configuration, limitations on space and variations in fastener usage or availability, and so on.

As the local design loads are always unavailable for airline design engineers, the principle for repair design is to restore the ultimate static strength and the equivalent fatigue life.

Through an example of a chord structure repair design, this paper provides an integrated methodology to design aircraft structure repairs beyond specification.

The repair design is based on static analysis. In order to determine the minimum number of fasteners to fulfill the ultimate static strength requirement, the general failure modes for the joint structure and the approach to get its allowable is described.

Since the end fasteners transfer more load than the center fasteners when parts are below yield, a joint modeling method is used to calculate the joint load distribution for the operating fatigue load. Based on the load distribution of the critical end fasteners and their geometry properties, the fatigue life could be calculated with a professional DTA (Damage Tolerance Analysis) software AFGROW. The results would be compared to the recommended SRM repair to check whether the fatigue life could be restored.

Following the method provided in this paper, engineers could design repairs which can restore the integrity of the damaged aircraft structures.

Keywords: *repairs beyond specification; fatigue life; damage tolerance analysis*

Abbreviations: DTA: Damage Tolerance Analysis; SRM: Structural Repair Manuals;

MMPDS: Metallic Materials Properties Development and Standardization;

1. Overview

The airline structure design engineers often need to design repairs to restore structural integrity for conditions not covered in the Structural Repair Manuals (SRM). This is normally called repair beyond specification. Reasons for having to modify an SRM repair include: variations in local structural configuration, limitations on space and variations in fastener usage or availability.

As the local design loads are normally unavailable for airline design engineers, the principle for repair design is to restore both the ultimate static strength and the equivalent fatigue life. In other words, the design loads for repair are usually determined either by the ultimate capability of an adjacent joint or by the ultimate strength of the damaged material.

Chord is one of the typical type of aircraft structure which popularly exists in stringers, frames, floor beams etc., therefore, damage on chord is one of the most common types of damage on aircraft structure. Figure 1 shows an example of chord corrosion damage. Through an example of a chord structure repair design, this paper provides an integrated methodology to design aircraft structure repairs beyond specification.

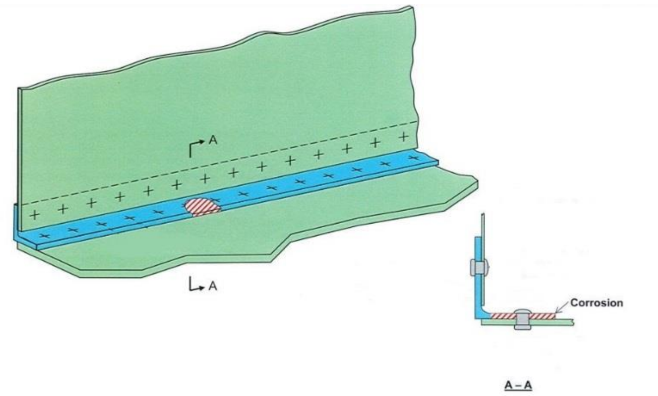

Figure 1 Chord Corrosion

2. Issues to be considered

Generally, when the damage is extensive along the width of the structure, the damaged section need to be totally removed and replaced by a splice.

Following the principle of restoring the ultimate static strength as well as the equivalent fatigue life, two issues need to be taken into account for repair design.

(1) Static issue:

Whether both the repair joint allowable and the splice load capability are equal or higher than the repair design loads?

(2) Fatigue issue:

Whether the fatigue life of the repair joint is equal or higher than the approved repair in SRM?

3. Repair design and analysis

Structure repair should be designed based on the approved data in SRM as well as the two issues mentioned above.

The basic procedure for aircraft structure repair design is summarized as shown in Figure 2.

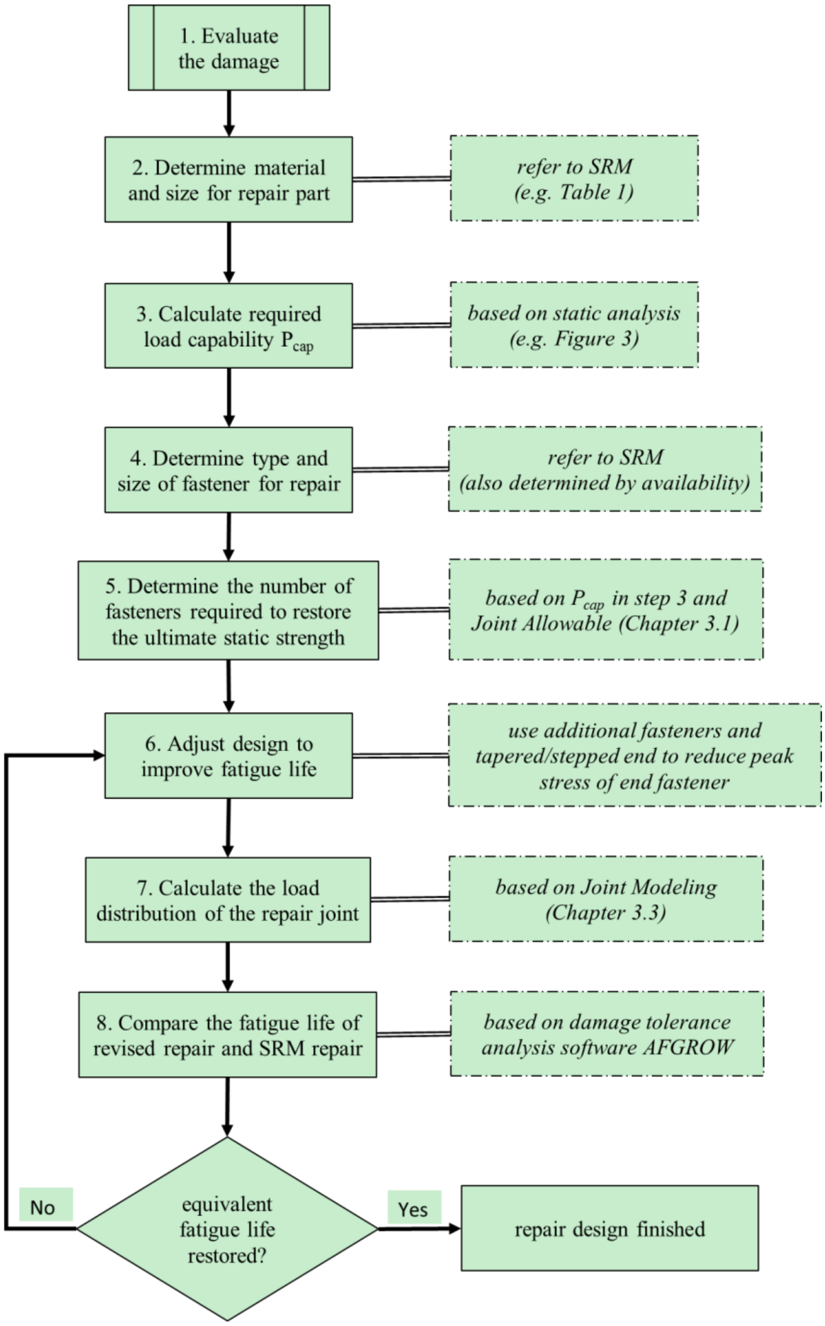

Figure 2 general procedure for aircraft structure repair design

In addition, there are also some other general steps including checking the fastener pitch, row spacing, edge margin, calculating the fastener head clearance, processing corrosion protection with sealing and surface finish etc. All these steps do not need stress analysis and therefore won't be discussed here.

3.1 Joint Allowable

Joint allowable is to be used to calculate the number of fasteners required to restore the ultimate strength.

The basic joint failure modes include 1) Net Area Tension; 2) Tear Out; 3) Bearing; 4) Fastener Shear. The overall joint capability is equal to the lowest allowable load of all the failure modes which is called the critical failure mode. Normally, there are two ways to determine the joint allowable.

3.1.1 Joint Allowable equations

According to the MMPDS, the equations for the four failure modes can be used alone to accurately estimate the capability of joints if all the following criteria are met:

1) The fastener is solid (no hollow shanks or heads);

2) For single shear, the fastener must be a tension protruding head bolt;

3) For double shear, the fastener must be a bolt;

4) The sheet thickness to fastener diameter ratio (t/D) must be equal to or greater than 0.18;

Figure 3 shows the failure modes for joint and is followed by the corresponding joint allowable equations.

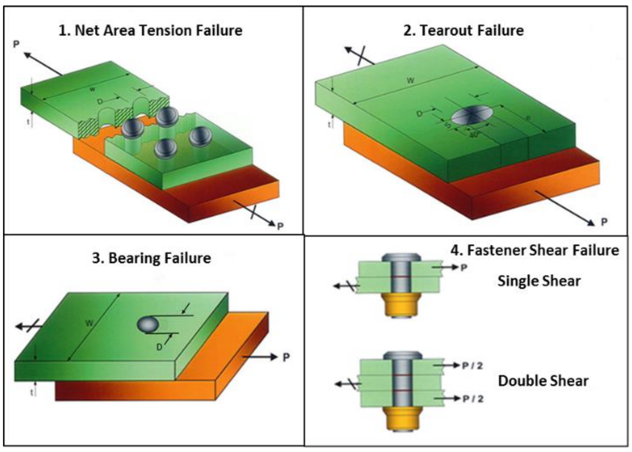

Figure 3 Joint Failure Modes

1. $P_{net} = F_{du} \times A_{net} = F_{du} \times (w - n_{fast} \times D) \times t$

2. $P_{tearout} = F_{su} \times 2 \times (e - S) \times t = F_{su} \times (2 \times e - 0.766 \times D) \times t$

3. $P_{brg} = F_{brg} \times D \times t$

4. $P_{SS} = F_{su} \times A_{shank} = F_{su} \times \pi \times D_{shank}^2/4$

5. $P_{DS} = 2 \times F_{su} \times A_{shank} = 2 \times F_{su} \times \pi \times D_{shank}^2/4$

Where:

w = width of cross-section, perpendicular to applied load (in)

n_{fast} = number of fasteners in cross-section

D = hole diameter (in)

t = plate thickness (in)

F_{du} = lesser of F_{tu} or $1.5 \times F_{ty}$ (psi)

$S = D / 2 \times \cos 40° = 0.383 \times D$ (in), 40° angle is determined from test

F_{su} = shear ultimate allowable (psi)

e = edge margin (in)

F_{brg} = lesser of F_{bru} or $1.5 \times F_{bry}$ (psi)

D_{shank} = fastener shank diameter (in)

3.1.2 Joint Allowable Tables

Tests must be conducted to determine joint strength for those joints that do not meet the criteria. A lot of data is available in MMPDS as well as in SRM.

3.2 Load distribution

Load distribution in a joint is comprised of bearing and bypass loads. Bearing load is the force applied through a fastener into a fastener hole. Bypass load is the remainder of the joint load not reacted by the fastener.

Load distribution would change when the applied load increases. Generally, end fasteners transfer more load than the center fasteners when parts are below yield. The load would be redistributed after the parts yielding until each fastener reach its ultimate load capability.

As a result, the ultimate capability of a multiple-fastener joint is assumed to be equal to the sum of the joint capabilities at each fastener location. The static analysis for repair design is based on this assumption. Regarding to DTA, as the fatigue load belongs to operating load which is on the level below parts yield, the load distribution need to be calculated through joint modeling.

3.3 Joint Modeling

Testing has shown that the fatigue life of a joint is a function of both the bearing and the bypass load at a given fastener location. The joint modeling is to be used to get the bearing and bypass load.

Joints may be modeled mathematically using a series of springs as shown in Figure 4. Springs simulate the stiffness of fasteners and plates in load direction.

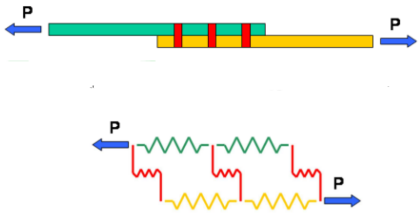

Figure 4 Example of a Joint model

3.3.1 Spring Compliance for Plates

The spring compliance for plate segments between fasteners could be easily calculated with the following equation:

$$C_{plate} = L/(A \times E)$$

Where:

C_{plate} = plate spring compliance (in/lb)

L = fastener spacing in direction of load (in);

A = cross-sectional area of plate between fasteners (in^2), A = w × t;

E = modulus of elasticity of the plate material (psi);

w = fastener spacing perpendicular to load (in);

t = plate thickness (in).

3.3.2 Spring Compliance for Fasteners

Numerous methods have been proposed for fastener spring compliance calculation. One commonly referenced paper that include equation for fastener compliance is FAA-AIR-90-01 written by Tom Swift. Other popularly used methods include Huth equation and a non-proprietary Boeing research paper written in 1969 on the stress severity factor concept.

Tom Swift equation: $C_F = [A + B \times (D/t_1 + D/t_2)]/(D \times E)$

Where:

C_F = fastener spring compliance (in/lb)

A = 5.0 for aluminum fasteners; 1.666 for steel fasteners

B = 0.8 for aluminum fasteners; 0.86 for steel fasteners

D = fastener diameter (in)

E = modulus of elasticity of the plate material (psi)

t1 = plate 1 thickness (in)

t2 = plate 2 thickness (in)

The Tom Swift equation has some limitations such as the fasteners may only be steel or aluminum and the plates must be of the same material.

For material types not covered by the Swift equations, the following equation is preferred.

$$C_F = \frac{4(t_i + t_j)}{9G_b A_b} + \frac{t_i^3 + 5t_i^2 t_j + 5t_i t_j^3 + t_j^3}{40E_{bb} I_b} + \frac{1}{t_i}(\frac{1}{E_{bb}} + \frac{1}{E_{ibr}}) + \frac{1}{t_j}(\frac{1}{E_{bb}} + \frac{1}{E_{jbr}})$$

where:

C_F = fastener spring compliance (in/lb)

t_i = thickness of plate i (in)

t_j = thickness of plate j (in)

G_b = shear modulus of the bolt material (psi)

A_b = cross-sectional area of the bolt (in^2)

E_{bb} = modulus of elasticity of the bolt material (psi)

I_b = moment of inertia of the bolt cross-section (in^4)

E_{ibr} = modulus of elasticity of plate i (psi)

E_{jbr} = modulus of elasticity of plate j (psi)

3.3.3 Load distribution calculation

Joint modeling deflection equations are shown in Figure 5 and the equations below.

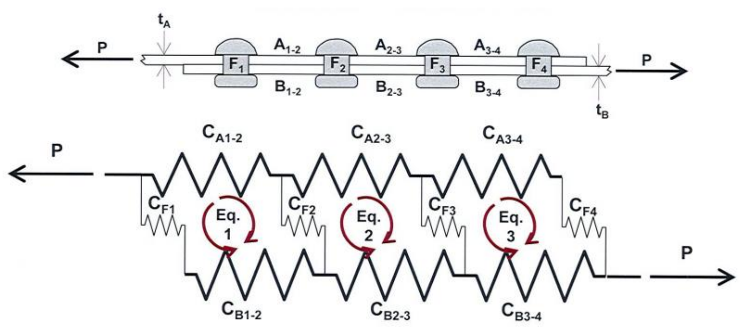

Figure 5 Joint modeling deflection equations

Equation 1: $C_{A1-2} \times (P - P_{F1}) + C_{F2} \times P_{F2} = C_{F1} \times P_{F1} + C_{B1-2} \times \ P_{F1}$

Equation 2: $C_{A2-3} \times (P - P_{F1} - P_{F2}) + C_{F3} \times P_{F3} = C_{F2} \times P_{F2} + C_{B2-3} \times (P_{F1} + P_{F2})$

Equation 3: $C_{A3-4} \times (P - P_{F1} - P_{F2} - P_{F3}) + C_{F4} \times P_{F4} = C_{F3} \times P_{F3} + C_{B3-4} \times (P_{F1} + P_{F2} + P_{F3})$

Equation 4: $P_{F1} + P_{F2} + P_{F3} + P_{F4} = \mathrm{P}$

Solving these equations can be done manually or with an existing FE software.

4. Instruction Case

A fictitious chord repair design is presented in this chapter to describe the whole process. MS Excel is a good tool for the related calculating work.

An upper chord of floor beam has been damaged due to corrosion (Figure 6). SRM repair is shown in Figure 7. Since the steel fastener BACB30FN8 is not available and the end fastener F7 would interfere with the seat track attach fitting, a revised repair need to be designed to restore the ultimate static strength and fatigue life.

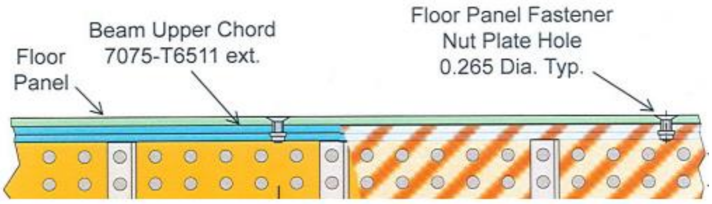

Figure 6 Floor Beam Upper Chord Corrosion Damage

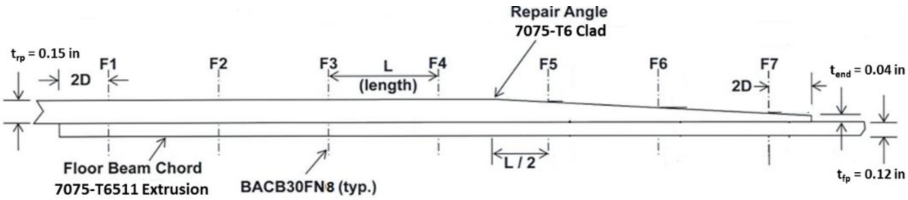

Figure 7 SRM repair

The dimensions and material of the floor beam upper chord are shown in Figure 8.

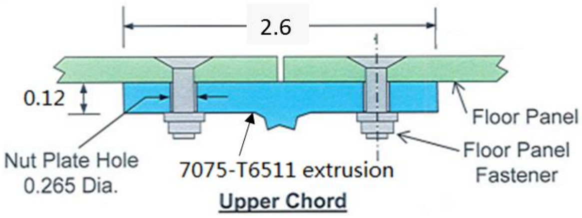

Figure 8 Material and Dimensions

Table 1 is a SRM table which shows the typical factor to calculate the minimum cross-sectional area of repair parts by multiplying the cross-sectional area of the initial part.

Table 1 SRM repair material

Initial Section Material	Repair Part Material	Repair Material Factor
Extruded 2024-T3 Or T3511	Sheet - Clad 2024-T3	1.25
Extruded 7075-T6 Or T6511	Sheet - Bare Or Clad 7075-T6	1.35
Extruded 7150-T77511	Sheet - Bare Or Clad 7075-T6	1.5
Extruded 7150-T77511	Extruded - 7075-T6	1.35

Figure 9 shows an Excel spreadsheet including the basic repair design steps based on static analysis. A kind of titanium fastener BACB30NW8K is used to replace the unavailable steel fastener BACB30FN8.

1. Calculate the load-carrying capability of factory part			
Factory Part Thickness (tfp) =	0.12	in	
Factory Part Width (wfp) =	1.3	in	
Factory Part Hole Diameter (dfp) =	0.265	in	*dfp=0 if no fastener hole exist in factory part*
Net Area (Anet) =	0.1242	in2	*Anet = (wfp - dfp) × tfp*
Material and Product Form =	2024 T3 ext.		
Ftu =	82	ksi	*refer to MMPDS*
Fty =	74	ksi	*refer to MMPDS*
Design Ultimate Allowable (Fdu) =	82	ksi	*Fdu = min (Ftu, 1.5 × Fty)*
Load Capability (Pcap) =	10184.4	lb	*Pcap = Fdu × Anet*
2. Determine the material and dimensions of repair part			
Material and Product Form =	2024 T3 clad		*refer to SRM repair*
Repair Factor (fac) =	1.25		*refer to table 1*
Repair Part Thickness (trp) =	0.15	in	*trp = fac × tfp*
3. Determine the type, size and quantity of fasteners to meet the load transfer requirements			
Fastener Code =	BACB30NW8K		*refer to SRM repair*
Joint Allowable (Pallow) =	3235	lb	*refer to MMPDS/SRM*
Number of Fasteners Required (nfast) =	4		*nfast = int(Pcap/Pallow) + 1*

Figure 9 Basic repair design steps based on static analysis

The end fastener F7 is to be removed because of interference. In order to restore the equivalent fatigue life, a revised repair with increasing the repair angle thickness is proposed as shown in Figure 10.

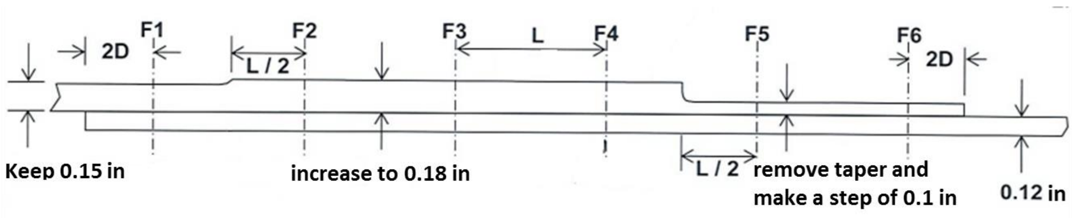

Figure 10 Revised repair to eliminate interference

Fatigue life comparison based on DTA will be conducted under a dummy applied load of 2000 lb. Following the methodology of joint modeling described in chapter 3, the bearing and bypass force for each critical location is shown in Table 2.

Table 2 Joint loads for critical locations

Unit: lb	Factory Part				Repair Part			
	Left Fastener		Right Fastener		Left Fastener		Right Fastener	
	F_{br}	F_{bp}	F_{br}	F_{bp}	F_{br}	F_{bp}	F_{br}	F_{bp}
SRM Repair	460	0	395	1605	460	1540	395	0
Revised Repair	440	0	367	1633	440	1560	367	0

As shown in Table 2, for the left end fastener location on factory part and right end fastener location on repair part, the loads of revised repair are obviously minor in comparison to SRM repair. Since the material and geometry dimensions are all the same, the equivalent fatigue life of these two locations could definitely be restored. So the DTA would only be implemented for the right end fastener location on factory part and the left end fastener location on repair part (with red borders in Table 2).

The fatigue life comparison is shown in Table 3. Since the fatigue life for the revised repair is higher than SRM repair for both locations, it can be concluded that the equivalent fatigue life is restored.

Table 3 Fatigue Life Comparison for Revised Repair and SRM Repair

Fatigue Life	**Factory Part**	**Repair Part**
SRM Repair	21600	46200
Revised Repair	21700	46500

5. Conclusion

Through the instruction case in chapter 4, a whole process for aircraft structure repair design and analysis is presented. In this procedure, the repair design is based on static analysis to guarantee the ultimate static strength could be restored. Four kinds of joint failure models as well as the joint allowable table are introduced to determine the required fastener number for repair. The character of joint load distribution is presented and the joint modeling method is used to calculate the bearing and bypass loads of a joint under operating fatigue loadcase. DTA conducted in AFGROW provides a way for fatigue life comparison between revised repair and SRM repair under a same invented load. Airline structure engineers can adjust their design according to the results until the equivalent fatigue life could be restored.

In conclusion, this paper provides a feasible methodology to design aircraft structure repair beyond specification.

Reference:

[1] 737-800 Structural Repair Manual, Boeing

[2] Metallic Materials Properties Development and Standardization Handbook, FAA

[3] Repairs to Damage Tolerant Aircraft, FAA-AIR-90-01, Tom Swift, 1990

[4] Stress Severity Factors for Axially Loaded Mechanically Fastened Joints, Boeing

[5] Airframe stress analysis and sizing, C.Y.Niu

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