Design of Aircraft Empennage Repair

August Honnell,
Chelsea Prufer,
Chih-Han Yang,
Jason Steadele,
Sameer Meshram,
Shunsuke Winston

June 13, 2019

MECHANICAL ENGINEERING
UNIVERSITY of WASHINGTON

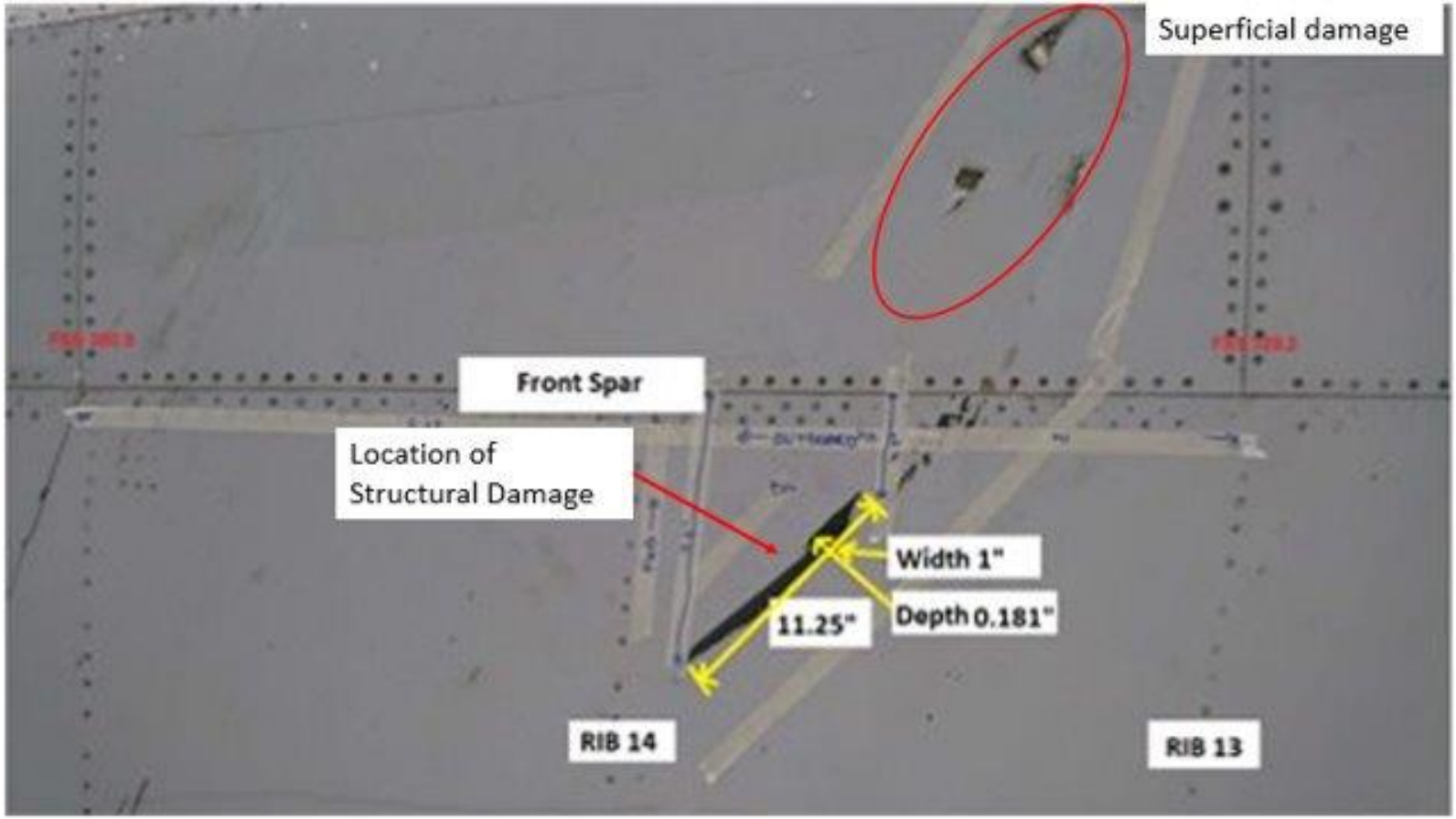
Contents

INTRODUCTION

Damage Extent and Service Request

Purple & Gold Airline Flight NABC123 → Sustains Impact Damage (H - Stab) → Service Request Received

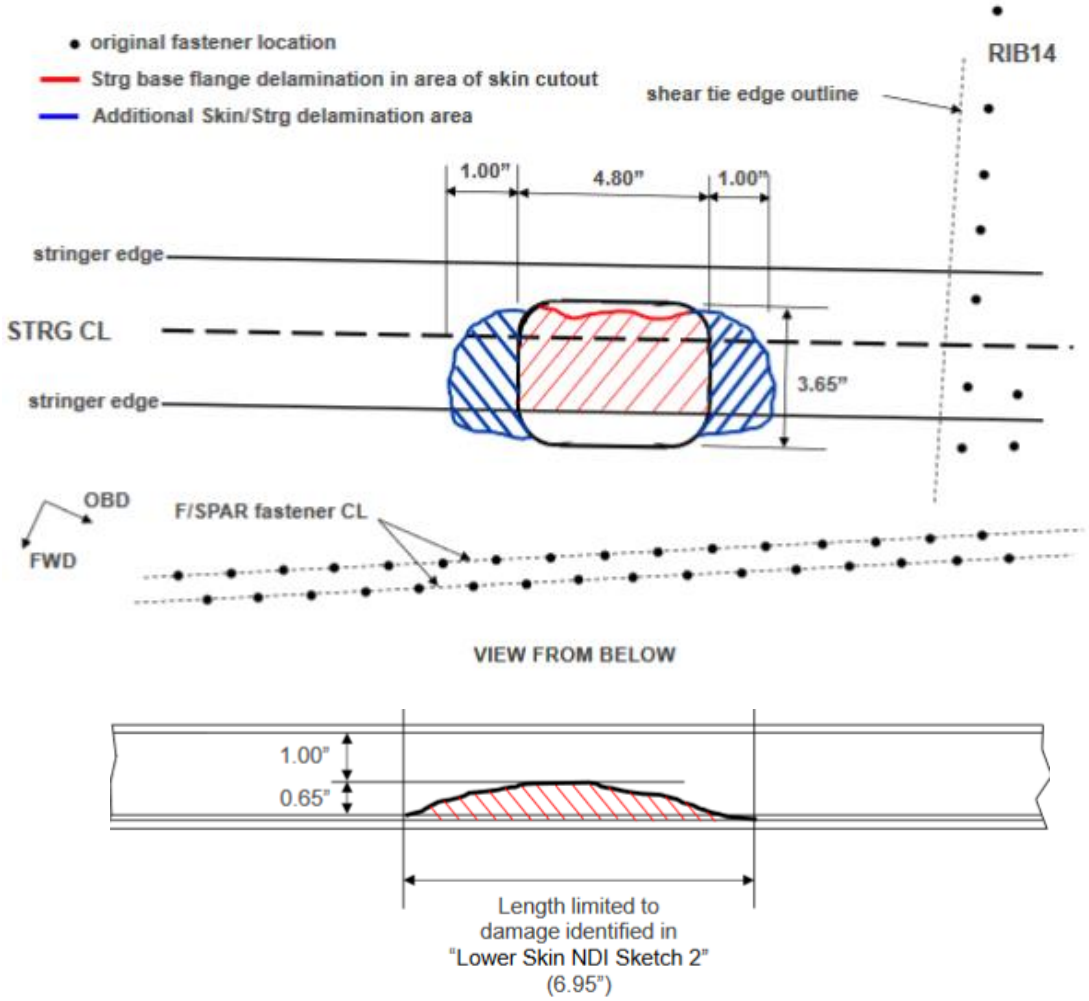
Damage Extent and Service Request (...)



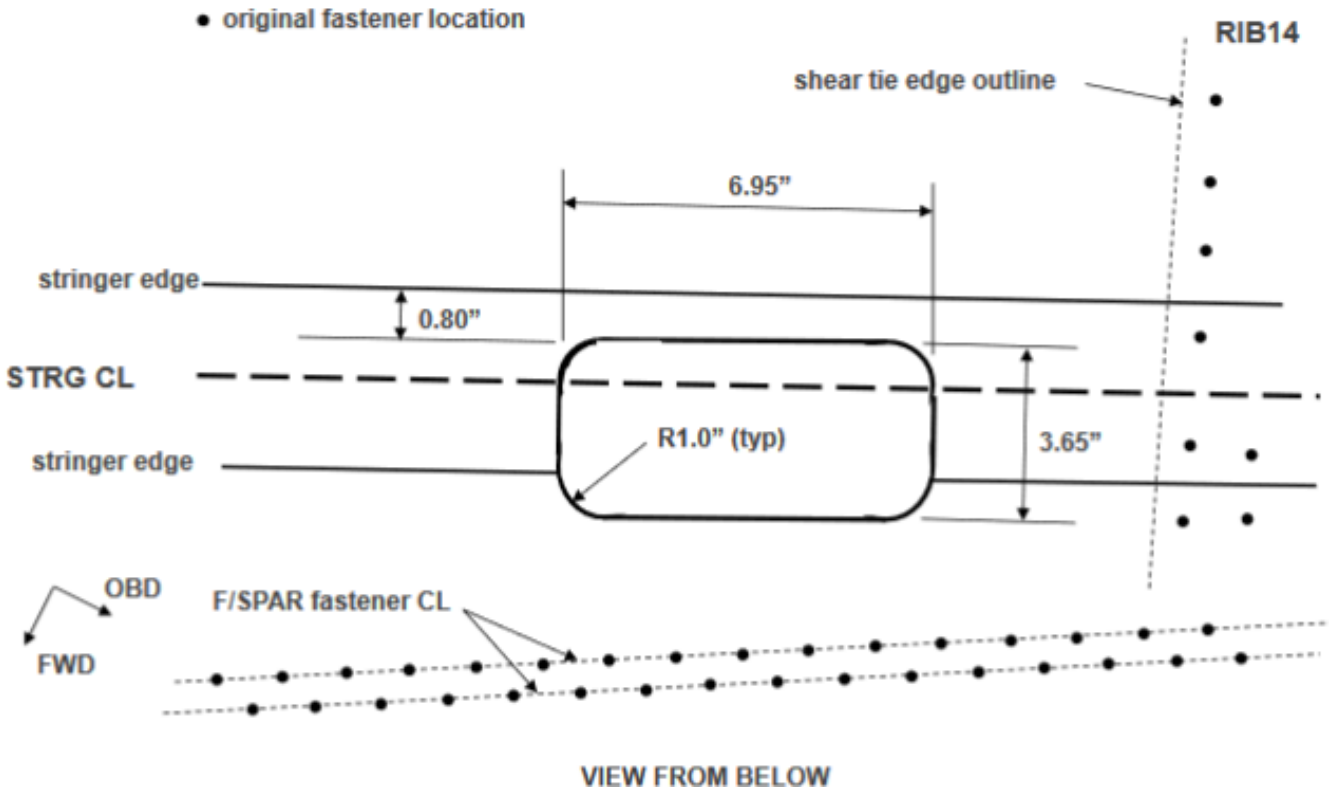
INTRODUCTION

Damage Extent and Service Request (...)

- Non-Destructive Inspection (NDI)



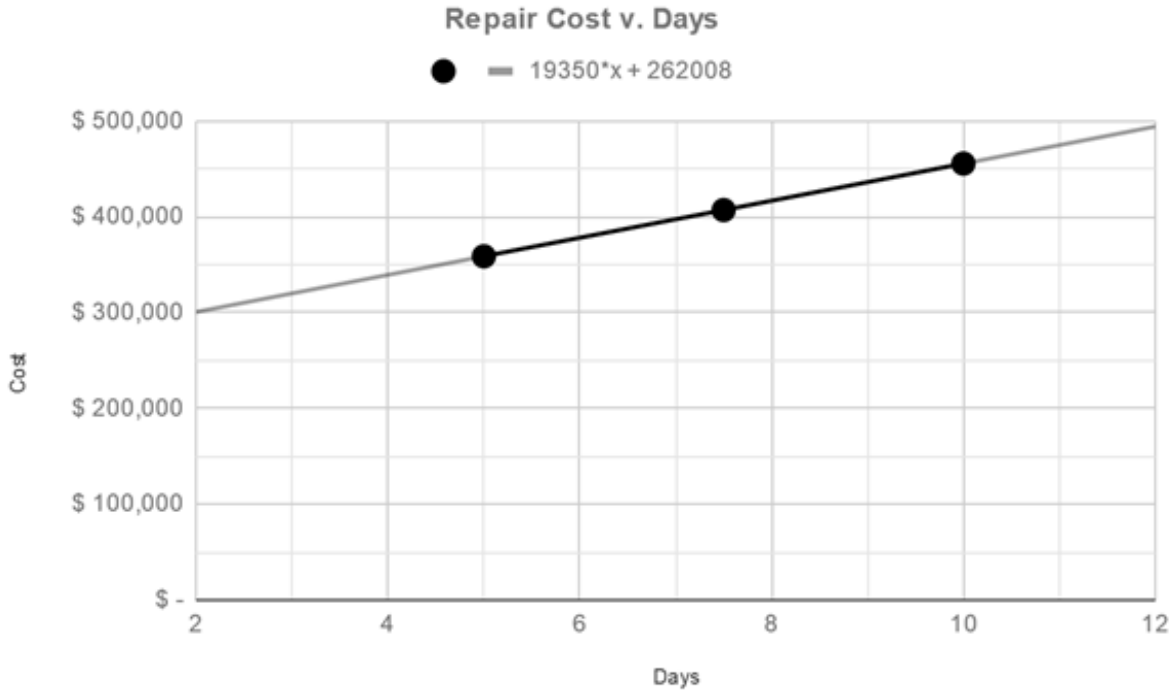
Damage Removal



Repair Cost Analysis

Considerations

- Lost Revenue/Alternate Operations (~$ 360,000 to 460,000)
- Material Cost (~$ 200)
- Fastener Cost (~$ 860)
- Labor/Machining (~$ 4500 to 9000)



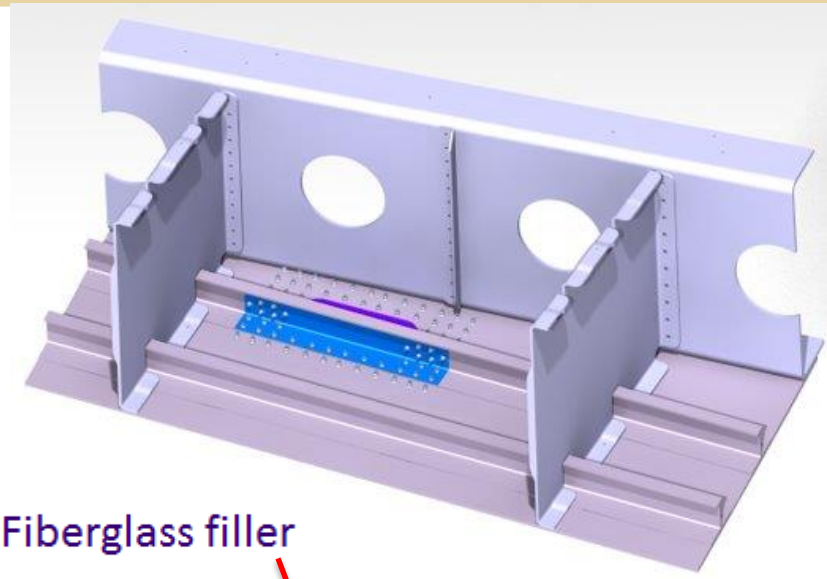
Cost of Lost Revenue >> Repair Cost

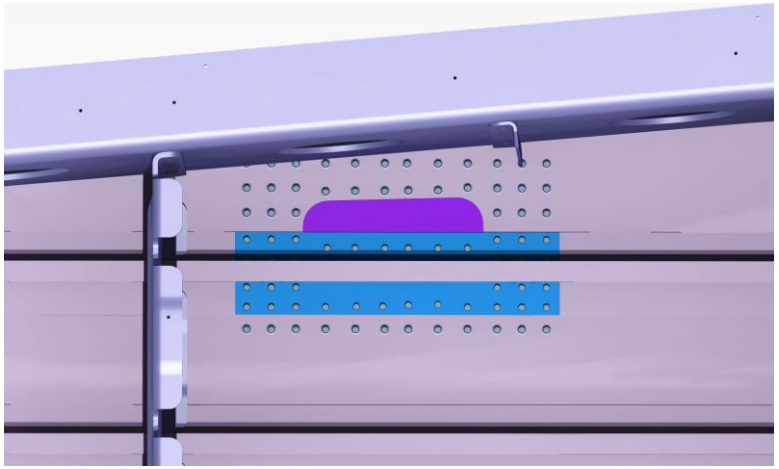
INTRODUCTION

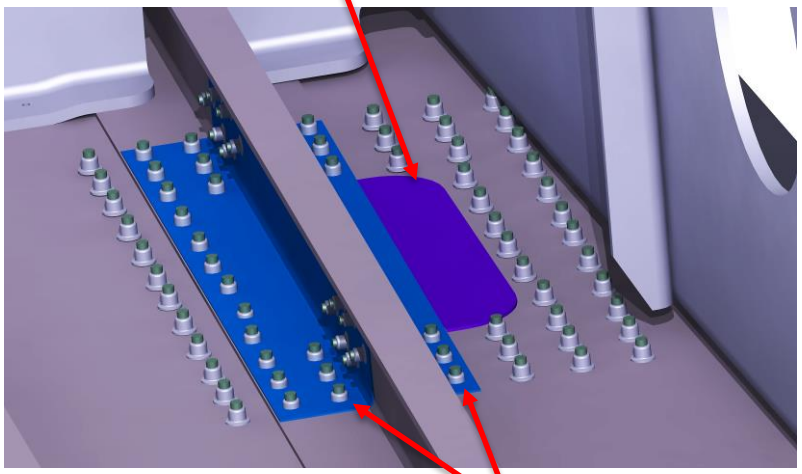
Repair Configuration

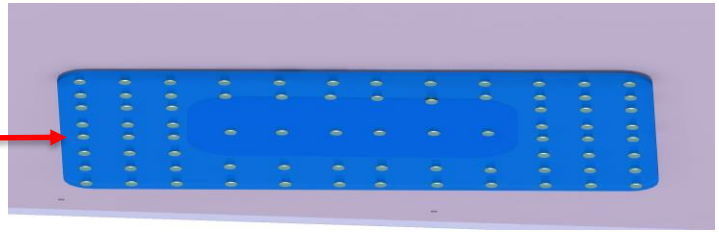
Parts

- Skin Doubler × 1
- Stringer Reinforcing Stiffeners × 2
- Fiberglass Filler for Skin × 1
- Fiberglass Filler for Stringer × 1



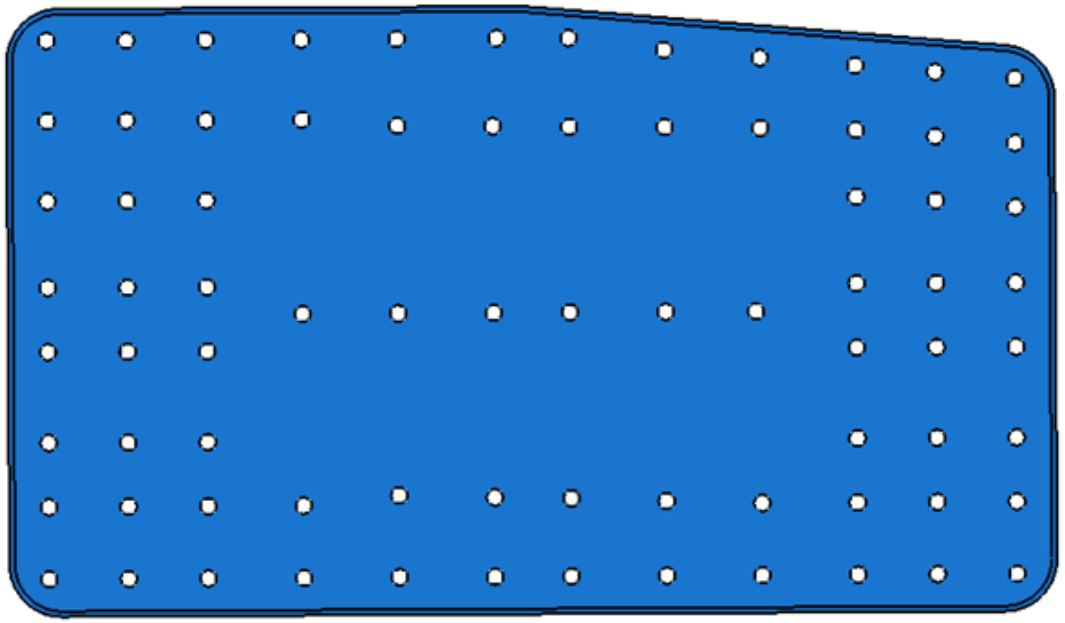






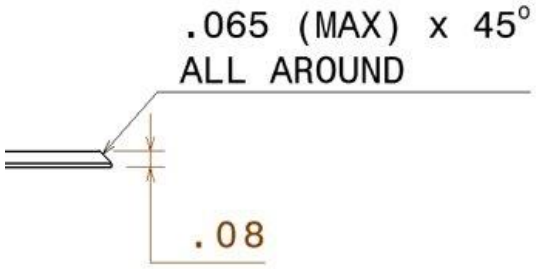
INTRODUCTION

Repair Configuration – Skin



Material Property	Ti-6Al-4V Annealed
Ftu (ksi)	139
Fty (ksi)	131
Fcy (ksi)	138
Fsu (ksi)	81
Fbru (ksi)	
e/D = 1.5	204
e/D = 2.0	264
Fbry (ksi)	
e/D = 1.5	178
e/D = 2.0	216
E = Ec (msi)	16.2
G (msi)	6.2
μ	0.31
α (μin/in°F)	4.9
ω (lbf/in^3)	0.160

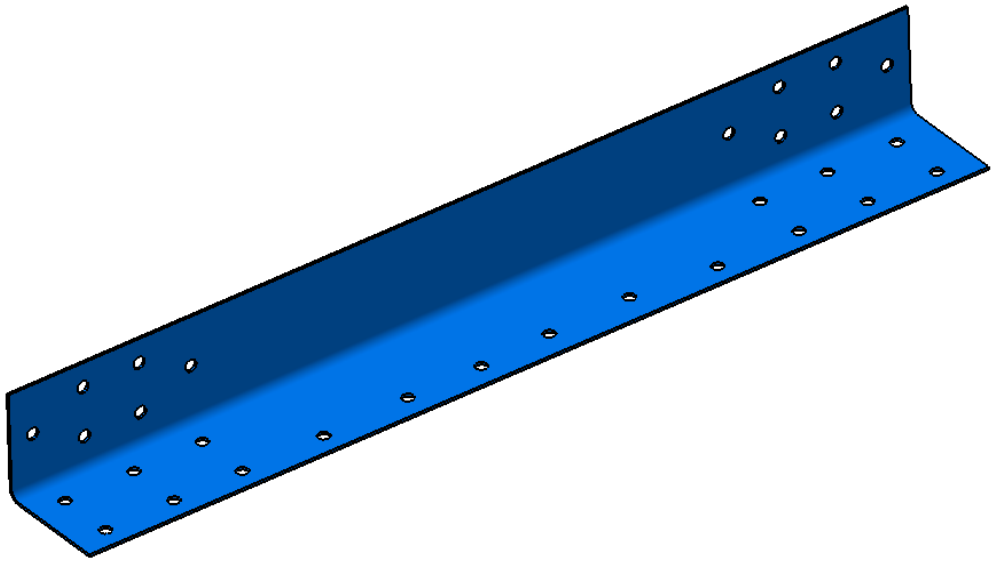
- Thickness: 0.08 inches
- Length: 12.5 inches
- Width: 7.2 inches



INTRODUCTION

Repair Configuration – Stringer

- Using Skin Doubler as template



- Thickness: 0.035 inches
- Length: 12.50 inches
- Width: 1.50 inches (includes thickness)
- Height: 1.50 inches

Material Property	Ti-6Al-4V Annealed
Ftu (ksi)	139
Fty (ksi)	131
Fcy (ksi)	138
Fsu (ksi)	81
Fbru (ksi)	
e/D = 1.5	204
e/D = 2.0	264
Fbry (ksi)	
e/D = 1.5	178
e/D = 2.0	216
E = Ec (msi)	16.2
G (msi)	6.2
μ	0.31
α (μin/in°F)	4.9
ω (lbf/in^3)	0.160

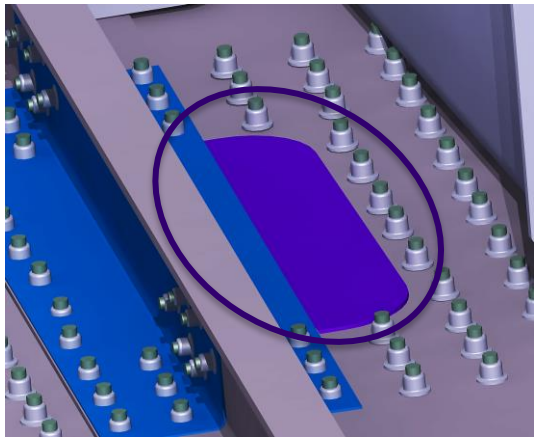
INTRODUCTION

Repair Configuration – Shimming

- 15-5 PH stainless steel (or equivalent) shimming between doubler & skin for gaps larger than 0.015 in
- Surface roughness ≤ 125 µin Ra
- Passivation

Repair Configuration – Fillers

- Fiberglass or Silicon based fillers in gaps



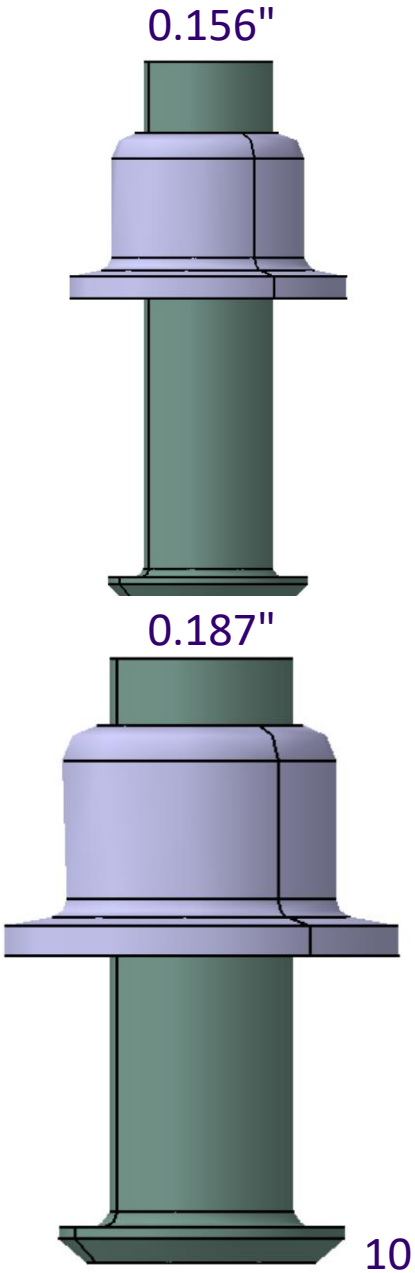
Material Property	15-5PH Steel
Ftu (ksi)	154
Fty (ksi)	143
Fcy (ksi)	150
Fsu (ksi)	97
Fbru (ksi)	
e/D = 1.5	357
e/D = 2.0	331
Fbry (ksi)	
e/D = 1.5	211
e/D = 2.0	246
E = Ec (msi)	29
G (msi)	11.2
µ	0.27
α (µin/in°F)	6.3
ω (lbf/in^3)	0.283

INTRODUCTION

Repair Configuration – Fasteners

Location	Description
Skin Doubler × 42	Ti Hi-Lok HL 10 & Hi-Lok 70 Collar 3/16 (0.18750) inch Fastener
Stringer Web × 12	Ti Hi-Lok HL 10 & Hi-Lok 70 Collar 5/32 (0.15625) inch Fastener
Stringer Flange × 36	Ti Hi-Lok HL 10 & Hi-Lok 70 Collar 3/16 (0.18750) inch Fastener

Material [Alloy]	Titanium	
	Hi-Lok HL Protruding Shear 100° Flush Shear Head [T-6Al-4V]	NAS 1270 Hex Head Bolt [T-6Al-4V]
Availability	5/32”, 3/16”, 1/4", 5/16”	1/4”, 3/8”
Ftu (ksi)	160[4]	160[4]
Fsu (ksi)	95[4]	95[4]

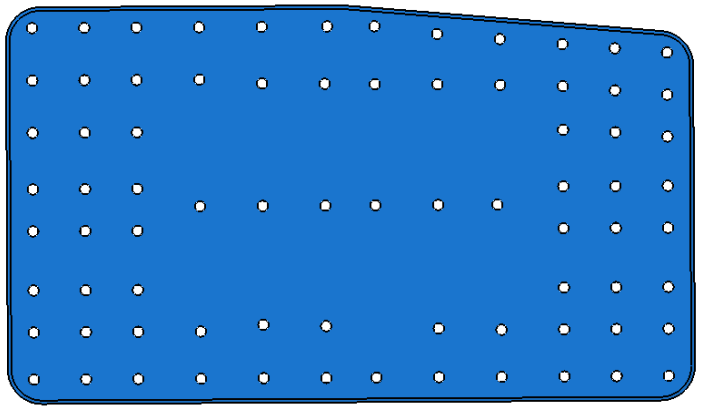


- Other Considerations
  - Location using templates
  - Deburring post drilling

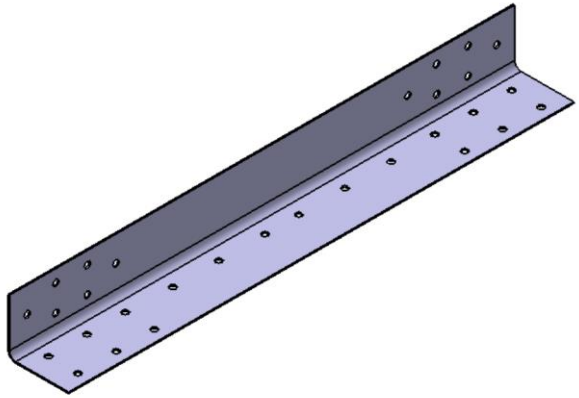
INTRODUCTION

Repair Manufacturing

- Skin Repair: Doubler (P/N 222X9999-1)
  - Apply chamfer to outer edge
  - Fillet all sharp edges
  - Use hole pattern as template to locate holes on skin panel and stiffener repair angles



- Stringer Repair: (P/N 222X9999-2/-3)
  - Maintain a minimum radius of 0.15 inches at bend (OML)
  - Hot brake forming may be required to maintain radius
  - Fillet all sharp edges

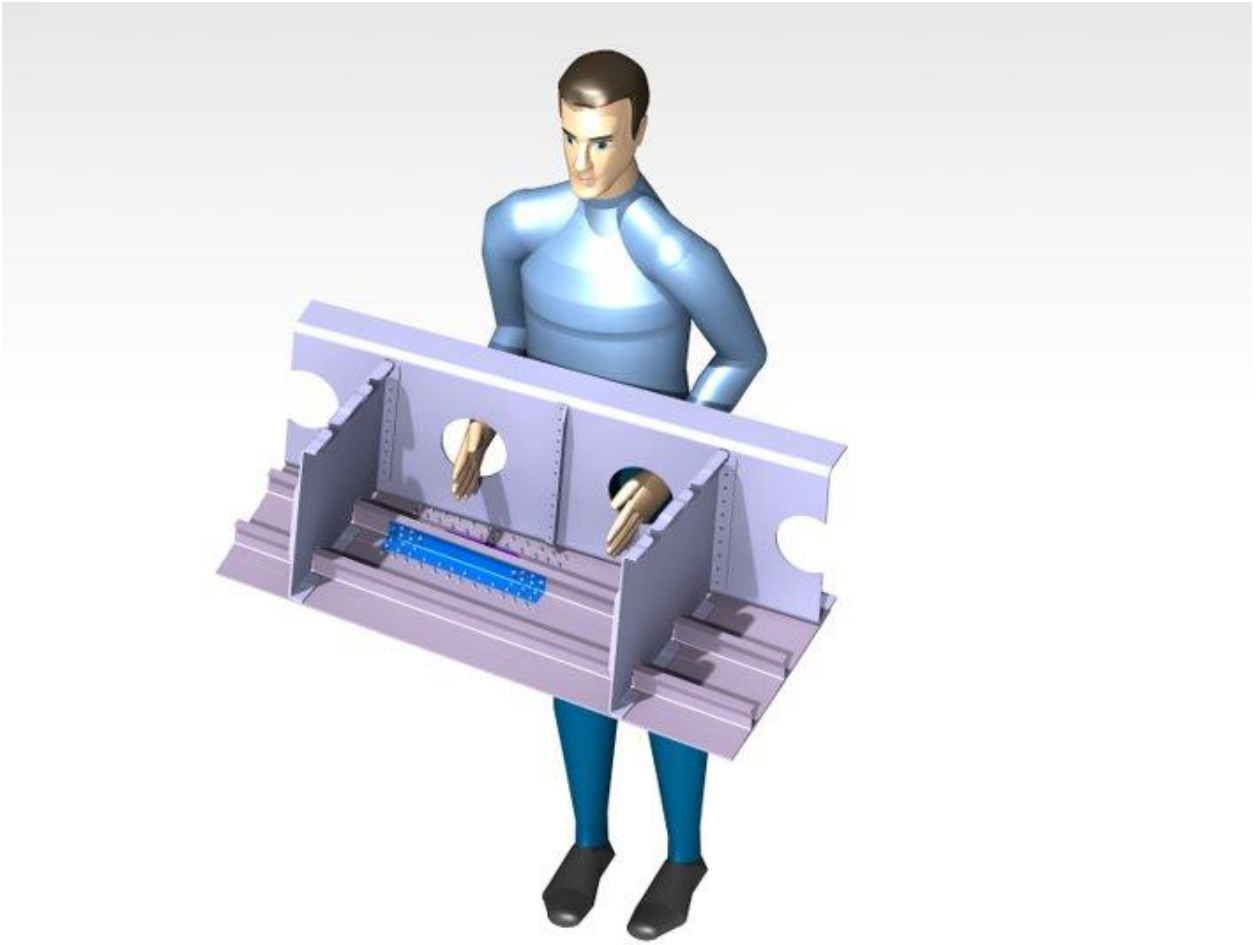


INTRODUCTION

Repair Installation

1. Gain access to area of damage by removing forward torque box lower panel and prepare surfaces by thoroughly cleaning using approved method. Consult SRM
2. Drill holes in skin doubler panel and stringer repair L-brackets using pattern & specifications provided. Hole sizes for fasteners per SRM.
3. Using doubler as a template, locate and drill base fasteners for stiffeners
4. Acceptable to temporarily bond fiberglass fillers (P/N 222X9999-4/-5) to stringer L-bracket to ease installation. Clearance holes (class 3) in all fillers.
5. Locate & drill stiffener angles in place to ensure proper hole pattern alignment.
6. Drill hole corresponding to the repair pattern through parent structure. It is advised to use backer plates when drilling through CFRP to minimize fiber breakout.
7. Install stringer repair L-brackets using 5/32 inch Titanium Hi Loc 10 fasteners in the web and 3/16 inch in the flange.
   - Note: Do Not install flange fasteners until skin doubler installed.
8. Install skin doubler repair using 3/16 inch Titanium Hi Loc 10 fasteners.
   - Use 0.02 - 0.03 inch shim stock to level doubler repair against skin.

Ergonomic Consideration



SUBSTANTIATION

Load Summary

Loading		Segment Loads (lbf)		Skin Flows (lbf/in)		
				Nx	Ny	Nxy
		Front Spar	Skin/ Stringer 5	All 3 Segments		
Mechanical	Compression	-48000	-38000	-3800	-70	200
	Tension	51000	40000	3900	50	450
Thermal	Compression (-65 °F)	-2400	-1900	-190	0	0
	Tension (160 °F)	1600	1250	125	0	0

- Other Loads
  - Ultimate Thermal
  - Fatigue
  - Limit Loads

SUBSTANTIATION

Static Analysis Considerations

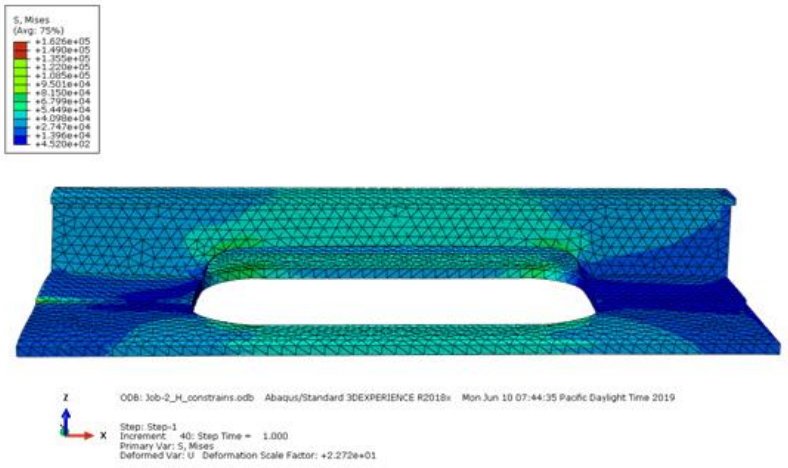
- Stiffness Checks (107.2%)
- Repair Bearing Checks
- Repair Net Section Checks
- Buckling Checks
- Fastener Shear Checks
- Fatigue Analysis
- Stress Concentration Checks

  e.g. Conventional Kt

  Strip Method

  FEA

Stress Concentration Without Repair with FEA		
Part	Stress (ksi)	Allowable (ksi)
Stringer Web	68.81	40
Stringer Base	NA	NA
Cap	NA	NA
Skin	66.11	32



SUBSTANTIATION

Margins of Safety (1/2)

ID #	Part/Detail	Check Performed	Tension/Compression, Limit/ Ultimate, Hot or RT or Cold	MS
1	Stringer Parent	Strength	Tension, Ultimate, Hot	0.17
2	Skin Parent	Strength	Tension, Ultimate, Hot	2.05
3	Stringer Repair	Strength	Tension, Ultimate, Hot	0.61
4	Skin Repair	Strength	Tension, Ultimate, Hot	1.78
5a	Stringer Web	Bearing	Tension, Ultimate, Hot	1.56
5b	Stringer Base	Bearing	Tension, Ultimate, Hot	0.61
6	Skin Parent	Bearing	Tension, Ultimate, Hot	0.60
7	Stringer Repair	Bearing	Tension, Ultimate, Hot	1.15
8	Skin Repair	Bearing	Tension, Ultimate, Hot	2.23
9a	Stringer Web	Fastener Shear	Tension, Ultimate, Hot	2.32
9b	Stringer Base	Fastener Shear	Tension, Ultimate, Hot	3.55
10	Skin Parent	Fastener Shear	Tension, Ultimate, Hot	0.80
11	Stringer Repair	Fastener Shear	Tension, Ultimate, Hot	2.32
12	Skin Repair	Fastener Shear	Tension, Ultimate, Hot	0.80

Margins of Safety (2/2)

13	Repair angle base	Net section	Tension, Ultimate RT	0.73
14	Repair angle Web	Net section	Tension, Ultimate RT	0.61
15	Skin Doubler	Net section	Tension, Ultimate RT	1.78
16	Repair angle base	Net section	Compression, Ultimate RT	4.40
17	Repair angle Web	Net section	Compression, Ultimate RT	4.40
18	Skin Doubler	Net section	Compression, Ultimate RT	5.75
13	Stringer Parent	Stress Concentration	Tension, Ultimate, Hot	0.17
14	Skin Parent	Stress Concentration	Tension, Ultimate, Hot	2.05
15	Stringer Parent	Local Stability	Compression, Ultimate, Cold	0.25
16	Skin Parent	Local Stability	Compression, Ultimate, Cold	6.15
17	Stringer Repair	Local Stability	Compression, Ultimate, Cold	1.74
18	Skin Repair	Local Stability	Compression, Ultimate, Cold	1.74
19	Skin Repair	Fatigue	Fatigue, Limit,Hot and Cold	2.94

SUBSTANTIATION

Damage Tolerance and Certification

- No special Inspection cycle is required for continued safe flight
- High fatigue margins support heavy check interval inspection (5000 hour):
  1. Access to inner box beam is required for detail visual inspection of all joints for cracks
  2. Tools and equipment required for inspection may include appropriate lighting and inspection mirror to fully examine all fasteners on both side of the repair
  3. Visual inspection of doubler on outside of horizontal stabilizer skin surface using lift or scaffolding as required.
- Repair certification with regulating bodies will be coordinated with OEM engineering Authorized Representative

CONCLUSION/DISCUSSION

- A repair was successfully designed for the request
- Considerations
  - Time
  - Cost
  - Mechanical/Thermal Design
  - Manufacturing
  - Installation/Ergonomics
  - Damage Tolerance
  - Certification

Thank You!

Questions/Comments

Assumptions

- Minimal drag penalty for external doubler and protruding fastener
- Maximum load carried by the repair part is all of the original load (conservative)
- Added absolute values of nx, ny, nxy values for total skin load (conservative)

Margin of Safety Summary

Table 2.1: Margin of Safety Summary Table

ID #	Part/Detail	Check Performed	Tension/Compression, Limit/ Ultimate, Hot or RT or Cold	MS
1	Stringer Parent	Strength	Tension, Ultimate, Hot	0.17
2	Skin Parent	Strength	Tension, Ultimate, Hot	2.05
3	Stringer Repair	Strength	Tension, Ultimate, Hot	0.61
4	Skin Repair	Strength	Tension, Ultimate, Hot	1.78
5a	Stringer Web	Bearing	Tension, Ultimate, Hot	1.56
5b	Stringer Base	Bearing	Tension, Ultimate, Hot	0.61
6	Skin Parent	Bearing	Tension, Ultimate, Hot	0.60
7	Stringer Repair	Bearing	Tension, Ultimate, Hot	1.15
8	Skin Repair	Bearing	Tension, Ultimate, Hot	2.23
9a	Stringer Web	Fastener Shear	Tension, Ultimate, Hot	2.32
9b	Stringer Base	Fastener Shear	Tension, Ultimate, Hot	3.55
10	Skin Parent	Fastener Shear	Tension, Ultimate, Hot	0.80
11	Stringer Repair	Fastener Shear	Tension, Ultimate, Hot	2.32
12	Skin Repair	Fastener Shear	Tension, Ultimate, Hot	0.80
13	Repair angle base	Net section	Tension, Ultimate RT	0.73
14	Repair angle Web	Net section	Tension, Ultimate RT	0.61
15	Skin Doubler	Net section	Tension, Ultimate RT	1.78
16	Repair angle base	Net section	Compression, Ultimate RT	1.25
17	Repair angle Web	Net section	Compression, Ultimate RT	1.09
18	Skin Doubler	Net section	Compression, Ultimate RT	2.56
13	Stringer Parent	Stress Concentration	Tension, Ultimate, Hot	0.17
14	Skin Parent	Stress Concentration	Tension, Ultimate, Hot	2.05
15	Stringer Parent	Local Stability	Compression, Ultimate, Cold	0.25
16	Skin Parent	Local Stability	Compression, Ultimate, Cold	6.15
17	Stringer Repair	Local Stability	Compression, Ultimate, Cold	1.74
18	Skin Repair	Local Stability	Compression, Ultimate, Cold	1.74
19	Skin Repair	Fatigue	Fatigue, Limit,Hot and Cold	2.94

Estimated Cost

Repair Material

Part	Material	Density of Material (lb/in^3)	Volume of Material (in^3)	Design Weight of Material (lb)	Ordering Weight (lb)	Cost per unit Weight ($/lb)	Total Cost ($)
Stringer Repair	Ti-6Al-4V	0.16	2.60	0.42	1	30.00	30.00
Skin Repair	Ti-6Al-4V	0.16	7.60	1.22	2	30.00	60.00
Fiberglass Filler	Fiberglass	0.07	5.33	0.35	1	15.00	15.00
Miscellaneous	Shims, Paint, Tape, etc.	NA	NA	NA	NA	NA	100
Sub-Total				1.98			205.00

Estimated Cost

Fasteners

Part	Material	Cross Section Area (in^2)	Cost per Fastener ($/fastener)	No. of Fasteners By Design	Weight (lb)	No. of Fasteners Required/ Ordered	Total Cost ($)
Fasteners Skin Repair 3/16"	Ti-6Al-4V	0.0276	7.887	42	0.139	51	402.25
Fasteners Stringer Web 5/32"	Ti-6Al-4V	0.0192	5.000	12	0.018	16	80.00
Fasteners Stringer Flange 3/16"	Ti-6Al-4V	0.0276	7.887	36	0.119	47	370.70
Sub-Total					0.277		852.95

> Total weight of repair is 2.257 lb

Estimated Cost

Repair Installation

Labor /Machining	Rate	No. of Days			Utilization	Total Cost ($)		
	($/hour)	Optimistic	Likely	Pessimistic	(hours/day)	Optimistic	Likely	Pessimistic
Labor	100	5	7.5	10	8	4000	6000	8000
Machine	50	5	6	10	2	500	600	1000
Sub-Total						4500	6600	9000

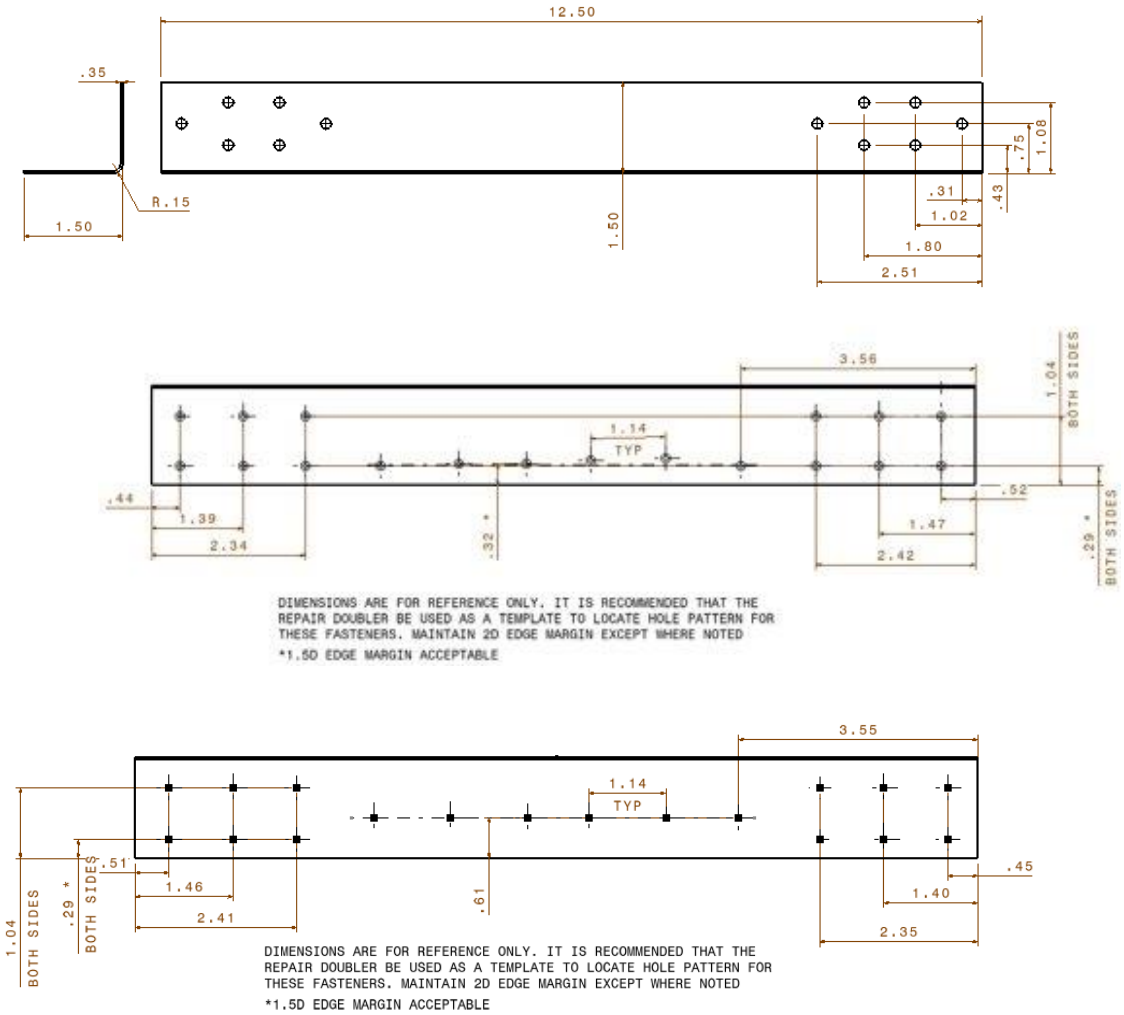
Estimated Cost

Lost of Revenue

Cost of Lost Revenue	Average Cost of Ticket	Passengers per Flight			Average Flights per Day	Total Cost ($)		
	($/P)	Optimistic	Likely	Pessimistic	(flights/day)	Optimistic	Likely	Pessimistic
Alternate Flight Operations	450	314	355	396	2.5	353250	399375	445500
Sub-Total						353250	399375	445500
		Total Weight (lb)		2.25	Total Cost ($)	358,808	407,033	455,558

Back-Up

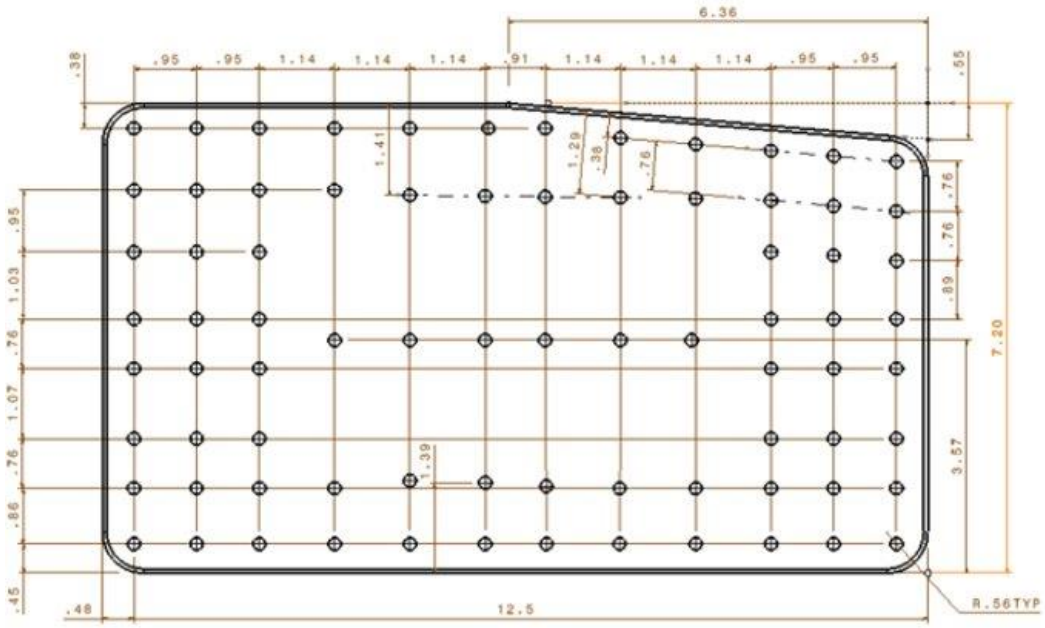
Repair Configuration – Stringer

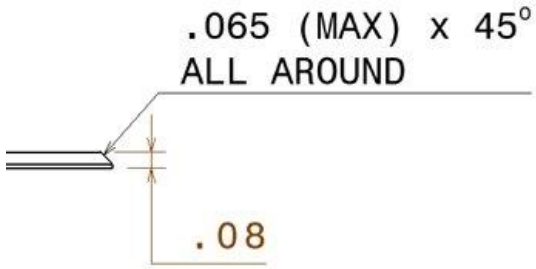


Material Property	Ti-6Al-4V Annealed
Ftu (ksi)	139
Fty (ksi)	131
Fcy (ksi)	138
Fsu (ksi)	81
Fbru (ksi)	
e/D = 1.5	204
e/D = 2.0	264
Fbry (ksi)	
e/D = 1.5	178
e/D = 2.0	216
E = Ec (msi)	16.2
G (msi)	6.2
μ	0.31
α (μin/in°F)	4.9
ω (lbf/in^3)	0.160

Back-Up

Repair Configuration – Skin





Material Property	Ti-6Al-4V Annealed
Ftu (ksi)	139
Fty (ksi)	131
Fcy (ksi)	138
Fsu (ksi)	81
Fbru (ksi)	
e/D = 1.5	204
e/D = 2.0	264
Fbry (ksi)	
e/D = 1.5	178
e/D = 2.0	216
E = Ec (msi)	16.2
G (msi)	6.2
μ	0.31
α (μin/in°F)	4.9
ω (lbf/in^3)	0.160

- Thickness: 0.08 inches
- Length: 12.5 inches
- Width: 7.2 inches

Load Summary

	Portion of load					
	tension load lb			compression load (lb)		
	Mechanical	Thermal	Total	Mechanical	Thermal	Total
stringer web	6386	200	6585	-6067	-303	-6370
stringer base	6894	215	7110	-6549	-327	-6877
cap	3096	97	3193	-2941	-147	-3088
skin	23624	738	24362	-22443	-1122	-23565
	40000	1250	41250	-38000	-1900	-39900

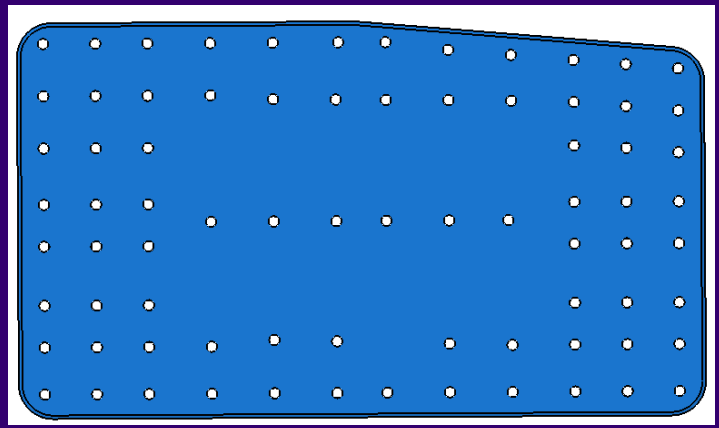
Repair Manufacturing

- Skin Repair: Doubler (P/N 222X9999-1)
- Material: Titanium (Ti-6AL-4V)
- Notes:

Apply chamfer to outer edge

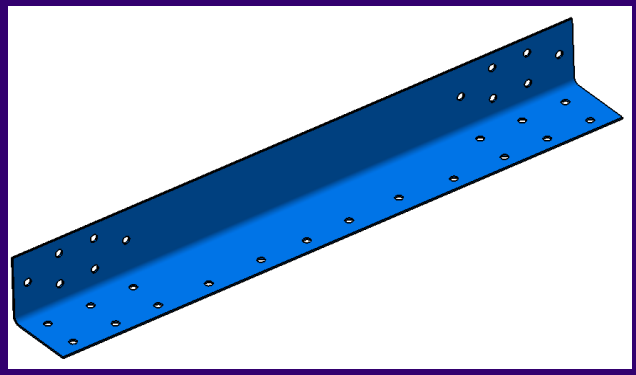
Fillet all sharp edges

Use hole pattern to locate holes and stiffener repair angles.



Repair Manufacturing

- Stringer Repair: (P/N 222X9999-2/-3)
- Material: Titanium (Ti-6AL-4V)



- Notes:
- Maintain a minimum radius of 0.15 inches at bend (OML)
- Hot brake forming may be required to maintain radius.
- Fillet all sharp edges

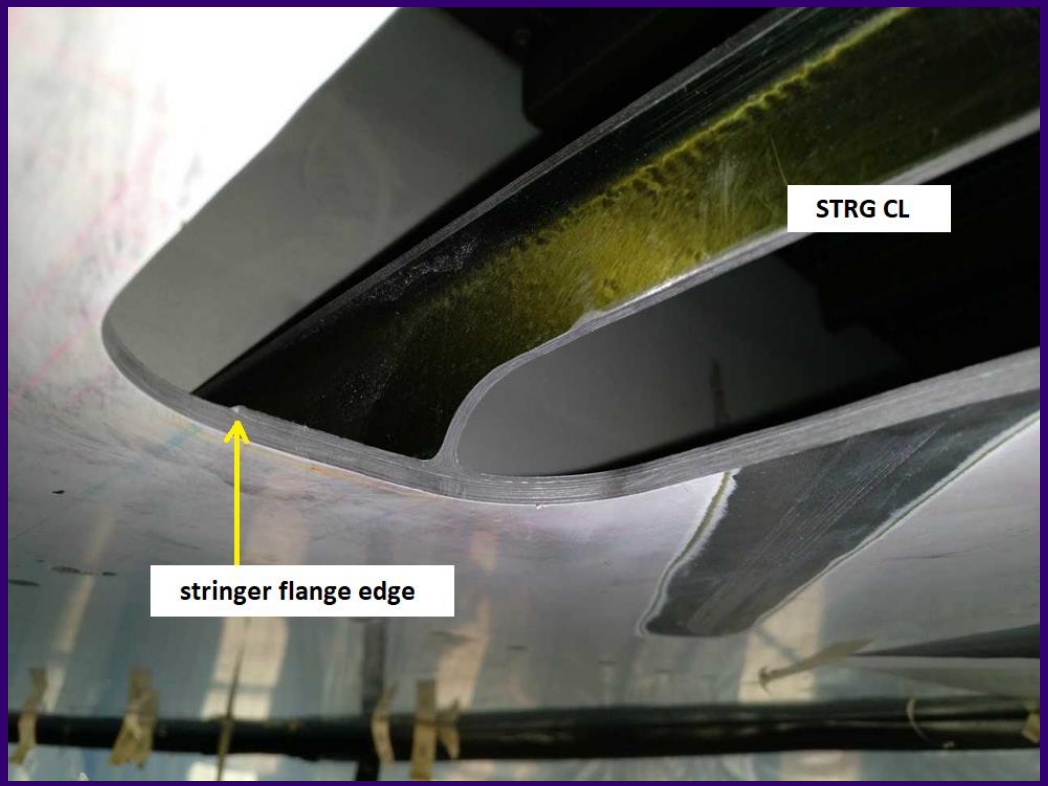
Repair

Fastener

- **Web:** Ti Hi-Lok HL 10 & Hi-Lok 70 Collar
- 5/32 inch Fastener Hole Details: Locate web holes per drawing provided. Use drilled angle to locate fastener pattern on parent stiffener
- **Flange:** Ti Hi-Lok HL 10 & Hi-Lok 70 Collar
- 3/16 inch Fastener Hole Details:
- **Skin:** Ti Hi-Lok HL 10 & Hi-Lok 70 Collar
- 3/16 inch Fastener Hole Details:
- General drilling instructions: Deburr all holes after drilling. Use of backing plate is encouraged when drilling composite to minimize fiber breakout

Extra Slide

Removal



Fastener number

> Critical margin for fastener shear and bearing in skin repair:

Fastener size (in)	C/S Area (in^2)	Fastener Ultimate Shear Load Allowable (lb)
5/32	0.0192	1821.6
3/16	0.0284	2693.5

$$P_{x-fastener} = \frac{nx \times 5d_{fastener}}{3} + \frac{nxy \times 5d_{fastener}}{2} = \frac{4025 \times 5(0.19)}{3} + \frac{450 \times 5(0.19)}{2} = 1488\ lb$$

$$P_{y-fastener} = \frac{ny \times 5d_{fastener}}{2} + \frac{nxy \times 5d_{fastener}}{3} = \frac{70 \times 5(0.19)}{2} + \frac{450 \times 5(0.19)}{3} = 176\ lb$$

$$P_{total-fastener} = \sqrt{P_{x-fastener}^{\ 2} + P_{y-fastener}^{\ 2}} = \sqrt{1488^{\ 2} + 176^{\ 2}} = 1498\ lb$$

$$MS = \frac{Load_{ulti,shear}}{Load_{fastener}} - 1 = \frac{2693.5}{1498} - 1 = 0.80$$

Fastener number

$$F_{br\,fastener} = \frac{P_{total-fastener}}{A_{fastener}} = \frac{1498}{0.19(0.21)} = 37.5\ ksi$$

$$MS = \frac{F_{bru}}{F_{br\,fastener}} - 1 = \frac{60}{37.5} - 1 = 0.60$$