   

CSAT 25 -26 June 2019
Quantifiable Structural Enhancement Outcomes using SPD (Cold Spray) Deposition

  

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Introduction

- ❖ Introduction
- ❖ Update
  - ➢ Applications
  - ➢ Portabilsation (Technology to Target)
- ❖ Quantifiable Structural Enhancement Outcomes
  - ➢ Quantifiable SI (Credits) Program #1 _ F/A-18 Door Frame 68
  - ➢ Quantifiable SI (Credits) Program #2 – Fast Jet Lower Wing Skin & Structure
  - ➢ Quantifiable SI (Credits) Program #3 – Maritime Wing Skin & Structure
- ❖ Acknowledgements
- ❖ Discussions/Questions

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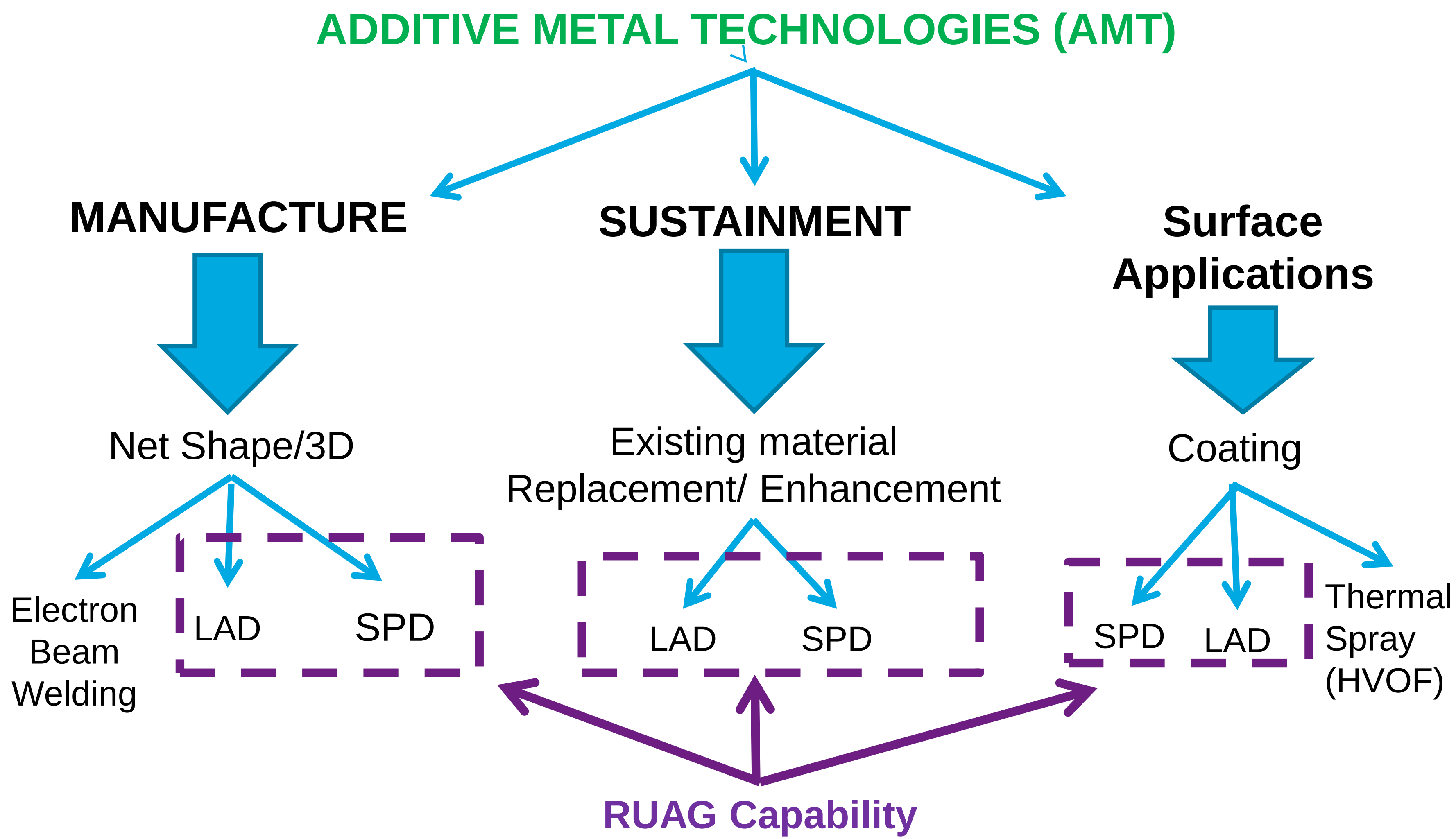
Additive Manufacture – *Changing Nature of Sustainment*



SPD	**Supersonic Particle Deposition**	**Cold Spray**
LAD	**Laser Assisted Deposition**	**Thermal**

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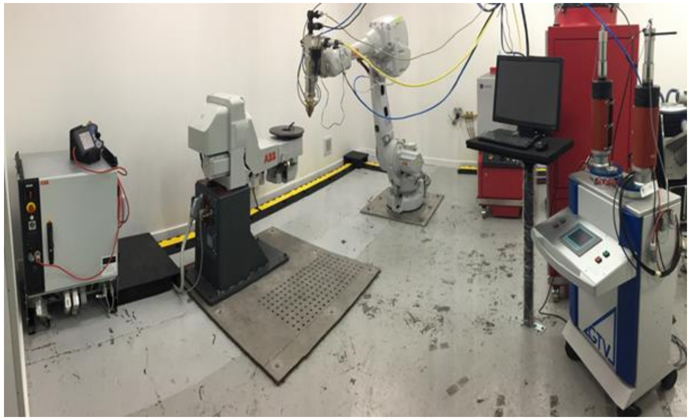
RUAG Australia Capability

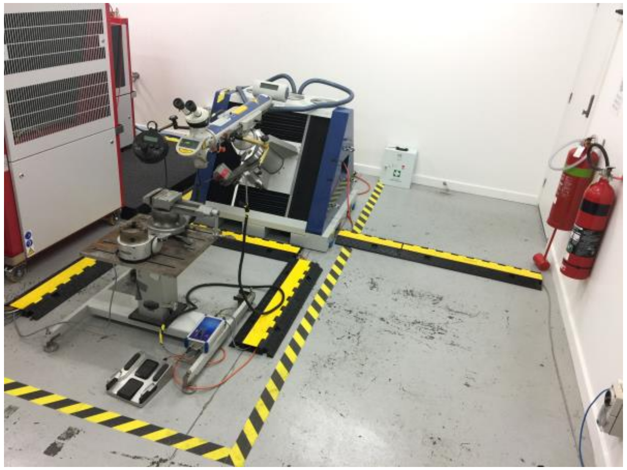
SPD Fixed System



Laser Powder System

Funded by CoA (A$2m for laser repair

SPD Portable Unit ***(Brolga)***



Laser Wire System

Acquired from RUAG Stanz

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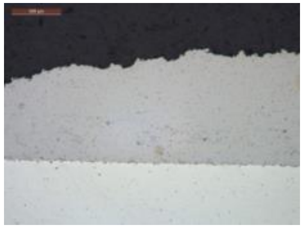
Successful SPD Summary

- ❖ **Successful deposition of the following metal powders; Aluminium alloys (2000, 6000 and 7000 series), Titanium, Nickel, Steels (stainless, low carbon, mild, invar etc), Inconel, tantalum.**
- ❖ **>50 certified SPD repaired products released back into service (3 aircraft types, > 9000 accrued flight hours)**
- ❖ **Continued savings for the Australian Defence forces approx $10M to date "***RUAG's commitment to improvement and efficiency has resulted in a $3M saving to the Commonwealth through the recovery of beyond-repair RI's and BDS by using advanced material additive repair schemes. TFSPO*
- ❖ **Successful applications to replace existing wet processes such as Nickel (Sulphamate & EN) & Chrome.**
- ❖ **Positive outcomes with regards to structural application potential**
- ❖ **On-going proof of concept for defence and international aerospace companies**

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Nickel application time comparison

Processing time to complete 4 cylinders

	E-Nickel	SPD	Time saving
Part marking	9		-
Temper Etch	6		-
MPI	2		-
Shot peen	6		-
Polish	4		-
E-Nickel	50	1.5	97%
Hone	16		-
CAD	28		-
MPI	2		-
Passivate	4		-
Assembly	6		-
Paint	16 (+ 24)		-
Rest	(4)		-
Final Inspection	(8)		-
TOTAL	149	100.5	32.6%

Nickel coating time (4 cylinders)

	E-Nickel	SPD	Time saving
Masking	16	0.5	-
Plating	8	0.5	-
De-Masking	2	0.5	-
Bake	24	-	-
TOTAL	50	1.5	97%

Process trade-offs

Advantages	Disadvantages
• Eliminate Nickel bath: • Chemical solution • Measurement time • Calibration • lab-time • Floor space	
• Eliminate baking time	
• Increase plating-shop capacity	
• Environmental: ✓ Good corporate citizen ✓ Less site contamination ✓ Less waste treatment	

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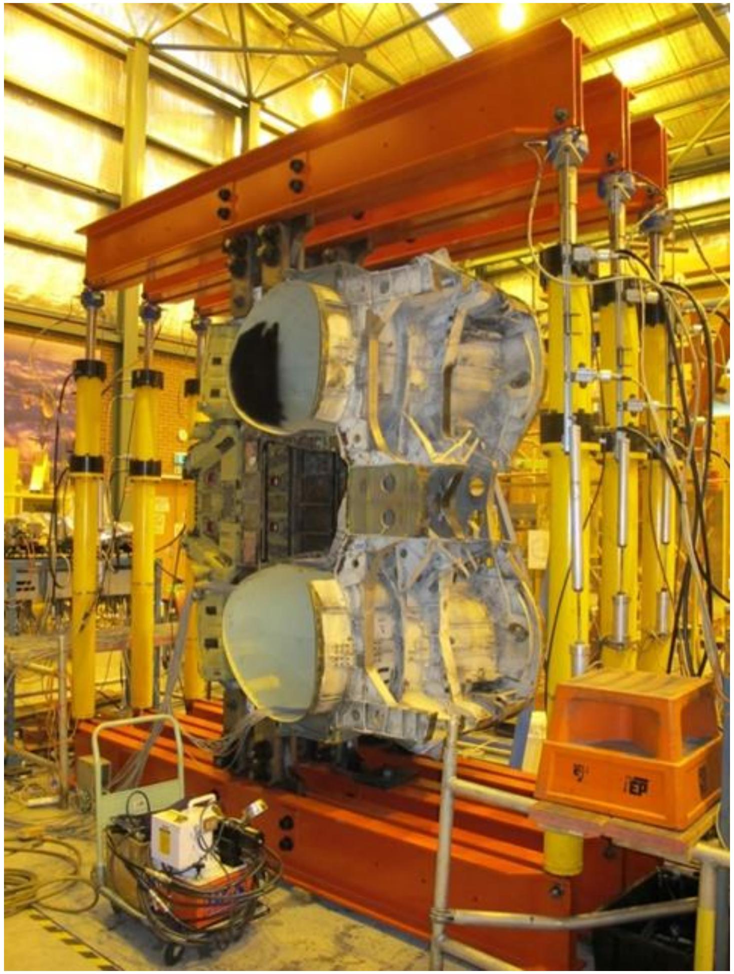
Quantifiable Structural Integrity (SI) Credits

Potential



- Previous research conducted by RUAG Australia and Monash University has shown that SPD using aluminium alloy 7075 metal powder to address a range of problems associated with aircraft structural integrity. *(A number of papers have been published commencing in 2011)*
- The potential of SPD to repair skin corrosion on tension dominated surfaces has been highlighted in previous work.
- Extensive 3D finite element analysis presented in previous work revealed the potential for SPD to restore the load bearing capacity of rib stiffened wing structures where the upper wing skin was badly corroded and under compression loading.
- As part of a RAAF/DSTO FLAW Identification Program 12 SPD doublers were applied to a centre barrel which was subjected to representative fighter wing root bending moment spectra until failure of at least one bulkhead. Failure of the bulkhead occurred at 18,000 test hours (3 aircraft lives). No SPD failures/disbonds. (peak stresses >200 MPa)

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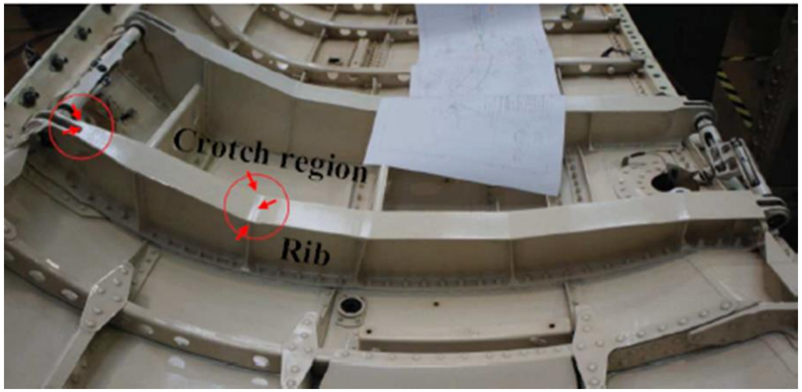
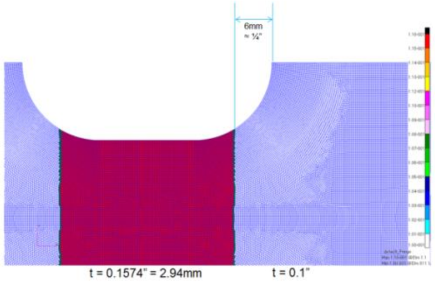
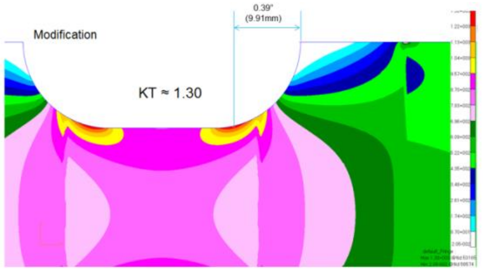
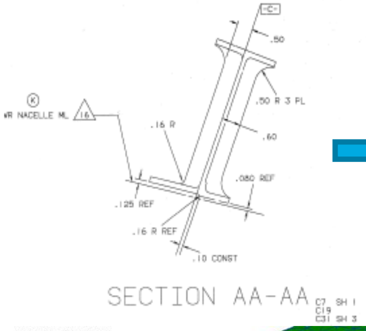
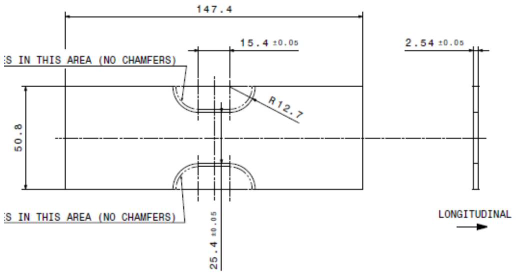
Quantifiable SI (Credits) Program #1 _ F/A- 18 Door Frame 68 *(RA/RAIA/Monash)*

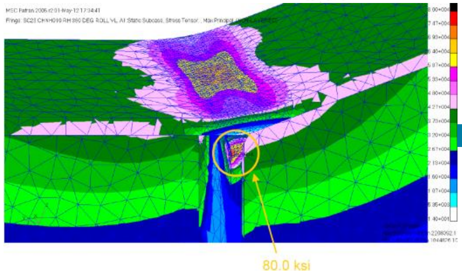


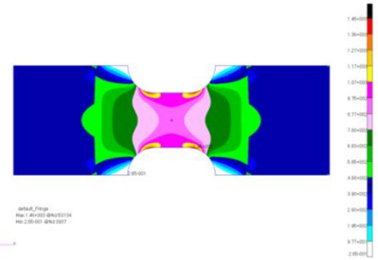




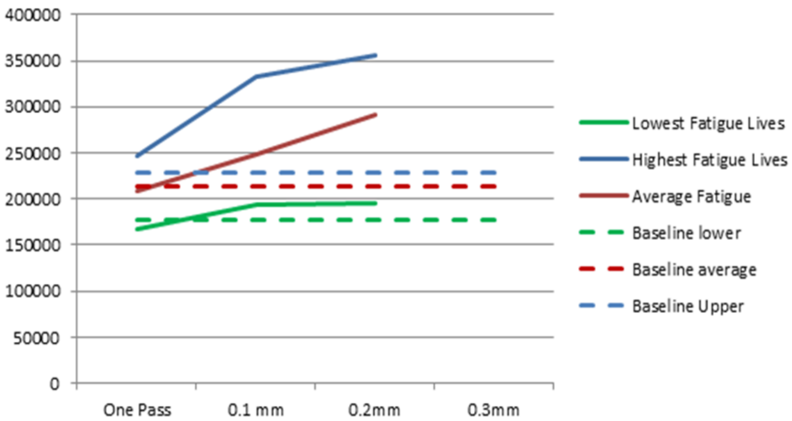








Static **Testing**



Fatigue Testing

Improved factored life on SPD Coupons by factor 1.6

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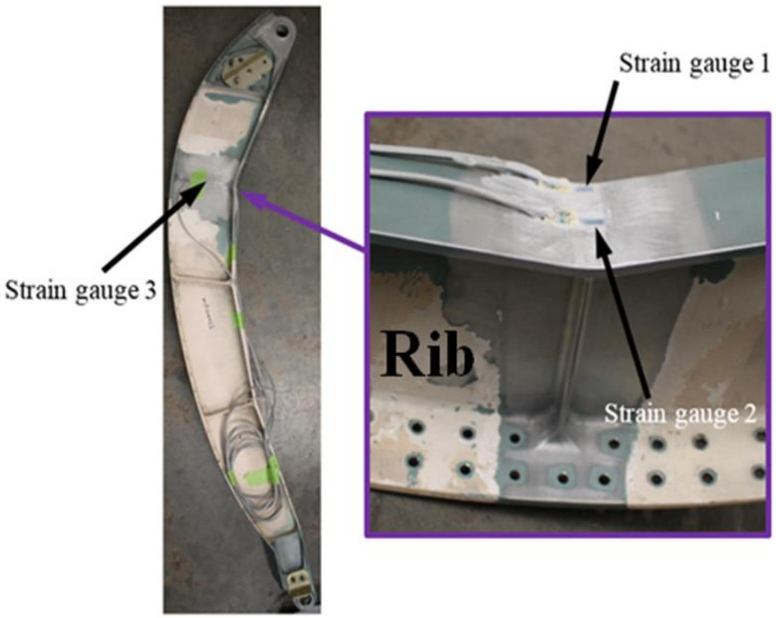
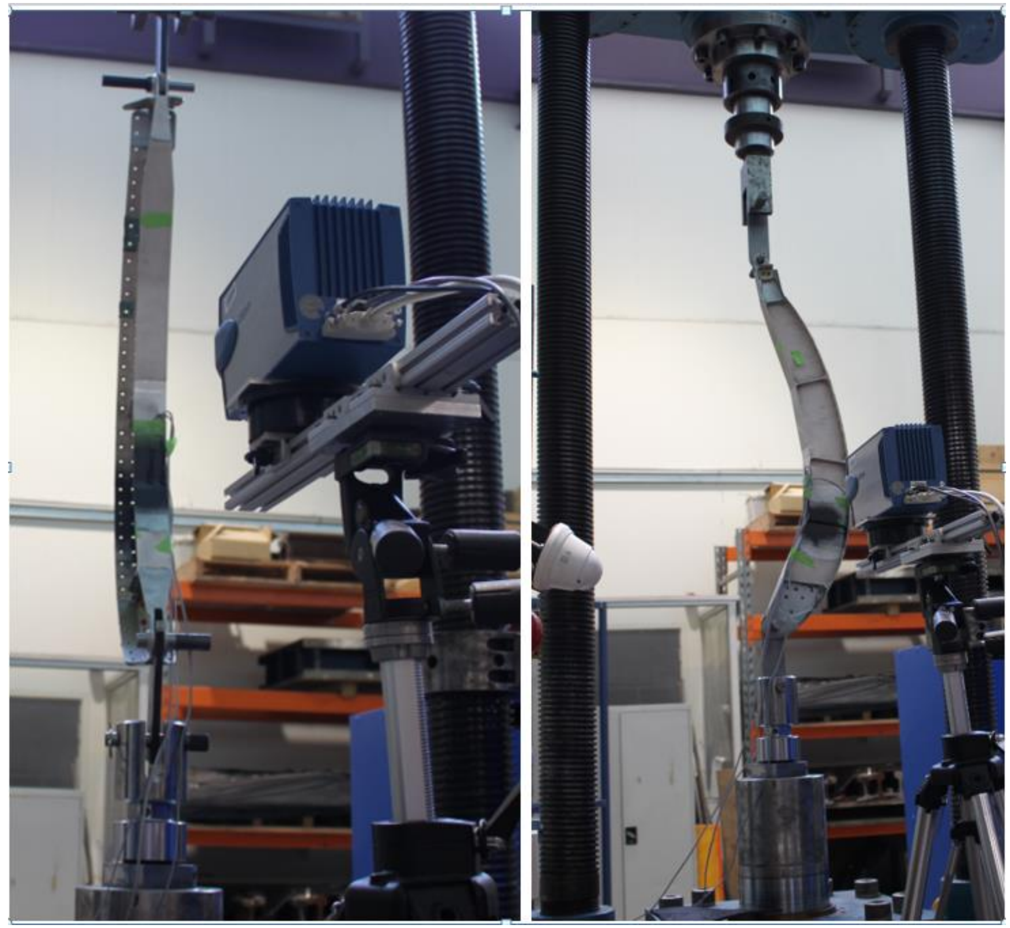
Quantifiable SI (Credits) Program #1 – F/A 18 Door Frame 68 *(RA/RAIA/Monash)*





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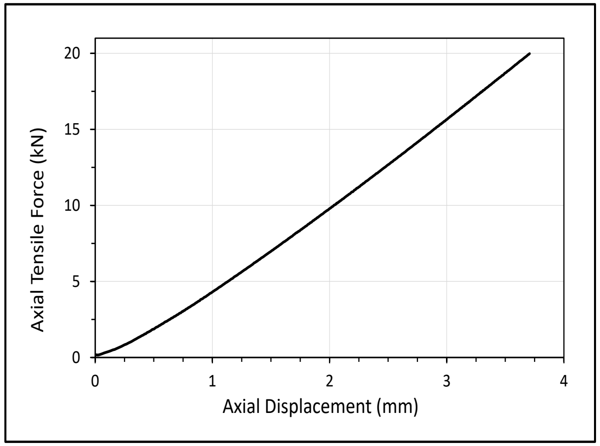
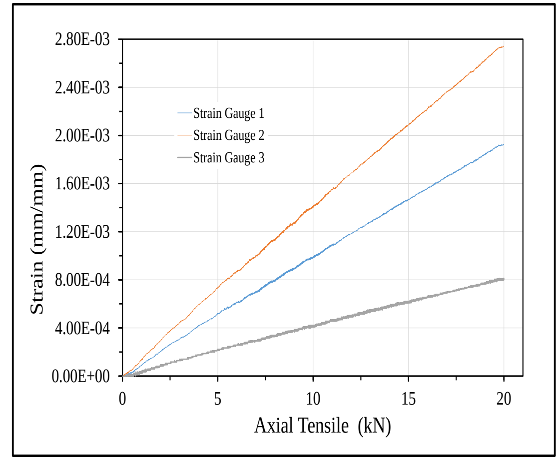
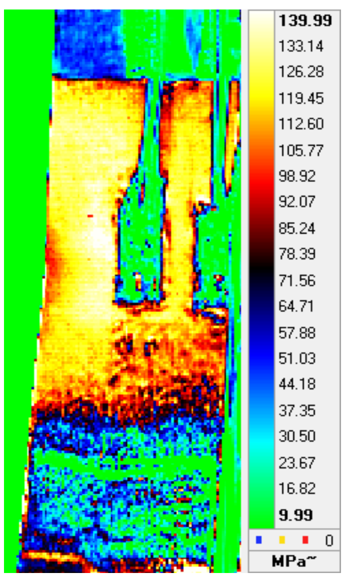
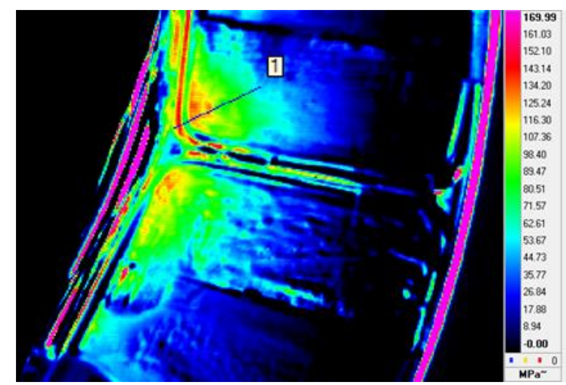






Strain Gauge Number	Strain mm/mm	Stress (MPa)	Stress from IR camera
1	1.73E-3	123	137
2	2.48E-3	176	173
3	7.24E-4	51.7	-



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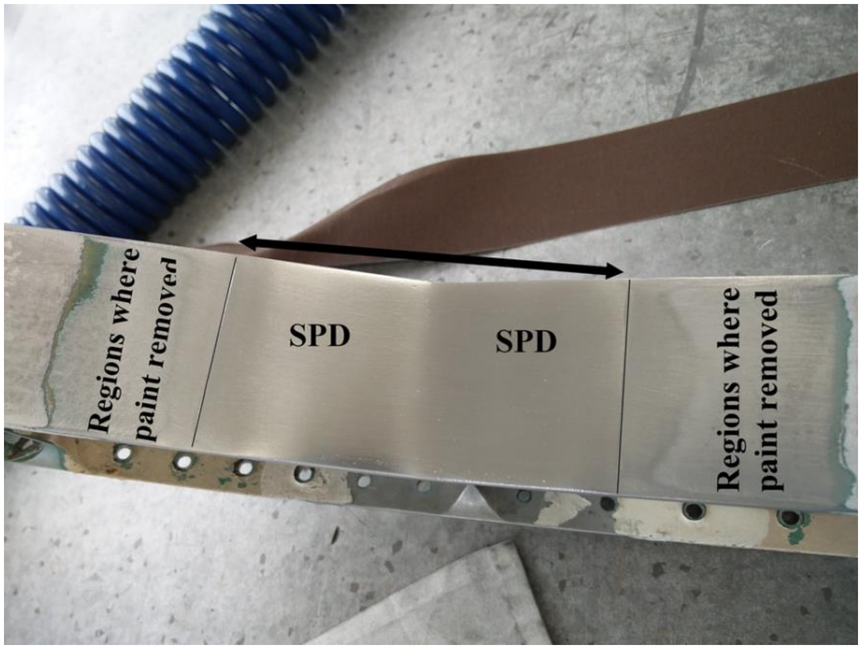
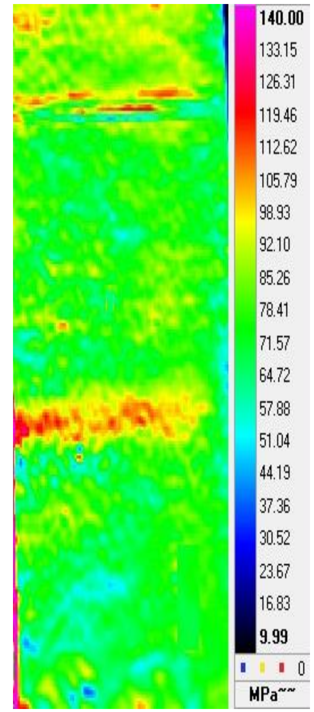
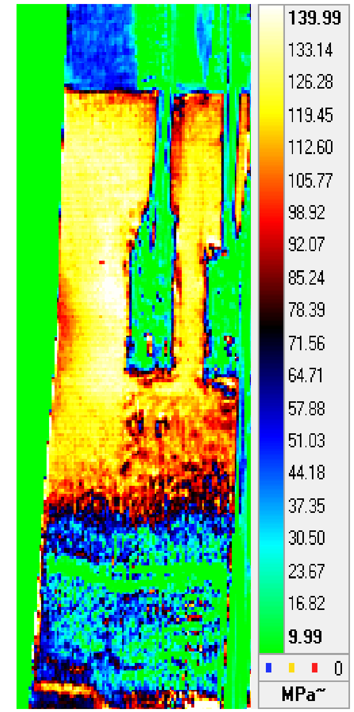
Quantifiable SI (Credits) Program #1 – F/A 18 Door Frame 68 *(RA/RAIA/Monash)*





SPD



No SPD

An SPD doubler was then deposited on the crotch surface of the former, and the infrared thermography test was repeated. The resultant infrared thermography stress picture show approximately 16% reduction in the stress field at the critical location.

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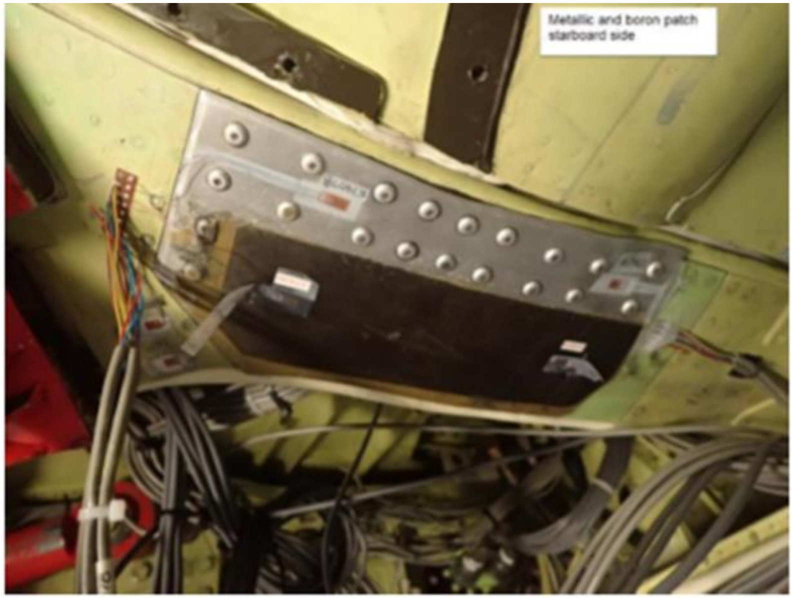
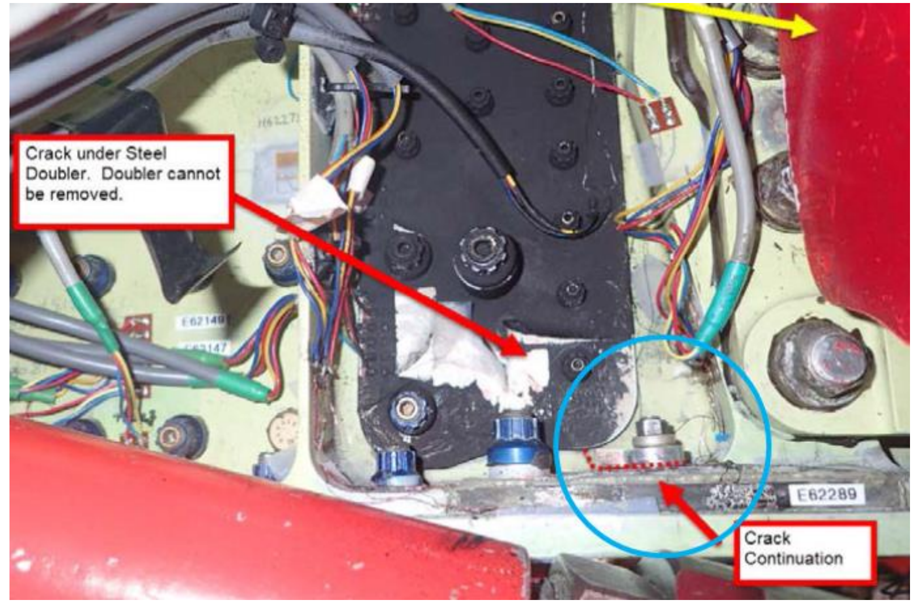
Quantifiable SI (Credits) Program #2 – Lower Wing Skin & Structure *(RUAG/Monash/OEM)*





Lower wing skin suffers fatigue cracking emanating from corrosion pits and around fasteners. A number of current repair techniques have been employed to stop/ limit crack growth. Stop drilling/cold working, metal patch & composite patch.

SPD was evaluated as a possible solution to repair skin and stop crack propagation

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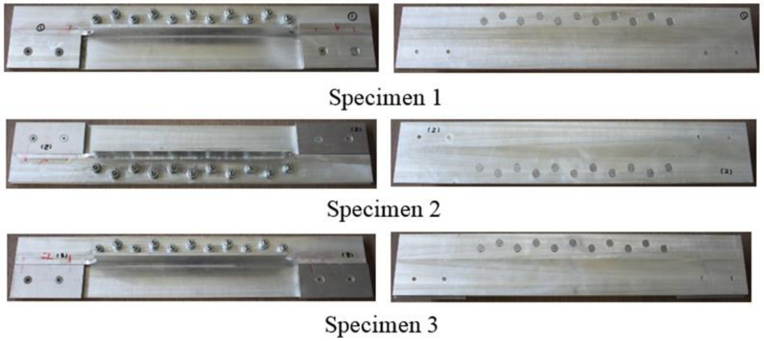
Quantifiable SI (Credits) Program #2 – Lower Wing Skin & Structure *(RUAG/Monash/OEM)*

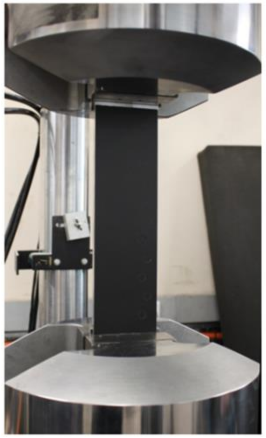
Three Specimens were designed/manufactured to represent the actual aircraft skin/spar structure.

Strain gauges were attached to interested points and tension and compression test were performed.
Loading: Pmax = 50 kN, R = 0.1, ΔP = Pmax – Pmin = 44 kN.
Frequency: 5 Hz

At the same time a infra-red stress distribution images were taken.

The result obtained from the gauge reading were compared with both the FEM simulation and stress distribution imaging results to validate the strain gauge/thermography methods so as to apply them to predict stress/strain information at critical spot(s).





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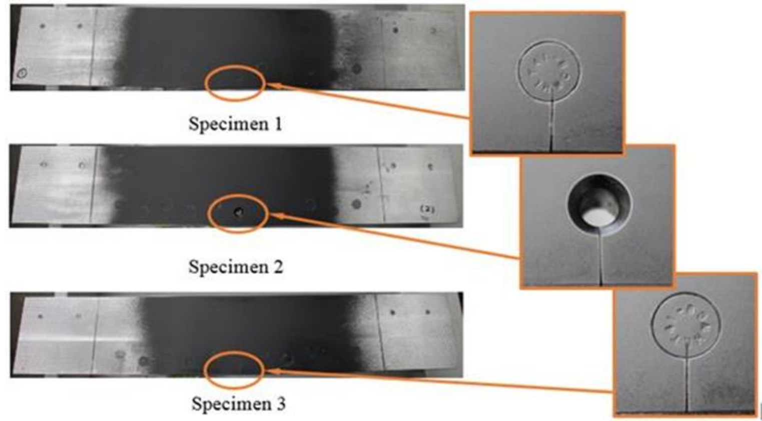
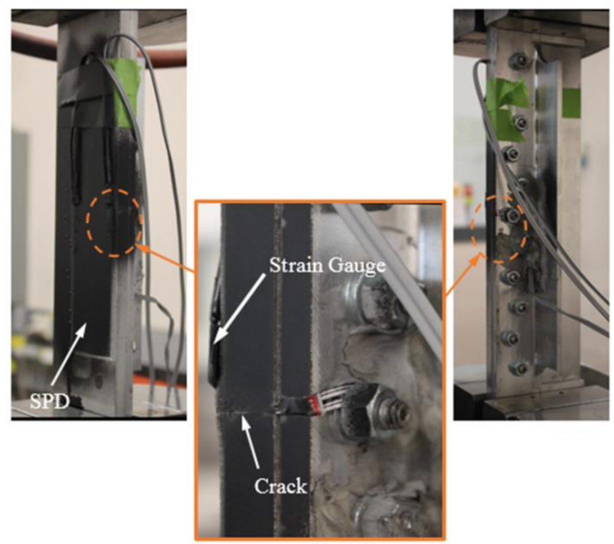
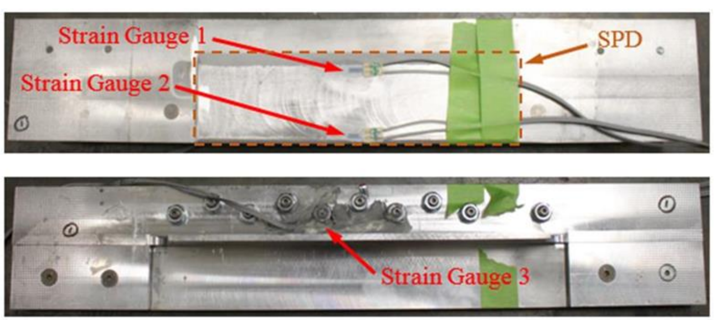
Quantifiable SI Program #2 – Lower Wing Skin & Structure *(RUAG/Monash/OEM)*

Using the above testing as base line, the specimen were cut at the skin to generate a crack into the fastener hole.

Further testing/FEM/Infra-red stress distribution were performed. The specimen then were SPD coated to form a patch over the cracked area The average thickness of SPD for Specimens 1 to 3 was 2.72, 2.73 and 3.94 mm respectively.







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Quantifiable SI Program #2 – Lower Wing Skin & Structure *(RUAG/Monash/OEM)*

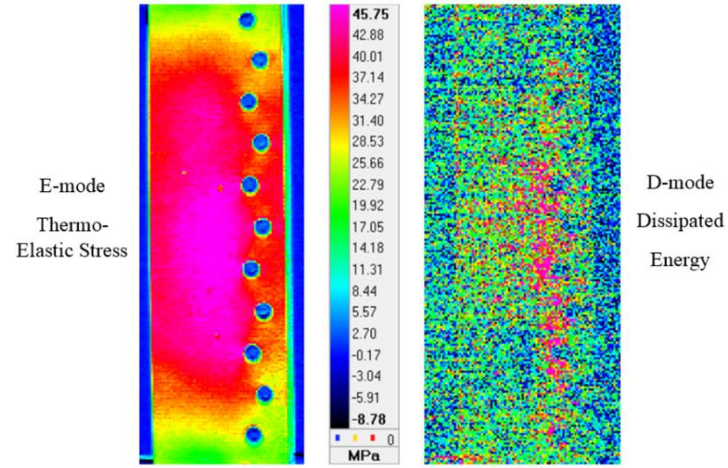
Test results can be summarized as below.

- Overall, FEM analysis and thermography measurement were in good agreement with the strain gauge measurement, usually <10% difference among them.

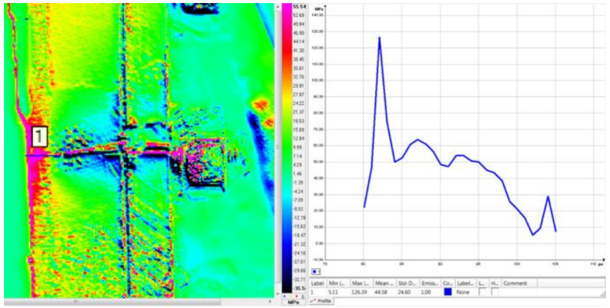
- As usually the crack does not cause material removal which will leave a gap at the cracked area, SPD 7075 can be directly applied to the cracked area.

- On average, SPD can reduce >20% load reduction depends on the SPD coating thickness. The stress reduction is in a linear relationship with SPD coating thickness within the tested range.

- Although the stress reduction is obvious at the uncracked surface, the linear relationship can not be applied to critical spots once there is a crack occurred. Nevertheless SPD can definitely reduce the stress level at those critical spots. In area vicinity to the crack, seen from FEM work, the stress level can be greatly improved with SPD coating.



Compare with no SPD, the stress at was significant reduced by SPD repair.



The SPD repair patching causes the critical stresses at the crack to be transferred

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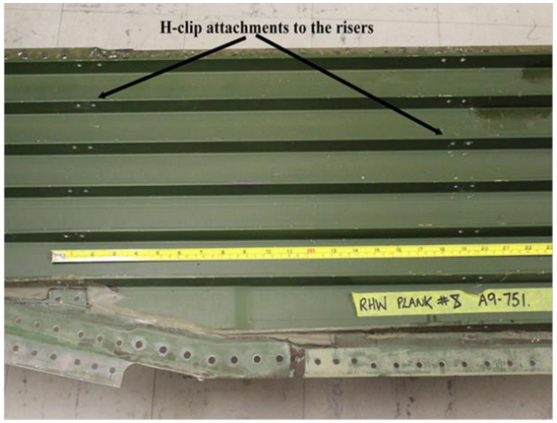
Quantifiable SI (Credits) Program #3 - Wing Skin & Structure Compressive Loaded *(RUAG/Monash/USN)*

FE Baseline Model (***Provided by Monash University)***

- A 500 mm (long) by 250 mm (wide) rib stiffened 7075-T6 aluminium alloy panel where the skin and the risers were both 4.3 mm thick.
- The panel contained 5 ribs
- The length of the panel was taken so as to approximate the distance been the H-clips that are attached to the risers.
- The risers were 30 mm deep and 50 mm apart.
- The skin thickness analysed was 2.1 mm.
- The unloaded edges of the panel were assumed to be simply supported (other cases were analysed

FE Model with Corrosion removal

- The corrosion was taken to be 40 mm in diameter with a depth of 1.05 mm. (50% of the total thickness of the skin)
- Centre of Panel for maximum Buckling stress



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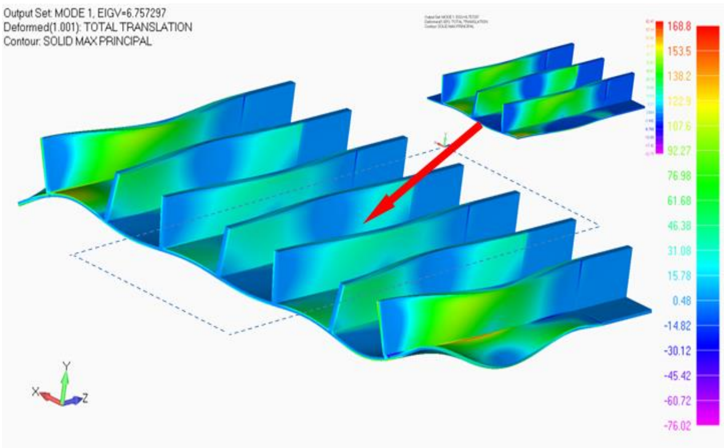
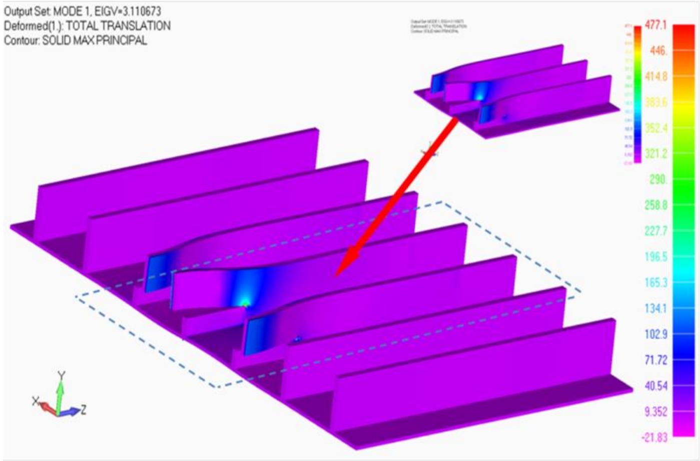
Quantifiable SI (Credits) Program #3 - Wing Skin & Structure Compressive Loaded *(RUAG/Monash/USN)*

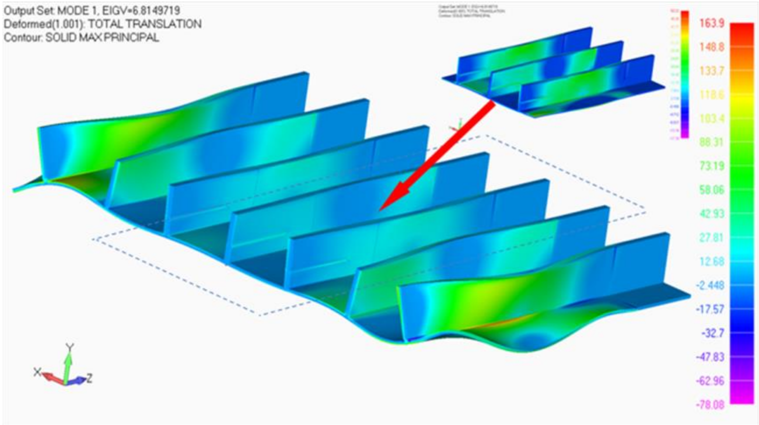
- FE Analysis was repeated for a 7 stiffener panel.



Buckling load (No SCC) - **946** kN



Buckling load (3 risers with SCC) - **510kN**



Application of 3 thin 0.2 mm thick, 10 mm wide, and 110 mm long SPD doublers essentially **restored** both the buckling load and the buckling mode.

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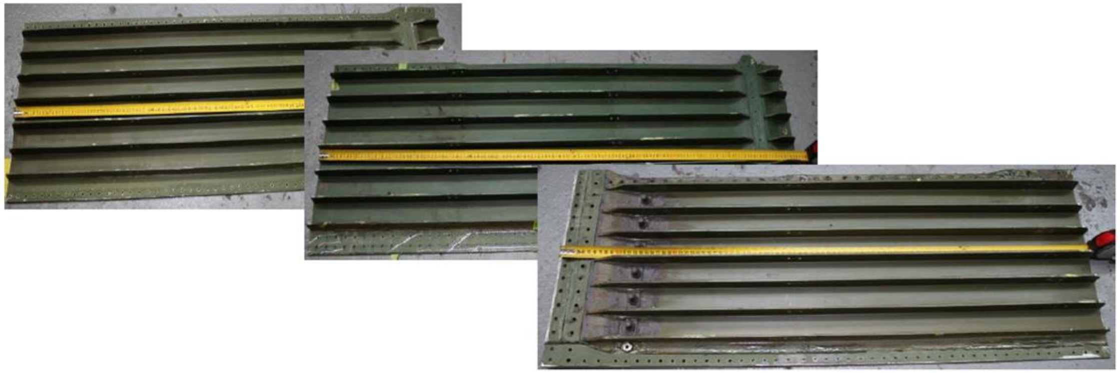
Quantifiable SI (Credits) Program #3 - Wing Skin & Structure Compressive Loaded *(RUAG/Monash/USN)*

***The overall program objective was to quantify the contribution of Al Alloy 7075 SPD to the structural integrity of a repaired aircraft 7075-T6 wing skin structure. Measurements were obtained from traditional strain gauging and thermography both under static and dynamic load conditions. The results were compared to analytical predictions*.**

- SPD applications were evaluated by assessing Wing Integrity with Upper Surface Corrosion Subject to Compressive Loading

- Ex-service wing plank segments from retired P3-C Orion aircraft courtesy of the Royal Australian Air Force (RAAF) were able to be obtained along with. to the in-service load spectra. These wing segments are also typical of framed elements which exist in other aircraft.



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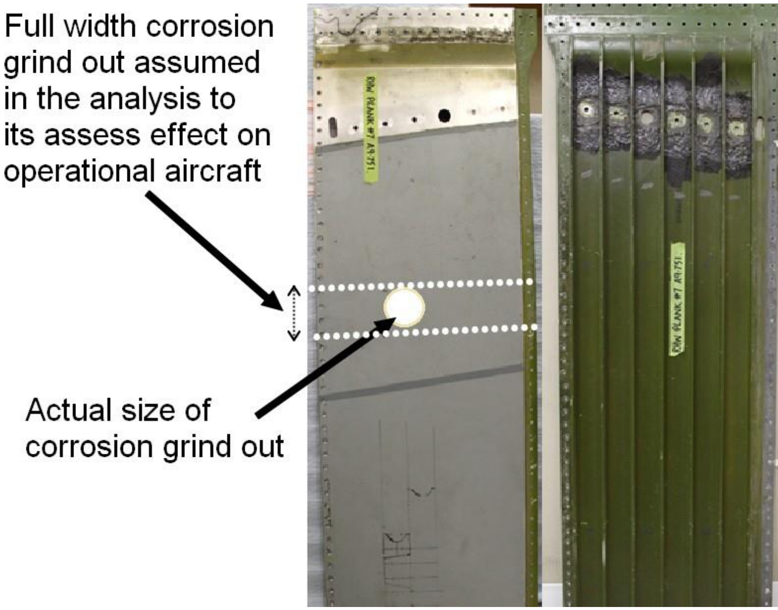
Assessment of Wing Integrity with Upper Surface Corrosion Subject to Compressive Loading

- Maritime Patrol System Project Office (MPSPO) advised that typical surface corrosion often has a near circular planform.
- When assessing the impact of corrosion a full width corrosion grindout was assumed.
- This assumption was applied when evaluating the SPD repair presentation solution
- In assessing the performance the position taken by the **US Joint Services Structural Guidelines JSSG2206** which **specifies that there must be no yielding at 115% Design Limit Load (DLL)** was utilised.



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Quantifiable SI (Credits) Program #3 - Wing Skin & Structure Compressive Loaded *(RUAG/Monash/USN)*

Test Program

Six (6) P3C wing plank specimens from 3 retired wings were tested were tested

No	Configuration	Test Condition	Comments
1#	Undamaged	Tested to failure	This specimen had previously been tested to establish the stress distribution in a pristine specimen. In the present study it was tested to failure.
6#	Undamaged	Elastic/Plastic Loading	This specimen was used to further establish the stress distribution in a pristine specimen. It was chosen since its dimensions were similar to that of Specimen 5 which contained simulated corrosion and was repaired using SPD. This test thereby enabled a direct comparison with Specimen 5.
2#	Simulated Corrosion	Tested to Failure	This specimen had previously been tested to establish the effect of the simulated corrosion on the stress distribution. In the present study this specimen was tested to failure.
4#	Simulated Corrosion	Tested to Failure	See 2# comments
3#	SPD Repair	Tested to Failure	This specimen had previously been tested prior to being repaired. This specimen was first tested to establish the effect of SPD repair to simulated corrosion on the stress distribution. They were then loaded to failure
5#	SPD Repair	Tested to Failure	See 5# comments

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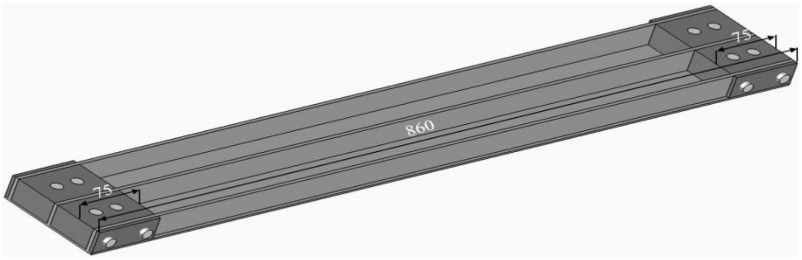
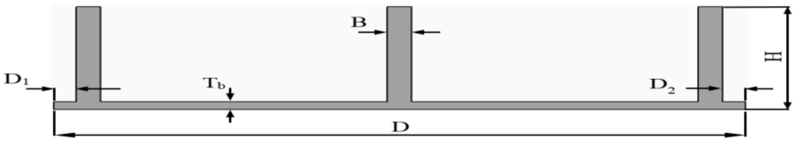
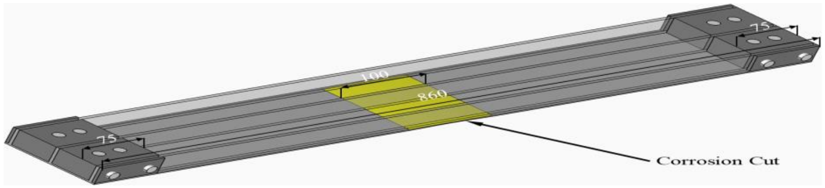
Quantifiable SI (Credits) Program #3 - Wing Skin & Structure Compressive Loaded *(RUAG/Monash/USN)*

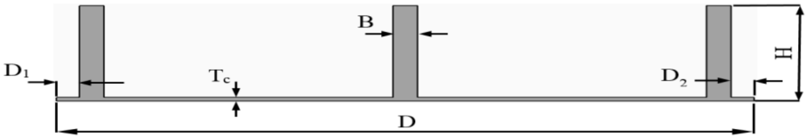
Test Specimen Geometries



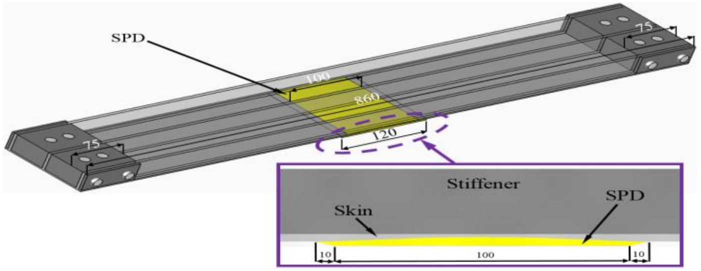


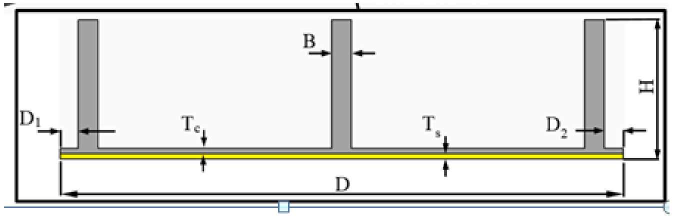
Pristine specimen





Specimen with Simulated Corrosion





Specimen with SPD repair to the Simulated Corrosion

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Quantifiable SI (Credits) Program #3 - Wing Skin & Structure Compressive Loaded *(RUAG/Monash/USN)*

Test Specimen Geometries

Dimensions	Specimen Number					
	1# (mm)	2# (mm)	3# (mm)	4# (mm)	5# (mm)	6# (mm)
B	4.27	4.37	3.97	4.07	3.95	3.98
H	32.80	32.90	30.70	30.90	30.60	31.20
D	122.40	122.00	113.00	114.50	113.90	113.70
D_1	4.00	3.00	1.50	2.00	2.00	1.50
D_2	4.50	4.50	2.30	2.00	0.50	1.00
T_B	2.26	2.72	2.25	2.32	2.22	2.46
T_c	-	0.95	0.93	1.38	1.05	-
T_s	-	-	2.73	-	2.42	-

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Quantifiable SI (Credits) Program #3 - Wing Skin & Structure Compressive Loaded *(RUAG/Monash/USN)*

Locations of Strain Gauges – Baseline and SPD

Baseline Specimen 6

Specimen 3 (with SPD repair)

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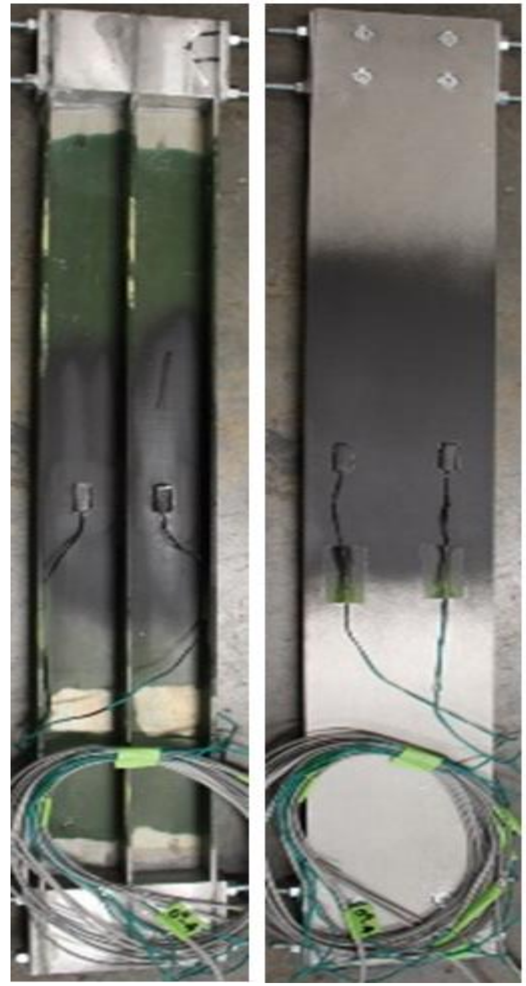
Stress Distribution Analysis

- Prior to testing the SPD repaired specimens to failure both strain gauge measurements and infra-red thermography stress measurements were performed. Two test programs were performed, these being:

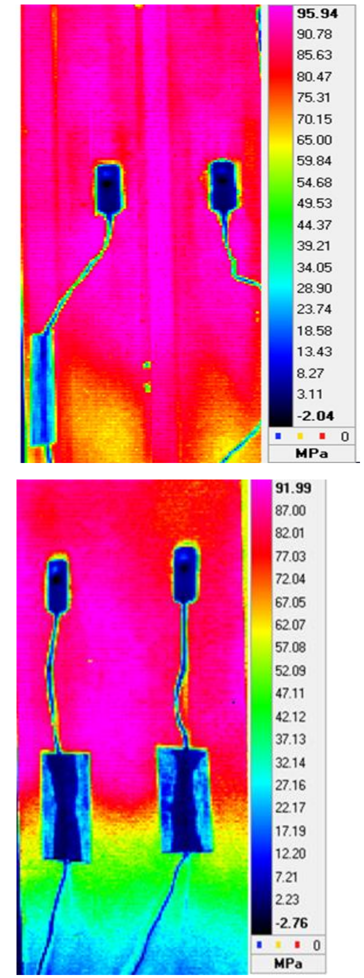
  1) A static compression test with the loads varying from 0 to -50 kN.

  2) *A cyclic load test with the loads varying from -5 kN to -55 kN at a frequency of 4Hz*



Strain Gauge Back & Front

Undamaged Specimen



Thermography Back & Front

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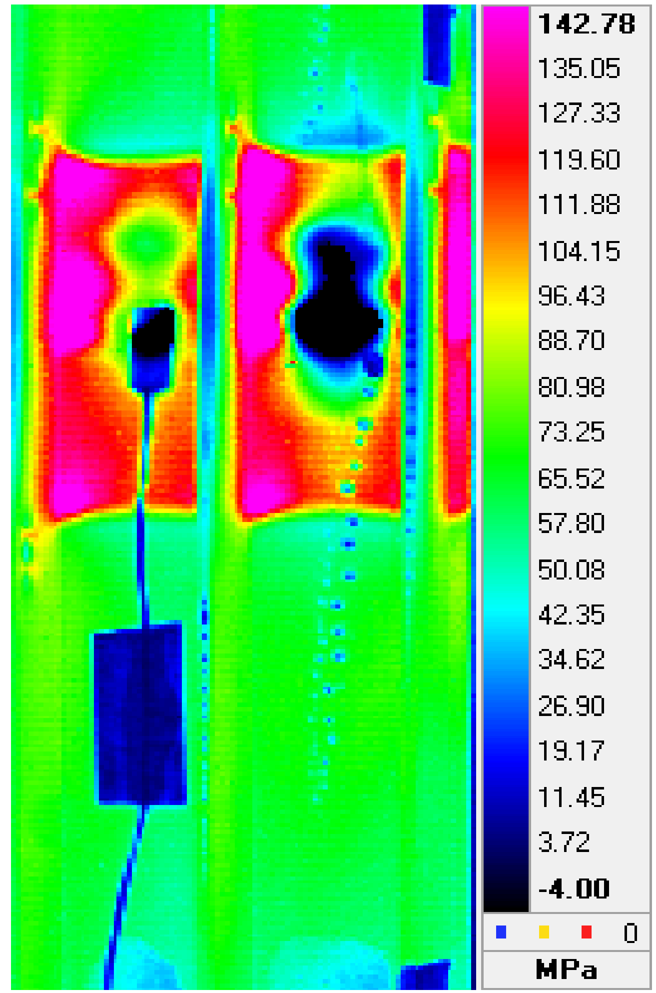
Effect of Skin Corrosion on Skin Stress



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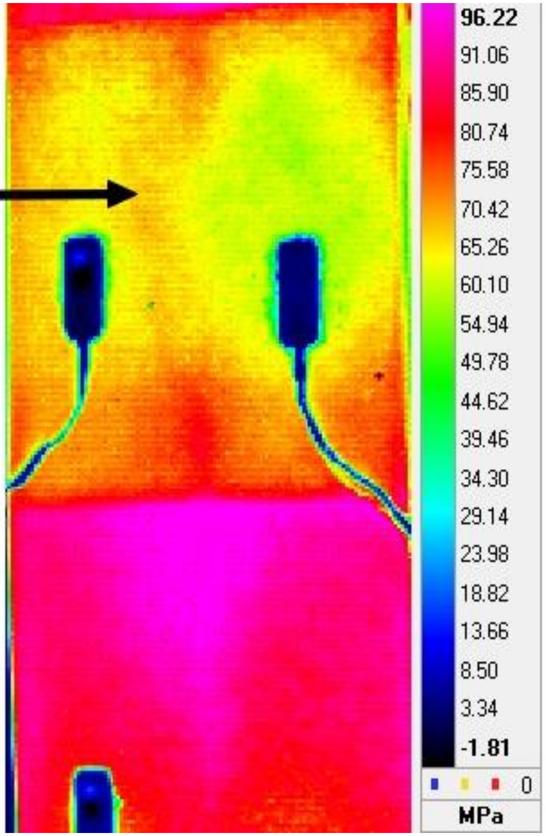
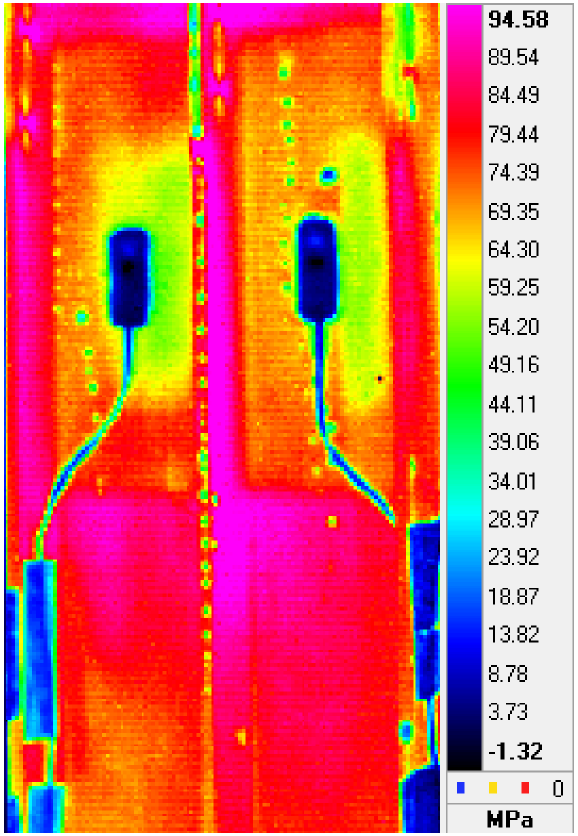
Effect of SPD Repair on Buckling Load

Reduced stress field due to the SPD repair sitting proud





Stress field on the upper and inner surfaces of the repaired P3C panel

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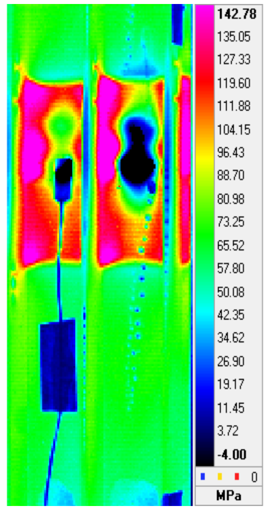
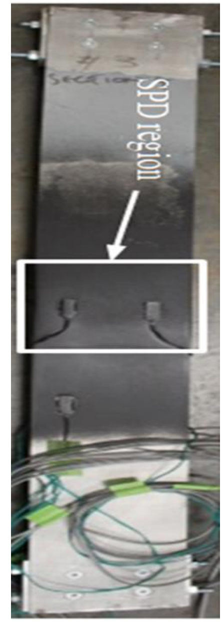
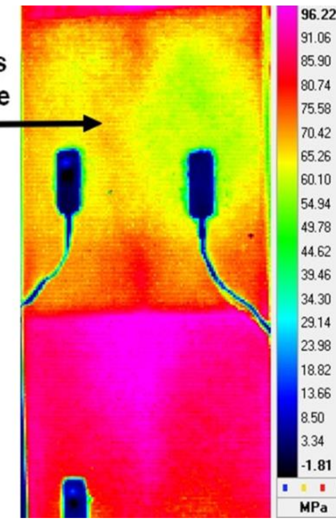
Stress Distribution Analysis

Simulated corrosion before SPD 3#





Reduced stress field due to the SPD repair sitting proud



Compression (-50 kN)	Location			
	1	2	3	4
	(MPa)			
Specimen 3	-92.7	-71.5	-77.2	-60.8
Specimen 5	-99.8	-80.6	-79.6	-82.9
Specimen 6	-99.1	-96.9	-99.4	-99.1

Measured stresses (Strain Gauged) at -50 kN

Cyclic test with loads ranging from (-5 to-55 kN)	Location			
	1	2	3	4
	(MPa)			
Specimen 3	-92.8	-71.7	-78.0	-61.2
Specimen 5	-99.4	-80	-78.7	-82
Specimen 6	-99.6	-95.7	-98.7	-99.2

Stress range measured during infra-red thermography test

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Quantifiable SI (Credits) Program #3 - Wing Skin & Structure Compressive Loaded *(RUAG/Monash/USN)*

Measured and Computed Buckling Loads

Specimen	Buckling load (kN)	Comment	Computed buckling load in kN. Difference from the measured load (%)
1 (pristine specimen)	233	Elastic buckling. On unloading the specimen returned to its original shape.	243 (4%)
2 (simulated corrosion)	143	Extensive plastic yielding. On unloading the specimen was extensively deformed.	143 (1%)
4 (simulated corrosion)	150	Plastic yielding. On unloading the specimen permanently deformed.	159 (6%)
3 (with an SPD repair to simulated corrosion)	206	Elastic buckling. On unloading the specimen returned to its original shape. The remote failure stain exceeded the Proof Load strains for the wing.	Specimen with the same geometry but no simulated corrosion and no SPD the computed buckling load was 218 kN. Thus allowing for errors the SPD repair essentially restored the buckling load to that of a pristine panel.
5 (with an SPD repair to simulated corrosion)	197	The SPD restored the buckling load. However, the post buckling resulted in both cracking and partial disbonding of the SPD. On unloading the specimen was permanently deformed. The remote failure stain exceeded the Proof Load strains for the wing.	For a pristine specimen with the same geometry, i.e. with no simulated corrosion and no SPD, the computed buckling load was 206 kN. Thus allowing for errors the SPD essentially restored the buckling load to that of a pristine panel.

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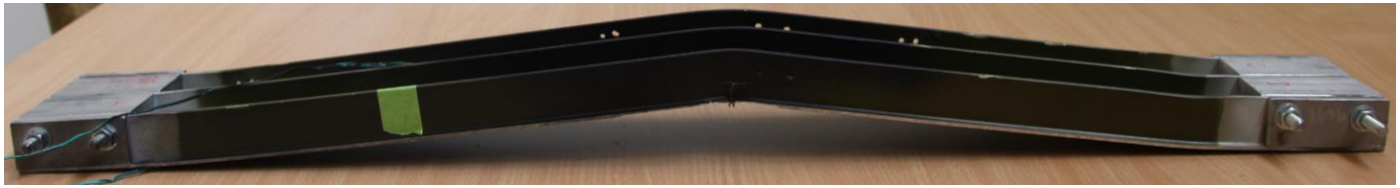
Specimen Failures

Pristine Specimen



Specimen with skin corrosion

SPD repaired specimen (3#) after testing

SPD repaired specimen (5#) after testing

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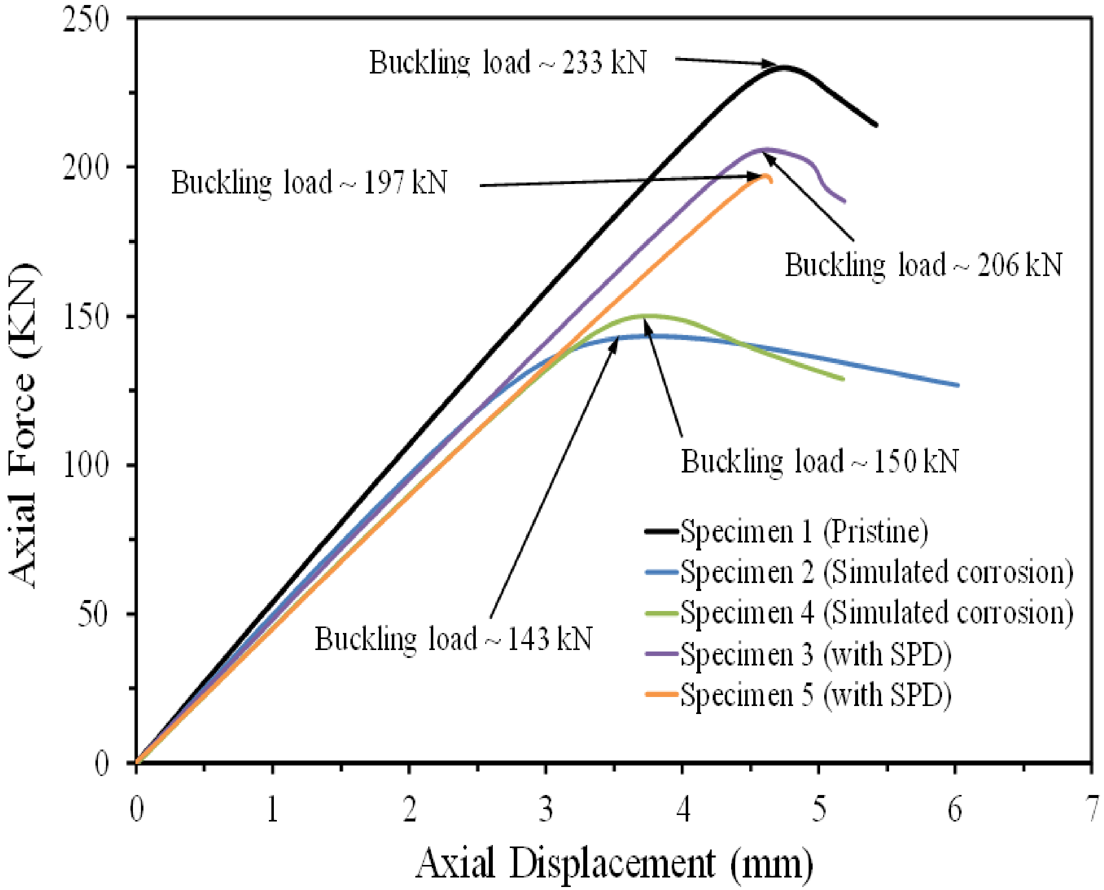
Effect of Skin Corrosion on Buckling Load



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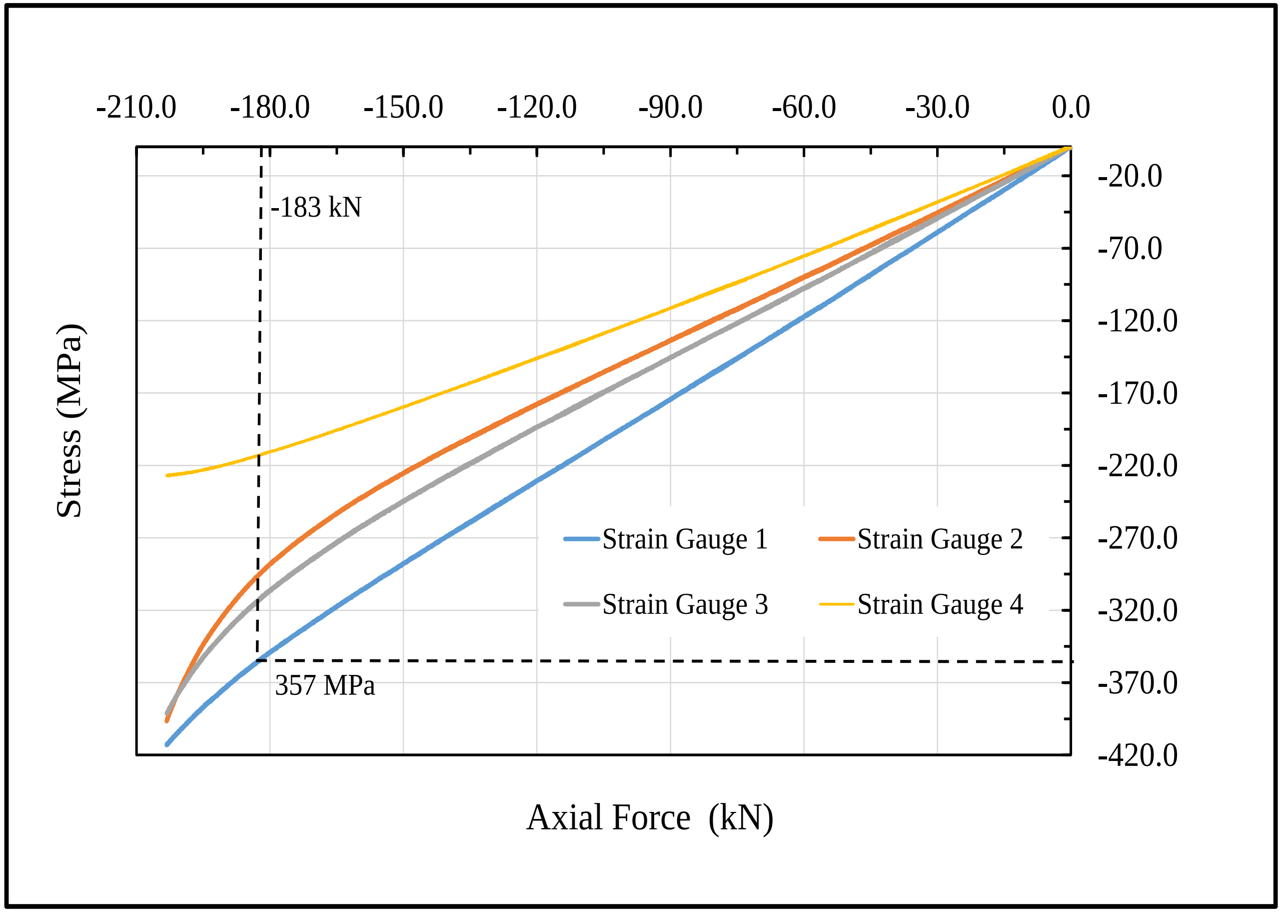
Effect of SPD on Skin Stresses



Panel stress at Limit load ~ 170 MPa.

SPD repaired panel can withstand proof load, with non linear behaviour at 115% DLL – A JSSG2006 requirement

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Conclusion

- The test program revealed that not only does the SPD eliminate the complex stress field associated with simulated corrosion, it also essentially restores the stress field, albeit to a slightly lower value than that of a pristine specimen. The Test Program revealed that whilst specimens with simulated corrosion, i.e. Specimens 2 and 4, have dramatically lower buckling loads, SPD repairs to the simulated corrosion essentially restore the load bearing capacity to that of the pristine structure*. Indeed, the strain gauge measurements reveal that the SPD repairs resulted in failure loads that were in excess of that corresponding to Proof Load.*

- It is also shown that there is excellent agreement between the computed and the measured buckling loads

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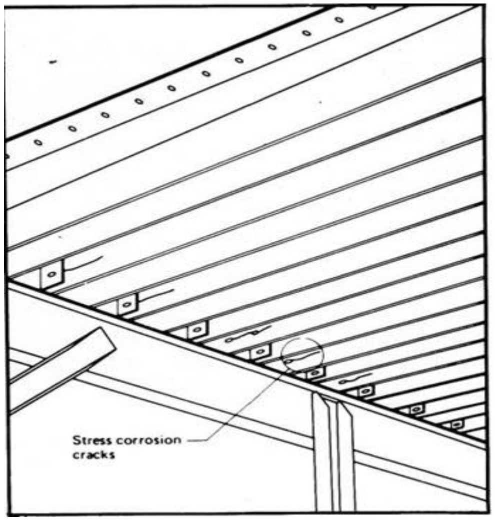
Stress corrosion cracking (SCC) in rib stiffened wing planks

- **Stress corrosion cracking (SCC) in rib stiffened wing planks** is common to both military transport and maritime reconnaissance aircraft.

- **SCC** is also seen in P3C Orion aircraft as is evident from SCC in RAAF AP3C aircraft A09-659. Data courtesy James Ayling (AGAP).

Number of SCC cracks and size (inches)	Location	Wing station
2 cracks, 0.250 & 1.5	Left hand aft upper spar	WS143
3 cracks, 0.200, 0.250 & 0.875	Left hand aft upper spar	WS209
1 crack, 0.875	Left hand aft upper spar	WS275
1 crack, 1.375	Left hand aft upper spar	WS346
1 crack, 2.25	Left hand aft upper spar	WS584
1 crack, 2.5	Left hand aft lower spar	WS349
1 crack, 0.375	Left hand aft lower spar	WS380



Schematic diagram of location of stress corrosion cracking

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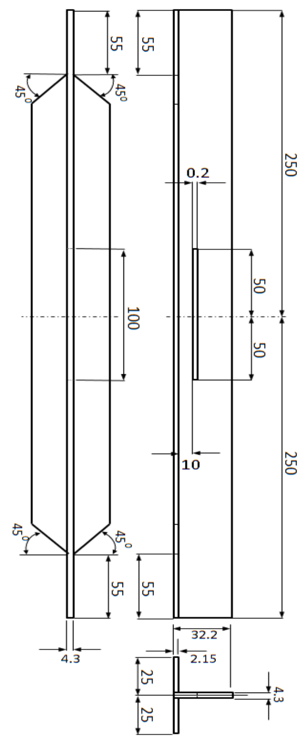
SPD Repairs on Compression Surfaces of a Wing Plank - Experimental Validation

- Nominally identical specimens were cut from a wing plank provided by MPSPO.
- Specimens with no SCC with 100 mm SCC and with both SCC and a SPD repair were tested.



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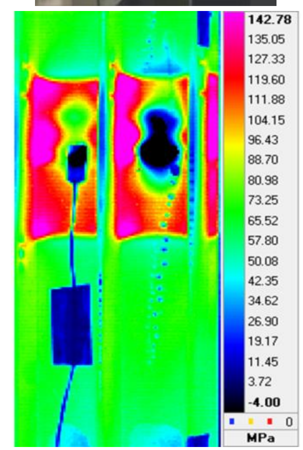
Quantifiable SI (Credits) Program #3 - Wing Skin & Structure *(RUAG/Monash/USN)*

- **USN (Mtech) - Additive metal solutions to corroded wing skins in operational aircraft (Actual aircraft skin sections)**

✓ The effect of SPD repairs can be accurately modelled and analysed and in most cases the analyses have been validated via coupon testing or simulated wing elements.

✓ *SPD repairs to skin corrosion on compression surfaces where there is up to a 50% loss of material between the risers can restore the load carrying capacity of the wing.*

✓ *Stress Corrosion Cracking (SCC) in risers can result in failure due to local buckling that can run the length of the section. Analysis and validation testing has shown that that for SCC in the risers an SPD repair can essentially restore the load carrying capacity of the wing.*



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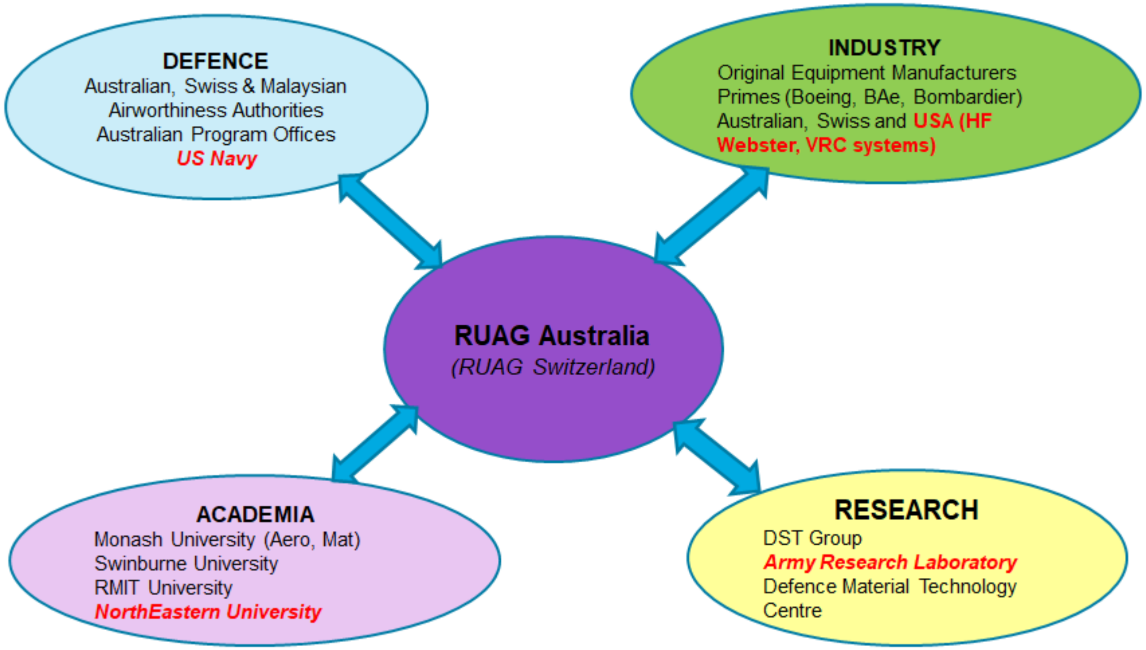
Acknowledgements

The Defence Industry Service Commendation awarded by the Minister of Defence Industry, reads: “In your role as Senior Manager, Advanced Technology and Engineering Solutions at RUAG Australia, and, as a pioneer in the use of Additive Metal Technologies, you helped protect aerospace components from corrosion and wear. Your research resulted in significant cost savings to Defence and improved aircraft availability. You contributed to achieving outstanding outcomes for the ADF.”



“***As you navigate through the rest of your life, be open to collaboration. Other people and other people’s ideas are often better than your own. Find a group of people who challenge and inspire you, spend a lot of time with them, and it will change your life.”*** *Amy Poehler, Actress, Comedian, Director and Producer From The Joy of Success: What It Means to Transform Success Into Excellence, Tochukwu O. Okafor MPA (2013) p. 53*

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QUESTIONS ?????

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