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Airframe Life Extension by Optimised Shape Reworking

Overview of DSTO Developments

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Context – Airframe life extension

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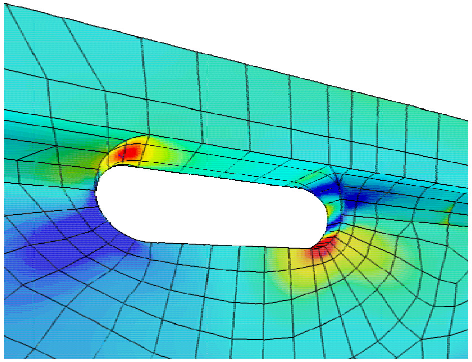

- Airframes contain many stress raising features
- Most shapes consist of straight lines & circular arcs
- Traditional shapes have localized peak stresses
- Cracking at only a few locations can define the economic fatigue life for an aircraft structure
- Hence reducing stresses at a few locations can provide significant benefits to the RAAF

  - safety, aircraft availability, cost saving

Context – Standard blend repairs

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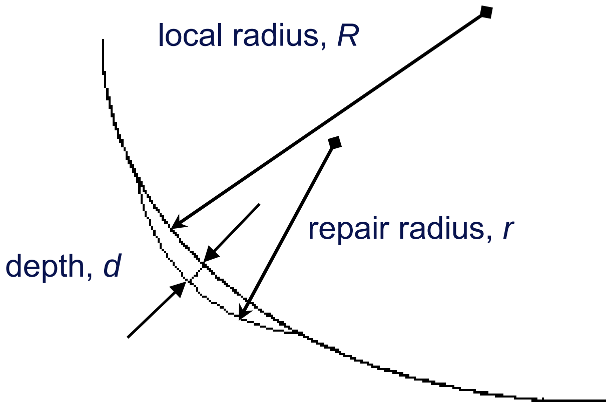
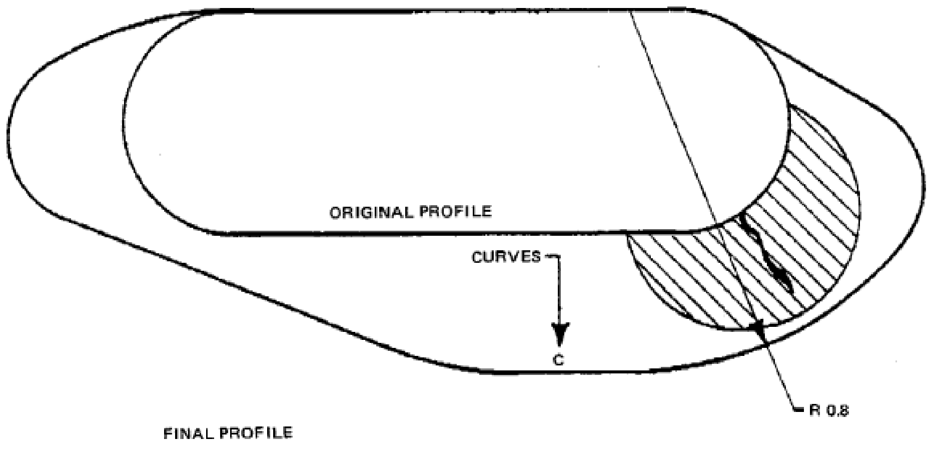
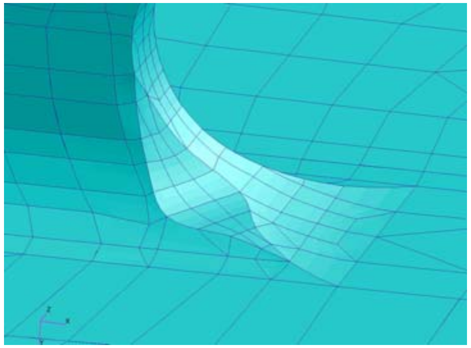
- Very common approach for removal of damage
- Applied to flat or curved surfaces
- May extend fatigue life
- Stresses higher than original shape







Concept of optimal reworking

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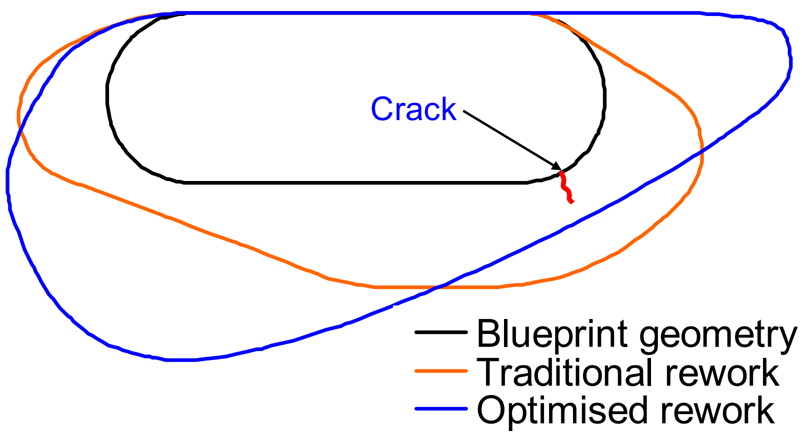
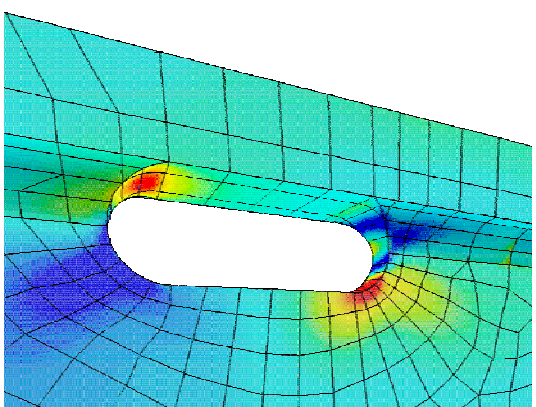
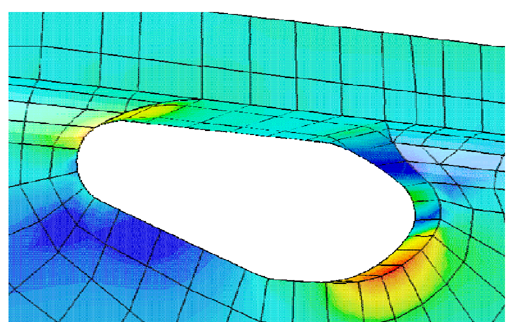
- Optimal shape removes the damaged material and minimises stresses
- For many practical problems there are no analytical solutions

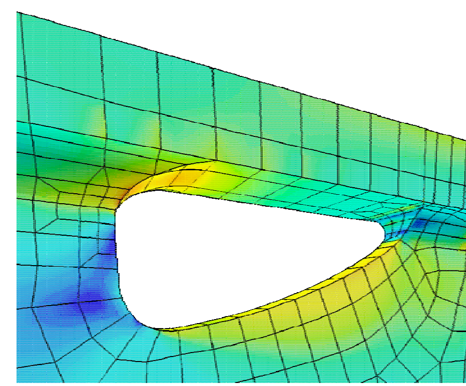




Initial shape



Traditional re-shape
(limited benefit)



Optimal re-shape *(free-form)*
(lowest stress)

Outline

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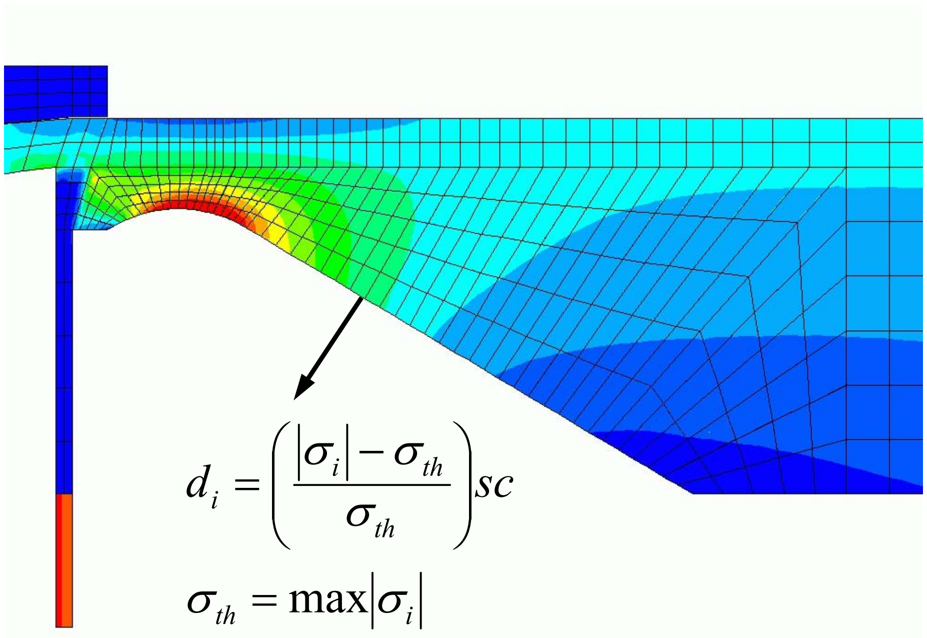
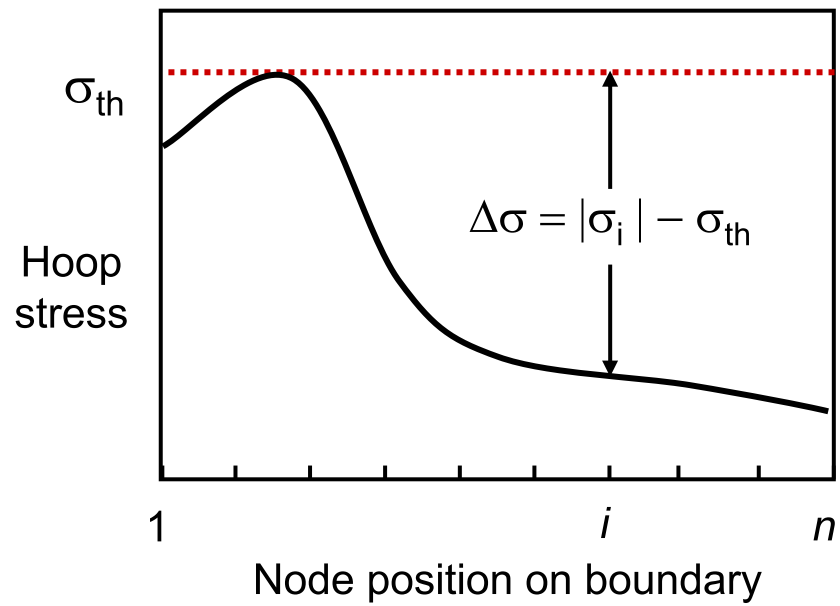
- *Context / concept*
- **Numerical approach**
- **F-111 WPF application & lessons learned**
- **Fatigue life trends**
- **Other design studies / applications**
- **Transitioning issues**

Numerical approach

Single peak stress minimisation





- Aim is constant local stress
- Iterative FE method based on biological growth
- Net material removal only
- Remeshing algorithms used – DSTO code

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Numerical approach

2D multi-peak stress minimisation

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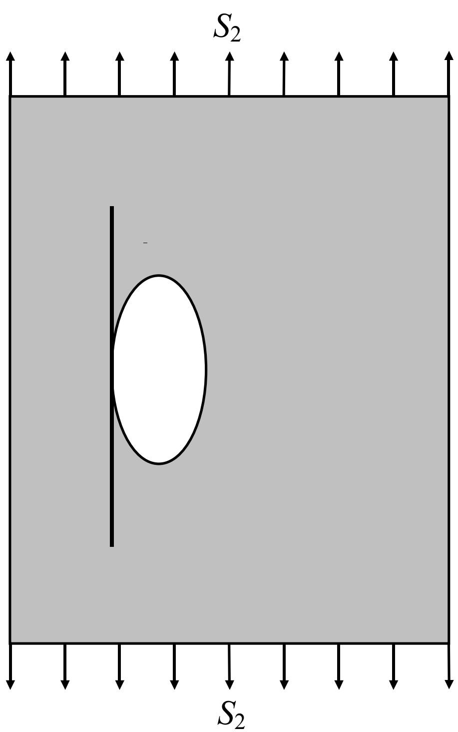
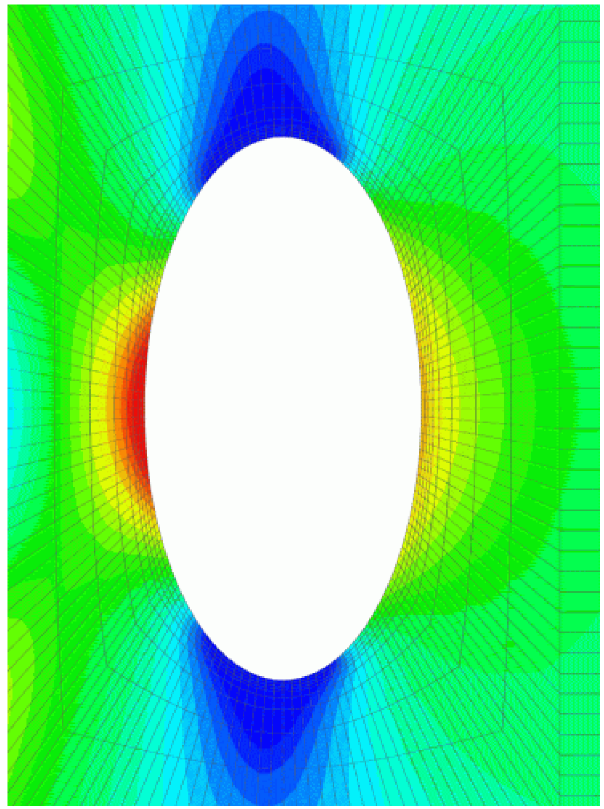
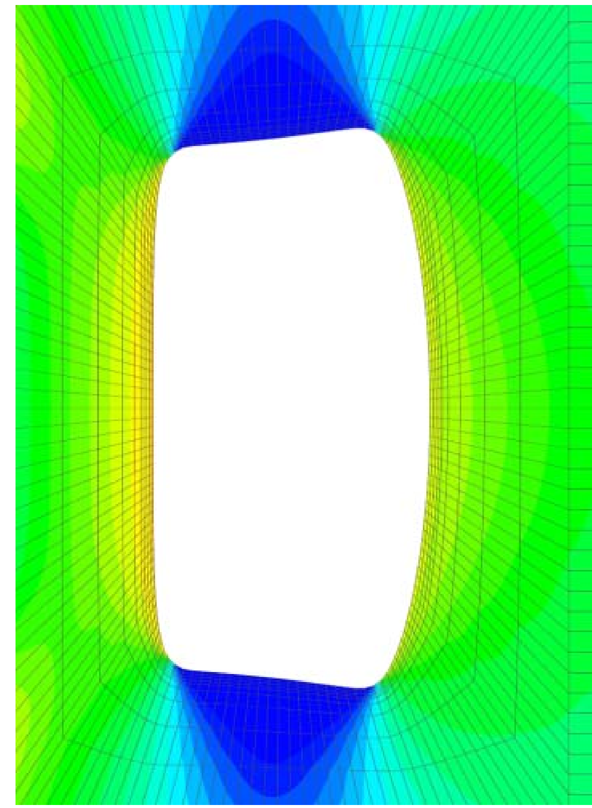




2:1 elliptical hole



2:1 optimal rework

- **21%** stress reduction compared to elliptical hole
- **43%** stress reduction compared to circular hole

Numerical approach

3D multi-peak stress minimisation

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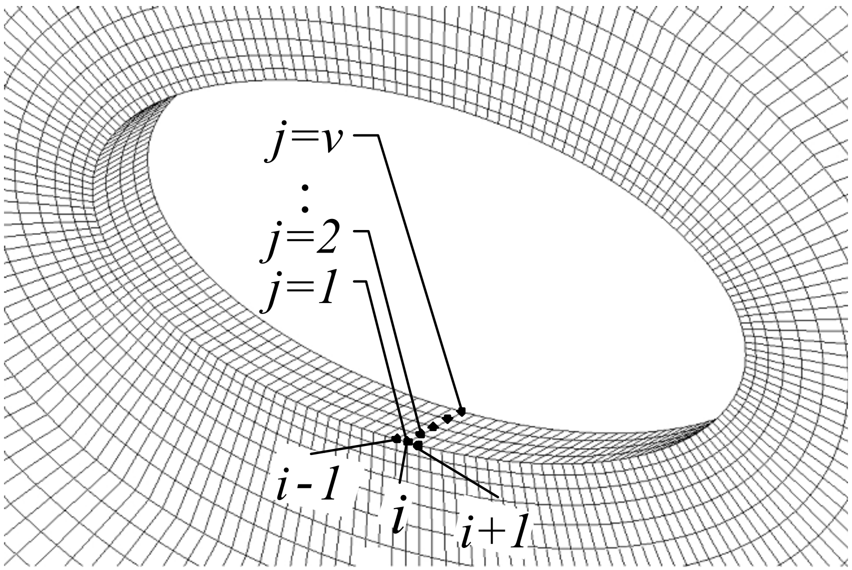

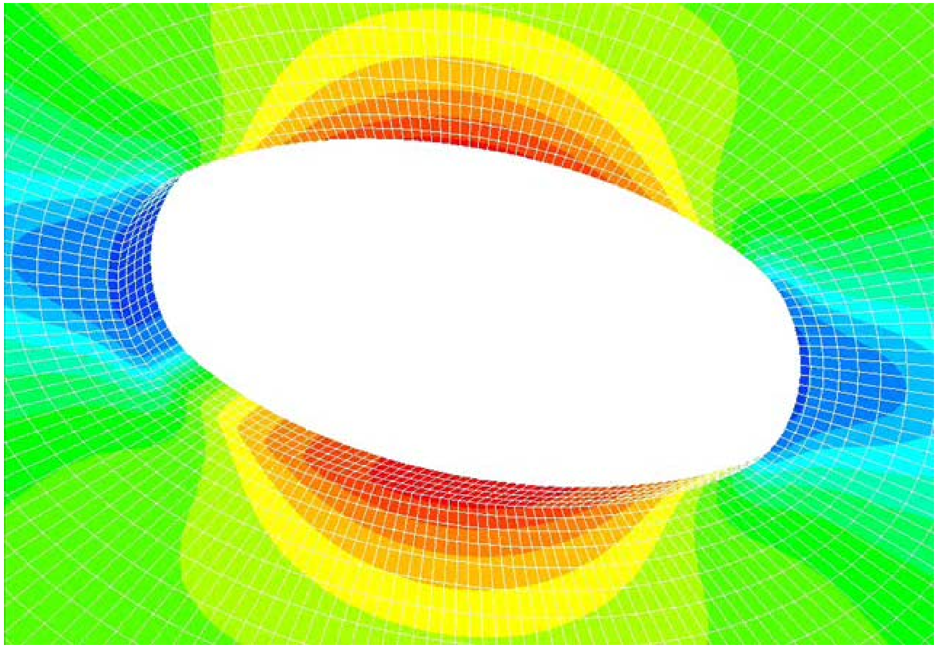

2:1 aspect ratio

Remote stresses, $S_2 = -S_1/4$

- 14 % stress reduction compared to elliptical hole

F-111 wing pivot fitting application

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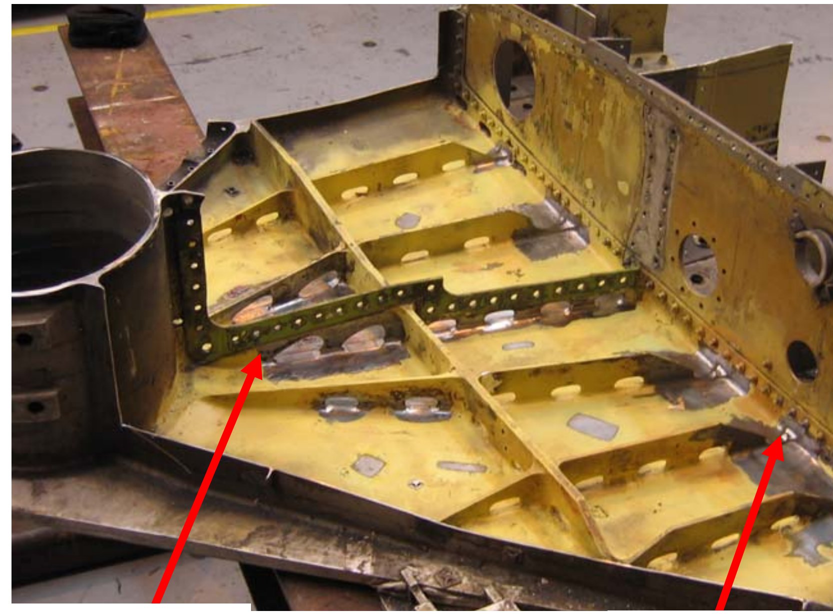

holes

runouts

Requirement:

- Improve shapes for fatigue prone holes and runouts
- Achieving PWD & extend inspection intervals

F-111 WPF application

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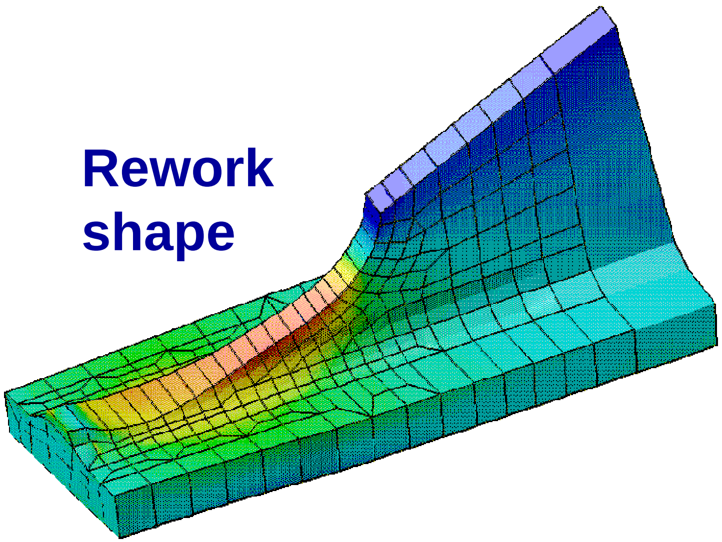
Stiffener runouts



- 30-40% reduction in peak stress
- 4 unique optimal shapes for 4 different locations
- buckling strength considered

F-111 WPF application

Fuel flow vent holes

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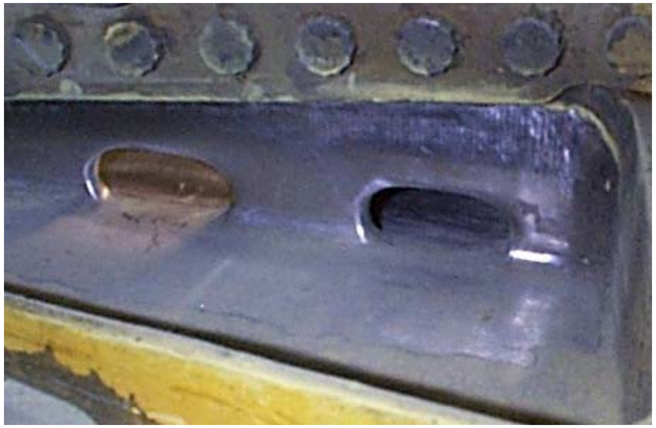
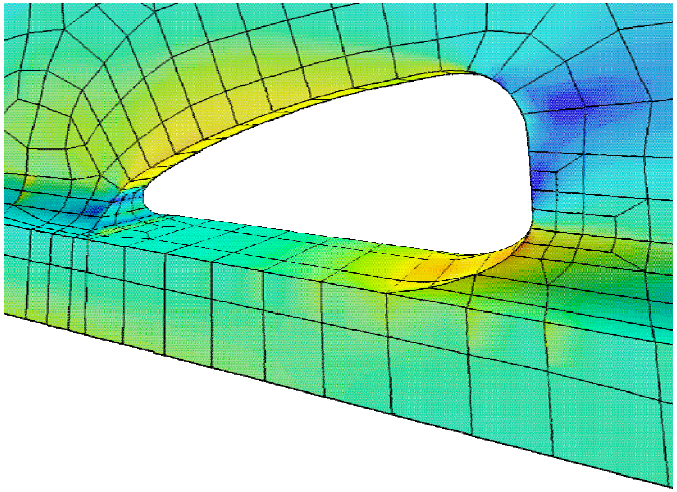
- 25 - 50 % stress reductions
- 4 unique optimal shapes for 4 different locations





F-111 WPF application

Manufacturing rework shapes

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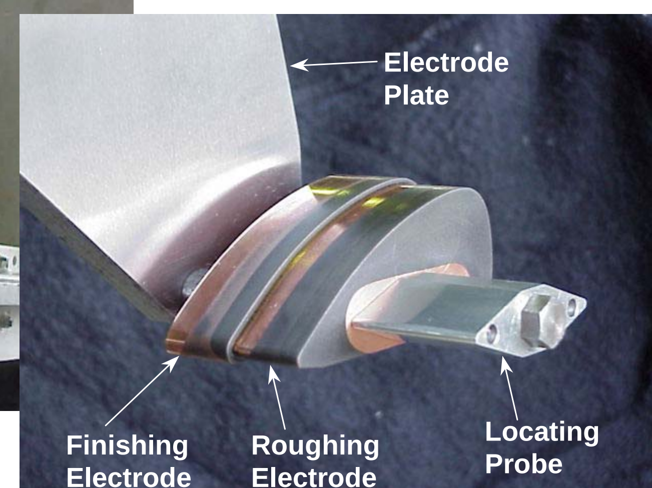
- Electrical discharge machining
- Worked - but complex with difficult access



F-111 WPF application

Experimental validation

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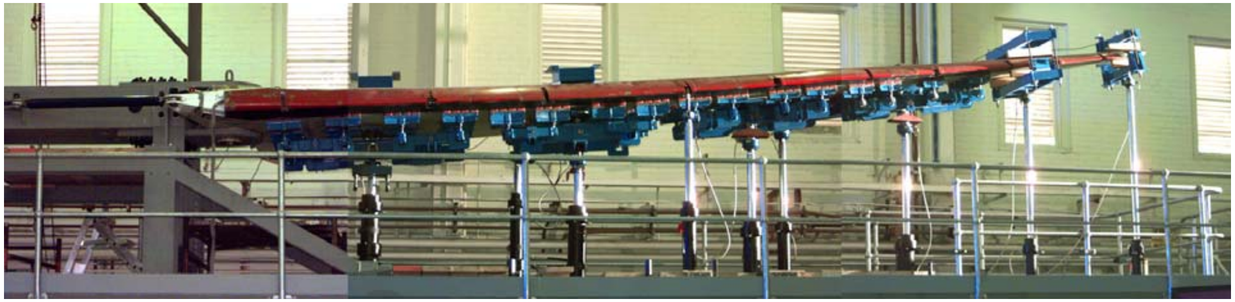
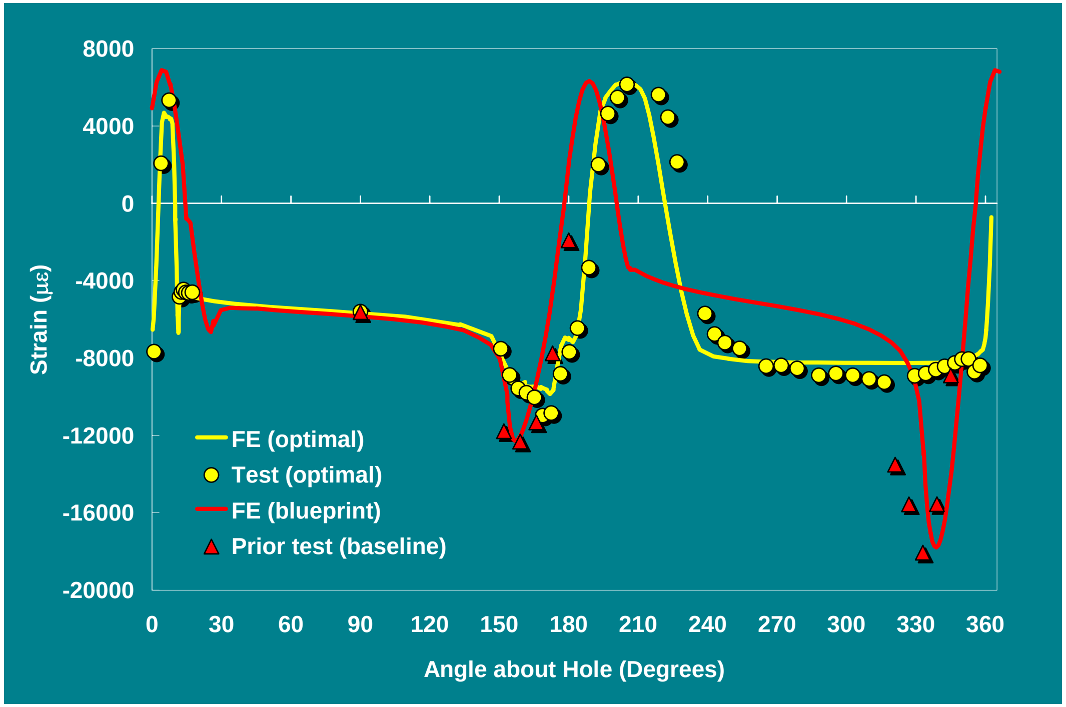
Static tests



Fatigue tests

- durability
- damage tolerance



F-111 WPF application

Lessons

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Reshaped holes

Reshaped SRO

Requirements:

1. Account for variations in fleet nominal geometry

2. Increased understanding re interaction of:
    - Hole size & aspect ratio
    - Manufacturing constraints
    - NDI constraints
    - Fatigue lifing philosophy

3. Need simpler in-situ manufacturing methods

Fatigue life trends

Safe life approach

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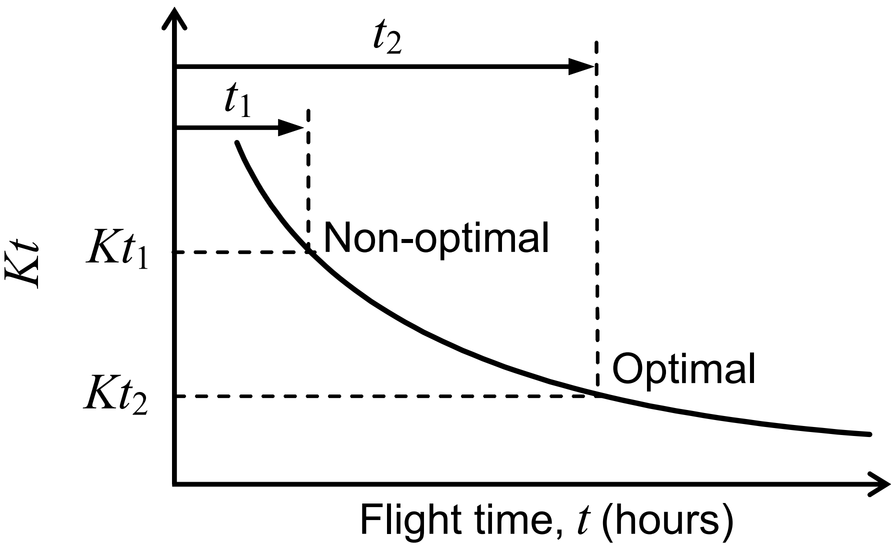
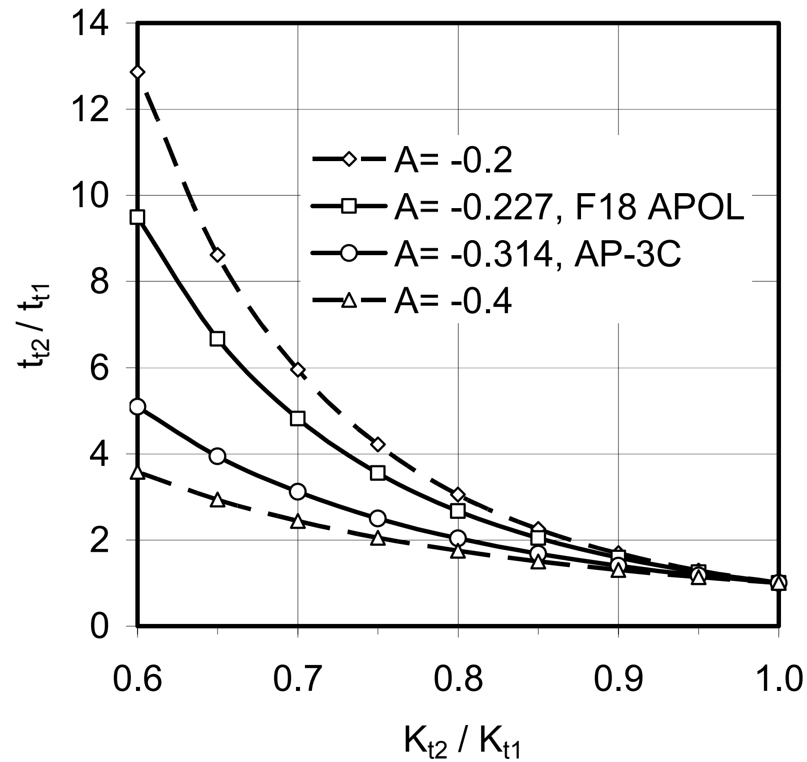
Shape optimisation increases life by reducing stress concentration





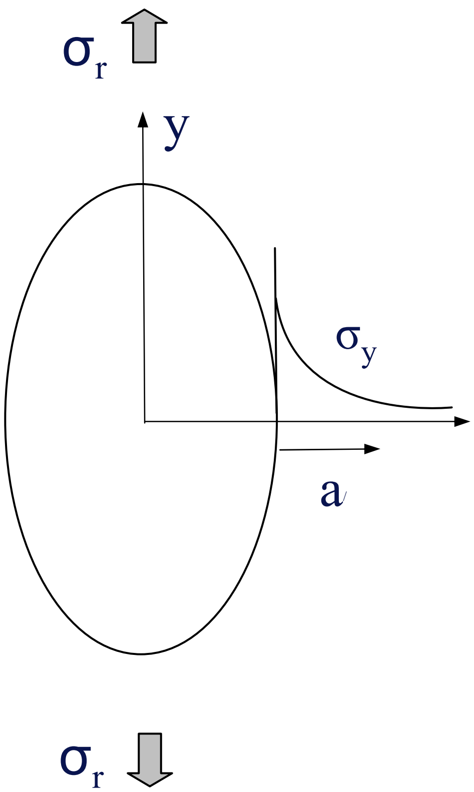
$$\ln(\sigma K_t) = A \ln(t_t) + B$$

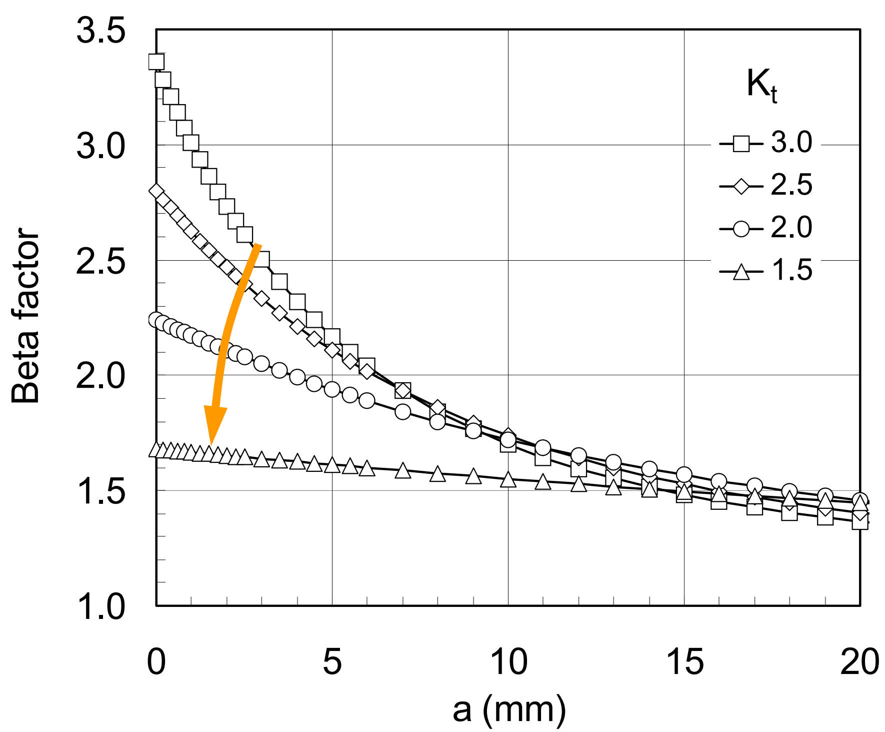
$$\frac{t_{t2}}{t_{t1}} = \left(\frac{K_{t2}}{K_{t1}}\right)^{1/A}$$

Fatigue life trends

Crack growth / SBI

Baseline is initial circular hole, r = 20mm





where $\beta = 1.12(\sigma_y / \sigma_{remote})$

Fatigue life trends

Crack growth / SBI

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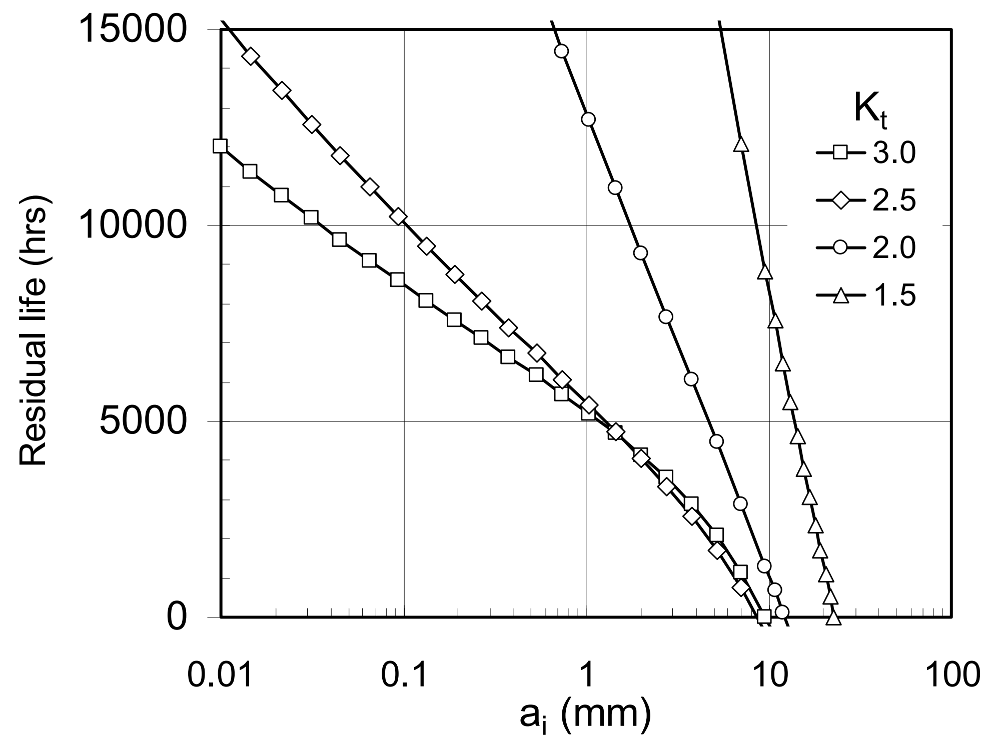
- Assume through crack
- Use "effective block" approach
- F/A-18 spectrum



$$\text{Life} = \int_{a_i}^{a_f} 1/[C(K_{\text{ref}})^m]\,da$$

$$\text{where } K_{ref} = 1.12(\sigma_y / \sigma_{\text{remote}})\sigma_{\text{ref}}\sqrt{\pi a}$$

Reduced rate of crack growth – typically gives longer inspection intervals

Simplified in-situ manufacturing method

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Non-circular hole in steel stiffener – F-111 FFVH test case

- Precise templates in conjunction with air-powered tooling

- Two main steps: 1. Coarse sanding drum,
  2. Fine abrasive drum, followed by polishing

Simplified in-situ manufacturing method

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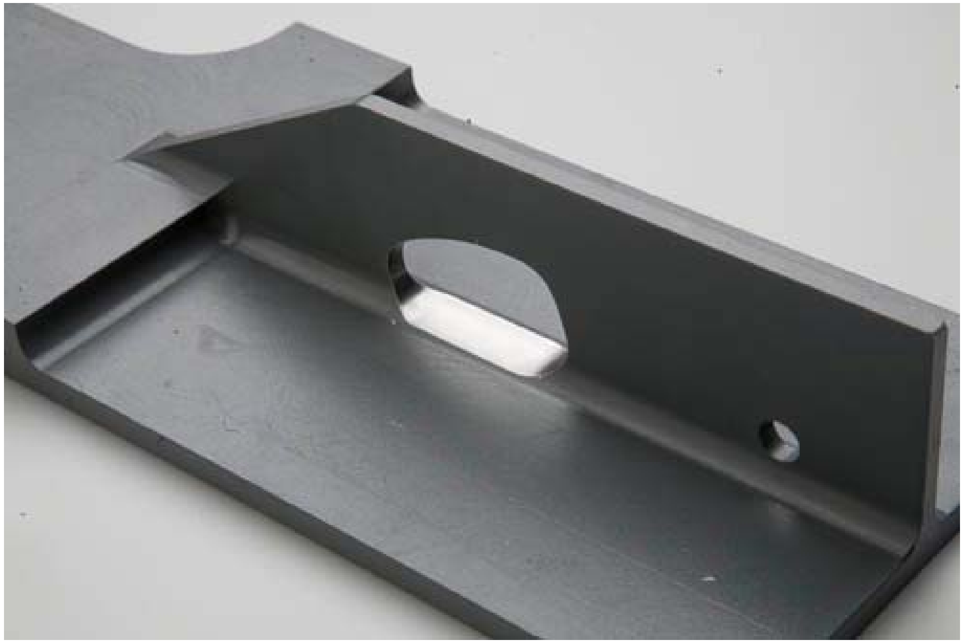
Non-circular hole in steel stiffener



coupon

wing pivot fitting

Simplified in-situ manufacturing method

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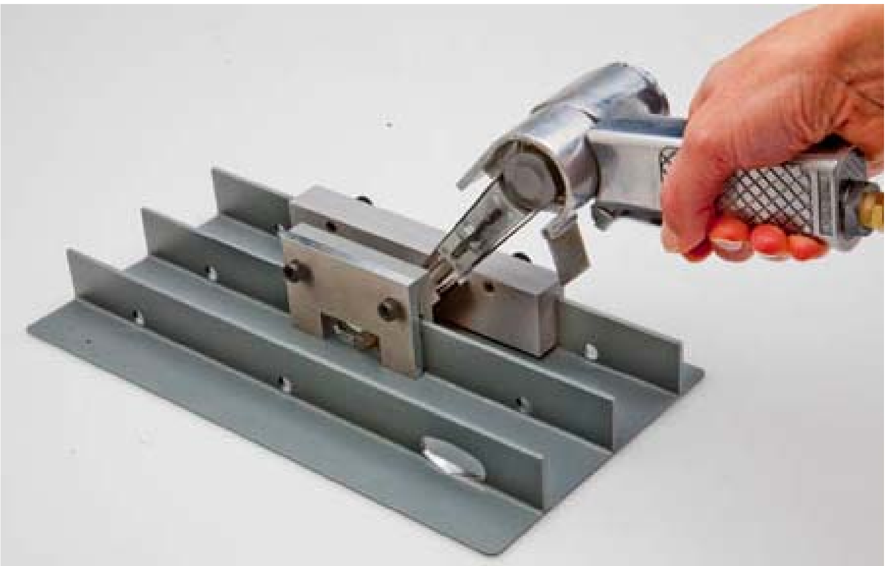
Non-circular hole in closely spaced al. alloy stiffeners



- For difficult to access locations
- Two main steps:
  1. Carbide burr cutting tool,
  2. Diamond coated abrasive tool, followed by polishing

Simplified in-situ manufacturing method

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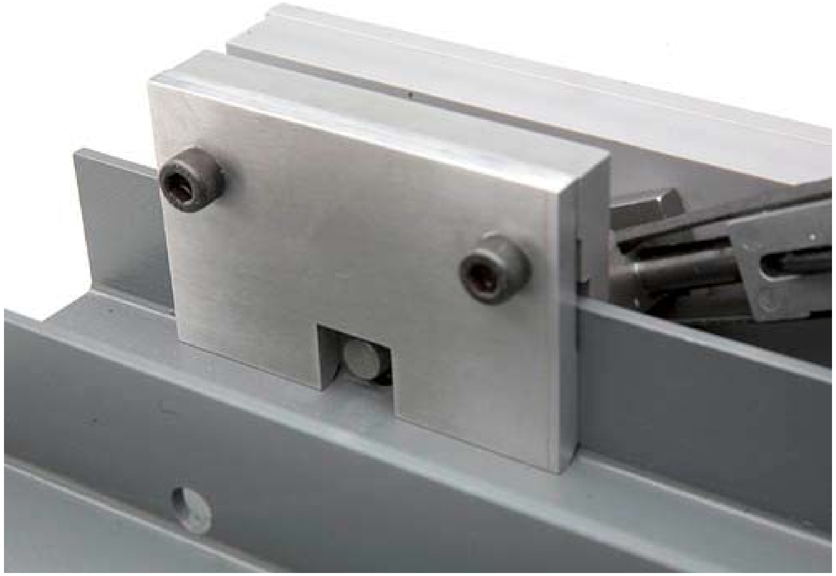
Oversized circular hole in closely spaced al. alloy stiffeners



- Oversized circular hole
- Height above skin of 0.01″

Simplified in-situ manufacturing method

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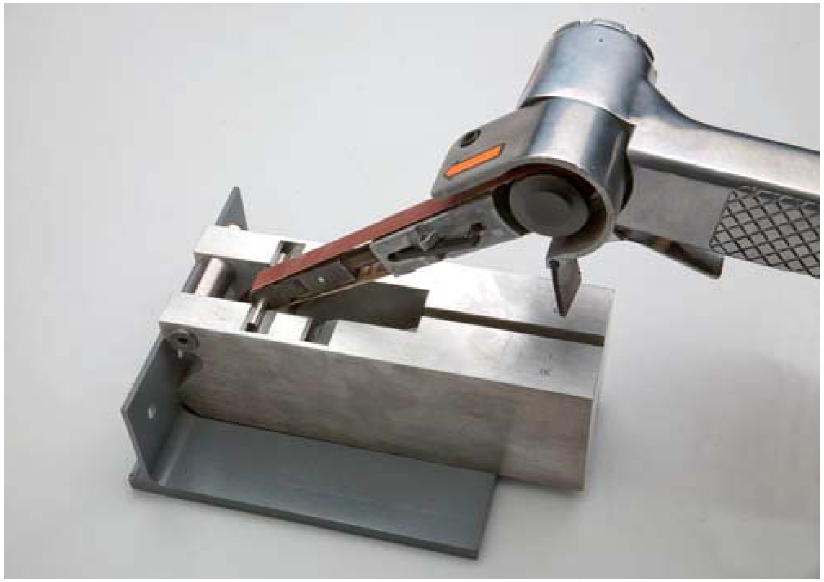
Non-circular runout in steel stiffener



Improved NC machining: F-WELD example

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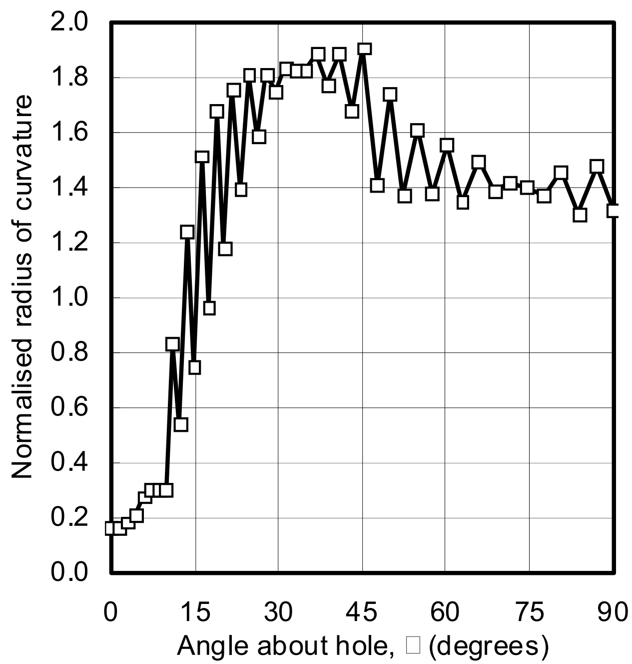
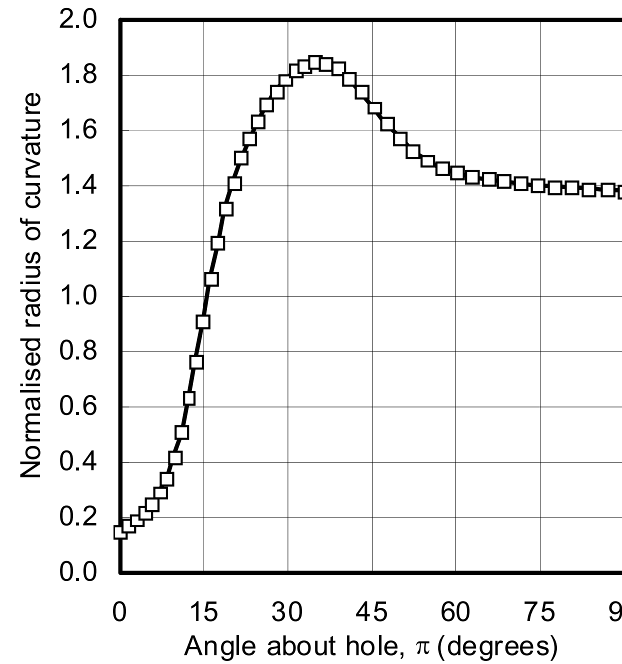
- Code for smoothing of raw FEA co-ordinates
- Shape has many circular arcs
- radius of curvature shown



before



after

Robustness for optimised shapes

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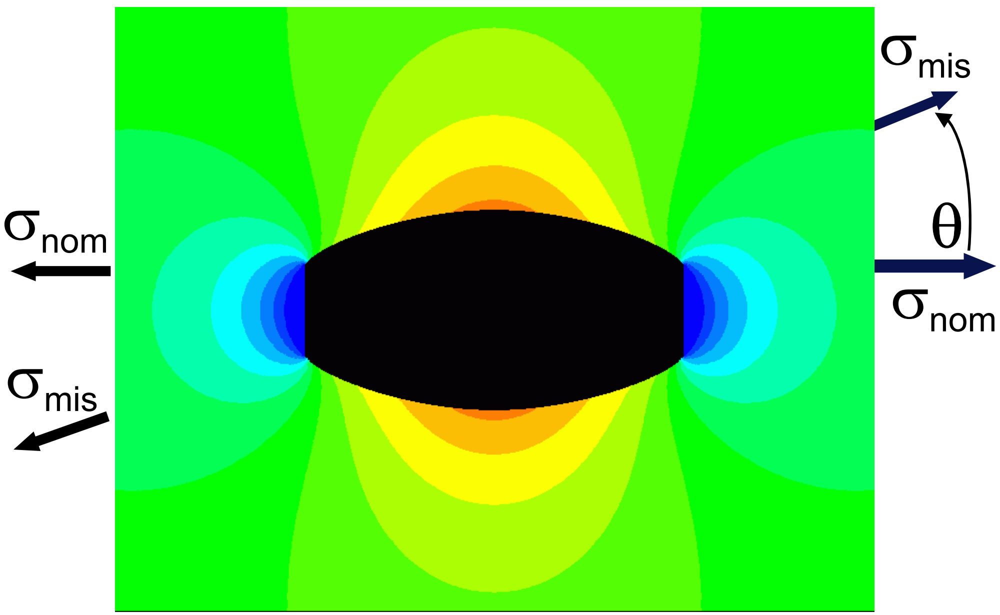

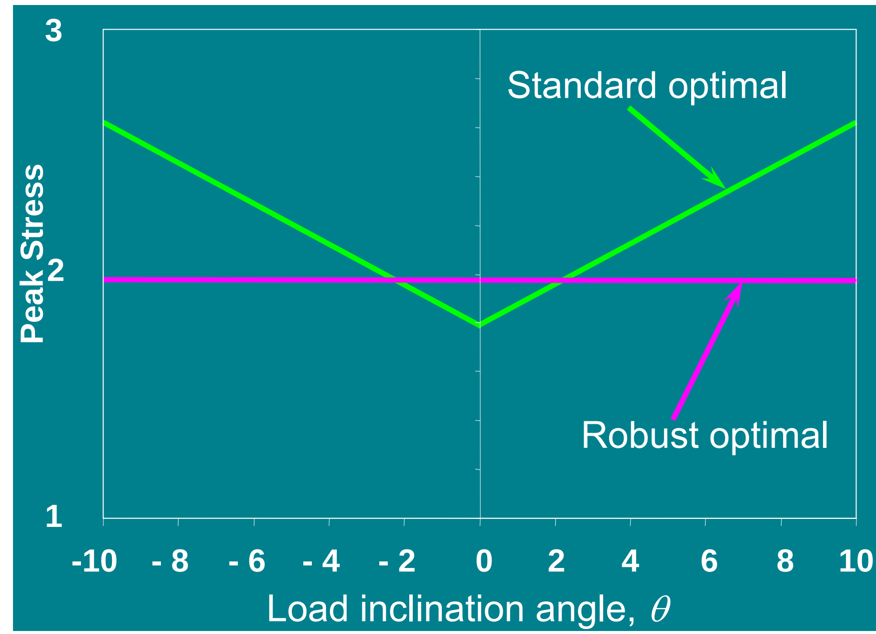

- Robust optimal has **constant** and **minimised** peak stress over expected 10 degree load misalignment range

- For variation of load orientations or multiple load cases

Other design studies & applications

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1. **Generic optimal solutions for loaded plates with:**
   - Single holes
   - Interacting holes
   - Edge notch coupons
   - Surface damage removal (3D)
   - Shoulder fillets
   - Crack stop holes

Other design studies & applications

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2. Applications / demonstrators with optimal reworks:

1.	F-111:	four fuel flow vent holes in WPF	**FEA, full scale tests, fleet**
2.	F-111:	four stiffener runouts in WPF	**FEA, full scale tests, fleet**
3.	F-111:	fuel pilot valve hole in upper skin	**FEA, full scale tests**
4.	F-111:	gravity refuel hole in upper skin	**FEA, full scale tests**
5.	F-111	wing pivot fitting bush	**FEA, full scale tests**
6.	F/A-18:	aileron hinge	**FEA, static tests**
7.	F-111	revised FFVH, SRO	**FEA, manuf. demo**
8.	AP-3C:	fuel flow hole in stiffener	**FEA, manuf. demo**
9.	B707:	surface damage removal	**FEA, manuf. demo**
10.	F/A-18:	vertical tail stub attachment	**FEA, manuf. demo**
11.	PC9/A:	lower wing skin at up-lock	**FEA**
12.	F/A-18:	FS 470 bulkhead	**FEA**
13.	F-35:	bulkhead access holes test case	**FEA**
14.	Other	low kt coupon design	**Fatigue tests, pending**

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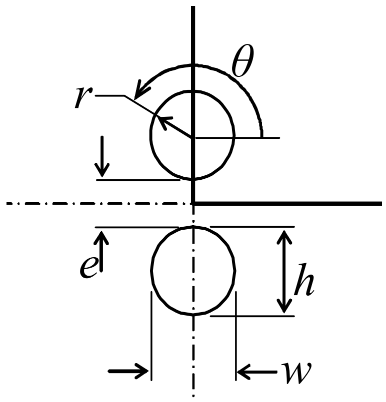
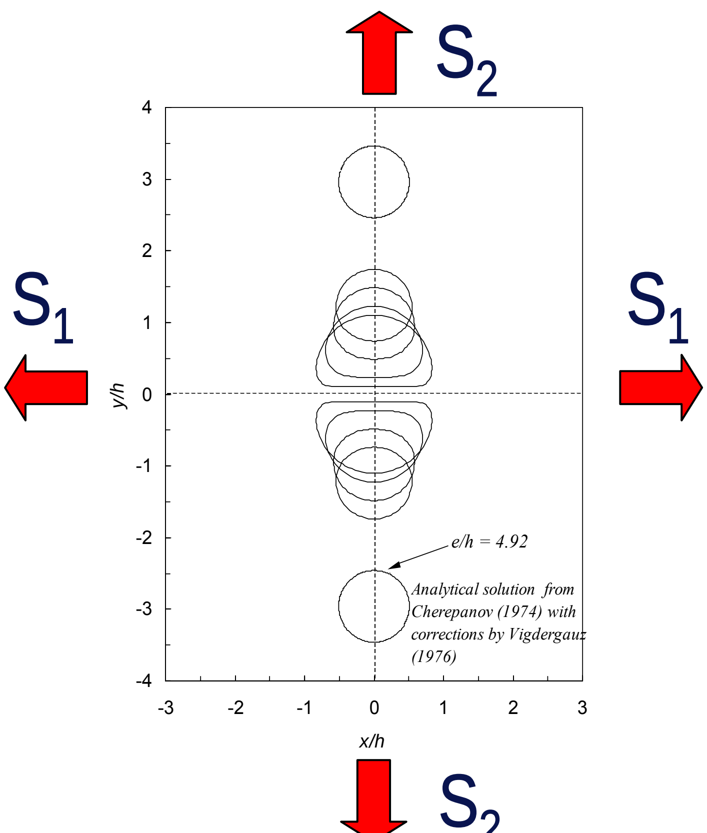
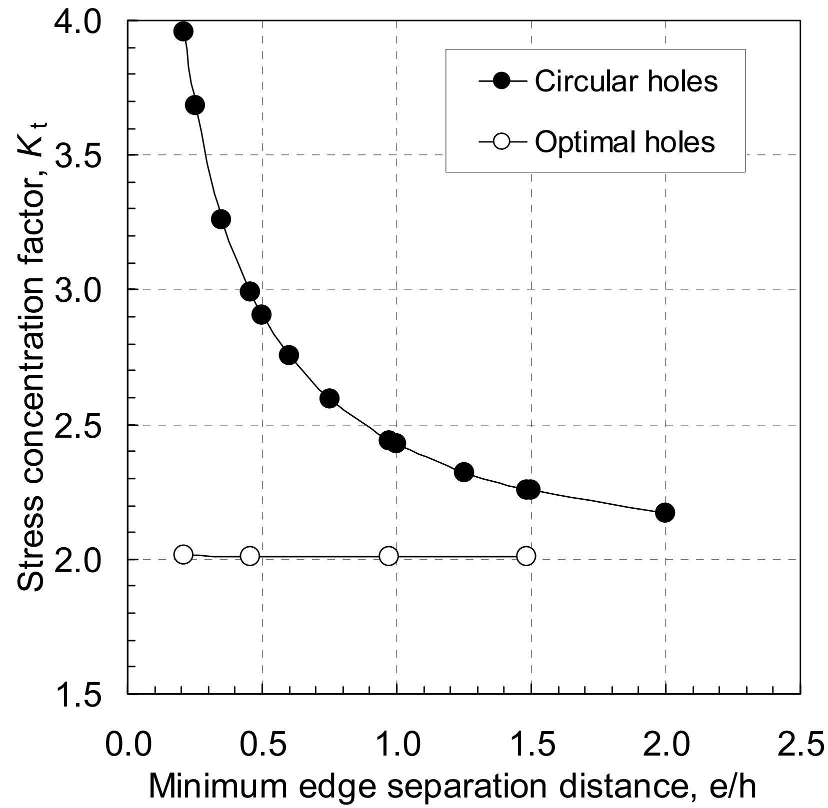
Design study

Generic interacting optimal holes

(loading $S_1 = S_2$)







- no interaction effects after optimisation
- optimal shapes approach half-circle as e/h approaches zero

Practical application example

F-111 WPF bush fillet redesign

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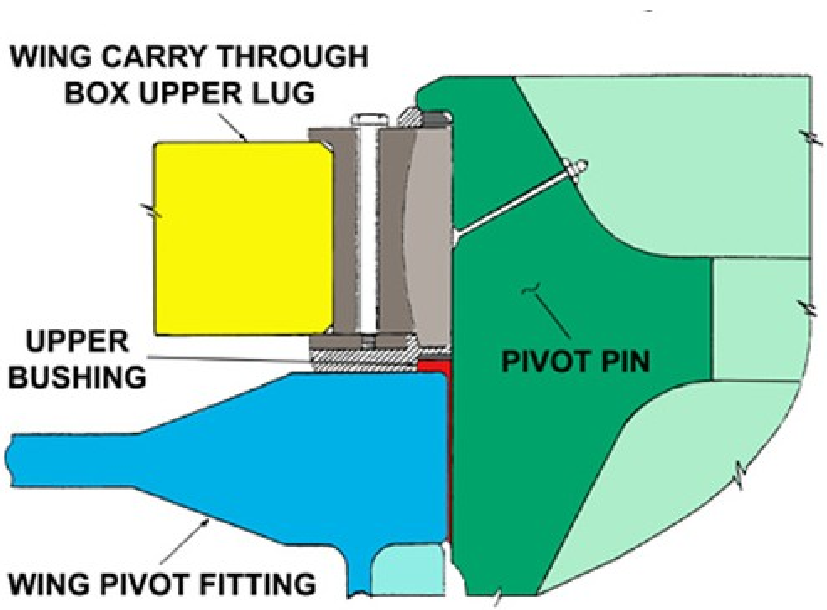

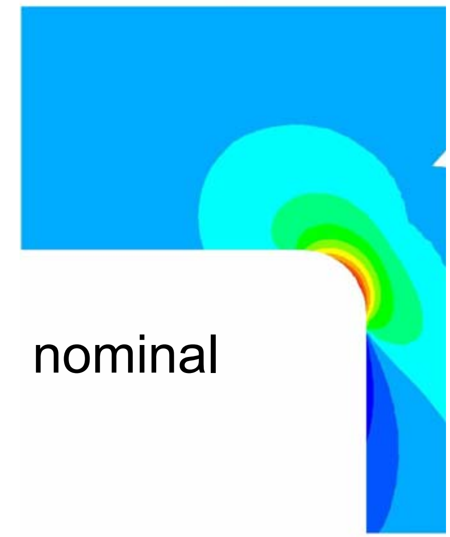

- used on F-WELD fatigue test
- 30% stress reduction
- Test life 12000 hrs, versus fleet replacement at least every 1025.

Design study

Robust hole in a shear panel

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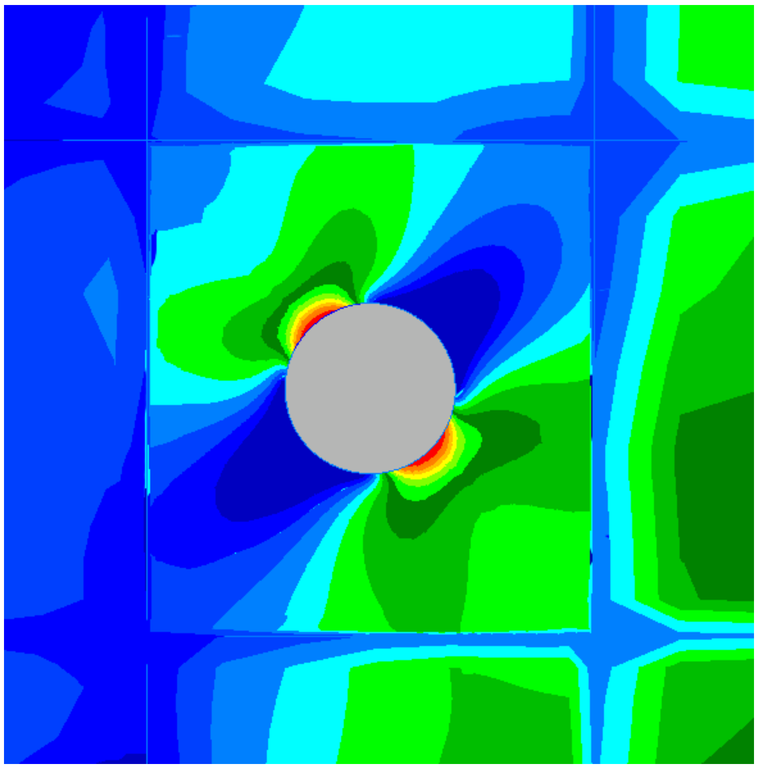

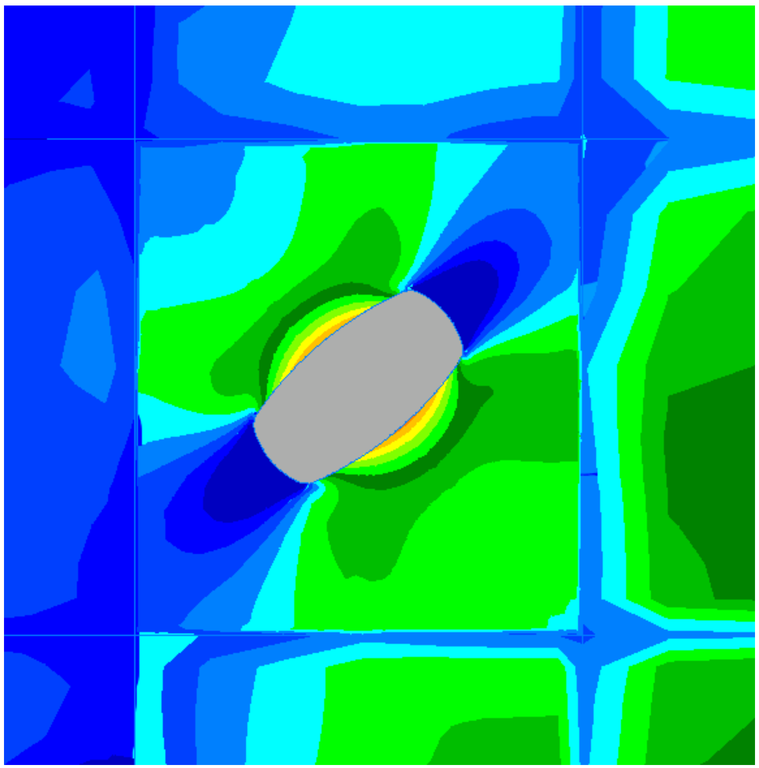

31% reduction in peak stress

(b)

Transitioning issues

Repair if re-crack occurs at optimal

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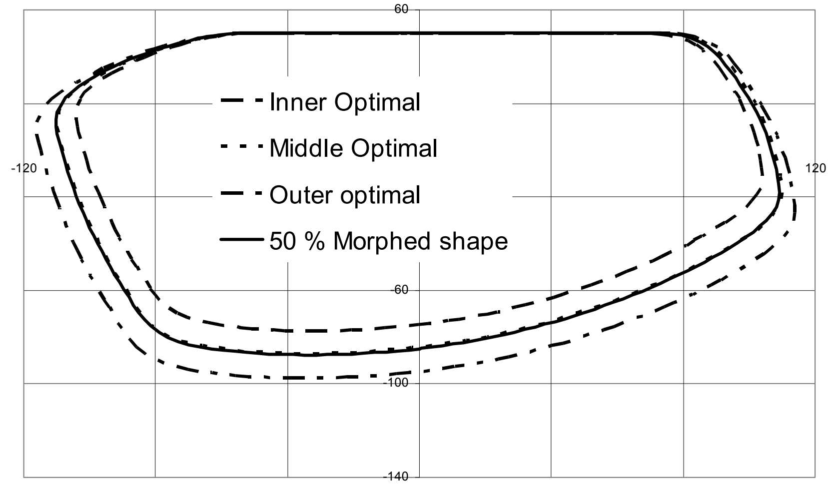
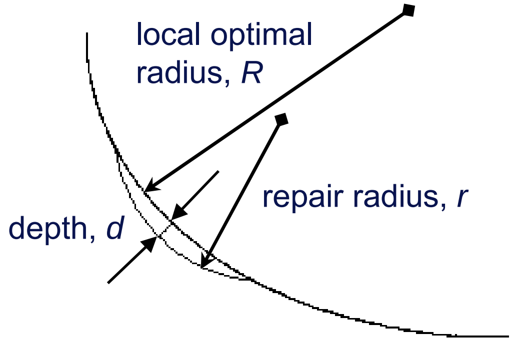
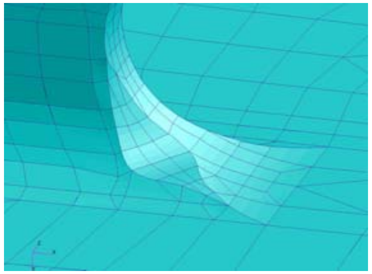
Options:

1. A family of morphed shapes,
   - negligible increase in peak stress



2. A local circular arc blend
   - small increase in in peak stress
   - partial or full thickness





Acknowledgements

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- RAAF ASI – DGTA (Sponsorship)
- Staff working on F-111 Sole operator program, including F-WELD
- Other DSTO staff
- RAAF Amberley
- Industry
  - Boeing, TAE, Amiga Eng., QinetiQ AeroStructures:

Conclusions

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- Rework shape optimisation a useful approach for life extension
- Shapes either:
  - Generic (symmetric)
  - One off optimal shapes

- Key technical impediments overcome
- DSTO keen to transition approach more widely
- Approach applicable to initial design