

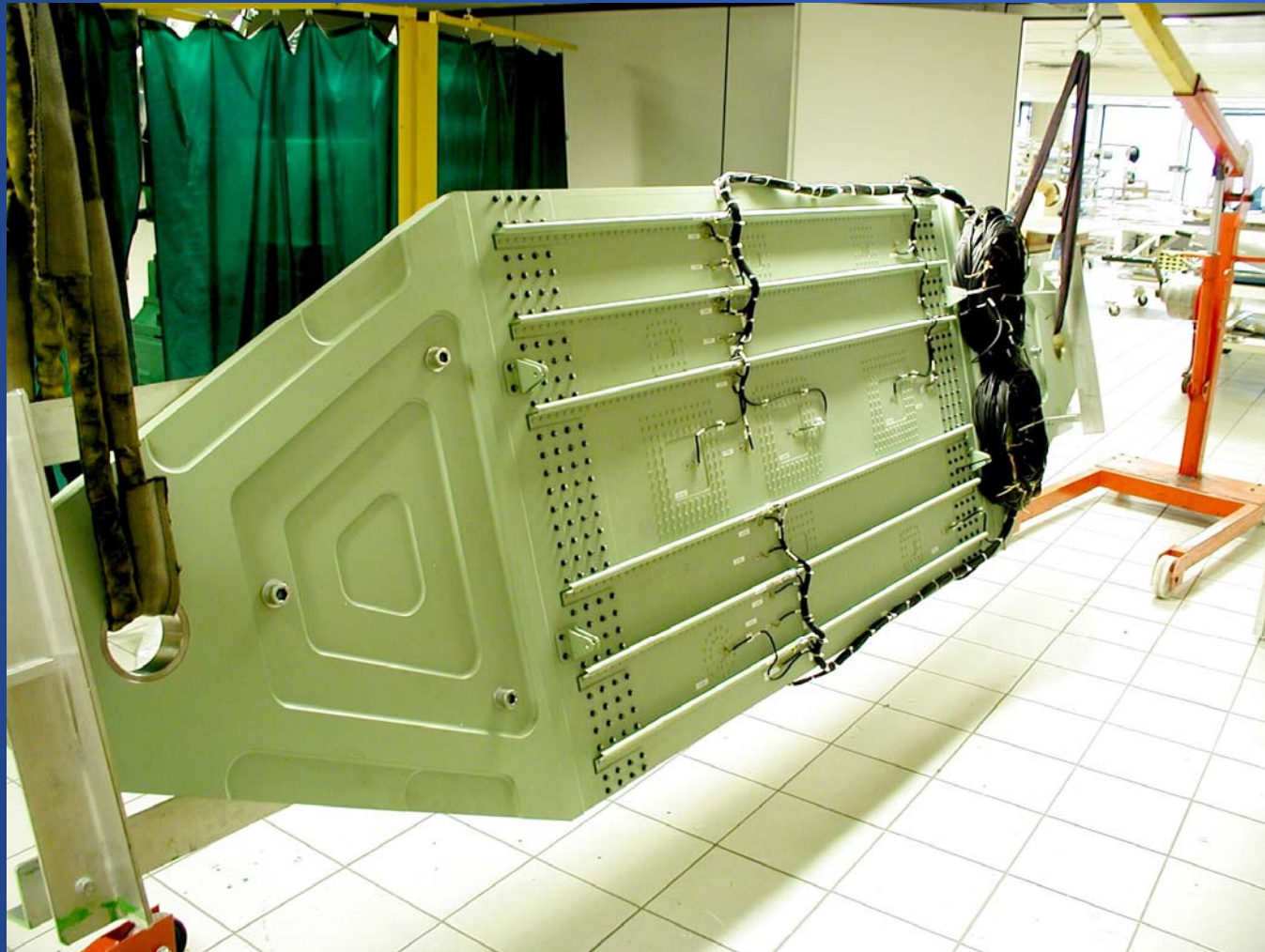
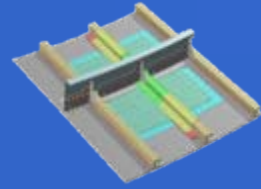
MSD CRACK PROPAGATION BY DBEM ON A REPAIRED AERONAUTIC PANEL

R. Citarella

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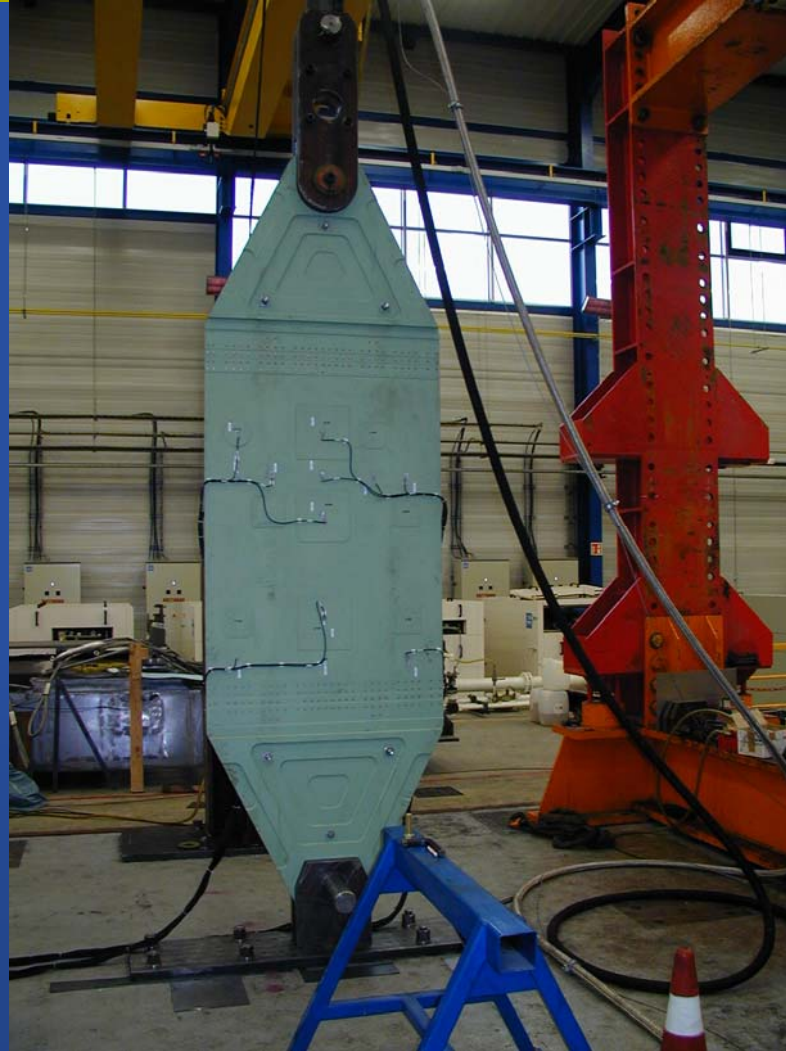
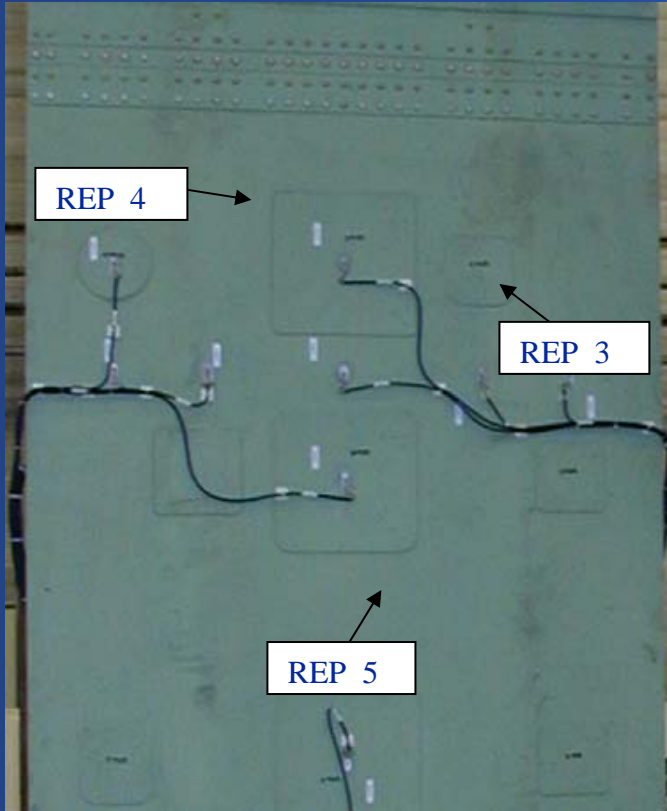
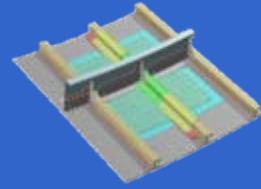


Fatigue flat riveted panel with skin repairs





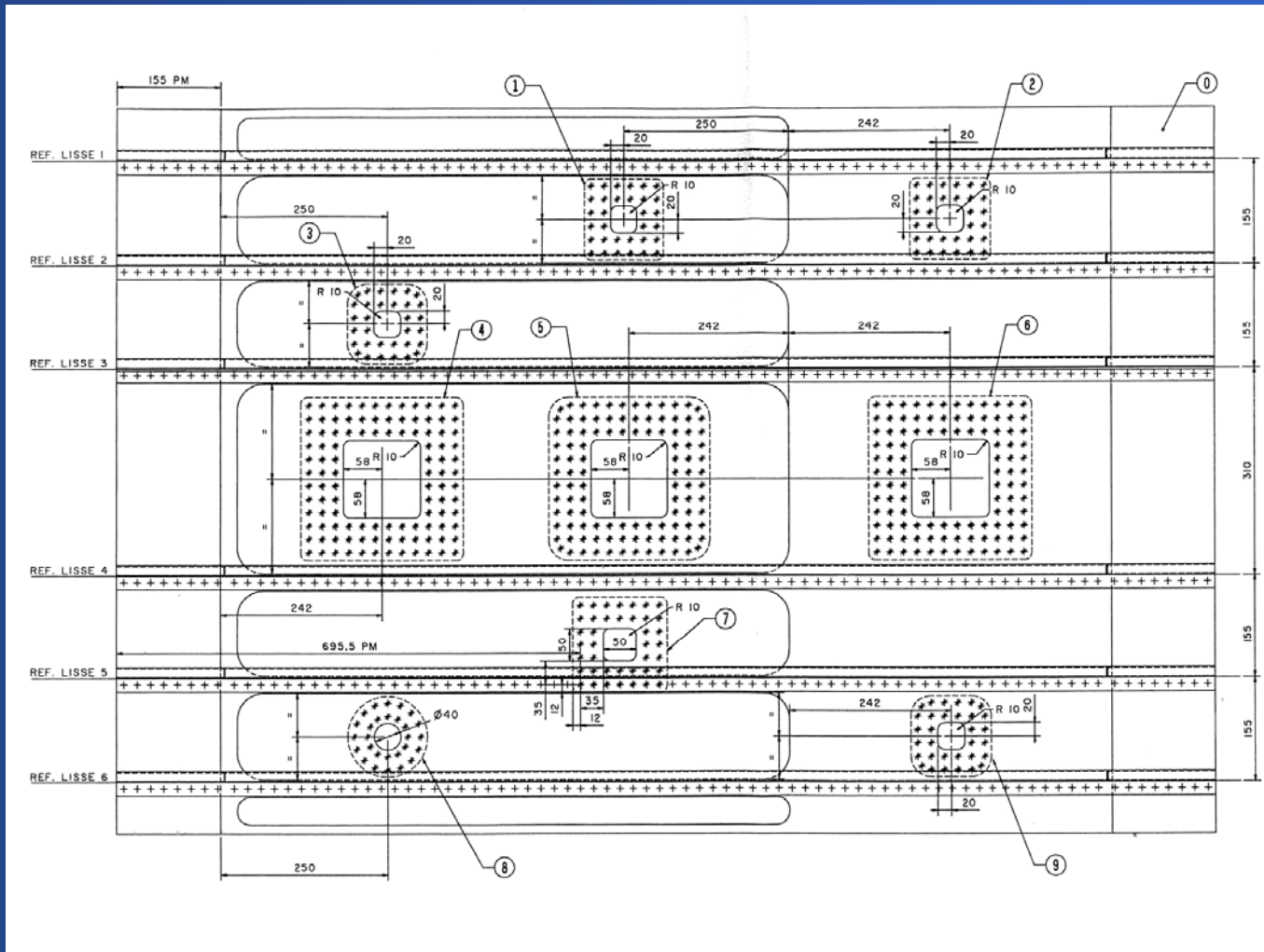
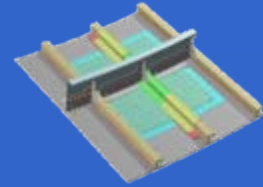
Panel in testing configuration: front view and backward view, with highlight of the repairs analysed: REP 3-5.





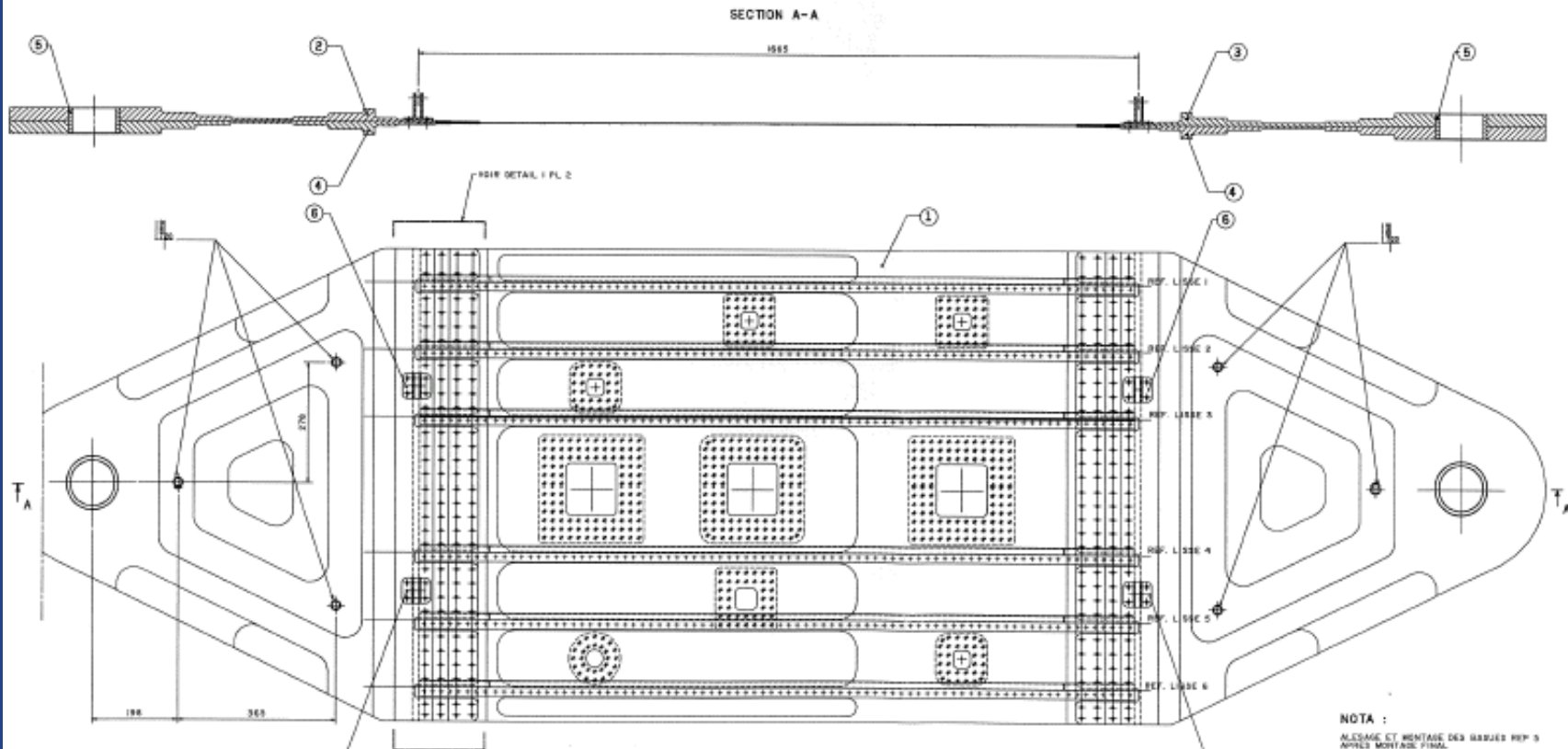
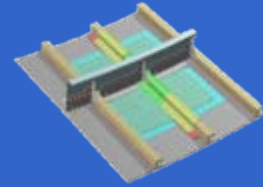
Fatigue flat riveted panel with skin repairs

Drawing of the riveted repairs (N. 3, 4 and 5 are analyzed).





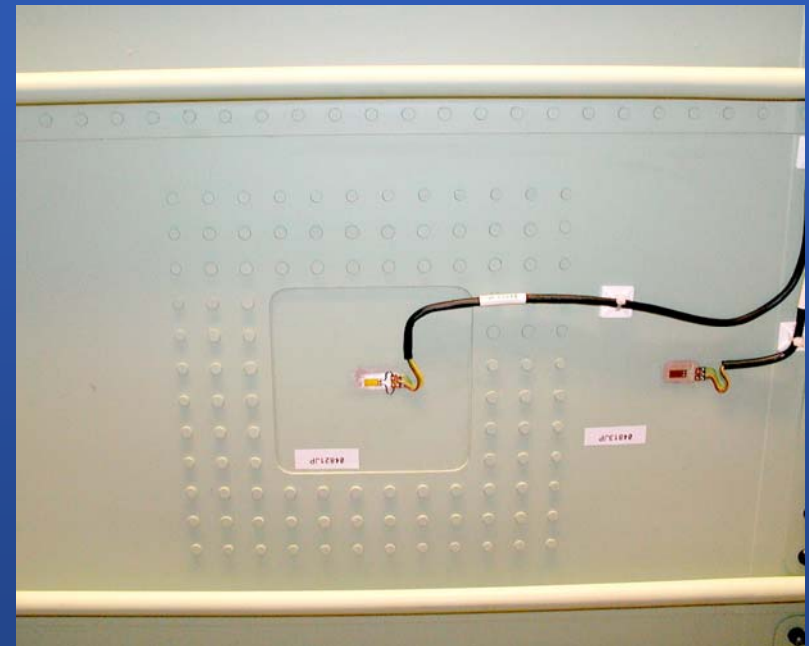
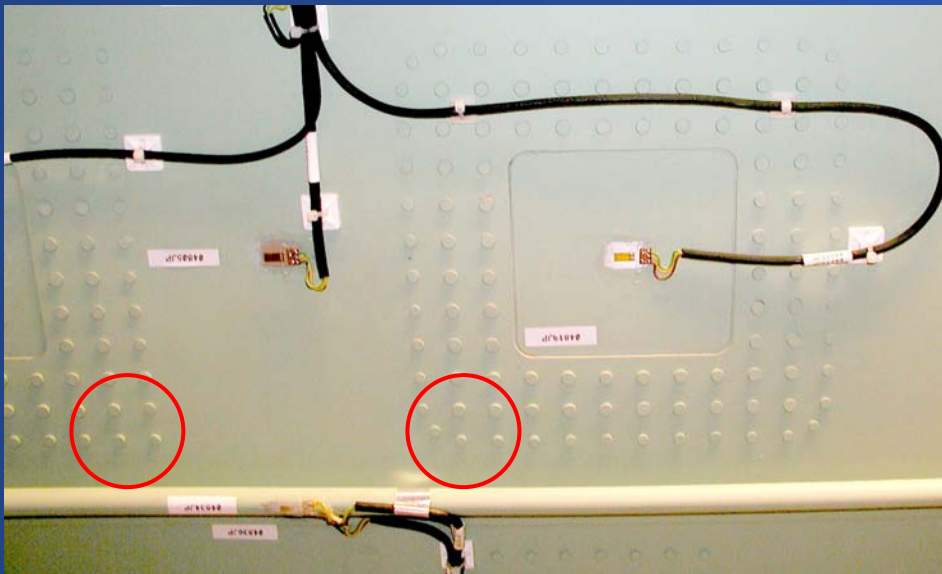
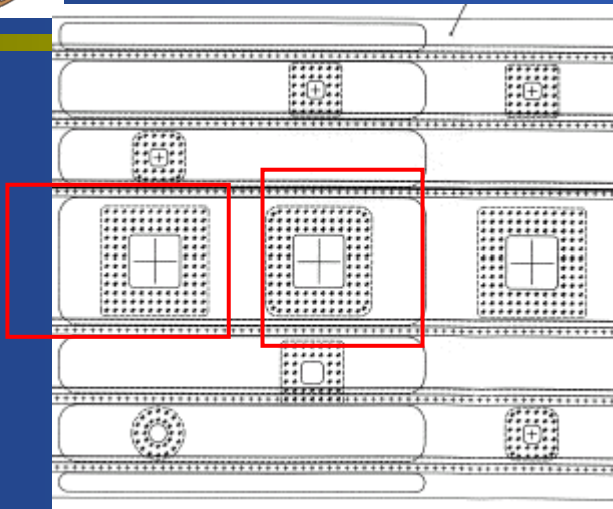
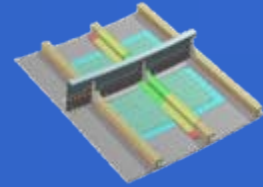
Fatigue flat riveted panel with skin repairs



Repair	Skin thickness (mm)	Doubler thickness (mm)	Stiffener section (mm ²)	Ø rivets (mm)	Rivet transversal stiffness (K_x, K_y) in N/mm
REP 3	1.65	1.8	99	4.0	2.9E+4
REP 4	1.65	1.8	99	4.0	2.9E+4
REP 5	1.65	1.8	99	4.0	2.9E+4



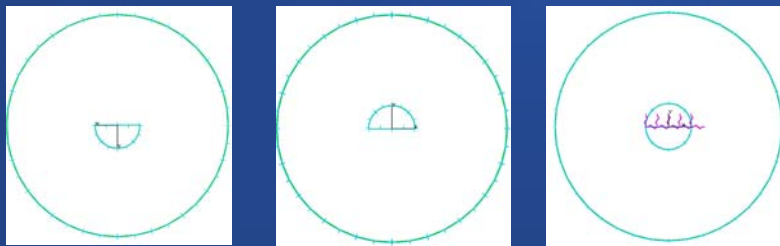
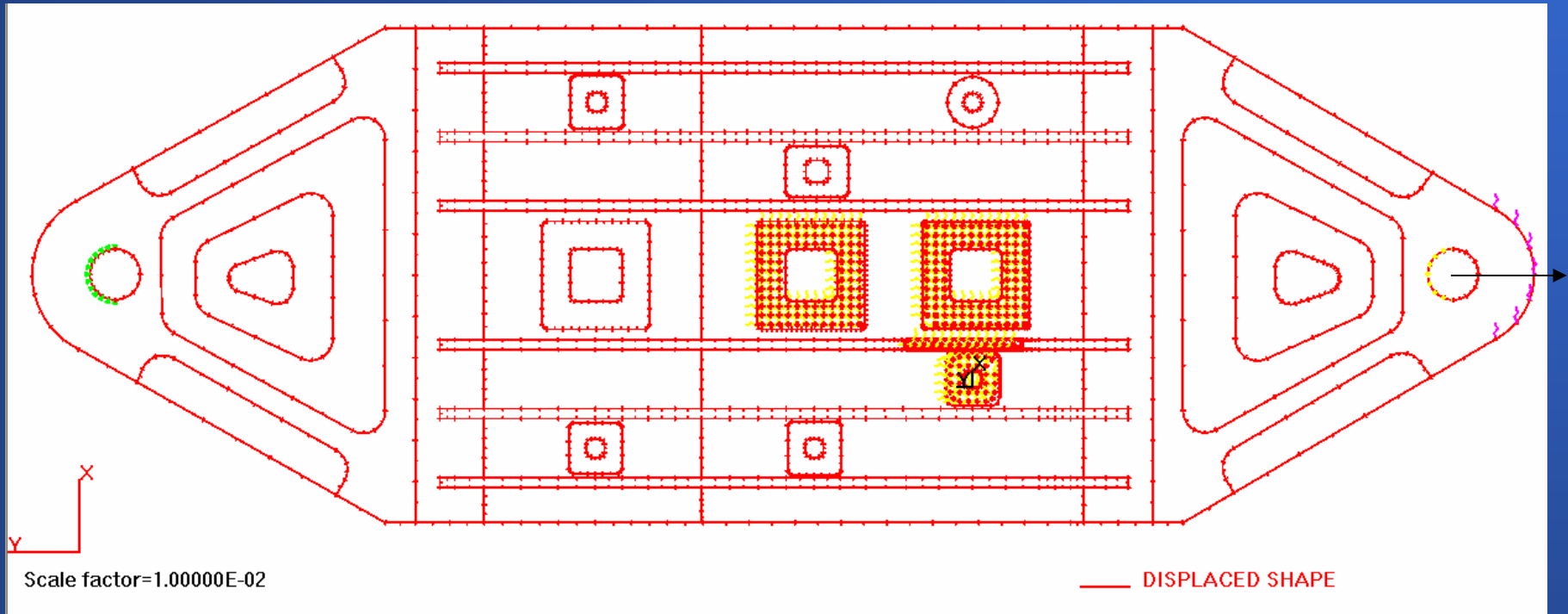
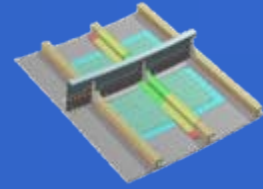
Standard & improved fastener location



Standard 3 rivet rows skin repair



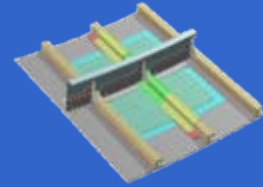
DBEM model of the repaired panel with highlight of analysed repairs, mesh and boundary conditions.



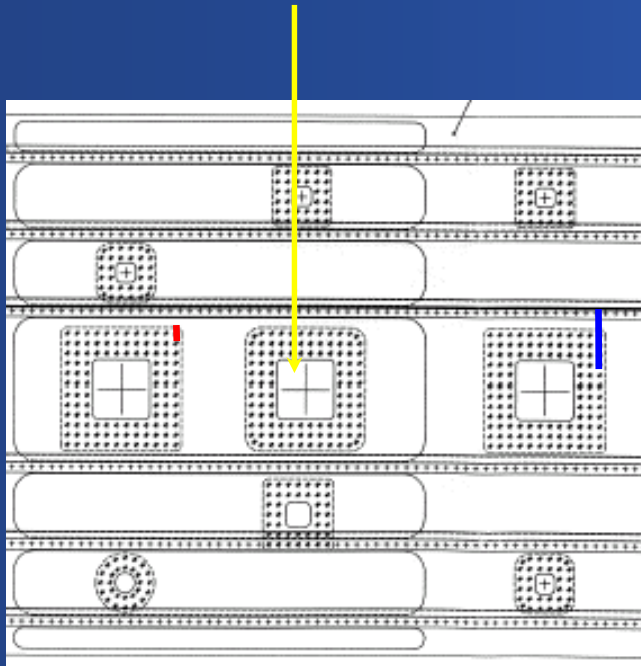
Rivet halves respectively engaged with the skin (left) and with the doubler (centre) to form the assembled rivet (right). The two halves are connected each other by “internal springs” (right).

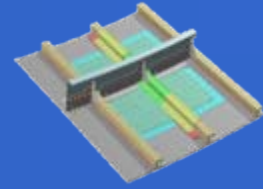


REP 4 : standard 3 rivet rows repair



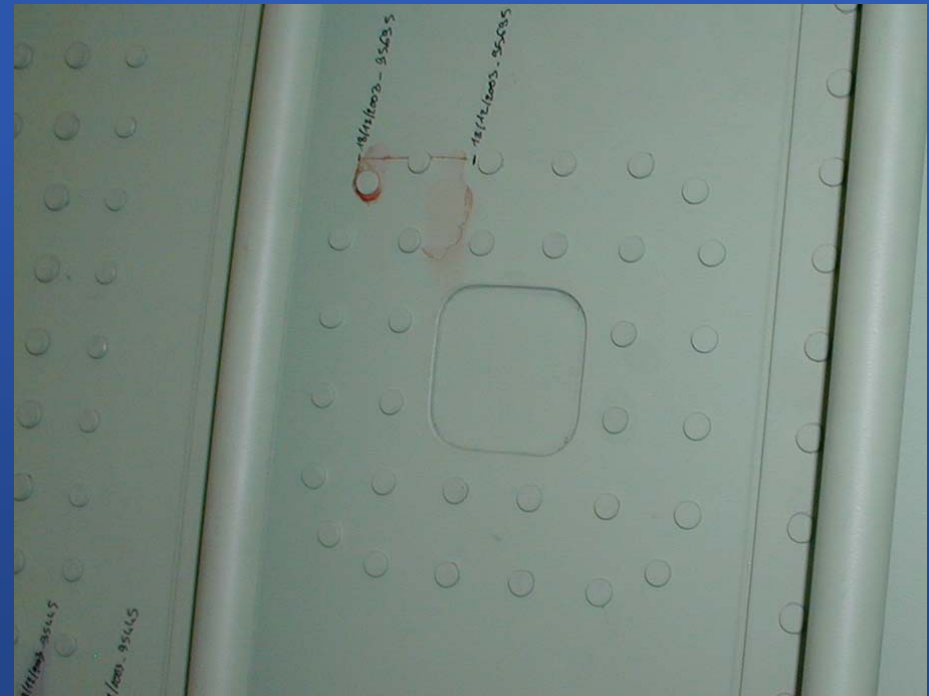
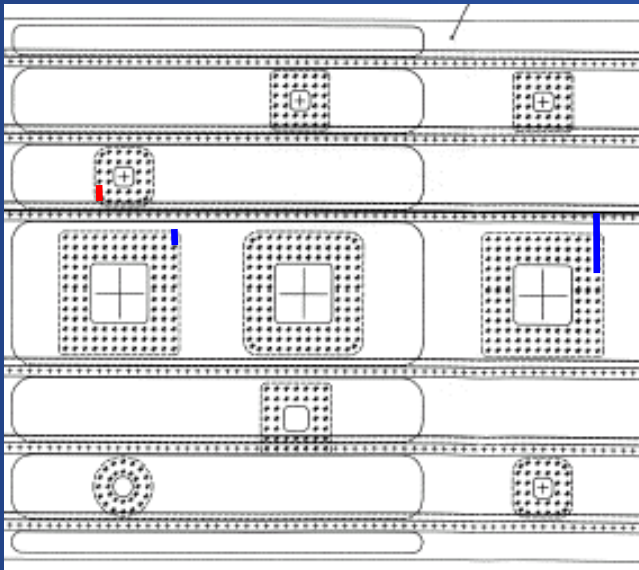
- ❑ 25 mm crack starting from the fastener located in the corner
- ❑ Fatigue life lower than similar improved 3 repair REP5 → good point

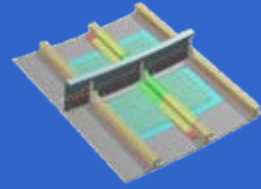




✓ At 95695 FC (250 cycles later), 1 other repair cracked :

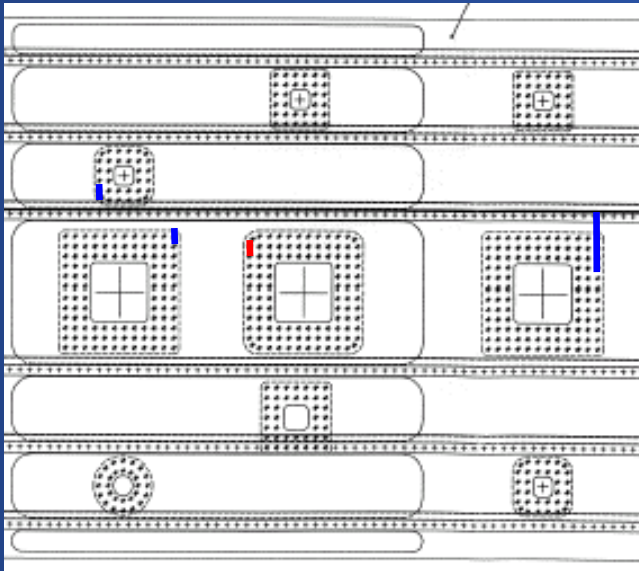
- REP 5 : Improved 2 rivet rows repair
 - ❑ 33.5 mm crack which initiated at critical fastener
 - ❑ Fatigue life lower than the similar standard 2 fastener rows repair REP 1
 - ➔ bad point.





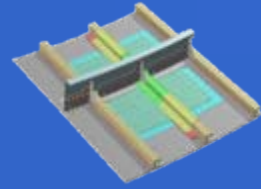
✓ At 97187 FC, REP6 :

- REP 6 : Improved 3 rivet rows repair
 - 17 mm crack which initiated at critical fastener





Crack propagation analysis



- remote fatigue load applied: $P_{max}=28405$ N with a stress ratio $R=0.1$
- crack edges discretized with discontinuous quadratic boundary elements
- Stress Intensity Factors (SIFs) calculated using the J-integral technique
- Crack propagation direction is derived by the Erdogan and Sih criteria

Fatigue properties of Al 2024 T3

NASGRO3 formula

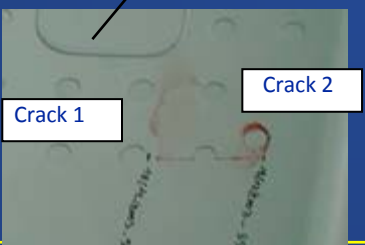
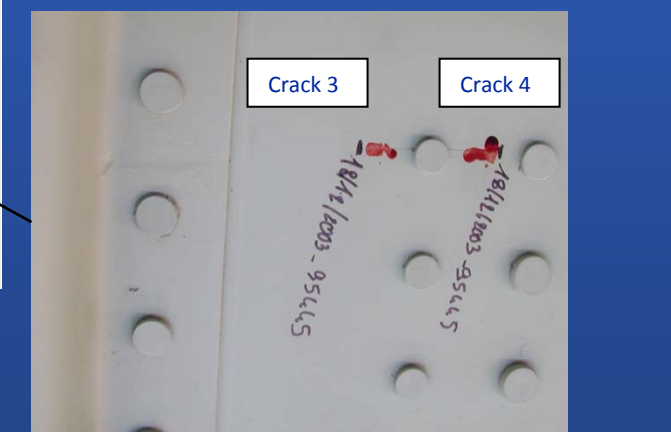
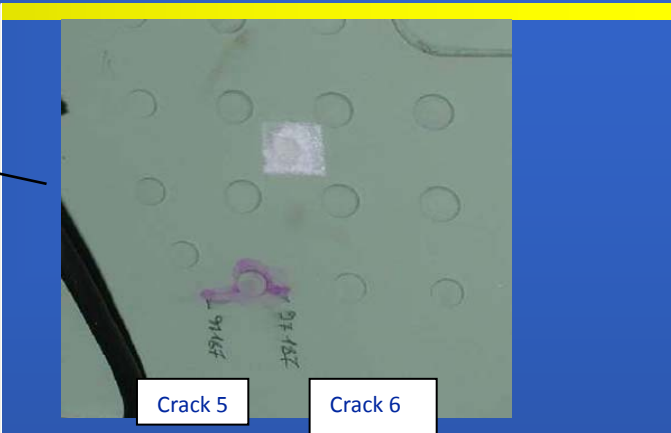
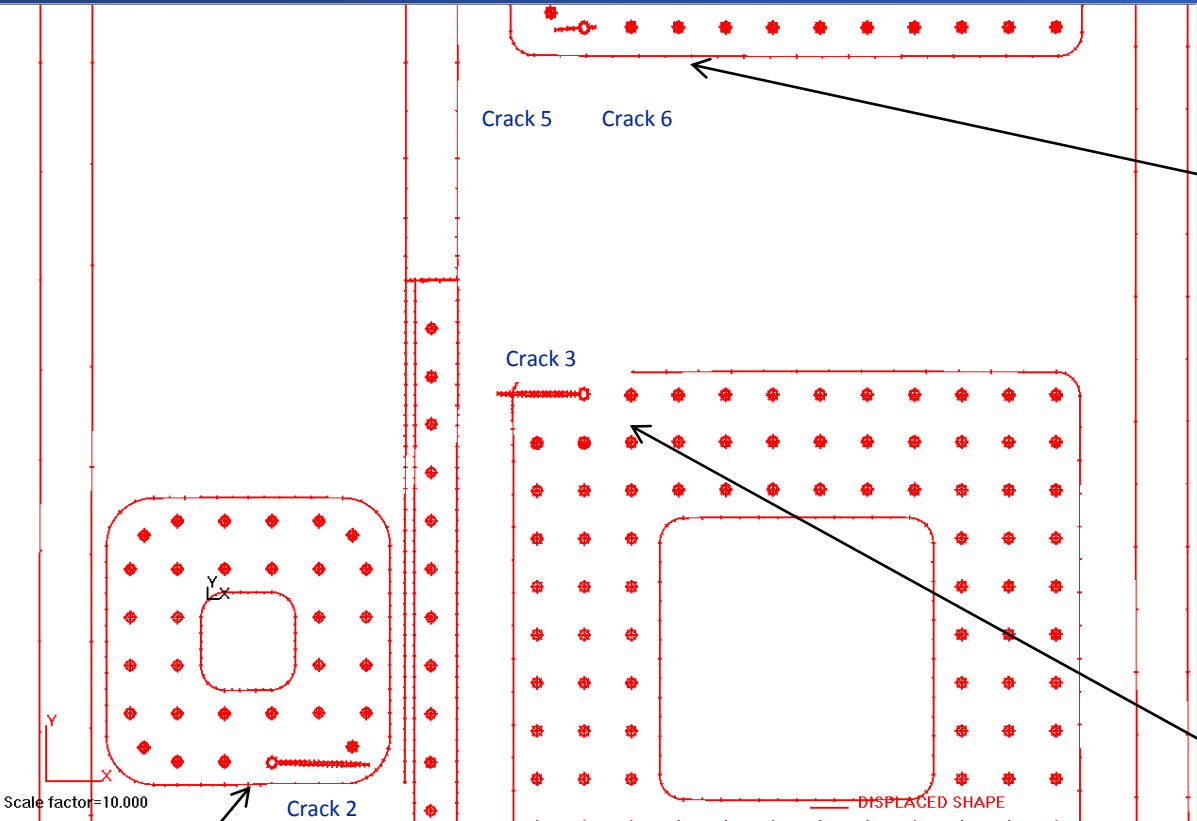
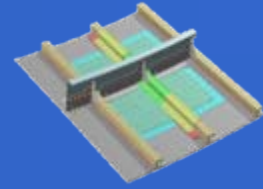
$$\frac{da}{dN} = \frac{C \cdot \Delta K^n \cdot \left(1 - \frac{\Delta K_{th}}{\Delta K}\right)^p}{\left(1 - \frac{\Delta K}{(1-R) \cdot K_c}\right)^q}$$

YIELD STRESS (YS [N/mm ²])	0.36540E+03
ULTIMATE TENSILE STRENGTH (UTS [N/mm ²])	0.45510E+03
PART THROUGH FRACTURE TOUGHNESS (K1E [MPa*mm ^{1/2}])	0.15984E+04
PLANE STRAIN FRACTURE TOUGHNESS (K1C [MPa*mm ^{1/2}])	0.11467E+04
AK COEFFICIENT (AK)	0.10000E+01
BK COEFFICIENT (BK)	0.10000E+01
CRACK GROWTH RATE COEFFICIENT (C)	0.18300E-11
N COEFFICIENT (N)	0.32840E+01
P COEFFICIENT (P)	0.50000E+00
Q COEFFICIENT (Q)	0.10000E+01
THRESHOLD SIF AT R=0 (DK0 [MPa*mm ^{1/2}])	0.10080E+03



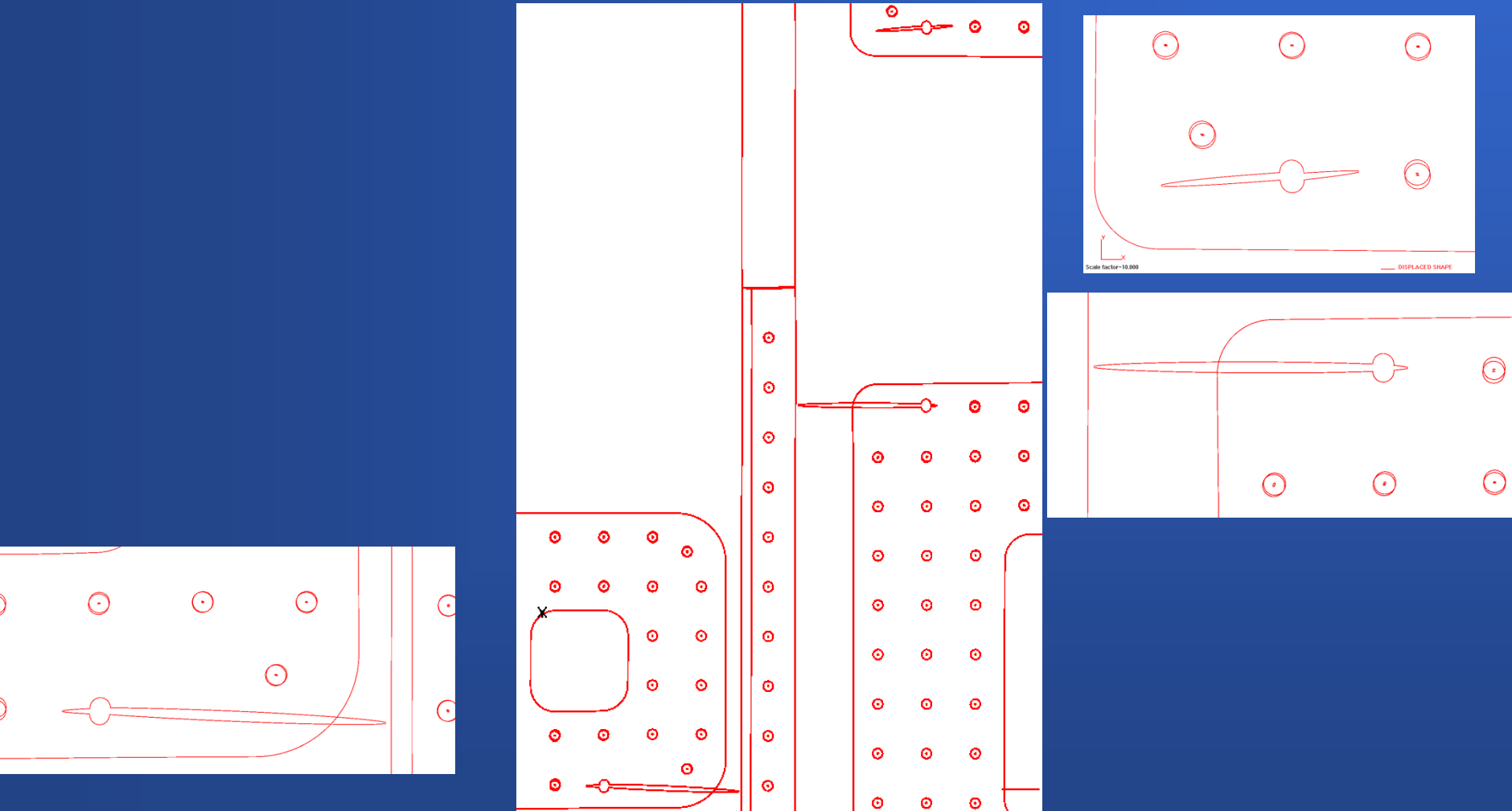
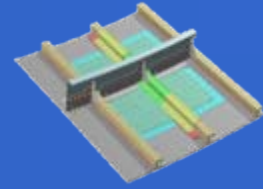
DBEM CRACK PROPAGATION

Cycle range: 97900-103465



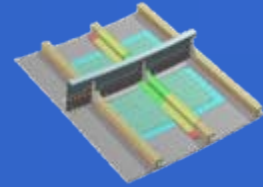


Deformed plot (scale factor 10) of the initial crack scenario at 103465 cycles, involving repairs REP 3, REP 4 and REP 5 with, respectively, crack 1-2, crack 3-4 and cracks 5-6 (cracks 1 and 4 have, at this stage, just been detected in the experimental test).

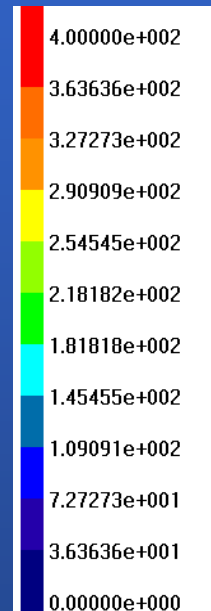
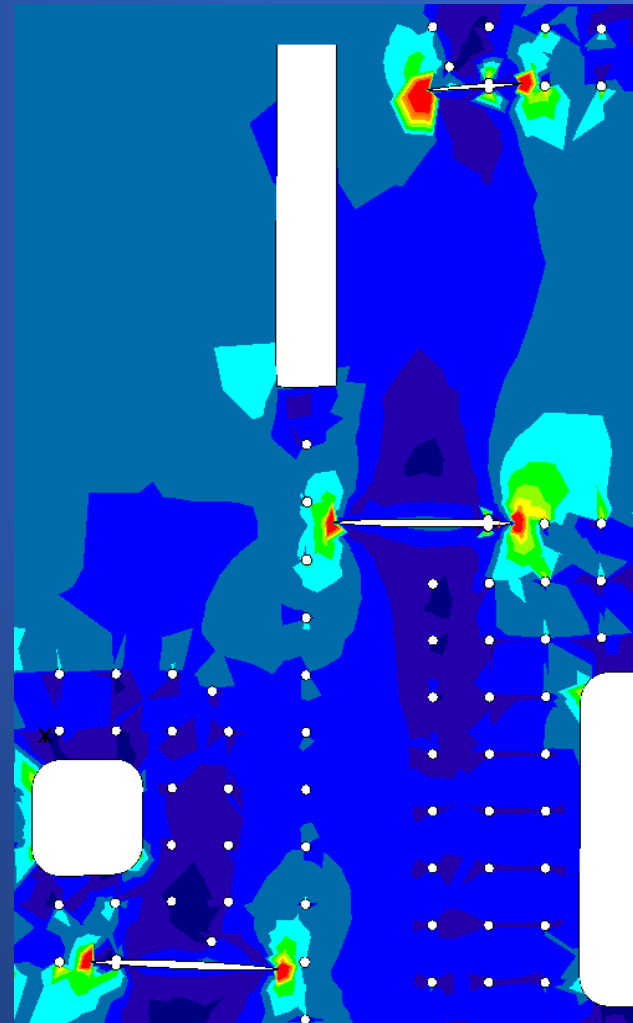
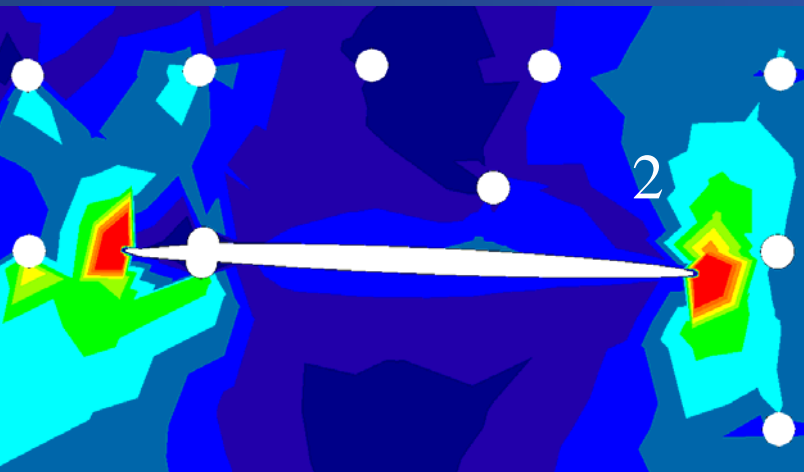




Cycle range: 103465-104620

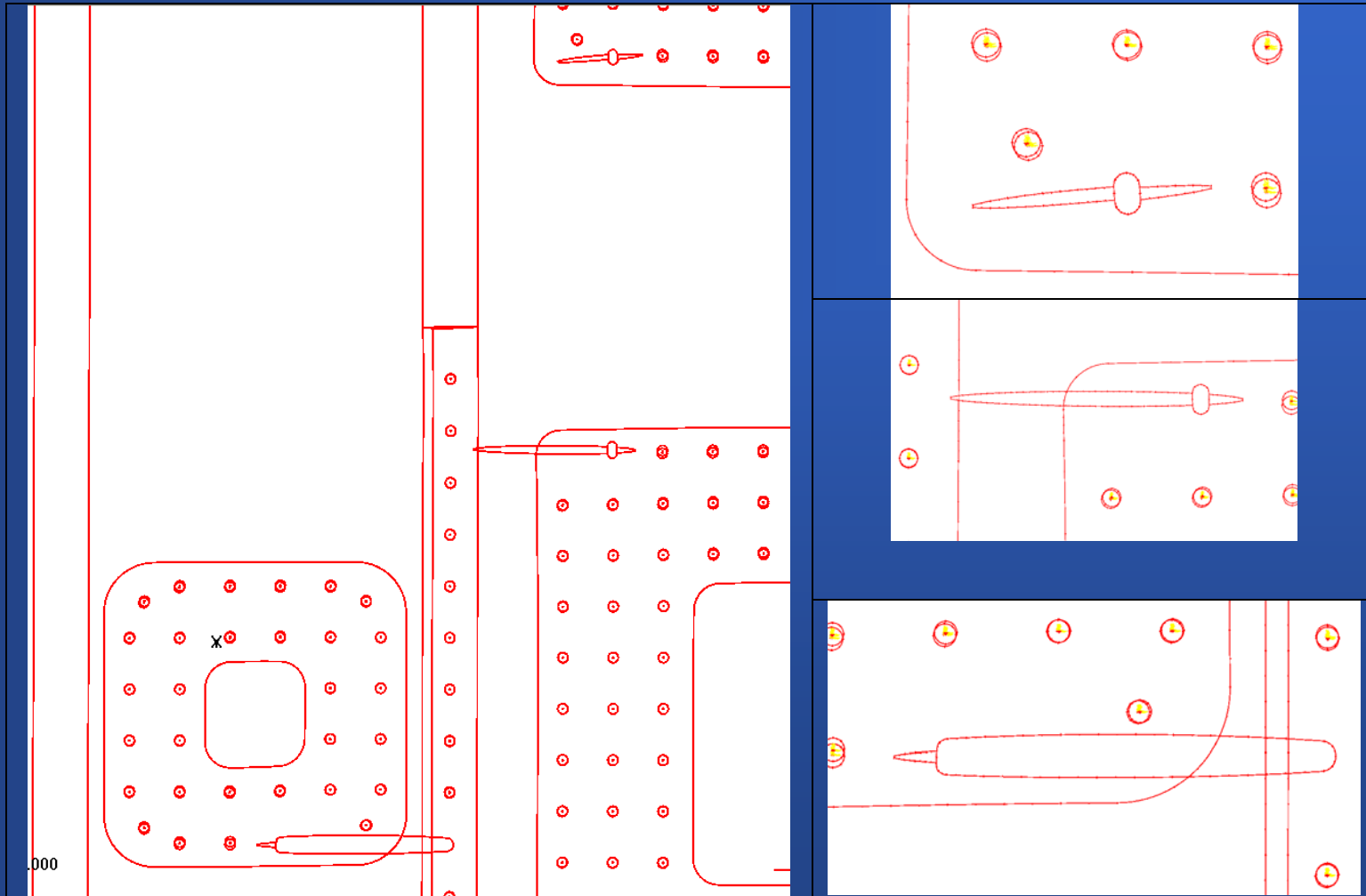
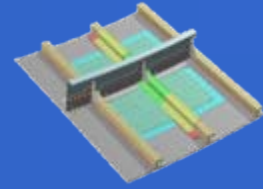


Von Mises stresses (MPa) on the skin deformed plot (scale factor 15), showing the crack scenario at 104620 cycles, with highlight of the stress state on the remaining ligament between crack N. 2 and the adjacent hole: here the ligament is fully plastic with consequent link-up



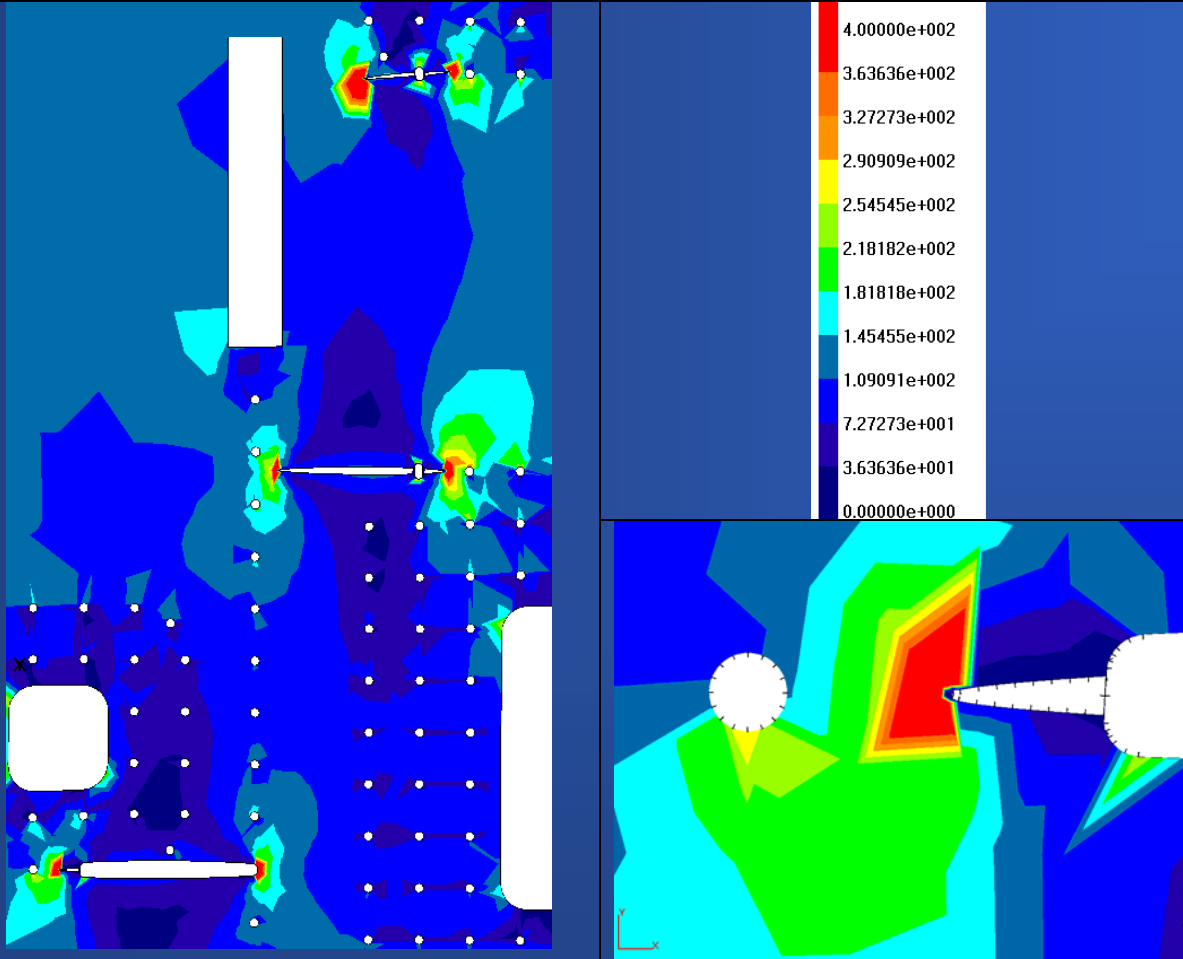
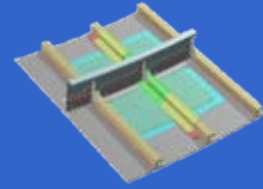


Deformed plot of the initial crack scenario at 104620 cycles, with highlight of the modeled link-up between the crack N. 2 and the adjacent hole (the crack is replaced by a slot).





Cycle range: 104620-104897

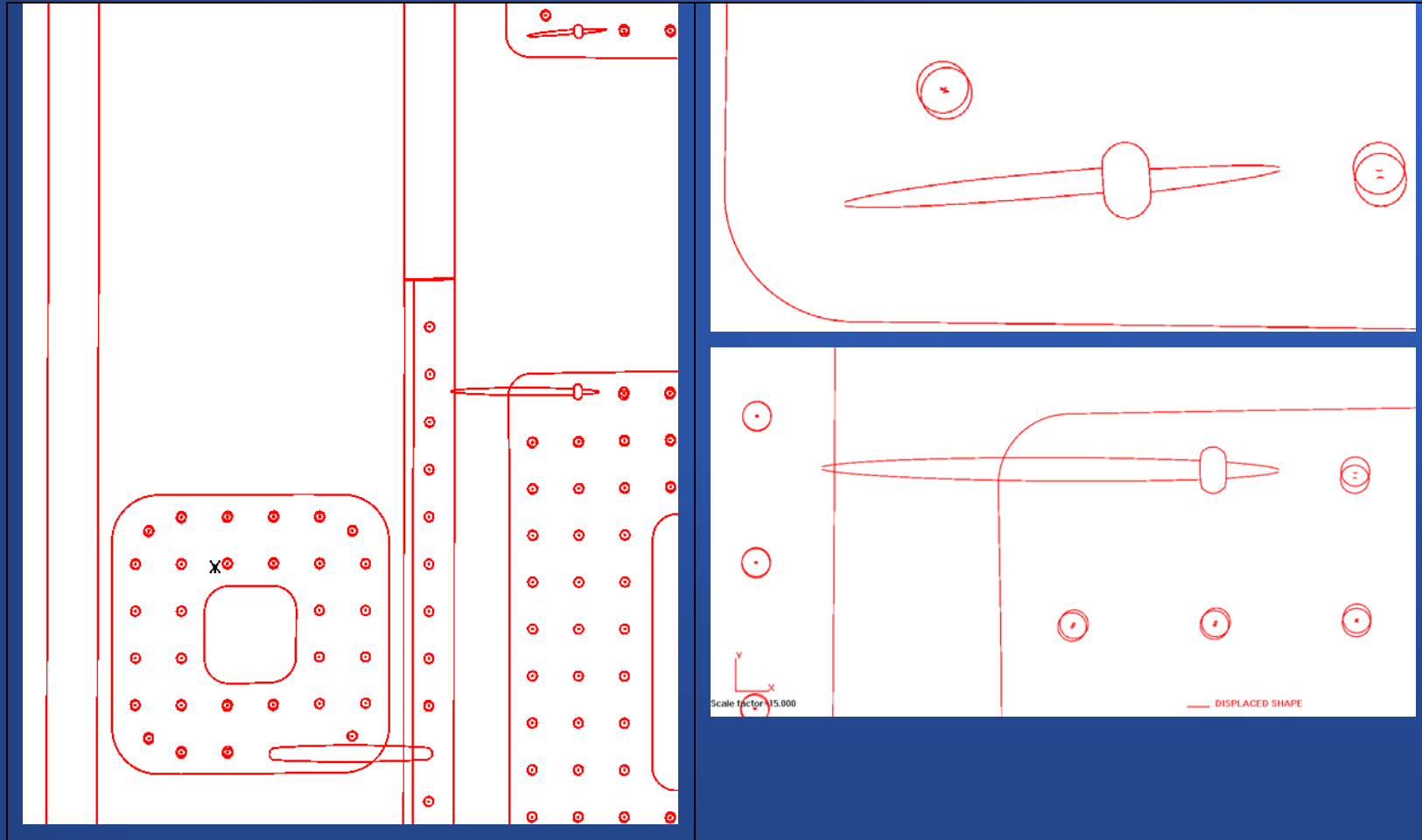
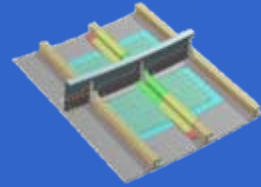


Von Mises stresses (MPa) on the skin deformed plot (scale factor 15), showing the crack scenario at 104897 cycles, with highlight of the stress state on the remaining ligament between crack N°1 and the adjacent hole: the ligament is mostly plastic with consequent link-up



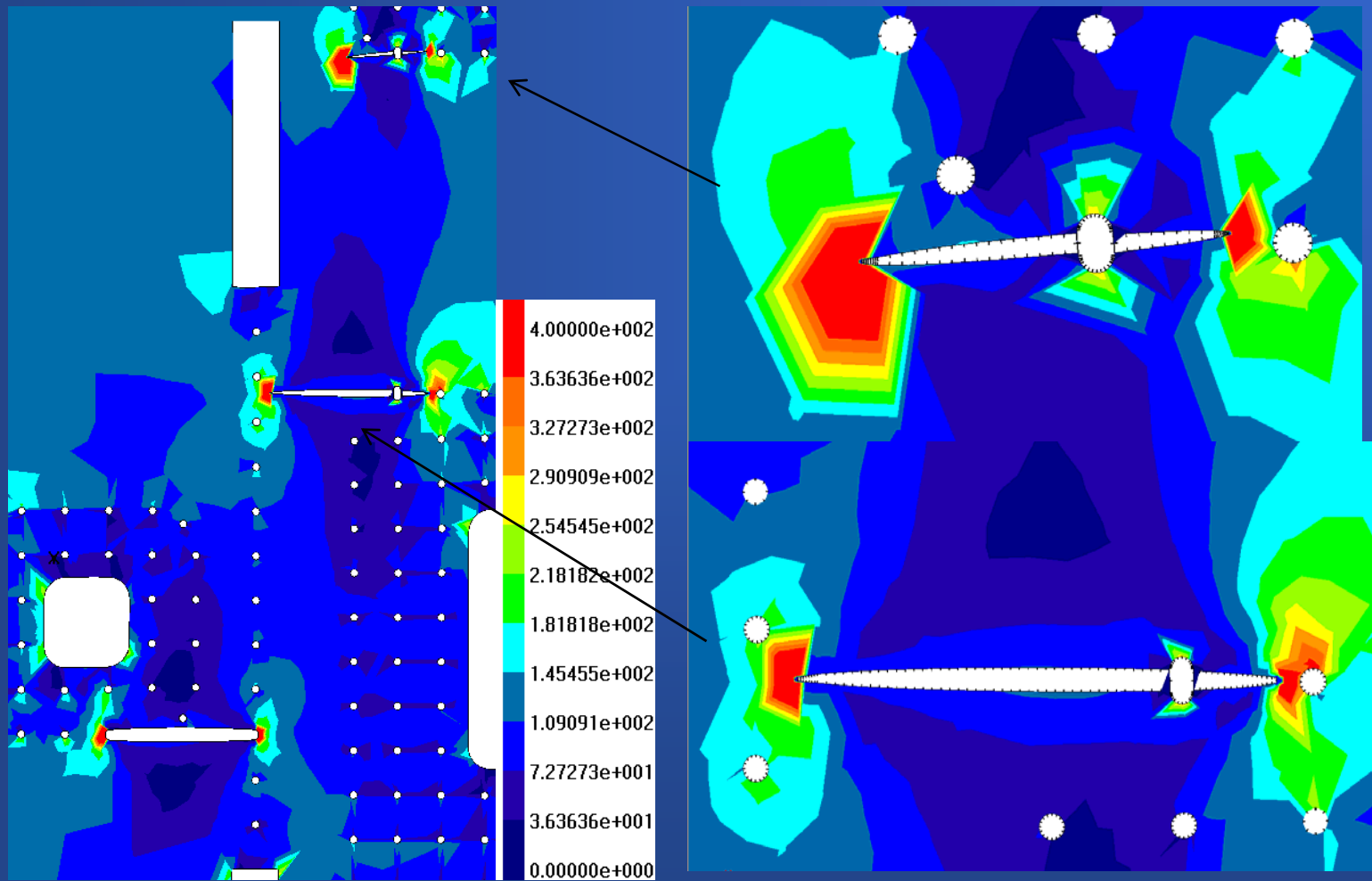
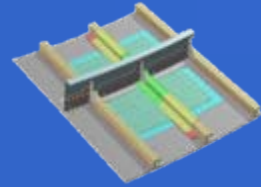
Cycle range: 104897-105937

Deformed plot (scale factor 15) of the initial crack scenario at 104897 cycles, with highlight of the modeled link-up between the crack N. 1 and the adjacent hole.



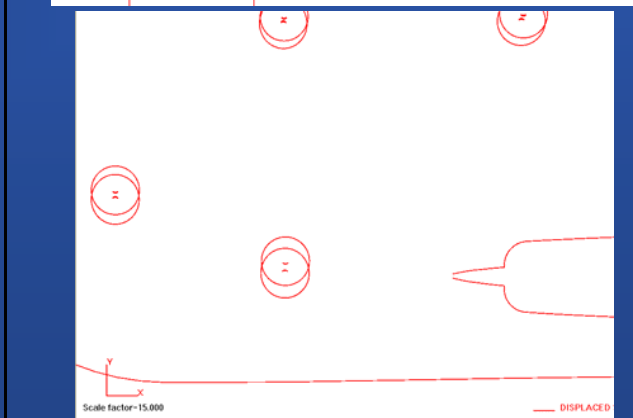
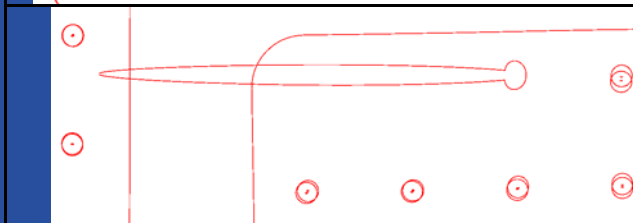
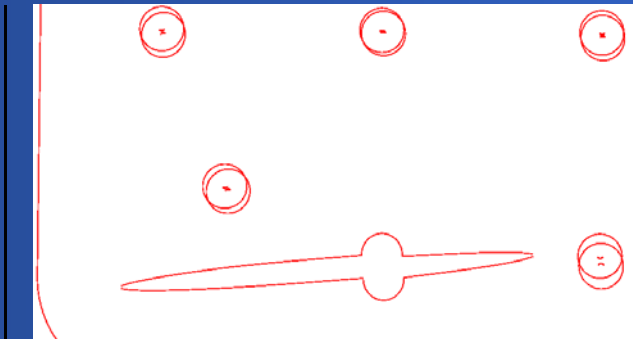
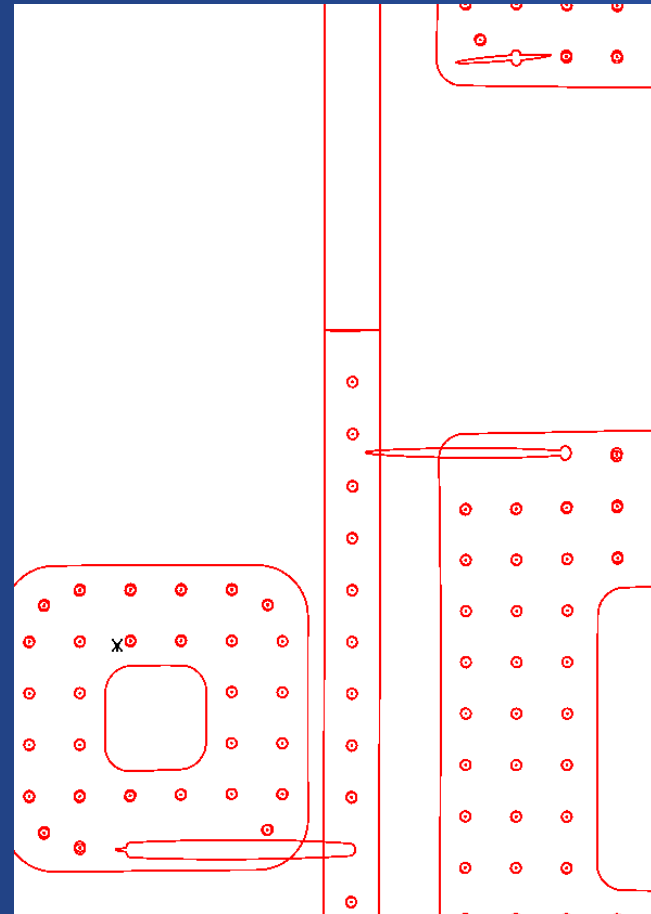
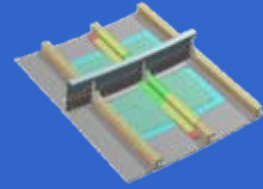


Von Mises stresses (MPa) on the skin deformed plot (scale factor 15), showing the crack scenario at 105937 cycles, with highlight of the stress state on the remaining ligament between crack N. 4 and the adjacent hole: the ligament is fully plastic with consequent link-up

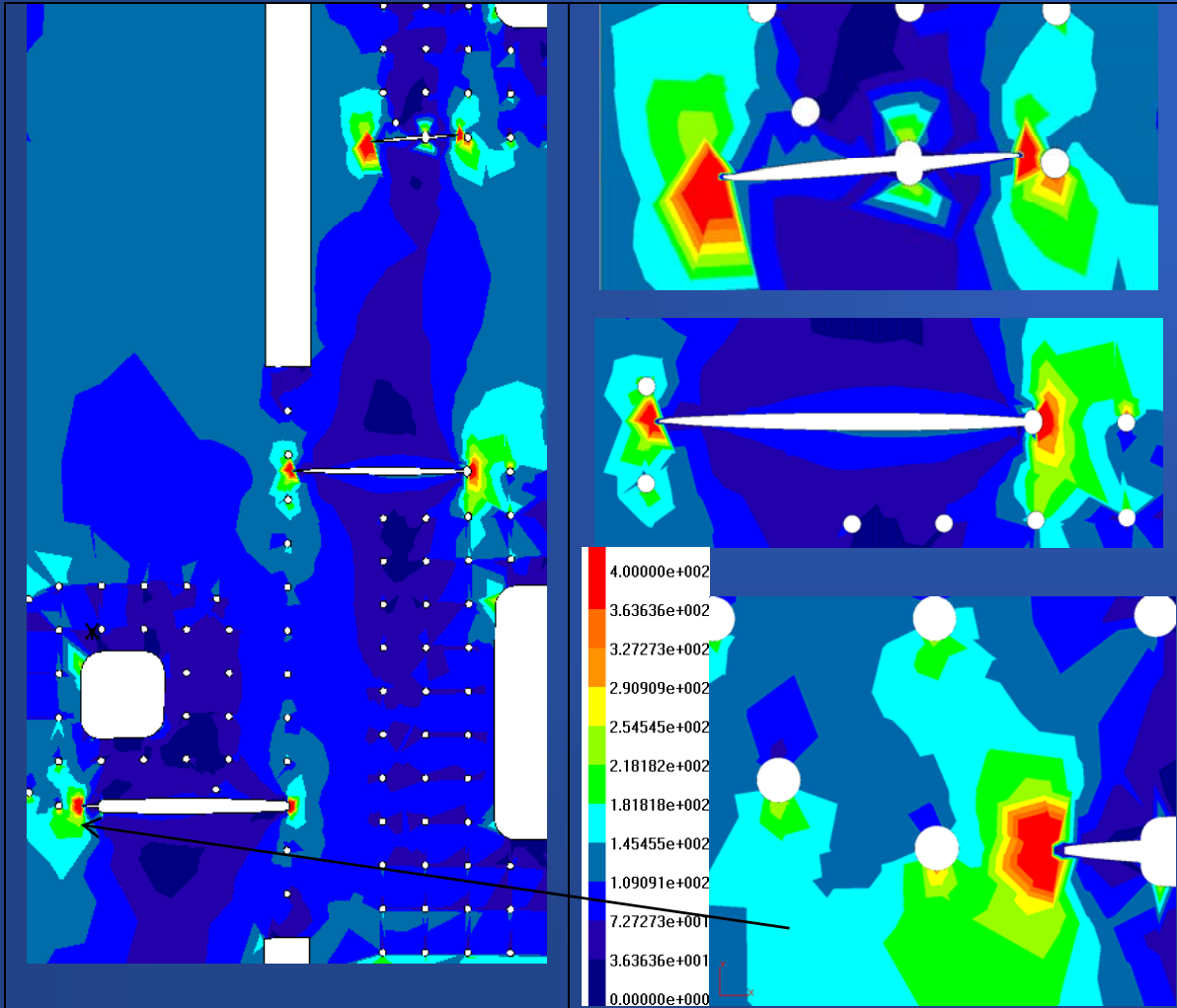
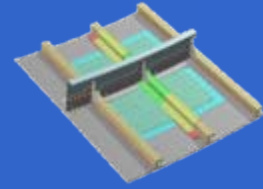




Cycle range: 105937-106793



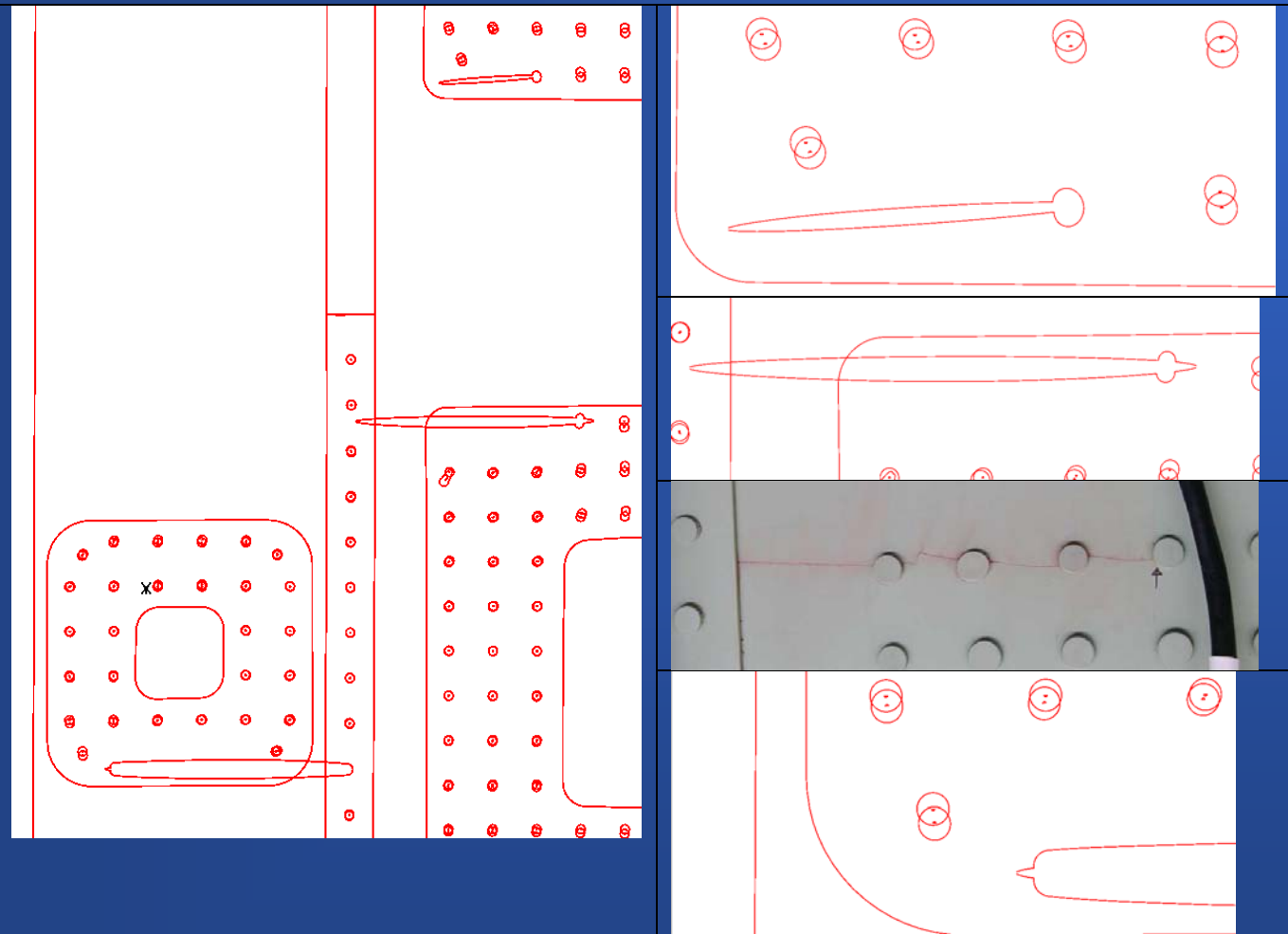
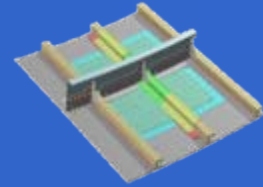
Deformed plot (scale factor 15) of the initial crack scenario at 105937 cycles, with highlight of the link-up between the crack N. 4 and the adjacent hole (middle-right), and of the new initiation of crack 1 (down-right).



Von Mises stresses (MPa) on the skin deformed plot (scale factor 15), showing the crack scenario at 106793 cycles, with highlight of the stress state on the remaining ligament between crack N. 1 and 6 and the respective adjacent holes: the ligament is mostly (crack N. 1) or fully (crack N. 6) plastic with consequent link-up.



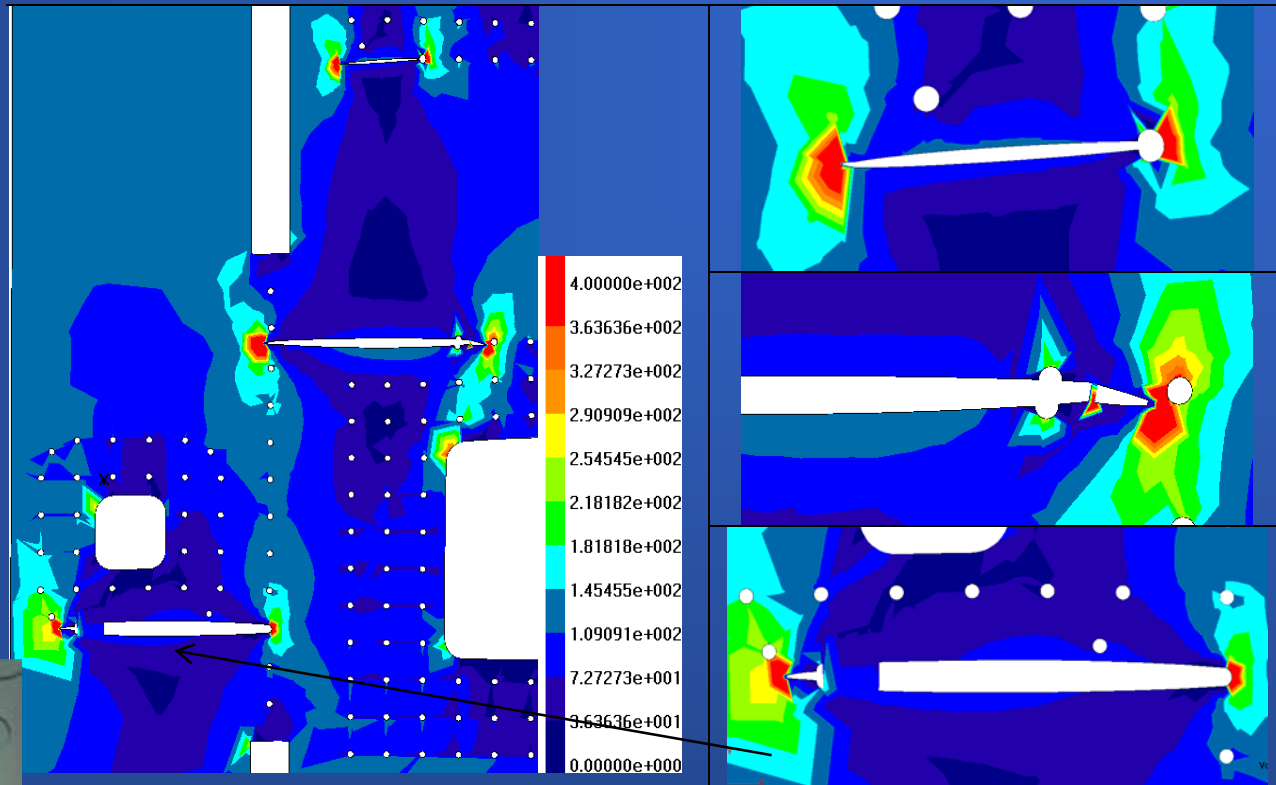
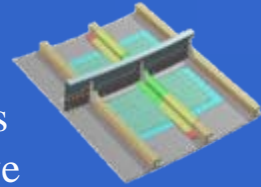
Cycle range: 106793-107831



Deformed plot (scale factor 15) of the initial crack scenario at 106793 cycles, with highlight of: the link-up between the crack N. 1 and the adjacent hole (down-right) with immediate new initiation; the link-up of crack 6, that, on the contrary, is arrested by the adjacent hole (up-right); the numerical vs. experimental scenario of cracks N. 5 and 6 (middle-right).



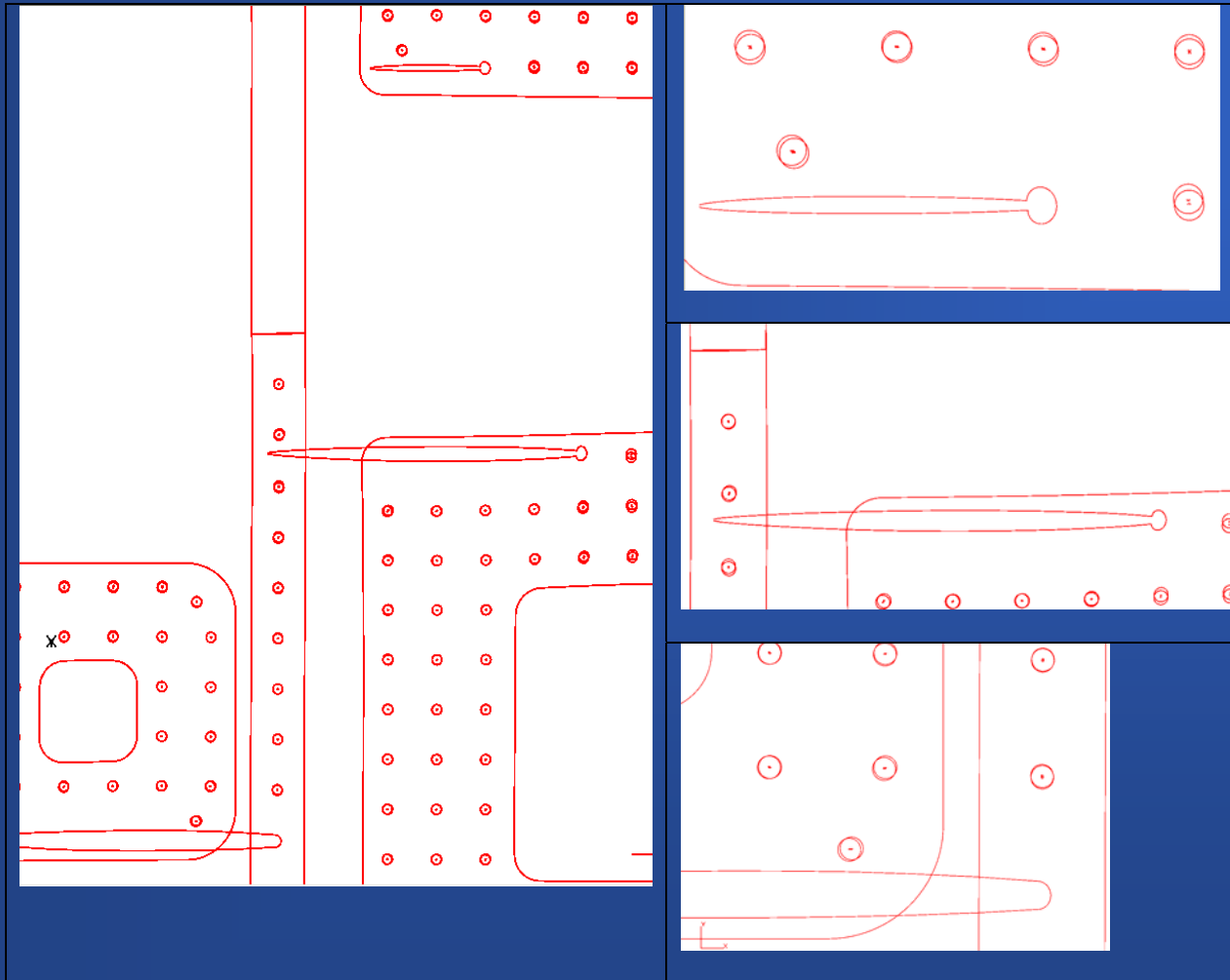
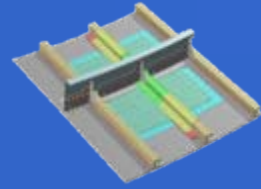
Von Mises stresses (MPa) on the skin deformed plot (scale factor 15), showing the crack scenario at 107831 cycles, with highlight of the stress state on the remaining ligament between crack 1 and 4 and the respective adjacent holes: the ligaments are fully plastic with consequent link-up.



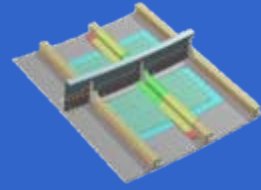
Temporary repair to arrest the propagation of crack N. 1



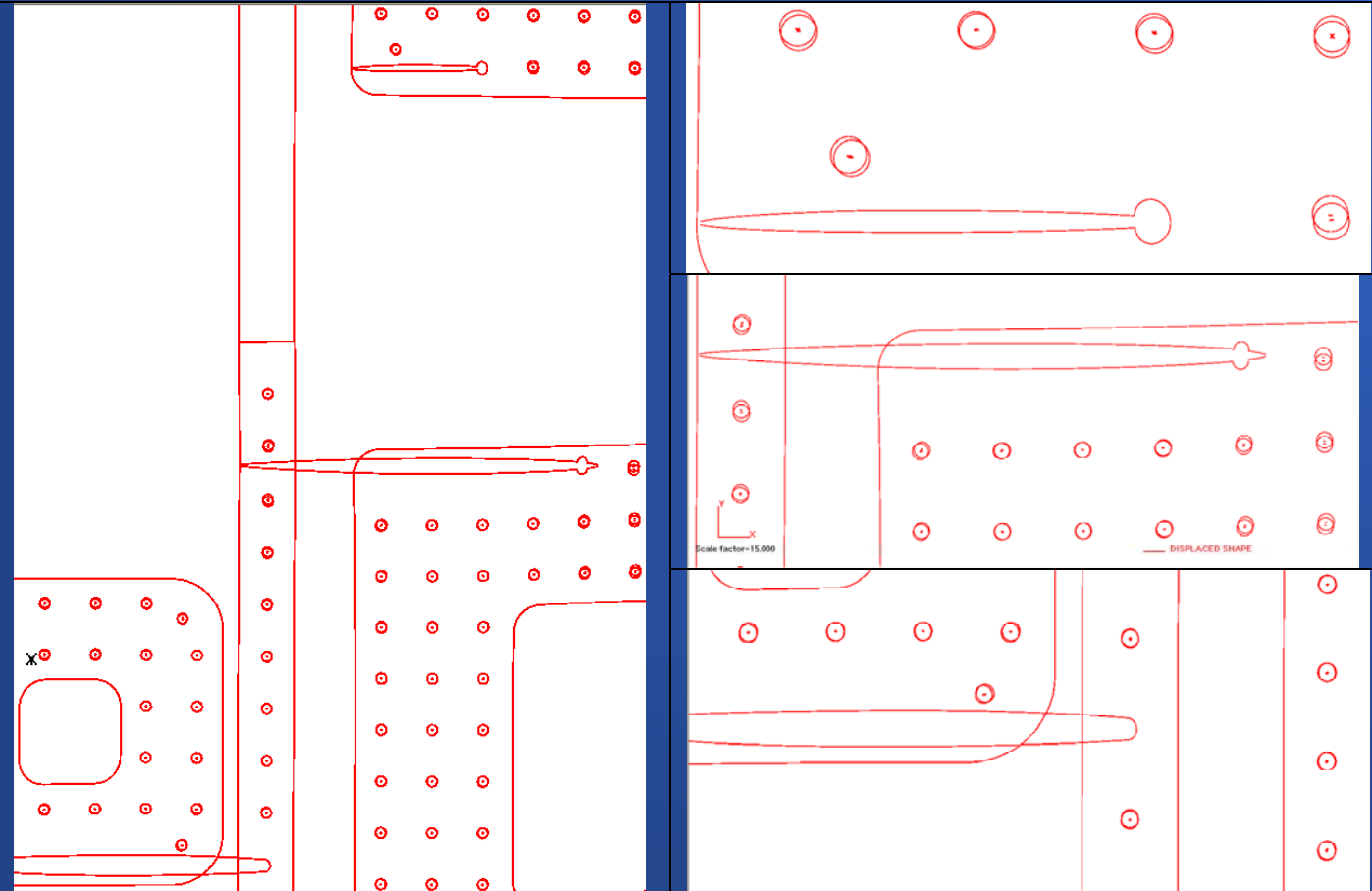
Cycle range: 107831-109200



Deformed plot (scale factor 15) of the initial crack scenario at 107831 cycles, with highlight of the modeled link-up between the crack 4 and the adjacent hole (middle-right).



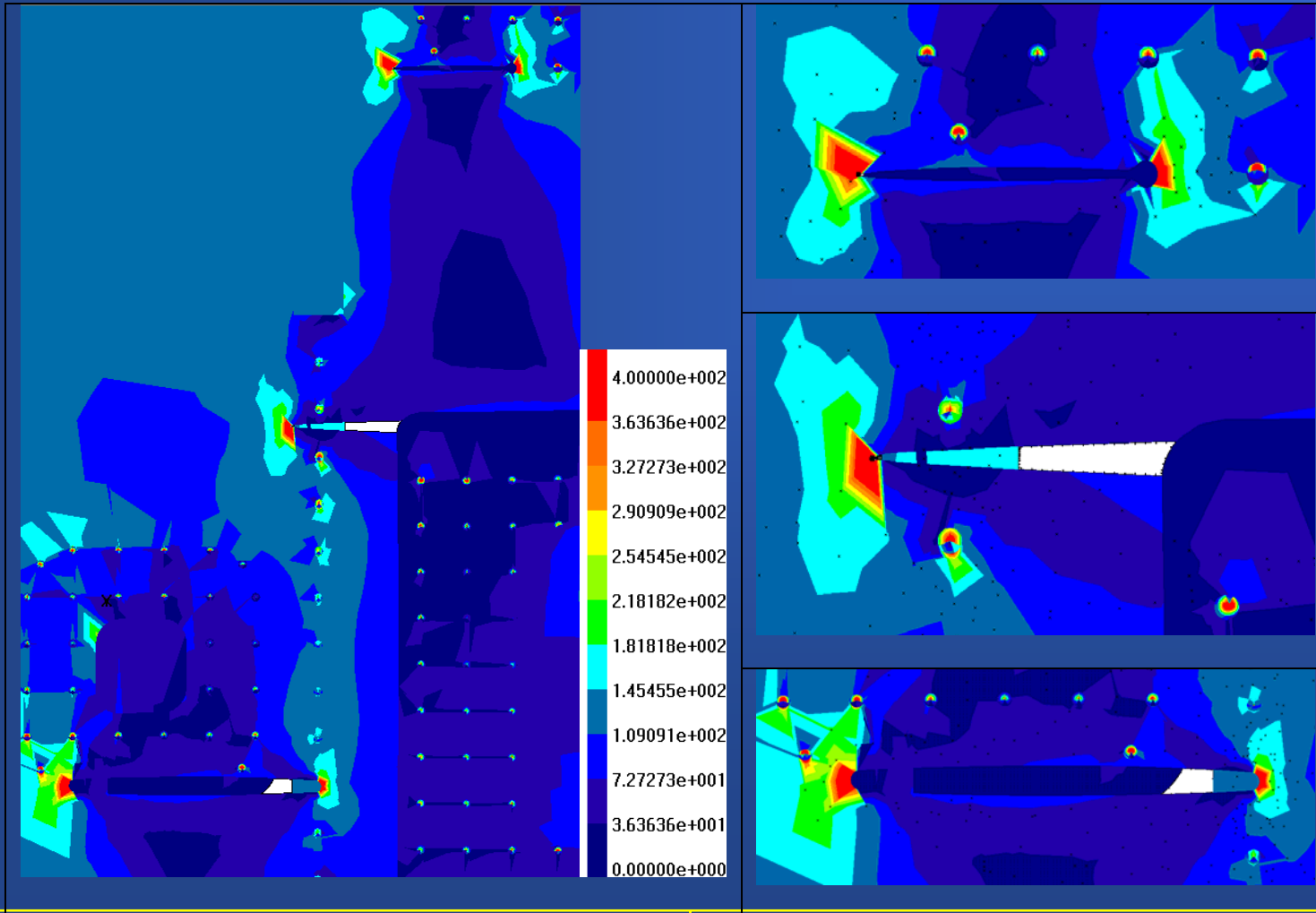
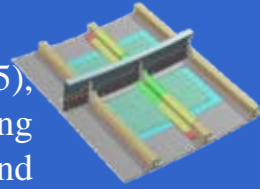
Cycle range: 109200-110000



Deformed plot (scale factor 15) of the initial crack scenario at 109200 cycles, with highlight of the modeled new initiation of crack N. 4 (middle-right).

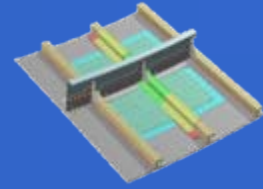


Von Mises stresses (MPa) on the stiffened plate deformed plot (scale factor 15), showing the crack scenario at 110000 cycles, with highlight of the skin underlying reinforcements and stiffeners (this time, together with the skin, also stringer and reinforcement are contoured and partially visible through the open crack).

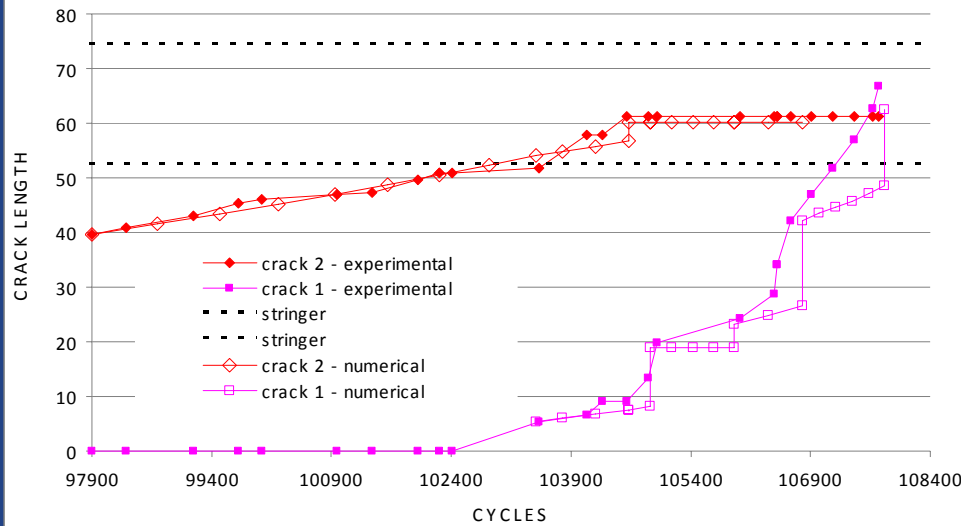




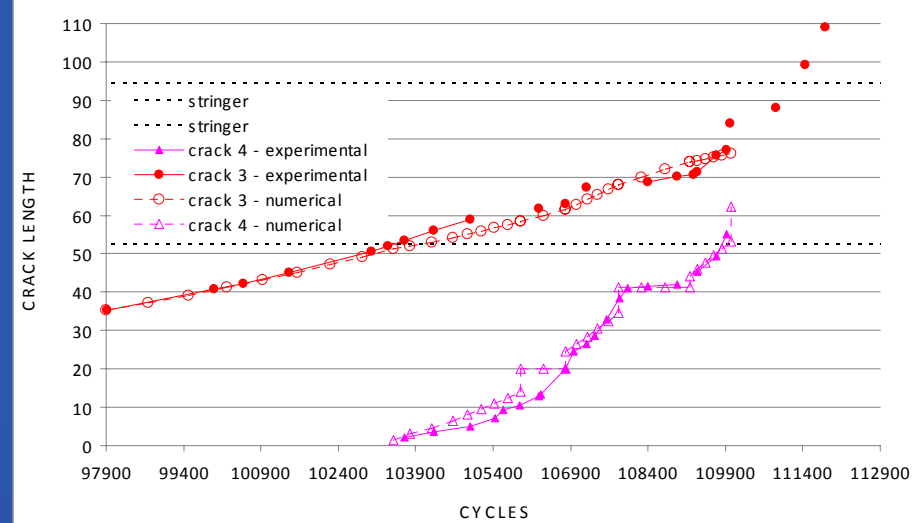
Numerical-experimental comparison



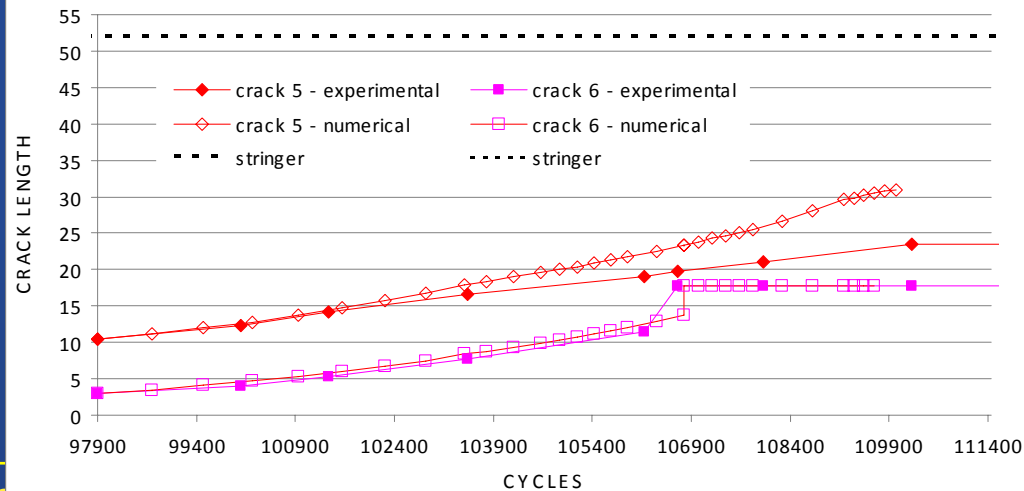
CRACKS ON REPAIR 3



CRACKS ON REPAIR 4

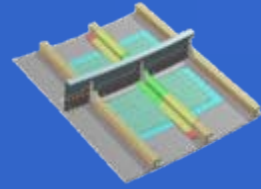


CRACKS ON REPAIR 5

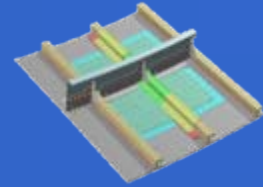




•CONCLUSIONS

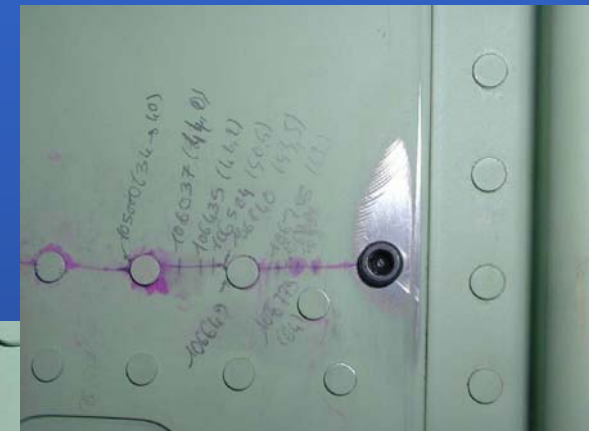
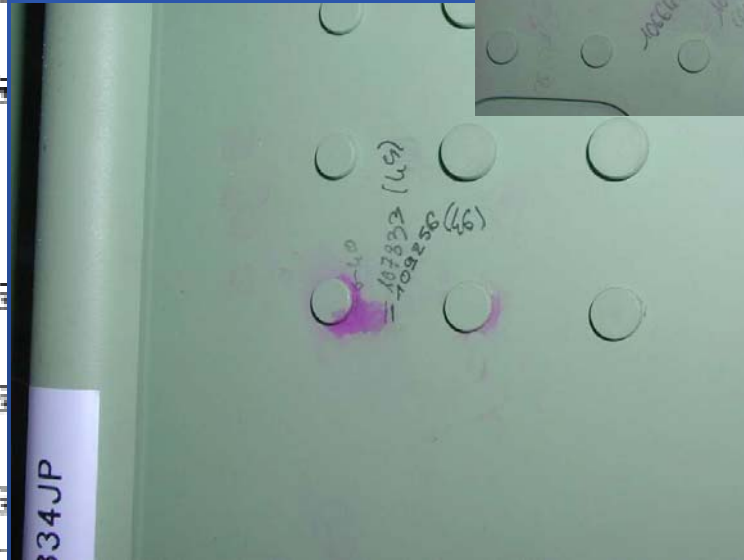
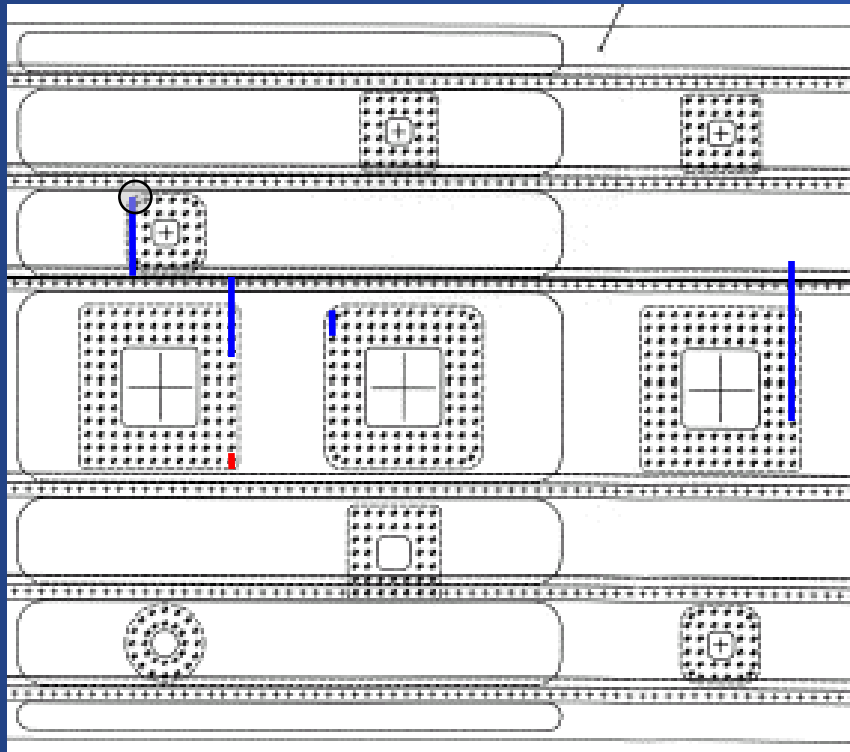


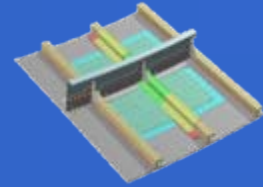
- wide range of possibilities offered for this kind of problems by the described DBEM approach, in terms of easy pre- and post-processing, reduced run-times and satisfactory accuracy.
- It becomes possible to make automatic the generation of many different cracked configurations, thanks to an in house made routine that, in combination with the main code, provides the automatic generation of the rivet connections in such a complex two-dimensional model.
- a complete multi site crack growth analysis can be performed in a few hours calculus with a standard PC.
- The future developments will be devoted to making automatic the model update when a crack link-up with a neighboring hole, with the addition of an approximate criterion to devise the remaining ligament failure.



✓ At 107 833 FC, :

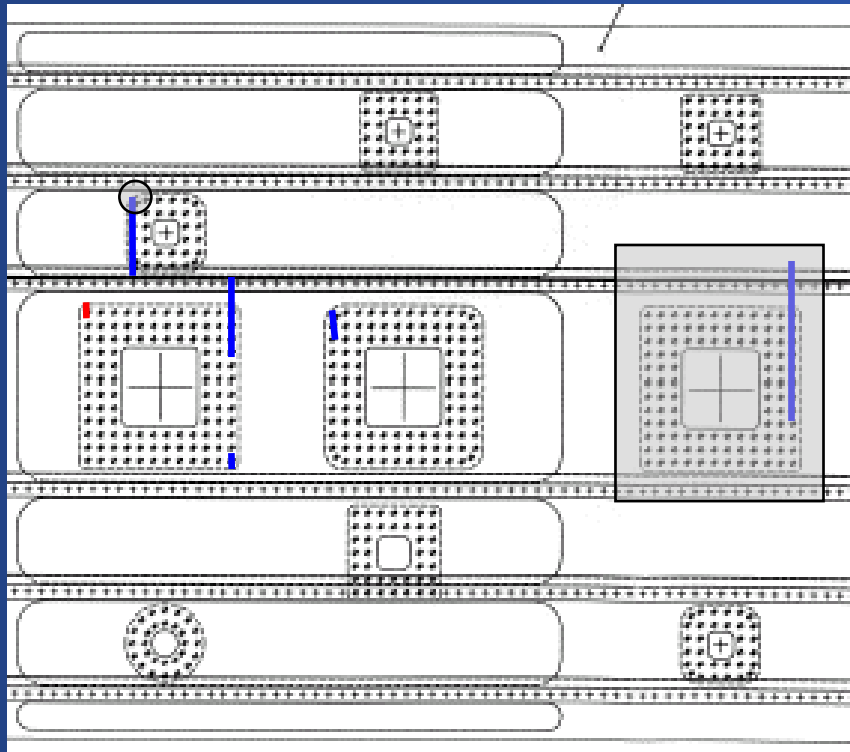
- REP 2 : Standard 3 rivet rows repair : 2nd crack initiates (5 mm)
- REP 5 : the whole 1st row cracked → temporary repair
- REP 6 : slow crack growth compared to REP 2

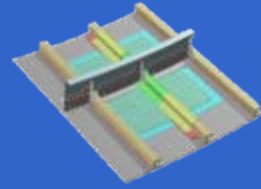




✓ At 110 000 FC, :

- REP 2 : Standard 3 rivet rows repair : 3rd crack initiates (15 mm)
- REP 4 : debonding
 - suppress doubler → rebond a full doubler (@109256)





- ✓ Today status : 112 104 FC simulated. No other crack initiates
- ✓ REP 2 high speed (350 mm crack) → suppress doubler + rebond a full doubler + temporary repair (to study REP5)

