FAILURE CASE ANALYSIS – EFFECT OF ENFORCED DISPLACEMENT IN SHEAR TIE COMPONENTS

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Abstract*. This work presents the investigation of failures occurred in Shear Tie components at the Full Scale Fatigue Testing. Local instrumentations were made with use of Strain Gages and LVDTs in order to measure local stresses and displacements. A refined F.E. model was made to check the hypotheses made and to try a solution approach. A Plane Strain F. E. M. study was carried on in order to find the crack nucleation location. A Fractographic analysis has presented the crack initiation points. Based on all these studies, it has been concluded that the crack has occurred due to a cyclic enforced displacement. Then a new design solution has been found and a dedicated experimental testing program took place. Small representative shear ties were subjected to cyclic enforced displacement in a separate testing set up. First the test had reproduced original shear tie failures. Then the solution design was tested and the result had confirmed that this new component design could safely operate during an entire life of the airplane.*

Keywords: *Failure, Shear Tie, Shear Clip, Displacement, Analysis*

1 INTRODUCTION

Airplanes have complex multiple load path structures and require a high level of structural analysis to guarantee a safety operation during its entire lifetime. Usually a global Finite Element Model where the entire airplane is discretized is used for overall analysis. But these models are built with a lot of simplifications. These simplifications are acceptable for the global analysis, once the forces do really pass from the application points to the constrained points. But for local analysis, usually at small components, the FE global model is not enough. Consequently it is easy to find components in which the real applied load is quite different than the predicted by theoretical analysis. In these cases, if the stresses are underestimated, it is possible to occur some component failures in the Full Scale Fatigue Testing. If this happens, then a Failure Analysis is done in order to find the real failure causes and also to find a solution for redesign the component. Failure Case Analysis is sometimes the only way to surely discover the real effects, mechanisms, or loads that the component is subjected.

2 FAILURE DESCRIPTION

During the Full Scale Fatigue Testing it was detected some crack occurrence at shear tie components in a specific region of the aircraft. Figure 1 shows typical cracks at the shear tie component.

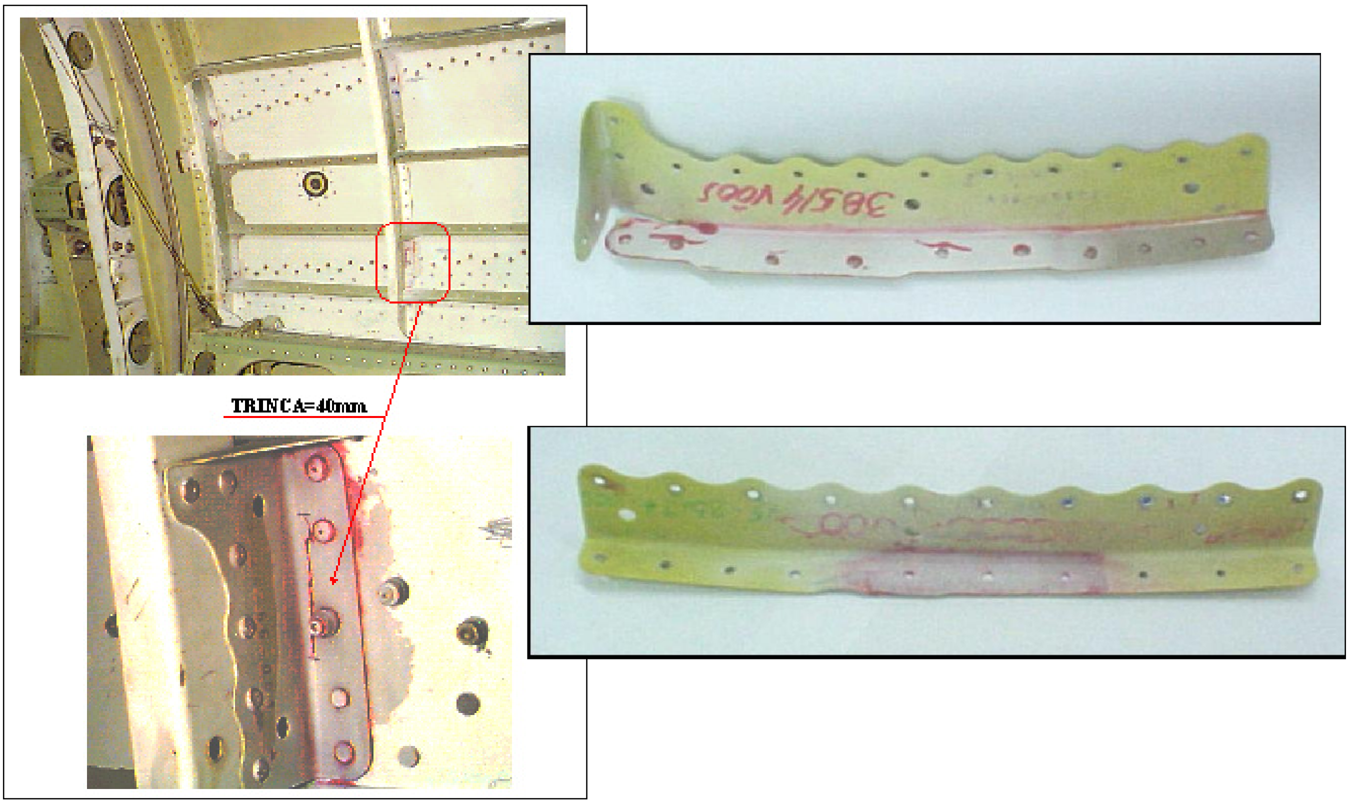


Figure 1: Crack found in a Shear Tie component at the Full Scale Fatigue Testing.

The shear ties are thin components cut from a 0.8mm thick aluminium sheet and cold bent to the final shape . They are designed to carry transverse internal loads from skin to frames and vice-versa, in order to maintain the fuselage external form. As can be seen at Fig. (1), a shear tie is a component composed in tree parts: the web, the flange, and the small flange. Their web is attached to the frames, the flange is attached to the skin of the fuselage and the small flange is attached to the stringers. All connections are made by ‘brile’ rivets, except for one specific point, where a Hi Lite fastener is used.

The cracks were detected at the first time with 15000 flight cycles, which means approximately 8 years of aircraft normal operation. The crack at these components initiates at the flange, just behind the commented Hi Lite and it propagates transversely to the shear tie following the flange direction. As usual, all the failed components have been replaced by new ones, and the airplane continued to fly. Cracks had recursively happened in the same place following a nucleation time of approximate 15000 flight cycles.

Following the rules, when a failure is detected in the Full Scale Fatigue Testing, a failure analysis takes place. It is necessary to find the real causes of the failure and to start a revision in design to avoid the occurrence of that failure in the real airplanes.

3 ANALYSIS

A failure analysis in aeronautical components usually is not easy to be done, once a lot of calculation and analysis had already been done in all parts of the aircraft during the certification process, and, in that moment, no failure possibilities were detected. Then a lot of work took place in order to solve these failures.

In this case, for solving the shear tie cracks, the following tasks have been done:

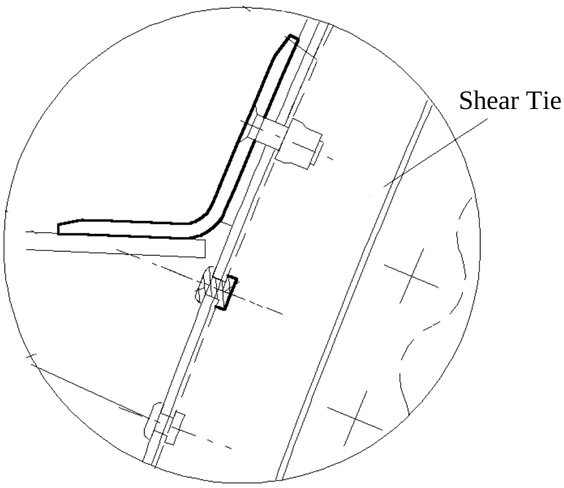
a) Visual analysis;
b) Local Instrumentations;
c) Refined finite element modeling (FEM);
d) Through the thickness Plane Strain FEM study; and
e) Fractographic analysis.

3.1 Visual Analysis

The shear ties are designed to carry transverse internal (= shear) loads from skin to frames, and these loads lays exactly at the same direction where the crack path had gone on. Nevertheless it was supposed that the crack path to have another direction different to that observed at the testing set-up. Surely it could be concluded that we are in front of some load effect different to that the component was designed for.

There are reproducibility and some characteristic geometric evidences that point through the real cause of these cracks. By using a simple visual analysis and observing the crack history it was verified that: 1) The crack always appears behind the Hi Lite position; 2) the crack decreases the propagation rate as it increases the length.

In drawings observation it was verified that the shear tie is connected to an external rigid “L” by means of that specific Hi Lite where the crack surges (Fig. 2). Then it was observed that could be possible the existence of some load deriving from that external “L” and coming inside to pull the shear tie, imposing to it a enforced displacement.



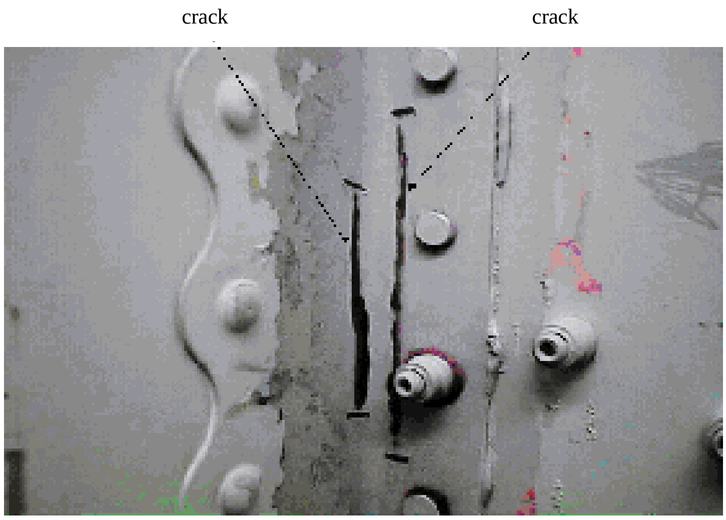


Figure 2: Hi Lite installation at the shear tie.

3.2 Local Instrumentation

In order to discover the stresses and displacements involved at this place, a local instrumentation were made by using Strain Gages and Linear Variable Displacement Transducers (LVDTs). The Strain Gage measurement has resulted only in few and poor conclusions, therefore the main conclusion is that the loads coming from the external "L" strongly interferes in the shear ties stresses.

The LVDT instrumentation installed at the shear clip Hi Lite can be seen in Figure 3 and has the objective of measure the Normal-to-Skin displacement of the Hi Lite. The LVDT fixity was done at the adjacent frame. Once it is possible to occur some small angle movement with the frame, then 2 LVDTs were installed in line from the frame, in order to capture this movement. Then it is possible to separate the two components obtaining the pure axial movement of the Hi Lite.

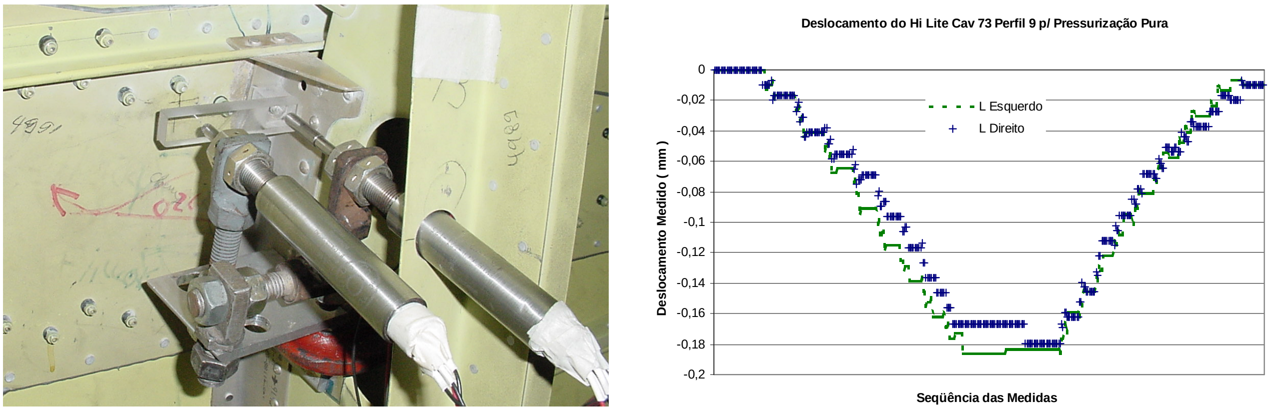


Figure 3: LVDTs instrumentation at the Shear Tie Hi Lite and typical result for pressurization.

A lot of flight configurations had been measured, within a representative number of flight segments. The LVDT measurement results for flights type 5 and type 7 are exposed at Table 1. It could be concluded that:

a) The displacement in Hi Lite happens mainly due to the external "L" movement at the Normal-to-Skin direction;
b) The displacement for a flight type 7 is approximately 0,38mm ;
c) The displacement for a flight type 5 is approximately 0.41mm .

In order to use one equivalent cycle per flight to simulate all the stress spectra, it have been took the enforced displacement value of **d = 0.40mm** once per flight.

Table 1: LVDT Measurement Results for segments from flight 7 and flight 5 , respectively

SEGMENT	Average Measure (mm)
0	0,000
138	-0,001
147	-0,022
165	-0,357
175	-0,257
164	-0,369
174	-0,252
163	**-0,376**
173	-0,245
88	-0,113
219	-0,029
0	0,006

SEGMENT	Average Measure (mm)
0	-0,002
136	0,003
145	-0,025
163	-0,382
173	-0,250
162	-0,394
172	-0,239
161	**-0,412**
171	-0,222
86	-0,123
219	-0,039
0	-0,007

3.3 Finite Element Model

Several refined FE model were made to check the hypotheses made and to verify the parameters variability.

Software MSC – Nastran for Windows 2001 was used. All models were built in Cylindrical Coordinates, with a refined mesh for each component. QUAD4 and TRIA3 Plate Elements were used to simulate Skin, Frames, and Shear Ties, and whenever possible QUAD4 elements were preferred. The Shear Ties are attached to the skin and to the frame by DOF-Spring Elements simulating the rivets, following Swift, 1971, procedure. The rivet heads were simulated by using interpolation rigid elements RBE3. Several DOF-Springs were strategically disposed to simulate contact, avoiding interpenetration.

The Boundary Condition applied to the models was made by imposing Cylindrical Symmetry at the 4 Skin borders and at the 2 Frame borders. This procedure simulates the continuity of these components through the entire Fuselage circumference. The Model can be seen at Figure 4.

The Swift procedure to simulate fasteners by using springs considers the application of 3 axial springs per each fastener, one spring per orthogonal direction, and the respective spring stiffness are calculated as follows:

Table 2: Swift procedure for simulating fasteners as DOF-Springs

$$K_1 = \frac{A_d E}{L} \qquad K_{23} = \frac{1}{F}$$

$$F = \frac{A + B\left(\frac{D}{T_E} + \frac{D}{T_B}\right)}{ED}$$

D=	Rivet diameter
E=	Young Modulus
A=	5.0 for aluminum rivets and 1.666 for steel rivets
B=	0.8 for aluminum rivets and 0.86 for steel rivets
TE=	Sheet 1 thickness
TB=	Sheet 2 thickness
Ad=	Rivet transversal section
L=	Rivet grip length

Load Cases studied: the pure Pressurization Load case and the pure enforced displacement Load case.

The pure applied pressurization gives us a local maximum stress equal to $\boldsymbol{\sigma_P = 15.3}$ **kgf/mm^2** at exactly the same point where the crack has nucleated.

By using a MIL HDBK 5H SN curves, and considering conservatively a failure occurrence at 10000 equivalent cycles (one equivalent cycle per flight), we obtain for the material involved, an actuating stress $\boldsymbol{\sigma_T = 48}$ **kgf/mm^2** .

Assuming that the stresses involved are resultant essentially from the pressurization and the displacement applied, and considering a linear analysis, it is easy to conclude that the stress due to the enforced displacement will reach a value of $\boldsymbol{\sigma_D = \sigma_T - \sigma_P = 48}$ **kgf/mm^2 - 15.3 kgf/mm^2 = ~ 33 kgf/mm^2**

Now, with this value in hands, and by a trial and error approach for the load case, we start looking for the amount of a enforced displacement, which corresponds to a maximum stress value of $\boldsymbol{\sigma_D}$ **= ~ 33 kgf/mm^2**

After some trials, it was found that, with the value of a enforced displacement **d = 0.4 mm** applied to the Hi Lite position, the stress obtained is $\boldsymbol{\sigma_D = 34}$ **kgf/mm^2** , see Fig. (4). Then this is the value of enforced displacement we were looking for. Realize that this value (d = 0.4 mm) is exactly the same obtained from the LVDT instrumentation procedure.

It is important to emphasize that the two procedures were made separately and with no connections of any way.

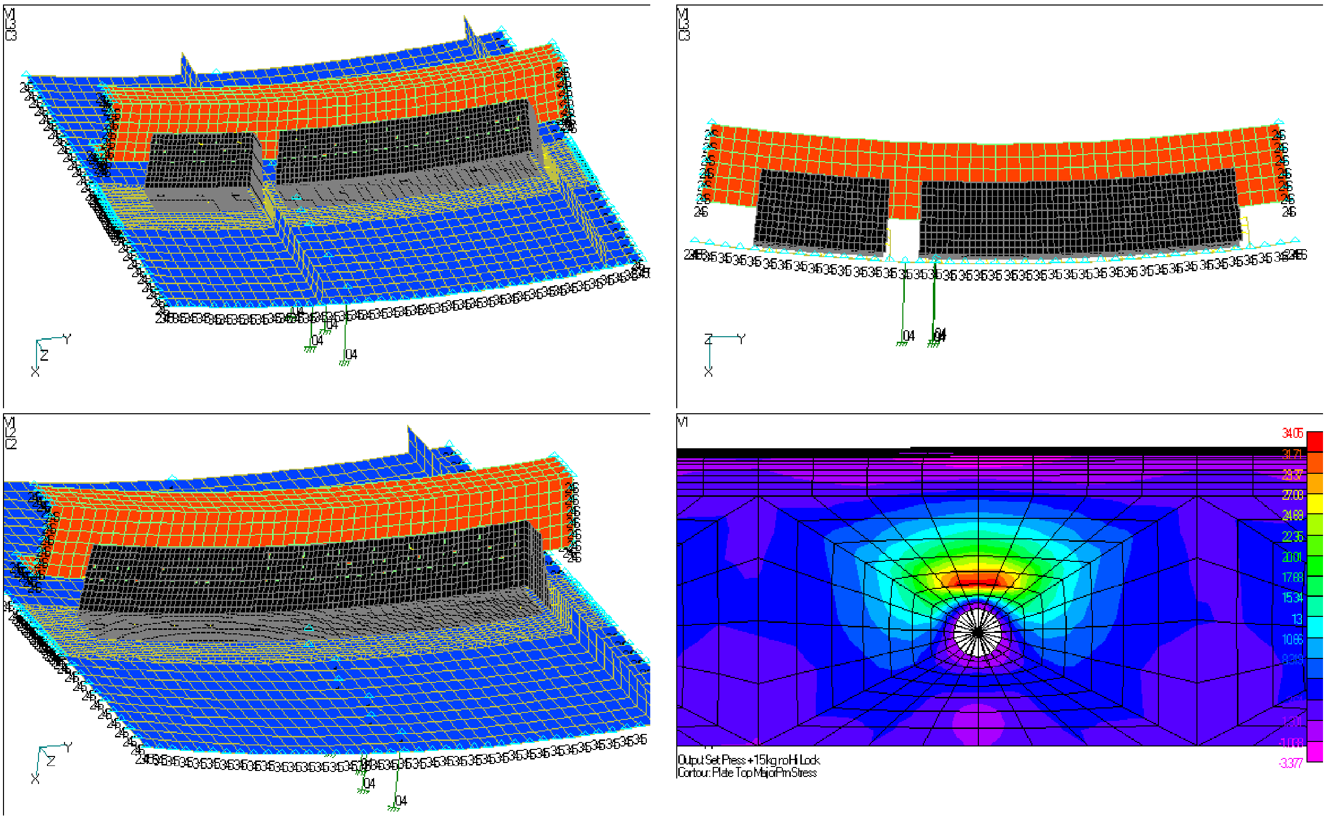


Figure 4 : Mesh visualization of the FEM used and Shear Tie maximum stress position and value obtained.

3.4 Plane Strain Study

A through the thickness Plane Strain FEM study was prepared in order to find the crack nucleation location. Some models representing the transverse section of the shear tie were built using 'Plane Strain' elements to simulate the occurrences along the thickness of the component.

In this study it was verified that the maximum stress region is located at the bottom side of the shear tie, exactly below and tangentially at the Hi Lite head, and after that, there exist another high stress region exactly at the final of the bend radius at the upper side of the shear tie - see Fig. (5).

After that, some parameters have been changed to check the influence of the thickness, the fastener position, and the frame attachment variations on the stress results. And with this approach, it was verified that an improving of the shear tie rigidity do not contribute to decrease the involved stresses, but exactly the opposite happens. Then the solution approach seems to be an improving of the flexibility or, in other words, to decrease the stiffness of the component.

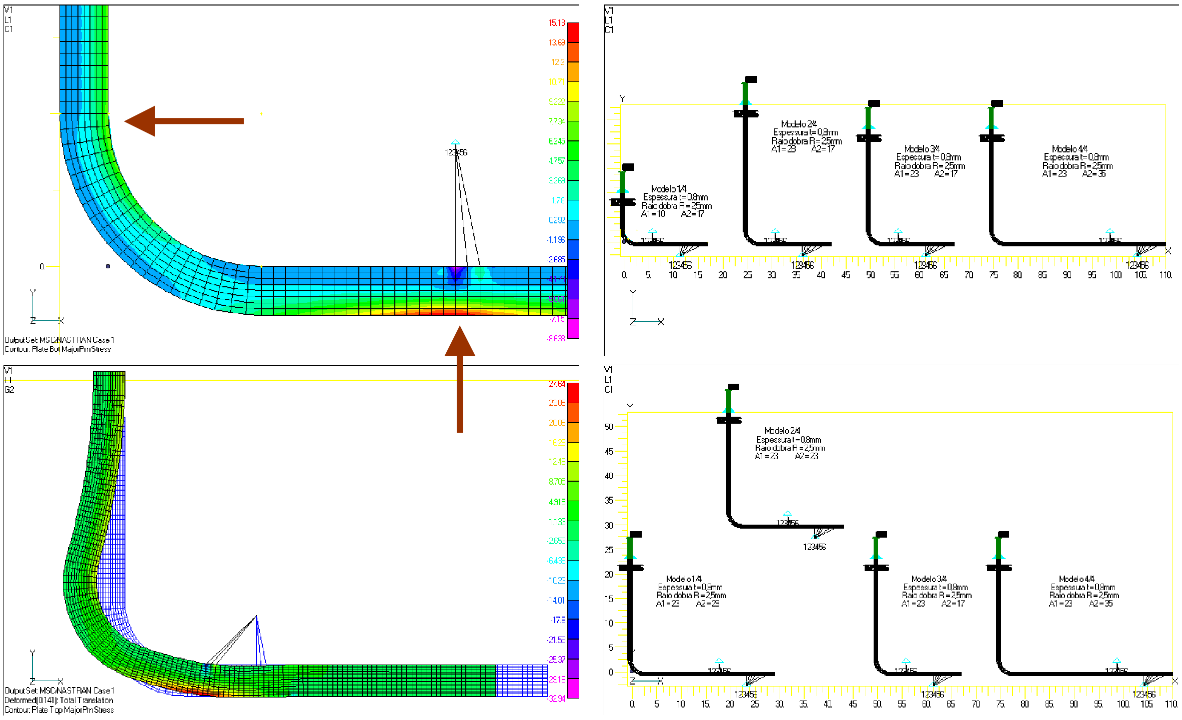


Figure 5 : Plane Strain Mesh Visualization : Some Models Used

3.5 Fractographic Analysis

The Fractographic analysis that was made at these components has the objective of locate the actual points of crack initiation for all the cracks found at these components (Fig. 6). The results show that all the crack near the Hi Lite had initiated at the bottom (inner) side and all the crack at the bent region had initiated at the top (outer) side – Fig.(7). And these are truly the same locations as what were predicted by the theoretical plane strain approach.

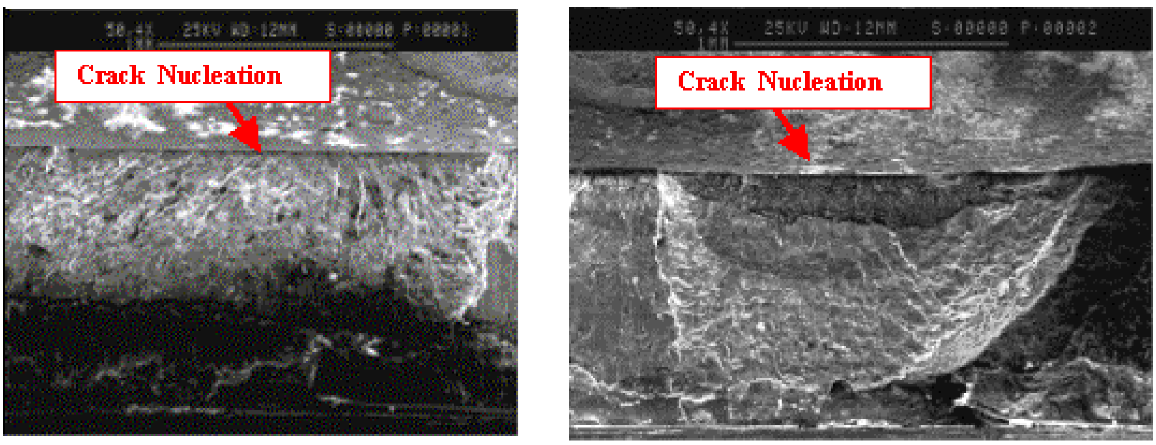
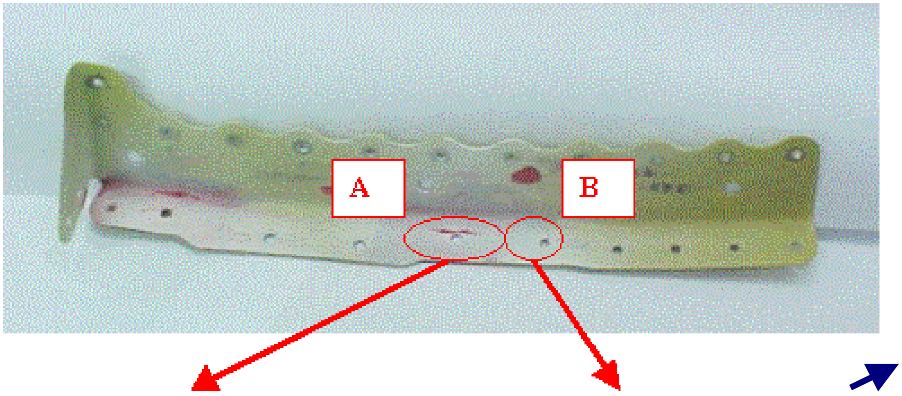


Figure 6 : Fractographic Analysis Results – MEV View



Crack Identification	Crack origin
a	*Outer*
b	Inner
c	*Outer*
d	Inner
e	Inner
f	Inner
g	Inner
h	Inner

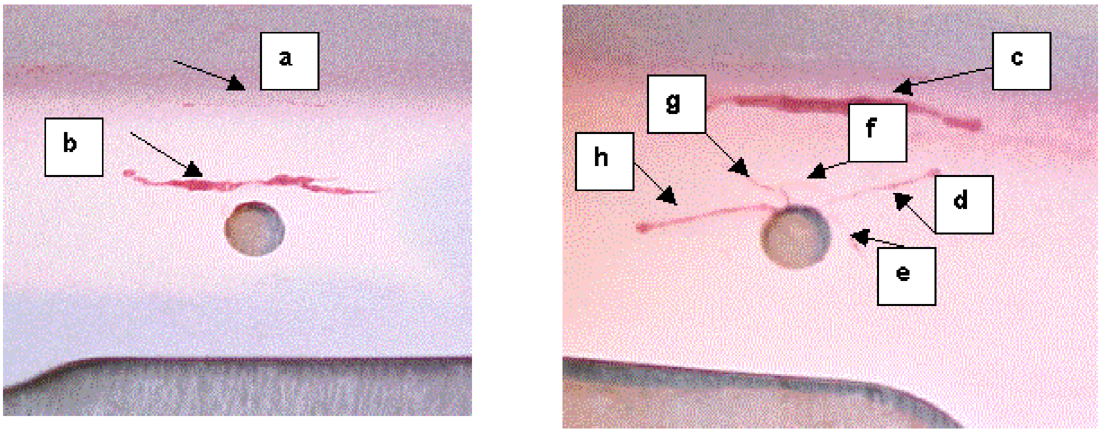


Figure 7 : Fractographic Analysis Results

3.6 Analysis Conclusion:

With all this results in hands, it is easy to see that :

a) Fractographic Analysis and Plane Strain Study lead to the same crack initiation location;
b) The Failure was caused by a Enforced displacement;
c) FEM Study and Local instrumentation had obtained the same value of " d = 0.4 mm " for the equivalent displacement that is causing the failure;
d) The solution approach seems to be to increase the component flexibility

It is important to emphasize that the FEM Study and the Plane Strain study were both based on theory generated by visual observations and, on the other hand, fractographic analysis and local instrumentation were both measurements of the actual situation of the shear tie in its effective operational life.

In this situation the study stands in a very comfortable position, once all the theoretical and experimental results are pointing to the same direction.

Based on all these studies, it has been concluded that the crack has occurred due to a enforced displacement to which the shear ties were subjected during the flights.

The solution will be to redesign the component in such a way that the new one will have lower stress levels and do not fail during its entire operational life. In this situation an improvement of the rigidity will not solve the problem. In fact, it will be needed to take the opposite way in looking for a solution. A new component must be designed in such a way that the applied stress need be sustained safely.

The only way to find it is to improve the component flexibility, but without loss of functionality.

4 SOLUTION APPROACH

Once it is already known that the flexibility needs to be improved, a lot of new design trials has been made and checked by using refined Finite Element Models. Finally a good solution approach has been found, and it consists in increasing the distance from shear tie web to the Hi Lite position in shear tie flange.

Using a FE detailed model and with a trial and error approach a new geometry solution has been found for the shear ties. It involves put the fasteners step by step increasing its distance from the web. It can be seen at Figure 8.

The original design configuration has all the fasteners positioned on the same line. And the distance from the web to the fastener position is approximately ~ 10mm.

The final solution has been found moving the Hi Lite and its two each side fasteners neighbors to a new position far away from the web. The new distances are: 13mm / 17mm / **20mm** / 17mm / 13mm . The Hi Lite distance from the web needs to be 20mm , and its firsts neighbors need to stay stepped little by little until reaching the standard value of the fasteners distance to the web, ~ 10mm.

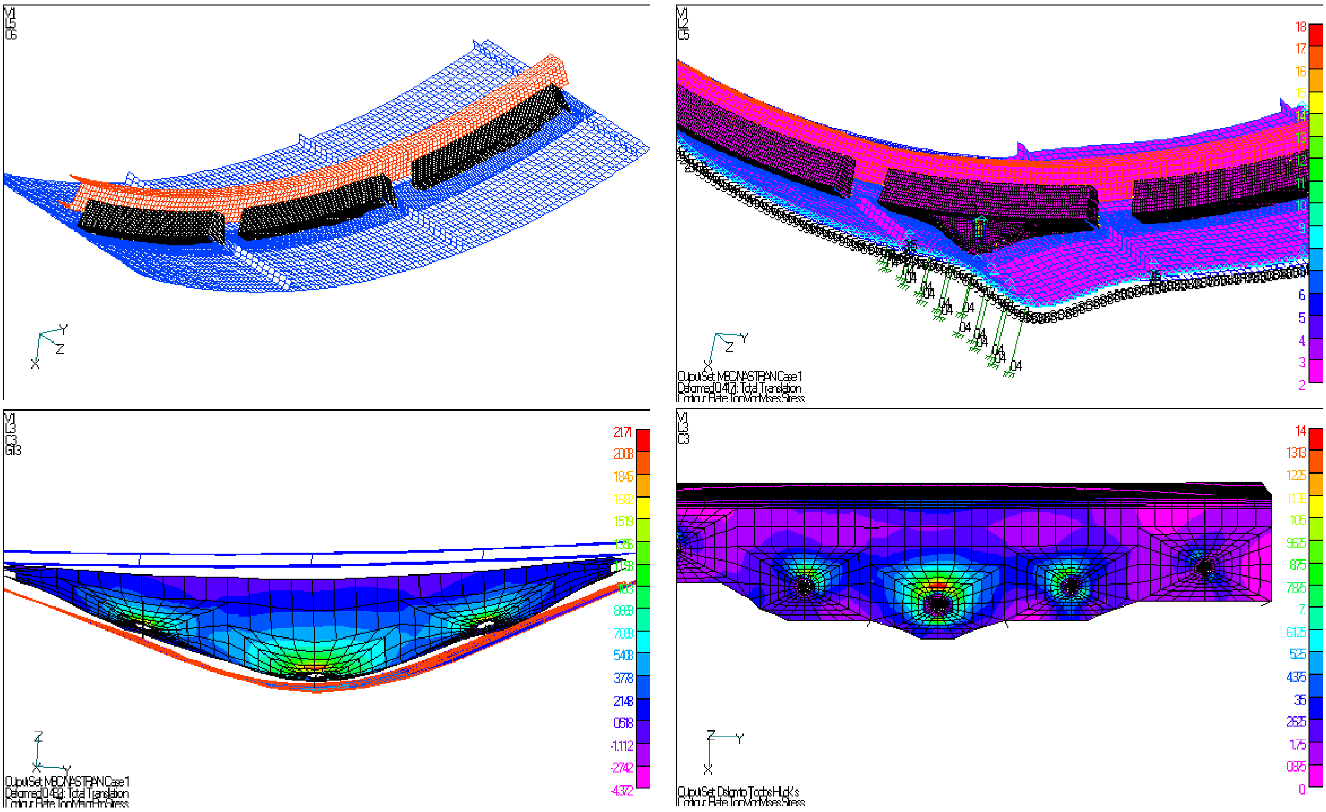


Figure 8 : Visualization of the FE Model simulating the solution.

5 EXPERIMENTAL TESTING PROGRAM

In order to confirm the analysis and the effectiveness of the solution, a dedicated experimental testing program took place. Small representative shear ties were subjected to cyclic enforced displacement in a separate testing set up. The coupon representing the shear tie can be seen at Fig. (9).

First the test had reproduced shear tie cracks exactly at the same location and same number of cicles of the crack found at the Full Scale Fatigue Testing. Three shear ties with standard distance (d = 10mm) were tested by applying a cyclic enforced displacement and they had cracked at 12 000 cycles (medium).

Then the solution design was tested and the result had confirmed that this new component design can safely operate during an entire life of the airplane. Three shear ties with the new geometry were tested by applying a cyclic enforced displacement and they had cracked after 100 000 cycles.

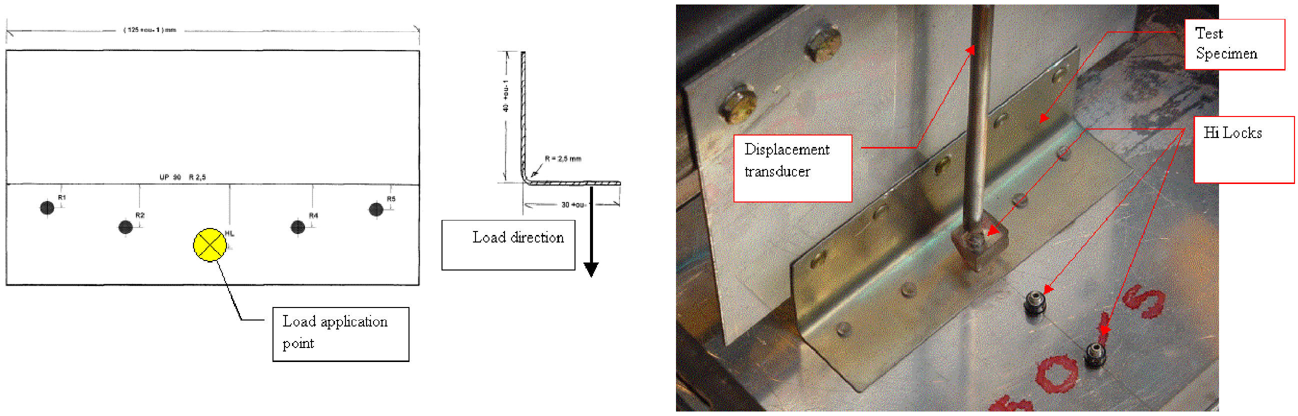


Figure 9: Experimental Testing Set-Up

6 CONCLUSIONS

The Failure encountered at the Shear Ties had occurred due to a cyclic Enforced Displacement.

All the cracks near the Hi Lite had initiated at the bottom (inner) side and all the cracks at the bent region had initiated at the top (outer) side.

In Cases where a component is subjected to Enforced Displacements instead of Forces, it is strongly desirable to have high Flexibility characteristics, instead of high rigidity.

For the specific case the shear ties herein studied, the proposed geometry modification had proved to be enough for the required solution.

7 ACKNOWLEDGEMENT

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