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R. Benedictus, J. Schijve, R.C. Alderliesten, J.J. Homan (Eds.)

EXPERIMENTAL AND ANALYTICAL INVESTIGATIONS ON THE CRACK INITIATION AND CRACK PROPAGATION BEHAVIOUR OF MECHANICALLY FASTENED FML JOINTS

F. Pellenkoft* and J.J. Homan†

* Airbus Deutschland GmbH,
Fatigue and Damage Tolerance Department
Kreetslag 10, 21129 Hamburg, Germany
e-mail: Fred.Pellenkoft@airbus.com

† Delft University of Technolgy, Faculty L&R,
Kluyverweg 1, 2629 HS Delft, The Netherlands
e-mail: J.J.Homan@tudelft.nl
Web page: www.vm.lr.tudelft.nl

Abstract. *Fibre Metal Laminates (FML) have been selected for Aircraft structures because of their excellent fatigue and damage tolerance (F&DT) behaviour, demonstrated with extensive test evidence. FML aircraft structures can have an operational life free of cost and time extensive Non Destructive Inspections, provided that for the FML structures the ultimate load capability can be shown throughout the life of the aircraft. In this paper it is shown that it is possible, though with conservative results, to predict crack initiation and propagation in FML structures, specifically joints. Validation has been done using a time and cost effective NDI technique, the CVM™ (Comparative Vacuum Monitoring™) technique. The validation shows that considering the complexity of load transfer and bending in mechanically fastened joints and the large number of parameters influencing fatigue crack initiation in joints, relative accurate predictions can be made. Crack propagation test results on FML joints show that the available methodology for predicting crack propagation rates is too conservative and needs improvements.*

1 INTRODUCTION

Civil airworthiness requirements (FAR/CS 23&25) require for almost the complete aircraft a damage tolerance design philosophy. Application of Fibre Metal Laminates (FML's) is of great value to make structures damage tolerant because the material shows intrinsic slow crack growth behaviour. How well this works and what the typical Fatigue and Damage Tolerance issues related with FML's are is already discussed in earlier papers by Alderliesten, Homan[1] and others[2,3,4].

A key issue in the design of pressurized aircraft fuselages are riveted longitudinal lap joints and circumferential butt joints. Each fastener hole acts as a stress raiser and there are thousands of them in an aircraft fuselage. Very often cracks start at approximately the same time at different holes, which will lead to a Multiple Site Damage (MSD) situation. The presence of a large number of relatively small cracks will reduce the residual strength of a joint considerably, much more than a single small crack will do, and even more than one large crack with the same accumulated size of the small cracks. Furthermore, interaction between different cracks often leads to an increased crack growth rate. The consequence of this

behaviour is either a low allowable design stress level or a small inspection interval.

This paper will discuss in more detail the Fatigue & Damage Tolerance (F&DT) behaviour and prediction methods for mechanically fastened joints in GLARE fuselage panels as applied by Airbus[5] for the A380 aircraft (GLARE is the FML family member that is being applied on the Airbus A380 aircraft) The approach for the F&DT analysis for joints in GLARE will be discussed, including Multiple Site Damage (MSD). The analysis and prediction methods are substantiated and validated by experiments.

2 FATIGUE & DAMAGE TOLERANCE ANALYSIS FOR JOINTS IN AIRCRAFT FUSELAGES

Crack propagation in GLARE is a very slow process. That implies that when using GLARE it is possible to select a relatively large allowable design stress level and still find an ultimate load life sufficient large to avoid (small) inspection intervals, even though relatively early crack initiation[6]. This ultimate load life can be well beyond the Design Service Goal of an aircraft. With this in mind it becomes attractive to design a joint such that it will be capable to sustain ultimate load during its complete design life. In that case, minimum values (so-called B-values) instead of typical values must be used to prove ultimate strength capabilities. Figure 1 gives an impression of initiation, crack propagation and residual strength for such a case.

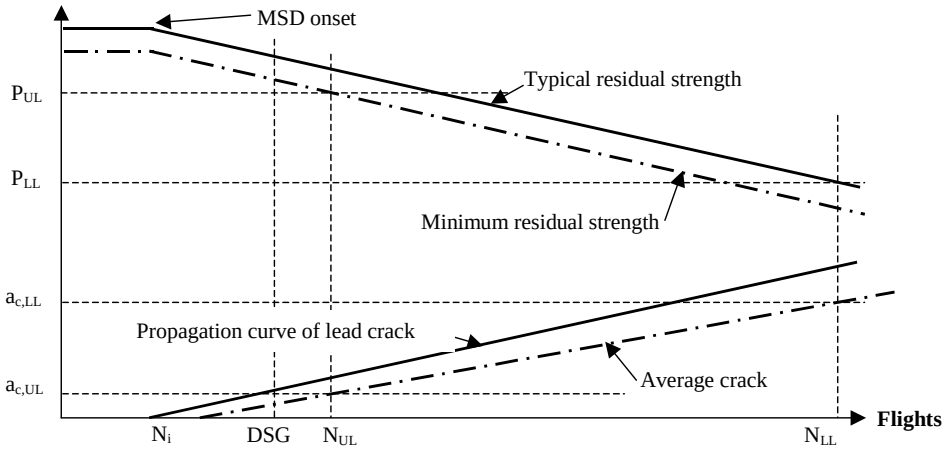

Figure 1: Initiation, crack propagation and residual strength behaviour of a joint with MSD in GLARE.

Certification of riveted joints in GLARE requires a damage tolerance analysis of these joints. Methods for establishing the initiation life of a joint are based on available methods for joints in monolithic aluminium[7] and extended for Fibre Metal Laminates[8]. Multiple Site Damage (MSD) is accounted for by applying stochastic approaches (Monte Carlo simulations) for crack initiation. The method for the prediction of the crack growth rates is explained in section 3 of this paper.

The crack propagation method is based on a through the thickness crack distribution as

shown in figure 2. Each layer is treated as a surface layer, discarding the above layers with the longer cracks. Crack propagation per layer is predicted using methods[9,10] for crack growth of surface cracks

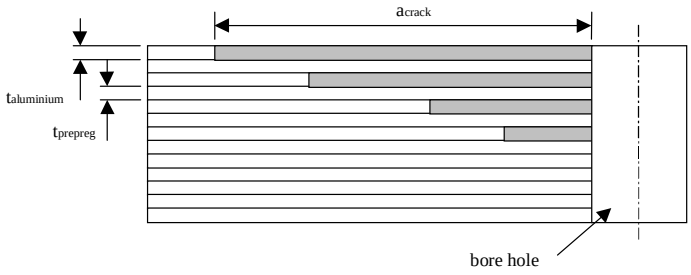

Figure 2: Through the thickness crack distribution in a GLARE joint.

The prediction of the residual strength is based on the method proposed by Müller[11] and extended by De Rijck[12].

As long as ultimate loads can be sustained no inspection is required. Since cracks are not visible from the outside of a joint, this can be a very pleasant side effect.

3 EXPERIMENTS

3.1 Comparative Vacuum Measuring (CVM™) Technique

In mechanically fastened joints, fatigue cracks normally initiated at the mating, non-visible, side of the fastened components (see figure 3). Therefore, non-destructive inspection (NDI) techniques are usually used to detect fatigue cracks. Due to the laminated composite built up of FML, the minimum detectable crack length in FMLs with conventional NDI techniques, without disassembling the joint, is significantly larger than for joints built up of monolithic components. For this reason, an alternative crack detection system was developed to detect fatigue cracks initiating from bore holes in joints, so called Comparative Vacuum Monitoring™ (CVM™) technique[13]. The basic principle of this measuring system is schematically shown in figure 4.

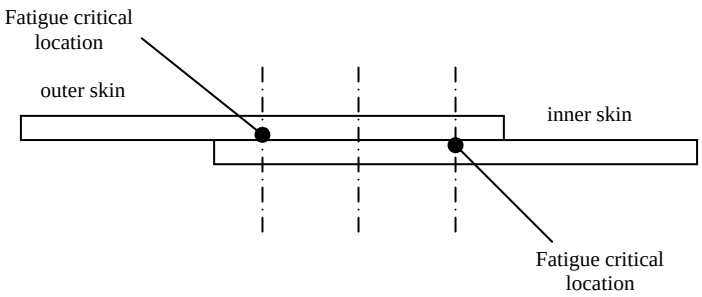

Figure 3: Schematic representation of a joint including the position of the potential fatigue critical locations.

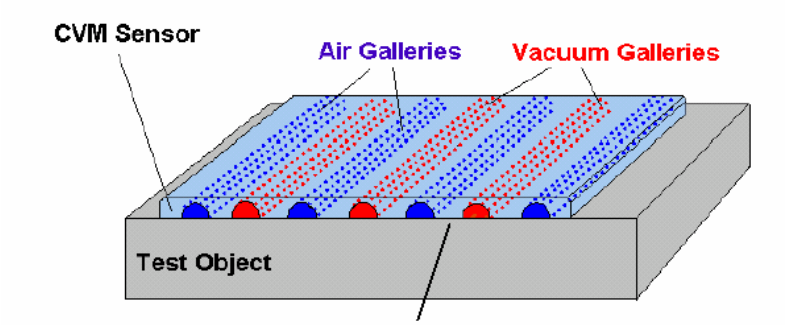

Figure 4: Schematic representation of CVM™ concept.

3.2 Obtaining Fatigue CI and CP test results.

CVM foils were used to find fatigue cracks in FML joints with different geometric configuration. Figure 5 shows an example of a fatigue-cracking scenario after detection of fatigue crack initiation with CVM™ foils.

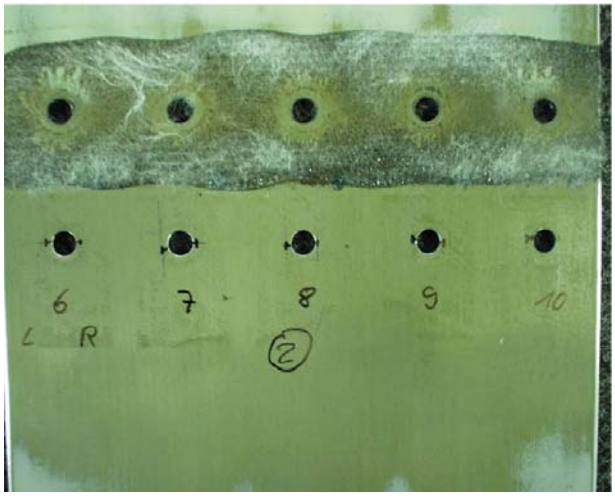

Figure 5: Example of a fatigue cracking scenario

The used foils are able to detect fatigue cracks with a minimum length of the crack from the bore hole of approximately 1.5 mm. However, the fatigue crack initiation point in FMLs is often defined as the number of cycles or flights until a crack of 1.0 mm is reached. To back-calculate the point of fatigue crack initiation from test results coming from the test results scenarios as described in figure 5, appropriate fatigue crack propagation rates can be used. In order to use accurate and relevant crack propagation results, preferably, crack propagation rates should be used coming from the same test specimen and the same fatigue crack initiation site. Therefore, fatigue testing is often continued for a defined number of cycles after re-assembling of the specimen. With a second measurement of fatigue crack lengths, the crack propagation rates can be determined, using the fact that fatigue cracks in FML joint propagate at a constant rate[4]. An additional third crack length measurement is often made to cover

scatter in crack initiation and crack propagation rates. The above-described principle is schematically shown in figure 6.

3.3 Description of test specimens and test.

Within the scope of this paper, only test and analysis results for single lap joint, three fastener row specimens have been used (see figure 7). Table 1 gives an overview of the tested and analysed specimens, i.e. one full GLARE joints and two hybrid Aluminium/GLARE joints. The detailed geometry and dimension of the specimens are not defined within this paper, as this is not relevant for the comparison between test and analysis.

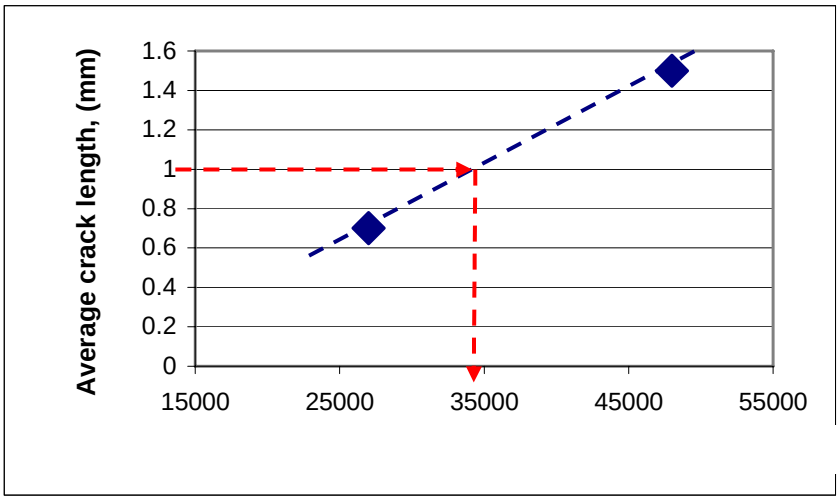

Figure 6: Schematic representation of determination of crack initiation life.

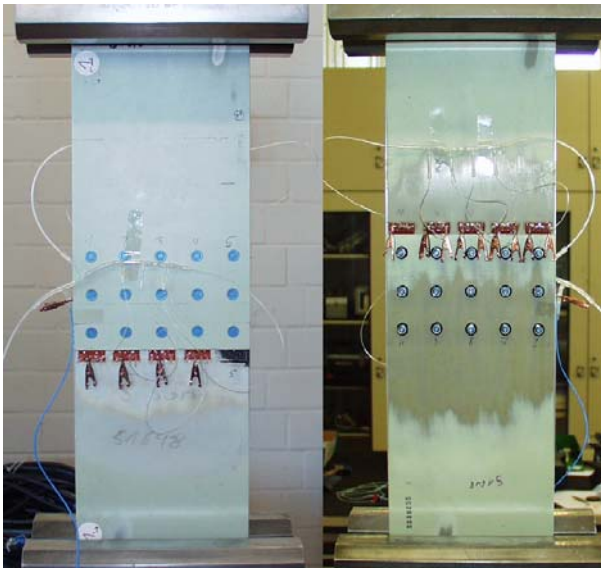

Figure 7: Test set-up for single lap joint testing including application locations of CVM™ foils

Table 1: Overview of specimen configurations and definition of specimen series name.

Joint group	Joint type	Number of holes	Sheet material	Fastener type
EK43-51648	Lap joint	10	GLARE 3-5/4-0.4 SSC	Hi-Lite ASN A2026T3A
EK43-51658	Lap joint	10	GLARE 3-4/3-0.4 + Al 6013T3	EN6101KE7
EK43-51659	Lap joint	10	GLARE 3-7/6-0.4 + Al 2524T3	Hi-Lite ASN A2026T3A

A number of 10 specimens were used per configuration to establish a crack initiation curve and to determine crack propagation rates at different applied stress levels. The specimens were all loaded under constant amplitude loading, at a test frequency of 10-12 Hz and under room temperature environmental conditions. The applied stress ratio was 0.1.

CVM™ was used for the detection of fatigue cracks at the critical fastener rows. The actual length of detected fatigue cracks was measured using an eddy current probe.

4 TEST RESULTS AND METHOD VALIDATION

4.1 Crack Initiation

The point of crack initiation for a fastener row in a joint is defined as the average number of cycles until fatigue cracks that initiate at the fatigue critical fastener hole have propagated to a length of 1.0 mm from the bore hole. For the crack initiation and crack propagation analysis of GLARE mechanically fastened joints, the FML Fatigue and Damage Tolerance (F&DT) toolbox analysis tool[5], version 1.80, was used.

Figure 8 to 10 show the comparison of the analysed test results and the crack initiation predictions (see also table 1 for name of configuration).

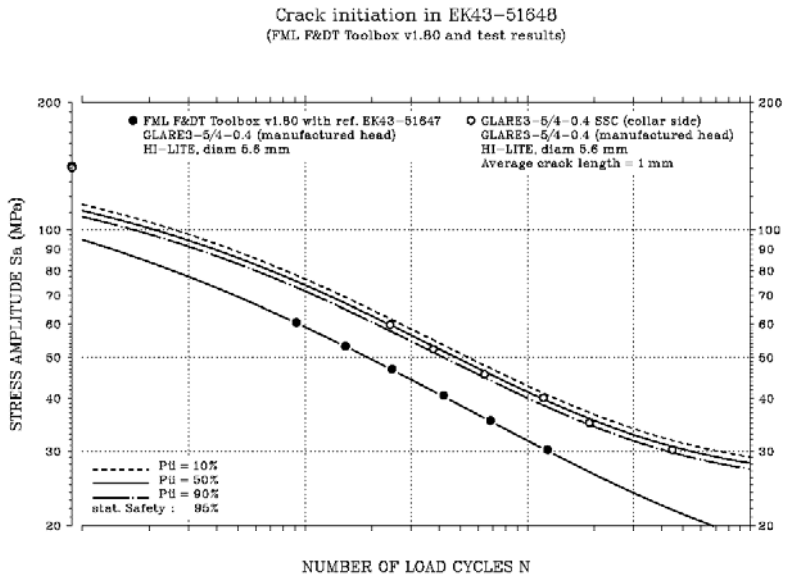

Figure 8: EK43-51648 FML F&DT Toolbox CI calculations compared to test results.

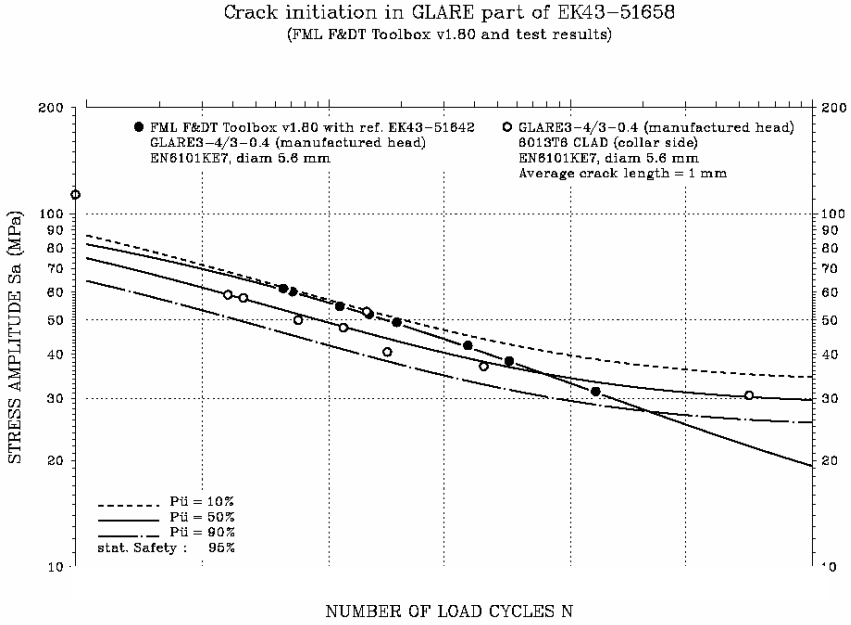

Figure 9: EK43-51658 FML F&DT Toolbox CI calculations compared to test results.

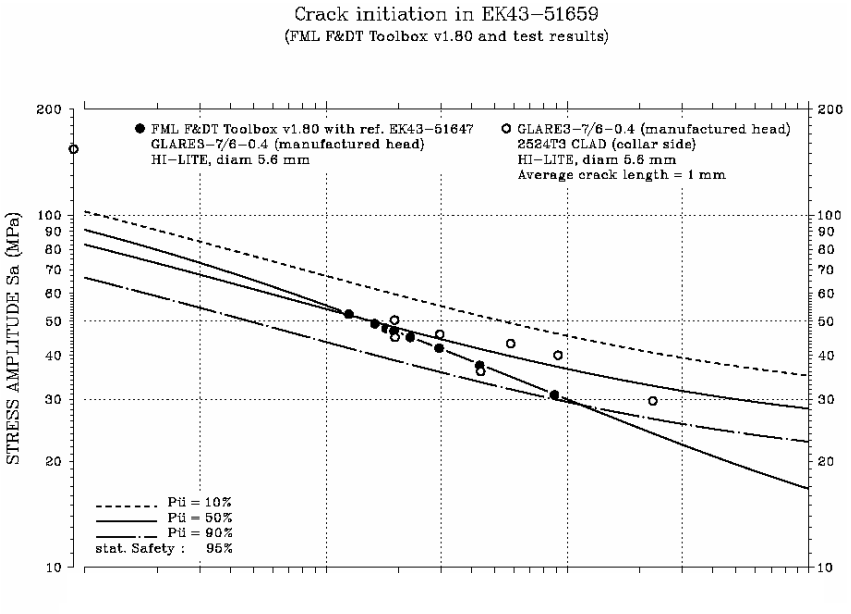

Figure 10: EK43-51659 FML F&DT Toolbox CI calculations compared to test results.

For the tested and analysed hybrid FML/Aluminium joints configurations, FML F&DT Toolbox crack initiation predictions are in good agreement with test results. For the full GLARE fastened joints, the crack initiation predictions are rather conservative compared to the test results.

4.2 Crack Propagation

The test results derived with the approach described in paragraph 3.2 were compared with the predictions made with the FML Fatigue and Damage Tolerance (F&DT) toolbox analysis tool, version 1.80. For the determination of the crack propagation rate, the average measured crack length at the critical fastener rows was used.

Figure 11 to 13 show the comparison of the analysed test results and the crack propagation rate predictions (see also table 1 for name of configuration).

For the tested configurations, the CP rate results achieved with the help of F&DT Toolbox[5] calculations are significantly conservative in comparison with test results. The conservatism ranges from a factor 2 to 6.

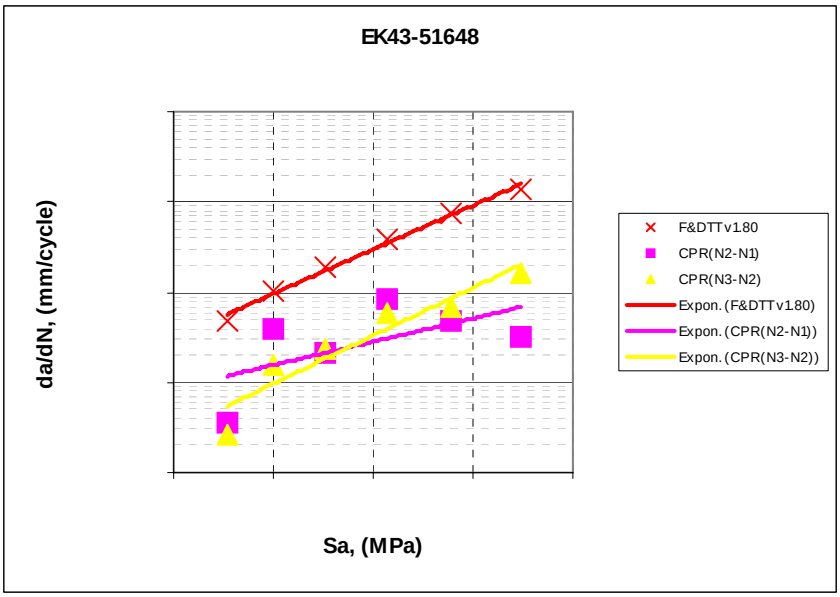

Figure 11: EK43-51648 FML F&DT Toolbox CP calculations compared to test results.

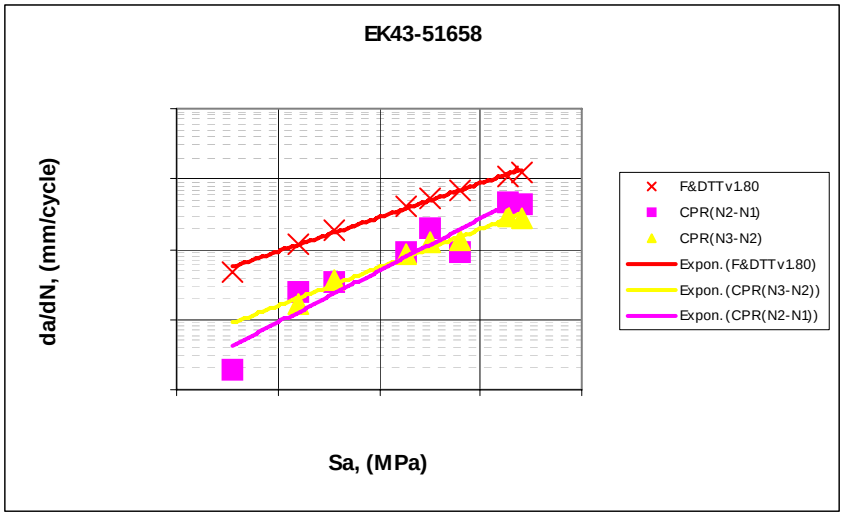

Figure 12: EK43-51658 FML F&DT Toolbox CI calculations compared to test results.

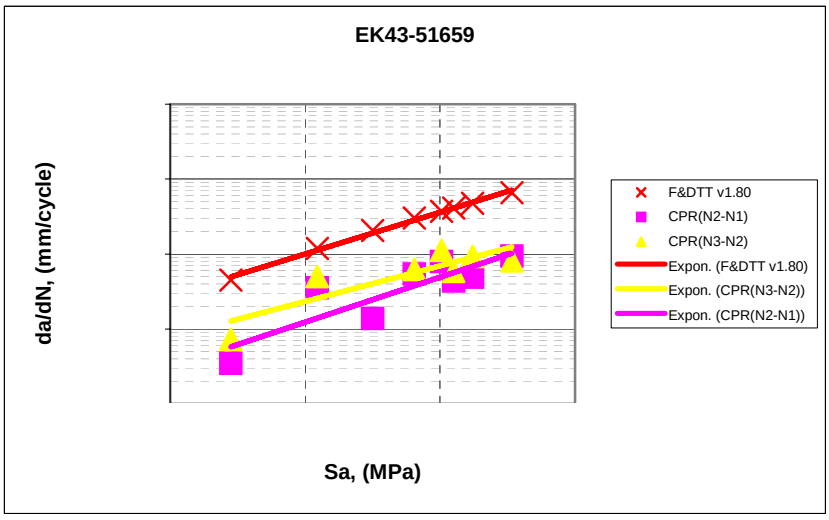

Figure 13: EK43-51648 FML F&DT Toolbox CP calculations compared to test results.

5 CONCLUSIONS

Test results derived with the support of the mentioned NDI techniques, were compared with the available crack initiation and crack propagation methodology, using the FML Fatigue and Damage Tolerance (F&DT) toolbox, version 1.80 as a tool. Summarising:

– The comparisons show that considering the complexity of load transfer and bending in

mechanically fastened joints and the large number of parameters influencing fatigue crack initiation in joints, relative accurate predictions can be made.

- Crack propagation test results on GLARE joints show that the available methodology for predicting crack propagation rates is too conservative and needs improvements.

Although the comparisons show adequate qualitative results, different joint configurations need to be analysed also, as well as joints on a more structural component level.

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