FATIGUE ASSESSEMENT OF WELDED BICYCLE FRAMES

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Abstract This paper presents the methodology developed by Decathlon, through its MKniX Engineering Center, to assess the fatigue behaviour of welded aluminium-alloy bicycle frame. The objective is to predict the reliability of the bicycle frame faced to the complex fatigue loading and therefore to optimize the design before the standardized testing. The fatigue assessment method is based on the usage of a unique S-N design curve whatever the geometry of the welded structure and the loading mode. The design stress is defined with a linear elastic finite element analysis using a specific meshing methodology and the application of the Dang Van criterion.

1 INTRODUCTION

Each bicycle frame has to face standardized fatigue testing covered by the normative context (European standard EN14764, EN14766, and EN14781). These tests take a long time to be realized and need a lot of physical prototypes. For years, in addition of classical finite element analysis, the frame fatigue design has been assessed by experience. Numerous physical prototypes were tests to optimize the product regarding the results of the fatigue testing. This iterative experimental method was time consuming and costly.
To optimize the time to market and reduce the design cost, the objective is that each frame will pass the standard tests at the first time. In addition, to guarantee the high level quality of our products, the fatigue reliability has to be mastered precisely by an appropriate statistical process control. Therefore a numerical fatigue and reliability assessment method was implemented to optimize the frame design and to reduce the time to market.
With very severe fatigue tests, fatigue failures always occur at the weld toes and classical weld fatigue analysis do not allow predicting correctly the fatigue strength of the structure, so we introduce the Dang Van criterion and a specific meshing methodology to assess the fatigue behaviour of our bicycle frames.

2 WELDED STRUCTURE AND STRESS CALCULATION

A typical frame is made of welded thin wall tubes. The geometries of welded areas are quite complex, especially in the bottom bracket area (see figure 1). These two facts limit the application of classical weld fatigue analysis like presented in literature.
The nominal stress approach, as for example in Eurocode 9 [1], concerns classify standard welded joint with a fatigue curve for each joints. Our joint may be different on each frames, thus it is not applicable.
The geometric stress approach, as presented in API rules [2] or in IIW [3] is not well applicable for thin shell structure. Indeed, aluminium tubes used for frames have a general thickness between 1.4mm and 1.8mm with small cross section. For the same reason, the local approach presented in IIW [3] is also not applicable as it will lead to a very small and complicated meshing for an everyday industrial application.

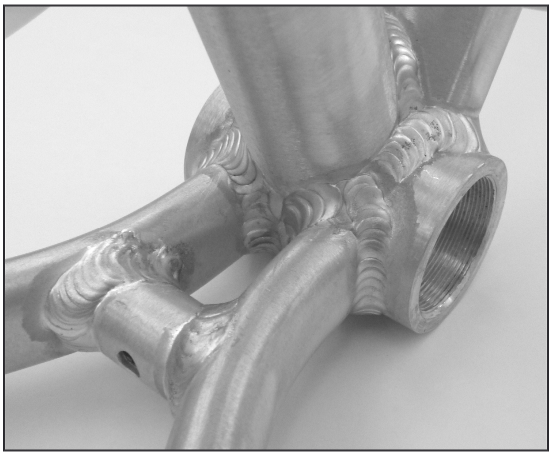

Figure 1. Typical aluminium welded frame – Bottom bracket area

In addition, finite element analysis shows that actual loading and standardized tests lead to multi-axial stress at critical points in these areas (table 1). This point guides us to the application of a multiaxial fatigue criterion.

	σxx (MPa)	σyy (MPa)	σzz (MPa)	σxy (MPa)	σxz (MPa)	σyz (MPa)
load step 1	61	36,5	4	-13	4,6	-4,8
load step 2	-20,5	-15	-28,5	26,5	29,5	-31,5

Table 1. Example of multiaxial Stress at critical points

The variety of welded areas leads us to choose the method develop by J-L. Fayard [4, 5] which has the advantage to use a unique S-N design curve whatever the geometry of the welded structure and the loading mode. This method is by the way used by different industrial applications [6, 7]. Moreover, for bicycle frames the welds are mainly handmade and there is a variety of weld size. This method fits perfectly to this context as it has the advantage to take in account the weld size thanks to a specific meshing rule.

3 DANG VAN FATIGUE CRITERION

The Dang Van criterion is preferred due to its efficiency in multiaxial fatigue context. The Dang Van criterion is moreover easy to characterize with only two parameters accessible with simple fatigue tests. Furthermore, it is programmable for every finite element codes and so its implementation perfectly fits to our finite element analysis software Ansys Workbench. Thus it is usable by designers who are not fatigue experts.
This fatigue criterion described in [5] is based on the ability to represent microscopic phenomenon, that pilot fatigue failure, by using macroscopic values calculated in design office through finite element calculation.
It is defined by a τ – p diagram (τ, shear amplitude and p, Hydrostatic pressure). The fatigue strength is represented in this diagram with a straight line defined by:

$$\tau = -\alpha.p + B \qquad (1)$$

where α and B are material parameters. Those parameters are defined from fatigue tests results (described below in 4.3) with two loading conditions, pure bending and pure torsion for example.
The cyclic stress path in critical areas of the structure is determined by calculating τ(t) and p(t) at each loading step. τ(cycle) is the local shear amplitude for a given material plane and it require the determination of the plane on which the set (τ(cycle), p(t)) is a maximum for a load fatigue cycle. This is done by identifying on each shear plane, the smallest circle circumscribe to the shear path.
The stress path is compared to the fatigue design line to determine the capacity of the structure to be safe or not.

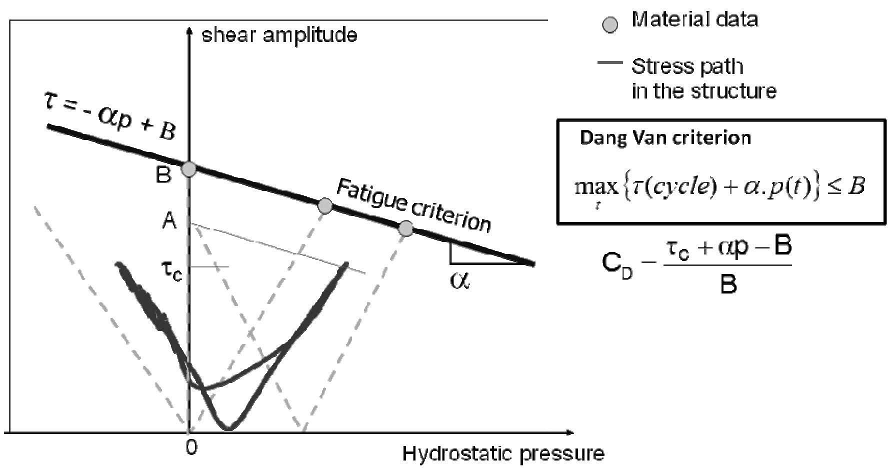

Figure 2. Dang Van diagram

The fatigue criterion can be written as following:

$$\max_t \{\tau(cycle) + \alpha.p(t)\} \le B \qquad (2)$$

In practice, a "danger" coefficient, C_D is introduced,

$$C_D = 1/B.\ (\tau_c - \alpha p - B)$$

B is the origin ordinate of the Design line

τ_c is the projection of the maximum of the stress path for a cycle.

if C_D >0, the failure risk is higher than the target reliability, the design is rejected.

if C_D=0, the design is optimize with regards to the target reliability.

if C_D <0, the failure risk is lower than the target reliability, the design is accepted, but it can be still optimized.

The next paragraph give an illustration of the C_D colour map of the fatigue analysis results and the Dang Van diagram for the worst elements on each welding line (see 4.4 Application to an aluminium bicycle frame).

4 FATIGUE ASSESSEMENT

4.1 Structural approach

In welded structures, when the industrial welding process is mastered to avoid a root failure, failures always occur at the weld toes. So the main concern is to find a solution to determine the damage in weld toes areas where cracks initiate on geometrical imperfection and lead to failure. In these highly damaged areas, local strains are not small and the material is not perfectly homogenous, so the mechanical behaviour in this zone is not accessible by the usual mechanics of solids. It is possible to determine an asymptotic solution at the periphery of this critical zone. This asymptotic solution is defined by a linear homogenous and isotropic elasticity in small strains calculation. This asymptotic value at the periphery of the critical zone enables to control and interpret correctly the fatigue damage in the critical zone (see [4]).

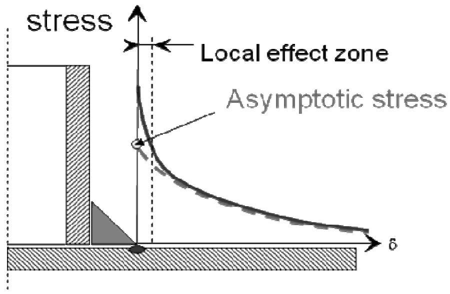

Figure 3. Asymptotic solution

As the asymptotic stress is in highly stressed zones with a sharp gradient, the calculation result will significantly depend on the modelling of the weld. Thus we apply a specific meshing methodology that takes into account the weld influence (local rigidity and size). Then we are able to determine the asymptotic design stress from a finite element calculation for every welded joint.

The method described above is very convenient as it uses the stress and strain analyse from a simple structural calculation. This is more accessible for an everyday engineer application than fracture mechanics or local approach.

4.2 Computing procedure

The computing procedure was adapted for Ansys from the one developed by J.L. Fayard [4] which is based on midsurface thin shell modeling and Rigid Body Element specific to Nastran (RBE2). The stress flow is going from one sheet to the other through the weld. This is represented by the RBE2 which links the two shells by the middle of the weld side (figure 4).

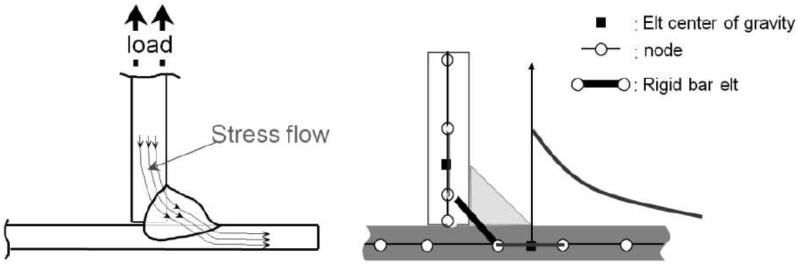

Figure 4. Modelling method

Thus, the design stress is calculated at the gravity centre of the element at top face without node interpolation. Therefore, the meshing and so the design stress is directly depending on the shell thickness and the fusion penetration length (see figure 5).

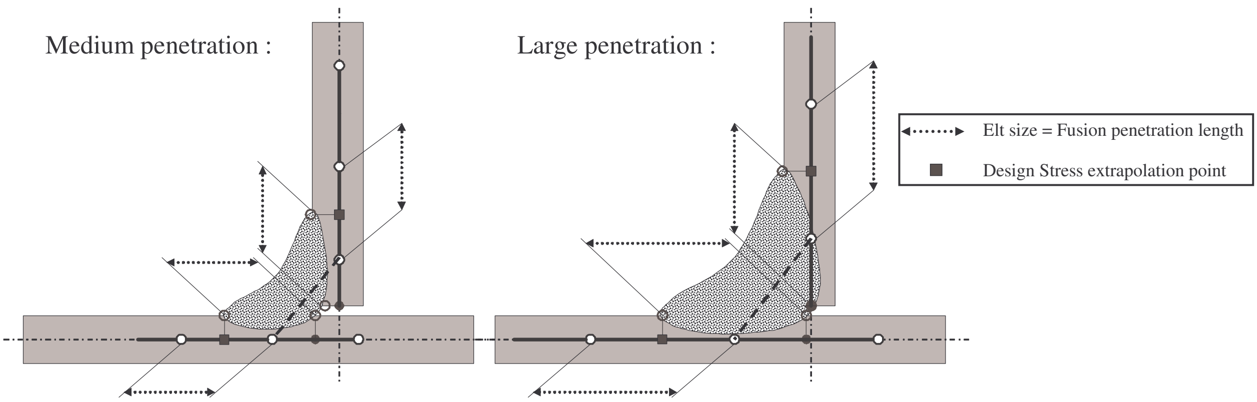

Figure 5. Effect of the fusion penetration length on the meshing

In order to validate this methodology to our frame, we measure with strain gauge chain the real stress gradient near the welding toe in critical areas. We compare these measurements to a 3D modelling and to the shell modelling.

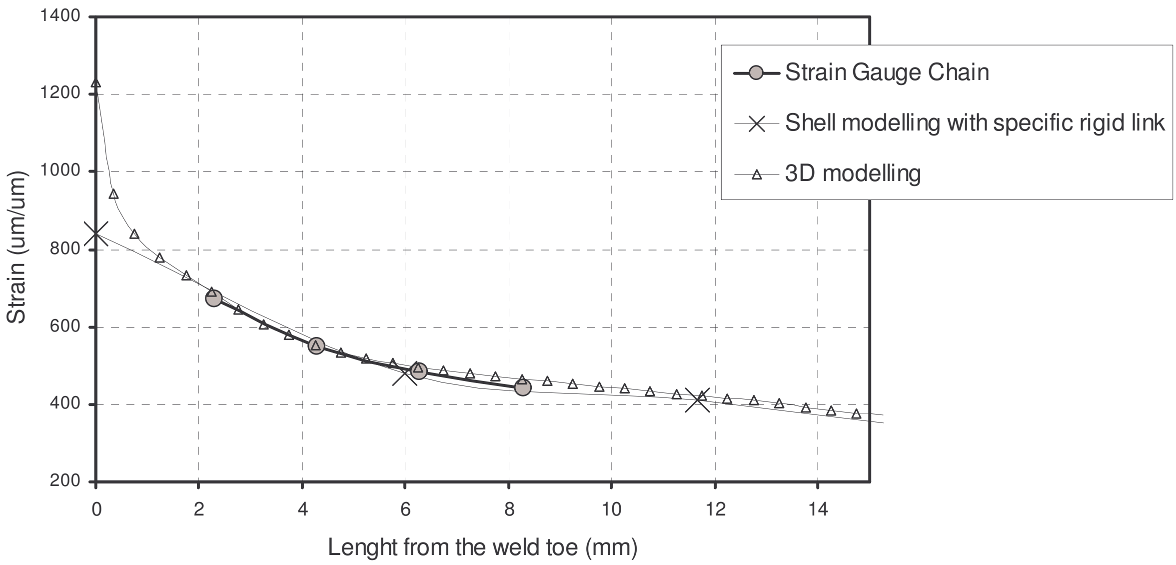

Figure 6. Comparison of the stress gradient between modelling and measurement

As shown in figure 6, this specific meshing method fits to our framework and gives accurate results.

As results, a new modelling methodology has been defined for our frame. It is the designer who is in charge of drawing the welding lines depending on its welding specification and on the welding areas. For the meshing, the automatic Ansys workbench meshing tool is used with some size adaptation to fit to the geometry and an in-house routine automatically places the rigid elements between the welding lines. Figure 7 shows a meshing application on the bottom bracket area

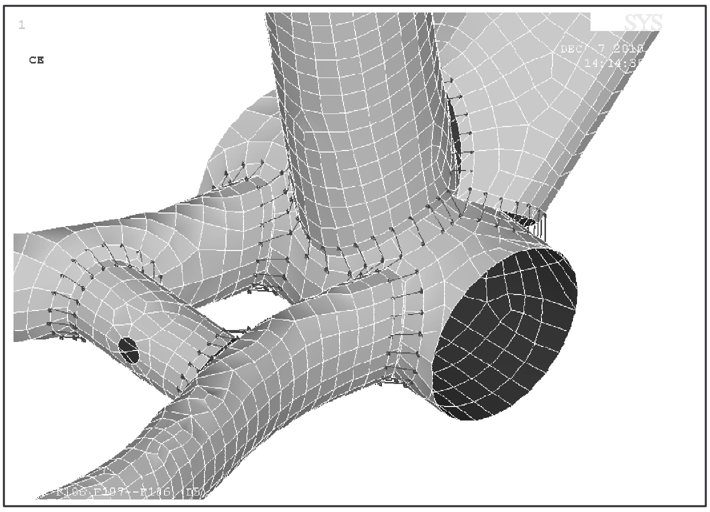

Figure 7. Meshing application on the bottom bracket area

4.3 Fatigue assessment

The unique S-N curve was defined using fatigue tests on an elementary welded tubular T joint (figure 8). The specimens were welded in a real production way to be representative of the bicycle frame. Fatigue tests with two loading conditions (pure bending, pure torsion) have been done to establish the Dang Van criterion for different number of cycles to failure (figure 9). From these curves an S-N representation (figure 10) is possible taking the Design Stress S as τ_c-αp.

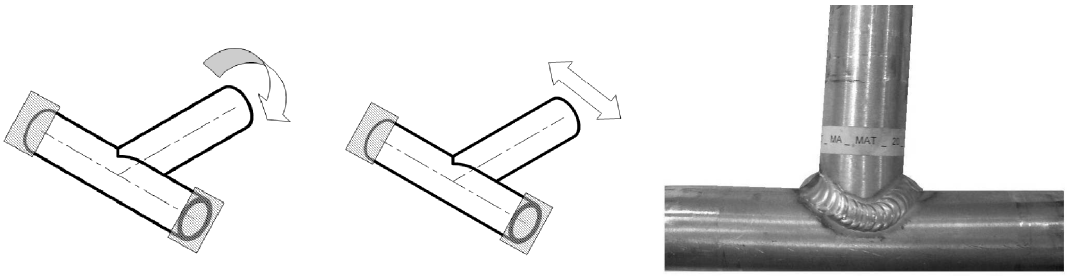

Figure 8. Elementary welded tubular T joint

The boundary conditions of our elementary welded tubular T joint have been correlated through multiple strain gauge and strain gauge chain measurement. This point is very important as our unique SN curve and the fatigue criterion derived from these tests results.

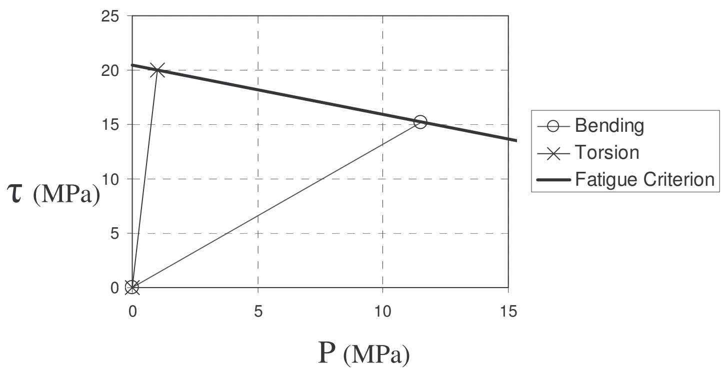

Figure 9. Dang Van diagram for bending and torsion test

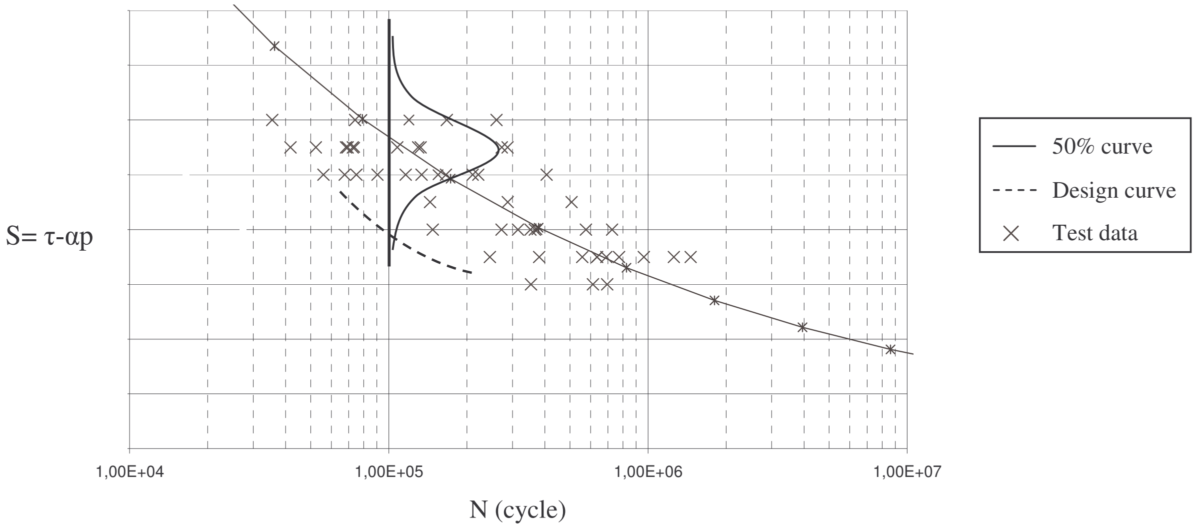

Figure 10. SN curve defined by tests

The unique S-N curve defined through elementary welded tubular joint was also confirmed by a posteriori analysis that integrates multiple old frame fatigue results. This allows completing our results and confirms that the use of a unique elementary welded tubular joint is enough and correct.

Frames normative fatigue tests have to pass 50.000 cycles or 100.000 cycles depending on the standard. As a result, we have defined two Dang Van fatigue Design lines, one for 50.000 cycles and one for 100.000 cycles. Those Design lines are defined for a given a level of reliability. These design lines can be adapted, depending on the supplier, on the quality policy and so on.

4.4 Application to an aluminium bicycle frame

Before any application of the fatigue assessment method, all our standard fatigue tests were correlated to ensure the accuracy of our modelling. An extensive welding fusion length measurement campaign has been done to verify that our welding specification and so the fusion length used for calculation is in accordance with the reality.

To test the numerical fatigue assessment approach, the method was applied through a simulation of a pedalling standard fatigue test. A display mapping of the Dang Van "danger" coefficient is shown figure 11. The elements appear in red if the failure risk is higher than what is required for the target of reliability.

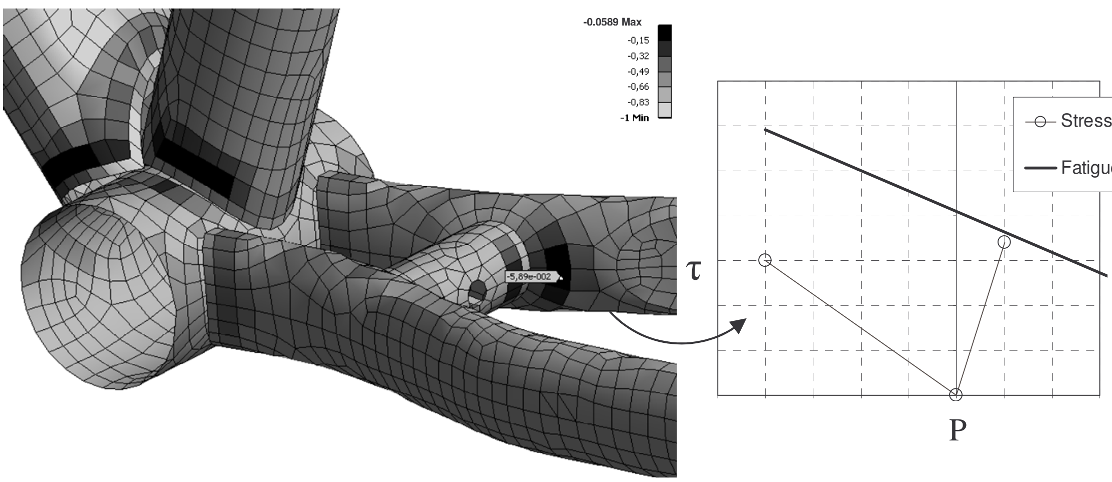

Figure 11. Results on a pedalling fatigue test – Bottom bracket area

On this example, there is no dangerous zone as all elements are below the Fatigue Design line. Nevertheless, the calculation shows us where the maximum stressed areas are and gives us the associated fatigue diagram.

This frame passes the standard test as calculated. Nevertheless it has been decided to push some tests until failure.

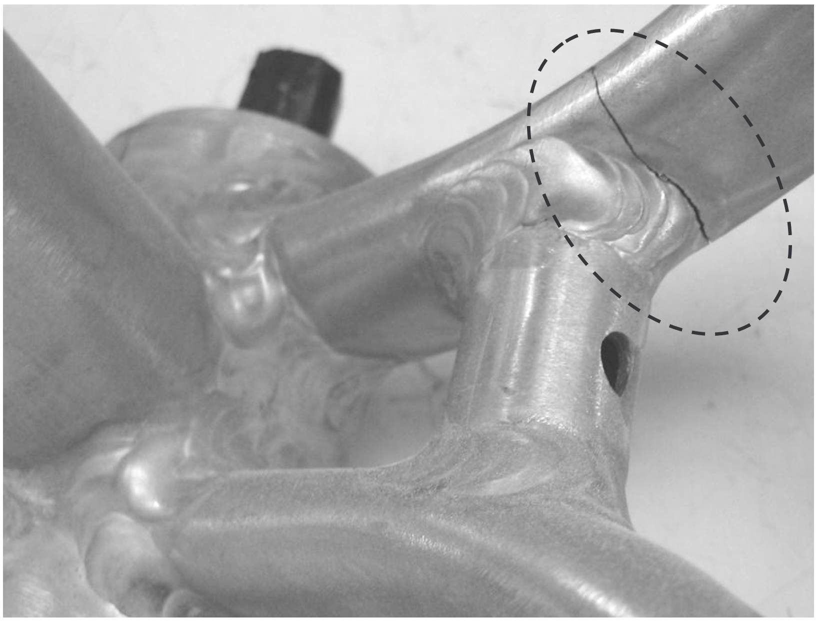

Figure 12. Fatigue crack location with pedalling test continued to failure

The failure mode during the pedalling test is at the area predicted by calculation. This has been done for numerous different new bicycle frames, and also on old frames that did not pass the new standard tests. The results were always in accordance to the reality by giving the right failure area, and so for every normative test.

5 CONCLUSION

The methodology presented above has been validated on bicycle frames and the fatigue strength prediction is excellent with regards to the standardized tests. The use of the Dang Van fatigue criterion confirms to be well adapted for the multiaxial stress in critical area of bicycle frames, and it is easy to characterize with simple fatigue tests. The automatic meshing developed was proven to be accurate for an industrial application. As it is dependent on fusion penetration length, it gives a powerful tool to link design and process.
The methodology is now included in the reliability assessment procedure at Decathlon. Design and validation of frames is now realized in one-shoot and it has a huge influence on the product quality, on the time to market and on the design cost.

6 REFERENCES:

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