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A reanalysis of the fatigue strength of steel plates with holes, for application of the notch stress approach

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1. Summary

The fatigue strength of steel plates with holes is classified in Eurocode 3 as FAT 90 for the net cross-section nominal stress. This classification is based on 3 sets of results (Mang et al., 1991), (JSSC, 1995), (Valtinat and Huhn, 2003), see (Sedlacek et al., 2003), without any requirements for the quality of the hole edges. Our re-analysis shows this FAT category to be non-conservative and that fatigue strength is highly dependent on the execution quality of the hole. They can be classified into two detail categories, FAT 71 and FAT 90. This reanalysis is made with the aim of characterizing not only the nominal but also the notch resistance of this detail to be used in local approaches such as the "effective notch stress method" or the "hot spot method".

2. Review of experimental results in literature

The experimental results collected from literature exemplify tests carried out in several leading European and American laboratories from 1960 to 2007. They were carefully selected in order to limit the scope to experiments in typical bridge steels. Only tests with $\Delta\sigma > 1{,}5 f_y$ thus above 1.10^4 cycles were considered, performed in plates under axial loading, and with the method of fabrication and crack path clearly specified. The dataset collected is in this point of view representative of a variety of steel types and working methods, thus suited for an analysis in the scope of Eurocode 3. An overview of the test data considered is given in Table 1 where out of a total of 491 fatigue results, 67 are "run-outs" not considered in our analysis.

Table 1 **Database for fatigue experiments in plates with holes.**

Reference	Steel	Plate width [mm]	Thickness [mm]	Hole diameter [mm]	Fabrication method	No. of tests
Kloeppel and Weihermuller 1960	St52	70	14	17.0	Drilled	38
Gurney 1965	BS 15, BS 968, QT	76	13	3.2	Reamed	31
Haibach 1975	FeE355, FeE460	~58	~12	12.1	Reamed	134
Mang et al. 1991	St37, St52, StE690	80-100	12, 20, 30	20-25	Flame cut, Plasmat	79
JSSC 1995					Drilled	37
Valtinat and Huhn 2003	S235 JR G2	80	10	15.0	Drilled, Punched	57
Sanchez et al. 2004	S355N, S460Q, S690Q	45	15	15.0	Drilled, Punched	34
Bergers et al. 2006	S460MC, S960QL, S1100QL	500	10	100.0	Plasma cut	9
Bennet et al. 2007	HPS-485W (70 W)	76	15, 19, 22, 25	24, 27, 30, 32	Drilled, Punched	30
Brown et al. 2007	A36, A572, A588	152	12.7-25.4	17.5-23.8	Reamed, Drilled, Punched	43

2.1. The Data set

Kloppel (Klöppel, K., Weihermüller 1960) performed tests in plates with drilled holes at 4 different stress ratios (R) and showed a strong dependence on that parameter. The regression analysis shows an m-slope close to 5 which indicates the presence of a significant life in initiation.

Gurney (Gurney 1965) carried out fatigue tests on mild and high strength structural steel plates with a hole drilled and reamed. A remarkable dependence on steel type was observed with an m-slope also close to 5.

In (Haibach 1975) fatigue tests were reported on plates with drilled and reamed holes. Some dependence on R-ratio was observed but not on steel type.

Results presented in (Mang et al. 1991) refer to holes made by flame or plasma cut. Each plate had 3 holes spaced longitudinally at 150 mm. Plate thickness of 12, 20 and 30 mm were investigated not showing any pronounced size effect. No effect was found for the steel quality (ST 37, ST 52 and St E690) which indicates that initiation life is small due to plasma and flame cut rugosity. Regression analysis shows m-slopes close to 3 indicating that the fatigue life is fully propagation. A reduction of 30% in fatigue strength is reported between flame cut and drilling, mainly because absence of drag lines and to the different hardness values.

The results presented by the Japanese Society of Steel Construction (JSSC 1995) are included in the background from Eurocode 3 but no information is available regarding specimen dimension or steel type. For the re-analysis presented in this paper, these results are only included in the nominal stress analysis and not in the notch stress.

Tests on galvanized plates with punched or drilled holes of 15mm are presented in (Valtinat & Huhn 2003). Tests on punched holes revealed that the cracks started at the edge where the punch goes in, propagating as a corner crack until the crack reached the edge on the opposite surface. This represented almost the entire life. Then the propagation as an edge crack (trough thickness) was very fast. The specimens with drilled holes showed cracks mainly initiated in the mid thickness of the plate, propagating as a semi-elliptical crack. The results for punched holes show a poorer fatigue performance than the drilled ones. The authors further conclude that galvanizing has also a negative effect on the fatigue resistance.

Tests on plates with punched or drilled holes are reported in (Sánchez et al. 2004). Again punched hole specimens were shown to have much lower fatigue life than the drilled ones. Punched holes behave with m-slope around 3 while drilled ones with an m-slope around 5. The fatigue crack for the punched specimens initiated at the transition point between the shear band and the tearing zones resulting from the punching process.

Fatigue tests in plates with plasma-cut holes were performed in (Bergers et al. 2006). Test were done on steels S 460 MC, S 960 QL, S 1100 QL but no evidence was found with the increase of steel grade. The results plot with an m-slope 3 indicating the predominance of propagation life due to the plasma cut surface defects. All cracks were reported to start in the inner edge of the hole.

Tests with holes done by punching, drilling or reaming are reported in (Bennett et al. 2007). The test with drilled or reamed holes were all stopped around 2 million of cycles and considered run-outs. The fatigue performance of the punched ones was again very poor compared to drilled or reamed.

The results reported in (Brown et al. 2007) in punched and drilled holes are not included in the notch analysis because the hole on the finite width plates was not symmetrical and no clear information about each crack path is given. The fatigue crack for the punched specimens initiated at the transition point between the shear band and the tearing zones resulting from the punching process. The report shows that punched holes have poorer fatigue resistance than drilled ones and that the reduction in fatigue life due to galvanizing was not so evident.

2.2. FAT classification

Holes in plates are classified in Eurocode 3 as FAT 90 for the **net cross-section** nominal stress based on 3 sets of results (JSSC 1995; Valtinat & Huhn 2003; Mang et al. 1991). However the re-analysis shows this FAT category to be non-conservative. Many authors report the results in terms of **gross cross-section** nominal stress, thus the results were converted to the net stress range by:

$$\Delta\sigma_{net} = \Delta\sigma_{gross}\cdot\left(\frac{w}{w-d}\right)$$

where w is the plate width and d is the hole diameter.

The results after this transformation are presented in Figure 1.

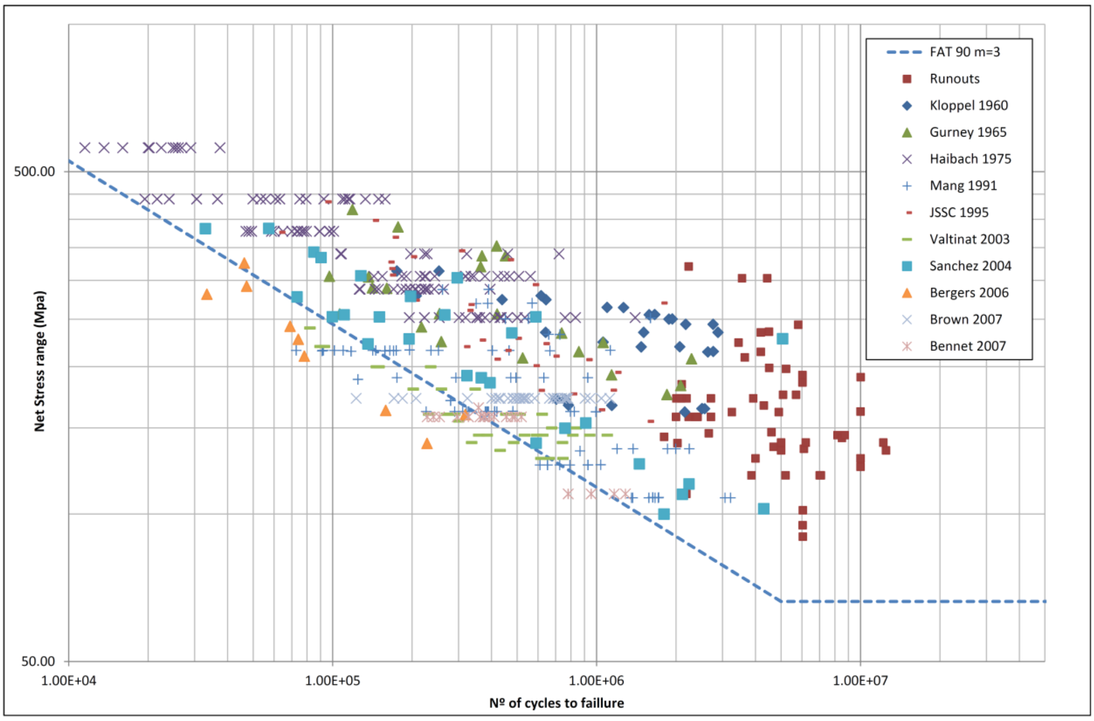

Figure 1 S-N data for plates with holes using nominal net stress.

The re-analysis of the data set shows that the fabrication method of the hole is the most remarkable parameter in plotting the fatigue results. Two different groups of holes were identified based on the rugosity profile Rz5. This parameter is obtained from the roughness profile height distribution (z) recorded over a length (L) and represents the ten-point roughness, average height from the five highest peaks and five lowest valleys over a given length (EN 9013):

$$R_z = \frac{1}{5}\left(\sum_{r=1}^{5}(Z_r)_{max} + \sum_{r=1}^{5}(Z_r)_{min}\right)$$

Thus the regression analysis was performed separating the data set in two quality groups, see Figure 2:

Quality Group 1: Drilled and Reamed holes (Rz5 Range 1) – **FAT90**

(mean FAT 145 with slope 3.03 and characteristic FAT 97 with slope 3)

Quality Group 2: Punched, Flame and Plasma cut holes (Rz5 Range 2) – **FAT71**

(mean FAT 91 with slope 2.62 and characteristic FAT 69 with slope 3)

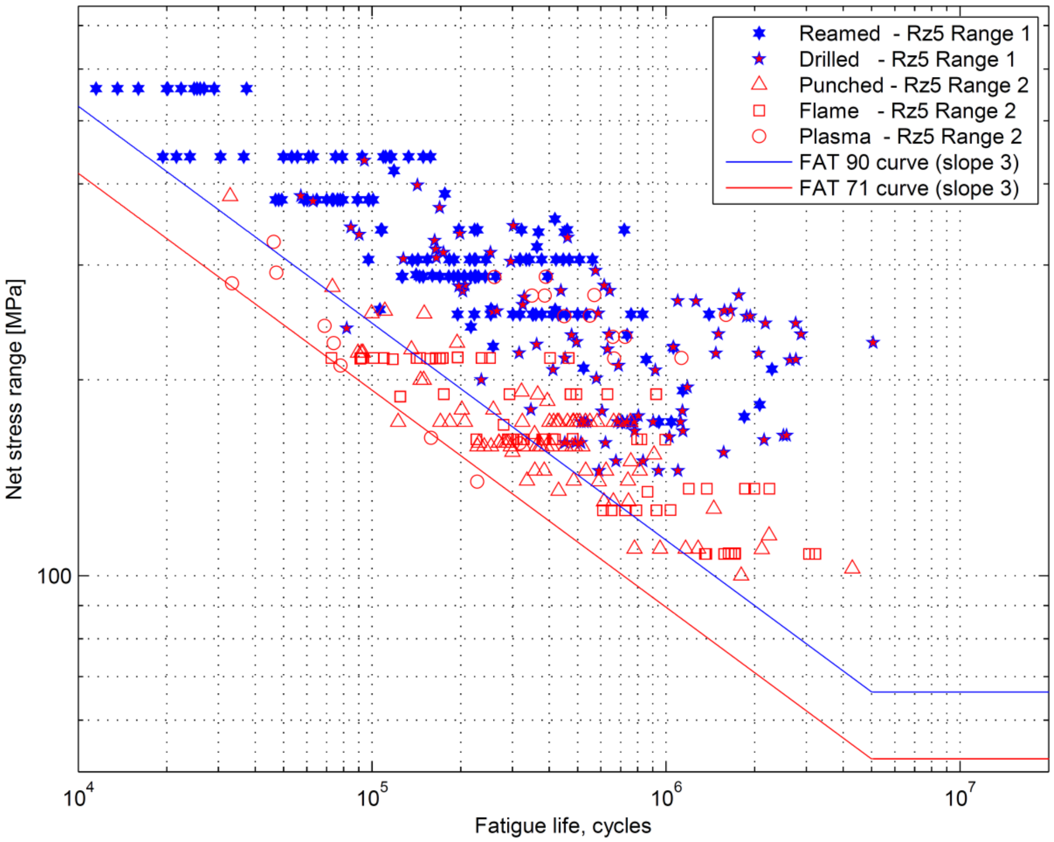

Figure 2 Nominal net stress FAT classification according to fabrication method

According to EN1090, holes may be formed by any process (drilling, punching, laser, plasma or flame cut) requiring the local hardness and quality of the cut surface to be checked. For the Execution Class 4 (EXC4) punching without reaming is not allowed. Local hardness values were measured by (Mang et al. 1991; Valtinat & Huhn 2003) for punched, flame and plasma cut holes for example and they were inside the allowable range (380HV10 for steel up to S460 and 450HV10 for steel up to S690). Also residual stresses were measured but the values close to the hole edge were low. The most important parameter distinguishing the 2 groups is the surface roughness in the hole, which may eliminate the initiation life, and introduce severe notches that act like initial fatigue cracks. The limits of roughness are defined according to the EN1090 for the Execution Class 4 (EXC4) as Range 2 quality for the mean height profile (Rz5) according to EN 9013, which means a maximum value of Rz5=40+(0.8*t[mm]) [microns], which for the maximum plate thickness t=30mm, leads to 64microns. As per the data set, surface quality was classified as Class 1 according to DIN 2310 in plasma cuts (Mang et al. 1991) which for t=12 gives Rz=65 [microns]. We recommend thus that for EXC4 subjected to fatigue loads the Range 1 is adopted Rz5=10+(0.6*t[mm]) [microns].

3. Linear elastic fracture mechanics

The characteristic fatigue curves from that represent the lower bond of the data set results presented in Figure 2 may also be obtained by a linear elastic fracture mechanics calculation, accounting for the initiation life in the Quality Group 1, and only for propagation stage in the case of Quality Group 2. A review of similar models is described in (Radaj et al. 2006) and has been adopted for plates with holes in low cycle fatigue by Sehitoglu 1983 or Pijpers 2011 to several high-strength steel details.

3.1. Stage 1 – Initiation

The resistance of steel to fatigue crack initiation includes nucleation and short crack growth. The initiation life is estimated with a method proposed by (Haibach, 2006) with endurance limit $\Delta\sigma_d$ =0, 45*fu* where *fu* is the tensile strength. Given that the tensile strength is often defined as a range in the data collected, for the specimens where this value is not explicitly defined by the author, we use the steel designation, the yield strength taken from the normative documents and the ultimate strength calculated with the following relation (Pijpers 2011):

The stress concentration factor is given for the net section as:

$$K_{tn} = 2 + 0,284\left(1 - \frac{d}{w}\right) - 0,6\left(1 - \frac{d}{w}\right)^2 + 1,32\left(1 - \frac{d}{w}\right)^3$$

The threshold of the endurance curve is $N_{th} = 10^{N_0}$ and $N_0 = 6{,}4 - \frac{2{,}5}{m}$.

The initiation period is completed when the microcrack growth is no longer dependant on the microstructure or surface conditions, and thus, the crack growth resistance of the material starts to control the crack growth. The size of the microcrack at the transition stage is thus material dependant. We adopted the range 2 limit Rz5=40+(0.8*t[mm]) [microns], which for the maximum plate thickness t=30mm, leads to 64 microns.

The results are presented in Figure 3.

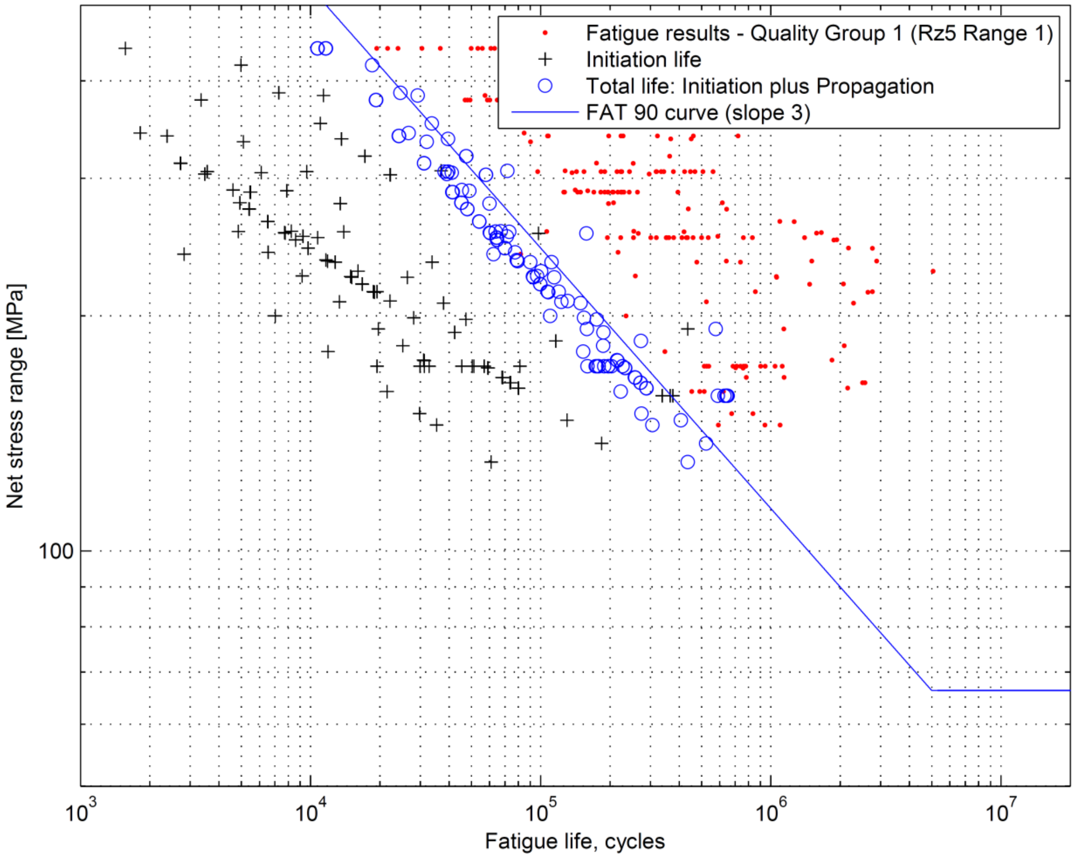

Figure 3 Characteristic fatigue curves obtained considering initiation and fracture mechanics (quality group 1)

3.2. Stage 2 –Propagation

In the propagation stage, Linear Elastic Fracture Mechanics explains the propagation. 2 types of cracks have to be considered to propagate the initial crack to a through-thickness crack. Observation of the failure surfaces of cracked specimens have shown [Mang 1991] that cracks propagate in this stage as corner crack or semi-elliptical cracks. Tests on punched holes revealed that the cracks started at the edge where the punch goes in, propagating as a corner crack until the crack reached the edge on the opposite surface. The specimens with drilled holes showed cracks mainly initiated in the mid-thickness of the plate, propagating as a semi-elliptical crack. In the final propagation stage, a through-thickness edge crack is considered. For modelling the total life, two cases are distinguished:

a) Quality Group 1: Initiation as seen in the previous section, then propagation first as semi-elliptical and final propagation as through-thickness crack;

b) Quality Group 2: No initiation, propagation first as corner crack and final propagation as through-thickness crack.

Bowie's solution is adopted for the stress intensity factor (Broek, 1986): $K = \sigma\sqrt{\pi \cdot a} \cdot f(a/T)$. The function *f(a/T),* where *a* is the crack length and r the hole radius is taken from (Paris and Sih, 1965) and approximated by $f(a/T) = \frac{0{,}65}{(0{,}08+0{,}5a/r)^{0{,}58}} + 0{,}61$. Since characteristic values have been adopted for the Paris law parameters, namely: C =$2\cdot 10^{-13}$ [$mm^{3/2}$/cycle] and m = 3, the estimated lives with fracture mechanics are close to the lower bounds of each of the quality group, curve 90 for quality group 1 and curve 71 for quality group 2. The results are show in figures 3 and 4.

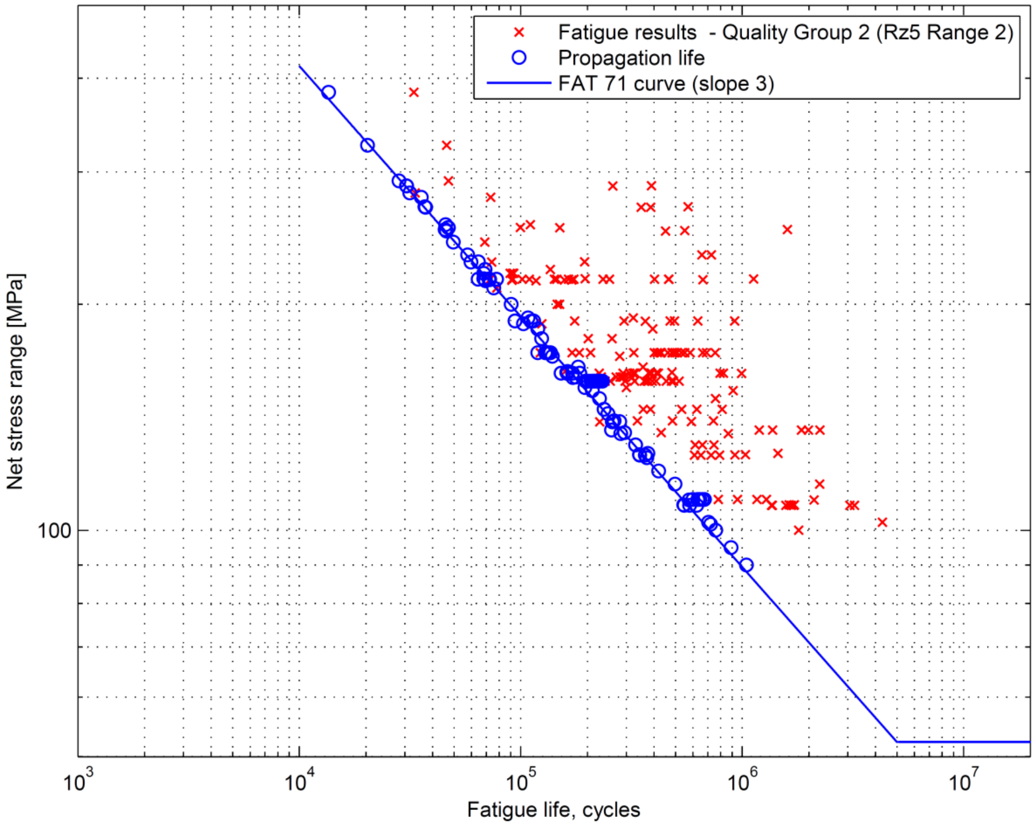

Figure 4 Characteristic fatigue curves obtained with fracture mechanics (quality group 2)

4. The notch fatigue strength

It was also shown that for more complex details, the **net cross-section** nominal stress is not unique, so that a value of stress limit is given to be used in complex analysis coupled with Hot Spot or notch stress analysis.

This may be due to not taking into account the geometric relation between the hole and the plate. For finite width plates of interest in bridge details, the concentration factor varies with the relation between the diameter and the plate width, so that different concentration factors are achieved for the same level of **net cross-section** nominal stress. This procedure may be valid if the initiation period is ignored, which is not the case for drilled or reamed holes, as shown for instance by (Gurney 1965) where fatigue strength is correlated with the ultimate tensile strength, thus having an important initiation life.

While the analysis of the entire data set doesn't show any influence of the steel type, a remarkable difference is seen for the results of Quality Group 1 which indirectly indicates the importance of the initiation life in drilled and reamed holes.

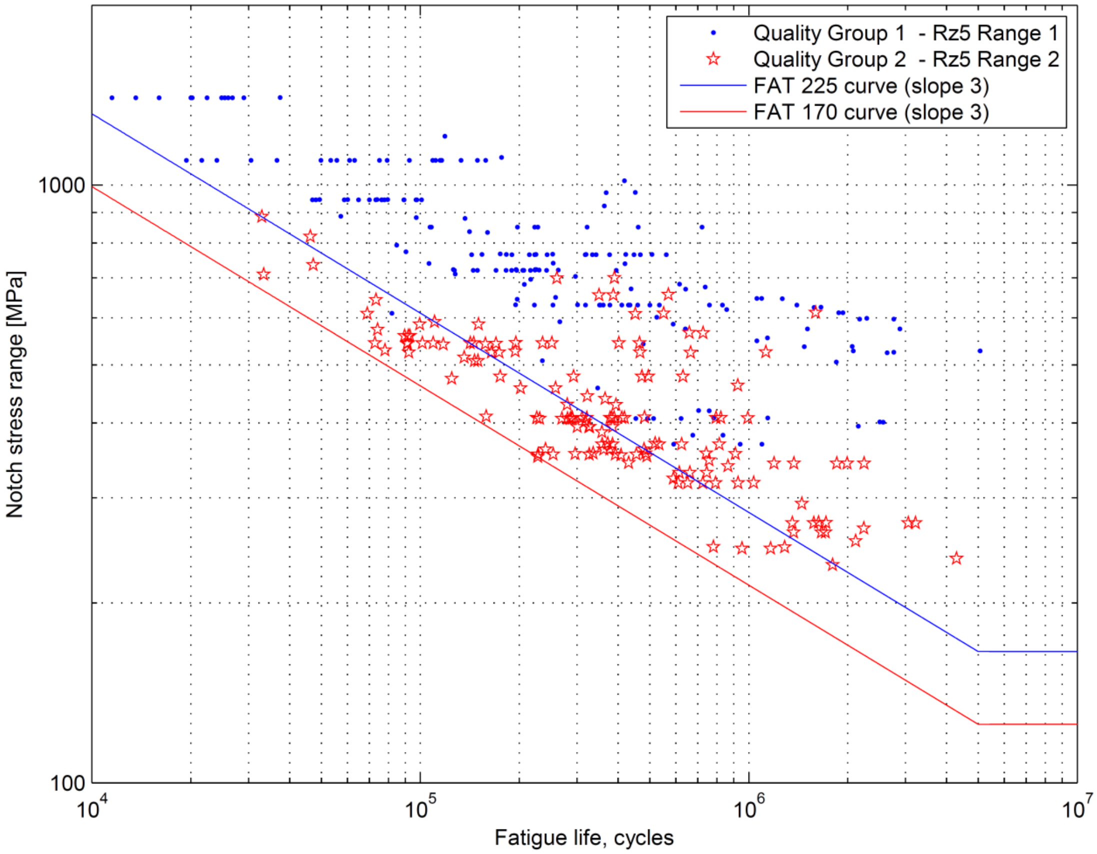

Figure 5 **Characteristic notch stress fatigue curves for quality groups 1 and 2**

As additional graphs, one can show the regression analyses with variable slopes, which show despite the slightly different FAT the validity of the approach with m = 3 fixed used.

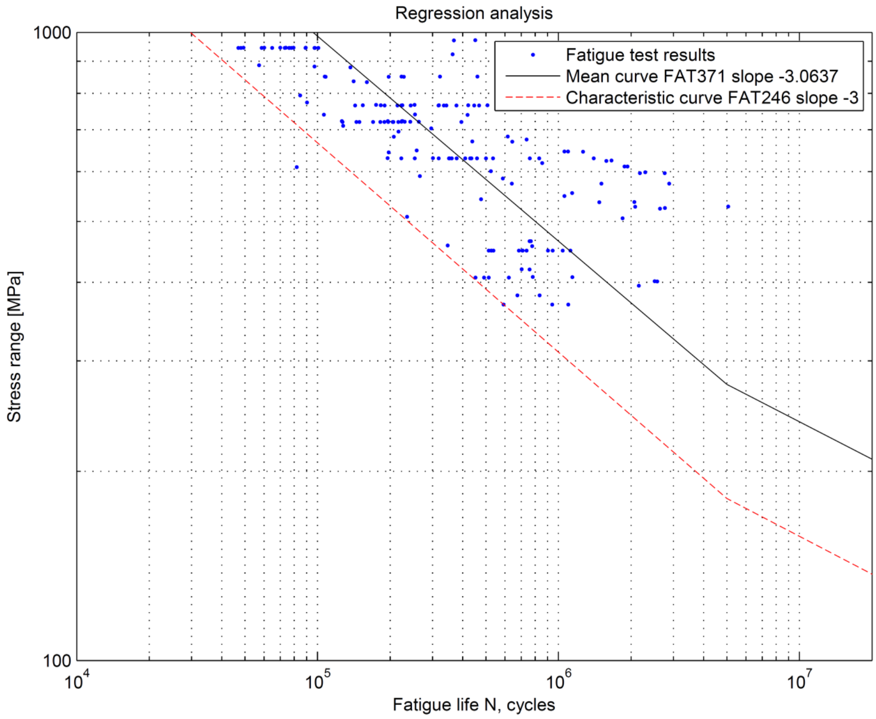

Figure 6 **Characteristic notch stress fatigue curve with m var, for quality group 1**

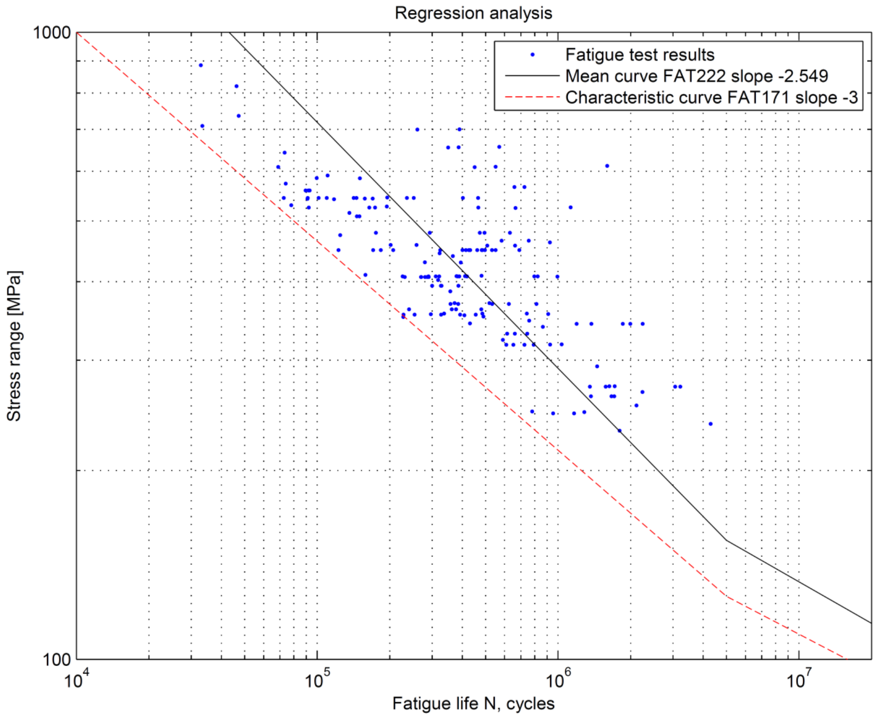

Figure 7 **Characteristic notch stress fatigue curve with m var, for quality group 2**

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