

# Crack propagation modelling for high strength steel welded structural details

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**Abstract.** Nowadays the barrier of applying HSS (High Strength Steel) material in bridge structures is their low fatigue strength related to yield strength. This paper focuses on the fatigue behaviour of a structural details (a gusset plate connection) made from NSS and HSS material, which is frequently used in bridges in Hungary. An experimental research program is carried out at the Budapest University of Technology and Economics to investigate the fatigue lifetime of this structural detail type through the same test specimens made from S235 and S420 steel grades. The main aim of the experimental research program is to study the differences in the crack propagation and the fatigue lifetime between normal and high strength steel structures. Based on the observed fatigue crack pattern the main direction and velocity of the crack propagation is determined. In parallel to the tests finite element model (FEM) are also developed, which model can handle the crack propagation. Using the measured strain data in the tests and the calculated values from the FE model, the approximation of the material parameters of the Paris law are calculated step-by-step, and their calculated values are evaluated. The same material properties are determined for NSS and also for HSS specimens as well, and the differences are discussed. In the current paper, the results of the experiments, the calculation method of the material parameters and the calculated values are introduced.

## 1. Introduction

To determine the fatigue lifetime of welded structural details modelling the fatigue crack propagation can be a more precise method than using the nominal stress based design approach. However, to apply this method specific material constants and loading parameters are required. The tests, which are necessary to determine the required material constants are usually expensive and cumbersome. The most of these experiments needs special equipment, and specimens with specific geometry (C(T) specimen). Another difficulty is, that the most of the previous tests were carried out on C(T) specimens and the main part of the applied structural details in bridges were not tested to determine these material constants. In the current paper a favourable method is introduced, which is able to determine the material constants of the Paris law of fatigue crack propagation for a selected structural detail. To calculate the constant parameter, strain gauge measurements are necessary during the laboratory tests. Using the measured data and the numerical model of the investigated detail the material constants can be determined. The fatigue behaviour of a gusset plate connection was investigated to present the applied calculation method. Fatigue laboratory tests are performed and the numerical model of the structural detail is developed. Applying the measured data, the  $C$  and  $m$  parameters of the Paris law (equation (1))



are determined, and the calculated values of specimens from S235 and S420 structural steels were compared.

## 2. Literature review

### 2.1. General remarks

The previous results show, that the dominant regime of the fatigue lifetime of a welded structural detail belongs to the crack propagation. The fatigue cracks readily initiate due to the presence of the welding, and the crack initiation part of the fatigue lifetime can be neglected [1]. Therefore, the fatigue lifetime of a welded structural detail can be determined using fracture mechanics. One of the most common and simplest form of the mathematical term of the crack propagation is the Paris law, shown by equation (1).

$$\frac{da}{dN} = C \cdot (\Delta K)^m \quad (1)$$

where  $C$  and  $m$  are material parameters,  $\Delta K$  is the stress intensity factor range,  $a$  is the length of the fatigue crack and  $N$  is the number of cycles. To apply the Paris law, the determination of the material constants is necessary. These parameters can be calculated from test results. The length of the crack, the number of cycles and the nominal stress range ( $\Delta\sigma$ ) are necessary to be measure during the tests. From the nominal stress range and the length of the crack, the stress intensity factor range can be calculated by equation (2).

$$\Delta K = \Delta\sigma\sqrt{\pi a} \quad (2)$$

The number of cycles and the nominal stress range is easy to measure, because they depend on the loading method and the geometry of the specimen, which is defined by the researcher. The measuring of the length of the fatigue crack is the most difficult part of the experiments. According to previous studies and standards there are two main methods to determine the length of the cracks. These methods are the visual method and the indirect methods [2].

### 2.2. Visual method of the measuring of the length of the fatigue crack

The initial and the final crack size can be determined from the crack surface after the failure of the specimen. The length of the initial or the final crack has to be measured several individual local points, then their lengths can be calculated by averaging the measurements. To measure the change in the crack size ( $\Delta a$ ), the front of the crack has to be marked by some treatment. One of the crack-front marking methods is cooling down the specimen to low temperatures, for example by immersing in liquid nitrogen. The fracture mechanics analyses are usually based on two-dimensional methods, the crack must be defined with a single length, but the crack exhibits a curved front, thus the averaging of the measured lengths is necessary. Visual crack-length measurements are usually done with a microscope on a calibrated traveling stage [2]. Another way to determine the length of a fatigue crack is measuring the surface crack length by an optical (Figure 1 a)) or scanning electron microscope. In this case the surface crack length has to be measured on the both sides of the specimen, then the crack length can be determined by statistical methods [3].

### 2.3. Indirect methods of the measuring of the length of the fatigue crack

Two methods will be presented in the following. On one hand these procedures do not measure the crack length directly, they use the deformation properties of the specimen or electric potential techniques to determine the length of the fatigue crack. On the other hand, it is a big advantage of these ways, that they average the crack length over the cross-section of the specimen.

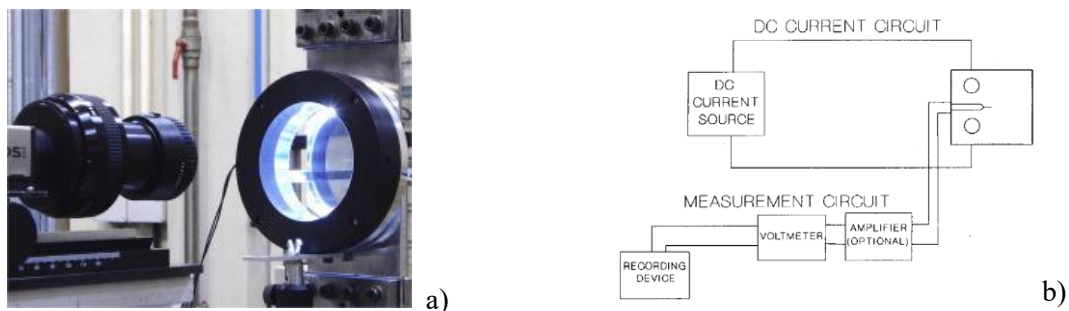
#### **Elastic compliance method**

This method uses the changing of the elastic compliance of the specimen to calculate the length of crack. When the crack length increases, the slope of the force-deformation diagram of the specimen varies, thus the tangential elastic compliance of the specimen varies as well. For a standard C(T) (compact

tension) specimen the normalized crack length-plane stress elastic compliance function is given in the standards [3], from which the actual length of the crack can be determined.

### ***Electrical potential difference (EPD) method***

This method is based on the principle, that the electrical field in a cracked specimen with a current flowing through it is a function of the crack size. For a constant current flow, the voltage drop across the crack plane will increase with increasing the length of the crack due to modification of the electric field. The alteration in voltage can be related to crack length through analytical or experimental calibration relationships (Figure 1 b)).

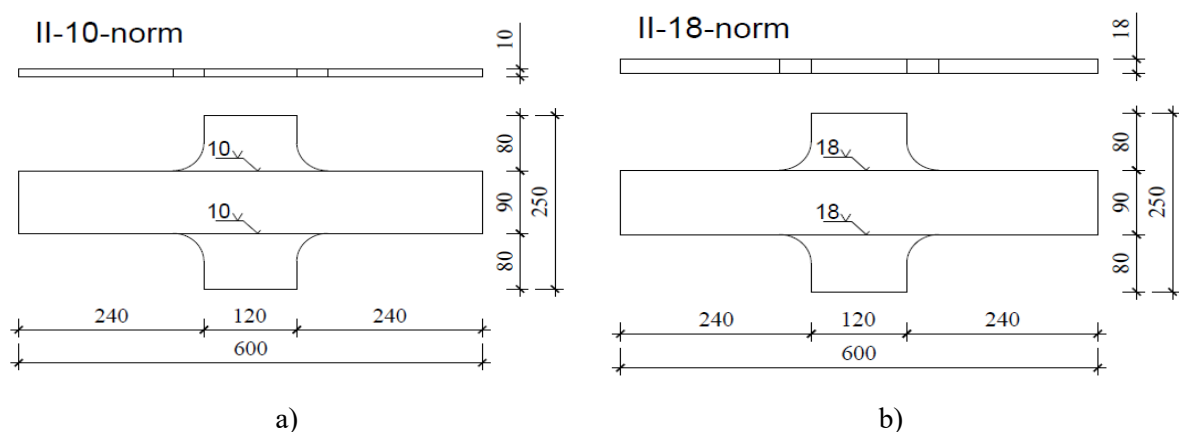


**Figure 1** a) Visual crack measuring; b) EPD test set up [ ]

## **3. Experimental research program**

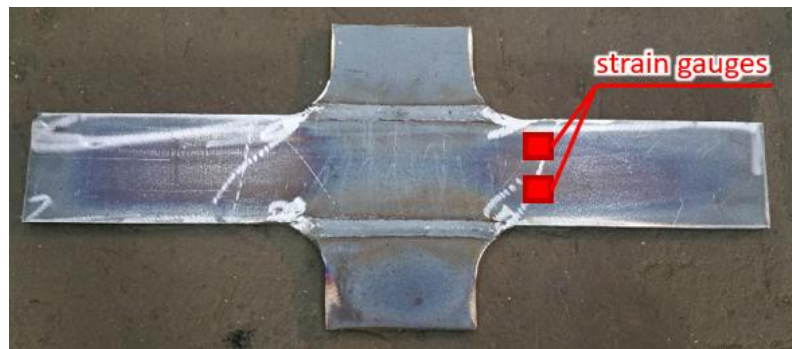
### ***3.1. Test specimens and test set up***

A total of 6 fatigue tests are conducted on flange gusset joint specimens. Two types of geometries are investigated within the current research program. The geometries and the dimensions of the specimens (II-10-norm and II-18-norm) are shown in Figure 2.



**Figure 2** a) Geometry of II-10-norm specimens; b) Geometry of II-18-norm specimens

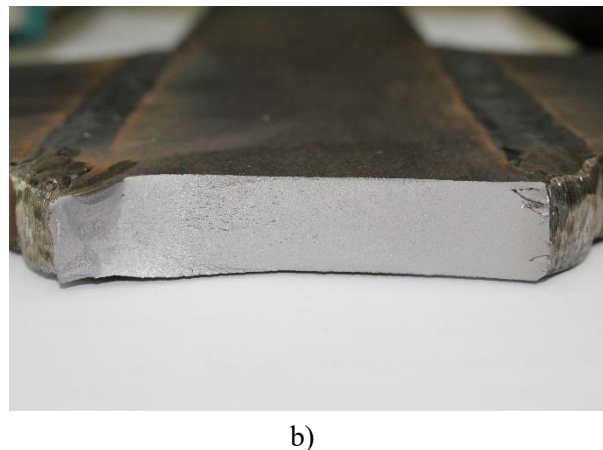
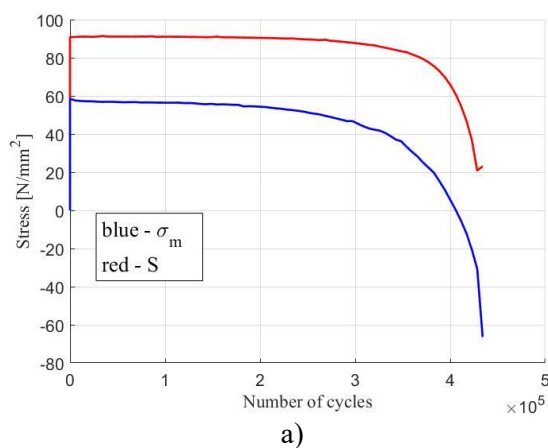
These test specimens are produced from NSS (S235) and from HSS (S420) material to be able to compare the fatigue behaviour of NSS and HSS structures. The another type of geometry and the dimensions of the specimens (X-18-norm) are also shown in Figure 2 b). These test specimens are produced only from NSS (S235) material to investigate the size effect on the fatigue behaviour. The post-weld treatment methods are also investigated on this structural detail. Several specimens are treated by disc grinding, and these specimens are also tested to determine the effect of the post-weld treatment method on the fatigue lifetime. The loading method of these specimens is the same as the loading method of the cruciform joint specimens.



**Figure 3** Position of strain gauges

### 3.2. Results of experiments

The aim of the research program is to recommend a fatigue crack propagation method. Therefore the main results of the experiments are the cyclic sample – stress range diagrams of the test specimens (Figure 4 a)), from which the material constants of the Paris law are recalculated. The other important information from the experiments are the crack patterns. One typical crack pattern observed for this specimen type is presented in (Figure 4 b)). From the pictures the point of the crack initiation and the path of the crack propagation can be clearly determined.

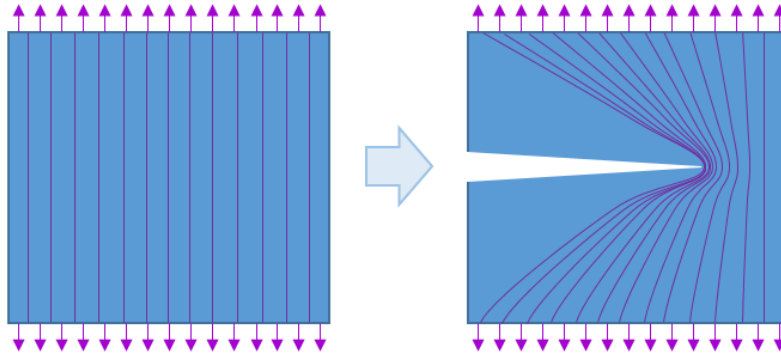


**Figure 4** a) Data measured by a strain gauge at the crack; b) crack pattern of the specimen

## 4. Processing of the test results

The experimental and numerical calculation methods to determine the material properties of the Paris law require special test specimens and special facilities, thus the tests become more expensive and more complicated. In this research program a different method is applied to determine the crack propagation constants of a structural detail. This method is based on the measured data of the strain gauges. When the length of the fatigue crack varies, the measured strains and therefore the calculated stresses are changing in the surrounding area of the fatigue crack. Investigating the measured data of the strain gauges it can be observed, as the length of the crack increases, the stresses next to the crack decrease, but the stresses on the opposite side increase. The reason of this phenomenon is that the path of the stress lines vary close to the fatigue crack, as presented in Figure 5. To calculate the material constants ( $m$  and  $C$ ), the crack propagation rates and the length of the cracks have to be determined from the measured data [4]. In this method an equivalent crack length (ECL) is used which differs from the real crack in its size and shape. The equivalent crack is a through-thickness crack and it has a crack front which is always perpendicular to the surface of the base plate. The direction of the crack propagation is always

perpendicular to the edge of the base plate. This neglecting is in good agreement with the analysis of crack pattern showed in Figure 4 b).



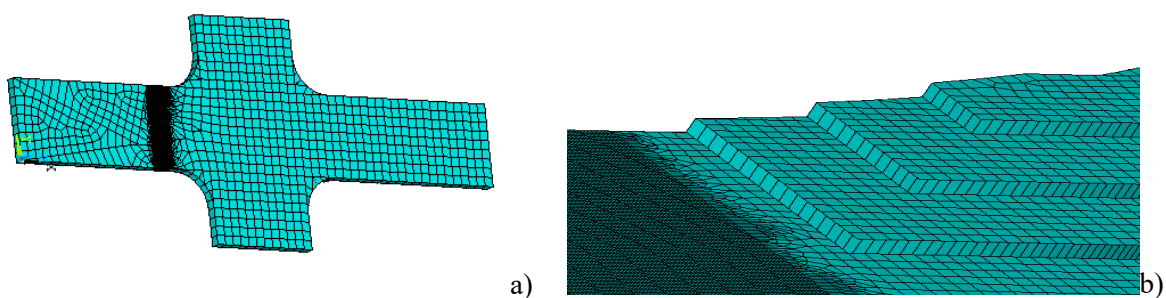
**Figure 5** Alteration of the stress field due to crack propagation

Another approximation is the simplification of the equation (1). The original differential equation was reduced to a simplified version as shown by equation (3).

$$\frac{\Delta a}{\Delta N} = C \cdot (\Delta K)^m \quad (3)$$

#### 4.1. Determination of the ECL

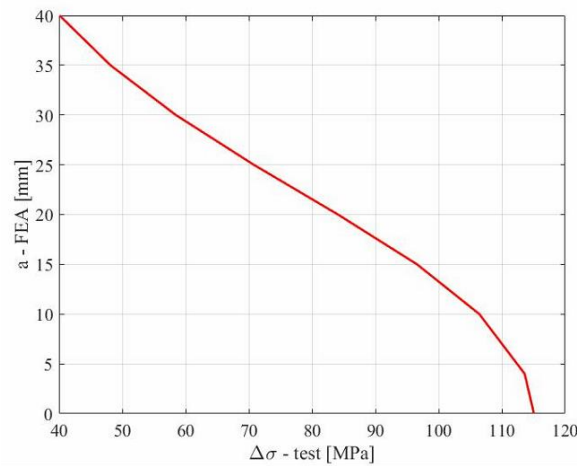
The numerical model of the investigated specimen is developed in ANSYS 17.2 [5]. The model is based on a full solid model using eight-node structural solid elements. To analysing the tip of the equivalent crack, a concentration keypoint is defined in the crack tip, thus the stress intensity factor could be determined in the crack tip using the FE model (Figure 6 a)). The geometry of the models is the same as the specimens' (Figure 6 b)). The ECL is a variable parameter of the numerical model from 0 to 40 mm. The stresses at the position of the strain gauges are calculated, hence the ECL can be plotted as a function of the measured stresses or the function of the stress ranges (Figure 7). Thus for an optional stress range ( $\Delta\sigma_i$ ) the ECL ( $a_i$ ) can be determined.



**Figure 6** a) FE model of the specimen; b) Modelled welded joint

#### 4.2. Determination of the number of cycles

According to the recorded data the length of a measurement (10 s) and the length of the break (900 s) between the measurements and the time of failure could be localized. By the frequency of the loading and the calculated time of a cycle the number of this cycle are determined. Using this calculation method for all measured parameter, a number of cycle – stress range diagram could be plotted. From this diagram the stress range ( $\Delta\sigma_i$ ) are determined for every number of cycles ( $N_i$ ).



**Figure 7** The ECL ( $a$ ) values as a function of the measured stress ranges ( $\Delta\sigma$ )

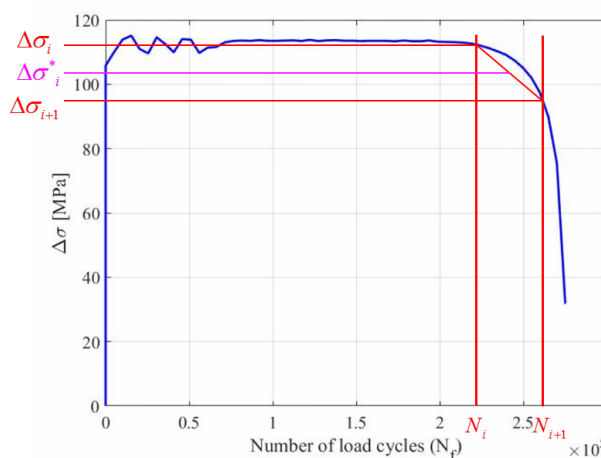
#### 4.3. Determination of the crack growth rate

According to the simplified equation (3) the crack growth rate is calculated by the ratio of  $\Delta a$  and  $\Delta N$ , where  $\Delta a$  is the difference of two ECLs and  $\Delta N$  is the difference of two numbers of cycles (Figure 8), which are calculated from two next test data. The crack propagation rate is calculated by equation (4).

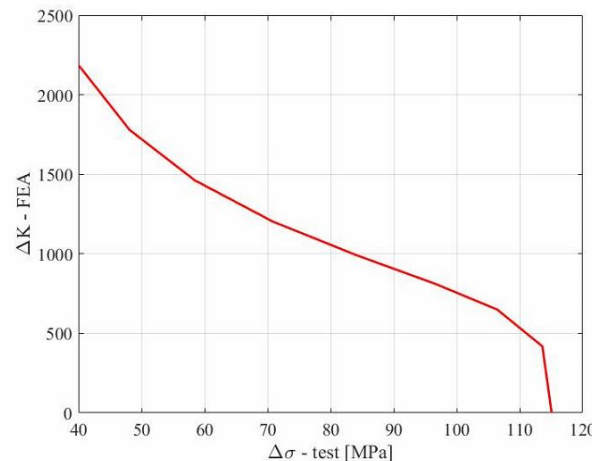
$$\frac{\Delta a_i}{\Delta N_i} = \frac{a_{i+1} - a_i}{N_{i+1} - N_i} \quad (4)$$

#### 4.4. Determination of the stress intensity factor range (SIFR)

The method, introduced in Section 4.1. can be applied to determine the stress intensity factor range ( $\Delta K_i^*$ ). Using the numerical model of the specimen, the stress range – SIFR diagram is plotted in Figure 9. However, there is a difference between the two cases. When the  $\Delta a$  is determined, two ECLs were used, thus two different stress ranges ( $\Delta\sigma_i$  and  $\Delta\sigma_{i+1}$ ) are applied for the calculation. Determining the stress intensity factor range is needed only one stress range. In this method the average of the two stress range is calculated (equation (5)), and it is used to get the SIFR from the stress range – SIFR diagram.



**Figure 8** Determination of SIFR ( $\Delta K$ ) and  $\Delta N$



**Figure 9** The SIFR ( $\Delta K$ ) values as a function of the measured stress ranges ( $\Delta\sigma$ )

$$\Delta\sigma_i^* = \frac{\Delta\sigma_i + \Delta\sigma_{i+1}}{2} \quad (5)$$

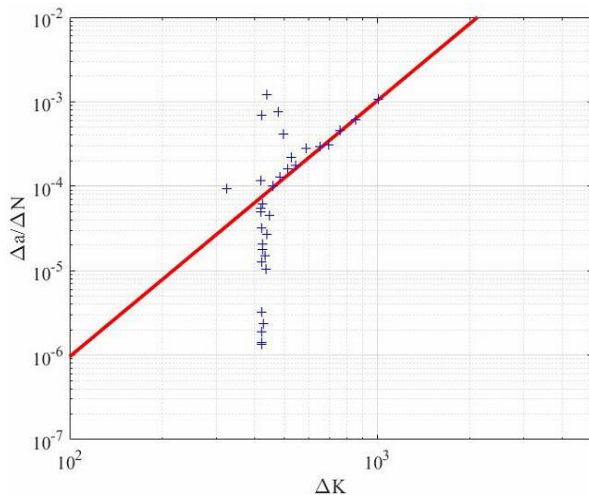
#### 4.5. Determination of the material constants ( $m$ and $C$ ) of the Paris law

When all required variables are calculated for all measurements, the crack propagation rates and the SIFRs can be write in the equation (1). This equation is an exponential equation, but the solution can be simplified if some reforming is applied, as shown by equation (6).

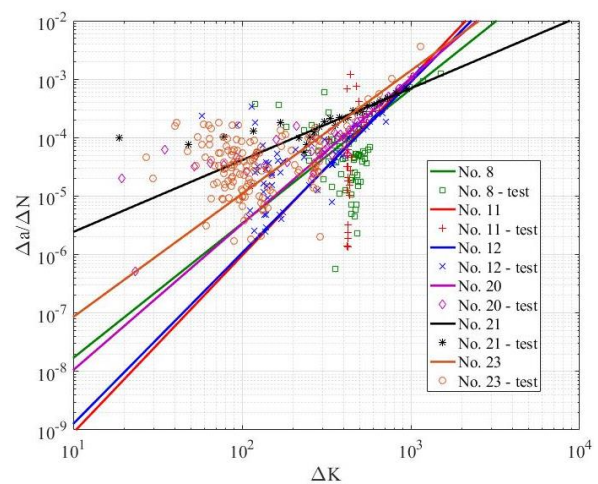
$$\log \frac{da}{dN} = \log C + m \cdot \log(\Delta K) \quad (6)$$

After the reformulation of the equation, the method of linear least squares is applied to calculate  $m$  and  $\log(C)$  from equation (6) using the previously determined parameters. The calculation results are summarized in

Table 1.



**Figure 10** Fatigue crack propagation diagram of specimen No. 11



**Figure 11** Fatigue crack propagation diagram of all specimens

Moreover, the final ECL is determined from the final measured data of the experiment. This ECL belongs the measured stress range next to the first value, which drops off to zero.

**Table 1** Parameters and results of the experiments

No. of the specimens	Material	Thickness [mm]	Post weld treatment	$\Delta\sigma$ [MPa]	$N_f$	$m$	$C$	$a_f$ [mm]
<b>8</b>	S235	10	disc grinding	100	672400	2.30	8.51E-11	33.533
<b>11</b>	S420	10	none	100	275200	3.03	8.31E-13	23.152
<b>12</b>	S420	10	disc grinding	78	530800	2.92	1.50E-12	33.855
<b>20</b>	S235	18	none	86	442200	2.50	3.34E-11	36.056
<b>21</b>	S235	18	none	74	519200	1.23	1.44E-07	35.654
<b>23</b>	S235	18	disc grinding	136	1310000	2.11	2.11E-10	32.641

$\Delta\sigma$  : stress range;  $N_f$  : fatigue lifetime;  $m$  and  $C$ : material constants of Paris law;  $a_f$  : final/critical equivalent crack size

## 5. Evaluation of the test results

Investigating the results and the calculated material constants the following conclusion are drawn. The most conspicuous one is that the slope of the crack propagation diagram in stage II is the commonly used value [6] ( $m = 3$ ) for S420, but it is smaller in the case of the S235 material. According to this conclusion if this type of structural details is analysed, the “ $m = 3$  constant” can be used for the crack propagation calculations, however using S235 steel, a more favourable behaviour is observed. The main part of the fatigue lifetime of the welded details comes from the crack propagation, thus applying the Paris law of crack propagation the fatigue lifetime can be calculated for the welded joint. To use this method, the material constants and the initial and final crack length (or ECL) is necessary. As the results of

Table 1 shows, the final ECL is approximately the same in all the analysed cases. There are different recommendations to the initial crack length for different structural details in [4] and [7]. Using the material constants of

Table 1 the fatigue lifetime of the investigated structural detail can be calculated. Investigating the effect of the thickness of the material it can be stated that the plate thickness has no significant effect on the slope of the crack propagation diagram. The same phenomenon is determined when the effect of the post weld treatment is analysed. The material constant ( $m$ ), which represents the slope of the crack propagation diagram in stage II, is the same to both as-welded and disc grinded specimens.

## 6. Summary

In this paper an alternative method is introduced to determine the material constants of Paris law of crack propagation. Using the measured data from strain gauges and the calculated results from the FEM, an equivalent crack length (ECL) is determined for every measurement regime. According to the results of the FEM, the stress intensity factor ranges (SIFR) are calculated for every ECL. Knowing the number of load cycles, the crack propagation rates are determined for every calculated SIFR, thus the crack propagation diagram are plotted for each specimen. If these diagrams are given, the material constants ( $C$  and  $m$ ) and the final (critical) ECL could be calculated. These parameters were compared in the cases of different plate thicknesses (10 and 18 mm) and different types of material (S235 and S420). It can be observed, that the crack propagation behaviour of the S235 material is more favourable in the cases examined. On the other hand, there is no significant effect of the disc grinding on the crack propagation behaviour. Thus it can be declared, that the higher fatigue lifetime of the specimen with post weld treatment comes from the crack development phase and it has no impact on the crack propagation phase.

## References

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